

京都大学工学研究科 融合光・電子科学の展望

高温超伝導体固有ジョセフソン接合の物理と応用

-超伝導フェイゾニクス(PHASONICS)へ

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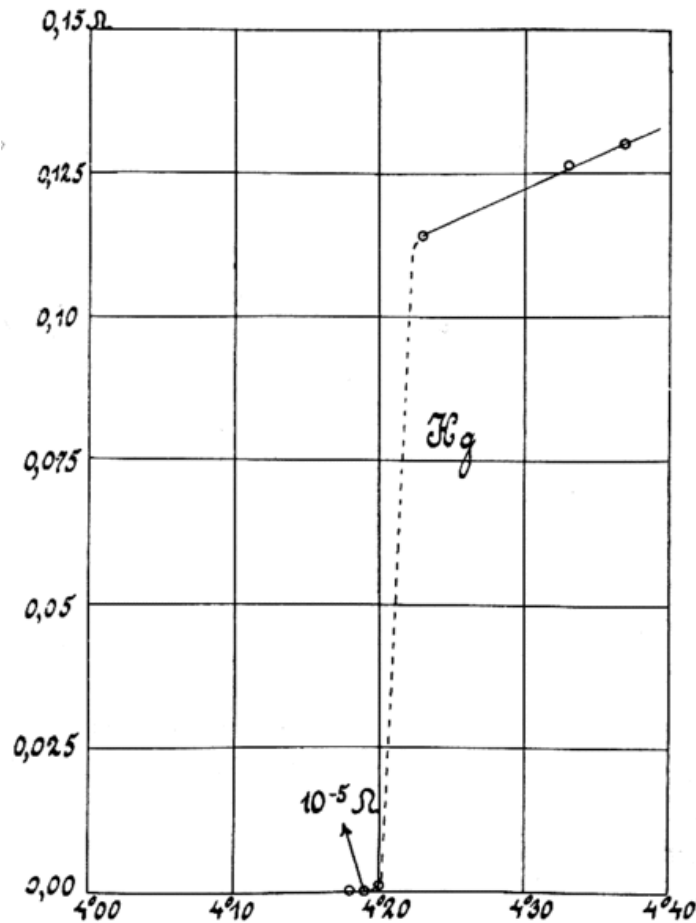
内容

- 超伝導の基礎概念
- 高温超伝導体をはじめとする新奇超伝導体
- 高温超伝導体における固有ジョセフソン接合
- 固有ジョセフソン接合からのTHz波発振
- 巨視的量子トンネル現象
- 超伝導量子コンピュータの開発状況

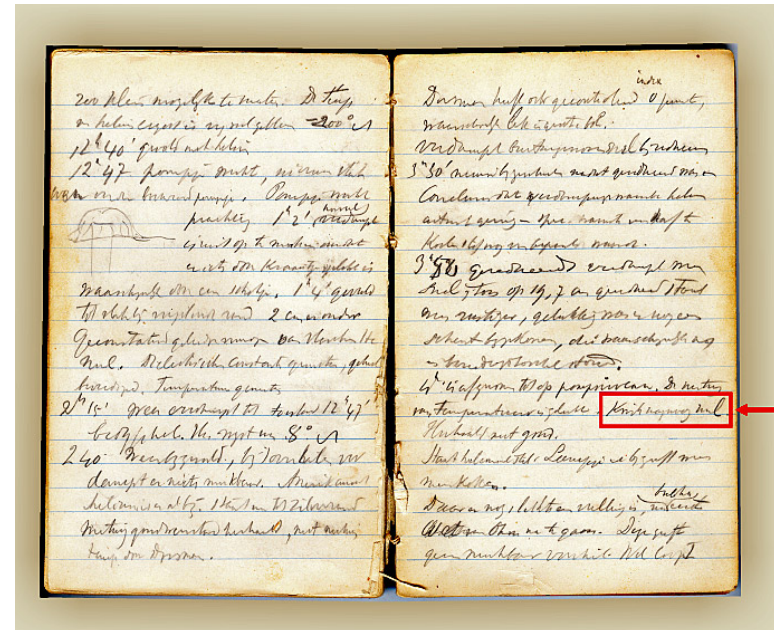
超伝導の基礎概念

- Discovery and its background
- Basic properties of superconductors

「超伝導」の発見



1911年、オネスによって発見された水銀(Hg)の抵抗変化。
データは数ヶ月に渡る数回の測定で取られた



“Kwik nagenoeg nul”

周期律表における超伝導元素

KNOWN SUPERCONDUCTIVE ELEMENTS

■ BLUE = AT AMBIENT PRESSURE
■ GREEN = ONLY UNDER HIGH PRESSURE

1	2											3	4	5	6	7	8	9	10
1	IIA											IIIA	IVA	VA	VIA	VIIA	0		
1	H																	2	He
2	3	4											5	6	7	8	9	10	
2	Li	Be											B	C	N	O	F	Ne	
3	11	12	IIIB	IVB	VB	VIB	VII B	VII			IB	II B	13	14	15	16	17	18	
3	Na	Mg											Al	Si	P	S	Cl	Ar	
4	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	
5	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	
6	55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	
6	Cs	Ba	*La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn	
7	87	88	89	104	105	106	107	108	109	110	111	112							
7	Fr	Ra	+Ac	Rf	Ha	106	107	108	109	110	111	112							

SUPERCONDUCTORS.ORG

* Lanthanide Series

58	59	60	61	62	63	64	65	66	67	68	69	70	71
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu

+ Actinide Series

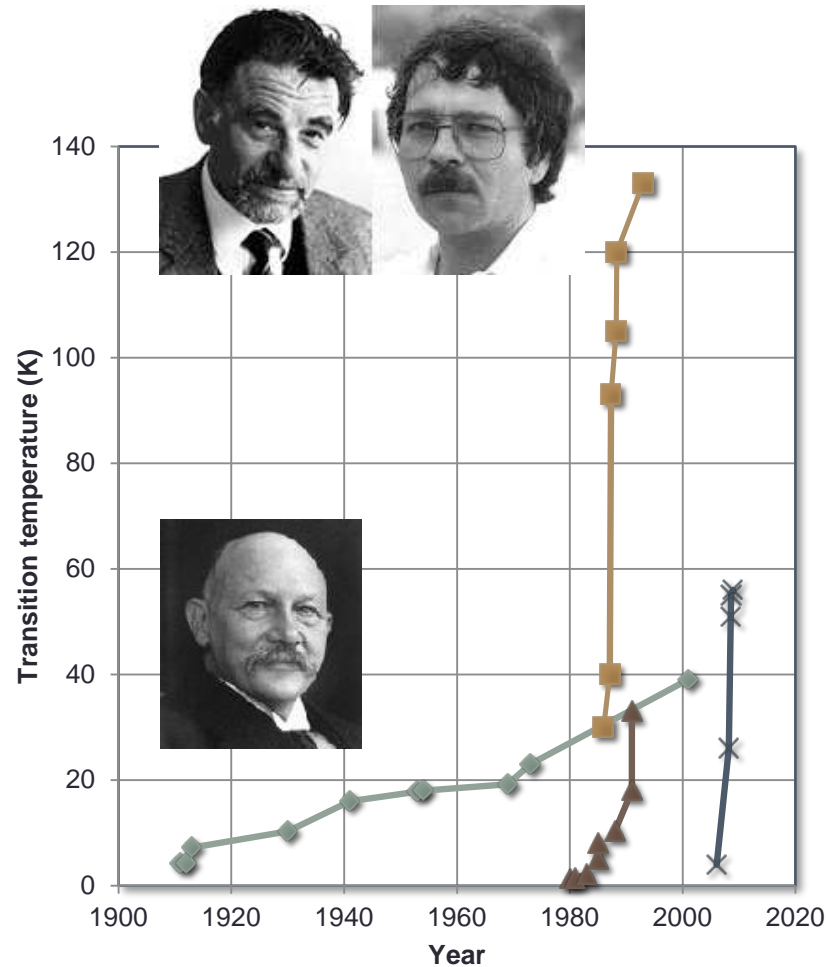
90	91	92	93	94	95	96	97	98	99	100	101	102	103
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

超伝導転移温度更新の歴史



Bernd Matthias

B. Matthias



H. Hosono

- ◆ BCS
- Cuprate
- ▲ Organic / Carbon-based
- × Fe based



J. Akimitsu

超伝導の特徴

- 完全導電性($R = 0$)
 - 超伝導電流は 10^{1000} ..年以上も減衰しない
- 完全反磁性($B = 0$)
 - マイスナー効果
- 磁束量子化
 - 磁束量子: $h/2e$
- ジョセフソン効果
 - 電圧と周波数の関係: $2eV = hf$

磁束の量子化

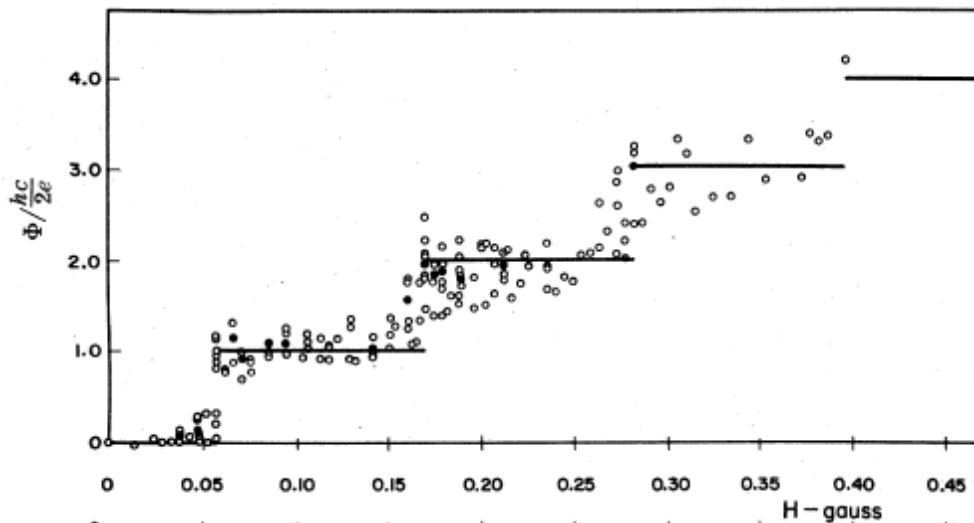
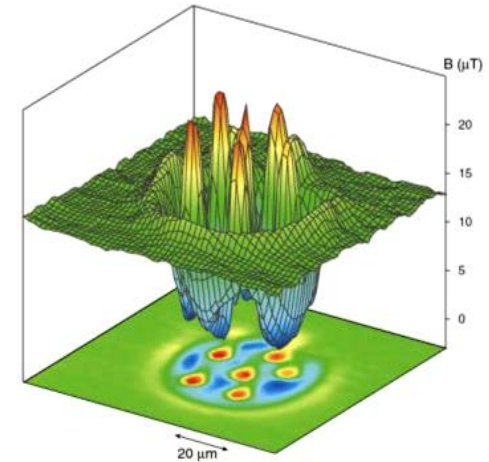
$$\Phi_0 = \frac{h}{2e}$$

