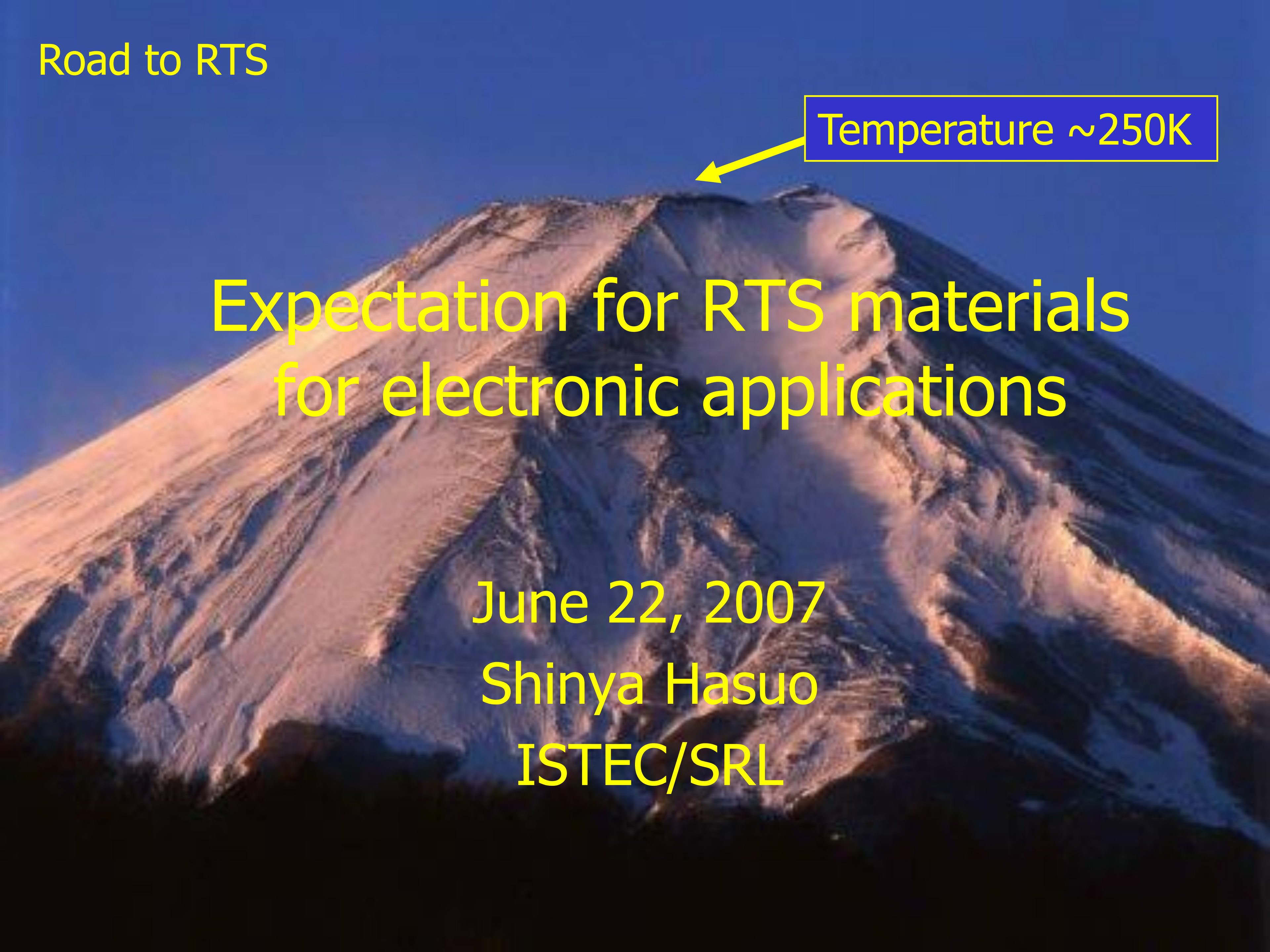


Expectation for RTS materials for electronic applications

June 22, 2007

Shinya Hasuo
ISTEC/SRL

Contents

- Classification of superconductive electronic devices
- Examples of LTS and HTS devices
- RTS material application to passive devices
- RTS material application to active devices
- Expectation for RTS materials for electronic applications
- Request for RTS materials from the viewpoint of an electronic device researcher

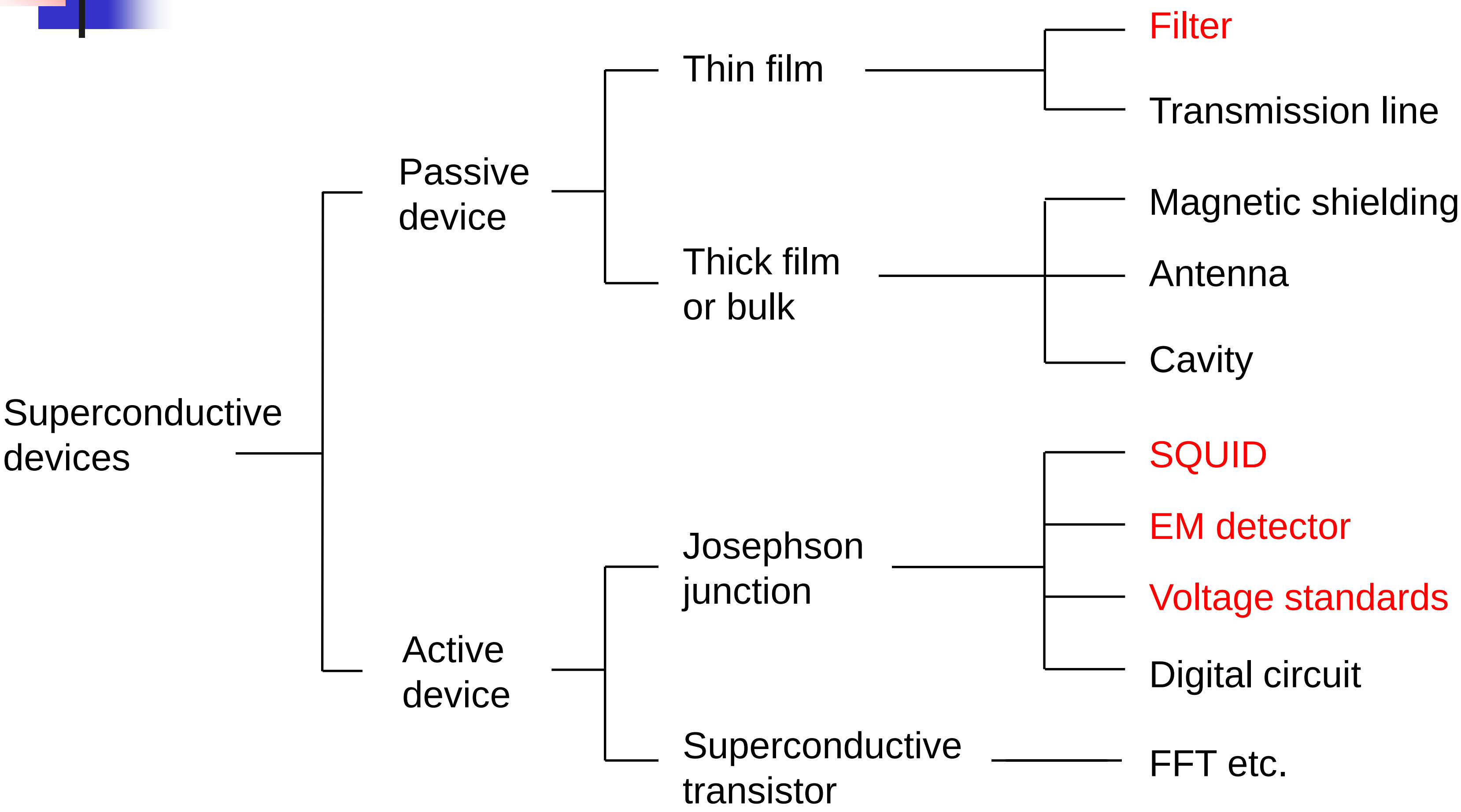
ISTEC

Contents

- Classification of superconductive electronic devices
- Examples of LTS and HTS devices
- RTS material application to passive devices
- RTS material application to active devices
- Expectation for RTS materials for electronic applications
- Request for RTS materials from the viewpoint of an electronic device researcher

ISTEC

Electronic applications of superconductive devices



Devices shown by red color are commercially sold.

Contents

- Classification of superconductive electronic devices
- Examples of LTS and HTS devices
- RTS material application to passive devices
- RTS material application to active devices
- Expectation for RTS materials for electronic applications
- Request for RTS materials from the viewpoint of an electronic device researcher

