Preface

On behalf of the organizing committee, we would like to cordially welcome to all participants to the *"9th International Symposium on Intrinsic Josephson Effects and THz Plasma Oscillations in High-T_c Superconductors (THz-Plasma2014)"* being held in Kyoto University Centennial Clock tower, Kyoto Japan, from November 30 to December 3, 2014.

The series of symposium was initiated by Professor T. Yamashita and Professor M. Tachiki on the occasion of the novel Josephson plasma phenomenon in high temperature layered superconductors. This symposium is the 9th one followed by Izmir (2012), Hirosaki (2010), Pohang (2008), London (2006), Tsukuba (2004), Pommersfelden (2002), and Sendai (2000, 1997). The conference will focus on various topics related to intrinsic Josephson junctions and novel phenomena in Josephson junction systems. The conference is intended to provide an opportunity to get together, to exchange information and ideas, to promote stimulus discussions and collaborations among participants and furthermore to foster young scientists. THz-plasma2014 is being the most comprehensive and scientifically popular conference in the hot topics related to strong, coherent and continuous terahertz radiation phenomena, including much of the advances in the field of terahertz science and applications and noble macroscopic quantum phenomena and others. No doubt, it provides an excellent opportunity for the participants to involve themselves in extremely fruitful interpersonal exchange of ideas, perspectives and outlooks.

Kyoto is a world-famous historic city, which has been the capital of Japan (the residence of the emperor *Tenno*) since 794 to 1867. The "Historic Monuments of Ancient Kyoto" has been listed by the UNESCO as a World Heritage Site since 1994. These include the Simo-Kamo shrines and Ginkaku-ji, which are located within walking distances from the conference venue. Furthermore, now, the deep autumn, is the best season for visiting Kyoto because we enjoy a striking contrast between colored leaves and stone gardens.

Finally, we want to express our special gratitude to all the participants, and we would also like to thank our colleagues in the organizing committee, whose commitment enabled us to achieve our goal. In particular, Dr. Manabu Tsujimoto, Ms. Reiko Nakanishi, and graduate students in Kyoto University are acknowledged for continuous support for the conference. Furthermore, we are grateful for financial and technical supports from Graduate School of Engineering, Kyoto University, Japan Society for Applied Physics Kansai Chapter, The Kyoto University Foundation, Nippon Sheet Glass Foundation for Materials Science and Technology, and other supporting companies and societies.

Sincerely yours,

Itsuhiro Kakeya
Kyoto University

Kazuo Kadowaki
University of Tsukuba

Chairs of the organizing committee

Committee Members

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Kazuo Kadowaki	University of Tsukuba
Itsuhiro Kakeya	Kyoto University

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Akira Fujimaki	Nagoya University
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Masashi Tachiki	Tohoku University
Tsutomu Yamashita	Tohoku University

Local organizing committee

Manabu Tsujimoto	Kyoto University
Shizuo Fujita	Kyoto University
Kentaro Kaneko	Kyoto University
Iwao Kawayama	Osaka University

Previous Conferences

1997	Sendai, Japan, February 23–25
2000	Sendai, Japan, August 22–24
2002	Pommersfelden, Germany, June 29 – July 4
2004	Tsukuba, Japan, November 26–28
2006	London, UK, July 17–19
2008	Pohang, Korea, July 17–19
2010	Hirosaki, Japan, April 29 – May 2
2012	Izmir, Turkey, June 10–13

Scope

- Physics on intrinsic Josephson junctions
- Terahertz radiation from superconductors
- Phase dynamics of Josephson junctions
- Superconductor-ferromagnet heterostructures
- Superconducting metamaterials
- High frequency and optical detection by Josephson junctions and superconducting nanowires
- Intrinsic Josephson effect and vortex physics in novel superconductors

Sponsors

THz-Plasma 2014 is sponsored by Graduate School of Engineering, Kyoto University, The Japan Society for Applied Physics (Kansai Chapter), The Kyoto University Foundation, and Nippon Sheet Glass Foundation for Materials Science and Technology.

We also thank the co-sponsors below:

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List of Presentations

Invited speakers

Steven Anlage	*University of Maryland*	Monday morning, Dec. 1
Hidehiro Asai	*AIST*	Wednesday morning, Dec. 3
Alexander Buzdin	*University of Bordeaux*	Monday afternoon, Dec. 1
Jian Chen	*Nanjing University*	Wednesday morning, Dec. 3
Edward Goldobin	*University of Tübingen*	Monday evening, Dec. 1
Xiao Hu	*NIMS*	Tuesday morning, Dec. 2
Akinobu Irie	*Utsunomiya University*	Monday afternoon, Dec. 1
Takekazu Ishida	*Osaka Prefecture University*	Wednesday morning, Dec. 3
Takanari Kashiwagi	*University of Tsukuba*	Monday morning, Dec. 1
Iwao Kawayama	*Osaka University*	Wednesday morning, Dec. 3
Reinhold Kleiner	*University of Tübingen*	Monday morning, Dec. 1
Richard Klemm	*University of Central Florida*	Tuesday morning, Dec. 2
Alexei Koshelev	*Argonne National Laboratory*	Tuesday morning, Dec. 2
Vladimir Krasnov	*Stockholm University*	Wednesday afternoon, Dec. 3
Yannis Laplace	*MPI for the Structure and Dynamics of Matter*	Wednesday afternoon, Dec. 3
Hu-Jong Lee	*Pohang University of Science and Technology*	Monday afternoon, Dec. 1
Chih-Wei Luo	*National Chiao Tung University, Taiwan*	Monday afternoon, Dec. 1
Hidetoshi Minami	*University of Tsukuba*	Monday afternoon, Dec. 1
Philip Moll	*ETH Zürich*	Tuesday morning, Dec. 2
Paul Müller	*University of Erlangen*	Tuesday morning, Dec. 2
Kensuke Nakajima	*Yamagata University*	Wednesday afternoon, Dec. 3
Shuuichi Ooi	*NIMS*	Monday morning, Dec. 1
Yukihiro Ota	*Japan Atomic Energy Agency*	Tuesday morning, Dec. 2
Lutfi Ozyuzer	*Izmir Institute of Technology*	Wednesday afternoon, Dec. 3
Paul Seidel	*Friedrich Schiller University Jena*	Monday evening, Dec. 1
Yury Shukrinov	*Joint Institute for Nuclear Research, Russia*	Monday evening, Dec. 1
Takashi Tachiki	*National Defense Academy of Japan*	Monday afternoon, Dec. 1
Francesco Tafuri	*Second University of Naples*	Wednesday morning, Dec. 3
Manabu Tsujimoto	*Kyoto University*	Monday afternoon, Dec. 1
Alexey Ustinov	*Karlsruhe Institute of Technology*	Wednesday morning, Dec. 3
Yoshinori Uzawa	*NICT*	Monday morning, Dec. 1
Huabing Wang	*NIMS*	Monday afternoon, Dec. 1
Ulrich Welp	*Argonne National Laboratory*	Monday morning, Dec. 1
Taro Yamashita	*NICT*	Monday afternoon, Dec. 1

Contributed talks

Muhammad S. Anwar	*Kyoto University*	Monday afternoon, Dec. 1
Gaku Eguchi	*Kyoto University*	Monday afternoon, Dec. 1
Min Ji	*Nanjing University*	Wednesday afternoon, Dec. 3
Hitoshi Kambara	*Kyoto University*	Wednesday afternoon, Dec. 3
Masaru Kato	*Osaka Prefecture University*	Wednesday morning, Dec. 3
Haruhisa Kitano	*Aoyama Gakuin University*	Wednesday afternoon, Dec. 3
Mohammad Kolahchi	*Institute for Advanced Studies in Basic Sciences, Iran*	Monday evening, Dec. 1
Sachio Komori	*Kyoto University*	Tuesday morning, Dec. 2
Feodor Kusmartsev	*Loughborough University*	Wednesday morning, Dec. 3
Masanori Nagao	*University of Yamanashi*	Tuesday morning, Dec. 2
Yilmaz Simsek	*University of Erlangen*	Wednesday afternoon, Dec. 3
Yoshihiko Takano	*NIMS*	Tuesday morning, Dec. 2
Tsuyoshi Tamegai	*The University of Tokyo*	Wednesday afternoon, Dec. 3
Chiharu Watanabe	*University of Tsukuba*	Wednesday afternoon, Dec. 3
Hiroki Yamazaki	*RIKEN*	Monday afternoon, Dec. 1

Poster presenters

Hiroki Akiyama	*The University of Tokyo*	THz-7
Yuki Arakawa	*University of Tsukuba*	Mat-1
Kentaro Asanuma	*University of Tsukuba*	THz-2
Shin-ya Ayukawa	*Aoyama Gakuin University*	JJ-9
Yasemin Demirhan	*Izmir Institute of Technology*	THz-11
Asem Elarabi	*Kyoto University*	Nano-6
Norio Fujita	*Osaka Prefecture University*	Nano-1
Saoto Fukui	*Osaka Prefecture University*	Nano-3
Zhao Huang	*NIMS*	JJ-10
Daiki Kakehi	*Aoyama Gakuin University*	JJ-1
Masataka Kashiwagi	*Osaka Prefecture University*	Nano-4
Takahiro Kato	*Nagaoka University of Technology*	JJ-3
Takeo Kitamura	*University of Tsukuba*	THz-1
Masashi Komatsu	*University of Tsukuba*	Mat-2
Kirill Kulikov	*Joint Institute for Nuclear Research, Russia*	JJ-7
Metin Kurt	*Izmir Institute of Technology*	THz-10
Moitri Maiti	*Joint Institute for Nuclear Research, Russia*	JJ-12
Svetlana Medvedeva	*Moscow Institute of Physics and Technology*	JJ-11
Holger Motzkau	*Stockholm University*	JJ-5
Kurama Nakade	*University of Tsukuba*	THz-4

Yuuya Nakagawa	*Kyoto University*	Mat-3
Tubasa Nishikata	*Nagaoka University of Technology*	THz-9
Taichiro Nishio	*Tokyo University of Science*	Mat-7
Yoshiki Nomura	*Kyoto University*	JJ-4
Tsuyoshi Oiwa	*Kyoto University*	Mat-8
Ilhom Rahmonov	*Joint Institute for Nuclear Research, Russia*	JJ-8
Noeru Sato	*University of Electro-Communications*	Nano-5
Yusaku Takahashi	*Aoyama Gakuin University*	JJ-2
Manabu Tsujimoto	*Kyoto University*	THz-6
Kohei Tsumura	*Tokyo University of Science*	Mat-5
Chien-Ming Tu	*National Chiao Tung University, Taiwan*	THz-12
Masaki Umeda	*Osaka Prefecture University*	Nano-2
Akira Uzawa	*Kyoto University*	Mat-4
Tim Wootton	*University College London*	JJ-6
Takashi Yanagisawa	*AIST*	JJ-13
Takaki Yasui	*University of Tsukuba*	THz-3
Tien-Tien Yeh	*National Chiao Tung University, Taiwan*	Mat-6
Yusuke Yoshioka	*Kyoto University*	THz-5
Xianjing Zhou	*Nanjing University*	THz-8

Scientific Program

Sunday, November 30

Arrival

18:00 – 20:00 Registration / Reception

Monday, December 1

Opening 9:00 – 9:10

Session: THz emission I 9:10 – 10:50 (Chair: Lutfi Ozyuzer)

9:10 – 9:35 **Reinhold Kleiner** 1
Hot spots and THz waves in $Bi_2Sr_2CaCu_2O_8$ intrinsic Josephson junction stacks: Recent developments

9:35 – 10:00 **Takanari Kashiwagi** 2
Development of THz imaging systems by using an IJJ emitter

10:00 – 10:25 **Ulrich Welp** 3
Current filamentation in large $Bi_2Sr_2CaCu_2O_{8+\delta}$ mesa devices observed via luminescent and scanning laser thermal microscopy

10:25 – 10:50 **Yoshinori Uzawa** 4
Performance of terahertz superconducting receivers for the ALMA telescope

Coffee break 10:50 – 11:10

Session: Nanostructure/Josephson 11:10 – 12:25 (Chair: Shiro Kawabata)

11:10 – 11:35 **Taro Yamashita** 5
Recent progress of superconducting nanowire single-photon detector and its applications

11:35 – 12:00 **Shuichi Ooi** 6
Detection of vortex state in mesoscopic intrinsic Josephson junctions stacks

12:00 – 12:25	**Steven Anlage** *Coherence and transparency in rf SQUID metamaterials*	7

Lunch 12:25 – 14:00

Session: THz emission II 14:00 – 16:05 (Chair: Alexei Koshelev)

14:00 – 14:25	**Huabing Wang** *Some efforts on improving performance and understanding mechanism of THz emission in intrinsic Josephson junctions*	8
14:25 –14:50	**Manabu Tsujimoto** *Dynamic control of temperature distributions and terahertz waves in stacks of intrinsic Josephson junctions in* $Bi_2Sr_2CaCu_2O_{8+\delta}$	9
14:50 – 15:15	**Hidetoshi Minami** *THz IJJ emitters operated at liquid nitrogen temperatures and 1.3 THz emission at 30 K*	10
15:15 – 15:40	**Akinobu Irie** *Fabrication and characterization of intrinsic Josephson junction THz oscillators*	11
15:40 – 16:05	**Takashi Tachiki** *Evaluation of cavity modes and radiation power of THz-wave oscillators using intrinsic Josephson junctions*	12

Tea break 16:05 – 16:30

Session: Interface/topological materials 16:30 – 18:30 (Chair: Xiao Hu)

16:30 – 16:55	**Alexander Buzdin** *Short vs long-ranged proximity effect in S/F/S Josephson junctions*	13
16:55 – 17:10	**Muhammad Anwar** *Development of ferromagnet* $SrRuO_3$ *and spin triplet superconductor* Sr_2RuO_4 *junctions*	14
17:10 – 17:25	**Hiroki Yamazaki** *Superconducting proximity effects in Nb/rare-earth bilayers*	15
17:25 – 17:50	**Hu-Jong Lee** *Josephson coupling via robust surface conducting layers in 3D topological insulators*	16

17:50 – 18:15 **Chih-Wei Luo** 17
THz emission and detection on surface carriers in topological insulators

18:15 – 18:30 **Gaku Eguchi** 18
Ideal surface Dirac cone and its transport properties in the topological insulator $TlBiSe_2$

Light meal 18:30 – 19:00

Session: Josephson junctions 19:00 – 20:30 (Chair: Vladimir Krasnov)

19:00 – 19:25 **Paul Seidel** 19
Modeling different kinds of Josephson junctions and circuits for interpretation of their electrical characteristics

19:25 – 19:50 **Yury Shukrinov** 20
Effects of coupling in intrinsic Josephson junctions under external electromagnetic radiation

19:50 – 20:15 **Edward Goldobin** 21
Experiments with ferromagnetic φ Josephson junctions

20:15 – 20:30 **Mohammad Kolahchi** 22
Resonance overlap as the origin of structured chaos in Josephson junctions

Tuesday, December 2

Session: THz emission III 9:00 – 10:40 (Chair: Kazuo Kadowaki)

9:00 – 9:25 **Xiao Hu** 23
Josephson phenomena in novel superconducting states

9:25 – 9:50 **Yukihiro Ota** 24
Numerical simulations of terahertz emission from intrinsic Josephson junctions with variation of the number of junctions

9:50 – 10:15 **Alexei Koshelev** 25
Role of dissipation, disorder, and thermal noise in synchronization of intrinsic Josephson junctions

10:15 – 10:40 **Richard Klemm** 26
Emission distributivities from novel geometrical antennas

Coffee break 10:40 – 11:10

Session: Intrinsic Josephson junction I 11:00 – 12:35 (Chair: Reinhold Kleiner)

11:00 – 11:25 **Phillip Moll** 27
Intrinsic Josephson junctions in the iron-based multi-band superconductor $(V_2Sr_4O_6)Fe_2As_2$

11:25 – 11:50 **Paul Müller** 28
Doping of high-T_c *superconductors by carrier injection*

11:50 – 12:05 **Yoshihiko Takano** 29
New BiS_2*-based superconductors*

12:05 – 12:20 **Masanori Nagao** 30
Growth and c-axis transport property of $PrO(F)BiS_2$ *single crystal*

12:20 – 12:35 **Sachio Komori** 31
Underdamped intrinsic Josephson junctions in $Pb_{1-y}Sr_2Y_{1-x}Ca_xCu_{2+y}O_{7+\delta}$ *epitaxial films*

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Poser session 18:30 – 20:30

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Session: Metamaterials 9:00 – 10:30 (Chair: Steven Anlage)

9:00 – 9:25 **Alexey Ustinov** 32
Superconducting metamaterials

9:25 – 9:50 **Hidehiro Asai** 33
Peculiar electromagnetic response of quantum metamaterial composed of Superconducting qubits

9:50 – 10:15 **Iwao Kawayama** 34
Nonlinear responses of superconducting thin films induced by intense terahertz pulses

10:15 – 10:30 **Fedor Kusmartsev** 35
Topological fractal metamaterials composed of electrically isolated Pi-rings for THz-radiation devices

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Session: Nanostructure/detector 10:50 – 12:20 (Chair: Paul Seidel)

10:50 – 11:15 **Francesco Tafuri** 36
Nano domain encoding in transport properties of unconventional Josephson junctions and nanostructures

11:15 – 11:40 **Takekazu Ishida** 37
Novel current-biased kinetic inductance detectors aiming at neutron radiography

11:40 – 12:05 **Jian Chen** 38
Terahertz detectors working at room temperature

12:05 – 12:20 **Masaru Kato** 39
Modified molecular-dynamics method for vortex dynamics in nano-structured superconductors

Lunch 12:20 – 14:00

Session: Intrinsic Josephson junction II 14:00 – 15:35 (Chair: Hu-Jong Lee)

14:00 – 14:25	**Vladimir Krasnov** *Generation-detection of nonequilibrium bosons using Bi-2212 intrinsic Josephson junctions: A hint about the pairing mechanism*	40
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16:45 – 17:00	**Tsuyoshi Tamegai** *Thermal imaging of Bi2212 mesas*	47
17:00 – 17:15	**Chiharu Watanabe** *The effect of temperature distribution on THz emission from high-T_c superconducting THz devices*	48
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JJ-12	*Response of unconventional Josephson junctions to external microwave radiation*	**Moitri Maiti**	61
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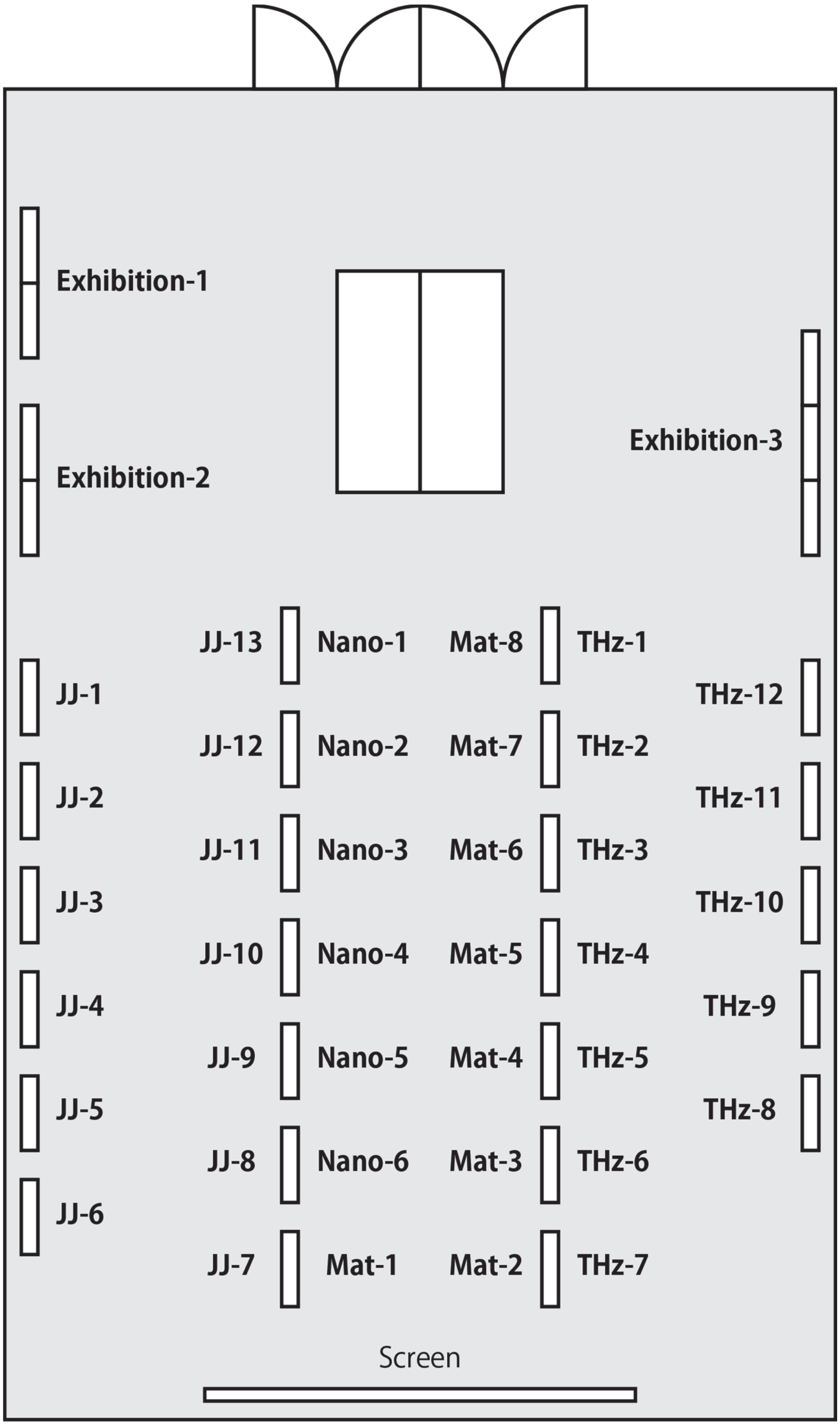
Poster Layout

Session room: International Conference Hall II



Timetable

Time	Sunday, Nov. 3	Monday, Dec. 1 (session)	Monday, Dec. 1	Tuesday, Dec. 2 (session)	Tuesday, Dec. 2	Wednesday, Dec. 3 (session)	Wednesday, Dec. 3	Thursday, Dec. 4
9:00			Opening	THz emission III	X. Hu	Metamaterials	A. Ustinov	Lab tour
10		THz emission I	R. Kleiner					
20					Y. Ota		H. Asai	
9:30			T. Kashiwagi					
40								
50					A. Koshelev		I. Kawayama	
10:00			U. Welp					
10					R. Klemm		F. Kusmartsev	
20			Y. Uzawa					
10:30							Coffee	
40					Coffee			
50			Coffee			Nano. /detector	F. Tafuri	
11:00				Intrinsic Josephson junction I	P. Moll			
10		Nano. /Josephson	T. Yamashita				T. Ishida	
20					P. Müller			
11:30			S. Ooi					
40							J. Chen	
50					Y. Takano			
12:00			S. Anlage		M. Nagao		M. Kato	
10								
20			Lunch		S. Komori		Lunch	
12:30								
40								
50								
13:00					Excursion			
10								
20								
13:30								
40								
50								
14:00		THz emission II	H. B. Wang			Intrinsic Josephson junction II	V. Krasnov	
10								
20			M. Tsujimoto				Y. Laplace	
14:30								
40								
50			H. Minami				H. Kitano	
15:00							H. Kambara	
10			A. Irie					
20							Y. Simsek	
15:30							Tea	
40			T. Tachiki					
50						THz emission IV	L. Ozyuzer	
16:00			Tea					
10								
20							K. Nakajima	
16:30		Interface/topological materials	A. Buzdin					
40							T. Tamegai	
50			M. Anwar					
17:00							C. Watanabe	
10			H. Yamazaki				M. Ji	
20			H. J. Lee					
17:30							Closing	
40								
50			C. W. Luo					
18:00	Registration/ Reception						Banquet	
10			G. Eguchi					
20								
18:30			Light meal		Poster session			
40								
50								
19:00		Josephson junctions	P. Seidel					
10								
20			Y. Shukrinov					
19:30								
40								
50			E. Goldobin					
20:00								
10			M. Kolahchi					
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Hot spots and THz waves in $Bi_2Sr_2CaCu_2O_8$ intrinsic Josephson junction stacks: Recent developments

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[keywords] intrinsic josephson junctions, THz emission, hotspots, low temperature scanning laser microscopy, linewidth of radiation

Stacks of intrinsic Josephson junctions made of the high temperature superconductor $Bi_2Sr_2CaCu_2O_8$ [1] emit coherent radiation at THz frequencies [2,3]. Emission can occur at relatively low bias but also at large input power. At high bias a hot spot forms [4], affecting both the intensity and the linewidth of THz radiation [5]. Despite of several years of research the mechanism of synchronizing the junctions in the stack and the relation of hotspots and THz emission is still under debate [6]. We investigated THz emission and hotspot formation using a combination of transport measurements, electromagnetic wave detection via a superconducting receiver and low temperature scanning laser microscopy [3,4,5]. In this talk recent experimental results of our collaboration will be presented and compared to numerical simulations.

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Development of THz imaging systems by using an IJJ emitter

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[keywords] Bi2212, IJJ, terahertz, imaging

Recently, compact and powerful generators of electromagnetic waves at terahertz (THz) frequencies based on semiconducting devices such as resonant tunneling diodes and quantum cascade lasers *etc.*, have been developed very rapidly, because such a frequency domain has become known to be highly useful not only for basic research in science and technology but also for a wide variety of many practical applications, with special emphasis on various kinds of imaging, high-speed communications, security inspections, medical diagnoses, *etc.*[1] The (sub-) THz electromagnetic wave emission can also be generated by using a high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) mesa structure (IJJ-THz emitter).[2] This emission is unique in operating principle because it is based on the AC Josephson effect and powerful, so far ~30 μW, stable and monochromatic.[1,3] The radiation frequency can be tuned in a frequency range between 0.3 and 1.0 THz by adjusting the size and the shape of the mesa structures. It is remarkable and is worthwhile to mention that a high power of 610 μW was recently reported in an array of three mesa structures operated synchronously.[4]

THz waves can penetrate many packing materials such as paper, cardboard, plastic, and wood, *etc*. In addition, THz waves can be used for the identification and inspection of materials, since many materials usually have their unique fingerprint spectra in this frequency range. We have developed transmission and reflection types of imaging systems for practical uses of our IJJ-THz emitter.[5,6] Hidden objects with high absorption coefficients in the THz region can be detected by using the reflection type of imaging systems. The transmission and reflection types of imaging systems may provide information regarding the bulk and surface structures of the sample, respectively. The different characteristics obtained from those two systems enable us to identify highly reflective and highly absorbing materials. In addition to that, we also developed a THz-wave computed tomography (THz-CT) imaging system which can provide cross-sectional views of the sample's internal structure.[7] By combining these three imaging techniques efficiently, one can obtain unique images useful for practical applications based on the characteristic features of THz waves. In this presentation, we are going to discuss these three THz-imaging systems in details.