F. London, 1950

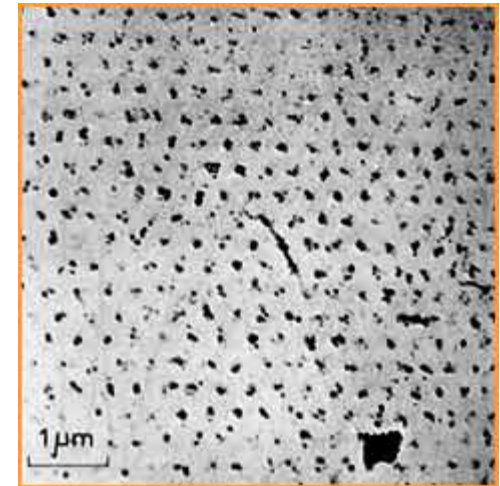
第1種超伝導体

A. A. Abrikosov, 1957

第2種超伝導体



Deaver and Fairbank 1961



U. Essmann and H. Trauble
[Physics Letters 24A, 526 \(1967\)](#)

ジョセフソン効果

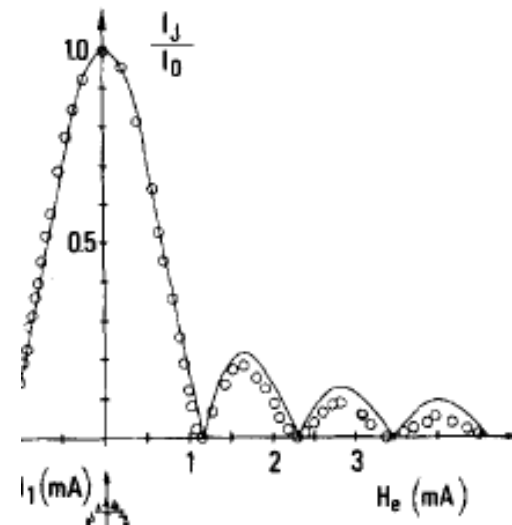
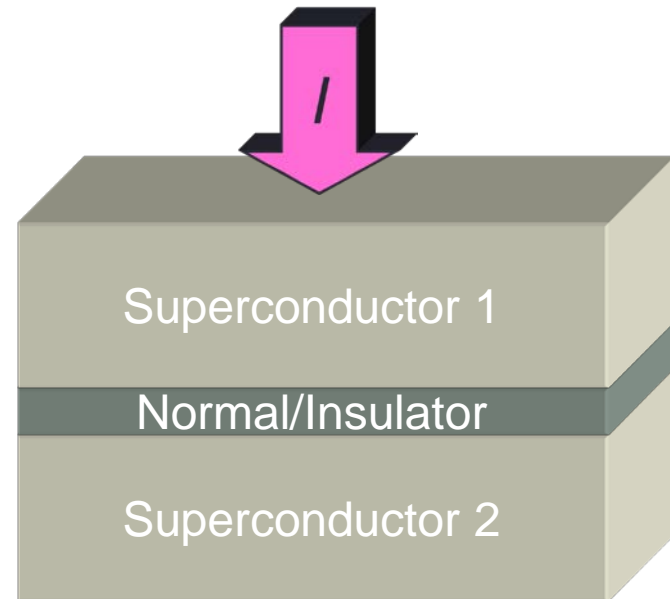
B. D. Josephson, 1962

$$I = I_c \sin \varphi, \quad V = \frac{\hbar}{2e} \frac{d\varphi}{dt}$$

$$\varphi = \phi_1 - \phi_2 - \frac{2\pi}{\Phi_0} \int \mathbf{A} \cdot d\mathbf{s},$$

ϕ_i : 秩序パラメタの位相
 \mathbf{A} : ベクトルポテンシャル

$$\frac{I_m(H)}{I_m(0)} = \left| \frac{\sin(\pi\Phi/\Phi_0)}{\pi\Phi/\Phi_0} \right|$$



Paterno and Nordman, 1978

高温超伝導体における 固有ジョセフソン接合

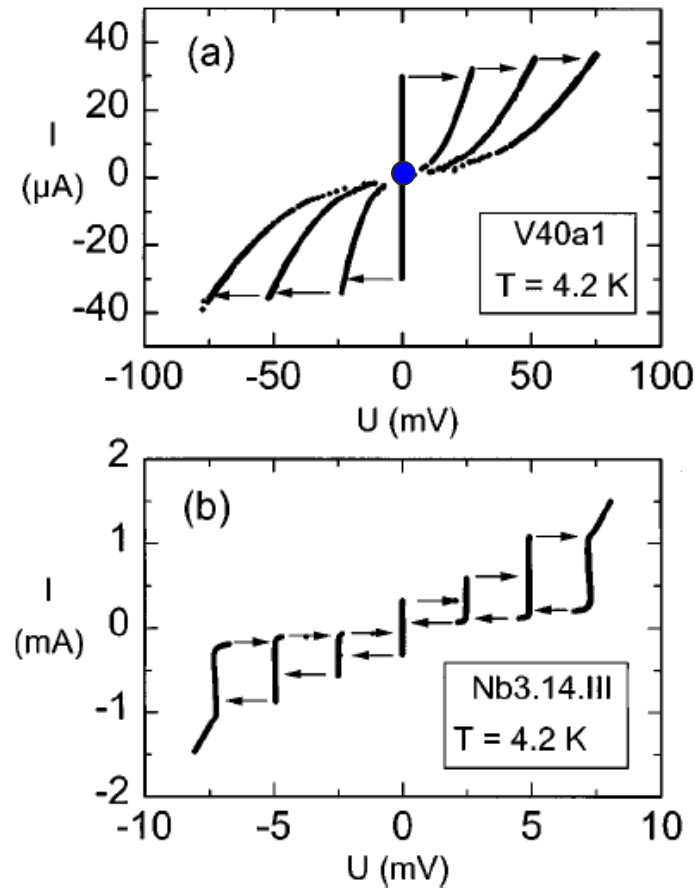
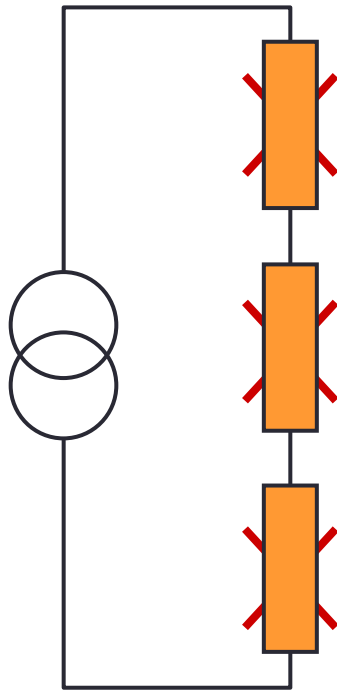
固有ジョセフソン接合

Crystal Structure of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+d}$

Kleiner et al., PRL 68, 2394 (1992)
 Sakai, Bodin, & Pedersen, JAP 73, 2411 1993
 Koyama & Tachiki, PRB 54 16183 (1996)

The figure illustrates the crystal structure and layered nature of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+d}$. On the left, a 3D ball-and-stick model shows the arrangement of atoms, with layers labeled 'S' (superconducting) and 'I' (insulating). To the right, a schematic diagram shows the layered structure with alternating red (SC) and yellow (I) layers. The diagram includes a wave function symbol Ψ and arrows indicating the direction of superconducting current flow. A label 'Inductive' is placed next to the schematic. Below the schematic, two photographs show a thin film (0.3 nm thick) and a bulk sample (1.2 nm thick) of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+d}$.

固有ジョセフソン接合の特徴

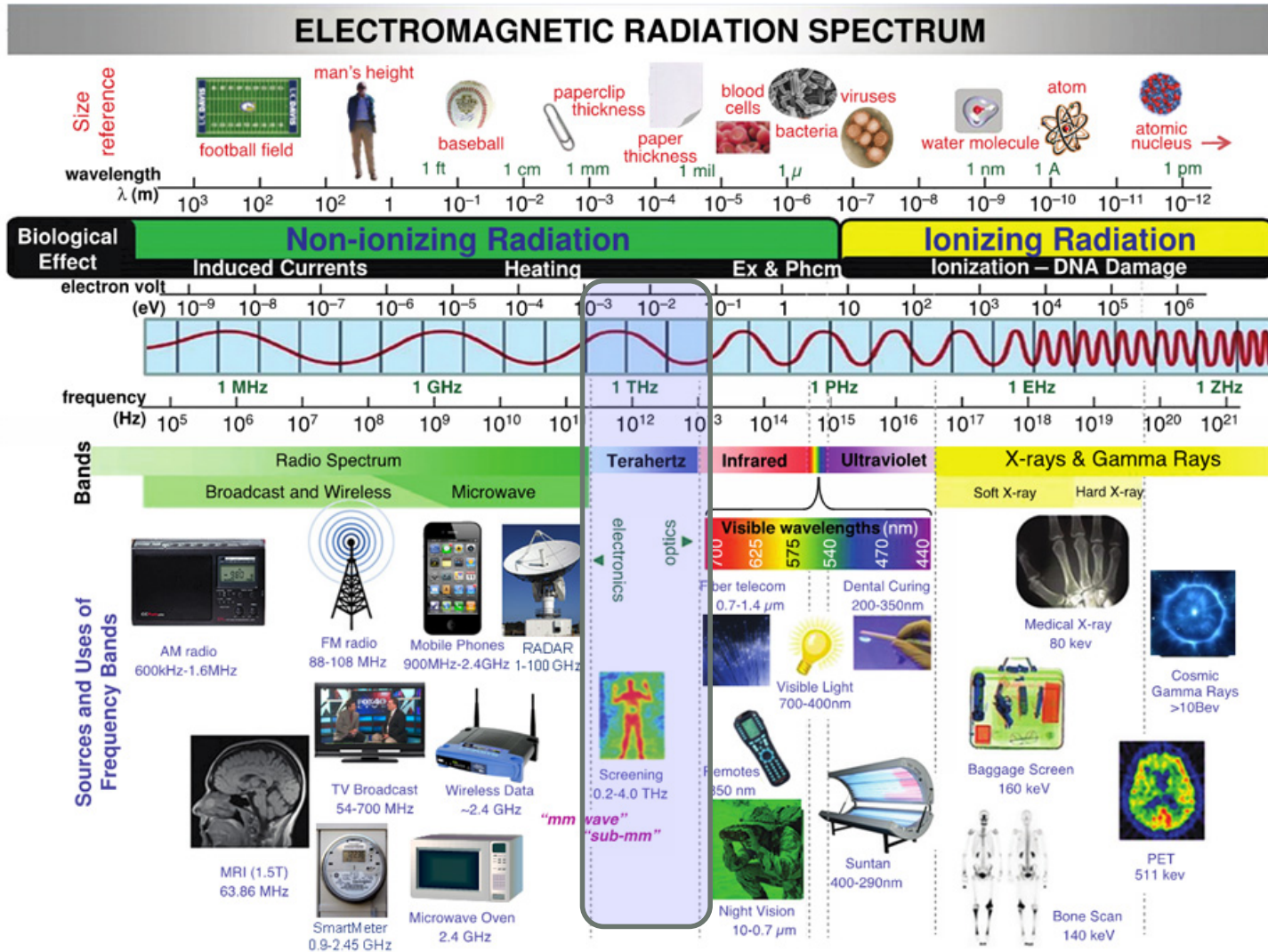


Schlenga et al, 1998

固有ジョセフソン接合からの テラヘルツ発振

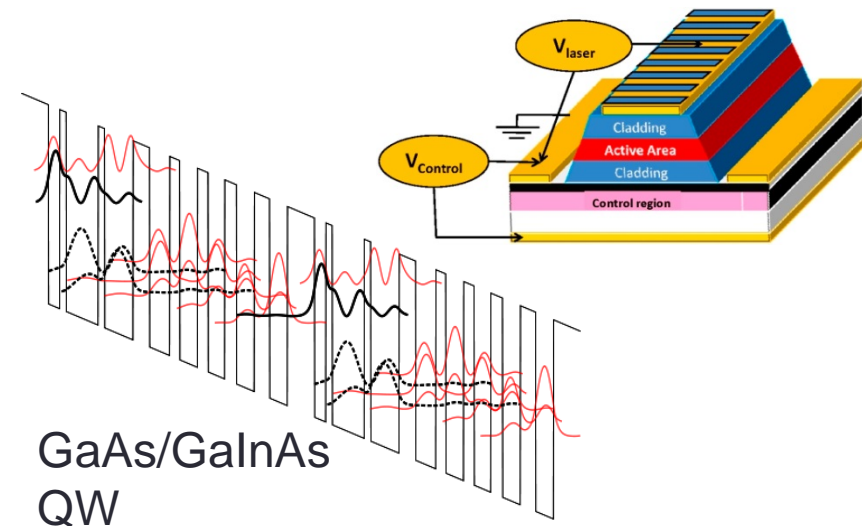
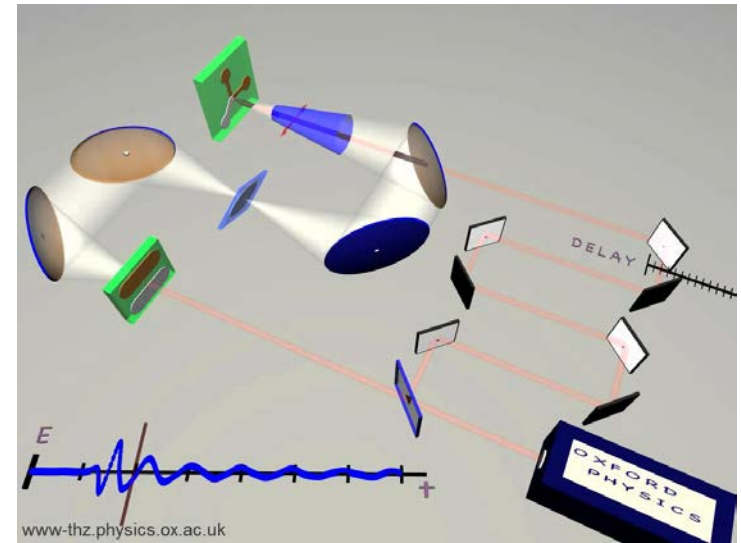
- Bi2212単結晶メサ構造からコヒーレントTHz波が放射
- 0.5THzで0.6mWの最大出力
- メサ形状により、偏光を制御できる