Example of commercially available or practical superconductive systems

Example of commercially available or practical superconductive systems

- HTS filters

An example of application for 2GHz-band receiving

For diversity receiving

Volume: 15L

A trial open-air subsystem
with developed HTS filters for 2GHz band

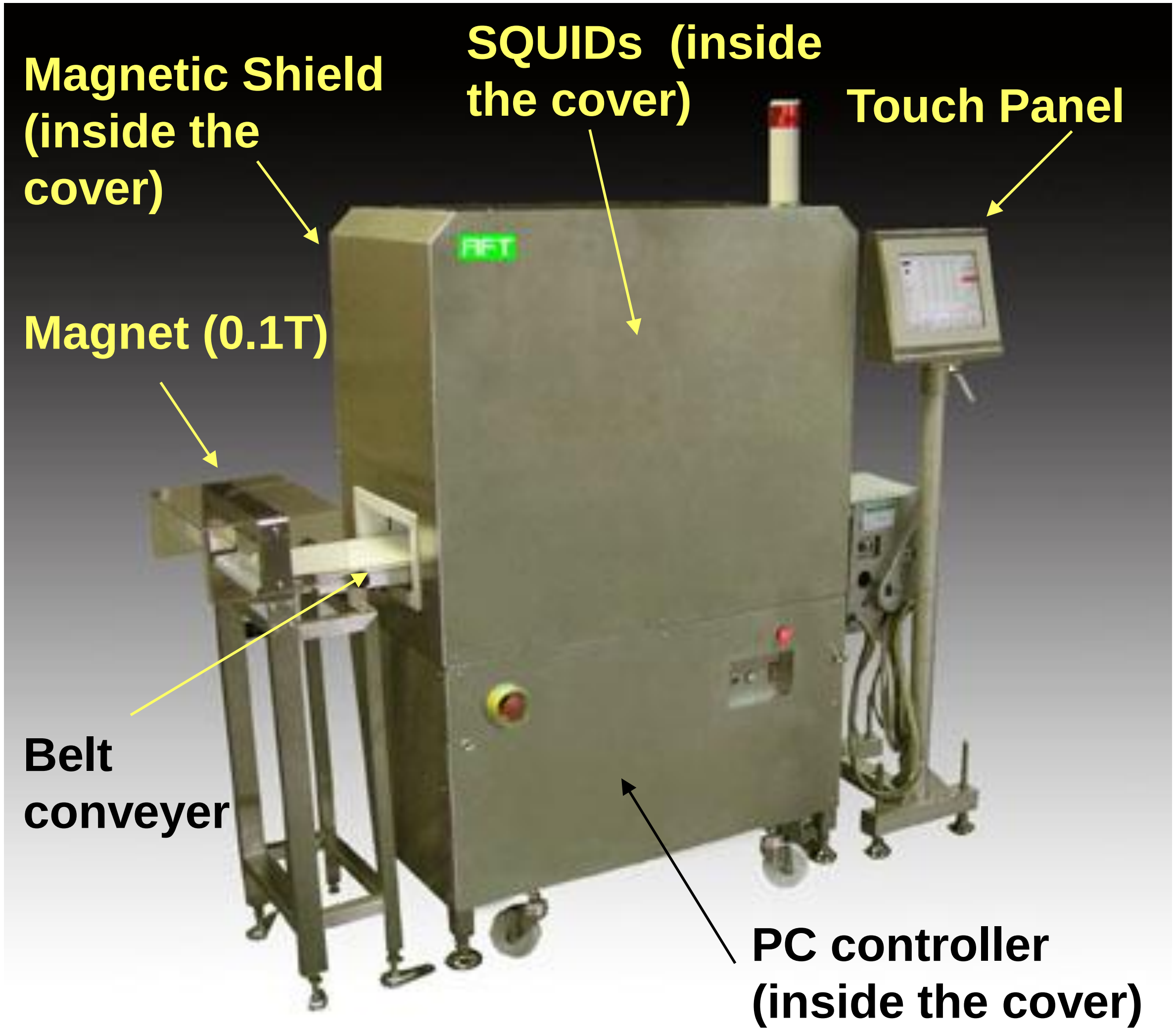
http://pr.fujitsu.com/jp/news/2002/09/20.html

FUJITSU

Example of commercially available or practical superconductive systems

- HTS filters
- HTS and LTS SQUID systems

SQUID for food inspection system



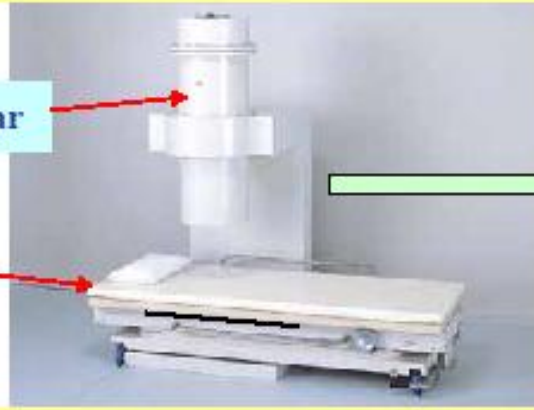
National University Corporation
Toyohashi Univ. of Technology

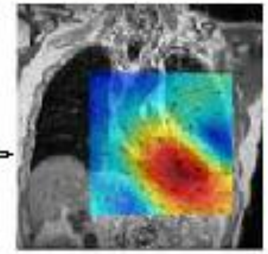
Advance Food Tech. Co.,Ltd.
Sumitomo Electric Hightechs Co.,Ltd.

Low-Tc 64ch SQUID System

Liq. He Dewar

Bed





Visualization of current distribution

Prototype High-Tc SQUID System

16 channel

MSR

High-Tc SQUIDs

51 channel

Suzuki et al., *JJAP*. 43(1) p 117, 2004.

Suzuki et. al, Japanese Biomagnetism 2004

This work was supported by the Ministry of Economy, Trade and Industry and the New Energy and Industrial Technology Development Organization (NEDO)

HITACHI Inspire the Next

Example of commercially available or practical superconductive systems

- HTS filters
- HTS and LTS SQUID systems
- LTS SIS mixers (for ozone monitoring system, for radio observatory)

ISTEC

Ozone monitoring system installed in 4K refrigerator

http://edevice.fujitsu.com/fvd/eco/siso_100.html

ISTEC

Nobeyama radio observatory

SIS mixers inside

From NRO home page

http://www.nro.nao.ac.jp/~nro45mrt/pictures/photo/image6/img203_800.jpg

ISTEC

Example of commercially available or practical superconductive systems

- HTS filters
- HTS and LTS SQUID systems
- LTS SIS mixers (for ozone monitoring system, for radio observatory)
- LTS voltage standard systems

ISTEC

Voltage standard system

From HYPRES home page
http://www.hypres.com/

High-speed digital circuit development

Present status of high-speed digital technology

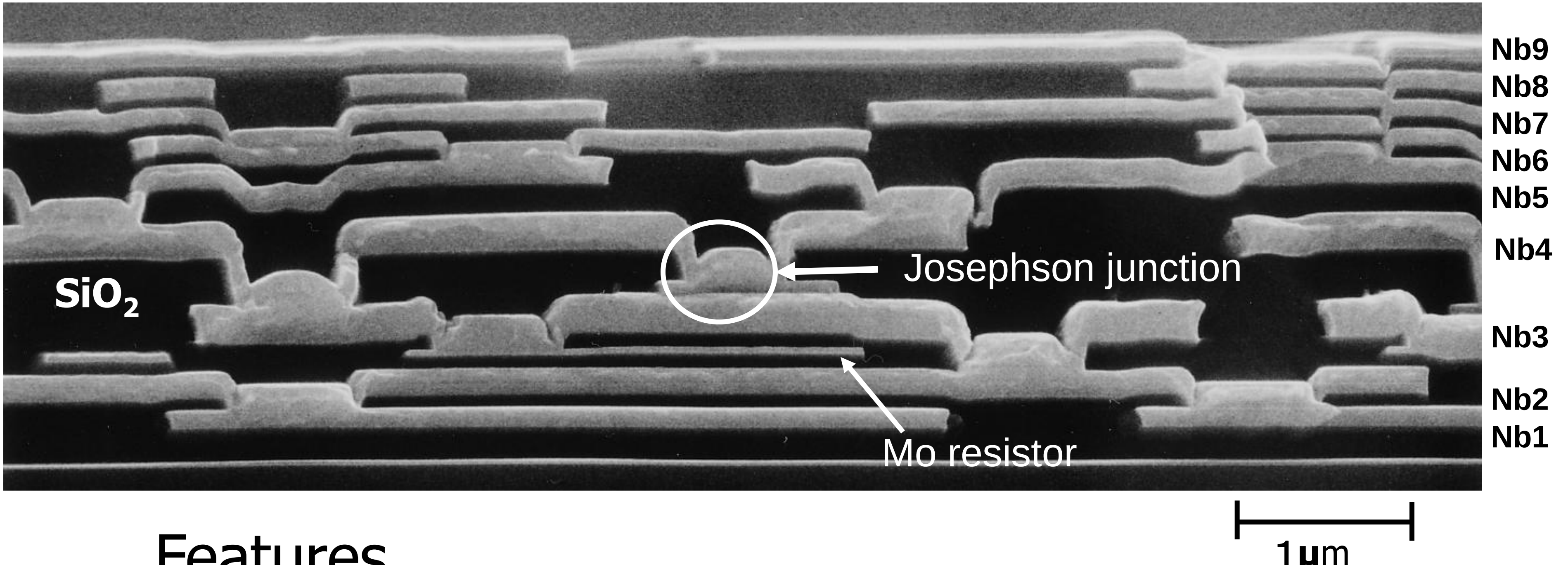
LTS circuits

- LSI design technology
  Semiconductor LSI designer can design SFQ LSIs.
- Fabrication Process technology
  One million JJ circuits are possible to make.
- High speed circuit operation
  20-50 GHz clock operation is feasible.

HTS circuits

- Fabrication Process technology
  100 JJ circuits are possible to make.
- Circuit operation
  A few tens JJ circuits are feasible to operate.

Niobium junction integration



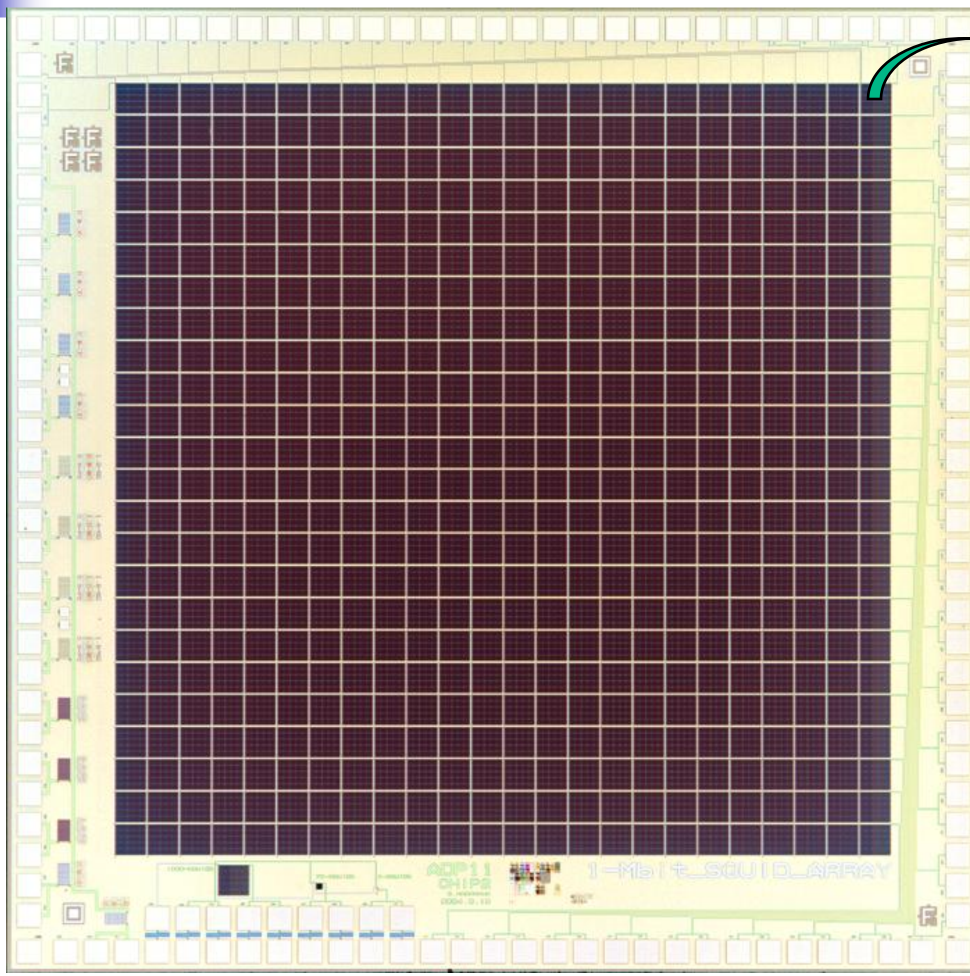
Features

- Planarized 9 Nb layers
- Nb/AlOx/Nb with critical current density of 10 kA/cm^2
- Minimum junction size : 1µm□