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Current filamentation in large $Bi_2Sr_2CaCu_2O_{8+\delta}$ mesa devices observed via luminescent and scanning laser thermal microscopy

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[keywords] thermal imaging, thermal breakdown, current filamentation, $Bi_2Sr_2CaCu_2O_{8+\delta}$ mesa

We have studied the self-heating of a large stack of $Bi_2Sr_2CaCu_2O_{8+\delta}$ intrinsic Josephson junctions, of a configuration designed for THz generation. We compare the results seen via a thermoluminescent imaging technique with those obtained via low-temperature scanning laser microscopy, and find that both techniques reveal the formation of a small hotspot associated with a current filament, whose dimensions and temperature dependence agree closely with theory. Hot spot formation strongly depends on details of the experimental set-up, particularly the efficiency of heat-sinking. By careful heat-sinking the sample we extend the range of thermal imaging to lower temperatures and observe a novel mode of thermal hot spot dynamics. At low temperatures hot-spots with sizes that are significantly smaller the sample size nucleate in a corner (at the edge) of the sample and undergo on increasing bias current a sequence of multistability and hysteretic jumps. Such findings are in agreement with model calculations of the stability of current filaments [1]. At higher temperatures the hot-spot size increases strongly resulting in a location near the center of the sample; and on further increasing temperature the hot-spot size would exceed the sample dimension and a thermal instability no longer occurs.

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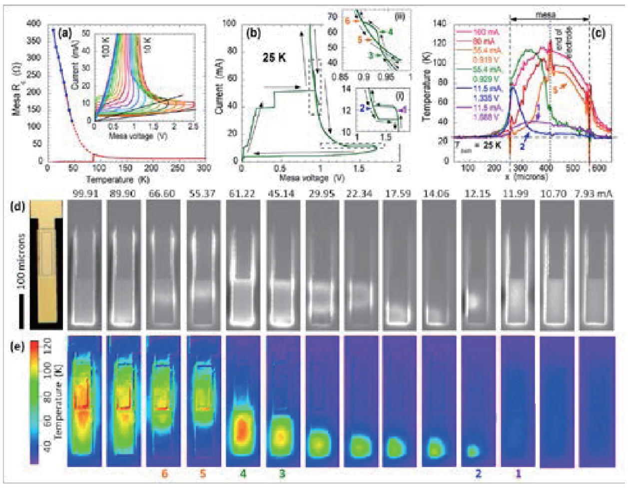

Figure 1: (a) Main image: R(T) for Bi-2212 mesa (red solid curve) measured in absence of self-heating, using 10 μA bias current. Values for $T < T_c$ (blue squares) were determined by extrapolating from the slope of the low-bias I-V characteristic. Inset: I-V curves on downward current sweep. (b) I-V curve for device at a bath temperature of 25 K. Insets (i) and (ii) show regions of I-V characteristic where it is hysteretic due to nucleation and relocation of the hotspot. (c) Temperature profiles of mesa, taken through centerline of hotspot in selected images from (e), which are temperature maps of mesa surface obtained by thermoluminescent imaging. (d) Left-most image is conventional optical micrograph of mesa, showing Au thin film electrode (500 nm thick) extending from right-hand end of the device. Black-and-white images are LTSLM raster scans of the mesa at the same set of bias currents.

Performance of terahertz superconducting receivers for the ALMA telescope

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[keywords] Atacama Large Millimeter/submillimeter Array, radio astronomy, SIS mixer, NbTiN, terahertz time domain spectroscopy

The Atacama Large Millimeter/submillimeter Array (ALMA) is the largest ground-based radio-astronomical telescope located in the Atacama desert, 5000 m above sea level in northern Chile, South America, as a collaboration between East Asia, Europe, and North America. The telescope consisted of 66 antennas covers atmospheric windows in the frequency range from 35 GHz to 950 GHz which is divided into 10 bands. One of Japan's roles in the ALMA project is the development and manufacturing of Band 4 (125-163 GHz), Band 8 (385-500 GHz), and Band 10 (787-950 GHz) heterodyne receivers to be installed in all the antennas. In total, 73 receivers including 7 spares are required for each frequency band.

The ALMA Band 10 receiver uses two double-sideband (DSB) waveguide superconductor-insulator-superconductor (SIS) mixers, one for each orthogonal linear polarization, to down-convert the incoming astronomical signals to a 4-12 GHz intermediate frequency (IF) bandwidth. The SIS mixer employs high-quality Nb tunnel junctions and $Nb_{1-x}Ti_xN$-based tuning circuitry with a large superconducting energy gap. We have tested two kinds of $Nb_{1-x}Ti_xN$ films, different in composition, to meet the ALMA specification for the noise performance of less than 230 K ($5hf/k_B$) for 4 K operation. One was prepared by employing a sputtering target with 20 wt.% Ti and 80 wt.% Nb (x=0.2), and another was with 30 wt.% Ti and 70 wt.% Nb (x=0.3). Both films are deposited on quartz substrates at ambient temperature by reactive DC-magnetron sputtering in a system equipped with a load-lock chamber. A terahertz time domain spectrometer was used to characterize the $Nb_{1-x}Ti_xN$ films. It was shown that the normal-state conductivity of the $Nb_{0.7}Ti_{0.3}N$ films was higher than that of the $Nb_{0.8}Ti_{0.2}N$ films. While the ratio between the superconducting energy gap and the critical temperature ($2\Delta/k_BT_C$) of the $Nb_{0.8}Ti_{0.2}N$ films was larger, meaning that the gap frequency of the films (x=0.2) is higher because T_C of the two kinds of films is similar. All the produced receivers used the $Nb_{0.8}Ti_{0.2}N$ films and successfully achieved excellent performance complying with the stringent ALMA specifications. These receives are now being installed in the ALMA antennas for the full operation. Some of test observation results by using the several receivers will be also shown.

Recent progress of superconducting nanowire single-photon detector and its applications

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[keywords] single photon detector, superconductor, thin film, nanowire

Recently, a superconducting nanowire single-photon detector (SSPD or SNSPD) has been a promising device applicable to a wide range of the research fields. SSPDs have already been used in the various fields, e.g., quantum communication, quantum optics, and life science, because of their many features such as high detection efficiency, low dark counts, and excellent timing resolution [1].

In this work, we present a recent development of high performance multichannel SSPD system [2]. The SSPD devices were fabricated using 5-nm-thick superconducting NbTiN films prepared on thermally oxidized Si substrates. The NbTiN films were formed into 100-nm-wide meandering nanowire covering a square area of 15 μm × 15 μm. In order to enhance the optical absorptance in the nanowire, a 250-nm-thick SiO and a 110-nm-thick Ag mirror covered the nanowire. Fabricated six devices were mounted on the compact fiber-coupled packages and installed in the practical Gifford-McMahon cryocooler system with 0.1 W cooling power. As shown in Fig. 1, the best device showed the system detection efficiency (SDE) of 74%, the dark count rate of 100 cps, and the full-width at half-maximum timing jitter of 68 ps under a bias current of 18.0 μA. For all devices, the SDEs higher than 63% at the dark count rate of 100 cps were achieved.

In the presentation, we also present a new strategy to improve the counting rate further by reducing the filling factor without a degradation of high SDE [3] and a recent development of multi-pixel SSPD array [4]. The developed high-performance and practical SSPD system opens the way for highly efficient and accurate measurements in various applications.

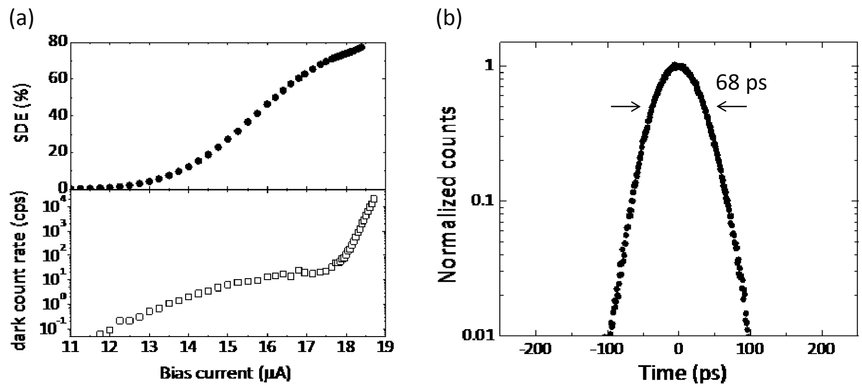

Fig. 1. (a) Bias dependences of SDE and the dark count rate. (b) Histogram of the time-correlated counts.

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Detection of vortex state in mesoscopic intrinsic Josephson junctions stacks

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[keywords] Vortex, Melting transition, mesoscopic Bi2212

Although, in past two decades, melting transition of pancake vortex lattice in the magnetic field perpendicular to the superconducting plane has been extensively studied in bulk single crystals of high-T_c superconductors, vortex state in mesoscopic-scale crystals is still remained as unexplored fields. It is interesting how the vortex phase diagram and the melting transition are modified there by the confinement effect of the boundary, which is not accessible using the conventional superconductors. Intrinsic Josephson junctions (IJJs) can be a probe to detect vortex state in tiny Bi2212 single crystals [1,2]. Then, we studied the c-axis resistance and the critical current of small IJJs stacks (1-10μm square) in the magnetic fields. In the stacks with 5-10 μm lateral sizes, we found an oscillatory behavior of the melting transition line. Since the number of vortices inside the stack is known from counting the resistive jumps by the individual vortex penetrations [2], relation between the oscillation periods and the vortex number can be examined. As a result, it is found that the period of the oscillations is explained by commensurability between square vortex lattice and the square boundary shape.

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Coherence and transparency in rf SQUID metamaterials

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[keywords] rf SQUID metamaterial, Kuramoto model, coherent Josephson oscillations, transparency

We have developed active metamaterials capable of quickly tuning their electrical and magnetic responses over a wide frequency range [1]. These metamaterials are based on superconducting elements to form low insertion loss, physically and electrically small, highly tunable structures for next generation rf electronics [2, 3]. The meta-atoms are rf superconducting quantum interference devices (SQUIDs) that incorporate the Josephson effect. rf SQUIDs have an inductance which includes a contribution from the Josephson inductance of the junction, which is strongly tunable with dc and rf magnetic fields and currents. Metamaterial arrays of interacting rf SQUIDs have been prepared in which the degree of coupling is varied by changing the density of the meta-atoms. The collective response of coupled arrays of rf SQUIDs as a function of dc magnetic field bias are observed to be surprisingly coherent. We examine the reasons for the coherence and quantify the limits for the collective behavior using a Kuramoto-style order parameter. We also observe a unique self-induced transparency of meta-atoms in a certain applied RF power range. Transparency is dependent on DC magnetic field, as well as power sweep direction. The results and interpretations are supported with numerical simulation and analytical modeling.

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Some efforts on improving performance and understanding mechanism of THz emission in intrinsic Josephson junctions

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[keywords] intrinsic Josephson junctions, THz emission, hotspots and standing waves, low temperature scanning laser microscopy

In recent years coherent terahertz (THz) radiation from stacks containing hundreds of $Bi_2Sr_2CaCu_2O_8$ (BSCCO) intrinsic Josephson junctions (IJJs) has attracted a lot of research interest [1-6]. However, in most cases, reported have been frequencies well below 1 THz, or typically around 500 GHz, which obviously can be a bottleneck for many applications. In addition, the mechanism of THz emission in IJJS is still open for discussion. In our study, by optimizing sample structures and material doping levels, we successfully observed THz radiation at fundamental frequencies up to 1.1 THz. We also developed a home-made system, by combining a low-temperature scanning laser microscope (LTSLM) and a THz interferometer. With this setup, we are able to detect THz emission and observe LTSLM images simultaneously. In this talk, we will report the emission over 1 THz obtained in a sandwich structure, the unambiguous observation of the correlation between the standing wave patterns, the hotspot formation and the THz radiation [7-9], and some other efforts on improving performance and understanding mechanism of THz emission in intrinsic Josephson junctions

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Dynamic control of temperature distributions and terahertz waves in stacks of intrinsic Josephson junctions in $Bi_2Sr_2CaCu_2O_{8+\delta}$

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[keywords] intrinsic Josephson junctions, terahertz emission, temperature imaging, hot spots, low temperature scanning laser microscopy

Since the discovery of intense, continuous, and coherent sub-terahertz emission from stacks of intrinsic Josephson junctions (IJJs) in high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) [1], there has been a great deal of interest in the field of both basic and applied researches. For a resent review, see [2]. In most of applications, high power emission of more than 1 mW is required. This could be achieved by using thicker stacks, because the emission power is proportional to the squared number of active IJJs [1]. However, with increasing the number of IJJs, a serious problem that local temperature exceeds even T_c due to the enormous Joule heating and low thermal conductivity of Bi-2212 is encountered. Interestingly, intense emission fairly occurs even in such a catastrophic temperature condition at the high-bias regime [3], affecting both the intensity and the linewidth [4]. Despite several years of research, the mechanism of synchronization in IJJ stacks based on the hot-spot formation is still under debate [5].

In order to clarify the role of temperature inhomogeneity in emission, we have measured local temperature distributions using a fluorescent imaging technique [6]. We studied the relationship between the hot-spot size and the emission intensity. The thermal response differs considerably between the high- and low-bias regimes. We identify the remarkable increase in the intensity by up to 20% by eliminating the excess Joule heat from the stack.

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THz IJJ emitters operated at liquid nitrogen temperatures and 1.3 THz emission at 30 K

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[keywords] Terahertz, Josephson effect, BSCCO, IJJ,

In a frequency region between electric and light waves of 0.3~10 THz, the frequency range of 1~2 THz is especially difficult to generate monochromatic and continuous electromagnetic waves with sizable power (terahertz gap).[1] Quantum-cascade lasers have expanded the frequency range down to 1.2 THz with continuous-wave power of 0.12 mW at 10 K in zero magnetic field,[2] but are necessary to cool below 80 K for getting the laser light below 2 THz.[3] Resonant tunnel diodes have expanded the frequency range up to 1.31 THz,[4] but the power at the frequency above 1 THz is low and at the level of 10 μW. Terahertz emitters composed of the intrinsic Josephson junctions (IJJ's) in high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) work with a quite different mechanism from those semiconductor electronics and photonics devices.[5] Since the BSCCO has the large superconducting energy gap of $2\Delta \sim 60$ mV, the emitting devices can in principle generate the frequency range of 1~2 THz, but the emission at this frequency could not be realized. Although the BSCCO has the superconducting transition temperature T_c of 90 K exceeding the boiling point of nitrogen, liquid helium is needed to cool the emitting devices, which has been an obstacle for practical uses. This work has been performed to overcome these problems.

The IJJ's in BSCCO single crystal work as a dc-voltage to high-frequency current converter, with 1 mV corresponding to 0.483 THz, according to the ac-Josephson effect. When the IJJ's so densely packed in an atomic scale are synchronized by the geometrical cavity resonance effect of a mesa structure, they generate coherently intensified terahertz radiation.[5] Under the application of dc bias, the mesa device suffers from significant Joule heat, resulting in self-heating. Below 50 K, this self-heating occurs very locally (hot-spot) at high bias currents and behaves a shunt register.[6, 7] Therefore, we adopted new device structures which can remove Joule heat more efficiently from the IJJ mesa structure. We have succeeded in optimizing the monochromatic radiation around 0.4 THz at the boiling point of nitrogen. Furthermore we observed the monochromatic radiation around 1.3 THz with TM (2, 0) or TM (3, 0) resonant mode and non-resonant radiation up to 1.65 THz. In this presentation, we show the device structures, the experimental setups and the results in detail.

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Fabrication and characterization of intrinsic Josephson junction THz oscillators

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[keywords] THz emission, intrinsic Josephson junction, cavity resonance, synchronization

Coherent and continuous terahertz (THz) electromagnetic wave radiation from intrinsic Josephson junctions (IJJs) in $Bi_2Sr_2CaCu_2O_y$ (BSCCO) single crystals has been intensively studied[1-3]. Most of the previous experimental studies performed with stacks composed of 500 or more IJJs suggest that the origin of the observable strong emission is related to the cavity resonance. In such a case, one of methods to increase the emission power is an increase in the number N of synchronizing junctions because the emission power is proportional to N^2. However, it causes a decrease in the maximum voltage across the stack which limits the highest oscillation frequency. On the other hand, THz radiation from stacks containing less than 400 IJJs was hardly studied because of not so high output power. In the present work, we have fabricated large IJJ mesas with the length of L=290 μm, width of w =40 - 90 μm and height of h = 150-1000 nm corresponding to the number of junctions N=100-670 and discuss their basic and emission properties. We used two different methods for sample fabrication : standard Ar ion milling and hydrochloric acid modification processes [4]. The latter allows us to fabricate the mesa containing large number of IJJs with comparative ease. The emission was measured by using high sensitivity detector constituted by a small IJJ mesa.

We show that the current-voltage characteristics of the oscillators are strongly influenced by self-heating even if the number of junctions in the stack is less than 400 but the series connection of two stacks improves the heating problem. On the other hand, we have successfully observed the emission from stacks with less than 300 IJJs, which consists of a small number of IJJs as compared with previous studies. Furthermore, it is found that the strong emission corresponds to the in-phase cavity resonance mode and its mode index becomes higher as the number of IJJs decreases.

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Evaluation of cavity modes and radiation power of THz-wave oscillators using intrinsic Josephson junctions

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[keywords] intrinsic Josephson junction, THz-wave oscillator, cavity resonance, radiation power

To increase the radiation power of terahertz (THz)-wave oscillators using intrinsic Josephson junctions (IJJs), cavity resonant modes in a stack of IJJs and the bias dependence of the radiation power were investigated experimentally and theoretically. Three radiation peaks were observed from a $Bi_2Sr_2CaCu_2O_{8+\delta}$ rectangular mesa with w = 78 μm, ℓ = 138 μm and h = 1.0 μm at appropriate bias voltages in low bias region in the *I-V* curves. The radiation frequencies measured using a FTIR spectrometer were 0.499 and 0.649 THz in the peaks at 0.68 and 0.89 V, respectively [1]. However, the frequency was hardly measured in the peak at 0.46 V.

An analytical solution of the coupled sine-Gordon equation was obtained by applying continuous approximation and a radiation boundary condition in a 3D-cavity model for a mesa whose sizes are same as the fabricated one mentioned above. The resonant frequency is [2, 3]

$$f_{mnp} = f_{\mathrm{pl}}\lambda_c \sqrt{\left\{\left(\frac{m\pi}{w}\right)^2 + \left(\frac{n\pi}{\ell}\right)^2\right\} \Big/ \left\{1 + \left(\frac{p\pi\lambda_{ab}}{h}\right)^2\right\}} \tag{1}$$

where f_{pl} is the Josephson plasma frequency. λ_c and λ_{ab} are the c-axis and in-plane London penetration depths, respectively. m, n, p are the mode numbers in the directions along the width w, length ℓ and height h of the mesa. Since the calculated resonant frequencies f_{111} = 0.494 THz and f_{121} = 0.648 THz agree well with the measured radiation frequencies, the observed peaks indicate THz-wave generation by the 111 and 121-mode resonances, respectively in the fabricated mesa. The bias dependence of radiation power obtained from the solution showed three peaks corresponding to the 112, 111 and 121-mode resonances in the bias region from low to high voltages, and traced the experimental result qualitatively. We obtained the radiation power with *mnp* mode

$$P_{mnp} = \frac{8\beta_{\mathrm{c}}\left(\Phi_0 f_{\mathrm{pl}}\right)^2}{\mu_0\, s\, \lambda_{ab} f_{mnp}\left\{1 + \left(\frac{p\pi\lambda_{ab}}{h}\right)^2\right\}^3}\left(\frac{J_{\mathrm{i}}}{J_0}\right)^2\left\{\frac{m\ell h}{w}\sinh\left(m\alpha_x w\right) + \frac{nwh}{\ell}\sinh\left(n\alpha_y \ell\right)\right\} \tag{2}$$

where β_{c} is the McCumber parameter, Φ_0 the quantum flux, s the interlayer spacing and J_0 the maximum Josephson current density. J_{i} is a parameter indicating inhomogeneity in the Josephson current density. α_x and α_y are attenuation coefficients of leaky electromagnetic fields on the edges of the mesa. The calculated power is 1-2 orders of magnitude higher than the experimental results. One can explain that unstable bias voltages prevent the power from attaining its maximum in the experiment.

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Short vs long-ranged proximity effect in S/F/S Josephson junctions

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The very special character of the proximity effect in superconductor-ferromagnet heterostructures is revealed in the damped oscillatory behaviour of the Cooper pair wave function. In diffusive regime this occurs at the very short range and leads to the formation of the special π-Josephson junctions. Such "π -junction" incorporated in a superconducting circuit may generate a spontaneous current. The quantum oscillations and the "π"-states should also be present in multiply connected ferromagnet–superconductor hybrids, for example in a thin-walled superconducting shell surrounding a ferromagnetic cylinder.

The proximity effect in S/F structures is usually short-ranged though it can become long ranged when the magnetic structure is non-collinear. Recently it has been demonstrated that the Josephson junctions with a composite ferromagnetic interlayer indeed reveal the triplet long-ranged superconducting current.

We will discuss the different mechanisms of the long range proximity effect in superconductor – ferromagnetic structures both in clean and diffusive limits. Even a small modulation of the exchange field along the quasiclassical trajectories is shown to provide a long range contribution to the supercurrent due to the interference effects. The underlying physics is the interference phenomena due to the magnetic scattering of the Cooper pair, which reverses its total momentum in the ferromagnet and thus compensates the phase gain before and after the spin–reversed scattering. We demonstrate that in the ballistic regime the presence of a small region with a non-collinear magnetization restores the critical current inherent to the normal metal. This phenomenon opens a way to easily control the properties of SFS junctions and, inversely, to manipulate the magnetic moment via the Josephson current.

The non-collinear magnetization of the layers provides the conditions necessary to generate the triplet superconducting correlations. It leads to the long-range induced magnetic moment, emerging in the superconducting layers and depending on the Josephson phase. By tuning the Josephson current, one may manipulate the long-range induced magnetic moment. This magnetic moment, controlled by the Josephson current may be used in spintronics devices instead of the spin-torque effect.

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Development of ferromagnet $SrRuO_3$ and spin triplet superconductor Sr_2RuO_4 junctions

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[keywords] spin triplet superconducting, ferromagnetic Josephson junctions, proximity effect, $SrRuO_3$ thin films, Sr_2RuO_4 superconductor

Conventional spin singlet superconductor (S) and ferromagnet (F) Josephson junctions have been extensively studied in the past, to investigate oscillating behavior of superconducting order parameter into the F-layer leading to a π-junction, and to study the spin-triplet odd-frequency Cooper pairs generation at the S/F interface. Josephson junctions based on a spin-triplet superconductor (T), with additional spin and orbital degrees of freedom, would be rather interesting. Theoretical study reveals that such junctions exhibit not only charge supercurrents but also spin supercurrents. More interestingly, spin and charge supercurrents can be controlled by magnetization direction of the F-layer.

To develop a T/F hybrid, we epitaxially grow a ferromagnetic $SrRuO_3$ thin film on the *ab*-surface of a single crystal of the spin-triplet superconductor Sr_2RuO_4 using pulsed laser deposition technique. $SrRuO_3$ thin films found under severe in-plane compressive strain because of 1.5% *a*-axis mismatch. Interestingly, ferromagnetic order in the films is appeared with Curie temperature T_{Curie} = 160 K, just like bulk or fully relaxed films. The easy axis of the magnetization is normal to the interface (*c*-axis) with magnetic moment of ~3.3 μ_B/Ru. Surprisingly, transport measurements reveal that the interface between $SrRuO_3$ and Sr_2RuO_4 is highly conducting in contrast with the interface between other normal metals and the *ab*-surface of Sr_2RuO_4. Our findings will lead us toward the spin-triplet Josephson junctions and the beginning of the *Superspintronics*.

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Superconducting proximity effects in Nb/rare-earth bilayers

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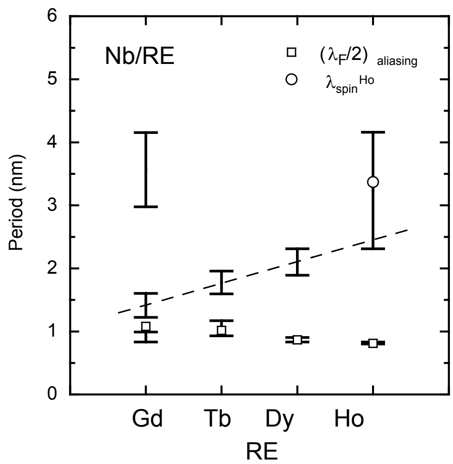
[keywords] superconductor-ferromagnet heterostructures, FFLO, heavy rare-earth, spin modulation.

We report a systematic study of the superconducting proximity effects in Nb/RE bilayers, where RE stands for Gd, Tb, Dy, and Ho, i.e. the first four heavy rare earth (RE) elements in the periodic table. At low temperatures, Gd (T<293 K), Tb (T<222 K), and Dy (T<85 K) are in ferromagnetic states, while Ho shows conical ferromagnetism (inhomogeneous magnetism) below ~20 K.

Using the epitaxial growth of $Al_2O_3(11\bar{2}0)$/Nb(110)/RE(0002), a single-crystal layer of RE was fabricated with its c-axis perpendicular to the sample plane. The superconducting transition temperature T_c of the Nb/RE bilayers was measured for $10 \le t_{RE} \le 20$ nm with an interval of Δt_{RE}=0.4 nm, where t_{RE} is the thickness of the RE layer. We carried out periodicity ananlysis on the $T_c(t_{RE})$ data using a quantitative fast Fourier transform (FFT) method. The results of the analysis are summarized in the figure below. Except the longest period (~3.5 nm) for Gd, two types of variations are seen in the element dependence of oscillation period: the long periods more than 1 nm (λ_L's) and the short periods about 1 nm (λ_S's). The spin modulation period intrinsic to Ho, $\lambda_{spin}{}^{Ho}$(=3.4 nm; open circle), is located within a broad distribution of λ_L for Ho. We recognize a linear change of λ_L (shown as a broken line) from Gd to Dy. The line is extrapolated to Ho, giving an extrapolated value of 2.45 nm.

According to the picture of the RKKY interaction between valence electrons and 4f moments, the exchange energy E_{ex} at 0 K scales linearly with the 4f spin moment S, where S=7 (Gd), 6 (Tb), 5 (Dy), and 4 (Ho) in units of μ_B. The spatial period of the FFLO-like oscillation, λ_{FFLO}, in the REs will therefore increase linearly from Gd to Ho at low temperatures, as long as $\lambda_{FFLO} \propto v_F/E_{ex}$ holds (a clean ferromagnet) and the Fermi velocity v_F is almost constant for the REs. The broken line actually follows $\lambda_L \propto 1/S \propto 1/E_{ex}$, and the values of λ_L for Gd and Ho are in good agreement with the literature data for λ_{FFLO} [1, 2]. We conclude that the broken line indicates the element dependence of λ_{FFLO}.

The Fermi wavelength λ_F of each RE was calculated from λ_{FFLO} (the broken line) and the experimental E_{ex} values for the Δ_2 valence states [3]. To date, there is a relative scarcity of experimental v_F and λ_F data for REs. The open squares show the calculated values of $(\lambda_F/2)_{aliasing}$, the aliased $\lambda_F/2$ by discrete-thickness sampling. They reproduce λ_S's well, suggesting that λ_S's reflect the formation of quantum well states (QWSs) in the RE layer, like that observed in a superconducting Pb film [4]. QWSs require the full-thickness penetration of Cooper pairs into the RE layer, so that the presence of λ_S's indirectly proves that of triplet pairs in the REs.