THz waves

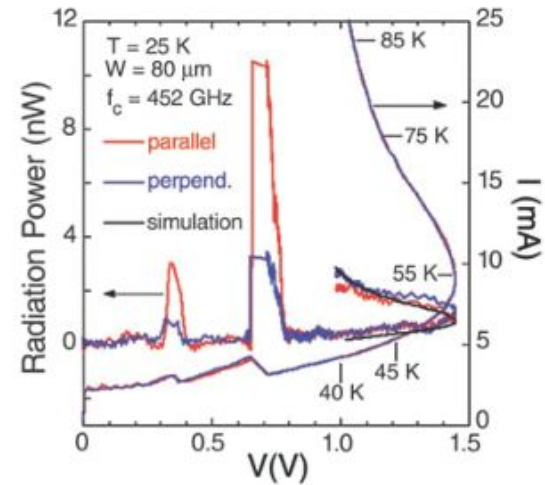
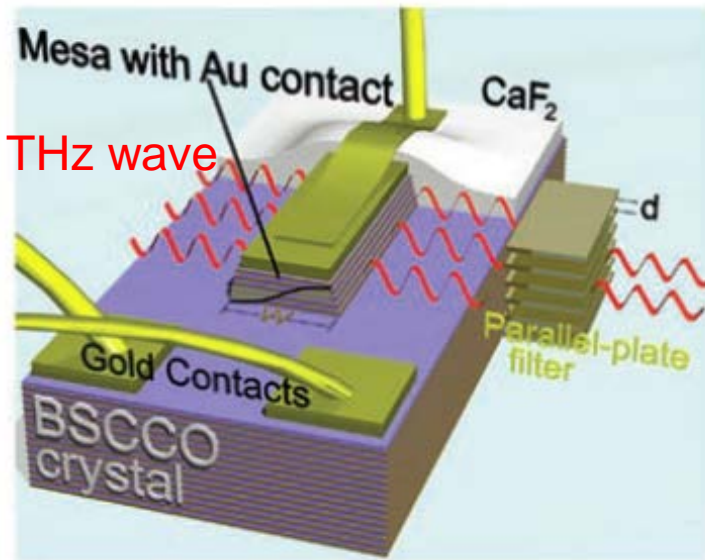


Sources of THz wave

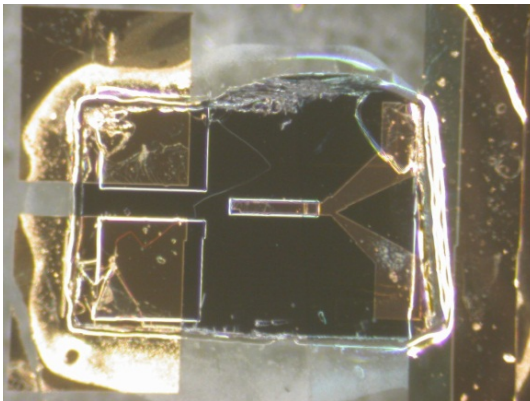
- Pulse generation with femtosecond laser
 - Photoconductive antenna
 - Semiconductor crystal
- CW generation from solid state devices
 - Quantum cascade laser
 - Resonance tunneling diode oscillators



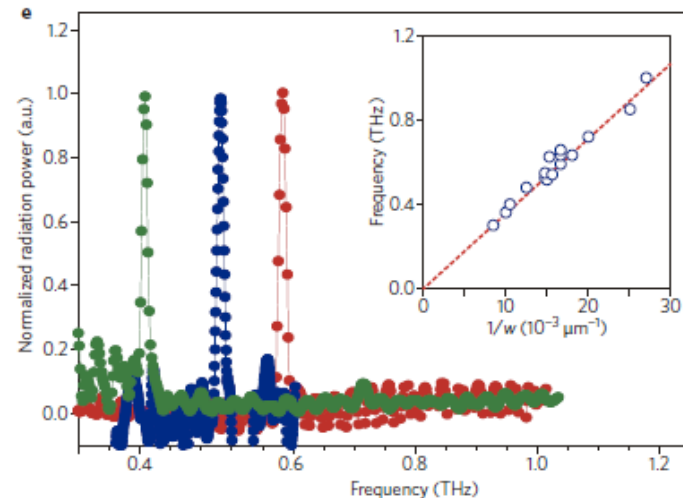
高温超伝導THz光源の実証



L. Ozyuzer *et al.*, Science 2007



K. Kadowaki *et al.*, Physica C 2008



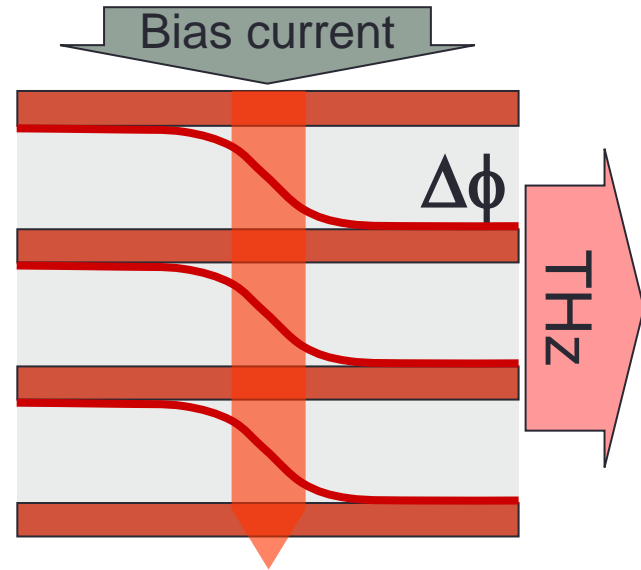
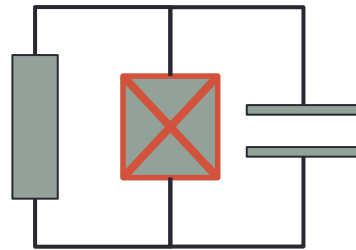
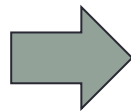
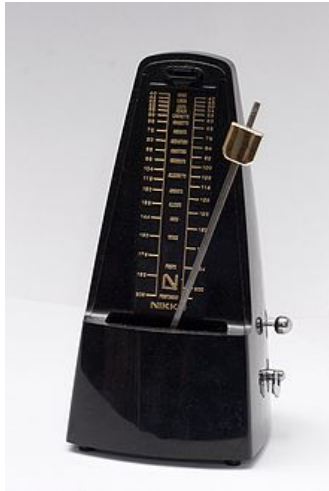
U. Welp *et al.*, Nature Photonics, 2013

Synchronization of Metronomes



<http://youtu.be/DD7YDyF6dUk>

Our interest

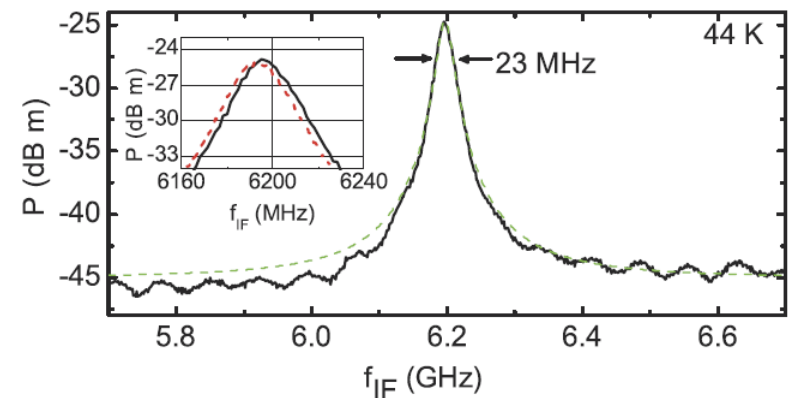
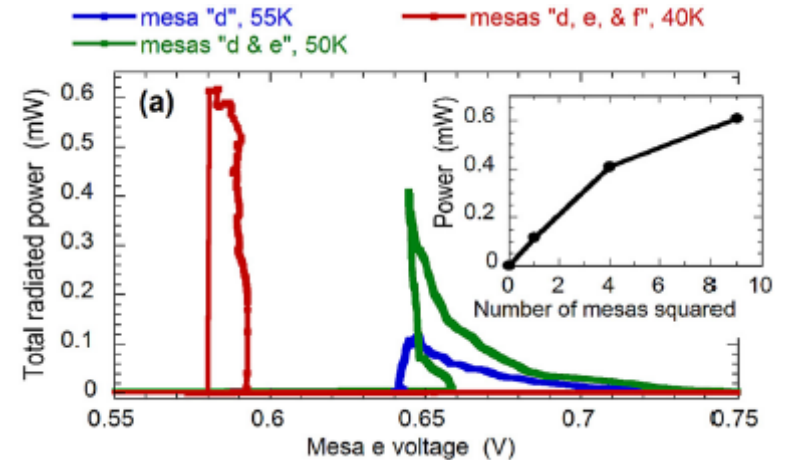


Is it possible to synchronize huge # of Josephson junctions?

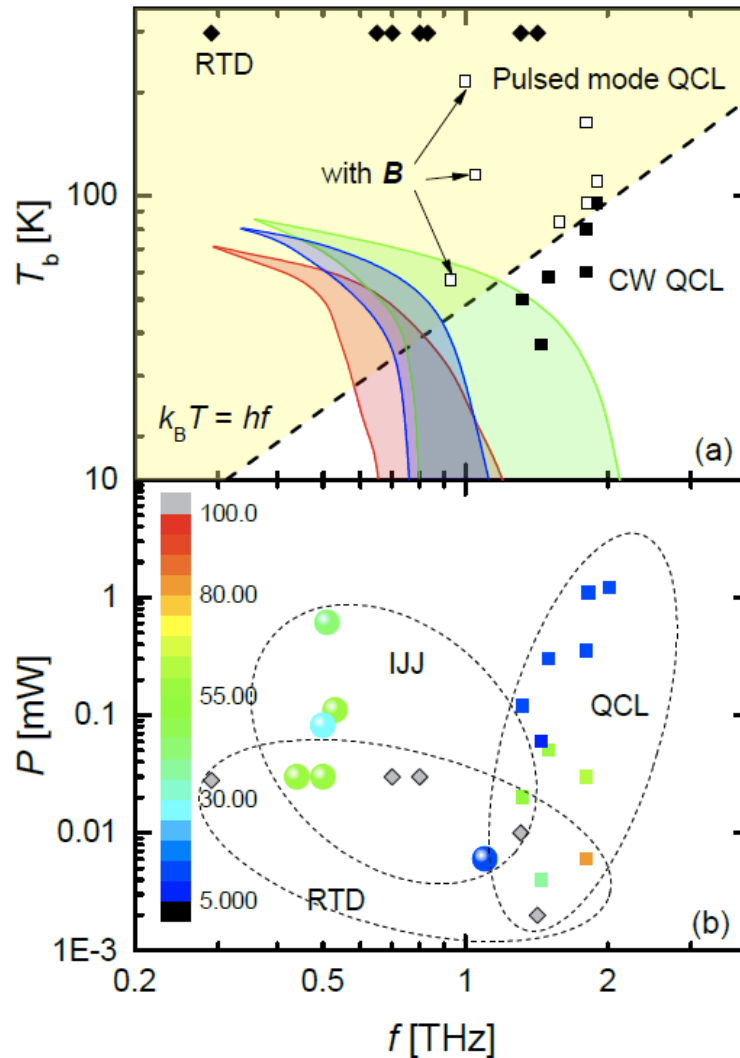
Yes, we did it!

重要な特性

- 連続波
 - Minami et al, APL **95** 232511 (2009)
- 最大出力: 0.6 mW
 - Benseman et al, APL **103** 022602 (2013)
- 狭帯域: ~ 10 MHz
 - Li et al., PRB **86** 060505 (2012)
- 周波数範囲: 0.2-1.6 THz
 - Kashiwagi et al, APL **106** 092601 (2015).
- 動作温度 < 84 K
 - Hao et al., PRApp. **3** (2015).