Ref: T.Satoh et al, Physica C (2006) P.445

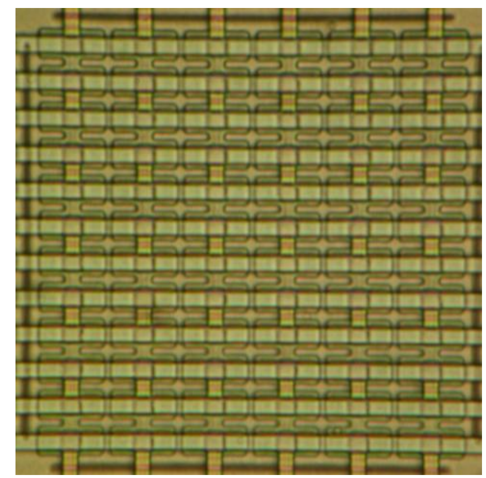
ISTEC

One million SQUID array for process check



Chip size: 8mm × 8mm

Magnified view of 1/25 of one unit cell of the left-hand side picture



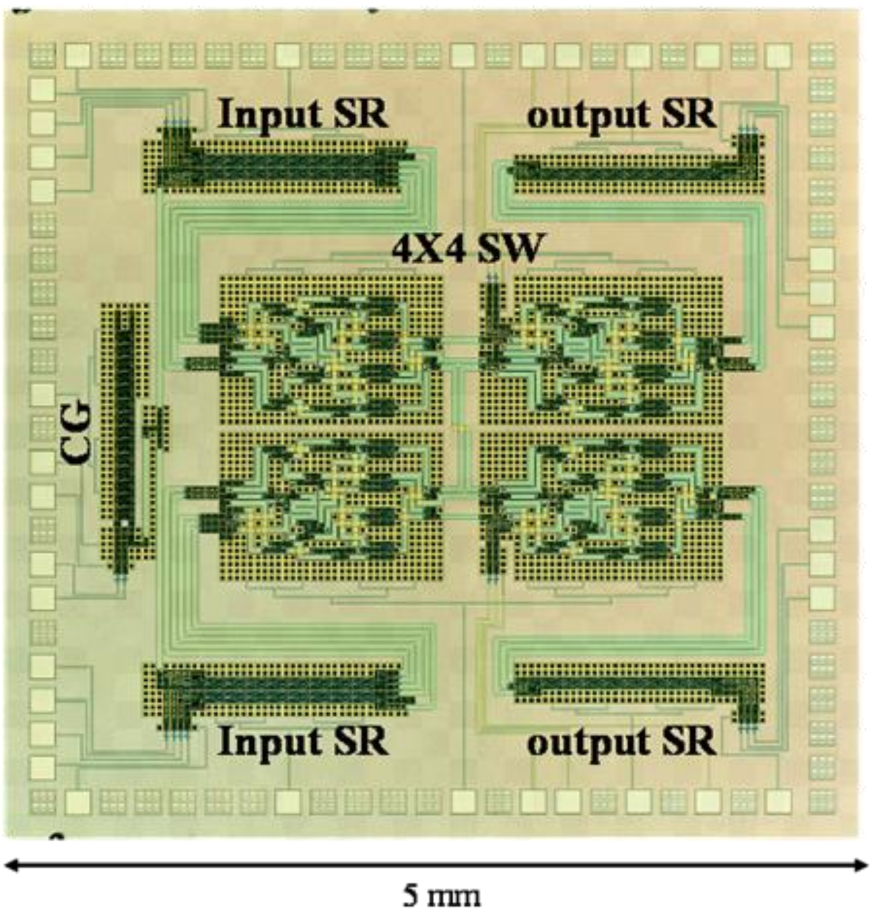
72 SQUID array

Left-hand side chip includes 72 x 25 x 24 x 24= 1,036,800 SQUIDs

Ref: M.Hidaka et al, Supercon. Sci. Tech. (2006) P.S138

ISTEC

LTS 4×4 SFQ switch



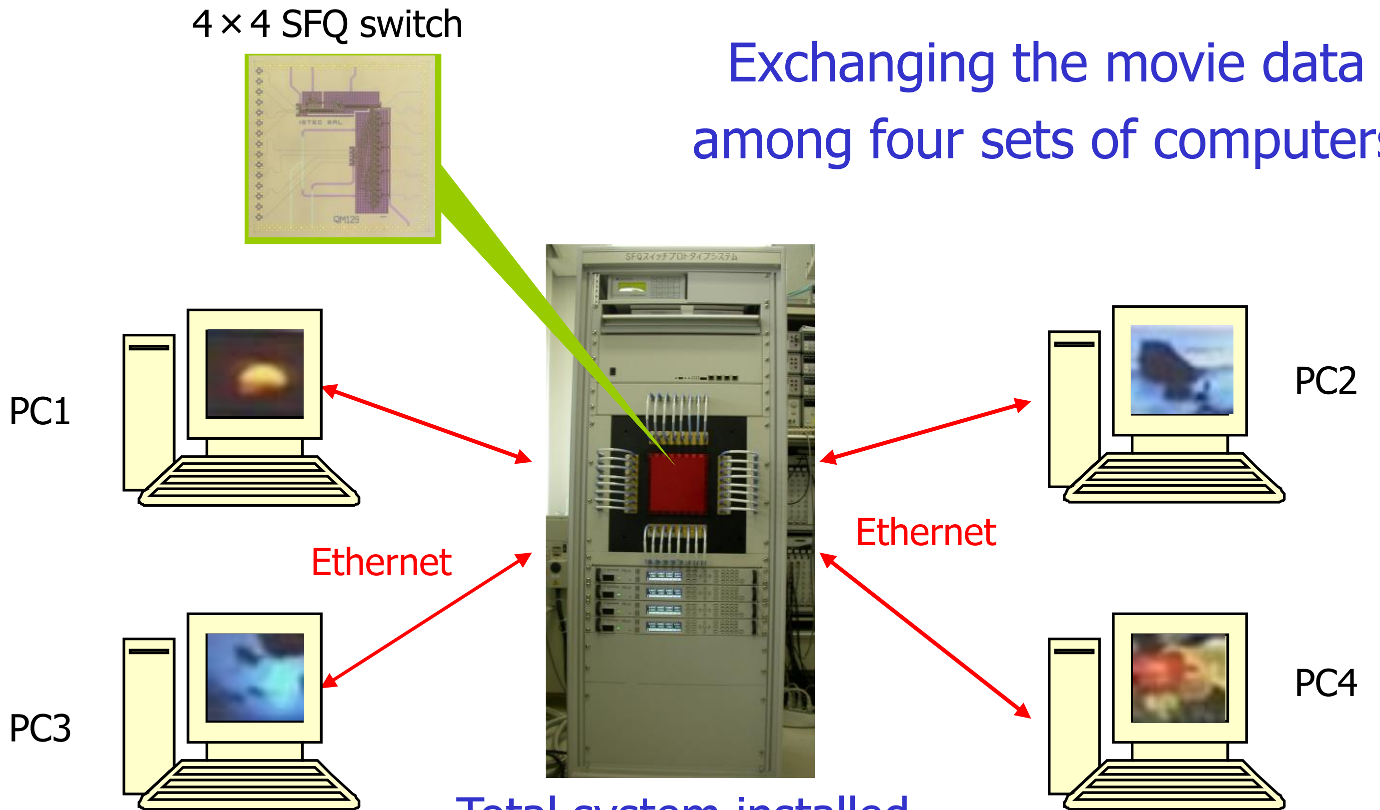
Number of JJ: 2812 JJ
（4×4 switch part: 1478 JJ）
Maximum clock frequency: 45 GHz