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Josephson coupling via robust surface conducting layers in 3D topological insulators

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[keywords] topological insulators, Josephson coupling, Fraunhofer interference pattern, surface pair current

In this talk, we report characteristics of the Josephson effect through the surface conducting channels in $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$ (BSTS) three-dimensional (3D) topological insulator (TI) single crystals. 3D TIs are characterized by the presence of an inverted band gap in their bulk state and a gapless Dirac band on their surface state, which induce a topologically protected surface conducting channels. Recently, many experimental schemes have been proposed to search for Majorana fermionic excitations [1] at an interface between an s-wave superconductor (S) and a TI, where spinless p_x+ip_y superconductivity is predicted to appear. In this study, as an initial step toward searching for the Majorana fermionic state, we fabricated S-TI-S proximity coupled Josephson junctions with surface-dominant conduction in the TI [2,3] and studied their Josephson coupling characteristics [4]. In a junction with 200 nm spacing between aluminum (Al) electrodes, we observed a clear Josephson critical current (I_c) as large as 120 nA, corresponding to $I_c R_N /e \sim 10$ μV. Modulation of the critical current in a perpendicular magnetic field, *i.e.*, the Fraunhofer diffraction pattern, persisted up to the superconducting critical field (~125 G) of Al electrodes, which could be described by the enhanced supercurrent distribution at the junction edge, arising from the side surface contribution. Interestingly, we also observed non-local current flowing on the surface of TIs, which cannot appear in Josephson junctions based on trivial 3D materials. With modulating I_c at the Josephson junction in a magnetic field, a Fraunhofer-like non-local voltage signal was also picked up between two normal Au electrodes that were arranged in a nonlocal way away from the source-drain electrodes. These features strongly suggest the Josephson coupling established via topologically robust conducting layers all over the surfaces of our BSTS TI crystal, including the top, side, and bottom surfaces.

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THz emission and detection on surface carriers in topological insulators

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[keywords] THz, topological insulator, surface carrier, Dirac fermion, pump-probe spectroscopy.

We report on THz emission from topological insulators Bi_2Se_3 and $Cu_xBi_2Se_3$ single crystals by ultrafast optical pulse excitation [1]. The generated THz power is strongly dependent on the carrier concentration of TIs. An examination of this dependence reveals that surface carriers are indispensable for two-channel free carrier absorption. Surface carriers in Bi_2Se_3 are significantly better absorbers of THz radiation than bulk carriers. Moreover, the femtosecond snapshots of the relaxation process were revealed by using optical pump midinfrared probe spectroscopy [2]. The rising time and decay time of the negative component in transient reflectivity changes, assigned to carrier relaxation in surface state, are ~1.62 ps and ~20.5 ps, respectively. The measured relaxation time of Dirac fermions was used to estimate the Dirac fermion-phonon coupling strength, which is from 0.08 to 0.19 while Dirac fermions were away from the Dirac point into higher energy states. Further, the energy-resolved transient reflectivity spectra disclosed the energy loss rate of Dirac fermions at room temperature was about 1 meV/ps. These results are crucial to the design of Dirac fermion devices.

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Ideal surface Dirac cone and its transport properties in the topological insulator $TlBiSe_2$

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[keywords] 3D Topological insulators, $TlBiSe_2$, electric transport, Shubnikov-de Haas effect, Berry phase

Surface metallic state of Dirac fermions, realized in the three-dimensional (3D) topological insulators, has several unique characteristics such as the lifted spin degeneracy due to the surface spin-orbit interaction and the robust protection from backscattering [1]. However, details of its electric transport properties are yet to be defined. This is because majority of topological insulators reported to date are the bulk metals, thus difficult to separate the surface-metallic conduction [2,3].

A ternary system $TlBiSe_2$ is one of the 3D topological insulators known to exhibit a simple Dirac cone, but also has the bulk metallic nature [2,4]. Recently, the carrier tuning and the bulk insulation were realized in self-doped $Tl_{1-x}Bi_{1+x}Se_2$ [5]. The $Tl_{1-x}Bi_{1+x}Se_2$ is appropriate for studies of the surface transport since the metallic behavior is ascribable to the surface Dirac fermions.

In this presentation, we report the electric transport properties of the bulk insulator $Tl_{1x}Bi_{1+x}Se_2$. Our results revealed the first demonstration of stable Dirac hole state [6]. It is also revealed the reversible electron-hole conduction within the bulk-insulating regime. The results are compared with that of other 3D topological insulators, and discuss the surface transport properties.

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Modeling different kinds of Josephson junctions and circuits for interpretation of their electrical characteristics

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[keywords] Josephson junctions, current-voltage characteristics, synchronization, tunneling

We present an overview on our recent activities relating the IV-characteristics (IVC) of single Josephson junctions (JJ) as well as different junction arrays and circuits. A transmission line model of coherent emission from the mesa structure of intrinsic JJ [1] shows self-induced resonant steps in the IVC. The Joule heating leads to local hot spots without radiation [2]. This model of synchronization describes the dependence of the frequency of the coherent emission on the width of samples like in our experiments with shunted linear arrays of Tl-2212 [3]. We found self-induced resonance jumps of voltages in the IVC originating from the interaction with the standing wave of the external radiation. Strong phase locking appeared in the vicinity of the first resonant jump. We investigated numerically the influence of a difference in temperature of junctions on synchronization [4] and show that strong synchronization of radiation can be obtained by means of external separate heating or cooling of some junctions. Two parallel stacks of coupled JJ are investigated to clarify the physics of transitions between the rotating and oscillating states and their effect on the IVC of the system [5]. The coupling between the JJ in the stacks leads to the branching of IVC and a decrease of the hysteretic region. The crucial role of the diffusion current is demonstrated. We studied the resonance features of JJ shunted by LC-elements under electromagnetic irradiation [6]. The analysis of the strong changes of the Shapiro step width dependence on the amplitude of microwave radiation at the double resonance condition when radiation frequency coincides with the Josephson and the resonance circuit frequency is presented. In [7] we showed that the presence of a lot of small metallic granules within the insulating barrier between two metallic electrodes can lead to the formation of resonance-percolation trajectories like in our experiments on tri-layered sandwiches consisting of superconducting MoRe electrodes and a W-doped silicon barrier layer. Our calculated supercurrent to excess current ratio fits to the experimental data without any adjustable parameters. We present experiments which yield new indirect arguments proving the existence of a superconducting current across a superconducting MgB_2 and half-metallic manganite ($La_{0.7}Sr_{0.3}MnO_3$) interface due to the singlet-triplet conversion. Finally, the mechanism of the formation of asymmetric IVC is studied on the examples of hybrid pnictide JJ.

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Effects of coupling in intrinsic Josephson junctions under external electromagnetic radiation

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[keywords] intrinsic Josephson junctions, Shapiro step, subharmonic, resonance, chaos

The results of a precise numerical studies of phase dynamics of intrinsic Josephson junctions [1] in high temperature superconductors under electromagnetic radiation are presented [2]. Various manifestations of coupling between intrinsic Josephson junctions in resonance and chaotic features are found. We demonstrate the charging of superconducting layers in bias current interval corresponding to Shapiro step subharmonics and the existence of a longitudinal plasma wave along the stack of junctions. We show that certain chaotic features are induced by coupling between junctions. We have found the devil's staircase in IV-characteristics within different bias current intervals. The observed steps form very precisely continued fractions [3]. An algorithm for the appearance and detection of subharmonics with increasing radiation amplitude is discussed.

The effect of external radiation on the phase dynamics of Josephson junctions shunted by an LC-circuit is examined. When the Josephson frequency is equal to the frequency of the formed resonance circuit (rc), additional rc-branches appear in the IV- characteristics [4,5]. We show that the amplitude dependence of the Shapiro step width crucially changes when the Shapiro step is on the rc-branch in comparison to the case of Josephson junction without shunt [6]. The experimental implementation of these effects might give important advantages for existing methods and technologies using intrinsic Josephson junctions.

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Experiments with ferromagnetic φ Josephson junctions

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[keywords] φ Josephson junction, π Josephson junction, ferromagnetic Josephson junction, periodic double well

Josephson junctions (JJs) with a ferromagnetic interlayer can be used to fabricate π JJs, which have a phase drop of π in the ground state in comparison to conventional JJs having a phase drop of 0 (0 JJs)[1–3]. One can use these π JJs in superconducting circuits as a device providing a constant phase shift, i.e. as a π phase battery[4, 5]. A generalization of a π JJ is a φ JJ[6], which has the phase ±φ in the ground state. The value of φ can be chosen by design and tuned in the interval $0 < \varphi < \pi$. The φ JJs used in our experiment are fabricated as superconductor-insulator-ferromagnet-superconductor (SIFS) 0-π JJs[3] with asymmetric current densities in the 0 and π facets [7]. This system can be described by an effective current phase relation, which is tunable by an externally applied magnetic field[8]. We present several recent experiments with such a φ JJ[9]. First, we demonstrate that the unknown state can be read out by measuring the critical current I_{c+} or I_{c-} and written in by applying a magnetic field. Thus, φ JJ can be used as a memory cell. Second, we study the retrapping of the phase by the φ JJ and discover a buttery effect not accompanied by chaos. New experimental results on escape and retrapping of the phase in φ JJ will be presented.

Support by DFG is acknowledged.

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Resonance overlap as the origin of structured chaos in Josephson junctions

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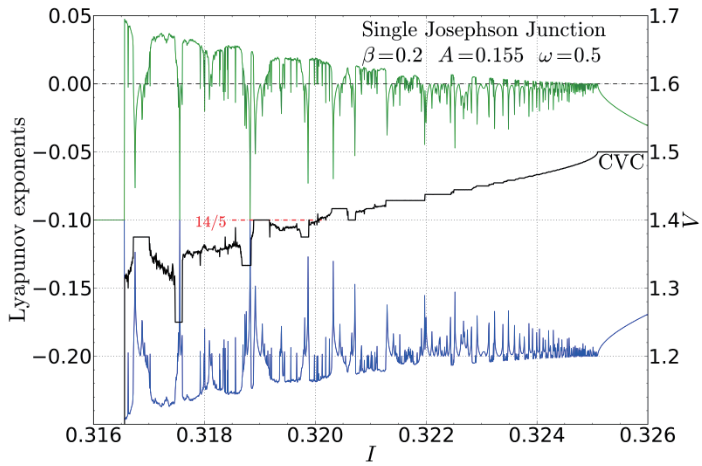
[keywords] Josephson junction, chaos, self-similar, resonance overlap

An underdamped Josephson junction, in the presence of external radiation, can be modeled as a nonlinear oscillator, fulfilling the minimum requirements for deterministic chaos. The current-voltage characteristics show the Shapiro steps and their sub-harmonics, as a result of phase locking between the Josephson frequency and the external frequency. The series of steps can form a self-similar structure, known as a devil's staircase [1]. We report an interesting case of the complete staircase being destroyed by chaos while preserving its self-similarity. The attached figure shows the Lyapunov exponents and current-voltage characteristics for a single junction in which the original staircase has been destroyed. Such results, to our knowledge, are the first demonstration of a self-similar structure that shows the onset of chaotic regions in a manner that preserves its original global self-similar structure. We therefore refer to this new phenomenon as structured chaos [2]. We furthermore conjecture that resonance overlap [3] brings about the chaotic intervals in the staircase (the regions where the Lyapunov exponents become positive in the adjacent figure), and at the same time explains the observed self-similarity. We discuss the implications of the chaotic regions for the coherence properties of a stack of intrinsic Josephson junctions irradiated by electromagnetic radiation.



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Josephson phenomena in novel superconducting states

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[keywords] THz radiation, π-kink state, multi-band superconductor, topological superconductor

Josephson effect provides unique notches for exploring superconductivity in many systems since it is associated with the broken U(1) symmetry. In this talk, I will discuss several interesting examples where other (broken) symmetries are involved: (1) cavity modes of Josephson plasma in intrinsic Josephson junctions of high-temperature cuprate superconductors, and THz electromagnetic radiation; (2) asymmetric critical currents in Josephson junction between a multi-band time-reversal-symmetry-broken superconductor and a conventional single band one; (3) fractional Josephson relation and Rabi oscillations in 1D topological superconductor with Majorana bound states.

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Numerical simulations of terahertz emission from intrinsic Josephson junctions with variation of the number of junctions

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[keywords] intrinsic Josephson junction stacks, numerical simulations, teraherz wave emission, the number of junctions

Since the observation of teraherz emission from mesas made of layered high-T_c superconductor $Bi_2Sr_2CaCu_2O_8$ [1], the mechanism of strong and coherent radiation attracts a great deal of attention from theoretical, experimental, and engineering points of view. The teraherz-wave emission has a strong connection with the dynamical aspects of superconducting phases, electromagnetic wave, and heat (See, e.g., [2]). Therefore, constructing a theoretical approach to integrating these physical degrees of freedom is highly desirable. A concrete way of resolving the issues is built up by three-dimensional dynamical simulations of intrinsic Josephson junction stacks with outside-vacuum contributions. Along this direction, a simulation method was developed in [3], leading to large-scale parallel computations.

In this article, we apply the approach in [3] to characterizing teraherz-wave emission in low-bias-current regions, with variation of the number of junctions inside a mesa sample. We mainly focus on a square-type mesa sample. A notable character of our simulations is to achieve the change of the junction numbers involved the sample. In all the previous three-dimensional numerical simulations, the periodicity along *c*-axis inside the intrinsic Josephson-junction stacks is imposed, to study idealized infinitely-long junction arrays. It indicates that such simulations never address how intrinsic Josephson junction stacks naturally overcome the so-called impedance mismatch between electromagnetic waves in matter and radiation fields in vacuum. We propose and implement a method of connecting junction regions and vacuum via Faraday's law, without the *c*-axis periodicity in junction arrays. We successfully reproduce the previous simulations of teraherz-wave emission [3], especially the emergence of "π-kink" [4] behaviors around the fundamental mode in the cavity-resonance condition. Then, we show the presence of a critical value of the number of junctions for a strong emission, via the dependence of the peak heights on the number of junctions. We will also discuss the present approach to high-bias-current regions, in which hotspots can be formed.

We would like to thank all the CCSE stuffs at Japan Atomic Energy Agency for their helpful supports about numerical simulations. The calculations were performed by Fujitsu BX900 at Japan Atomic Energy Agency and Fujitsu FX10 at University of Tokyo.

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Role of dissipation, disorder, and thermal noise in synchronization of intrinsic Josephson junctions

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[keywords] intrinsic Josephson junctions, synchronization, terahertz radiation, cavity resonance

Powerful terahertz radiation generated by BSCCO mesas becomes possible because of synchronization of oscillations in the intrinsic Josephson junctions [IJJs] mediated by the internal cavity resonance [1]. In spite of considerable progress [2], the achieved radiation powers remain significantly smaller than the theoretical predictions [3], most probably because of materials problems. In order to probe the role of disorder, we performed simulations of dynamics in the IJJ stacks using the highly-efficient three-dimensional CUDA code. We explored stability of dynamic coherent state with respect to disorder and noise at different levels of quasiparticle dissipation and stack widths. We found that the coherent state is only formed if the dissipation exceeds a certain critical value which depends on the junction width and strength of disorder.

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Emission distributivities from novel geometrical antennas

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[keywords] coherent terahertz emission, electromagnetic cavity modes, equilateral triangular cavities, pie-shaped wedge cavities, transverse magnetic modes

We model the angular distributions of the emissions from the transverse magnetic cavity modes of two types of antenna shapes. The six degenerate fundamental cavity excitations of a thin equilateral triangular antenna are studied using the magnetic Love equivalence principle [1,2,3], and used to fit the angular distributions of the emissions observed in two planes from such antennas consisting of mesas fabricated from the high-temperature superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) [2,3]. Similar fits are obtained for the dual-plane emissions detected from a thin acute isosceles triangular mesa antenna [4], which we model as a narrow-angle pie-shaped wedge antenna. The predictions for the TM$(2,0)^o$ cavity mode are found to be in good agreement with experiment [4] . Then we study the many predicted TM cavity modes present in thin pie-shaped wedge antennas of various wedge angles. Three-dimensional plots of some of the predicted angular distributions of the emissions from a variety of modes in a variety of pie-shaped wedge cavities are presented.

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Intrinsic Josephson junctions in the iron-based multi-band superconductor $(V_2Sr_4O_6)Fe_2As_2$

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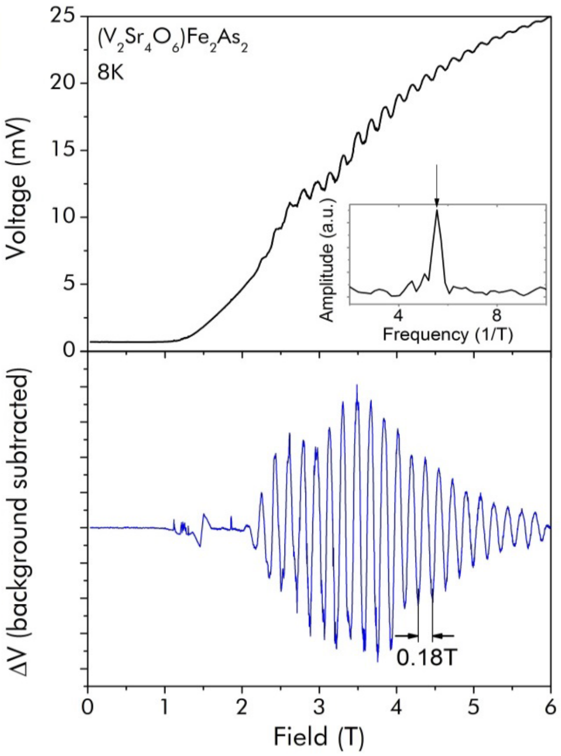
[keywords] iron-pnictides, multi-band superconductivity, intrinsic Josephson Junction, vortex physics



We report clear experimental evidence for iJJ behavior [1] in the iron-based multi-band superconductor $(V_2Sr_4O_6)Fe_2As_2$ (T_c~20K[2]). The intrinsic junctions are identified by periodic oscillations of the flux flow voltage upon increasing a well aligned in-plane magnetic field, which are observed over an extended temperature range. This periodic flux flow modulation is a hallmark signature of Josephson vortices confined junctions within the unit-cell, and is quantitatively explained by commensurability effects between the Josephson vortex lattice and the crystal structure[3]. The observed oscillation structure, periodicity and onset magnetic fields are comparable to previous observations in copper based superconductors.

The iron-pnictide $(V_2Sr_4O_6)Fe_2As_2$ is found to be an interesting candidate for novel phase-coherent quantum applications exploiting the multi-band nature of the material. In particular, the additional tunneling channels related to the inter- and intra-band coupling terms are expected to lead to new effects.

$(V_2Sr_4O_6)Fe_2As_2$ is particularly well suited for the search of such new physics due to its large tunneling barrier compared to other pnictides. It arises from strong vanadium d-orbital correlations, which are found to drive the separation layer into a strongly Mott-insulating state [4].

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Doping of high-T_c superconductors by carrier injection†

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[keywords] intrinsic Josephson junctions, carrier doping, cuprates, pnictides, carrier injection

The generic structure of high-T_c superconductors is a stacking sequence of superconducting planes separated by so-called charge reservoir layers. It is well known that carrier doping of these materials is achieved either by substitution of atoms or by nonstoichiomety in the charge reservoir layer. The alternating type of stacking causes yet another two important consequences. First, the transport anisotropy of these materials is so high, that in the superconducting state the c-axis transport is governed by the intrinsic Josephson effect, and second, as the transport across the doping layers is accomplished by tunneling, the kinetic energy of carriers can exceed by far the one of thermalized transport and can even overcome the threshold energy of charge trapping in the charge reservoir layers. Therefore it is possible to deposit a substantial amount of charge only by injecting large c-axis currents. By charge compensation, this increases the concentration of holes in the conducting layer of the material. The consequence is an increase of mobile carriers in hole-doped materials and a decrease of mobile electrons in electron-doped materials.

This is a fully electronic type of doping, and can be nicely characterized by normal resistance, superconducting critical temperature, interlayer critical current, and, especially, by the quantities characteristic for the Josephson effect, and even the parameters from macroscopic quantum tunneling, like bare Josephson plasma frequency, and thermal-to-quantum crossover temperature. Our most spectacular results include the creation of high-T_c superconductivity in non-superconducting $Bi_2CaSr_2Cu_2O_{8+\delta}$ and the spectacular increase of critical temperature by carrier injection into overdoped 1111 as well as 1048 pnictide superconductors. Our systematic doping experiments revealed a drastic increase of the interlayer capacitance. Apparently, carrier doping significantly increases the effective thickness of the superconducting layer while the thickness of the insulating region is decreased.

† This paper is dedicated to the memory of our good friend, the late Prof. Dr. Yuri Latyshev (26.2. 1950 – 10.6. 2014), Laboratory of Low Dimensional Nanostructures, Kotel'nikov Institute of Radioengineering and Electronics of the Russian Academy of Sciences.

New BiS_2-based superconductors

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[keywords] BiS_2, $BiSe_2$, new superconductor

Layered crystal structure is commonly found in many exotic superconductors such as cuprate and Fe-based superconductors, which have been interested in the higher Tc and unconventional pairing mechanism. Recently, our group discovered new BiS_2-based layered superconductors $Bi_4S_4O_3$ and $LaOBiS_2$ systems [1,2]. The $LaOBiS_2$ has layered crystal structure composed of BiS_2 superconducting layer and LaO blocking layer which is similar to that of 1111 type iron-based superconductor. With doping of F at O site, LaO1-xFxBiS_2 shows clear superconducting transition around 4K. Interestingly the Tc dramatically elevated up to around 10K by high pressure sintering [3]. The analogous member of $CeOBiS_2$ was also successfully synthesized by standard solid state reaction and high pressure sintering. $CeO_{1-x}F_xBiS_2$ shows superconductivity together with ferromagnetism, and transition temperatures of superconductivity and magnetism are increased with increasing of F doping level x [4]. It seems that the superconductivity and magnetism are closely related. In my presentation, I will talk about detailed of superconductivity and magnetism of BiS_2-based superconductors.

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The 9th International Symposium on Intrinsic Josephson Effects and THz Plasma Oscillations in High-Tc Superconductors (THz-PLASMA 2014)
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Growth and *c*-axis transport property of $PrO(F)BiS_2$ single crystal

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[keywords] BiS_2-based superconductors, superconducting anisotropy, intrinsic Josephson junctions, Josephson vortex

BiS_2-based superconductors form a layered structure. The chemical composition of BiS_2-based superconductor are $RO_{1-x}F_xBiS_2$ (R=La,Ce,Pr,Nd,Yb $0<x<1$). We grew BiS_2-based superconducting single crystals using CsCl/KCl flux [1,2]. We measured superconducting anisotropies (γ_s) of the grown BiS_2-based superconducting single crystals using "effective mass model". The γ_s of $PrO_{0.66}F_{0.34}BiS_2$ single crystal was highest in the obtained BiS_2-based single crystals. And, the coherence length (ξ_c) on *c*-axis direction of $PrO_{0.66}F_{0.34}BiS_2$ single crystal was estimated from upper critical field (H_{c2}) under the magnetic field parallel to the *c*-axis. The γ_s, ξ_c and *c*-axis lattice constant of $PrO_{0.66}F_{0.34}BiS_2$ and $YBa_2Cu_3O_y$ superconducting single crystalline samples are shown in table I. That $YBa_2Cu_3O_y$ sample showed the intrinsic Josephson junctions [3]. These values were compared between $PrO_{0.66}F_{0.34}BiS_2$ and $YBa_2Cu_3O_y$. They are relatively-near value. We expected that $PrO_{0.66}F_{0.34}BiS_2$ single crystal shows the intrinsic Josephson junctions. We fabricated the in-line intrinsic Josephson junctions of $PrO_{0.66}F_{0.34}BiS_2$ single crystal using focus ion beam [4]. Figure 1 shows current-voltage (*I-V*) characteristics of the fabricated $PrO_{0.66}F_{0.34}BiS_2$ single crystal. However, the multi-branched structure from intrinsic Josephson junctions was not observed. Figure 2 shows the angular dependence of flow voltage under the magnetic field. The flow voltage (V_{ff}) increased on magnetic field parallel to the *ab*-plane. We assume that phenomenon is "Lock-in" phenomenon from Josephson vortices (JVs) [5]. This result indicated that *c*-axis transport property of $PrO_{0.66}F_{0.34}BiS_2$ single crystal behaves like intrinsic Josephson junctions.

Table I γ_s, ξ_c and *c*-axis lattice constant of $PrO_{0.66}F_{0.34}BiS_2$ and $YBa_2Cu_3O_y$

$YBa_2Cu_3O_y$ (High-T_c)	Superconductors	$PrO_{0.66}F_{0.34}BiS_2$ (BiS_2-based)
11.69	*c*-axis lattice constant (Å)	13.49
2	ξ_c(Å)	4.8
37-46	γ_s	53-58

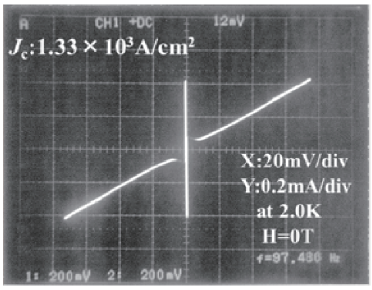

Fig. 1 *I-V* characteristics of the fabricated $PrO_{0.66}F_{0.34}BiS_2$ single crystal

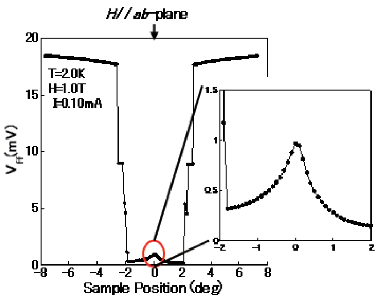

Fig. 2 Angular dependence of flow voltage under the magnetic field

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Underdamped intrinsic Josephson junctions in $Pb_{1-y}Sr_2Y_{1-x}Ca_xCu_{2+y}O_{7+\delta}$ epitaxial films

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[keywords] intricsic Josephson junctions, Pb-based cuprate, *ex situ* growth, anisotropy

For high power and high frequency application, it is important to find the low anisotropic cuprate with underdamped intrinsic Josephson junctions (IJJs). In ideal superconductor/insulator/ superconductor JJJ, the current-voltage characteristics show a hysteresis and resistive branches which correspond to the resistive states of the individual IJJs. Generally, it is very difficult to observe these IJJ characteristics in low anisotropic cuprate because lower anisotropy usually causes higher damping. In YBCO, small hysteresis and resistive branches are observed only when the small junctions are fabricated in highly under-doped samples[1-3]. We report the first observation of underdamped IJJ characteristics in $Pb_{1-y}Sr_2Y_{1-x}Ca_xCu_{2+y}O_{7+\delta}$ (Pb1212) which has low anisotropic crystal structure ($\gamma \approx$ 10[4]) similar to YBCO.

Pb1212 (x = 0.35, y = 0.2) epitaxial films have been grown on $SrTiO_3$ (100) substrates by a two-step method consisting of a low temperature sputtering step and a high temperature *ex situ* growth step. Then, small mesa structures (S = 4 μm^2) have been fabricated on a film surface using a standard photolithography and an Ar ion milling technique. The superconducting transition temperature of the IJJ mesa is 43 K. Hysteretic current-voltage characteristics and multiple branches, which are peculiar features of IJJs, have been observed below 39 K. At 4.2 K, the value of J_c (the critical current density) is 2.2 kA/cm^2. The depth of the hysteresis defined as $\alpha = (J_c - J_R)/J_c$ is 0.89, where J_R is the return current density. The McCumber parameter β_c (a measure of the damping of IJJs) is estimated to be 130 from the value of α. The fact that multiple branches can be observed even near T_c and large values of α and β_c suggest that IJJs of Pb1212 exhibit highly underdamped behavior like those of Bi-family.