半導体THz光源との比較



IK and H. B. Wang, Supercond. Sci. Technol., **29**, 073001 (2016)
doi:10.1088/0953-2048/29/7/073001

Mechanism

$\lambda/2$ Cavity resonance

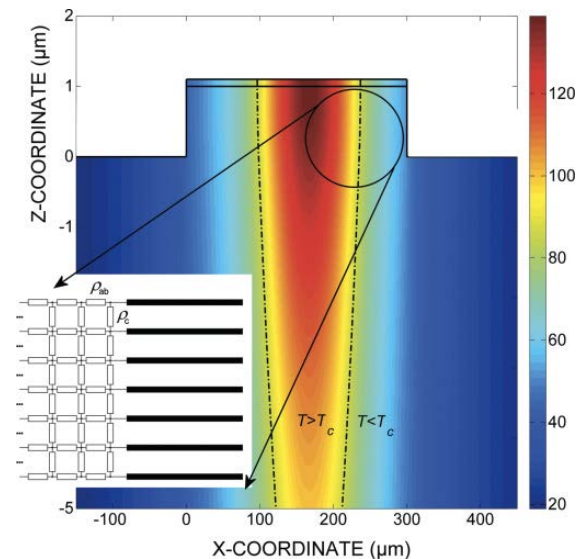
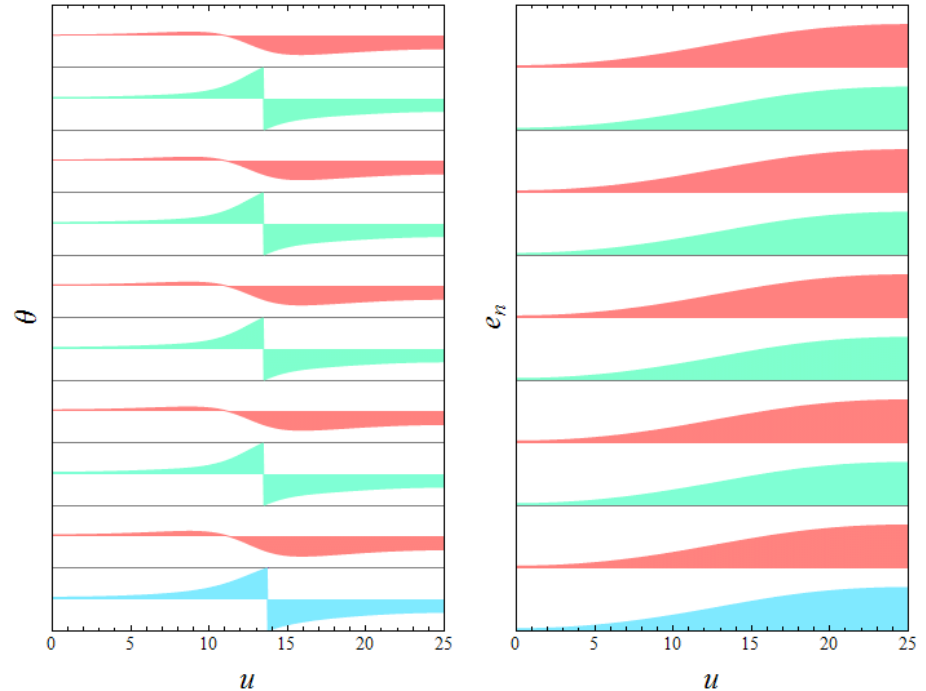
$$\nu = \frac{c}{2nw}$$

AC Josephson

$$\nu = \frac{2ev}{h} = \frac{2eV/N}{h}$$

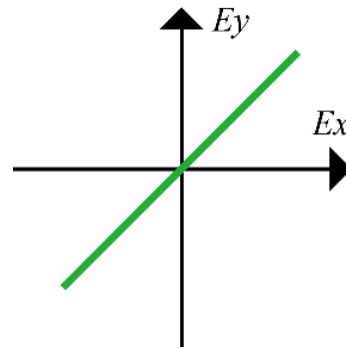
Intense THz emission is due to:
Synchronization of Josephson plasma waves with a cavity mode.

Local temperature rise possibly induces the synchronization.

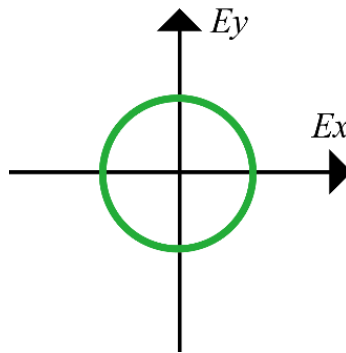
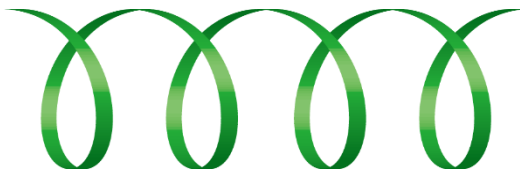


Circular polarization

Linear polarization



Circular polarization



Apps. Circular-polarized wave

- Wireless communications
- Circular dichroism spec.

Patch antenna theory:
Truncations at corners of square antenna allow to generate C-polarized waves.



Truncated mesa possibly generate C-polarized waves

Fabrication of truncated mesa

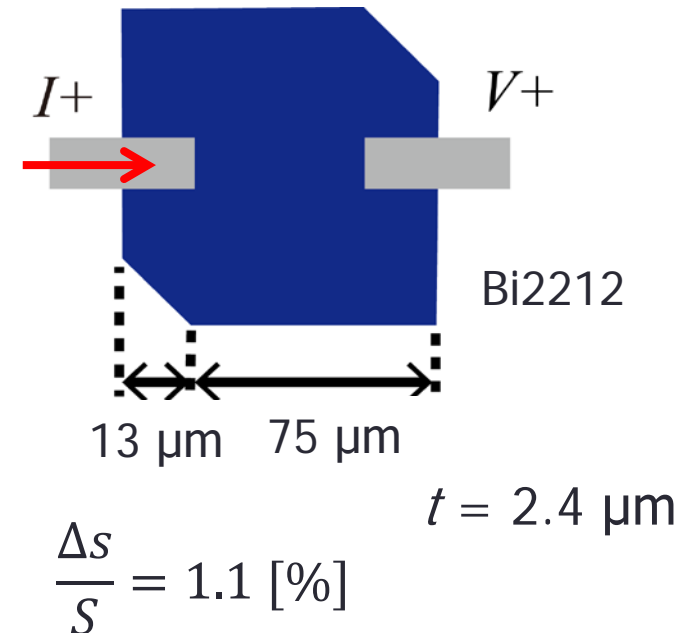
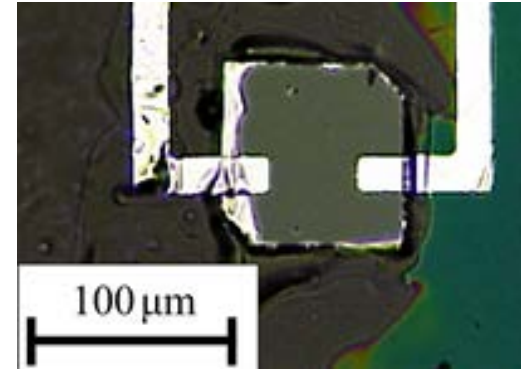
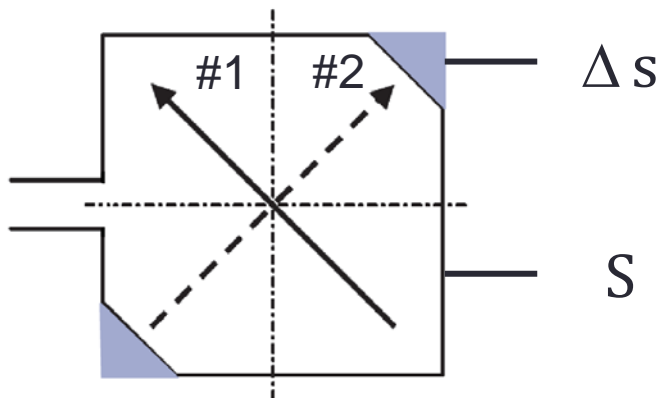
Patch antenna theory

Condition for C-polarization

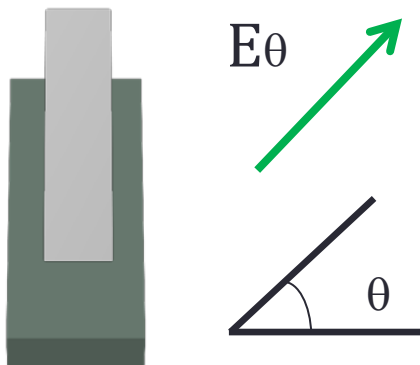
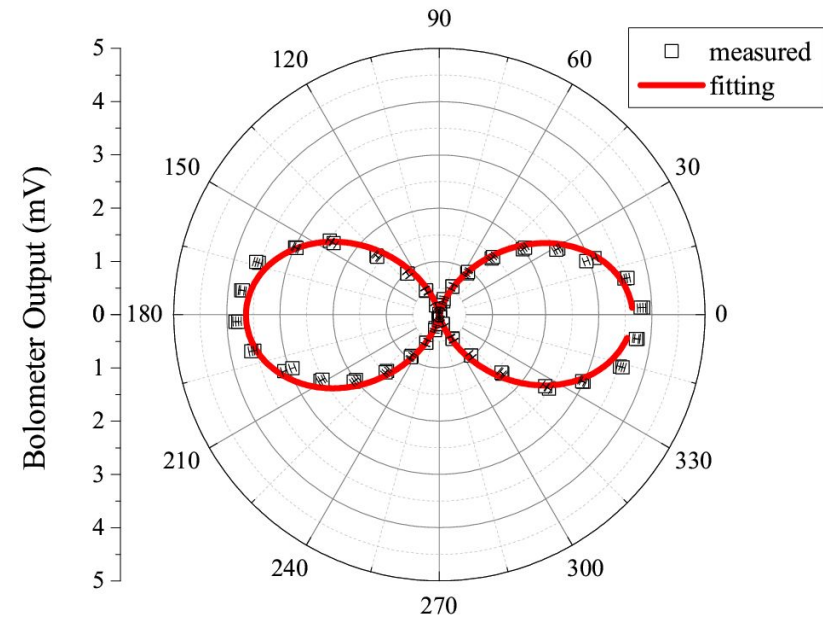
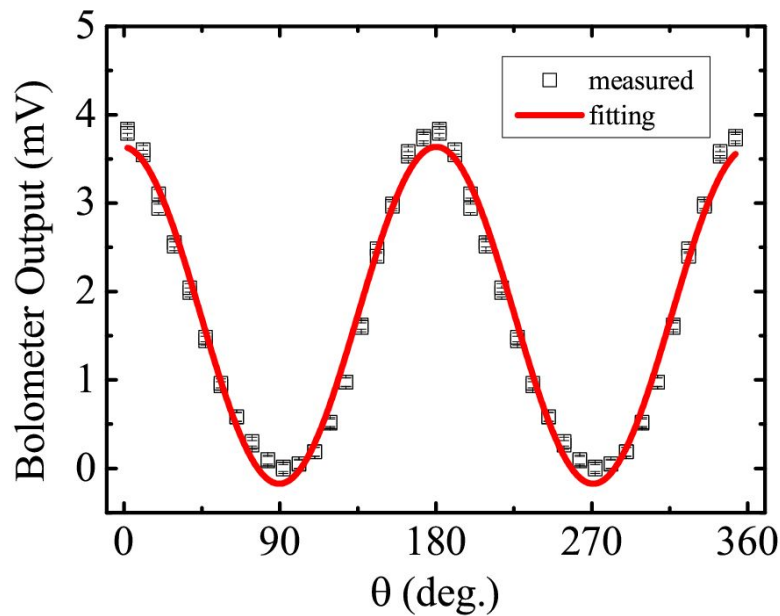
$$\frac{\Delta s}{S} = \frac{1}{4Q} = 0.025$$

$$Q \approx Q_c = \frac{t}{\delta} \quad \begin{array}{l} \text{Thickness of antenna} \\ \text{Skin depth} \end{array}$$