Ref: S.Yorozu et al, HPSR 2004

ISTEC

Superconductive LAN system with SFQ switch

Exchanging the movie data
among four sets of computers

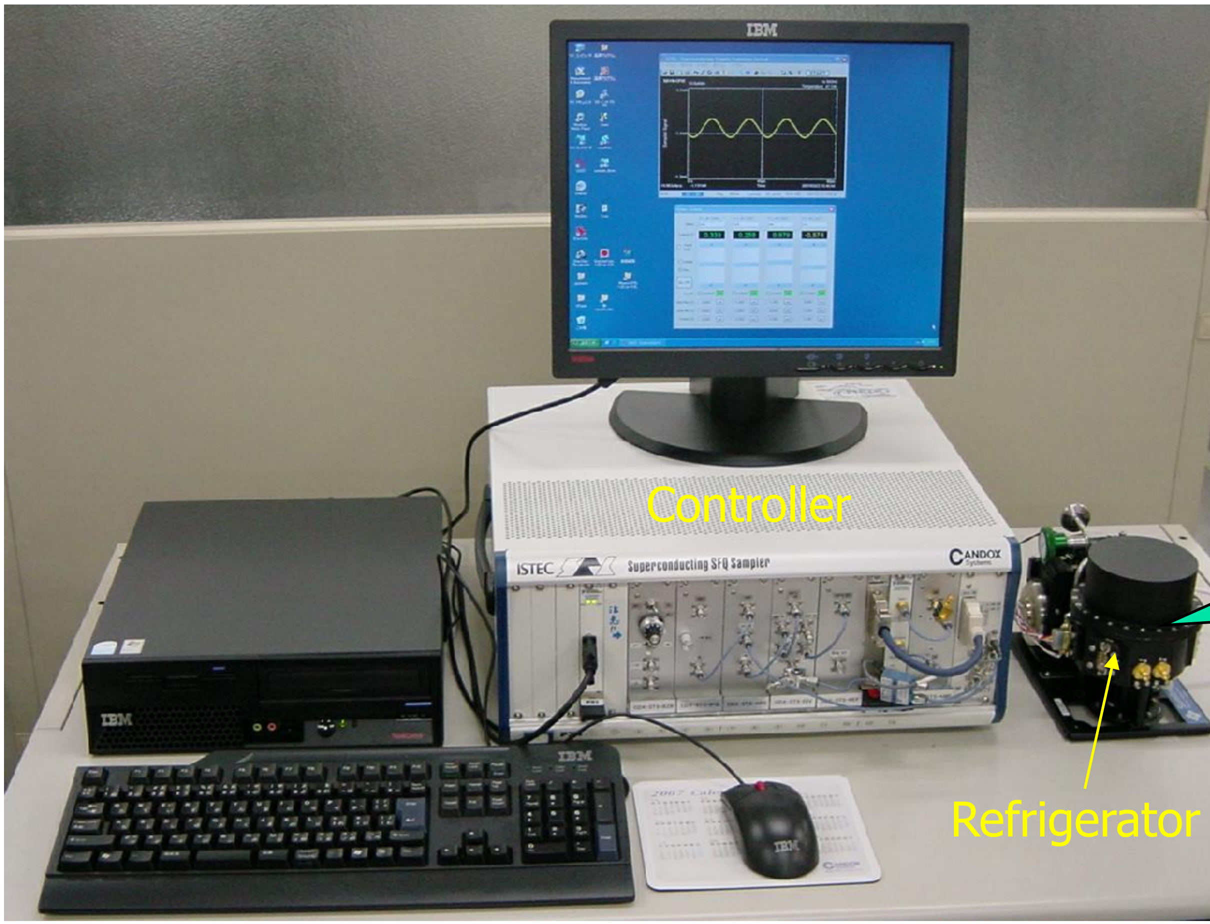


Total system installed
in a refrigerator

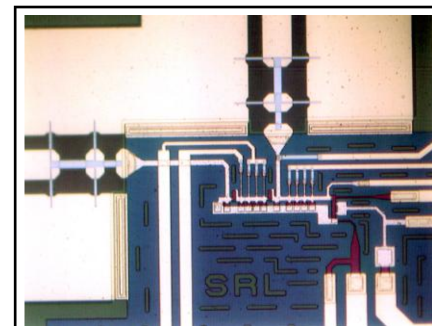
Ref: Y.Kameda et al, ISEC2007

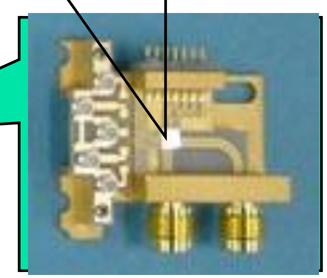
ISTEC

HTS sampler system



HTS sampler chip
(2.5 mm□)





High frequency
module (24.7 g)

Ref: H.Suzuki et al, ISEC2007

ISTEC

Contents

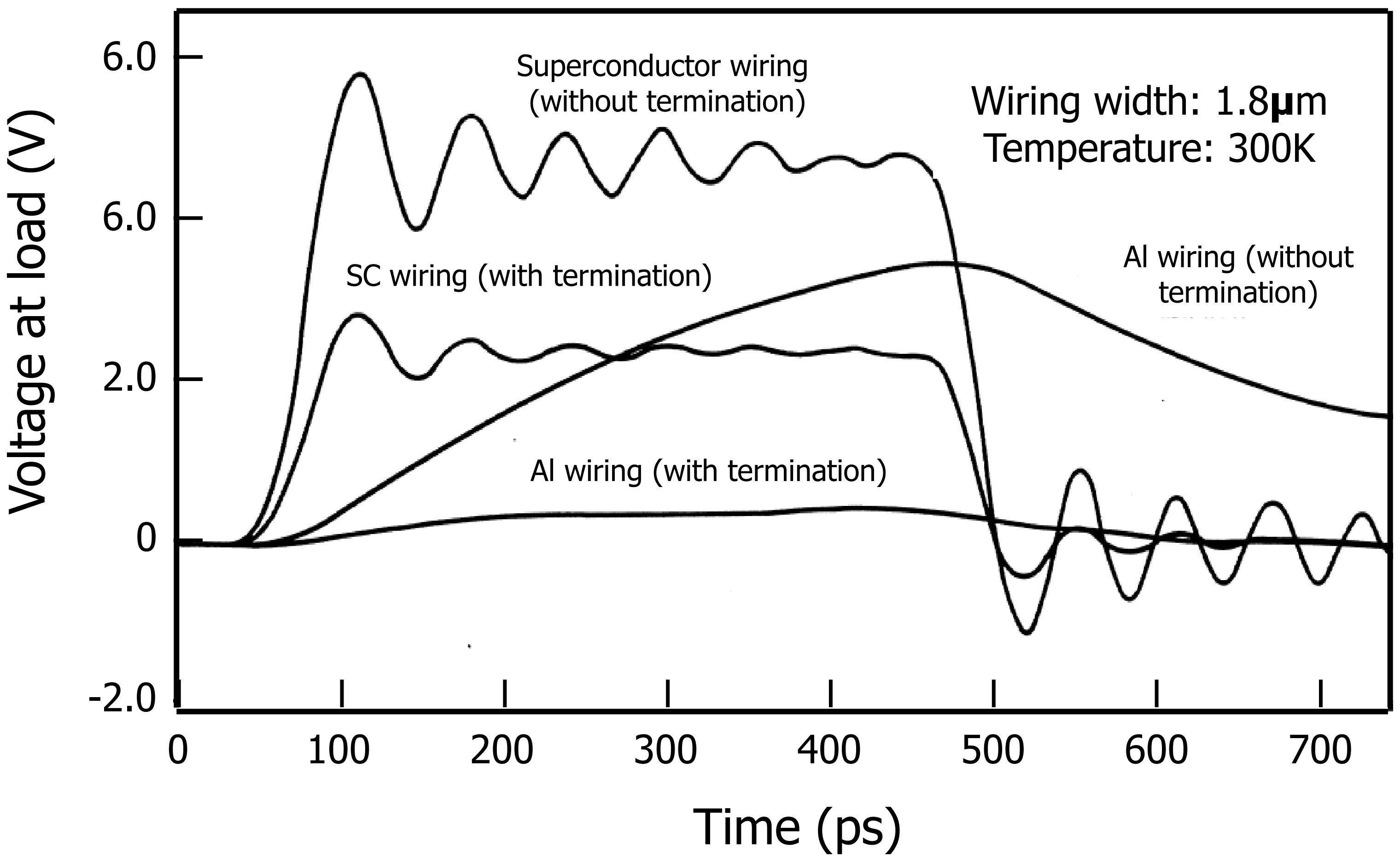
- Classification of superconductive electronic devices
- Examples of LTS and HTS devices
- RTS material application to passive devices
- RTS material application to active devices
- Expectation for RTS materials for electronic applications
- Request for RTS materials from the viewpoint of an electronic device researcher

ISTEC

RTS material application to passive devices

- Wirings (LSI wirings, printed circuit board, co-axial cables, and all other cables)

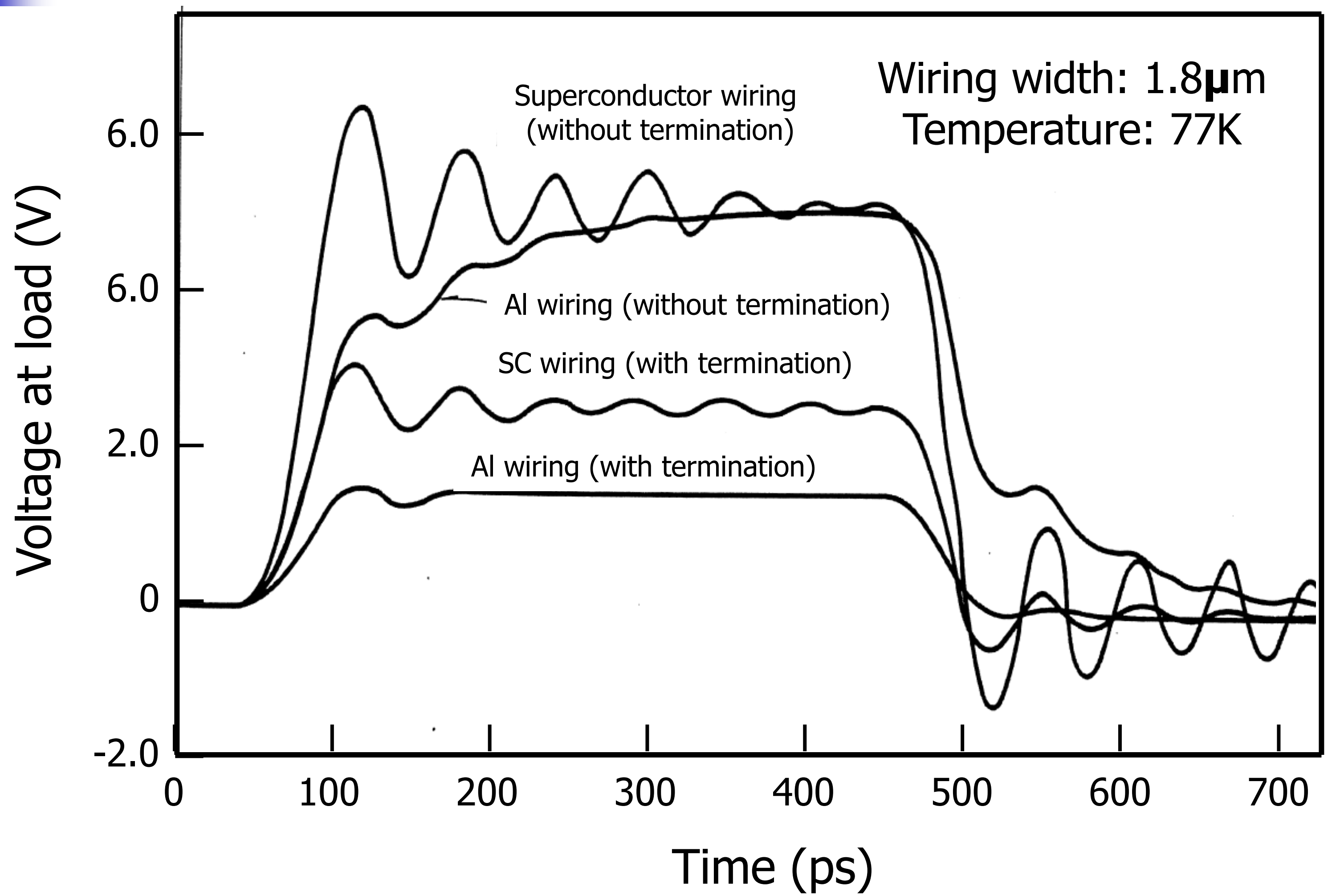
LSI operation at 300K with 1.8μm width wiring