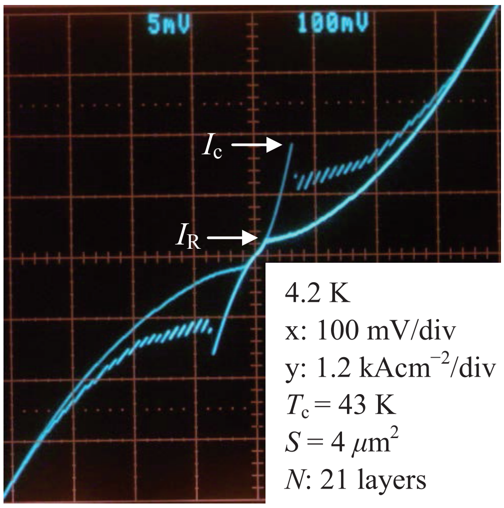

Fig. 1: $I-V$ characteristics of Pb1212 intrinsic Josephson junctions

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Superconducting metamaterials

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[keywords] Josephson junctions, microwave resonators, SQUIDs, metamaterials, antennas, arrays

In this presentation, I will review experimental studies performed within recently established collaboration between German and Russian laboratories jointly working on various aspects of superconducting and quantum metamaterials. The focus of our experiments is on ultra-low loss electromagnetic medium comprised of networks of compact superconducting resonators. The design flexibility of superconducting thin-film resonators and circuits allows for utilizing small structures down to the nanoscale while maintaining low loss properties, very strong and well-controlled nonlinearity, and frequency tunability in the microwave and mm-wave frequency range [1,2]. This approach opens up an opportunity to develop superconducting metamaterials with non-trivially tailored electromagnetic properties, which can be functionalized as ultra-compact resonant magnetic dipole arrays [3-6], integrated tunable non-reciprocal circuits [7], left-handed transmission lines [8], optically switchable microwave propagation media [9], active emitter arrays, phase modulators, etc. Another interesting spin-off of superconducting metamaterials is going to be quantum metamaterials comprised of arrays of superconducting qubits [10]. This directing is an emerging new field for fundamental studies in quantum optics using microwaves, opening a possibility to explore collective quantum dynamics of artificially tailored two-level systems under very strong coupling with electromagnetic field.

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Peculiar electromagnetic response of quantum metamaterial composed of superconducting qubits

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[keywords] metamaterial, superconducting qubit, light-matter interaction, lasing

Metamaterials are artificial electromagnetic materials consisting of artificial atoms, that is, artificial structures whose sizes are small compared to the wavelength of respective electromagnetic (EM) wave. The effective permittivity and permeability of metamaterials can be controlled at will by changing shapes and arrangements of the artificial atoms. The concept of metamaterial is quite useful for fabricating novel optical devices such as cloaking devices [1].

Recently, quantum metamaterial (QMM), which utilizes superconducting qubits as artificial atoms, has been theoretically proposed [2] and its first prototype fabricated [3]. Unlike conventional metamaterials composed of classical elements, QMMs are expected to show several unique EM responses originating from quantum superposition and entanglement of qubits.

In this talk, we will present our recent theoretical studies on the EM dynamics of a QMM based on superconducting charge qubits. First, we report the EM pulse propagation in the QMM and show unique lasing phenomena due to the non-linear interaction between EM field and qubits [4]. In addition, we will discuss peculiar superconducting-vortex state under static magnetic field, which is originating from the coherent superposition of qubits [5].

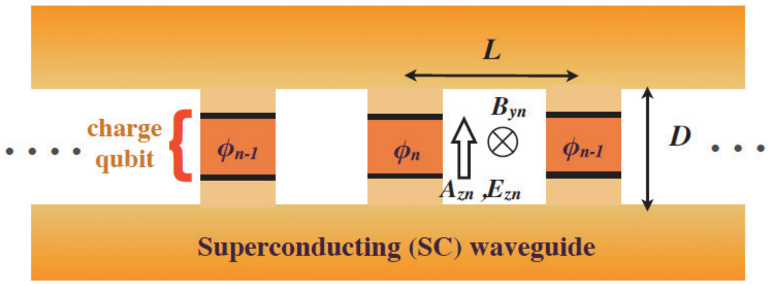

Figure: A quantum metamaterial based on superconducting charge qubits

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Nonlinear responses of superconducting thin films induced by intense terahertz pulses

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[keywords] terahertz wave, pair breaking, nonlinear responses, metamaterial

The direct accessibility of the temperature- and frequency-dependences of the conductivity with terahertz time-domain spectroscopy (THz-TDS) has allowed for a detailed examination of superconducting parameters such as the plasma frequency, the supercarrier density or the London penetration depth. The study of the nonlinear response to intense THz pulse of superconductors is not only important for potential applications, but it also provides important information for understanding the nature of superconductors.

Recently, we have employed intense THz pulse to investigate the time-resolved nonlinear behavior of superconductors, including low temperature superconductor NbN thin film [1] and high temperature superconductor $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin film in *ab*-plane [2]. With this method, we could separate the field-induced changes to the superconductivity from other effects, particularly heating and photon-induced Cooper pair breaking. In the case of low field strengths, the behavior of the thin films agrees with previous examinations by means of conventional, low-power THz-TDS. However, for strong THz electric fields, it was found by analysis with the two-fluid model that the superfluid population decreases dramatically, possibly due to Cooper pair breakup, even though the THz photon energy is clearly smaller than the energy gap of YBCO (~20-30 meV) and NbN (5 meV).

Moreover, we demonstrate the nonlinear response of superconducting metamaterial in the terahertz regime, which is comprised of an array of sub-wavelength split-ring resonators (SRRs) made from NbN film [3,4]. The nonlinear response of the metamaterial lies in the suppression of the superconductivity of NbN thin film induced by the intense terahertz wave. As the variation of the incident intense terahertz field alters the intrinsic conductivity in the NbN, a consequent giant amplitude modulation is observed due to the strong nonlinearities. Increasing or decreasing the incident terahertz field strength, one can creates a sharper “off” or “on” transmission of the chosen SC metamaterial at the resonance frequency.

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Topological fractal metamaterials composed of electrically isolated Pi-rings for THz-radiation devices

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[keywords] topological metamaterials, superconductors, Josephson junctions.

In this paper we have introduced a general concept of topological metamaterials[1]. In this framework we developed and designed fractal metamaterials which consist of arrays of nano and micron sized rings containing Josephson junctions which play the role of “atoms” in such artificial materials. We shown that if some of the junctions have **Pi**-shifts in the Josephson phases that the “atoms” become magnetic and their arrays can have tuned positive or negative permeabilty. Each individual “**Pi**-ring” - the Josephson ring with one **Pi**-junction[2] - can be in one of two energetically degenerate magnetic states in which the supercurrent flows in the clockwise or counter-clockwise direction.

This results in magnetic moments that point downwards or upwards, respectively. The value of the total magnetization of such a metamaterial may display fractal features. We describe the magnetic properties of such superconducting metamaterials, including the magnetic field distribution in them (i.e. in the network that is made up of these rings). We also describe the way that the magnetic flux penetrates into the Josephson network and how it is strongly dependent on the geometry of the system. We have also demonstrate that such metamaterials are ideal to design various devices operating in radiation in THz frequency range. The artificially structuring superconducting rings on the subwavelength scale can produce nonlinear and switchable metamaterials [1–5]. Arrays of rings of Josephson junctions or systems of superconducting islands on normal metal films can be excited by electromagnetic radiation [6] and support the propagation of electromagnetic waves [7], thus significantly modifying vacuum permeability. Even the sign of the permeability can be changed in such a system. Each superconducting ring is a “meta-atom” or “molecule” and the arrays of rings make up the “metamaterial”. These rings can have currents induced into them by the application of electromagnetic fields and well suited to demonstrate clocking effect for THz radiation.

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Nano domain encoding in transport properties of unconventional Josephson junctions and nanostructures

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Nanoscale experiments can play a relevant role in enlightening novel aspects of the physics of high critical temperature superconductors (HTS) and more in general of strongly correlated systems.
The properties of different HTS nano-sized systems ranging from YBaCuO nano-junctions and nano-channels to hybrid systems, give complementary evidence of mesoscopic and phase coherent quantum phenomena. The scaling lengths of HTS contribute to define peculiar transport and flux dynamics regimes.
We mostly focus on escape dynamics in YBCO grain boundary Josephson junctions where macroscopic quantum phenomena have been investigated for different levels of dissipation. By investigating escape dynamics, we extract the quantum signature of a junction encrypted in macroscopic quantum phenomena. The moderately damped regime gives new opportunities to explore novel aspects on the interplay between coherence and dissipation, of interest for various quantum hybrid architectures. Dualism and coexistence of nano domain encoding and collective long-range order in escape dynamics of Josephson junctions and nanostructures are finally discussed.
Results encourage the integration of HTS nanostructures in hybrid systems functional to various applications, and the procedures might be of reference for most junctions composed of unconventional superconductors. In nano-devices standard issues of coherence might be subtly combined with the still unknown nature of HTS.

Novel current-biased kinetic inductance detector aiming at neutron radiography

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[keywords] superconducting detector, kinetic inductivity, pulsed neutron, radiography

Superconducting devices are a promising technology when they are utilized as detectors and logic circuits with extreme high sensitivity, high-speed operation or low power consumption. We succeeded in demonstrating a novel neutron detector based on an Nb superconducting nanowire detector with ^{10}B conversion layer and obtained averaged neutron flux from a pulsed neutron. In recent years, we proposed a novel current-biased kinetic inductance detector (CB-KID) [1] for multi-pixel utilization. The CB-KID consisting of superconducting Nb nanowire can be used as a neutron detector by superimposing a ^{10}B converter layer. The Nb CB-KID is fabricated on a single silicon chip (22 mm x 22 mm x 0.7 mm in size) and designed as 40 nm in thickness with three different line widths of 0.6 μm, 1 μm, and 3 μm. At the center of the chip, the effective area (8 mm x 8 mm) is covered with a ^{10}B converter layer of thickness 300 nm deposited by an electron beam evaporator in an ultra-high-vacuum molecular beam epitaxy chamber. We used a Gifford-McMahon (GM) refrigerator to cool the CB-KID down to 4 K. The CB-KID was fed by constant DC current at 4 K [1]. Our system was tested by irradiating pulsed neutrons at a beam line BL10 of Materials and Life Science Experimental Facility (MLF) in the J-PARC center. We made a great progress that the Nb CB-KIDs with ^{10}B converter layer recovered a signal of a single neutron clearly with the response time of Nb CB-KIDs was as fast as tens of ns. We also succeeded in measuring averaged neutron flux from pulsed neutrons as a function of time. The averaged neutron flux histogram in 0.1 ms thus obtained is in good agreement with the simulated results for BL10. We consider that this is convincing evidence that our detector is able to detect pulsed neutrons from MLF. A plan for developing an imager system with mega pixels using the CB-KIDs will be explained in details [2].

Acknowledgements
The devices were fabricated in CRAVITY facilities at AIST. This work is partially supported by a Grant-in-Aid for Scientific Research (S) (No. 23226019), a Gran-in-Aid for Young Scientists (B) (No. 26820130) and a Gran-in-Aid for Young Scientists (A) (No. 24684027) from JSPS.

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Terahertz detectors working at room temperature

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[keywords] terahertz (THz), detector, room temperature (RT), microbolometer

Terahertz (THz) detector working at room-temperature (RT), consisting of a Nb_5N_6 thin film microbridge and a dipole planar antenna, is reported. Due to the high temperature coefficient of the resistance (*TCR*), which is as high as -0.7% K^{-1}, of the Nb_5N_6 thin film, such an antenna-coupled microbolometer is quite suitable for detecting THz signals. Previously, THz detectors working at 0.1 THz have been reported [1]. Here, the results around 0.3 THz will be presented.

The detector consists of a gold dipole planar antenna and a microbridge, which is the core element and is made of properly patterned Nb_5N_6 film. The software named HFSS is used to carry out numerical simulations for this antenna structure and to optimize the sizes. In the process of Nb_5N_6 microbolometer fabrication, a SiO_2/Si (100) combination substrate is used, where SiO_2 with 100 nm thick, is deposited by thermal oxidation on Si (100) substrate with high resistivity ($\rho > 1000\ \Omega\cdot$cm). Such a combination is chosen because of its low loss at THz frequencies and ease of fabricating an air-bridge. Then, we used radio frequency (RF) magnetron sputtering to deposit a Nb_5N_6 film (120 nm thick). The film was patterned into microbridges using photolithography and reactive ion etching (RIE). The dipole antenna was then integrated with the Nb_5N_6 microbridge by depositing a 5-nm-thick aluminum film firstly, a 220-nm-thick gold later, and then pattern into the right shape and size as designed by the software. Finally, an air-bridge, which reduces the effective thermal conductance of the substrate to further enhance the responsivity, was formed under the Nb_5N_6 microbridge by etching 1 μm of the Si part of the substrate.

The DC responsivity at RT, calculated from the measured current-voltage (*I-V*) curve of the Nb_5N_6 microbolometer, is about -760 V/W. A typical noise voltage as low as 10 nV/√Hz yields a noise equivalent power (NEP) of 1.3×10^{-11} W/√Hz. The best measured RF responsivity at 0.28 THz, is about 580 V/W, which corresponding NEP of 1.7×10^{-11} W/√Hz.

Using above detectors, an active imaging system at 0.22 THz has been constructed using a Cassegrain reflector with the diameter of 30 cm. The special resolution of about 1.41 cm is obtained. Also, this work could offer a candidate to develop a large scale focal plane array (FPA) with simple technique and low cost. The details will be discussed in the presentation.

Acknowledgements

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Modified molecular-dynamics method for vortex dynamics in nano-structured superconductors

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[keywords] vortex dynamics, molecular dynamics, nano-structured superconductors, heat transport.

For applications of superconductors, vortex dynamics is a key feature, because when vortices move, the zero resistivity of a superconductor is destroyed. In order to investigate the dynamics of many vortices theoretically, we use the molecular dynamics method [1]. However, in this method, several features are missing, when we consider real superconducting systems. For example, when vortices moves, heat generation occurs. When vortex motion is not uniform, such as in a corbino disk [2], non-uniform heat generation occurs and then non-uniform temperature distribution appears. A vortex has a transportentropy, and then motion of the vortex is affected by this temperature distribution. In order to incorporate such effect, we solve the heat transport equation with the molecular dynamics equation for vortices. Another feature is a retardation effect, which comes from quasi-particle recombination after fast movement of vortices [3]. After a vortex moves, the order parameter that was inside of the vortex core is restored to the uniform value, but it takes a time for recombining Cooper pairs. Then, if vortices move fast, the vortex motion is affected by a preceding vortex. In order to incorporate such retarded effect, we introduce a condensation energy field, which is proportional to the square of the absolute value of the order parameter. Then we solve following equations [4],

$$\eta \frac{d\boldsymbol{v}_i}{dt} = \boldsymbol{f}_{di} + \boldsymbol{f}_{vi} + \boldsymbol{f}_{pi}^{imp} + \boldsymbol{f}_i^H + \boldsymbol{f}_{Ti} + \boldsymbol{f}_{Ri} + \boldsymbol{f}_{fi}$$

Here, $\boldsymbol{v}_i$ is a velocity of i-th vortex, and $\boldsymbol{f}_{di}$, $\boldsymbol{f}_{vi}$, $\boldsymbol{f}_{pi}^{imp}$, $\boldsymbol{f}_i^H$, and $\boldsymbol{f}_{fi}$, are a driving force from an external current, a vortex-vortex interaction from other vortices, a pinning force from impurities, a force from a screening current and an external field and a thermal fluctuation force, respectively. $\boldsymbol{f}_T = -S_\phi \mathrm{grad} T$ is a entropy force from the temperature distribution. $\boldsymbol{f}_{Ri} = -\mathrm{grad} V_{cond}(\boldsymbol{r})|_{\boldsymbol{r}=\boldsymbol{r}_i}$ is a force from the condensation energy distribution.

We solve these equations and investigate the vortex dynamics, especially structures of dynamical vortex lattices. They depend on magnitude of the driving forces, heat conductance of the superconductor and heat resistance between the superconductor and its substrate. We show these dependence of dynamical vortex lattices.

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Generation-detection of nonequilibrium bosons using Bi-2212 intrinsic Josephson junctions: A hint about the pairing mechanism

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[keywords] hole doped cuprates, pairing mechanism, nonequilibrium phenomena

Superconductivity is caused by pairing of electrons resulting from virtual exchange of bosons. In low-temperature superconductors Cooper pairing is mediated by phonons, but for high-temperature superconductors the pairing interaction is not yet confidently known. Here I overview our recent experimental study [1] which sheds light on this problem by performing a new type of non-equilibrium boson generation-detection spectroscopy. In contrast to the conventional tunneling spectroscopy we probe not the single electron current into the sample, but directly hunt down the emission of nonequilibrium bosons that are responsible for Cooper pairing. When non-equilibrium electrons recombine into Cooper pairs, the binding energy is carried away by recombination bosons that are mediating in pairing. Identification of such bosons provides a direct clue about the pairing ``glue". We employ intrinsic Josephson junctions, built in the crystalline structure of a layered $Bi_2Sr_2CaCu_2O_{8+d}$ cuprate for generation and detection of recombination bosons. We observe that bosons are well defined and carry clear spectroscopic information about the superconducting energy gap. Bosons decay at a ~μm distance, which together with a ~ps decay time yields the boson propagation speed of 10^6 m/s. This is more than two orders of magnitude larger than the phononic (sound) velocity and is close to the electronic Fermi velocity. This provides a direct and unambiguous evidence for involvement of an unconventional electron-electron pairing mechanism in cuprates.

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Controlling High-Tc Josephson plasmonics with strong THz fields and optical cavities

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[keywords] high-Tc superconductors, josephson plasma resonance, THz laser

We will present recent experiments that pave the way toward the coherent control of the Josephson plasma resonance in high-Tc cuprates. This is of fundamental importance for the manipulation of the superconducting wave function of high-Tc superconductors and of practical interest to realize analogues of non-linear optics in the so called “THz gap”. Coherent control of the superconducting order parameter phase has been achieved with strong THz radiation tuned in the vicinity of the Josephson plasma resonance. A single cycle THz electric field is shown to trigger coherent oscillations between the superconducting and ohmic states [1], whereas narrow band THz free electron laser radiation is used to excite Josephson plasma solitons [2]. We will discuss some future directions, making use of complex oxide heterostructure engineering to couple the high-Tc superconductors to the THz field of an optical cavity, thereby implementing the guiding principles of cavity electrodynamics to the control of high-T_c cuprates. As an example, we will show that this cavity may be used to cool the interlayer superconducting phase fluctuations of high-Tc cuprates.

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Possibility of macroscopic quantum tunneling in higher order switching events of $Bi_2Sr_2CaCu_2O_8$ intrinsic Josephson junctions

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[keywords] intrinsic Josephson junctions, macroscopic quantum tunneling, switching current distribution, microwave

Macroscopic quantum tunneling (MQT) in the intrinsic Josephson junctions (IJJs) of $Bi_2Sr_2CaCu_2O_y$ (Bi2212) cuprate superconductors has attracted great interest toward a future realization of quantum information processing using high-T_c cuprates. As for the first switch (1st SW), that is, a switch from the zero-voltage state to the first resistive state in the multiple-branched structure of *I*-*V* characteristics for IJJs, the occurrence of MQT below T^*_{1st} (~1 K) have been well-established by several experiments for this decade [1-5]. In addition, the microwave (MW)-induced resonant switch was successfully demonstrated in the MQT state, suggesting a quantum-mechanical nature of phase dynamics due to the energy level quantization (ELQ) [2,4].

On the other hand, for the second switch (2nd SW), although a MQT-like behavior (the T-independent behavior of an effective phase escape temperature) was observed below T^*_{2nd} (~10 K) [3,4], which was much higher than T^*_{1st}, the interpretation on this behavior has been controversial, since the MW-induced resonant switch suggesting ELQ has not been observed [3]. Furthermore, a recent report [6] that the value of T^*_{2nd} is almost the same as that of T^*_{1st} for the tri-layered IJJs in $Bi_2Sr_2Ca_2Cu_3O_y$ (Bi2223) clearly rules out a possibility that the MQT-like behavior in the 2nd SW is due to the dissipative current after the 1st SW, and provides a new question on the effects of the electromagnetic coupling between IJJs to the MQT-like behavior in the 2nd SW.

Here, we present a systematic study on the phase escape experiments for the higher order switches (at most the 5th SW) down to ~2 K, by using several samples of the bridge-type Bi2212 IJJs. Note that the fabricated IJJs include much smaller number of Josephson junctions (at most ~25 junctions) than that in the previous report [4]. We found that the MQT-like behavior reported for the 2nd SW was common to the higher order switching events. We also discovered the MW-induced resonant switches for the 2nd SW for the first time, which was qualitatively similar to the previous results on the MW-induced switch for the 1st SW in the MQT state [7]. These results suggest that the occurrence of MQT is possible even for the higher order switches. Our results also show that the MW-field plays an important role in enhancement of the electromagnetic coupling between IJJs.

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Switching characteristics of BSCCO intrinsic Josephson junction on a cross-type device: a systematic study by sequential doping

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[keywords] IJJ, BSCCO, MQT, sequential doping, Josephson penetration depth

The crystal structures of cuprate superconductors comprise layers of superconducting CuO_2 atomic sheets interspersed with layers of insulating sheets. The interfaces between the layers are termed intrinsic Josephson junctions (IJJs) [1]. $Bi_2Sr_2Ca_{n-1}Cu_2O_{4n+2+\delta}$ (BSCCO) is promising as material of quantum bits because BSCCO IJJ shows the highest Q-factor in cuprate IJJs. So, switching characteristics of BSCCO IJJ, especially macroscopic quantum tunneling (MQT), was intensively studied [2]. However, the lack of systematic and reproducible experiments in previous studies makes universal understanding in the MQT of IJJ difficult. This is caused by poor controllability of physical properties of BSCCO IJJ which depend on its carrier doping level [3] and by damage to the IJJ when a focus ion beam (FIB) is used for micro-fabrication.

In this study, we developed a cross-typed device of $Bi_2Sr_2CaCu_2O_8$ (Fig. 1) by a double-side process [4] which enables fabrication without using a FIB. This device has small IJJs bared to the atmosphere, the minimum of the junction area is less than 3 micron square, which enables sequential control of its doping level with a fixed device structure by post annealing (Fig. 2). Thus, it is possible now to study switching characteristics of BSCCO IJJ systematically by sequential doping. In this lecture, we discuss a size effect related with the Josephson penetration depth on each doping level.

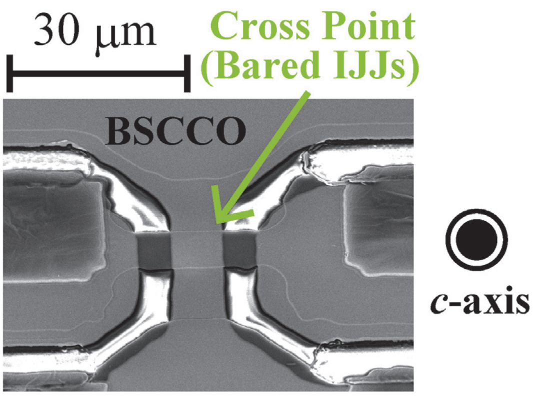

Fig. 1 A SEM image of a cross-type device.

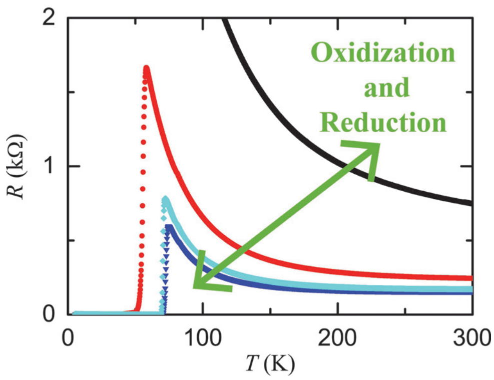

Fig. 2 Post annealing effect on temperature dependence of resistance of the device (cross point).

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Current injection into hole and electron doped high-T_c superconductors

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[keywords] current injection into hole and electron doped high-T_c superconductors

Doping by carrier injection provides the possibility to observe the evolution of c-axis transport properties of high-T_c superconductors from the antiferromagnetic state up to the superconducting, even overdoped phase of one and the same sample. In a series of publications we were able to show that by injection of electrons into the insulating BiO layers of $Bi_2CaSr_2Cu_2O_8$ the hole concentration of the adjacent CuO planes is increased by charge compensation. Even oxygen-depleted, nonsuperconducting $Bi_2CaSr_2Cu_2O_8$ could be converted into optimum-T_c superconducting material exclusively by carrier injection. In this sense, doping appears as intrinsic field effect. It is interesting to confirm this interpretation by carrier injection into electron-doped materials. We present our recent experiment of carrier injection into 1111 pnictides like fluorine-doped LaOFeAs and into 1048 pnictides like Pt-doped $(CaFeAs)_{10}Pt_4As_8$.

Area dependence of Josephson critical current density in superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ mesa structures for terahertz emission

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[keywords] terahertz emission, Josephson junctions, $Bi_2Sr_2CaCu_2O_{8+\delta}$

Sensing and imaging using terahertz (THz) waves is a rapidly progressing technology which has wide-range applications in different areas such as security, medicine, quality control and environmental monitoring [1]. In this technology, compact, continuous wave (CW) solid-state terahertz wave sources are necessary with practical emission power. High-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) single crystal is emerging as compact source of coherent, continuous-wave electromagnetic radiation in the subterahertz and terahertz frequency ranges. The basis of their operation is the Josephson effect, which intrinsically occurs between the superconducting layers [2]. In our previous studies, we were successfully detected strong, coherent, continuous-wave radiation in the THz frequency range and observed emission powers up to 60 μW at frequencies up to 0.85 THz [3-4]. Since the critical temperature, c-axis resistivity, and critical current of intrinsic Josephson junctions can be tuned in a large range from underdoping to overdoping in Bi2212, the obtained results for THz emission strongly suggest that heating problem have to be solved in order to fabricate efficient devices. In this study, we report on critical current density dependence of mesa area and the crystal inhomogenity to eliminate heating problem for terahertz radiation. We have fabricated triple mesa structures from Bi2212 single crystal using e-beam lithography and argon ion beam etching techniques with same area and different area on the same chip. Our experimental results clearly show that the Josephson critical current density is decreasing when the area of mesa is increasing. Furthermore, the backbending voltage points are increasing since heating effects dominate for the large areas of the mesa structures. Because of small critical current, large area mesas fabricated from underdoped crystals cause less heating and backbending occurs after the cavity resonance in voltage scale. So, powerful THz radiation can be obtained before heating severely affects the local mesa temperature. The experimental results will be discussed further in detail.