for $\delta = 0.2 \mu\text{m}$ and $t = 2.0 \mu\text{m}$



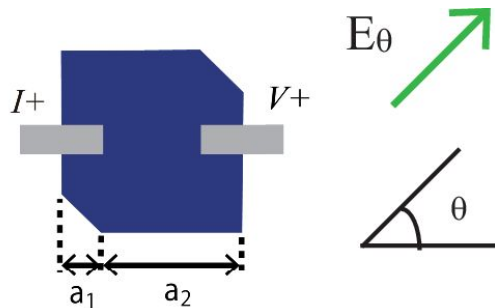
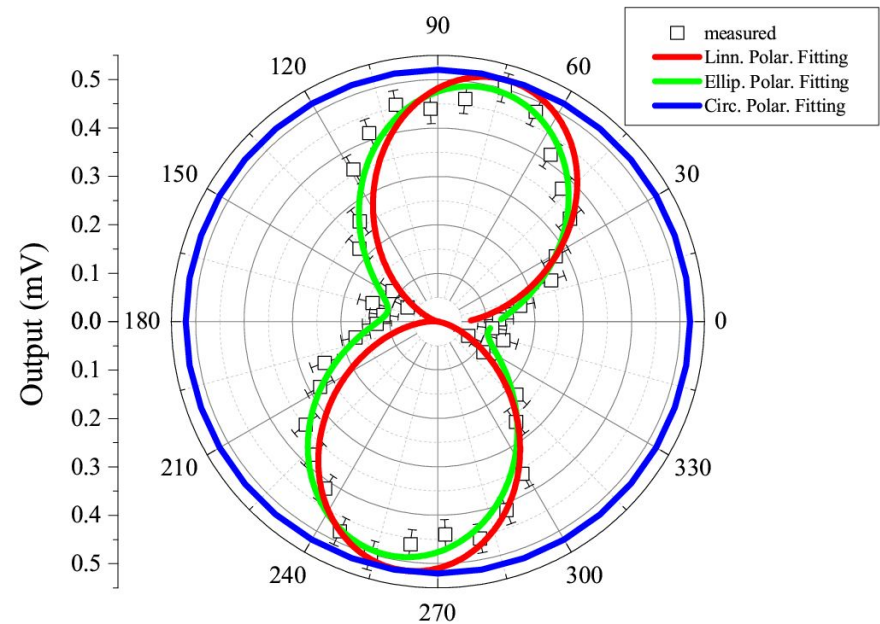
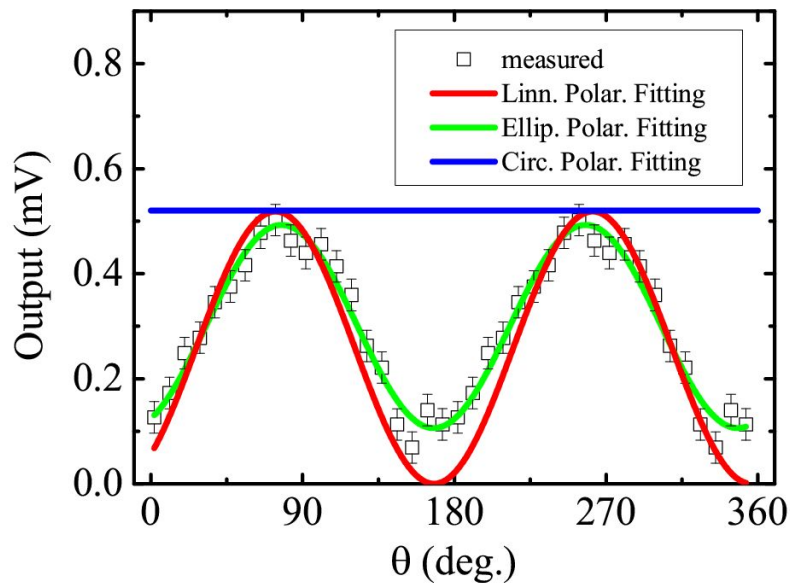
Polarization of rectangular mesa



- Linear polarization with $e < 0.1$
- TM(1,0) mode E-direction

Linear: $|\vec{E}_1|^2 \cos(\theta - \theta_1)$

Polarization of notched mesa



- Elliptic polarization with $e = 0.5$
- Tilted long E-axis with $\theta_1 = 75^\circ$

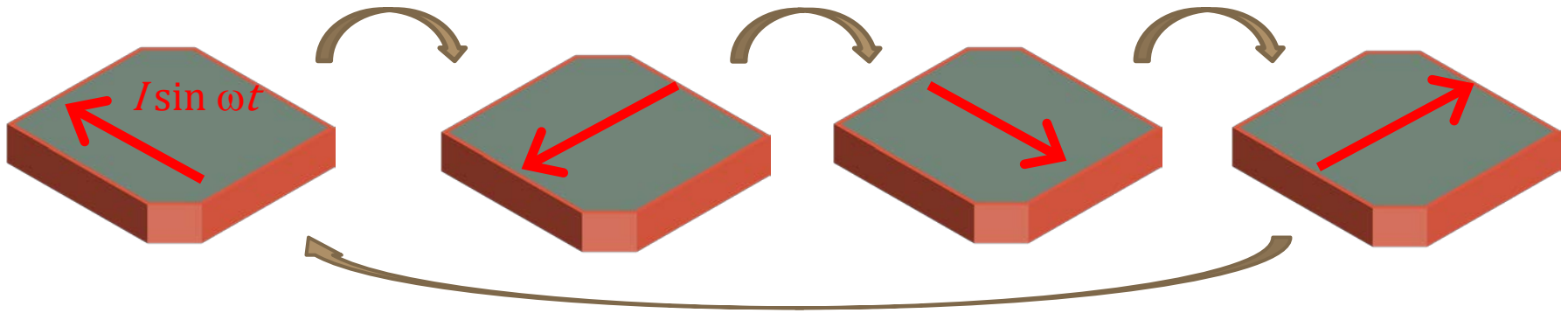
Linear : $|\vec{E}_1|^2 \cos(\theta - \theta_1)$

Elliptic : $(|\vec{E}_1|^2 - |\vec{E}_2|^2) \cos(\theta - \theta_1) + |\vec{E}_2|^2$

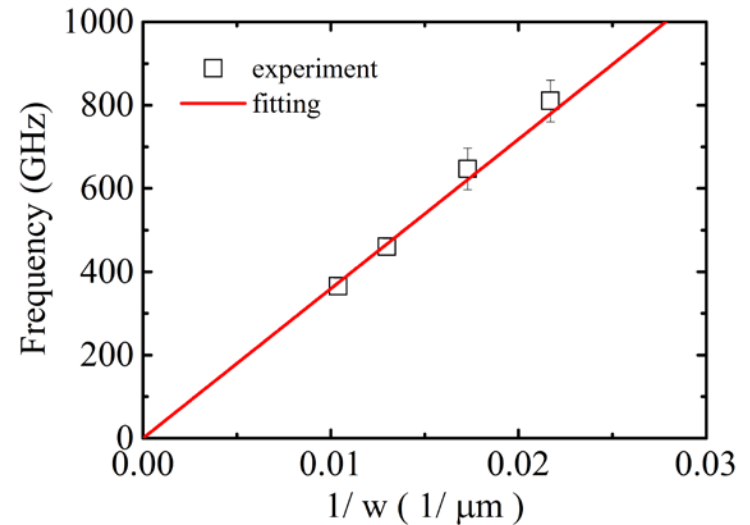
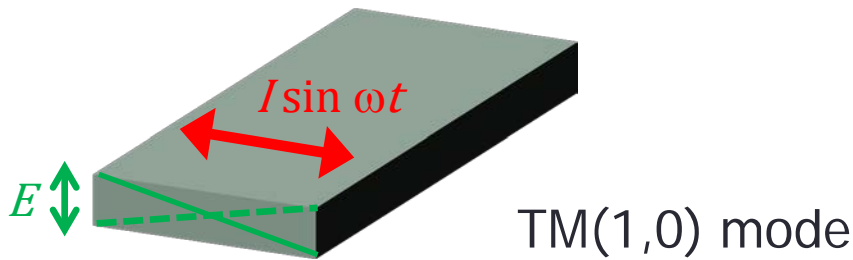
Circular : $|\vec{E}_1|^2$

Truncated vs rectangular

Truncated



Rectangular



Summary for THz emission

- The relevance of the T distribution to the emission intensity is demonstrated.
 - More intensive THz wave is emitted from less heated case.
 - The emission intensity increases by up to 20% with a decrease in the hot-spot size.
- Polarization of the emitted THz wave is investigated
 - Elliptically polarized wave is emitted from the truncated mesa structure.

固有ジョセフソン接合における 巨視的量子トンネル現象

- ジョセフソン接合における量子トンネルを電流電圧特性に観測
- 複数自由度の超伝導体のモデル
- 量子ビットへの応用も可能

RCSJ model of JJ

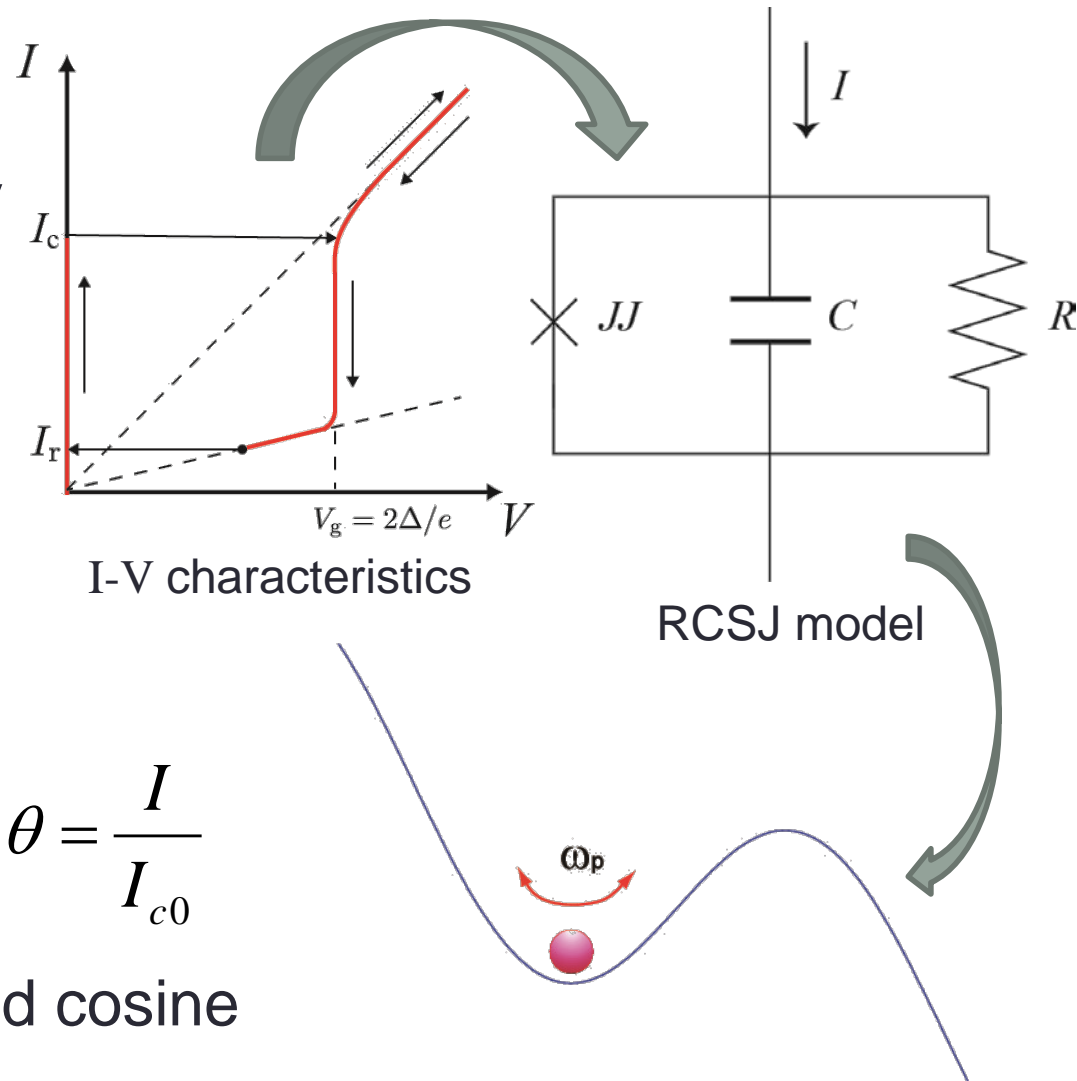
IV characteristic of JJ:
resistively and capacitively
shunted Junction

$$I = I_{c0} \sin \theta + \frac{V}{R} + C \frac{dV}{dt}$$

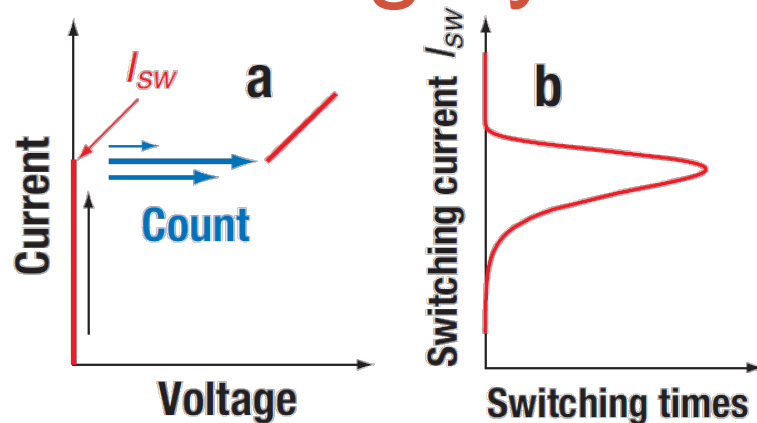
$$\frac{d\theta}{dt} = \frac{2eV}{\hbar}$$

$$\frac{1}{\omega_{p0}^2} \frac{d^2\theta}{dt^2} + \frac{1}{\omega_{p0}^2 RC} \frac{d\theta}{dt} + \sin \theta = \frac{I}{I_{c0}}$$