M.Taguchi, Nikkei Electronics, 1987, Nov.30 issue, p.153

ISTEC

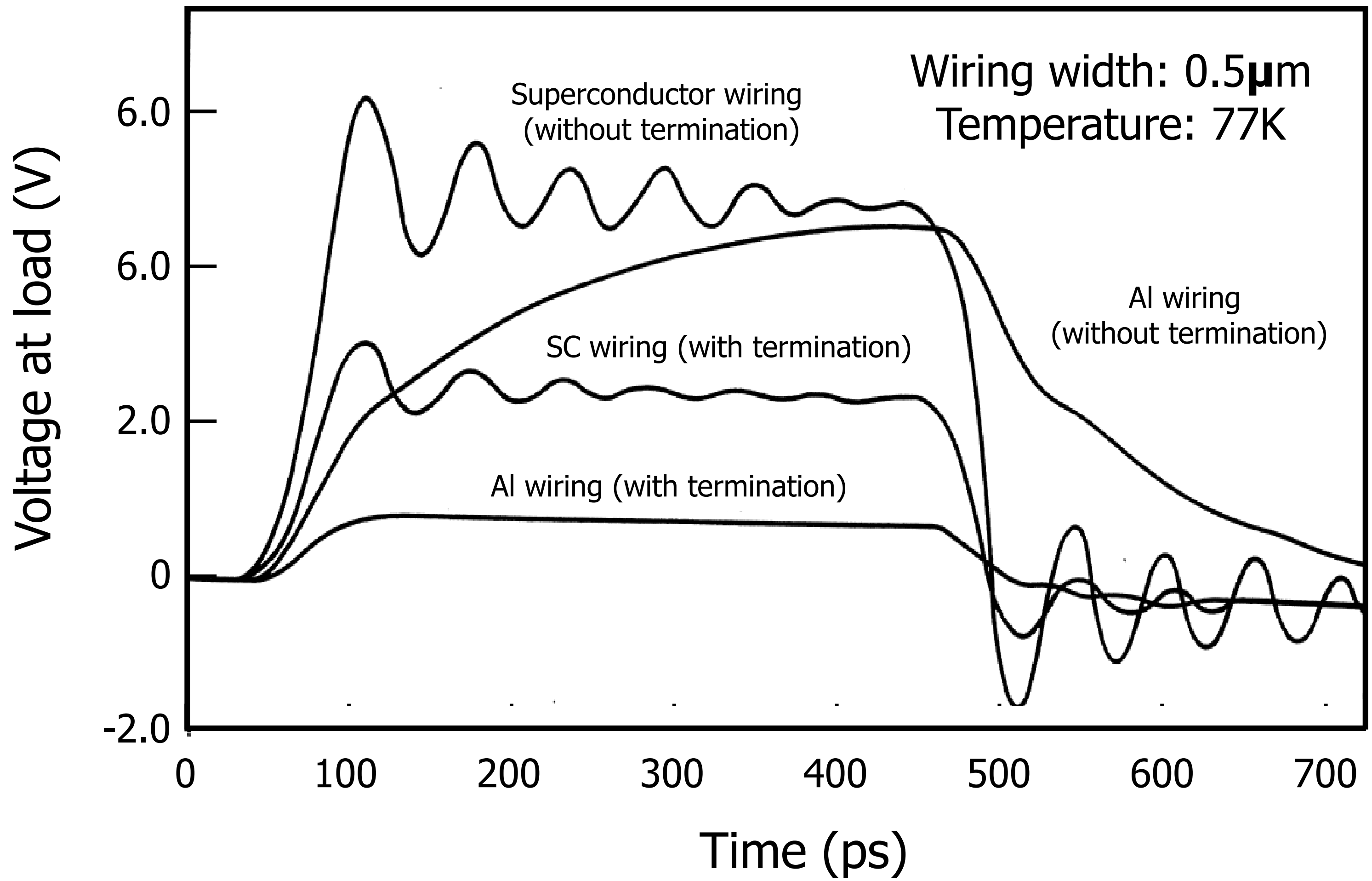
LSI operation at 77K with 1.8μm width wiring



M.Taguchi, Nikkei Electronics, 1987, Nov.30 issue, p.153

ISTEC

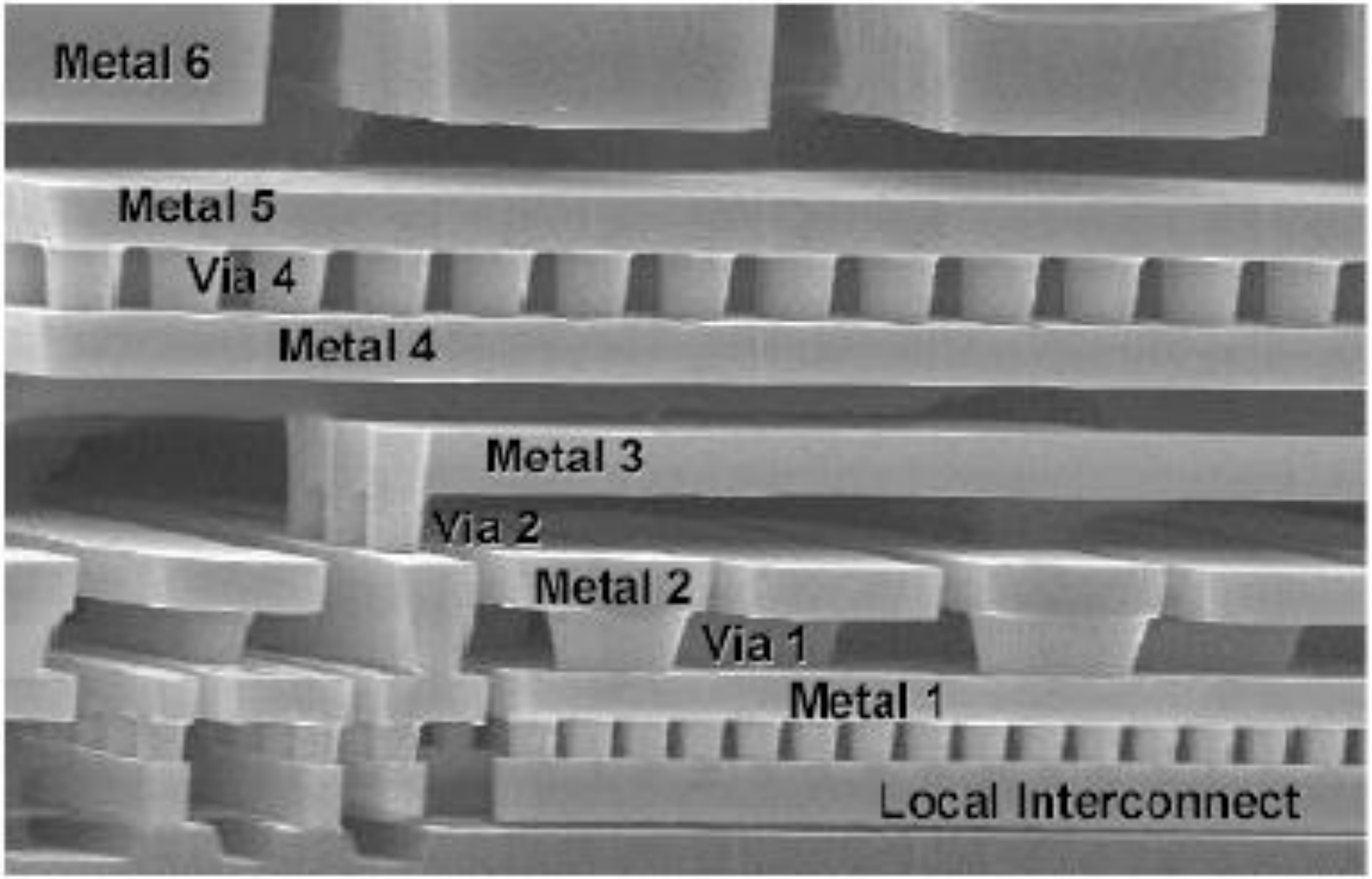
LSI operation at 77K with 0.5μm width wiring



M.Taguchi, Nikkei Electronics, 1987, Nov.30 issue, p.153

ISTEC

LSI cross section



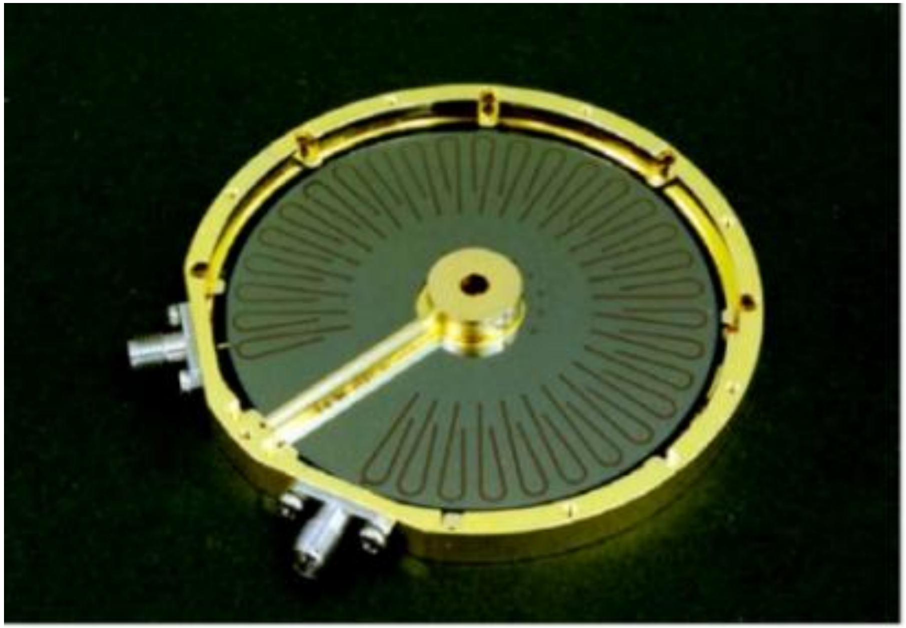
http://home.hiroshima-u.ac.jp/nanostr/sonota.pdf

ISTEC

RTS material application to passive devices

- Wirings (LSI wirings, printed circuit board, co-axial cables, and all other cables)
- Microwave components (filters, antennas, transmission lines and cavities)

Superconductive filters



HTS filter should be installed in a refrigerator.