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Successful terahertz emission from monolithic Bi-2212 intrinsic Josephson junctions near below 77K

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[keywords] intrinsic Josephson junction, terahertz, thin film

Now, it admits of no argument that Bi-2212 intrinsic Josephson junction (IJJ) devices show promise for the application of terahertz emission. We have been developing monolithic Bi-2212 IJJs which can be fabricated using only standard lithography processes suitable for manufacturing scene. In this presentation, we report the first successful terahertz wave emission from the thin monolithic Bi-2212 IJJ. The monolithic IJJ exhibits excellent heat dissipation and the maximum emission is observed at 75K near below 77K. Frequency of emission is measured by a terahertz lamellar grating interferometer to be around 0.6 THz. It is shown that the bias voltage satisfies the Josephson relation multiplied by the number of junction consisting of Cu-O double layers of Bi-2212 crystal and the frequency is in good agreement with the fundamental half wave resonance frequency of the junction width. Emission power is estimated to be 1.7μW based on the calibration using black body radiation. These results prove that that the monolithic Bi-2212 IJJ could be a practical terahertz emitting device operating at 77K.

Thermal imaging of Bi2212 mesas

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[keywords] Thermal imaging, Bi2212 mesa, THz generator

In 2007, an intense THz radiation has been generated from a $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) mesa when the current is fed along the *c*-axis [1]. Since then, intensive research activities are devoted to this fascinating THz generator, which can fill the so-called "THz gap". *S*-shaped current-voltage (*I*-*V*) characteristics strongly indicate that heating effect is involved in this phenomenon. Mapping of local characteristics such as local hating-induced dissipation by means of LSM has shown the presence of intriguing wavy pattern with hot spots [2]. Direct thermal imagings of the mesa have also been attempted, and hot spots were observed [3,4]. Still the detailed mechanism of the hot spot and its relationship between THz generation are unclear.

Thermal imaging by utilizing the blackbody radiation is not good at low temperatures, because the radiation intensity is proportional to the fourth power of temperature. Certain classes of materials are known to show strongly temperature-dependent fluorescence. Thermal imaging using such material is known as fluorescence thermal imaging (FTI). Here we combine our long-term expertise of magnetooptical imaging with FTI. Since the sample to be thermally imaged is expected to be inhomogeneous, careful calibration procedure is indispensible to obtain reliable results. By calibrating the temperaturedependent fluorescence intensity for each pixel of CCD camera, we attained high spatial resolution with high temperature resolution. As a first example, we applied FTI to the case of Bi2212 mesa (Fig. 1). At the bath temperature of 10 K, we observed a development of a clear hot spot in this mesa by feeding current only through the right electrode as shown in Fig. 2.

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Fig. 1 An optical image of the Bi2212 mesa.

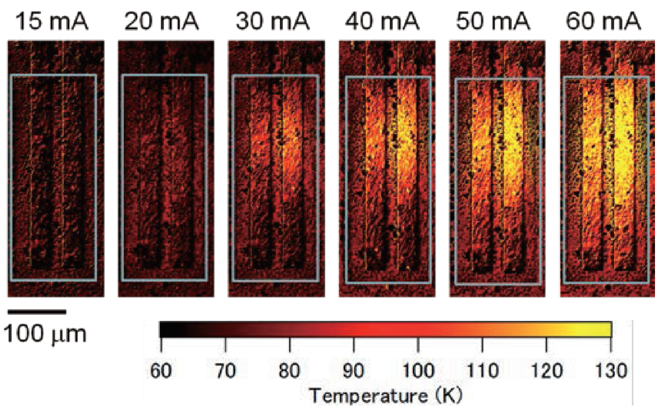

Fig. 2 Thermal imaging of the Bi2212 mesa at 10 K when the current is fed only through the right electrode.

The effect of temperature distribution on THz emission from high-T_c superconducting THz devices

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[keywords] Josephson junction, THz wave, $Bi_2Sr_2CaCu_2O_{8+\delta}$, hot spot

The THz electromagnetic waves are known to be generated from high temperature superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) that is comprised of multi-stacks of intrinsic Josephson junctions when the mesa structure made of Bi2212 crystals is biased by dc-voltage[1]. Since this radiation is stable, coherent and continuous with sufficient power of ~30 μW as a new type of source of THz radiation, it is expected that it has enormous potential for various kinds of applications.

Since a relatively large current is fed into the mesa for THz emission, considerable Joule heating can be generated. As a result, inhomogeneous temperature distribution (often called as hot spot, which stands for the spot where the temperature locally exceeds the critical temperature) has been observed by the previous studies[2,3]. However the hot spot does not play an essential role for the THz emission[3,4] in contrast to the previous claims[2] that the intensity of the THz emission is affected very much.

As the bias current is changed, the jump of the position of the hot spot was found[4]. In order to understand this phenomenon we tried to control the position of the hot spot by using the negative temperature coefficient of the Bi2212 crystals. Actually, we succeeded in making a control of the position of the hot spot and the improvement of the emission intensity by heating the mesa locally by the laser beam radiation.

In order to understand the effects of the hot spot on the emission characters, we observed electrical potential distribution in the mesa by attaching many electrode terminals on the surface of the mesa (see Fig. 1). In the conference, we show how the temperature and the electrical potential distribution influence the emission characters

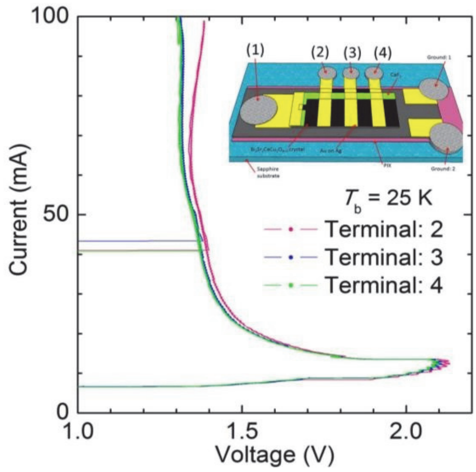

Fig. 1: The inset shows a schematic drawing of the device. There are 4 terminals along the length direction. The current was biased from Terminal 1. The main panel shows the electrical potential at terminals (2)-(4). The differences of the electrical potential were observed at high current range due to the occurrence of the hot spot (the normal part of the mesa).

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Terahertz radiation above 1 THz from intrinsic Josephson junction arrays

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[keywords] Josephson junctions, terahertz radiation, continuous wave, coherent emission

In recent years, high temperature superconductor (HTC) $Bi_2Sr_2CaCu_2O_8$ (BSCCO) devices have become indispensable for generating electromagnetic coherent terahertz (THz) radiation and attracted a lot of research interest [1-6]. It has been reported, that an optimized GBG (gold-BSCCO-gold) sample structure with a BSCCO stack embedded between two gold layers, can give rise to strong and tunable coherent emission. However, the observation of THz emission from these GBG and other conventional mesa structures shows, that the frequencies are well below 1 THz, which limits the application of THz technology. In our experiments, we improved the sample structure by gluing a second, thermally anchored substrate onto the surface of a GBG sample, which leads to better cooling. Investigations of the stacks using the same measurement methods demonstrated that the sample with new structure allows for a remarkable increase in emission frequency compared to the previous designs. The maximum voltage of this better cooled and dimension-unchanged sample was increased and, accordingly, both the emission frequencies and the tunable frequency range were significantly increased to 1.05 THz and 0.71 THz, respectively [8].

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Phase escape and retrapping in higher order switching events of $Bi_2Sr_2CaCu_2O_8$ intrinsic Josephson junctions

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[keywords] intrinsic Josephson junctions, phase escape, phase retrapping, switching current distribution, moderately damped

The intrinsic Josephson junctions (IJJs) of $Bi_2Sr_2CaCu_2O_y$ (Bi2212) cuprate superconductors has been extensively investigated both theoretically and experimentally. In particular, the recent discovery of the macroscopic quantum tunneling (MQT) occurring below ~1 K motivates many studies on the complex phase escape in the multi-junction systems such as IJJs. For instance, one of unresolved issues on the MQT in IJJs is a MQT-like behavior in the switching current distribution for the second switch (2nd SW) [1-3], that is, the temperature-independent behavior of an effective escape temperature for a switch from the first resistive state to the second resistive state in the multiple-branched *I-V* curves. In earlier reports [1,2], the self-heating effects due to finite dissipative current after the 1st SW has been discussed as an origin of the MQT-like behavior.

In this work, we study on the effects of dissipative current in the finite voltage state to the switching rate in higher order switching events, by considering multiple-retrapping processes after the escape events in the moderately damped regime. Small stacks of IJJs build in a narrow bridge of Bi2212 single crystal were fabricated by using focused ion beam (FIB) techniques. Experimental apparatus and method are almost the same as those described in the previous work [2]. We found that the switching rate for the 2nd or 3rd SW as a function of bias current showed a slight convex curvature in a lower bias current and higher temperature region, in contrast to that for the 1st SW. This feature cannot be explained by the conventional thermally-activated escape model at all. In addition, the effective escape temperature estimated from the switching current distribution data was found to be quite different from that from the switching rate data at high temperatures. Recently, Bae *et al.* showed that the convex feature in the switching rate could be explained by considering the multiple-retrapping effects in the running state from an occurrence of escape event to the detection of switching event [4].

We applied this model to the fittings of both the switching current distribution and the switching rate for the higher order switches, and confirmed that the effective escape temperature estimated from both data showed a good agreement with a bath temperature at high temperatures. This strongly suggests that the multiple-retrapping effects are quite important for higher order switching events and that the finite dissipation after the escape events contributes to the phase retrapping rather than the self-heating.

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Large reduction of number of junctions in bridge-type intrinsic Josephson junctions using focused ion beam technique

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[keywords] intrinsic Josephson junctions, macroscopic quantum tunneling, pseudogap, number of junctions, focused ion beam milling

Fabrication of small intrinsic Josephson junctions (IJJs) of cuprate superconductors is quite useful to investigate both the macroscopic quantum tunneling (MQT) phenomena occurring at lower temperatures [1] and the pseudogap (PG) phenomena appearing above a superconducting critical temperature, T_c [2]. It is considered that the understanding of MQT in IJJs is a key to realize future quantum information processing using IJJs, while that of PG is a key to understand the mechanism of high-T_c superconductivity. Although there are mainly two types in the structure of small IJJs (one is a mesa-type structure and the other is a bridge-type structure), a serious problem in the fabrication of bridge-type IJJs is that it is quite difficult to reduce the number of junctions included in IJJs down to a few junctions, showing a sharp contrast to the mesa-type IJJs.

In this work, we present a study to reduce the number of junctions in the bridge-type IJJs using a focused ion beam (FIB) technique. Although the fabrication method of the bridge-type IJJs is almost the same as the previous report by Ota *et al* [3], we improved the FIB milling processes to control the number of junctions more precisely. In addition, our method is based on the use of standard FIB milling technique, in contrast to a combined FIB/argon ion beam etching technique, which was recently reported by Kubo *et al* [4].

We succeeded in fabricating the bridge-type IJJs consisting of only 10 junctions. To determine the number of junctions, the multi-branched current-voltage (*I-V*) characteristics were measured by a short pulse method. The switching current density to the first resistive state and the retrapping current density to the zero-voltage state were 2.65×10^3 A/cm^2 and 83 A/cm^2, respectively. These results strongly suggest that the fabricated IJJs with a lateral area of ~1 μm^2 show so excellent *I-V* characteristics that the MQT and PG phenomena deserve to be investigated. Thus, our results clearly indicate that a remarkable reduction of the number of junctions in the bridge-type IJJs can be realized even by using the standard FIB milling techniques.

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Characteristics of $Bi_{2-x}Pb_xSr_2CaCu_2O_{8+\delta}$ intrinsic Josephson junction in subgap regime

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[keywords] intrinsic Josephson junctions, acid treatment process, Pb doped Bi-2212, jump voltage, return current

The layered $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) single crystal represents natural stacks of atomic scale intrinsic Josephson junctions (IJJs) with interlayer spacings of 1.55 nm [1]. Interlayer tunneling spectroscopy is a powerful tool for the fundamental study of bulk property in Bi-2212 superconductor [2]. We have reported current voltage characteristics, such as return current switching back from voltage to zero voltage state and jump voltage between two adjacent branches, in subgap regime [3, 4]. However these characteristics of Pb doped Bi-2212 stack have not been investigate yet.

In this symposium we will report jump voltage and return current of Pb doped Bi-2212 stacks fabricated by acid treatment process and characteristics of acid treated product produced from Pb doped crystal.

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Coupling effects of macroscopic quantum tunneling in $Bi_{2-x}Pb_xSr_{2-y}La_yCuO_{6+\delta}$ intrinsic Josephson junction

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[keywords] macroscopic quantum tunneling, Bi2201,

Recently, several intriguing phenomena on macroscopic quantum tunneling (MQT) have been reported in intrinsic Josephson junctions (IJJs) included in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) [1-4]. MQT is observed by measuring switching probability distributions (SPDs) which are histogram of currents where a Josephson junction switches from zero voltage state to resistive state. The switch is mainly caused by thermal activation (TA) or MQT. In IJJs, Multiple switches are observed. The first switch is the transition from zero voltage state to first resistive state and the second switch is the transition from the state that one junction is finite voltage. Recently several groups reports that the temperature independent behavior observed below ~ 8 K for the second switch in Bi2212. This behavior cannot be explained by MQT in a single Josephson junction because the temperature is one-order higher than the theoretical crossover temperature [2-4].

In this study, we measure the SPD of the first switch and the second switch in IJJs of $Bi_{2-x}Pb_xSr_{2-y}La_yCuO_{6+\delta}$ (Bi2201). The effective temperature (T_{eff}) of the first switch does not show temperature independence below 0.6 K. Meanwhile, T_{eff} of the second switch does not shows temperature dependence below 2 K. This behavior of the second switch cannot be explained by the single junction model because the expected crossover temperature is 0.35 K. T_{eff} in the TA region of the first and second switch is almost identical. This is a sharp contrast to the MQT region. The increase in T_{eff} with MQT region can be explained by the increase in the Josephson plasma frequency due to the charge coupling rather than the change in the potential barrier in the resistively and capacitively shunted junction model due to the inductive coupling. Therefore, we propose that the increase in T_{eff} of the MQT region of the second switch is attributed to the capacitive coupling effect. [5].

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Resonant phenomena in small $Bi_2Sr_2CaCu_2O_{8+x}$ intrinsic Josephson junctions

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[keywords] polaritons, flux-flow, angular dependence, radiation, calorimeter

$Bi_2Sr_2CaCu_2O_{8+x}$ high-temperature superconductors naturally form a layered metamaterial composed of metallic CuO bilayers sandwiched between ionic BiO planes, forming Josephson junctions on an atomic scale.

We experimentally study the interaction of phonons and electromagnatic waves in small, well defined stacks of such junctions, which enhances the quality factor of geometric and phonon resonances. We observe that electromagnetic waves strongly interact with several infrared and Raman-active transverse optical *c*-axis phonons and form phonon-polaritons. Those coherent, monochromatic phonon-polaritons have power densities in the order of kW/cm^2. As misalignment leads to intrusion of Abrikosov vortices at high field, we analyze the angular dependence the the resonances and describe the accurate sample alignment needed.

We study the interaction with external GHz-radiation and observe resonances attributed to an induced flux-flow. Furthermore we carry out several experiments attempting to detect radiation from small mesa structures of $Bi_2Sr_2CaCu_2O_{8+x}$ and $Bi_{1.75}Pb_{0.45}Sr_2CaCu_2O_{8+x}$. For this, different hot-electron bolometers and calorimeters with detection sensitivities of up to 100 fW have been used to cover a high solid angle of the structures. No distinct radiation with emission powers higher than ≈ 20 pW could be detected.

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Intrinsic Josephson junction arrays in $Tl_2Ba_2CaCu_2O_8$ on vicinal substrates

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[keywords] TBCCO, vicinal substrates, focused ion beam

It has been shown by Benseman *et al.* using $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) mesas, that by coupling multiple stacks of intrinsic Josephson junctions (IJJs) together, terahertz emission powers of 0.6 mW can be achieved[1]. However, mesa devices suffer from Joule heating due to the high bias required for emission. Thermal management is a significant factor limiting emission. By orienting the ab-planes perpendicular to the substrate surface, self-heating is reduced[2] and it may be possible to achieve higher emission power[3]. In this context, a-axis oriented cuprate thin films would be ideal. No one has yet grown an a-axis oriented BSCCO or $Tl_2Ba_2CaCu_2O_8$ (TBCCO) films. TBCCO films have been grown on vicinally cut substrates[4]. Here the cuprate planes are at an angle to the substrate surface. These films may therefore provide an advantageous geometry for thermal management.

We have fabricated stacks of IJJs in a TBCCO thin film grown on a 20^o vicinally cut $LaAlO_3$ substrate. The TBCCO film is grown by first r.f. sputtering from a Ba-Ca-Cu-O ceramic target and then annealing in a closed crucible with thallium powder. Device patterning was performed using a gallium focused ion beam (FIB). The stacks have been fabricated in series and parallel arrangements and we have measured the current-voltage characteristics. We have also fabricated junction stacks using a neon FIB, which may result in less sample poisoning.

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Resonances in Coupled Josephson junctions shunted by LC-circuit.

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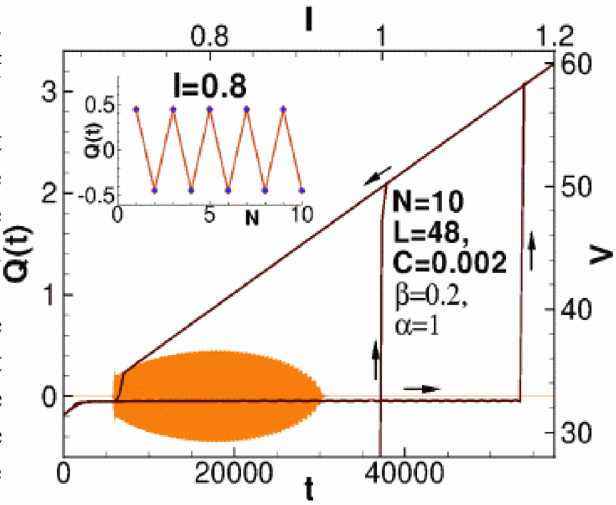
[keywords] intrinsic Josephson junctions, terahertz wave, longitudinal plasma wave, resonance frequency.



We study the effect of inductively-capacitively (LC) shunting on the system of coupled Josephson junctions (JJ). In Ref.[1,2,3] it has been shown that additional resonant circuit (rc) branches appear in the current–voltage characteristics of the junctions when the Josephson frequency ω_J is equal to the natural frequency ω_{rc} of the formed resonance circuit. The resonance of Josephson oscillations with the natural oscillations of an LC resonance circuit can also be responsible the excitation of the longitudinal plasma wave, i.e., lead to the double resonance condition $\omega_J = \omega_{rc} = 2\omega_{LPW}$, where ω_{LPW} is the frequency of the longitudinal plasma wave. This situation is demonstrated in Figure, where the current–voltage characteristics are given along with the time dependence of the charge in the superconducting layers in a stack with 10 junctions at L=48 – shunt inductance, C=0.002 – shunt capacitance, α=1 – coupling parameter and β=0.2 – dissipation parameter (all parameters in dimensionless form). Figure shows a charge in the superconducting layers at ω_{rc} =3.2596 which is observed in a current interval much narrower than the dimension of the rc branch itself. The distribution of charge along the stack at I=0.8 is demonstrated on the insert. With a decrease in the natural frequency from ω_{rc} =3.336 till ω_{rc} =2.868 the amplitude of the charge increases and the current interval corresponding to the "charged" rc branch expands. We assume that the resonance of Josephson oscillations and oscillations of the LC circuit is a trigger for the parametric resonance caused by the oscillatory circuit. The possibility of experimental implementation of the effects is considered.

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Novel collective excitations in the stack of long Josephson junctions

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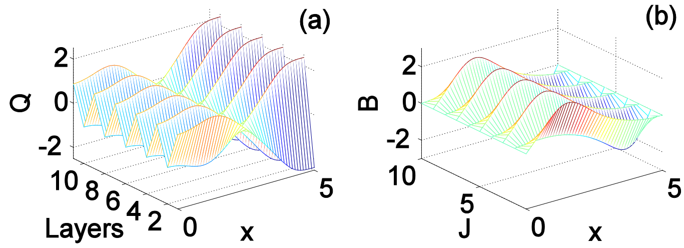
[keywords] intrinsic Josephson junctions, longitudinal plasma wave, charge travelling wave, inductive coupling, capacitive coupling.

We investigate the phase dynamics of the stack of long Josephson junctions (JJ) with inductive and capacitive couplings. The current--voltage characteristics (CVC), the spatiotemporal dependence of electric charge in superconducting layers and magnetic field in the JJs was calculated. Calculations have been done for the following values of model parameters [1]: JJs number N=10, length of JJs L=5, inductive coupling S=-0.05, capacitive coupling parameters s_c=-0.05, D_c=1.1, dissipation parameter β=0.2. We have shown an appearance of longitudinal plasma wave (LPW) and realization of parametric resonance [1,2]. The coexistence of a fluxon state and LPW is predicted. The charge distribution along the stack and coordinate x at the parametric resonance at a fixed time is shown in Fig.(a). The longitudinal plasma wave with the wavelength λ = 2 (in units of the lattice period d =d_I + d_s, where d_I and d_s are thicknesses of the superconducting and insulating layers, respectively) is observed. Charge distribution along the coordinate x is nonuniform in all JJ of the system due to the excitation of the fluxon (antifluxon) states. This conclusion is confirmed by the distribution of the magnetic field in Josephson junctions along the stack and x coordinate, which is shown in Fig.(b) at the same parameters of the model. This distribution demonstrates the presence of a fluxon (antifluxon) in each JJ of the stack. This fact can be interpreted as the possibility an appearance of a new collective excitation that is a composite state of the LPW and vortex magnetic field [3]. Also, the coexistence of the charge travelling wave [4] and fluxons has been found.



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Study on Josephson effects along the *c*-axis of $FeSe_{1-x}Te_x$ single crystals using FIB milling technique

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[keywords] iron-based superconductor, intrinsic Josephson effect, focused ion beam, relief structure

Iron-based superconductor $FeSe_{1-x}Te_x$ has a simply stacking structure of iron-chalcogenide layers, which is similar to the intrinsic Josephson junctions (IJJs) in the high-T_c cuprate superconductors. Although the anisotropy of transport properties ($\rho_c/\rho_{ab} < 10^2$) is not so large [1], it is interesting to investigate whether IJJs are also formed in $FeSe_{1-x}Te_x$ or not. In addition, the Josephson effects in multi-gap superconductors such as iron-based superconductors recently attract the interest of researchers by a theoretical proposal about a new detection of $\pm s$-wave symmetry in multi-gap superconductors [2].

In this work, we studied the *c*-axis charge transport in $FeSe_{1-x}Te_x$ (x=0.7) single crystals. The standard focused ion beam (FIB) technique was used to fabricate a microbridge and a small stack of the superconducting Fe layers in $FeSe_{1-x}Te_x$ single crystals [3]. We found that a ratio of the dc resistance of the small stack to that of the microbridge was slightly increased with decreasing temperature down to a superconducting critical temperature T_c. The current-voltage (*I-V*) characteristics for the small stack shows clear hysteresis below T_c, although a multiple-branched structure in the *I-V* curves is not shown, in contrast to the case of IJJs in $Bi_2Sr_2CaCu_2O_y$ cuprates. Rather, our results are very similar to those in a small stack of $LaFeAsO_{0.7}$ single crystal, which were recently reported by Kashiwaya *et al* [4]. We also found that the magnitude and the temperature dependence of mean switching-current to the voltage state were successfully explained by the conventional Ambegaokar-Baratoff theory assuming that the small stack intrinsically includes several tens of Josephson junctions [3]. These results suggest that the small stack of the superconducting Fe layers behave as like an underdamped IJJs. Similar results were also obtained for a small stack of FeSe (x=0) single crystal.

In the FIB milling of $FeSe_{1-x}Te_x$ crystals, we found that fine relief structure was formed on a surface where a beam of Ga^+ ions was not directly applied. SEM-EDX analyses on the surface suggest a possibility that some compounds consisting of iron and gallium were formed on the surface. Although the details of the fine relief structure remain unknown, it seems that the superconducting properties of the small stack were not so seriously influenced.

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Asymmetric critical currents in Josephson junctions with multi-band superconductors

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[keywords] multi-band, time-reversal symmetry, Josephson effect, critical current, Shapiro step

The multi-band superconductivity attracts a lot of interest after the discovery of MgB2 and iron-based superconductors, where multiple superconducting condensates couple to each other. In superconductors with three or more bands, a frustrated state can emerge as a compromise of repulsive interband couplings. In this case, phase differences among superconducting order parameters are neither 0 nor π, leading to broken time-reversal symmetry [1, 2].

Here we consider a Josephson junction between a single-band superconductor and a threeband time-reversal-symmetry-broken (TRSB) superconductor as shown in Figure 1. We study the Andreev spectra and Josephson currents with Bogoliubov-de Gennes (BdG) equations. Unequal critical currents in opposite directions as a consequence of broken TRS is obtained [3]. Upon microwave irradiation, prominent subharmonic Shapiro steps appear due to interference among different condensates.

It is intriguing to notice that unequal critical currents and subharmonic Shapiro steps have already been observed in a Josephson junction between a single-band superconductor and an iron-based superconductor [4]. Therefore TRSB states might have already been realized in iron-based superconductors in the light of our present work [3].

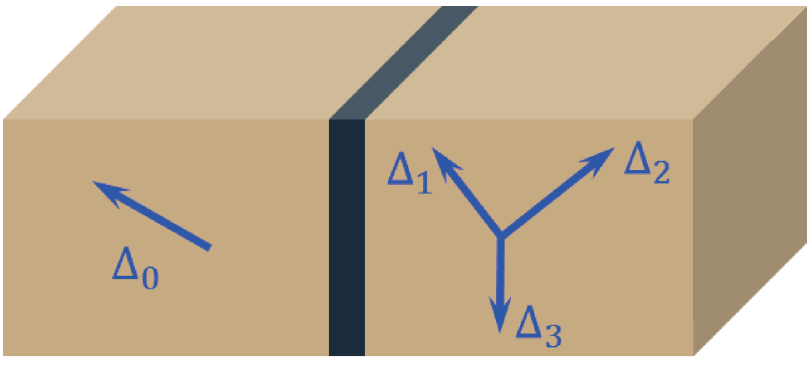

Figure 1: Schematics of Josephson junction between single-band and three-band TRSB superconductors, where $\{\Delta_0\}$ and $\{\Delta_1, \Delta_2, \Delta_3\}$ are superconducting order parameters respectively.

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Chaos in the stack of coupled Josephson junctions

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[keywords] Josephson junctions, chaos, bifurcations, nonlinear systems.

Like many natural systems, Josephson junctions are inherently nonlinear. Such systems are interesting for scientists and engineers because they exhibit a variety of different types of interesting behavior. It is known that the Josephson junction can be used as a model system for the investigating of chaotic features. Chaotic behavior in the rf-biased single Josephson junction was studied in details by Kautz and Monaco [1]. Here we present results for systems of coupled junctions and compare them with a case of single junction.

We use the resistively and capacitively shunted junction model (RCSJ) for the single junction and capacitively coupled Josephson junctions with diffusion current (CCJJ+DC) model for the stack. To simulate the IV-characteristics and the Poincaré sections we solve the system of nonlinear differential equations using the 4th order Runge-Kutta method [2].

Results of study of the influence of the radiation and Josephson junction parameters on the structured chaos [3] in case of coupled junctions are shown. We found that the structured chaos is a stable formation over a wide range of parameter values. We present results demonstrating the influence of the coupling parameter on chaotic regions. The effect of coupling between junctions on the current voltage characteristics at dissipation parameter β=0.3, frequency of external radiation Ω=0.5 and amplitude A=0.8 is studied in detail. Lastly we discuss a nontrivial disappearance of Shapiro step subharmonics with increase in the coupling parameter.