Motion of a particle in a tilted cosine potential



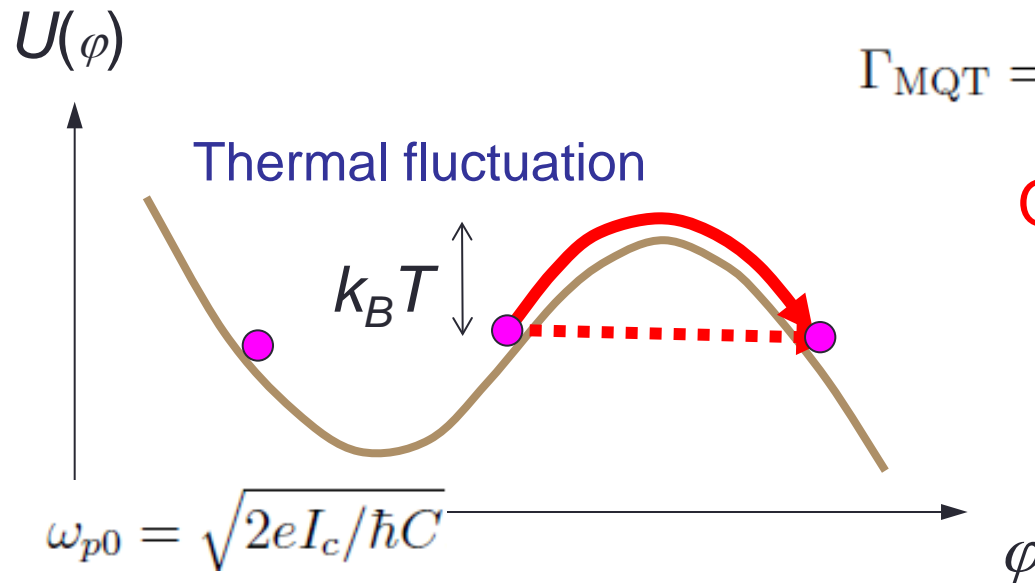
Switching dynamics of JJ



Distribution of I_{sw} is a function of I_{c0} , C , T (TA)

$$\Gamma_{TA} = a_t \frac{\omega_p}{2\pi} \exp\left(-\frac{\Delta U}{k_B T}\right)$$

Thermal escape

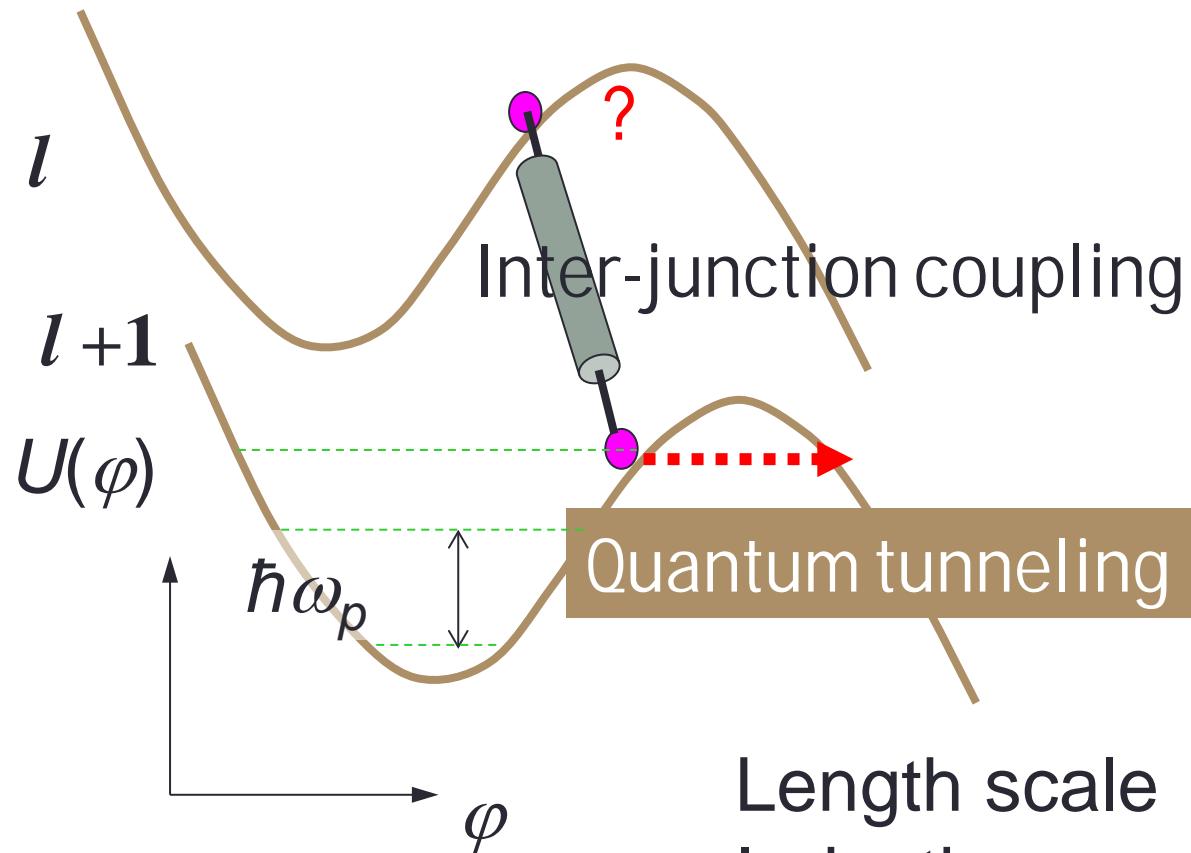


$$\Gamma_{\text{MQT}} = \frac{\omega_p}{2\pi} \sqrt{\frac{864\Delta U\pi}{\hbar\omega_p}} \exp\left(-\frac{36\Delta U}{5\hbar\omega_p}\right)$$

Quantum tunneling

Superconducting phase qubit

Peculiarity of MQT in IJJs

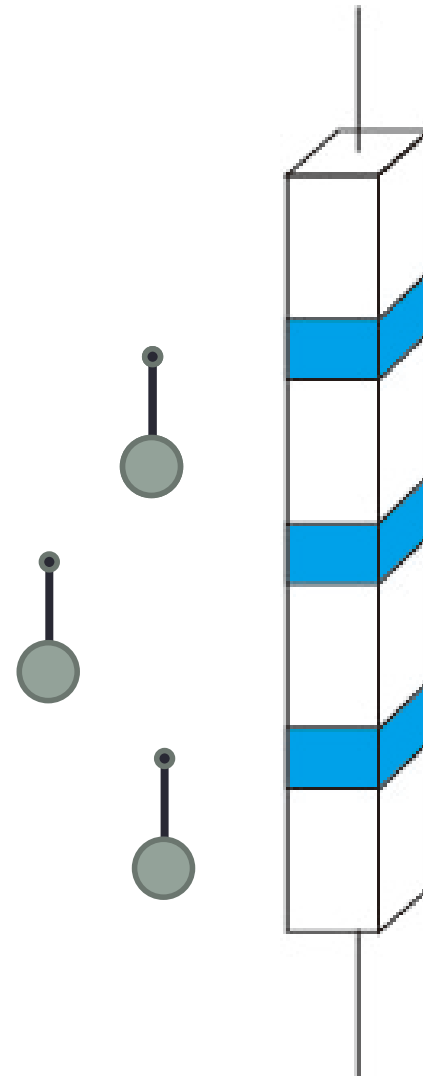


Inductive coupling: $\lambda \sim 100$ nm

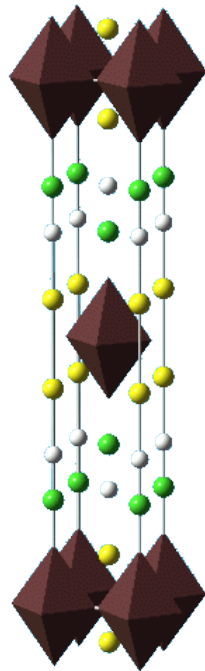
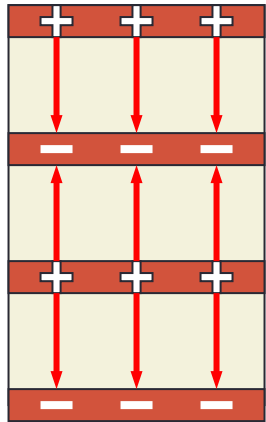
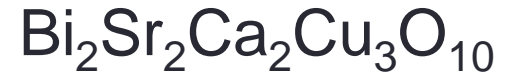
Capacitive coupling: $\mu \sim 1$ nm

Assumption

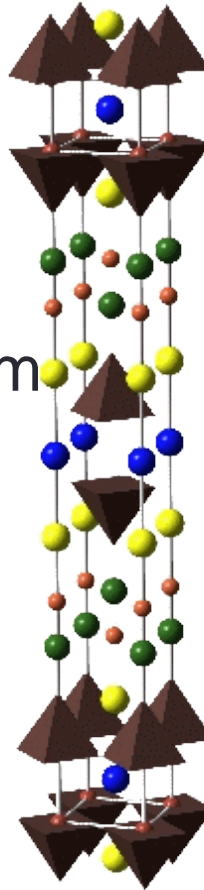
- Inter-JJ coupling enhance escape from the trapped state of a JJ when an adjacent JJ is in the running state.
- Its strength is varied by the thickness of SC electrode.



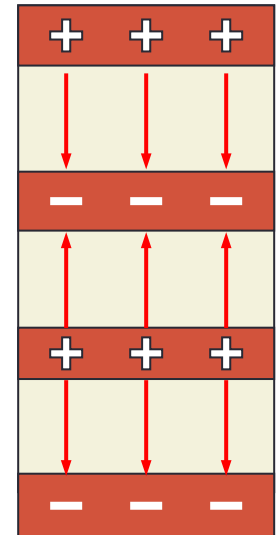
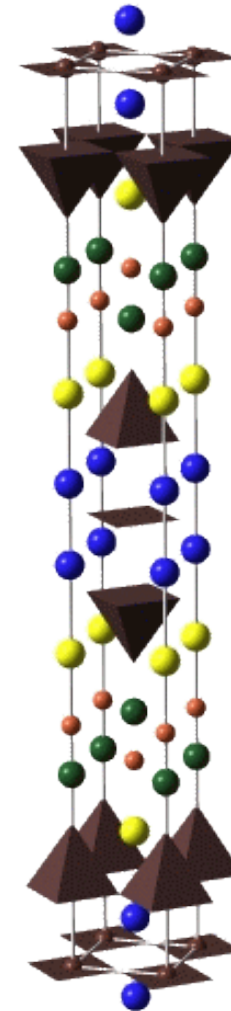
Crystal structures of three BSCCOs