↓

RTS filter can be used as it is.

Easy for installing in a base station

ISTEC

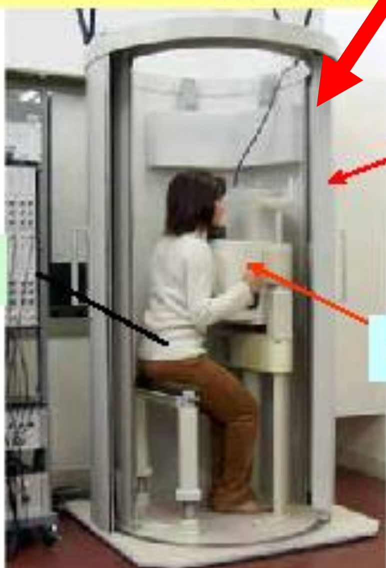
RTS material application to passive devices

- Wirings (LSI wirings, printed circuit board, co-axial cables, and all other cables)
- Microwave components (filters, antennas, transmission lines and cavities)
- Magnetic shielding

Low-Tc 64ch SQUID System

Superconductive magnetic shielding will be used with conventional high-μ shielding

Prototype High-Tc SQUID System



16 channel

MSR

High-Tc SQUIDs

51 channel

Suzuki et al., *JJAP*. 43(1) p 117, 2004.

Suzuki et. al, Japanese Biomagnetism 2004

This work was supported by the Ministry of Economy, Trade and Industry and the New Energy and Industrial Technology Development Organization (NEDO)

HITACHI Inspire the Next

RTS passive devices

- Basically we can apply RTS materials to any passive electronic components and systems.

- It is most important whether the RTS material can be processed to desired shape and it exhibits necessary performance.

- Present HTS materials have some restrictions such as substrate selection and high processing temperature.

Contents

- Classification of superconductive electronic devices
- Examples of LTS and HTS devices
- RTS material application to passive devices
- RTS material application to active devices
- Expectation for RTS materials for electronic applications
- Request for RTS materials from the viewpoint of an electronic device researcher

ISTEC

Effects of thermal noise

- Passive devices are not fatally affected by thermal noise.
- Performance of active devices are strongly affected by thermal noise.
- Thermal noise

V_n= SQRT(4k_BTRB)

i_n=SQRT(4k_BTB/R)

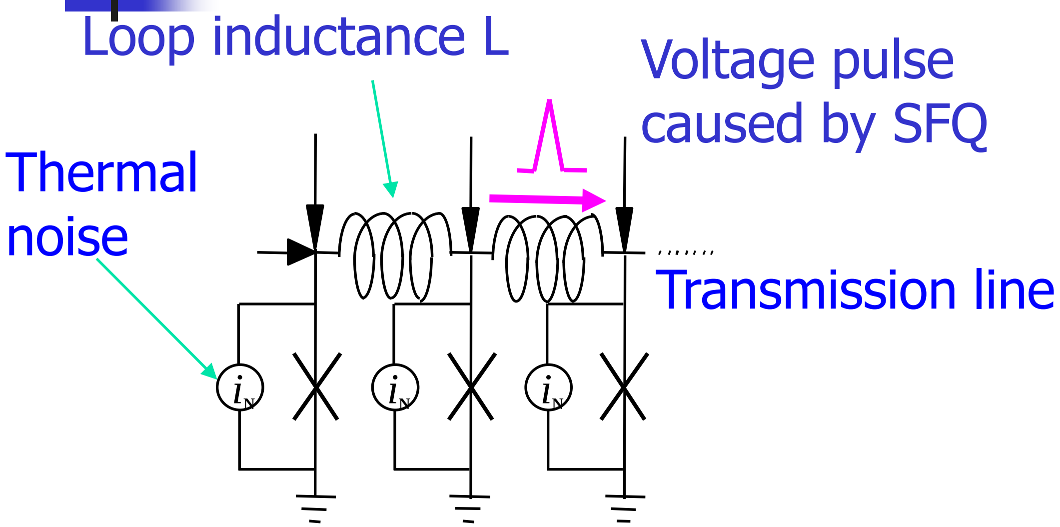
P_n=4k_BTB

P_n=16.56nW@300K, B=1THz

0.232nW@4.2K, B=1THz

ISTEC

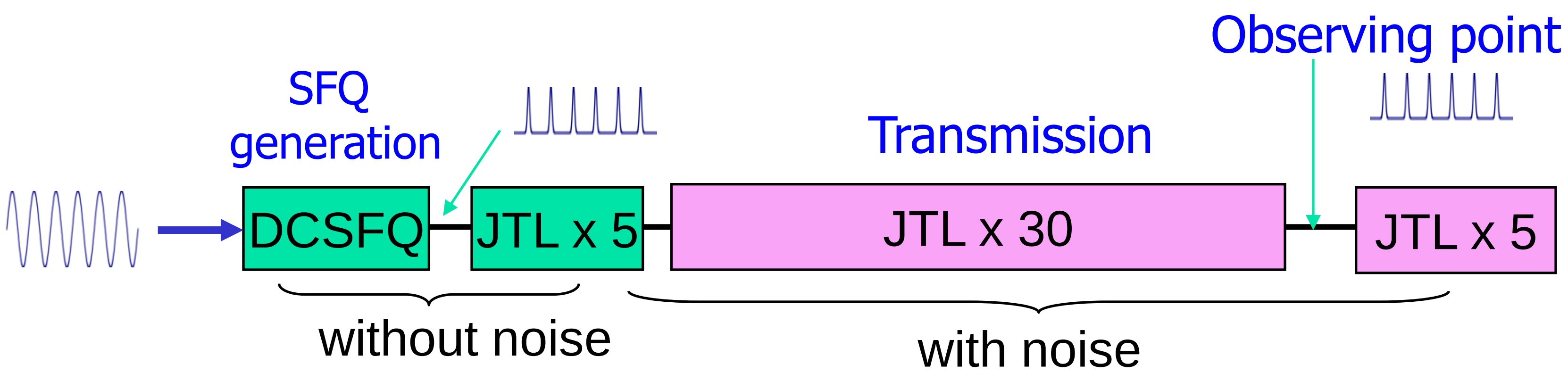
Josephson Transmission Line (JTL)