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Response of unconventional Josephson junctions to external microwave radiation

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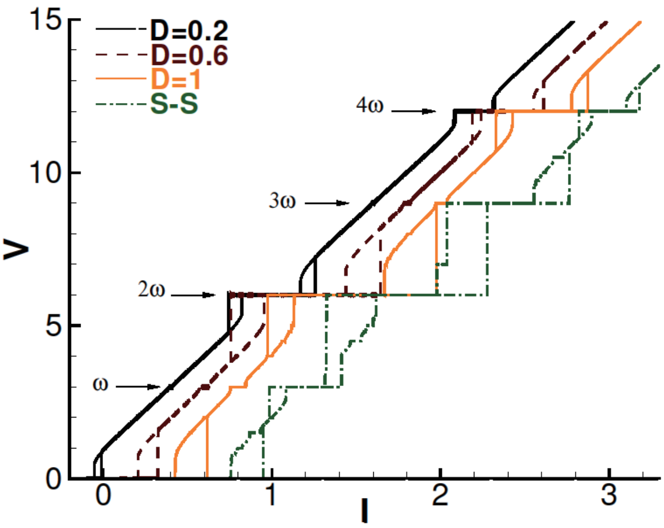
[keywords] unconventional Josephson junctions, Majorana fermions, Shapiro steps



An important method which has been recently proposed to detect Majorana fermions is to use Josephson effects in superconducting junctions [1,2,3]. Observation of even Shapiro steps (SS) has been predicted in junctions of 1-d superconductors which contains pair of Majorana fermions. In these systems the Josephson current exhibits 4π periodicity with the superconducting phase difference. We analyze the current-voltage (I-V) characteristics in a RCSJ model for a Josephson junction formed by two p-wave superconductors which is characterised by the transmission co-efficient D, for different amplitudes (A) of the external microwave radiation. We observe of appearance of even SS structure for smaller values of A (~1). This observation confirms the predictions of ref. [4]. In addition, for relatively larger values of A (=30), we also observe SS for odd harmonics and the width is always found to be smaller than the width of SS for even harmonics starting with the first even harmonics i.e 2ω. We illustrate this observation in the plot of I-V characteristics of p-wave junctions for different values of D *viz.* 0.2, 0.6, 1 (shifted in I axis by appropriate units) for amplitude A=30 and frequency ω=3 (all parameters are dimensionless). We show that on increasing the values of D, the width of the SS increases for both odd and even harmonics. We also compare the SS structures for the p-wave and the s-wave junction in the same plot. For the p-wave junction, the width of the odd harmonics is smaller than that of the even harmonics. This is in stark contrast with the SS observed in a s-wave superconducting junction where width of the SS decreases monotonically with higher harmonics (here, 2ω to 4ω as shown in the figure). These key features of the even SS structures observed in the p-wave Josephson junction are an important and robust method to detect clearly the presence of Majorana fermions in the system. Our analysis can be easily generalized to other unconventional Josephson junctions.

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Fluctuations, Nambu-Goldstone modes and time-reversal symmetry breaking in frustrated Josephson effects

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[keywords] frustrated Josephson effect, time-reversal symmetry breaking, chiral state, NambuGoldstone modes, fluctuation effects, fluctuation-induced gapless modes, fractional vortices

Frustrated Josephson effects induce many interesting phenomenon in superconductors. They are, for example, time-reversal symmetry breaking, the existence of massless and lowenergy excited states and fractionally quantized flux vortices. These occur due to the breaking of U(1) rotational invariance of the gap function. In general, they are described by using a family of sine-Gordon models.

The time-reversal symmetry breaking (TRSB) in frustrated Josephson systems is characterized by a geometrical condition. It has been shown that the TRSB state exists in a wide range of the parameter space of Josephson couplings. The condition of TRSB is given by a polygon condition in some simple cases. Gapless modes exist at the same time when this condition holds.

Here we present a new mechanism of fluctuation-induced Nambu-Goldstone bosons in superconductors, which are regarded as Higgs-Josephson systems. We consider a simple scalar field theory with $U(1)^n$ rotational symmetry. When there is an interaction that violates the rotational symmetry, the Nambu-Goldstone bosons become massive and massless bosons are concealed. Remarkably we present a model where the massive boson becomes a massless boson as a result of the fluctuation of rotational symmetry. In our model the Z_2-symmetry associated with the chirality is also broken. That is, the Nambu-Goldstone boson is induced by the chirality transition. The ground state at absolute zero will flow into the state with more massless bosons due to fluctuation effects at finite temperature. The KosterlitzThouless (KT) transition is derived for a sine-Gordon model in two dimensions. The KT transition temperature T_{KT} is, in general, different from the critical temperature of the chirality transition T_{chiral}.

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Single crystal growth and transport properties of $EuFe_2(As_{1-x}P_x)_2$

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[keywords] Fe-based superconductors, Eu122, single crystal growth, transport properties

$EuFe_2As_2$ is one of the 122 (AFe_2As_2 with A = Ba, Ca, or Sr etc.) families and it behaves as a special system since the A site is occupied by Eu^{2+}, which has an S-state rare-earth ion possessing $4f^7$ electrons with the total electron spins $S = 7/2$[1]. $EuFe_2As_2$ shows two phase transitions, at $T_0 \sim 190$ K and $T_N \sim 19$ K. The transition at T_0 is a combined structural and magnetic transition (SDW), and the transition at T_N is the antiferromagnetic ordering of the Eu^{2+} moments[2]. By doping with P at the As-site, SDW order is suppressed and superconductivity is induced at $x = 0.2$, due perhaps to "chemical pressure"[3]. It is reported that superconductivity can coexist with the strong Eu^{2+} magnetism[4].

We are interested in coexistence of superconductivity and magnetism in the $EuFe_2(As_{1-x}P_x)_2$ system. In order to understand the role of Eu^{2+} magnetism on the formation of superconductivity, we focus on the study of high-quality single crystal growth and transport properties of $EuFe_2(As_{1-x}P_x)_2$.

To grow high-quality single crystals, we first synthesized $EuFe_2As_2$ using several methods because undoped sample is easier to grow. In this poster, we will discuss the detail and compare the result of these samples by several measurements. In addition, we measured magnetoresistance on undoped and P-doped samples to understand how to change the relation between Eu^{2+} magnetism and transport properties by doping with P. Figure 1 shows the magnetoresistance on $x = 0$ and $x = 0.1$ in B // ab at T = 5 K. Each curve has two anomalies. The first anomaly is shown at B = 0.5 – 0.7 T on $x = 0$ and 0.3 T on $x = 0.1$, while the second anomaly is shown at B = 0.9 – 1.1 T on $x = 0$ and 0.7 T on $x = 0.1$. The first anomaly is due to a spin flop transition of Eu^{2+}, while the second anomaly is due to an entrance into the field-induced ferromagnetic state of Eu^{2+}. On the sample of $x = 0$, anisotropy in the ab plane was shown, while the anisotropy was suppressed on the sample of $x = 0.1$. In this poster, we will discuss the detail.

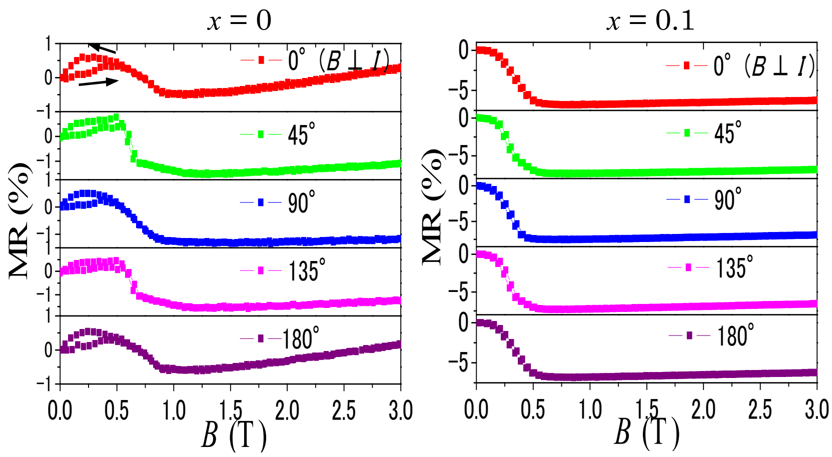

Fig. 1 : Magnetoresistance on $x = 0$ and $x = 0.1$ in B // ab at T = 5 K.

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Superconducting properties of topological insulator $Cu_xBi_2(Te_ySe_{1-y})_3$

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[keywords] Topological insulator, Superconductor, $Cu_xBi_2Se_3$, Carrier concentration.

It is well known that Cu-doped topological insulator $Cu_xBi_2Se_3$ ($0.1 \leqq x \leqq 0.3$) becomes superconducting with a maximum transition temperature $T_C \approx 3.6$ K [1]. This material can be regarded as a typical candidate for the topological superconductor. In this system, Cu atoms are intercalated into the layered topological insulator Bi_2Se_3 with the carrier concentration of 10^{20}cm^{-3} and makes it electron doping. When Cu is assumed intercalate between layers, one electron per Cu atom may be donated to the conduction band. The carrier concentration is expected to increase with increasing Cu concentration. However, From the Hall effect measurement this electron doping shows a tendency to saturate above x = 0.10, and tends to decrease above x = 0.25. This indicates that the electron number of doping by Cu does not give one electron in the conduction band any more above x = 0.10 and number of conducting carriers is suppressed to compensate the electrons perhaps by producing the additional holes introduced by the Cu substitution for Bi. This peculiar carrier concentration behavior seems to occur in this material and this behavior can only be found in the system where the Hall constant is saturated or decreased.

In order to understand the role of carrier doping by Cu intercalation on the occurrence of superconductivity in more detail, we have investigated $Cu_{0.25}Bi_2Se_3$ and Bi_2Se_3 systems by substituting whose carriers were compensated. This doping is believed to occur naturally by compensating Se vacancies by Te perhaps suppressing substitution Te for Bi, which effectively reduces carrier concentration [2].

In fact, we observed a suppression of carrier concentration with increasing Te concentration as seen in Fig.1. We also measure the composition of the samples with a variety of Te compensation concentration. Further experimental results will be analyzed and argued assuming the free electron model, such as Hall effect, the electrical resistivity, the effective mas, the mobility.

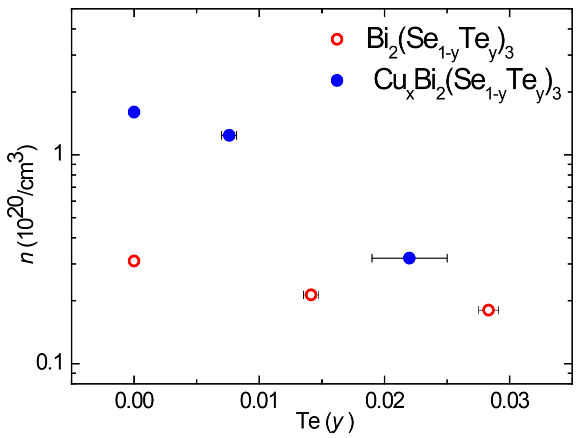

Fig.1 The Te concentration dependence of carrier concentration n for various x and y- values.

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Growth and characterization of $BaBiO_{3-x}F_x$ thin films

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[keywords] $BaBiO_3$, fluorine doping, topological insulator

$BaBiO_3$ (BBO) is the parent compound of $BaPb_xBi_{1-x}O_3$ and $Ba_{1-x}K_xBiO_3$, which are well known superconductors. Recently, Yan *et al.* indicated through ab initio calculations that BBO emerges as a topological insulator in electron-doped region [1]. BBO exhibits a larger energy gap of 0.7 eV than that of the known topological insulator materials, and is stable against surface oxidization and degradation. BBO may be a suitable topological insulator for applications in quantum information and spintronics and therefore it is important to verify that BBO actually becomes a topological insulator. Doping electron into BBO can be achieved by substituting F for O atoms, however no one has reported the substitution. We have been trying the growth of F-doped BBO thin films on MgO (001) substrates by magnetron sputtering method, and analyze their crystallographic characteristics. So far, we have obtained F-doped BBO with lattice constants being 2.3 percent larger than that of non-doped BBO. In the symposium we will discuss the fundamental physical properties of F-doped BBO such as the temperature dependence of the resistance and the magnetic properties.

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Electronic states of $BaPb_{1-x}Bi_xO_3$ observed by THz time domain spectroscopy

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[keywords] $BaPb_{1-x}Bi_xO_3$, THz-TDS, topological insulator, charge density wave

$BaPb_{1-x}Bi_xO_3$ (BPBO) have interesting features: high superconducting transition temperature (T_c=13 K at x=0.25[1]) with respect to low carrier density (order of 10^{21} cm^{-3}), charge ordering of Bi^{3+} and Bi^{5+}, and the possibility that pseudogap exists in spite of *s* wave superconductor. Furthermore, recent band calculation indicates that electron doped $BaBiO_3$ is possibly a topological insulator which have large topological energy gap (0.7eV) [2]. This means that BPBO is an intriguing material to fabricate high quality interface between superconductor and topological insulator. Motivated by these fact, we study superconducting state of BPBO by terahertz time domain spectroscopy (THz-TDS).

200nm thick BPBO epitaxial thin film on $LaAlO_3$ (100) substrate is prepared by rf magnetron sputtering. Temperature dependence of resistivity shows that superconducting transition temperature is 7.8 K, and energy dispersive X-ray spectrometry shows that x = 0.25.

We obtained the temperature dependence of transmission spectra of THz-TDS as shown in Fig. 1. This result reveals the temperature dependence of the superconducting gap by taking the frequency where the transmissivity comes the unity. Fitted by phenomenological equation [3], the ratio of Superconducting gap at T=0 to k_BT_c comes to 3.72$\pm$0.18.

This result suggests that BPBO is a weak-coupling superconductor. This conclusion is consistent with the consequence of point-contact tunneling spectroscopy [4].

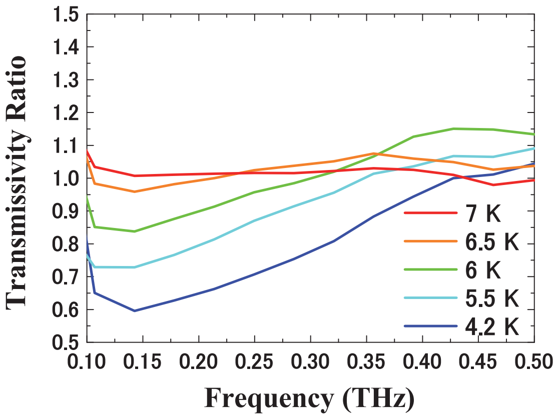

Fig. 1: Temperature dependence of transmission spectrum. Transmissivity is normalized by data at 10 K.

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Optical effect on proximity-induced superconductivity in graphene

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[keywords] graphene, superconducting proximity effect, optical effect.

Graphene is an ideal two-dimensional sheet made of carbon atoms. Their splendid and peculiar electronic properties are suitable for novel electronic devices those operate with new principles. Photoresponse is one of such properties and an ultrafast photoresponse that is potentially faster than 500 GHz has been reported [1]. If we combine proximity-induced superconducting state in graphene with it, new functionalities will be created like superconducting LEDs where normal metal electrodes of usual LEDs are substituted by superconducting electrodes [2].

Here we report on optical modulation of proximity-induced superconducting state in graphene. Sample studied is a superconductor/graphene/superconductor (SGS) junction made of monolayer graphene and Al as superconducting electrodes. We measured current-voltage characteristics under the illumination with light at the wavelength of 1.310 μm at T = 40 mK. Josephson supercurrent flowing through graphene channel was observed under illumination power (P) smaller than 5 μW. Figure 1 shows critical current (I_c) and normal state resistance (R_n) as a function of back-gate voltage (V_{bg}) without illumination. At the same time R_n decreases, I_c increases with V_{bg}. Figure 2 illustrates normalized R_n and normalized I_c to their values without illumination as a function of P at V_{bg} = 60 V. In this case, I_c monotonically decreases with increasing P though R_n does not change at all. Variation of I_c and R_n with V_g can be accountable by considering that V_g modulates the carrier density in graphene. Their dependence on P, however, cannot be easily understood. This result is completely different from those in superconductor-semiconductor-superconductor junctions, where increased carrier density by optical excitation results in enhancement of I_c [3]. To identify the origin of our observations, we need further measurements, such as excitation energy dependence of I_c or its time evolution.

Fig. 1.

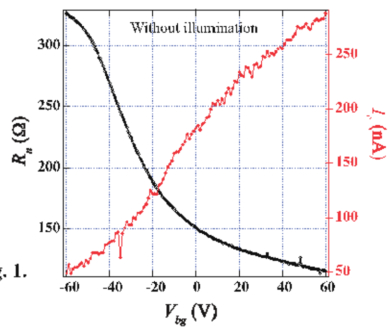

Fig. 2.

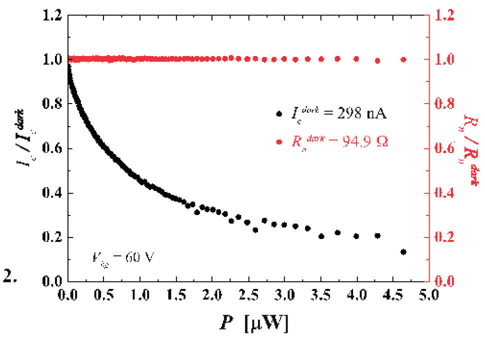

Fig. 1: R_n and I_c of SGS junction as a function of V_{bg} without illumination at T = 40 mK.
Fig. 2: Normalized R_n and normalized I_c to their values without illumination as a function of P at V_{bg} = 60 V.

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Ultrafast dynamics in Topological Insulators

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[keywords] topological insulator, ultrafast dynamics, pump-probe spectroscopy, carrier dynamics

We report on the ultrafast dynamics of topological insulator Bi_2Te_2Se crystals by using optical pump ultra-broadband mid-infrared probe spectrocsopy. After pumping with the photon energy of 1.55 eV and fluence of 67 μJ/cm^2, the reflected intensity of mid-infrared probe pulses, generated by the four wave mixing [1, 2], on a sample can be measured by using chirp pulse up-conversion and a visible dispersive spectrometer [3]. The complete ultrafast carrier dynamics in topological insulators can be clearly resolved by the broad MIR detection range from 500 to 5000 cm^{-1} and discussed detailedly.

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Observation of a quantum oscillation in a narrow channel with a hole fabricated on a film of multiband superconductors

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[keywords] quantum oscillation, little-parks experiment, multiband superconductivity, cuprates

We have observed oscillations in resistivity as a function of magnetic field at 80 K in a 5 μm wide channel with a 100 nm-size hole fabricated on a film of the multi-band superconductor $(Tl_x,Cu_{1-x})(Ba_y,Sr_{1-y})_2Ca_2Cu_3O_z$ [1]. In the oscillations, a phase shift is shown at magnetic fields around 200 mT, which is similar to previous observations [2] in mesoscopic superconducting rings with two order parameters. We discuss the implication of the oscillations in multiband superconductivity.

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Fabrication and transmission measurements of superconducting terahertz metamaterials

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[keywords] metamaterial, superconductor, YBCO, terahertz

Terahertz metamaterials are utilized for novel filters of THz frequency region. Highly conducting metal like silver and gold are usually used for metamaterials. Meanwhile, superconducting metamaterials have an advantage for active filters either by applying magnetic field by varying temperature because high frequency conductivity of a superconductor is quite sensitive for such external perturbation.

In this study, we have fabricated split-ring resonator(SRR) arrays made of $YBa_2Cu_3O_7$(YBCO) thin films. YBCO epitaxial film was grown on $LaAl_2O_3$ substrates by the DC off-axis sputtering method. The SRR pattern was formed by photolithography and Ar ion milling. Transmission properties of the YBCO metamaterials are measured by the THz time domain spectroscopy(THz-TDS). Strong absorption of the THz wave is possibly observed at the resonant frequency of the SRR. Temperature dependence of the resonance frequency can be explained by the temperature dependence of the London penetration depth.

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Twin boundary effects on spontaneous half-quantized vortices in superconducting composite structures (d-dot's)

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[keywords] *d*-wave superconductivity, half-quantized vortex, Ginzbrug-Landau equations, twin boundary

A d-dot is a nano-sized composite structure that consists of a *d*-wave superconductor embedded in an *s*-wave matrix, as shown in Fig.1(a). Since the phase of the superconducting order parameter in the *d*-wave superconductor depends on direction, phase difference appears at a corner junction between *d*wave and *s*-wave superconductors. Compensating this phase difference, a spontaneous half-quantized vortex appears. This is a feature of d-dot's[1].

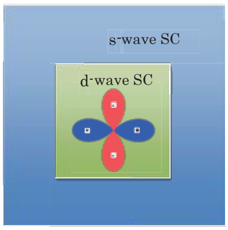
$YBa_2Cu_3O_{7-\delta}$ (YBCO) is orthorhombic because CuO chains break tetragonal symmetry of CuO_2 planes. CuO chains have two possible orientations and lead to formation of twin domains separated by twin boundaries (TBs). It is pointed out that the spontaneous magnetic flux may not appear if phase differences across TBs in the YBCO exist.

In order to analyze effects of twin boundaries on spontaneous half-quantized vortices, we introduce orthorhombic structure of YBCO to two-components Ginzburg-Landau (GL) equations[2] in terms of anisotropy of effective mass of electrons in YBCO. Then we have following modified twocomponents GL equations.

$$\begin{cases} \tilde{\Delta}_s^* = 2\lambda_d \left(\dfrac{V_s}{V_d}\right) \tilde{\Delta}_s^* \ln\left(\dfrac{2e^{\gamma}\hbar\omega_D}{\pi k_B T}\right) - 2\lambda_d \left(\dfrac{V_s}{V_d}\right) \alpha \left[\left(\dfrac{\varepsilon_F}{2m_x^*}\Pi_x^2 + \dfrac{\varepsilon_F}{2m_y^*}\Pi_y^2\right)\tilde{\Delta}_s^* + \left(\dfrac{\varepsilon_F}{4m_x^*}\Pi_x^2 - \dfrac{\varepsilon_F}{4m_y^*}\Pi_y^2\right)\tilde{\Delta}_d^* + \left|\tilde{\Delta}_s\right|^2 \tilde{\Delta}_s^* + \left|\tilde{\Delta}_d^*\right|^2 \tilde{\Delta}_s^* + \dfrac{1}{2}\tilde{\Delta}_d^{*2}\tilde{\Delta}_s^* \right] \\ \tilde{\Delta}_d^* = 2\lambda_d \tilde{\Delta}_d^* \ln\left(\dfrac{2e^{\gamma}\hbar\omega_D}{\pi k_B T}\right) - 2\lambda_d \alpha \left[\left(\dfrac{\varepsilon_F}{4m_x^*}\Pi_x^2 + \dfrac{\varepsilon_F}{4m_y^*}\Pi_y^2\right)\tilde{\Delta}_d^* + \left(\dfrac{\varepsilon_F}{4m_x^*}\Pi_x^2 - \dfrac{\varepsilon_F}{4m_y^*}\Pi_y^2\right)\tilde{\Delta}_s^* + \left|\tilde{\Delta}_s\right|^2 \tilde{\Delta}_d^* + \dfrac{3}{8}\left|\tilde{\Delta}_d^*\right|^2 \tilde{\Delta}_d^* + \dfrac{1}{2}\tilde{\Delta}_s^{*2}\tilde{\Delta}_d \right] \end{cases}$$

Using the finite element method and solving these equations self-consistently, we investigate the effects of twin boundaries on spontaneous half-quantized vortices.

(a)



(b)

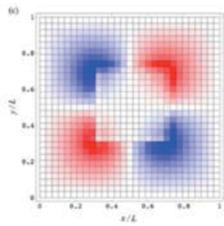


Figure 1. (a)A Schematic diagram of a d-dot. (b)Magnetic field distribution calculated by two-components GL equations with the finite element method

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The origin of rise of transition temperature of nano-structured superconductors

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[keywords] nano structured superconductivity, transition temperature, finite element method, Gor'kov equation

Transition temperature T_c of nano-sized superconductors depends on their sizes. Experimentally, a bulk nano-structured metal prepared by high-pressure torsion shows T_c enhancement [1]. We study size effects on nano-structured superconductors' T_c [2] numerically. T_c oscillatory increases with decreasing superconductors' size.

In this study, we investigate the condition of this T_c 's oscillation. We use Gor'kov equations, because we want to treat the impurities effect using Green's function, and the finite element method. Therefore we use following equations .

$$\sum_{i_1 i_2}\left[\left(i\hbar\omega_n+\mu\right)I^e_{ii_1}-\frac{\hbar^2}{2m}\sum_\alpha K^{e\alpha\alpha}_{ii_1}\right]\mathcal{G}^{ee'}_{i_1 i_2}I^{e'}_{i_2 j}+\sum_{i_1 i_2 i_3}I^e_{ii_1 i_2}\Delta_{i_1}\mathcal{F}^{\dagger ee'}_{i_2 i_3}I^{e'}_{i_3 j}=\hbar I^e_{ij}$$

$$\sum_{j}\left[\left(-i\hbar\omega_n+\mu\right)I^e_{ii_1}-\frac{\hbar^2}{2m}\sum_\alpha K^{\alpha\alpha}_{ij}\right]\mathcal{F}^{\dagger ee'}_{i_1 i_2}I^{e'}_{i_2 j}-\sum_{i_1 j}I^e_{ii_1 i_2}\Delta^*_{i_1}\mathcal{G}^{ee'}_{i_2 i_3}I^{e'}_{i_3 j}=0$$

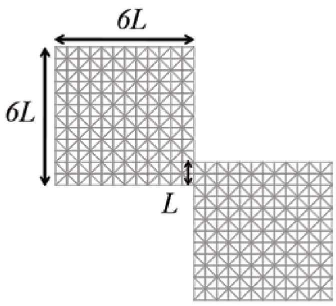

Fig1. Connected Squares

Then if we define C_{ij} from the self-consistent equation as,

$$C_{ii_1}=\left(i\hbar\omega_n+\mu\right)I^e_{ii_1}-\frac{\hbar^2}{2m}\sum_\alpha K^{e\alpha\alpha}_{ii_1},D_{ii_1}=\left(-i\hbar\omega_n+\mu\right)I^e_{ii_1}-\frac{\hbar^2}{2m}\sum_\alpha K^{e\alpha\alpha}_{ij},$$

we get

$$\sum_{i_1}\left[I^e_{ii_1}-\frac{g}{\beta\hbar}\sum_{\omega_n}e^{-\omega_n\eta}\sum_{i_1' i_2'}\sum_{i_2 i_3}\left(D^{-1}\right)_{i_1' i_2}I^e_{i_1 i_2 i_3}\left(C^{-1}\right)_{i_3 i_2'}I^e_{ii_1' i_2'}\right]\Delta^{*e}_{i_1}=0$$

We obtain the T_c when the smallest eigenvalue of this matrix is zero. Also we obtain the order parameters, which depend on space coordinates, from the eigenvector which belongs to the eigenvalue. We will present on size effects on T_c for three kinds of shapes, square, rectangle, and connected two squares.