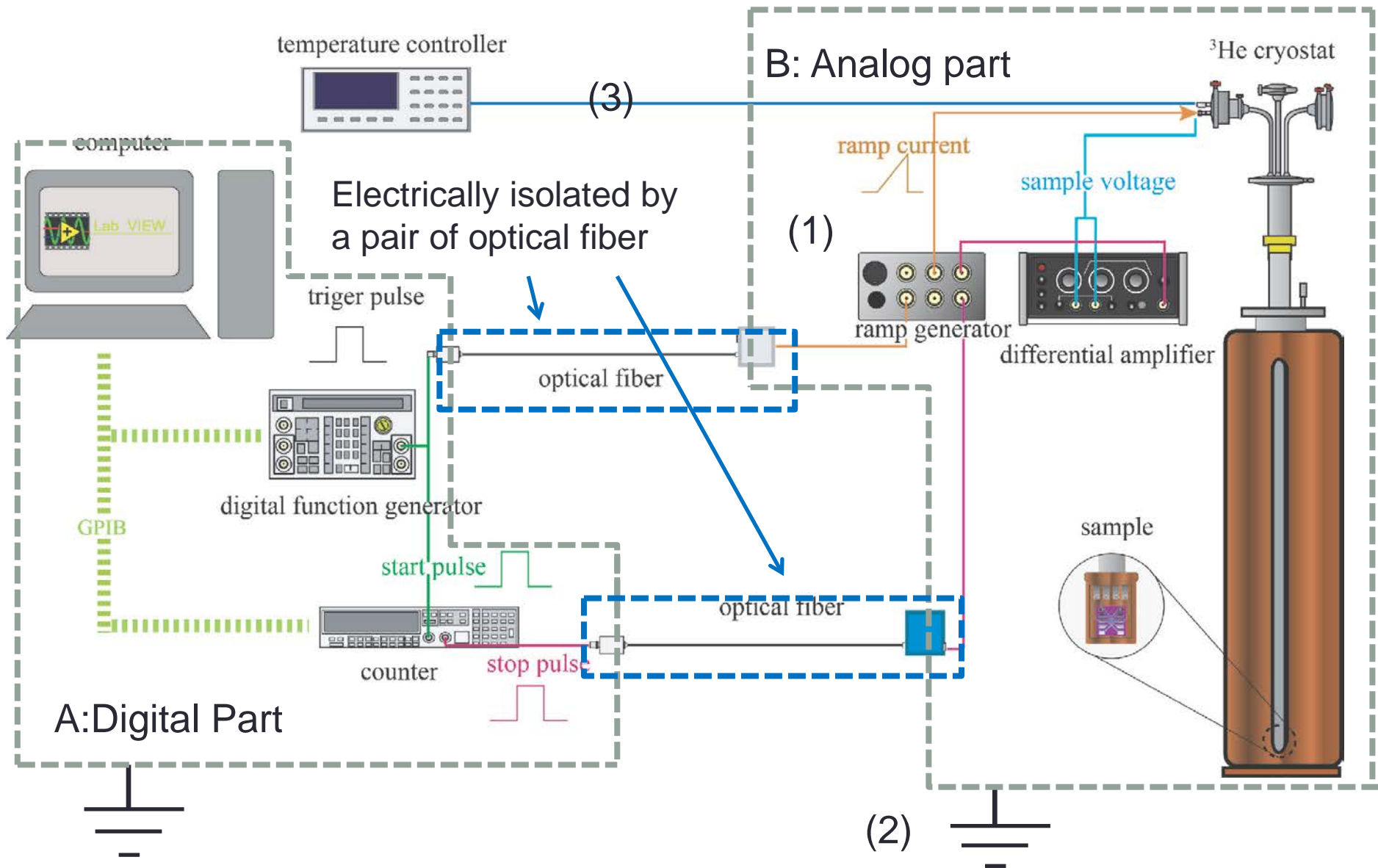
0.3 nm



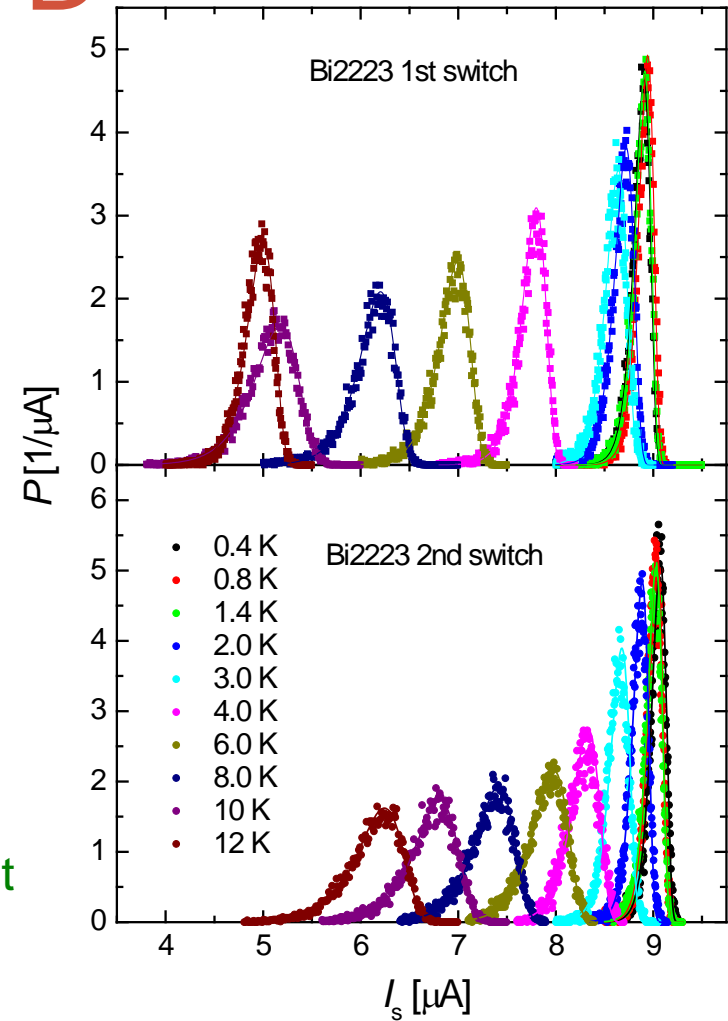
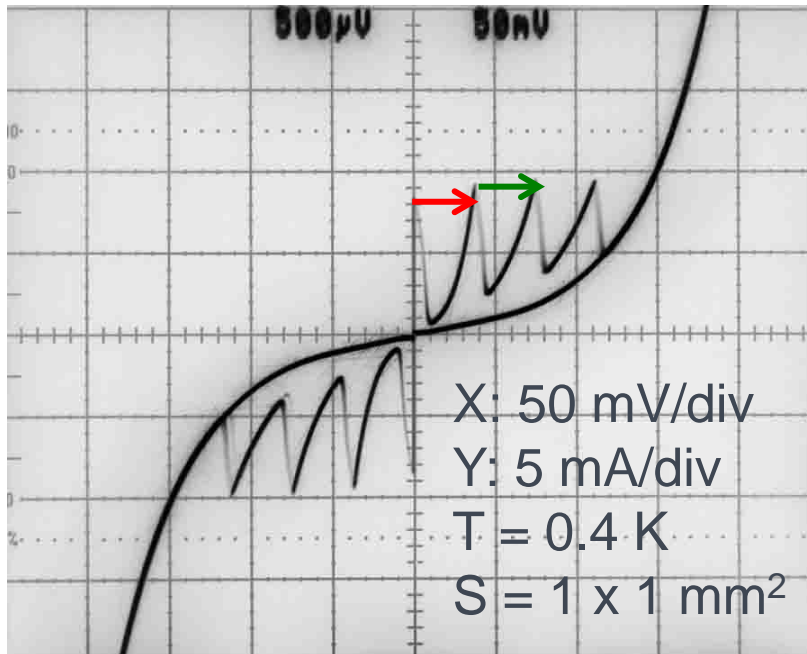
0.6 nm



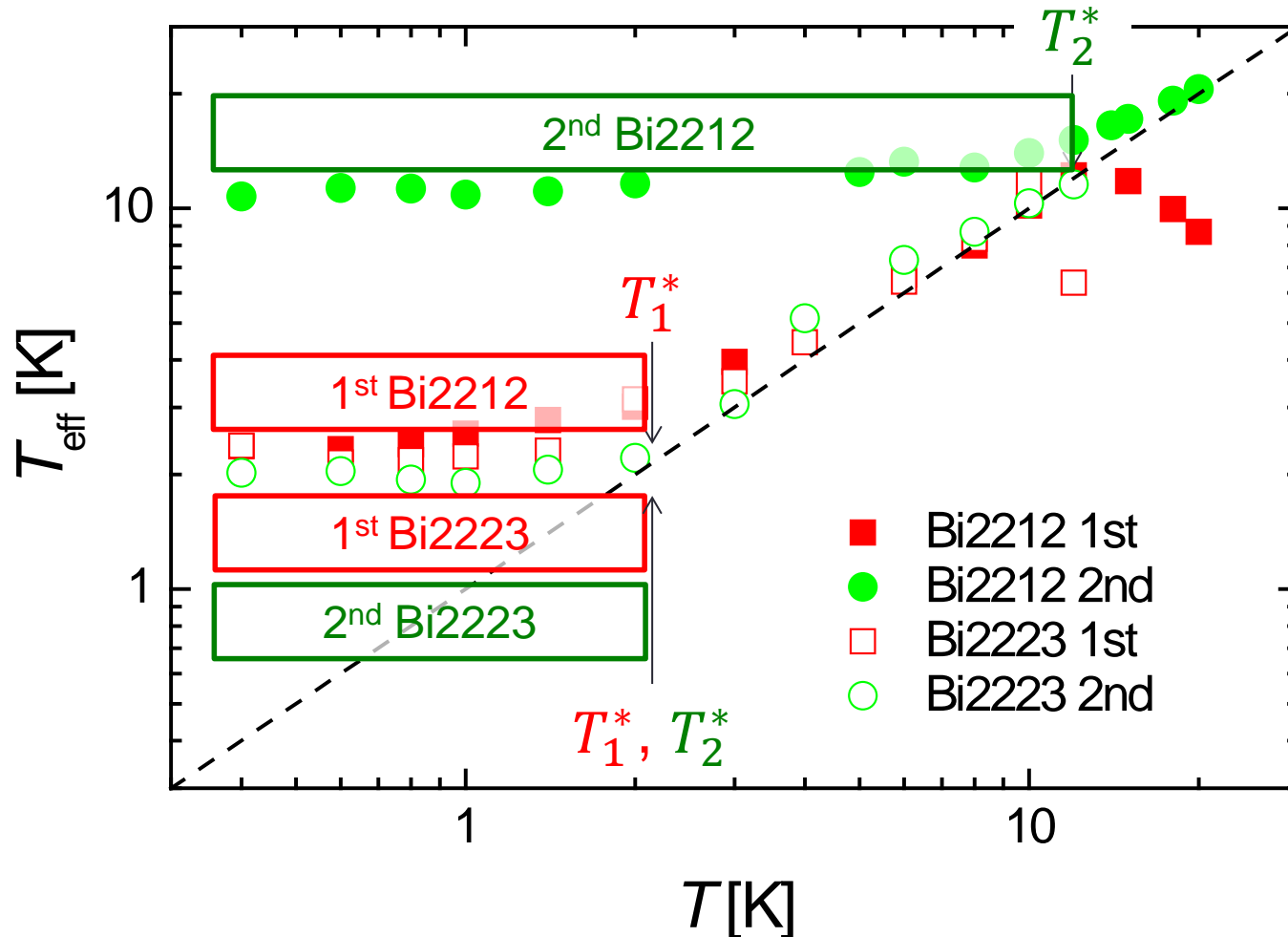
Measurement setup



Bi2223 1st and 2nd SPD



MQT regime in Bi2212 and Bi2223



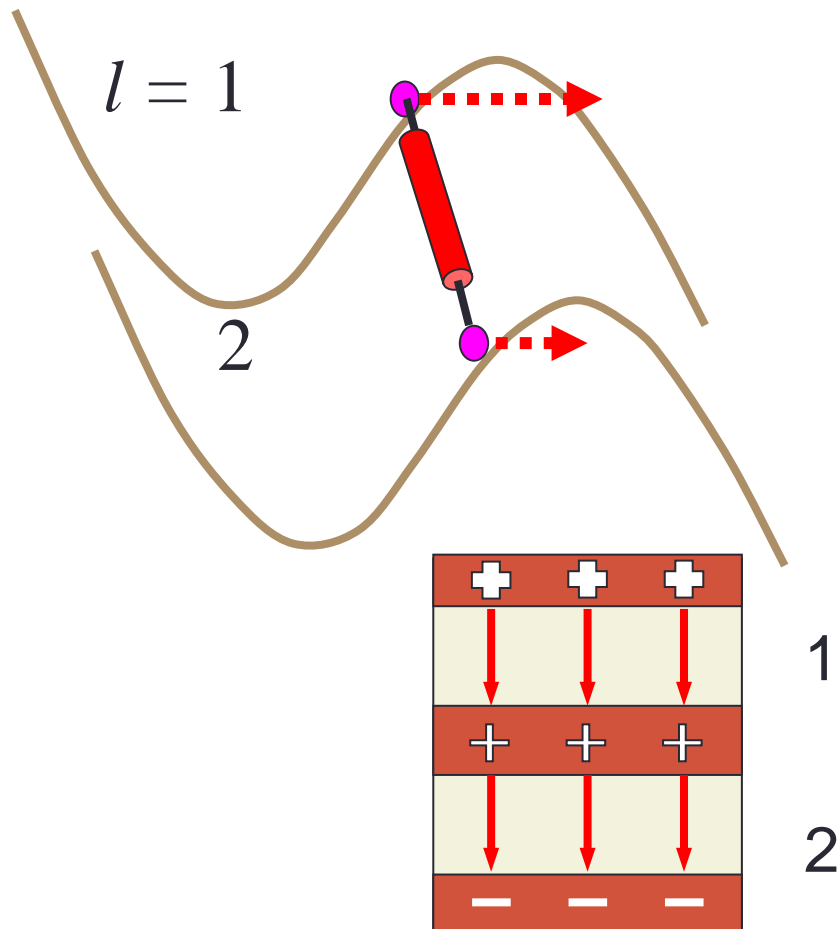
Results summary

	T^* (Exp.)	T_{cr} (SJ model)	T^*/T_{cr}
Bi2201 1st	0.6 K	0.35 K	1.7
Bi2201 2nd	2.0 K	0.30 K	6.7
Bi2212 1st	2.0 K	0.72 K	2.8
Bi2212 2nd	10 K	0.95 K	11
Bi2223 1st	2.0 K	0.55 K	3.6
Bi2223 2nd	2.0 K	0.59 K	3.4