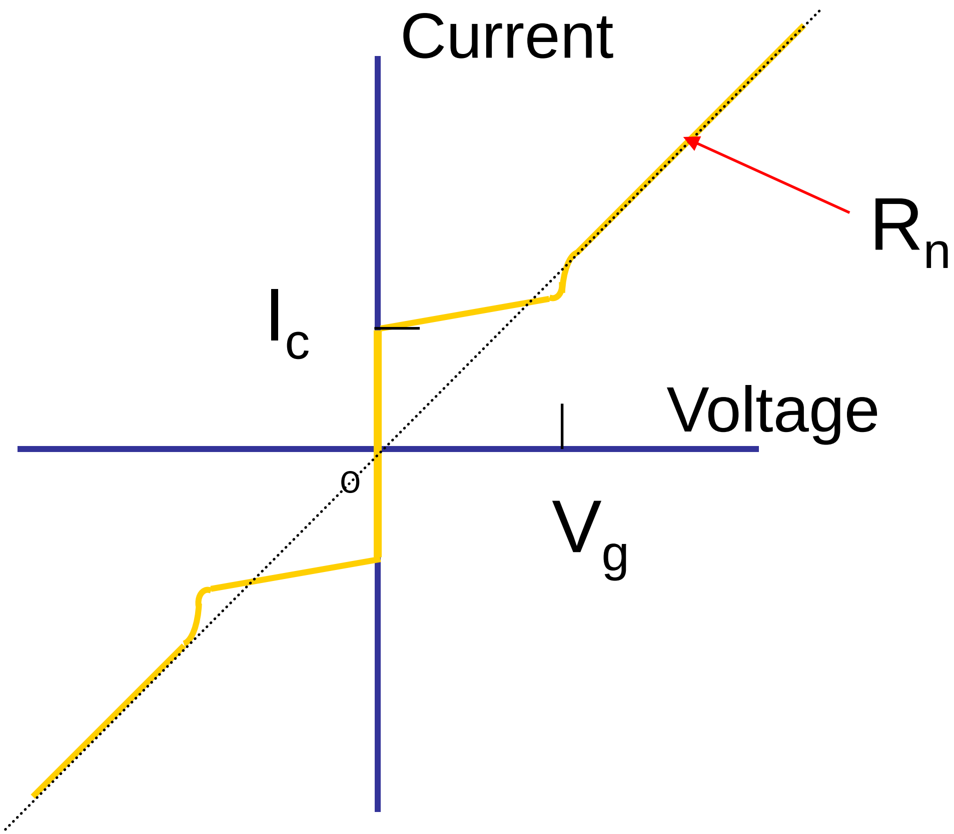
$$L\,I_c = 0.5\varphi_0$$

$$\beta = 1$$

$$i_N = \sqrt{\frac{4k_B TB}{R}}$$



I_cR_n product of Josephson junction



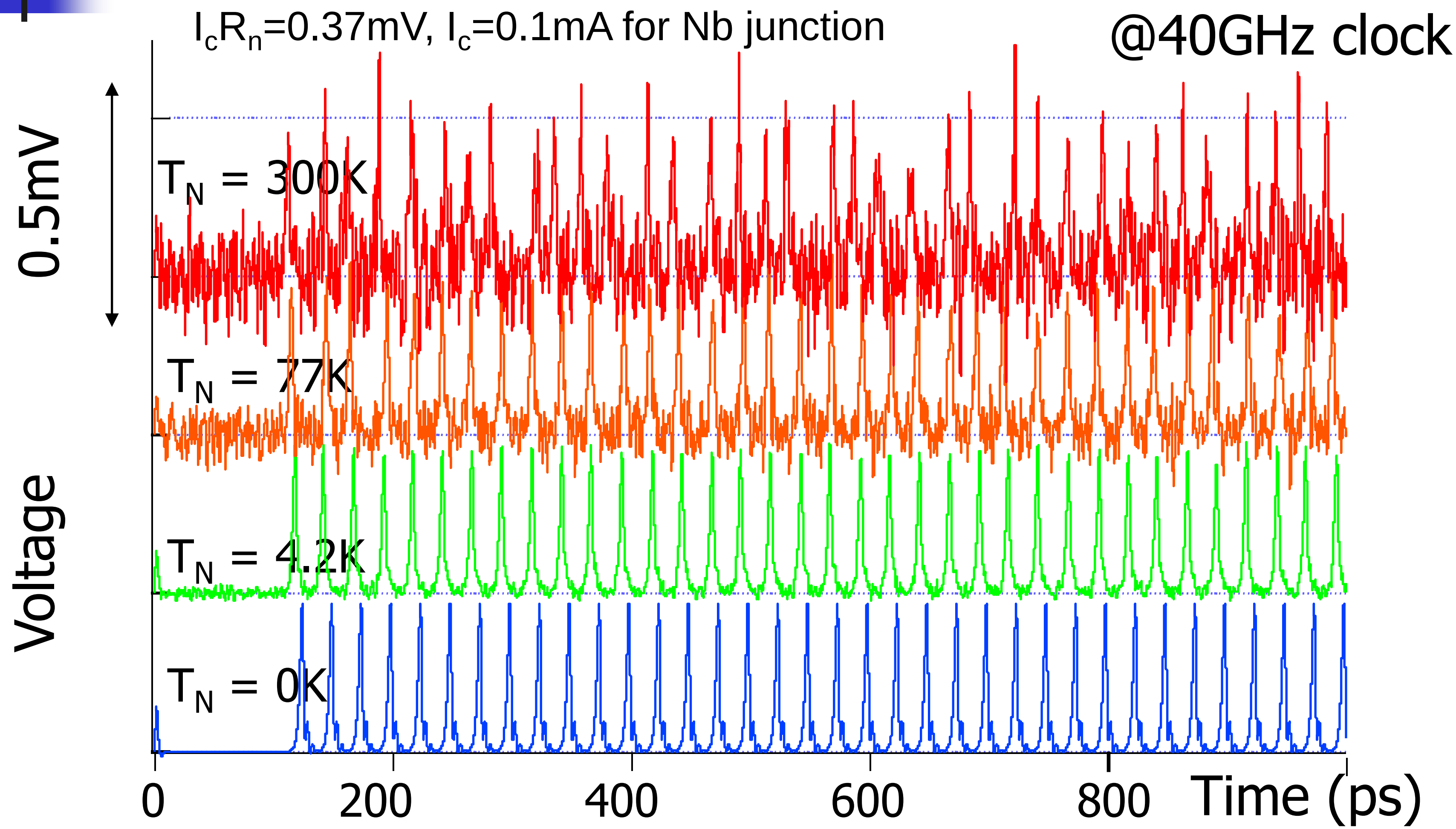
Current-Voltage characteristics of a Josephson junction

I_cR_n product is an important parameter for digital circuit.

$$T=\Phi_0/2\pi I_cR_n$$

ISTEC

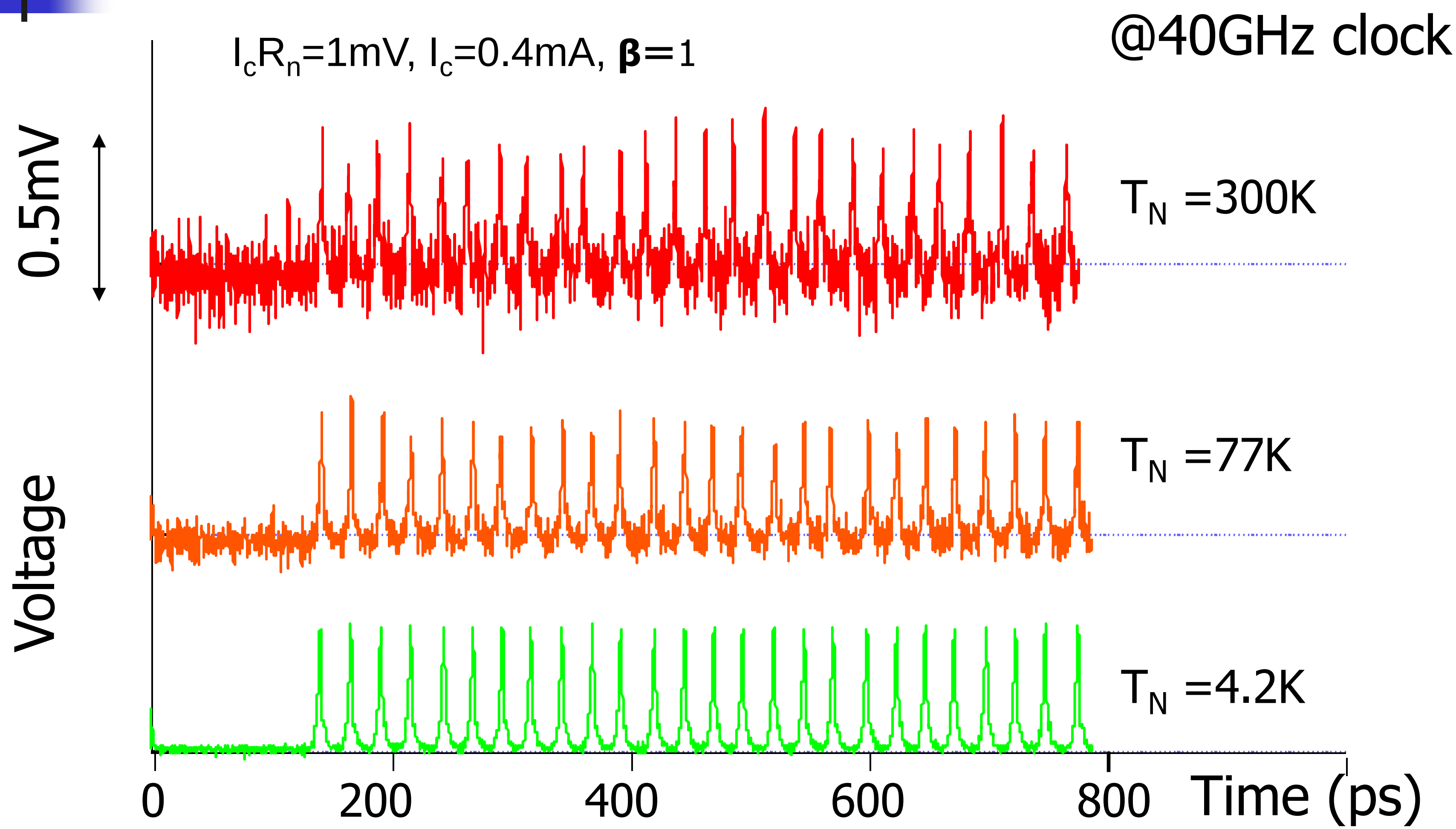
Temperature dependence of SFQ pulse waveform