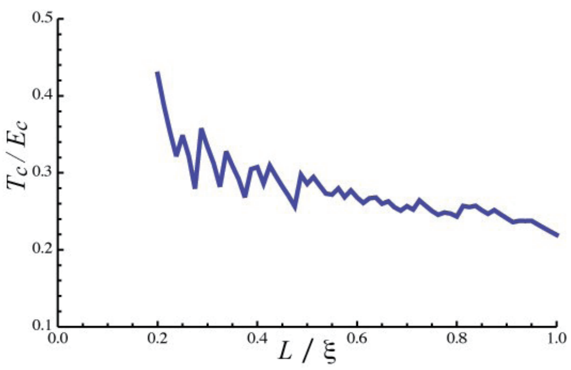

Fig2. Size dependence of Tc for connected squares

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Vortex structures in a chiral helimagnet/superconductor bilayer structure

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[keywords] superconductor / magnet bilayer, chiral helimagnet, Ginzburg-Landau equations, vortex, finite element method

Superconductor/ magnetic material layer structures provide some specific physical properties by the interaction between subsystems. For example, in superconductor/ ferromagnet bilayer structures, vortex structures in superconductors are affected by ferromagnets, and there are strong pinning effect and matching effect [1].

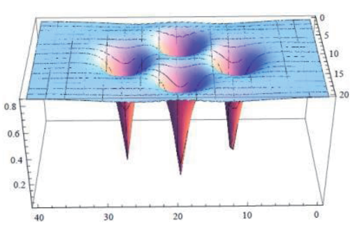
Superconductor/ ferromagnet layer structures have been studied for decades, but there are not many studies on the bilayer of the superconductor with other magnetism, for example, paramagnets, antiferromagnets, or chiral helimagnets. So, we focus on a chiral helimagnet/ superconductor layer structure. A chiral helimagnet comes from competition of the ferromagnetic exchange interaction and Dzyaloshinsky-Moriya (DM) interaction, which tilts spins slightly. The chiral helimagnet shows like helical rotation of spins along one direction, and has been focused in the development of new magnetic devices and the field of spintronics recently. In addition, chiral helimagnets show a chiral soliton lattice in which helix loosens periodically due to the applied magnetic field [2]. We investigate the effects of the chiral helimagnet on the vortex structure in the superconductor.

In this study, we will present numerical simulations on vortex structures in the chiral helimagnet/ superconductor bilayer structure. We solve Ginzburg-Landau (GL) equations with the finite element method:

$$\alpha|\psi|^2 + \beta|\psi|^2\psi + \frac{1}{2m^*}\left(\frac{\hbar}{i}\boldsymbol{\nabla} - \frac{e^*}{c}\mathbf{A}\right)^2 \psi = 0$$

$$\boldsymbol{J} = \frac{e^*\hbar}{2m^*i}(\psi^*\boldsymbol{\nabla}\psi - \psi\boldsymbol{\nabla}\psi^*) - \frac{e^{*2}}{m^*c}\psi^*\psi\mathbf{A}$$

We consider only z-component $H_z(\mathrm{x})$ of the magnetic field and two-dimension vector potential $\mathbf{A}$. we express vector potential as $\mathbf{A} = (0, \int H_z(\mathrm{x})\mathrm{dx}, 0)$, where $H_z(\mathrm{x})=H_0\cos(2\sin^{-1}(\mathrm{sn}(cx|k))+\pi)+H_{ext}$. Here H_{ext} is an external field, H_0 is the magnitude of the magnetic field from chiral helimagnet, $\mathrm{sn}(cx|k)$ is the Jacobi's elliptic function, and c and k are functions of the external magnetic field. We investigate vortex structures, solving these equations numerically. Figure 1 shows the distribution of the order parameter and the distribution of the magnetic field.



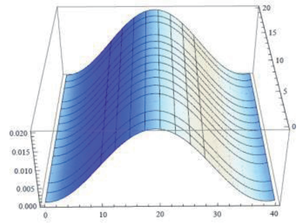


Figure 1: (Left) The distribution of the order parameter, (Right) The distribution of the magnetic field

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The 9th International Symposium on Intrinsic Josephson Effects and THz Plasma Oscillations in High-Tc Superconductors (THz-PLASMA 2014)
Kyoto University, Kyoto, Japan, November 30 - December 3, 2014

Structure of the odd-frequency superconductivity in nanostructured superconductors under magnetic field

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[keywords] odd-frequency superconductivity, nano-structured superconductors, Eliashberg equation, finite element method

Superconductivity consists of pairs of electrons called Cooper pairs because of phonon-mediated attractive interaction. When a Cooper pair is formed from two electrons by this phonon-mediated interaction, the retardation effect between two electrons appears. Therefore, anomalous Green's functions characterizing superconducting states depend on space coordinates, spins and frequency. In accordance with Fermi-Dirac statistics, the symmetry of anomalous Green's functions must have a sign change with the exchange of two electrons. Therefore, the symmetry of anomalous Green's functions is classified into four groups, i.e., (i) even-frequency spin-singlet even-parity (ESE), (ii) even-frequency spin-triplet odd-parity (ETO), (iii) odd-frequency spin-triplet even-parity (OTE), and (iv) odd-frequency spin-singlet odd-parity (OSO). Matsumoto et al's[1] show that since the timereversal symmetry is broken under the Zeeman magnetic field, the odd-frequency pairs appear in the even-frequency superconductors in the bulk systems. This situation corresponds to the superconductors in a uniformly penetrated magnetic field. Hence, we propose nano-structured superconductors are systems, where this situation is more easily realized, since the magnetic field uniformly penetrates into nano-structured superconductors. We solve the Eliashberg equation to treat the odd-frequency pairs incorporating the effects of interacting electron and phonon using the finite element method in real space.

$$\sum_{i_1,i_2}\left[i\omega_n \boldsymbol{G}^{ee'}_{i_1i_2}(i\omega_n) I^{e}_{ii_1} I^{e'}_{ji_2} - \check{\tau}_3\frac{\hbar^2}{2m}\sum_{\alpha} K^{e\alpha\alpha}_{ii_1}\boldsymbol{G}^{ee'}_{i_1i_2}(i\omega_n) I^{e'}_{ji_2} - h\check{\tau}_3\hat{\sigma}_z \boldsymbol{G}^{ee'}_{i_1i_2}(i\omega_n) I^{e}_{ii_1} I^{e'}_{ji_2}\right] - \sum_{i_1i'_1}\sum_{i_2}\Sigma^{e}_{i_1}(i\omega_n)\boldsymbol{G}^{ee'}_{i'_1i_2}(i\omega_n) I^{e}_{i_1i'_1i} I^{e'}_{i_2j} = \delta_{ee'} I_{ij},$$

$$\sum_{i_1}\left[-i\Sigma^{\omega}_i(i\omega_n) + \Sigma^{h}_i(i\omega_n)\check{\tau}_3\hat{\sigma}_z + \Delta^{e}_i(i\omega_n)\check{\tau}_2\hat{\sigma}_y + i\Delta^{o}_i(i\omega_n)\check{\tau}_1\hat{\sigma}_x\right] I_{ii_1} = -g^2\frac{N_p}{\Omega}T\sum_m D_0(i\omega_n - i\omega_m)\check{\tau}_3\sum_{i_1,i_2}\boldsymbol{G}^{ee}_{i_1i_2} I^{e}_{i_1i_2i}\check{\tau}_3,$$

Here, D is a Green's function for free phonon. N_p is the number of phonon's sites. Ω is the volume of this system.

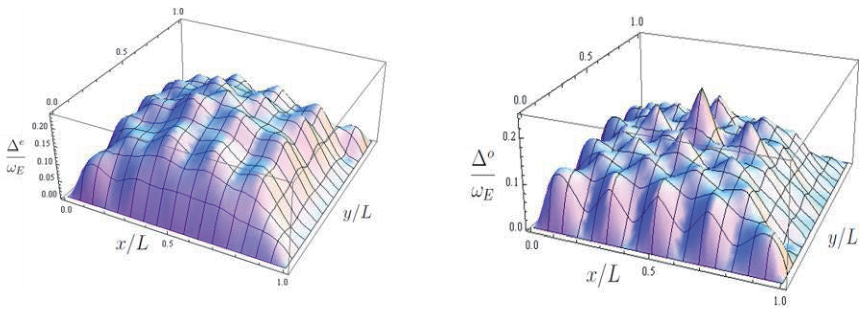

Fig. 1: Spatial structure of even-(left) and odd-(right) frequency components in magnetic field h=0.3

We examine the spatial dependence of the order parameter of the odd-frequency pair. The oddfrequency pair was induced with the even-frequency pair by magnetic field (Fig.1).

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Transport properties of superconducting amorphous NbGe nanowires

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[keywords] Superconducting nanowires, amorphous material, quantum phase slips

Recent advances in microfabrication techniques have provided a unique opportunity to investigate fundamental phenomena associated with the superconductivity in quasi-onedimensional thin wires. While this issue contains a practical importance for the application as a highly promising photon counting device for infrared wavelengths [1], there remains a fundamental question as to how the superconductivity in thin wires is destroyed as its diameter is reduced. In addition to the enhanced Coulomb interaction due to the inevitable quenched disorder involved in thin wires, thermal [2] and quantum phase slips [3] are supposed to suppress the superconductivity, resulting in unique tail behavior in temperature dependence of wire resistance. Although many experimental tests for these physical mechanisms have been done so far, there remain controversial as to the material inhomogeneity[3] or the effect of substrate proximity [4].

In this study, we present transport properties in homogeneous amorphous NbGe nanowires fabricated by e-beam lithography and subsequent reactive dry etching techniques. We find that the mean-field superconducting transition temperature T_c of nanowires is reduced systematically with reducing the width of nanowires and they are controlled by the cross section area of nanowires, rather than the normal state resistance. Far below T_c, our nanowires exhibit resistive tail behavior, of which temperature dependence is much weaker than that in thermally activated phase slips model. The observed features are likely understood in terms of a scenario of quantum phase slips.

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The 9th International Symposium on Intrinsic Josephson Effects and THz Plasma Oscillations in High-Tc Superconductors (THz-PLASMA 2014)
Kyoto University, Kyoto, Japan, November 30 - December 3, 2014

Magnetization switching assisted by bias voltage in a single electron transistor comprising an aluminum island and cobalt leads

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[keywords] single electron transistor, ferromagnet/superconductor, spin current, magnetization reversal

Recently, Single electron transistors (SET) with ferromagnetic (FM) leads and superconducting (SC) island has been the focus of several studies [1], which showed various interesting phenomena caused by the interplay between superconductivity and ferromagnetism. The SET is a device consists of a small island connected to two electrodes by tunnel junctions.
Conventionally, magnetization switching in magnetic tunnel junctions (MTJ) is done by applying external magnetic field. However, recent studies showed that it can also be done by injecting a pure spin polarized current [2], or assisted by it [3].
In our experiments we attempted to study the magneto-resistance on FM/SC/FM SET within several bias voltages in order to understand the influence of superconductivity on the device's operation.
For that to happen, we have fabricated a single electron transistor with cobalt leads, and an aluminum island separated by aluminum-oxide tunnel barriers (Figure.1). To measure the magneto-resistance we applied a magnetic field in-plain perpendicular to the island.
The magneto-resistance is then observed when the magnetization in the two leads switches direction. Current versus external magnetic field characteristics is shown in Figure.2.
The graph shows the magnetization switching points which are noted by a sudden decrease in current. The magnetization reversal points show a clear dependence on the applied bias voltage. As the applied bias voltage increases the ferromagnetic leads magnetization becomes easier to reverse under the applied magnetic field. The probable cause for this behavior is the increase in the spin polarized current injected into the island which minimized the field required to reverse the magnetization.

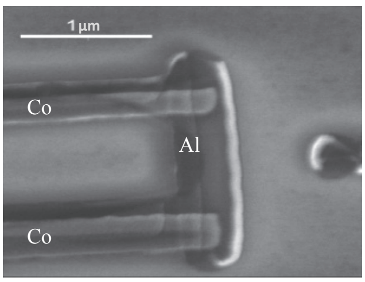

Fig.1 SEM image of fabricated device.

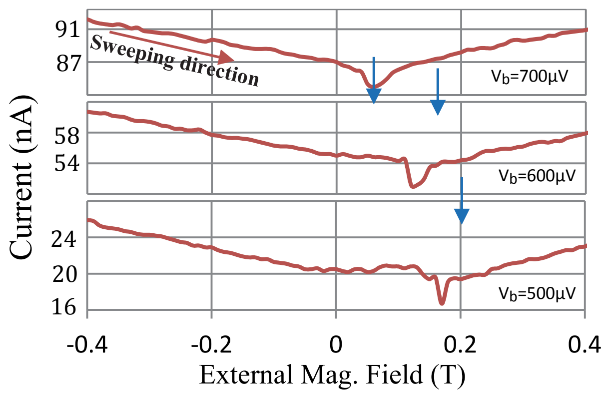

Fig.2 Current vs. magnetic field in different bias voltages.

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Intense and high-frequency THz radiation from $Bi_2Sr_2CaCu_2O_{8+\delta}$ stand-alone mesas

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[keywords] Bi2212, IJJ, THz, stand-alone mesa.

Since the first report of the strong THz radiation from high temperature (high-T_c) superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) [1], a great deal of both theoretical and experimental research into the fundamental mechanisms and applications has been performed [2]. Recent observation of severe self-heating giving rise to a hot-spot in a mesa structure made of Bi2212 has attracted much attention because it seems that the hot-spot formation is directly related to the radiation mechanisms [3-7]. In our previous studies, however, it was shown experimentally that the hot-spot formation or large inhomogeneous temperature distribution does not help THz radiation [7]. Furthermore, it was demonstrated that improving heat removal from the substrate more efficiently, the temperature dependence of the THz radiation intensity become higher at higher temperature around 55 K, and the radiation frequency become higher in accordance with the large hysteresis of the *I-V* characteristic curve [8]. Considering these experimental observations, THz radiation may be improved very much using mesas with better cooling condition. An idea for this may be realized by making a stand-alone type of mesas, in which a mesa is attached on the sapphire substrate by metal films without using thermal agent like polyimide or Ag-paste used in the past studies. This concept was supported theoretically and actually has demonstrated to make high power radiation of a few tens of microwatt by removing the Bi2212 substrate beneath the mesa [9, 10]. Moreover, such a simple structure of the stand-alone mesa enables us to construct external structures such as antennae for practical use.

Due to the many advantages mentioned above, we have tried to make stand-alone mesas and have improved radiation characteristics. This attempt was successful and resulted in demonstrating THz radiation near 77 K, high power radiation of a few tens of microwatt between 55 K and 65 K, and high frequency radiation over 1.0 THz between 10 K and 20 K.

In this poster, we describe the preparation method of the stand-alone mesa structures, and properties such as *I-V* characteristics and radiation frequency are given. We will also discuss the effects of the hot-spot on the THz radiation.

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Towards high-frequencies of high temperature superconductor single crystal $Bi_2Sr_2CaCu_2O_{8+\delta}$ THz radiation devices

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[keywords] Bi2212, IJJ, THz, stand-alone mesa.

Recently, research and development of the devices prepared by high temperature superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) single crystal is actively conducted[1]. This devices are known to work as continuous, monochromatic THz radiation emitters by simply applying dc voltage when the AC Josephson effect and the cavity resonance of mesa are satisfied[2]. Although the intensity of the emission is strong about 30 μW at present, the power is not enough most of application. Similarly the frequency of the device is limited to 1.6 THz[3]

We have tried to observe radiation from narrower width of mesa which is typically 35 μm in order to obtain higher frequency above 1 THz, because THz radiation frequency from mesa is inversely proportional to width of mesa[4]. However, for the conventional type of mesa which is Bi2212 superconducting substrate just below the mesa, THz radiation with frequency higher than 1 THz radiation has not been obtained. It seems that THz radiation is prevented by the self-heating of mesa due to bad heat conductivity of the mesa and the interface between mesa and the thermal bath.

The Stand-alone mesa[5], which is removed the superconducting substrate and directly connected to the thermal bath, is expected to improve the thermal conduction and remove heat generated in the mesadevice efficiently to the thermal bath. Moreover, high power emission is also expected theoretically in the stand alone mesa. In this study we have tried to sandwich the stand-alone mesa between two sapphire substrates to cool effectively. As a resulted we observed the monochromatic radiation up to 1.36 THz with TM (2, 0) resonant mode at 15 K.

In this poster, we describe the two types of device structure: One is stand-alone mesa whose size is 58 × 375 μm^2 wide and 6.4-μm-thick just putting on a sapphire substrate(#1) and the other whose size is 57 × 385 μm^2 wide and 6.3-μm-thick is sandwiched between two sapphire substrates(#2), and properties such as *I-V* characteristics (Fig. 1) and radiation frequency are given. We will also discuss the linewidth on the THz radiation.

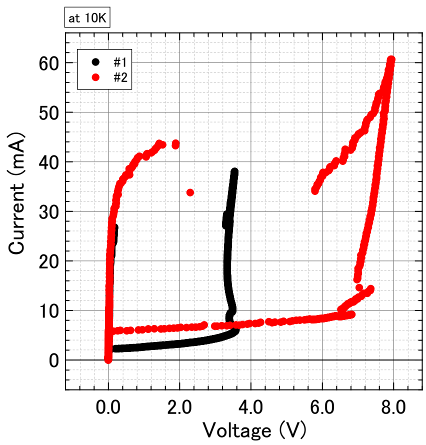

Fig. 1: *I-V* characteristic curve of stand alone mesa with only one sapphire substrate (black symbols, #1), between two sapphire substrates (red symbols, #2).

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Evaluation of comparative study of characteristics of the THz oscillator using high temperature superconductor Bi2212 single crystal mesas

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[keywords] Bi2212, IJJ, THz.

High temperature (high-T_c) superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$(Bi2212) consists of the stack of superconducting CuO_2 and insulating Bi_2O_2 layers in an atomic scale, which is known as intrinsic Josephson junctions (IJJs). By fabricating Bi2212 to the mesa structure and applying dc bias voltage to the *c*-axis of that, THz radiation can be obtained. The emission condition has to be satisfied the ac Josephson effect and the cavity resonance [1]. Though several applications of IJJs emitters has been reported [2], [3] and [4], for more practical uses of these devices, high power, with wide frequency range and reproducible emitters are desired.

To check the yield of the IJJs emitter, we made several two types of mesas and measured *R*-*T* characteristics, *I*-*V* characteristic curves and radiation characteristics. Type ① is the conventional form (with Bi2212 substrate). Type ② is the stand-alone mesa structure (without Bi2212 substrate). In type ①, since bias voltages were different from each samples in the *I*-*V* characteristic, we were not able to observe intended radiation intensities. We think that these differences were caused by the difference of Bi2212 substrate thickness and the volume of polyimide because these samples are cooled from the bottom. In comparison of type ①, with type ② (stand-alone mesas), the maximum radiation intensities measured by a Si bolometer were over 100 mV (fig.1) at 50 K. From the results, stand-alone mesa structure (type ②) had higher radiation intensities and better yield than conventional ones (type ①).

In this poster, we describe the details of the preparation method of the mesa structures, and show the properties comparatively such as *I*-*V* characteristics and radiation characteristics are given.

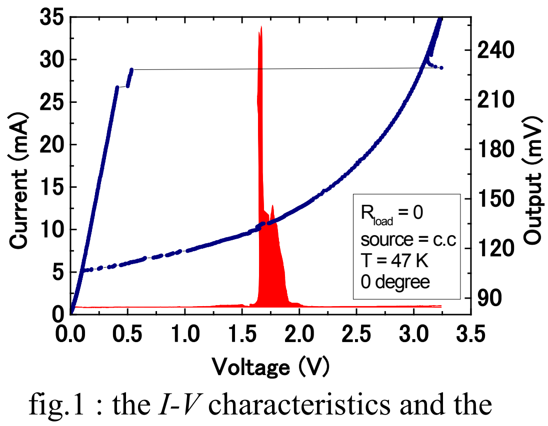

fig.1 : the *I*-*V* characteristics and the bolometer output voltages of the stand-alone mesas

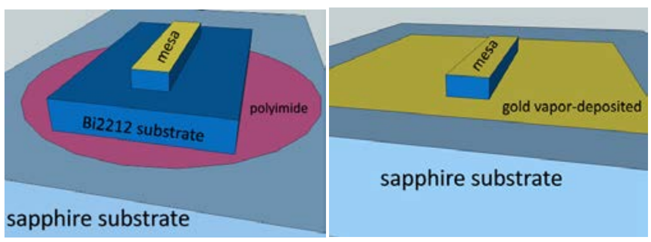

fig.2 : the image of type ① mesa (right) and the image of type ② mesa (left)

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Terahertz imagingsystems by using an IJJ emitter

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[keywords] Bi2212, IJJ, terahertz, imaging.

A unique (sub-) terahertz (THz) source based on intrinsic Josephson junctions (IJJs) made of high temperature superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$(Bi2212) single crystals (IJJ-THz emitter) was discovered in 2007 [1]. Since then, many experimental and theoretical researches have revealed characteristics of the device [2]. The maximum radiation power so far detected is ~30 W from single mesa [3], though 620 W was claimed from a synchronized three-mesa array [4], and the radiation frequency can be tunable between 0.3 and 1.6 THz [5]. The IJJ-THz emitter has enormous potential for many applications because monochromatic THz electromagnetic waves with tunable frequency can be generated simply by applying dc voltage. As an application of the device, a transmission type THz imaging system was shown in the previous report [6]. In this poster presentation, we report the reflection type THz imaging system [7] and the THz computed tomography (THz-CT) system [8] we have developed in order to apply IJJ-THz emitter for various practical applications.

Since THz electromagnetic waves can penetrate many dry and nonmetallic materials similar to microwaves and provide better spatial resolution than microwaves in the millimeter or sub-millimeter range according to its wavelength, THz imaging can reveal hidden objects or internal structure. THz imaging is an important technology expected for many applications such as non-destructive evaluation, security, medical diagnosis, biotechnologies [9].

Transmission type images mainly offer information about absorption in bulk structure. On the other hand, reflection type images mainly offer information about surface structure. In addition, the reflection type imaging system can be applied for more various samples than the transmission type imaging system. THz-CT images obtained by reconstructing of angular dependence of line scan profiles reveal the cross-sectional views of samples. Combining these three imaging systems with different characteristics give unique and/or high sensitive images. The details and characteristics of our three systems (optical systems, imaging resolution, *etc.*) will be discussed.

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Circular polarization of the THz wave from Bi2212 intrinsic Josephson junctions

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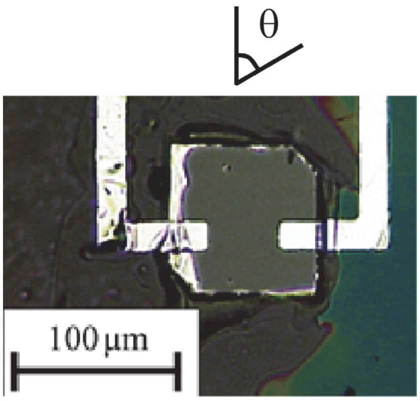
[keywords] terahertz emission, intrinsic Josephson junction, Bi2212, polarization

Radiations of monochromatic and continuous electromagnetic waves with frequencies ranged between 0.3 and 0.9 THz and powers up to 30 μW from mesa structures of Bi2212 intrinsic Josephson junctions (IJJs) have been reported[1,2]. Then it has also been reported that the terahertz wave from mesa structure of Bi2212 IJJs is linearly polarized [3]. So far, however, an elliptical or circular polarized terahertz wave from mesa has scarcely been observed. Therefore, the goal of this study is to generate a circularly polarized terahertz wave by varying the device parameters: geometries of the mesa and the electrode.

We report on emission of terahertz electromagnetic wave from a notched square mesa structure of Bi2212. The radiation at T = 40.0 K is detected by a Si-bolometer and the emission frequency is determined as 0.44 THz by an FT-IR spectrometer. This result shows a close agreement with the cavity resonance model with TM (1, 0) model. The polarization of the emitted terahertz wave is measured by a wire grid polarizer. Then we find that the emitted terahertz wave is elliptically polarized and the polarization ratio is about 2.2. The long axis of the ellipse is tilted about 20 degrees from a vertical direction in Fig. 1. We attribute the tilted-ellipse to the phase difference between two internal standing waves excited along the diagonals of the notched square.



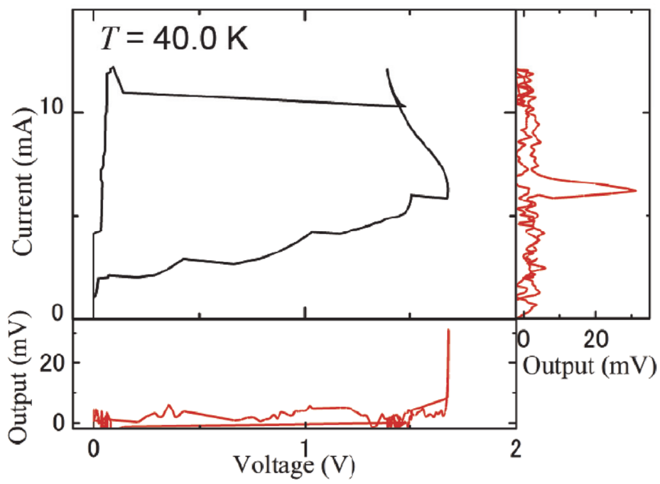


FIG. 1: Left: A photograph of a notched square mesa structure. Right: The *I-V* characteristic and the radiation power.

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Terahertz emission from a stack of intrinsic Josephson junctions in Pb-doped Bi-2212

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[keywords] Terahertz emission, Intrinsic Josephson junctions, Pb-doped Bi-2212

The terahertz wave with a frequency band in the range of 0.3-10 THz is thought to be the most unique electromagnetic wave, since it provides numerous opportunities for a host of applications. Recently, terahertz generation using stacks of intrinsic Josephson junctions (IJJs) in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) has become a major focus of research, both experimental and theoretical [1]. The mesa structures were milled from slightly underdoped Bi-2212 single crystals in order to excite the transverse magnetic cavity mode: in the case of a long rectangular mesa, a cavity condition for the TM (1, 0) mode is expressed in the form: $f_{10} = c_0 /2nw$, where c_0, n, and w are the speed of light in vacuum, the refractive index of Bi-2212, and the width of the mesa, respectively [2].

An important challenge to the development of IJJ sources is to extend the maximum emission frequency. So far, an emission frequency of 1.05 THz was obtained using a double-sided cooling technique [3]. From a material point of view, the use of different compounds with smaller n is a promising method for enhancement of the emission frequency according to the cavity resonance conditions. In Bi-2212, partial substitution of bismuth (Bi) with lead (Pb) was shown to reduce a dielectric constant n^2 [2]. It is also interesting to note that the superconducting gap parameter that relates to the junction voltage in the current-voltage characteristics is less affected by Pb doping [4].

In this presentation, we fabricate IJJ emitting samples using Pb-doped Bi-2212 single crystals. We measure terahertz radiation spectra using a FT-IR spectrometer, and analyze the data using the cavity resonance model to compare it with that from nondoped Bi-2212 (cf. Figure). We find that the emission frequency can be enhanced by Pb doping in agreement with the far-infrared optical spectroscopic measurements. This finding allows for the construction of high frequency terahertz sources that are able to fill the terahertz gap.

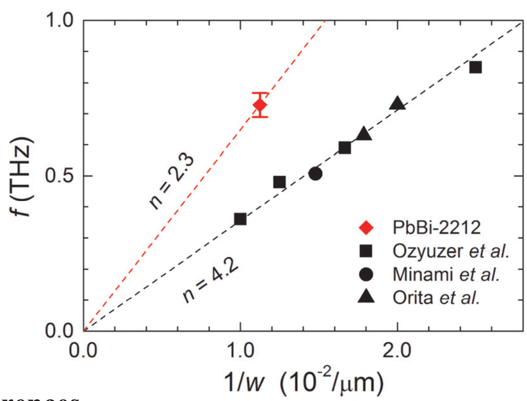

FIG: Plot of emission frequency f vs. $1/w$ for Pb-doped (red, this study) and nondoped Bi-2212 (black, from Refs.).