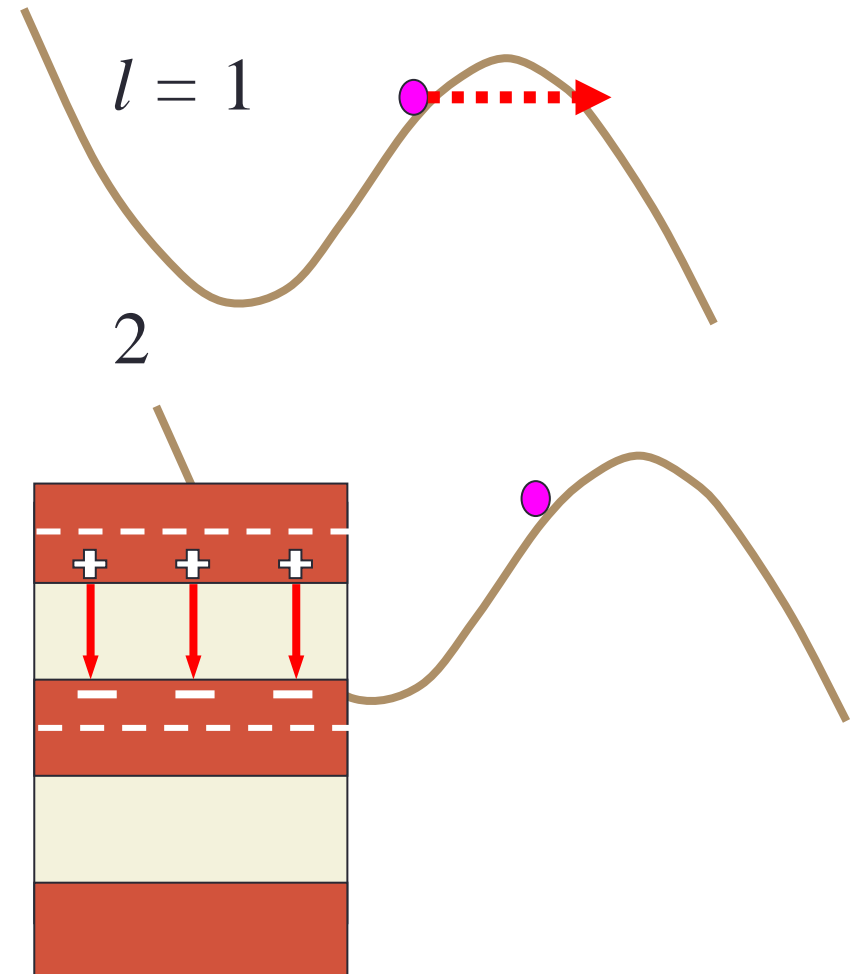
$T_{2nd}^*/T_{cr} > 5$ in Bi2201, Bi2212

Coupled quantum tunneling

Bi2201, Bi2212



Bi2223



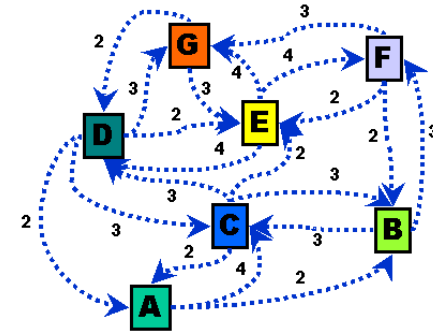
Summary for MQT

- 3種のBSCCOについてMQTを観測した
 - 量子領域における第2スイッチの増加は、 $t < 0.3$ nmの固有接合に共通の現象
 - CuO_2 層における電荷中性の破れに由来(電荷結合)
 - 固有接合系は、複数の秩序パラメタが相互作用するモデル

超伝導量子コンピュータの開発

- 機械学習から人工知能へ
- D-Wave, Google, IBMなどがハードウェア開発
- 巨大国家プロジェクトが続々スタート、日本は・・・

世界初の商用量子計算機D-Wave



Google

Goldman
Sachs

intel

LOCKHEED MARTIN

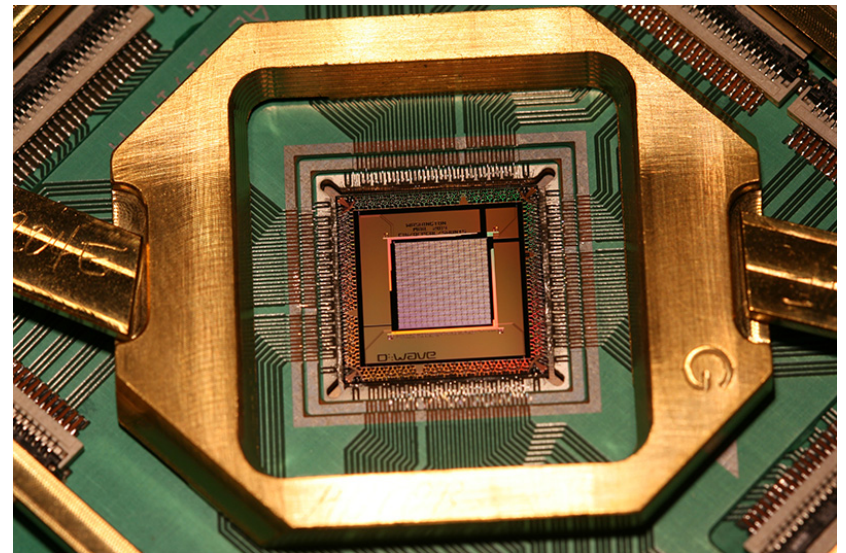
量子アニーリングにより組み合わせ最適化問題を解く。
D-Wave One (128 qubits): 2011年
D-Wave Two (512 qubits): 2013年
D-Wave 2X (1024 qubits): 2015年

経路、情報伝達、投資の最適化

D-waveのテクノロジー

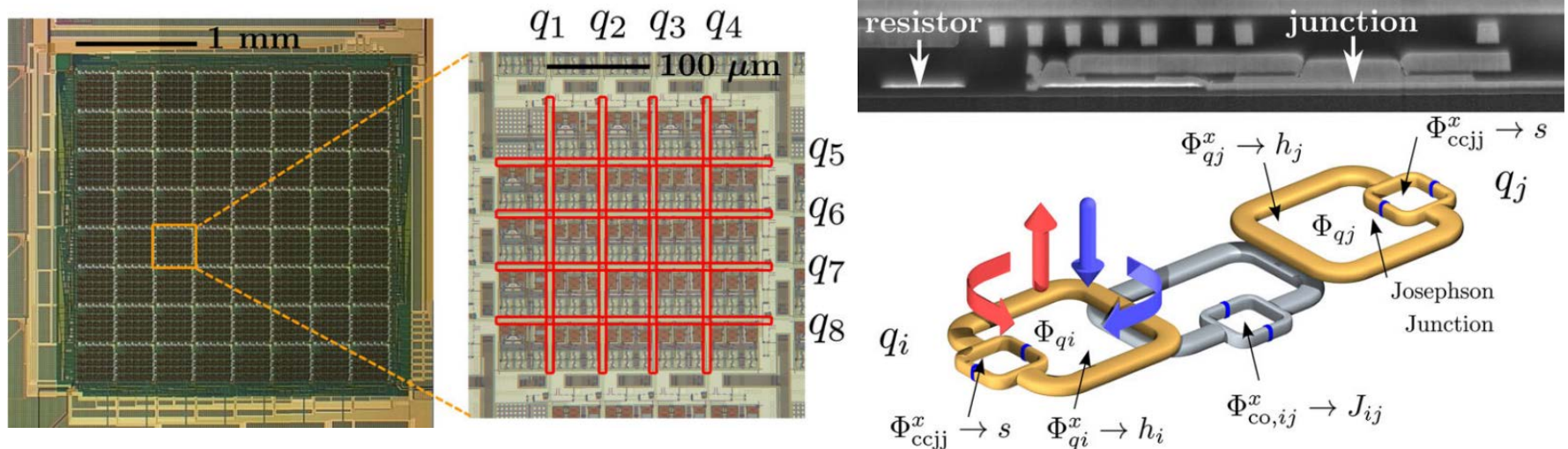


希釈冷凍機によって12 mKまで冷やされた超伝導デバイス



[D-waveウェブサイト](http://www.dwave.com)より

D-waveの超伝導回路 (SQUID)



T. Lanting *et al.* Phys. Rev. X **4**, 021041 (2014)

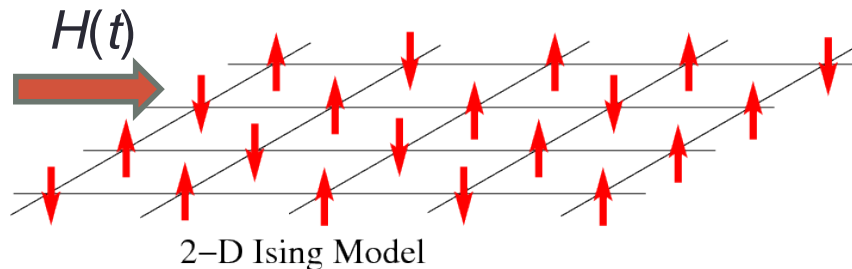
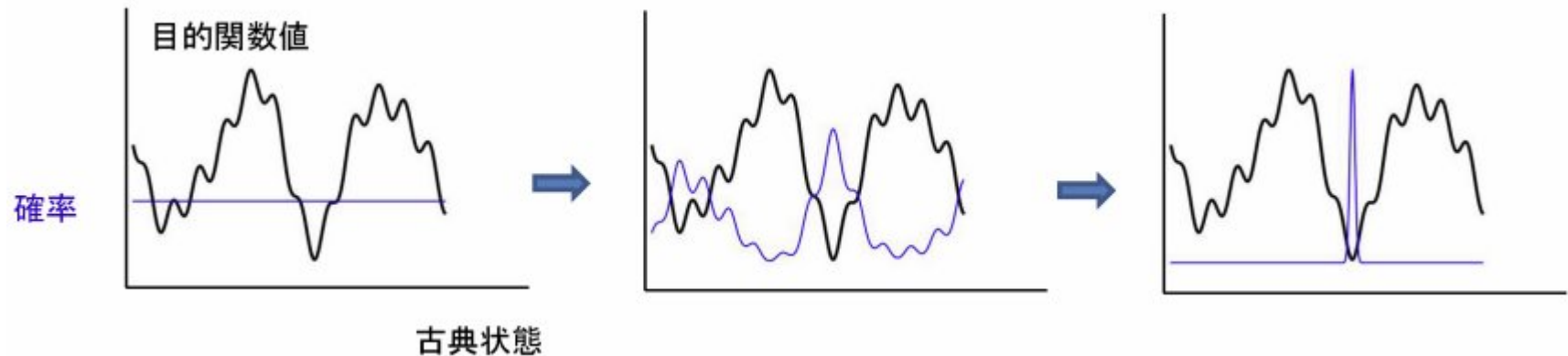
$$\mathcal{H}_P = -\sum_i h_i \sigma_i^z + \sum_{i < j} J_{ij} \sigma_i^z \sigma_j^z$$

最新のD-wave 2X (1024 qubits) では、128,000個のジョセフソン接合

量子アニーリングとは？

量子トンネルを取り入れた最適化問題の解法として、東工大の西森らが1998年に提案

T. Kadowaki and H. Nishimori, [Phys. Rev. E58 \(1998\) 5355](#).



$$H = - \sum J_{ij} \sigma_i^z \sigma_j^z - \Gamma(t) \sum \sigma_i^x$$

イジングスピン 横磁場

西森 秀稔教授のサイト <http://www.stat.phys.titech.ac.jp/~nishimori/>

最急降下法、シミュレーテッド・アニーリングと比較して、計算が高速化できる

量子計算機をめぐるここ数ヶ月の動き

- IBMが量子計算を誰もが実験できるクラウドサービスとして提供 (2016/05)
 - 5 qubitsの量子計算をwebサイトで提供: [IBM Quantum Experience](#)
- Googleが量子ゲート方式の計算機で量子アニーリングをシミュレート (2016/06)
 - "[Digitized adiabatic quantum computing with a superconducting circuit](#)" をNatureに発表
- [Googleの量子人工知能研究所](#)は、高機能の量子アニーリング装置“Quantum Annealer Ver. 2.0”の製造を開始 (2016/06)
 - Adiabatic Quantum Computing Conference 2016, June 27-30, 2016, Google LA での発表
- 産総研・日立・理研などによる高速・低消費電力で処理するアニーリングマシンの開発がNEDOプロジェクトに採択 (2016/07)

Summary of lecture

- 超伝導量子計算機は、すでに商用化されている
- 高温超伝導デバイスが一般に行き渡る日はすぐそこに来ている
 - テラヘルツ光源は小型スターリングクーラーで動作
- 巨視的秩序パラメータの位相を操る「フェイゾニクス」の確立が必須である
 - スピントロニクスとの融合
- 固有ジョセフソン接合、テラヘルツ時間発展の研究は未開の沃野である
- 超伝導フェイゾニクスは量子計算技術と融合して AI分野への発展が期待される

レポート課題

- 超伝導デバイスについて、講義で紹介したものでないものを挙げ、そのデバイスの超伝導に由来する特性を説明せよ
- 最適化問題の解法について調査し、それらの特徴を述べよ
- 量子計算機について、超伝導を用いない方式を挙げよ
- 講義の感想・意見・質問