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Thermal imaging of Bi2212 THz oscillator

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[keywords] Bi2212, THz oscillator, thermal imaging

It was discovered that $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) mesas generate THz radiation in a particular configuration [1]. Bi2212 mesas are promising for THz oscillator, which can fill the frequency range around “THz gap”. On the other hand, it is known that Bi2212 mesas show self-heating effects (hot spots) when the current is passed to Bi2212 mesas due to the low thermal conductivity along the *c*-axis. While some studies reported that the hot spot promotes the coherent THz emission from Bi2212 mesas [2], other studies showed that it is unrelated to THz emission [3]. Further investigations on the relation between the hot spot and THz emission from Bi2212 mesas are necessary.

In order to address this issue, imaging of temperature distribution on Bi2212 mesas is expected to be effective. We obtained the surface temperature distribution of the sample by fluorescent thermal imaging (FTI) method [4]. Figure 1 and 2 show the optical image and *I*-*V* characteristics of our Bi2212 mesa, respectively. This sample has two parallel electrodes on the mesa as shown in Fig.1. Figure 3 show the thermal imaging of the sample with current flow from only the right electrode. A-F in Fig. 3 corresponds to each point in *I*-*V* characteristics. Figure 3 reveal that the right region have a larger temperature rise, which is related to the current injection. In this work, we report further investigation of the relation between temperature distribution and *I*-*V* characteristics.

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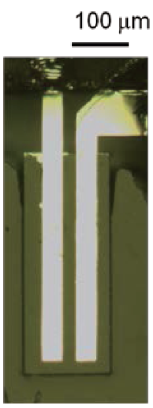

Fig. 1 Optical image of the Bi2212 mesa.

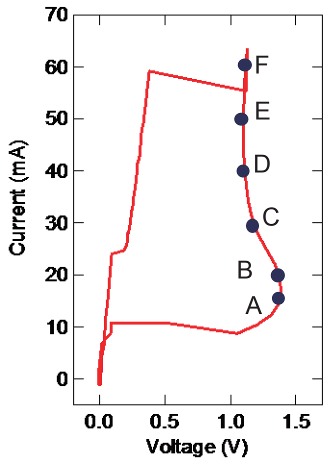

Fig. 2 *I*-*V* characteristics of the Bi2212 mesa.

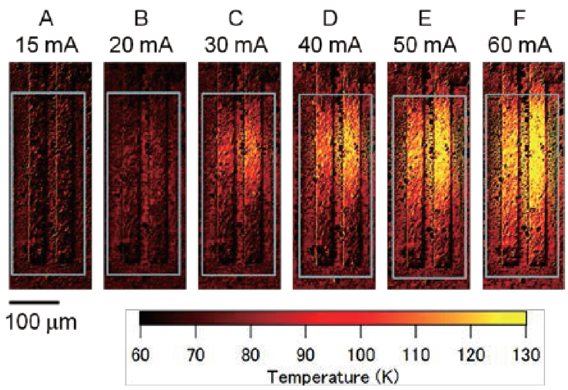

Fig. 3 Thermal imaging of the Bi2212 mesa with current flow from only the right electrode.

Manipulating terahertz emission of intrinsic Josephson junctions with a focused laser spot

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[keywords] terahertz emission, intrinsic Josephson junctions, hot-spot, local heating

To make intrinsic Josephson junctions (IJJs) formed naturally in $Bi_2Sr_2CaCu_2O_8$ realistic terahertz wave sources, various efforts have been paid to optimize the power, frequency, and tunability of terahertz emission since it was first observed in 2007 [1-7]. At the high-bias regime, a hot-spot appears in large-sized samples, indicating inhomogeneous temperature distribution along the mesa, and plays a critical role in the terahertz emission [4-13]. The area where the temperature is close to the critical temperature T_C is sensitive to external heating. With this property, we manipulated the emission state of IJJs mesa by locally heating the mesa with a focused laser spot about 1 μm^2 large. At a certain bath temperature, the emission power at the same biased current can be varied from 0% to 47% continuously with a little shift in frequency [14]. This method may play an important role in enhancing terahertz emission from IJJs.

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Thermal imaging and characteristics of Bi-2212 THz emitter fabricated by double-sided fabrication process

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[keywords] intrinsic Josephson junctions, double sided fabrication, terahertz emission, thermal imaging

$Bi_2Sr_2CaCu_2O_x$ (Bi-2212) crystal behaves as a stack of intrinsic Josephson junctions (IJJs). Recently many researchers have reported THz electromagnetic radiation from large mesa structures patterned on Bi-2212 crystal [1]. A novel feature of the THz radiation is that a hot spot over T_c can exist in the Bi-2212 mesa in high bias current regime [2-4]. Advantage of such the hot spot is that it helps a synchronized oscillation and a narrow THz radiation line width [4]. A formation of the hot spot, to our knowledge, has been observed experimentally through the mesa with metal electrode. Since we are interested in control of the hot spot formation, we fabricate Bi-2212 stack structures without metal electrode by double-sided patterning (DSP) process. To confirm the THz emission from the stack fabricated by DSP, we investigated current voltage characteristics and bolometric detection of the THz radiation from the Bi-2212 stack with size of $183\times38\times0.81$ μm^3.We detected the emission signal at 30, 40 and 50 K. Voltage appeared in a clear response of the bolometer was 510 mV at 30 K. Also the voltage decreased with increasing temperature from 510 mV at 30 K to 260 mV at 50 K.

In this symposium we will report the next step to observe the hot spot in the stack by DSP process and discuss the relationship between THz emission and the temperature distribution in the stack.

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Characterization of superconducting Bi2212 single crystal for the detection of THz waves

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[keywords] superconducting Bi2212, bolometer, terahertz waves, log-periodic antenna

Since terahertz (THz) waves can pass through materials like clothing, plastic, wood, ceramic, leather and without any harm to the body [1], it can be used for characterization, detection and 3D imaging of these materials. THz application area expands day by day such as high-speed wireless communications, medical imaging, security in airports and shopping centers and detection of chemical and biological materials [2]. Rapidly increasing applications of the electromagnetic waves (EM) in the under developed terahertz frequency (0.1-10 THz) range requires a well understandings of efficient terahertz wave detection. Today, there are several deficiencies in different types of bolometers that are used for detection of THz waves and they require very difficult and costly cryogenic spending, detectivity has to be high and response time should be low [3, 4]. An intense, coherent and continuous electromagnetic wave source is obtained by high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) single crystal. At the same time Bi2212 single crystal can detect THz waves in suitable conditions. In this study, single crystal of Bi2212 is cleaved to layer by layer by scotch tape until the necessary thickness is reached. Afterwards, it is pasted on a sapphire substrate and the scotch tape is etched with the aid of chloroform solution and ultrasonic cleaner. Then, the samples were annealed at 600 ^{o}C for 1 hour in order to adjust the oxygen doping level. Later, it was deposited with 150 nm Au layer by thermal evaporation. Afterwards they were annealed again at 425 ^{o}C for 30 minutes to decrease the contact resistivity. In the clean room process, our log-periodic antenna design was formed on the crystal by using e-beam lithography and Ar-ion beam etching step by step. For electrical characterization, four probe wires were connected to the two contact paths on the log-periodic antenna by silver epoxy. Finally, the temperature dependence of a-b axis resistivity (R-T) for Bi2212 single crystals were performed for suitability of the detection THz waves.

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Log Periodic Antenna Structures Fabricated on Intrinsic Josephson Junctions of $Bi_2Sr_2CaCu_2O_{8+\delta}$ for Terahertz Detection

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[keywords] terahertz radiation, Josephson junctions, hot electron bolometer

Recent studies at science and technology are interested in the electromagnetic waves in terahertz (THz) frequency range because of their important application areas including physics, biology, chemistry, astronomy, medicine and the detection of explosives [1]. The importance of developing passive and active devices which work in either terahertz or millimeter wave frequencies is ever more increasing in this popular field. The devices fabricated with intrinsic Josephson Junctions are promising candidates to operate in the desired regime [2-3]. Detectors with high sensitivity, wide-band frequency coverage and large arrays are required for THz imaging [4]. In this study, we have fabricated log-periodic antenna structures from $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) single crystals in order to understand the THz detection properties of hot electron bolometers. A type of classical wide-band antenna is log-periodic antenna which is based on resonance effects where the logarithm of the frequency is periodically repeating. Generally, the THz signals intensity is low and the effective detection area of the sensors is very small. We have designed the log-periodic antenna structures with optimized geometrical parameters by CST microwave studio. In the experimental procedure, a 100-500 nm thick Bi2212 thin film on sapphire substrate is patterned into the arrays of log-periodic antenna using electron beam lithography and ion beam etching techniques. Finally for the electrical characterization, resistance versus temperature (R-T) behaviour were measured by four probe technique in He flow cryostat controlled by Labview program.

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Observation of THz radiation from topological insulators

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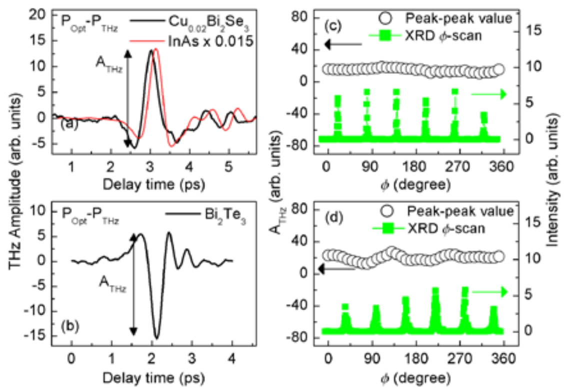
[keywords] topological insulator, ultrafast THz generation, second surface state, carrier dynamics

Topological insulators (TIs) are fascinating quantum matters that possess a narrow band gap of bulk and a Dirac cone-like conducting surface state. The surface state results from a strong spin-orbital interaction, band inversion, and exhibits novel properties, such as time-reversal protection against backscattering from nonmagnetic impurities, and spin-polarized current. In the viewpoint of experimental study on TIs, one key issue is to determine the surface state and to characterize the properties of Dirac fermions. Several experimental techniques, such as, angle-resolved photoemission spectroscopy (ARPES) and scanning tunneling microscopy (STM), have successfully determined the surface states. Optical techniques also have been applied to study characteristics of TIs. Especially, regards as nonlinear optical techniques, Second harmonics generation (SHG) has been observed from the surface of Bi_2Se_3 by illumination of ultrafast optical pulse and the band-bending associated with the surface electrons affects the SHG response [1]. However, under ultrafast optical irradiation, the materials' response would not limit only in SHG. Here, we report THz radiation generated from the surfaces of the n-type $Cu_{0.02}Bi_2Se_3$ and p-type Bi_2Te_3 single crystals by ultrafast optical pulse excitation. We find that the polarity of THz radiation pulse affected by the doping type of TIs. The poarity-receral cannot be explained by the photo-Dember effect, which is usually used to explain THz radiation from conventional narrow bandgap semiconductors. This unusual phenomenon can be interpreted with the knowledge of the recently discovered 2nd SS and bulk bands [2]. We also observe the THz radiation due to optical rectification. These findings provide alternative approaches to understanding the characteristics of TIs.



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IR Floating zone Furnace “SCW1”
単結晶育成装置　SCW1

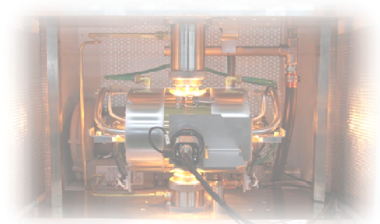
Feature / 特徴

Temperature range　MAX. 2100℃
到達温度

Max. Growth Stroke　MAX. 150mm
最大結晶育成長

Downsizing
コンパクトサイズ化

Optional feature available
オプション機能



Standard Specification / 標準仕様

Temperature region 温度域	Temperature 到達温度（カタログ）	Max.2100℃ 650W × 2pcs
Mirror 反射鏡	Mirror type 反射鏡タイプ	Double elliptic mirror (small) / 2楕円
	Crystal diameter 結晶育成例（直径）	For example :approx. Φ7.5mm(TiO2) 結晶育成例 :約ϕ7.5mm（TiO2）
Shaft motor drive 主軸駆動	Lower shaft stroke 下主軸ストローク	150mm
	Upper shaft stroke 上主軸ストローク	175mm
	Growth speed 育成速度	0.2mm～20mm/hr
Heating method 加熱方式	Halogen lamp ハロゲンランプ	650W × 2pcs
	DC Power supply DC電源	DC110 20A × 1set
	Output stabilization 電源出力安定度	±0.005% + 3mV of span
	Overall stabilization 総出力安定度	±0.1% of span
Power utility 用力	Electric power 電力	Φ3 AC200V 40A（Japan Ver.）
	Water cooling 水冷	Built – in cooling water pump system 水冷ポンプシステム本体内蔵

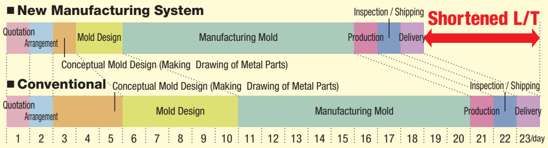
Please note that Specifications may change without prior notice.
※仕様は予告なく変更する場合がございます。

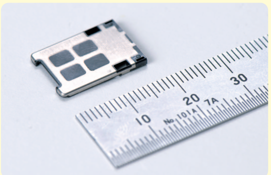
CANON MACHINERY INC.
85 Minami Yamada-cho, Kusatsu-shi, Shiga pref.
525-8511,Japan
Phone. +81-77-566-1823 Fax. +81-77-566-1825

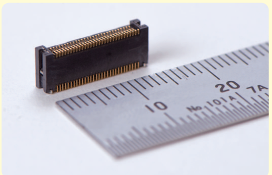
Prototyping result : more than 400 projects per month

Prototype ~Metal/Resin Sets~

Our integrated manufacturing process enables us to provide everything from the design of injection molding dies through to manufacturing and molding, insert molding, and assembly processing with metal parts.

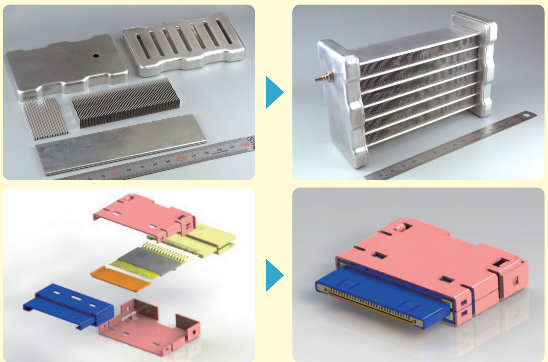






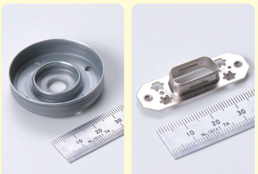
Prototype ~Assembly~

Avairable for various kinds of assembly such as assembly of plural parts (metal & mold parts), using cutting parts and rubber.



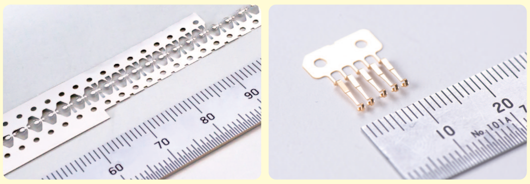
Prototype ~Precision Drawing~

Circular drawing, Square drawing, Complex shape drawing, Deep drawing, Drawing+Ironing



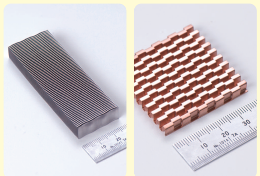
Prototype ~Microscopic Thin Sheet Metal Prototype (Less than 2mm square parts)~

Conventionally, a metal die-sets that is the same type as the mass production die-sets is manufactured when manufacturing microscopic/superfine prototypes. However, at Saijo INX, we have established new manufacturing technology for manufacturing prototypes that maintains the same level of quality as in mass production.



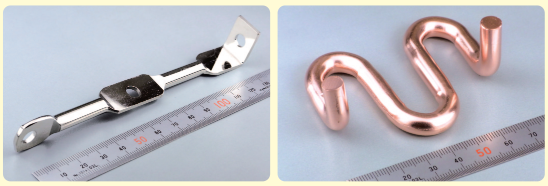
Prototype ~Fin~

Corrugated fin, Offset fin, Inner fin, Louver fin, Waving fin, Slit fin.



Prototype ~Round Bus Bar~

It is avairable for improving the space efficiency of products and attaching the insulation properties (insulating layer, surface treatment, thermal expansion tube, molding and etc.).



Prototype ~Thin Sheet Metal Parts~

We make up products immidiately, as soon as we get the drawing from customers.

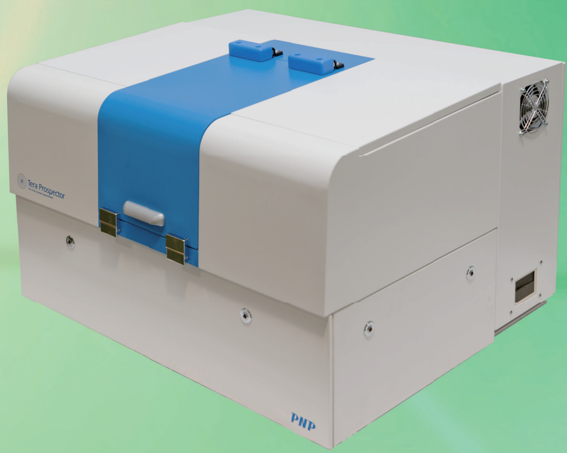
SAIJOINX Co., Ltd
Locations: 5 Nishikotobuki-cho, Saiin, Ukyo-ku, Kyoto, Japan
TEL: +81-75-312-8590, FAX: +81-75-312-0041
E-mail: info@saijoinx.co.jp（to Sales Dept.）
※For the details, please inquire of Mr. Ishikawa.
URL: http://www.saijoinx.com/en/

検査・分析の未来を拓く

テラヘルツ分光装置ならPNP

汎用分光装置

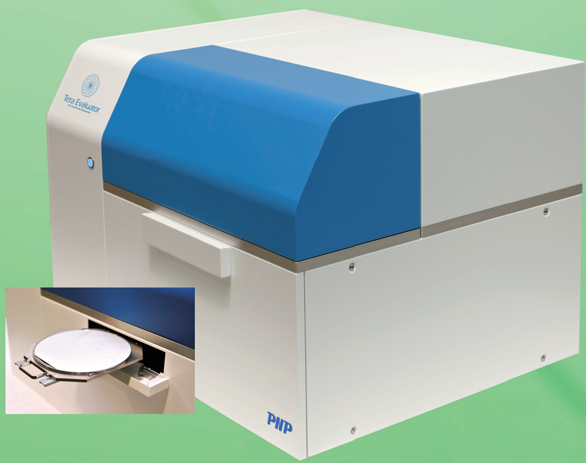
Tera Prospector



汎用性を重視したテラヘルツ分光装置です。

THz-TDS に不可欠なフェムト秒レーザー光を外部から取り入れることも可能です。
お持ちのフェムト秒レーザーをご使用いただく事により、テラヘルツ分光装置の導入を低価格で実現できます。

広い試料室空間を確保することで、様々な目的に応じた付属光学系の導入を可能にしました。



エリプソ分光装置

Tera Evaluator

THz-TDS にエリプソメトリの技術を導入した新しいテラヘルツ分光装置です。

反射光学系により、不透明な材料の測定に最適です。

4インチ、6インチウェーハ用のマッピングステージを標準搭載しています。

半導体ウェーハの非破壊検査に有効な装置です。

Tera Prospector と同様にレーザー光を外部から取り入れることが可能です。

Tera Prospector、Tera Evaluator を合わせてご利用いただく事で、多様な分野に適用可能です!!

Tera Prospector、Tera Evaluator は日邦プレシジョン（株）の登録商標です。

PNP 日邦プレシジョン株式会社

〒407-0175 山梨県韮崎市穂坂町宮久保７３４
TEL : 0551(22)8998(代) FAX : 0551(22)8935
URL : http://www.pnp.co.jp

NIKI GLASS CO.,LTD. 仁木工芸株式会社

無冷媒 3He 冷凍機

LTS-HE3-LV

当社オリジナル製品の無冷媒 3He 冷凍機は、定評のあるクライオメック社製パルスチューブ冷凍機を採用し、液体ヘリウムを使用することなく全自動運転で試料ステージ温度を 300mK まで冷却できます。

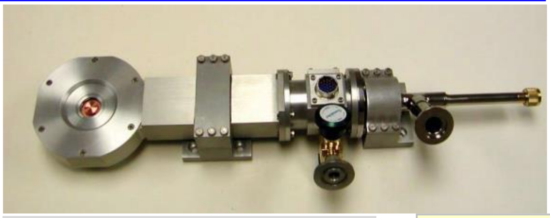
光学用途に対応した窓加工、テラヘルツ分光に適した窓材のご提供もご相談に応じて対応させていただきます。

光学用スプリット型超伝導マグネットも取り付けられます。

基本性能

- 最低到達温度　：　≦300mK
- ﾍﾞｰｽ温度保持時間　：　＞100 時間
- 冷凍能力　：　100μW@350mK
- 試料ｽﾃｰｼﾞ変位振動　：　0.1μm@10Hz
- 初期冷却時間　：　約 16 時間

光学用クライオスタット



RC102-CFM-NOMOVE
顕微分光用クライオスタット

連続フロー式クライオスタットで、LHe/LN2 のどちらでも使用できます。顕微鏡下での使用に際し、低振動・低ドリフトでご使用いただけます。

- ﾀｲﾌﾟ　：ﾊﾞｷｭｰﾑﾛｰﾄﾞ型
- 温度範囲：3.2-325K
- 温度安定性：±0.05K
- 振動ﾚﾍﾞﾙ　：20 nm
- ﾄﾞﾘﾌﾄ　：±150 nm
- 窓開口角　：130～152°

冷凍機冷却4K クライオスタット (各種設計対応)

当社では、GM 冷凍機、パルスチューブ冷凍機を使用した、各種光学用途の冷凍機冷却型の4K クライオスタットを、お客様のご希望仕様に合わせて設定対応しています。

※ 直結型、ﾄｯﾌﾟﾛｰﾄﾞ型、低振動型、各種対応

(下：ｺﾞﾑﾍﾞﾛｰ低振動型)

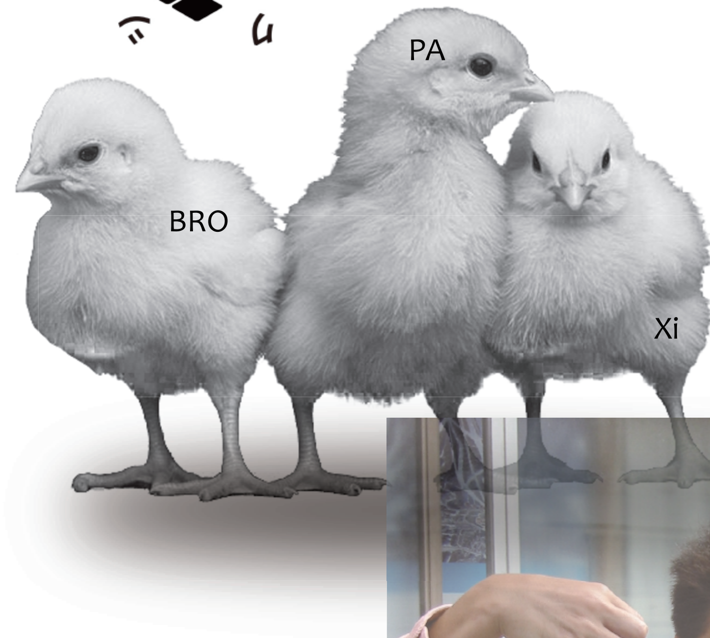
RC152･RC151 連続フロー式
トップロードクライオスタット

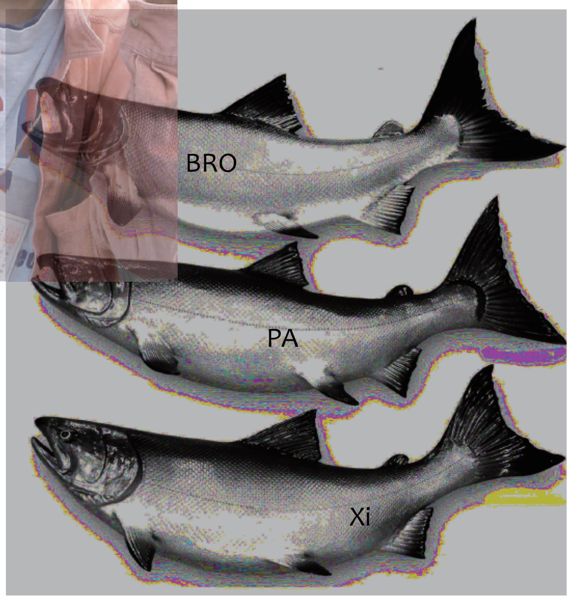
試料交換のし易い、トップロード型の連続フロー式クライオスタットです。バッファータンク内蔵型では、2K 以下で長時間運転も可能です。

- ﾀｲﾌﾟ ：ﾄｯﾌﾟﾛｰﾄﾞ型
  RC152(ﾀﾞｲﾅﾐｯｸ型)　RC151(ｽﾀﾃｨｯｸ型)
- 温度範囲：<1.5K－300K
- 温度安定度：　0.05K

仁木工芸株式会社　http://www.nikiglass.co.jp
東京ｵﾌｨｽ　〒108-0073　東京都港区三田 3-9-7　ﾆｷｸﾞﾗｽﾋﾞﾙ
大阪ｵﾌｨｽ　〒532-0011　大阪市淀川区西中島 6-2-16

BROPAXi Joint Venture, Japan





BROPAXi are

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Pax Inc. : www.papapax.jp, toiawase@papapapax.jp, 81-42-486-7178

PHLUXi Inc. : www.phluxi.com, sales@phluxi.com, 81-3-5534-8867

JECC TORISHA Co., Ltd.

We, Japanese leading company in Cryostat, over 60 years.

Liquid Nitrogen, Helium Cryostats

LN2 Temp. Control Cryo8stat

80 ~ 300 K
Optical Window is available

LHe Temp. Control Cryostat

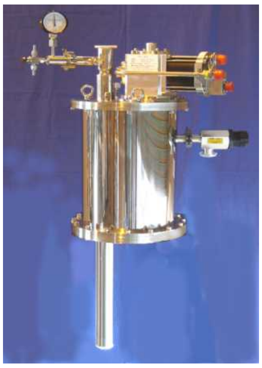
4.2 ~ 300 K
Optical Window is available

Pressurized He II
Superconducting Magnet

Superconducting Magnet

Helium Refrigerator

Cryogen-Free Cryostats



Top Load Type
4.2 ~ 300 K

Standard Type
4.2 ~ 300 K
Optical Windows is available

High Current loading type
Max load current: 500 A
Min Temperature: <10 K

Liquid Helium Dewar

Liquid Nitrogen Container

Liquid Helium Level Controller

You find solutions in here !

Head Office and Factory

8-52, Yoshinodai 2-chome, Kawagoe-shi, Saitama 350-0833, Japan

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