Simulated by Akira Yoshida

ISTEC

Temperature dependence of SFQ pulse waveform for larger I_c and I_cR_n

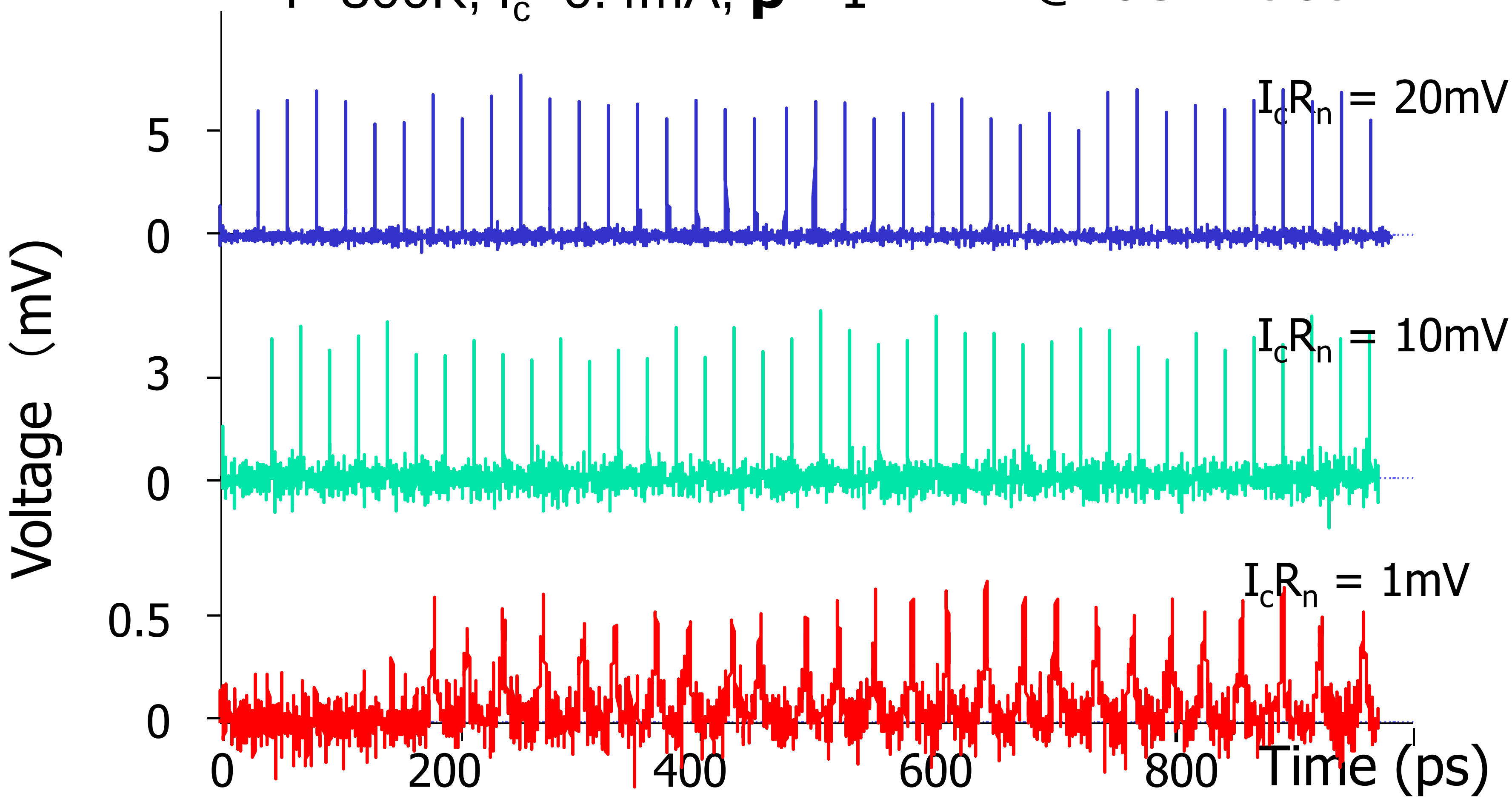


Simulated by Akira Yoshida

ISTEC

I_cR_n dependence of SFQ pulse waveform at room temperature

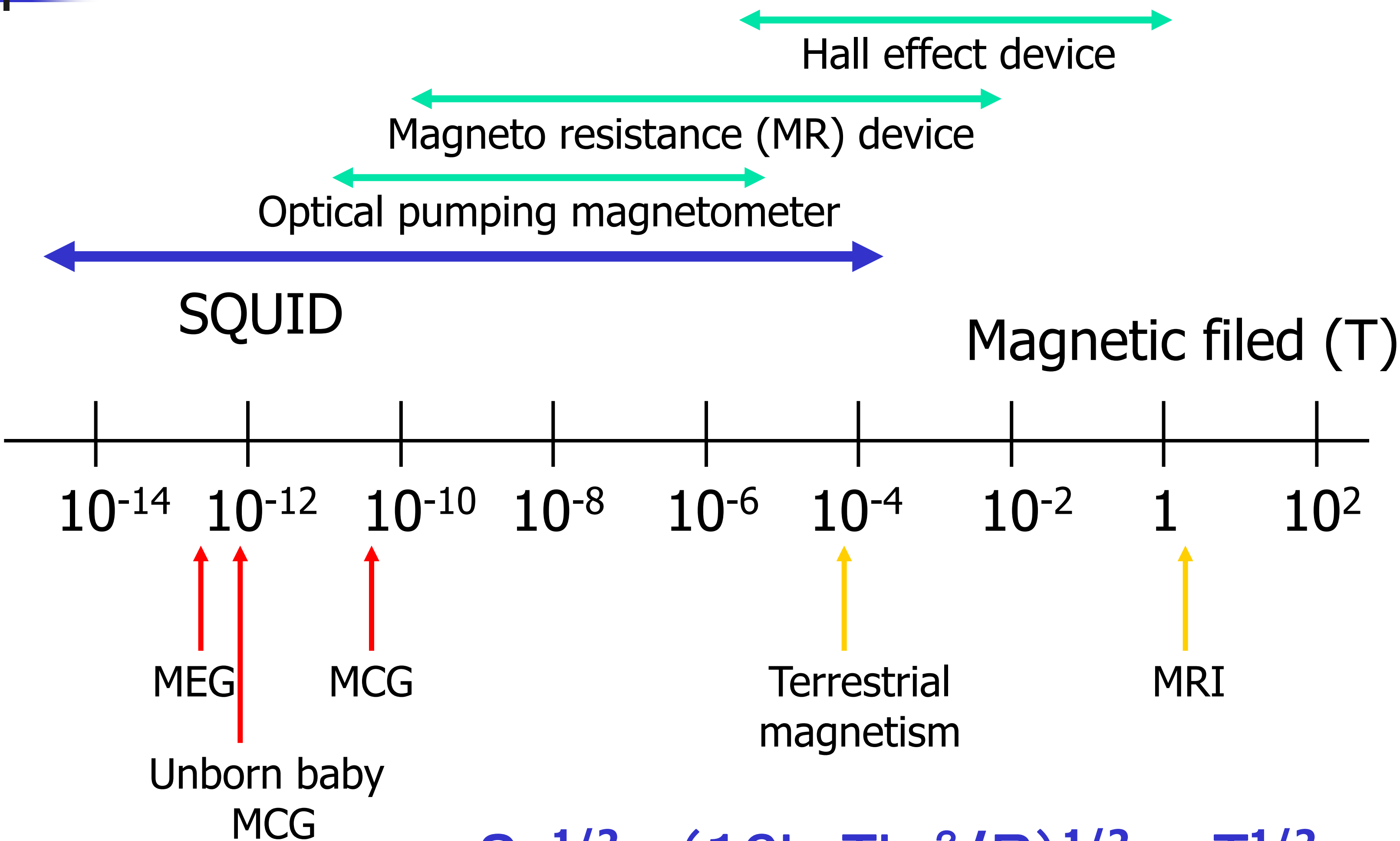
T=300K, I_c=0.4mA, β=1 @40GHz clock



Simulated by Akira Yoshida

ISTEC

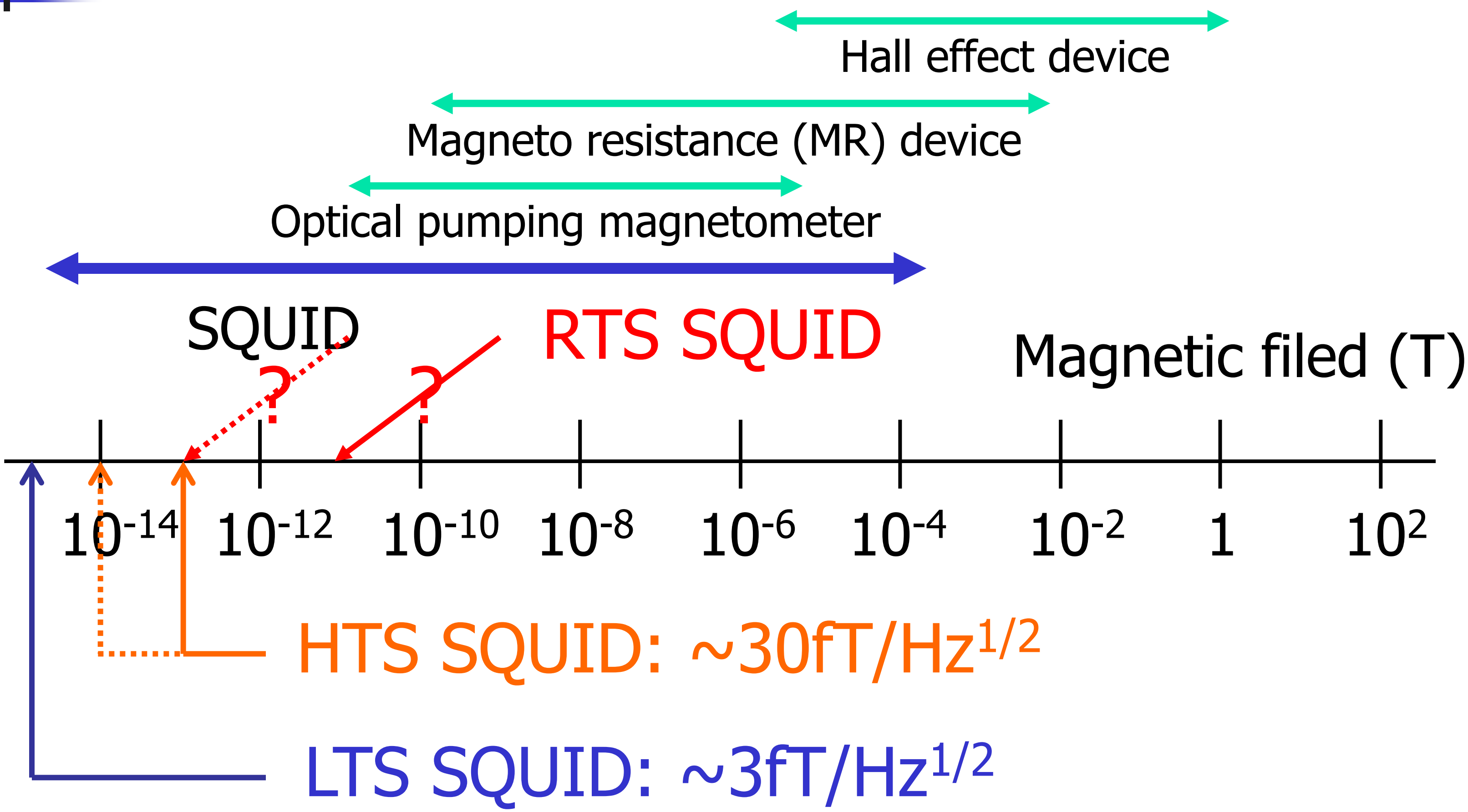
SQUID sensitivity



$$S_{\Phi}^{1/2} = (16 k_B T L_s^2 / R)^{1/2} \propto T^{1/2}$$

ISTEC

SQUID sensitivity



$$S_\Phi^{1/2} = (16 k_B T L_s^2 / R)^{1/2} \propto T^{1/2}$$

ISTEC

SIS mixer (EM detector)

Noise temperature (Sensitivity limit)

$T_N = \sim h\nu / k_B$

$= 48K@1THz$

$= 4.8K@100GHz$

Experimental result (Example)

$T_N = \sim 60K@430GHz$

$= \sim 3h\nu / k_B$

Ambient temperature: 300K

ISTEC

RTS material application to active devices

- Handy SQUID system may be useful for a convenient MCG or other applications.
- SFQ digital circuits are not hopeful because of crucial thermal noise.
- SIS mixers has also problem of thermal noise.
- Voltage standards may be possible if we can make uniform Josephson junction array.

High-quality Josephson junction is a key for active device applications of RTS.

ISTEC

Contents

- Classification of superconductive electronic devices
- Examples nt status of LTS and HTS devices
- RTS material application to passive devices
- RTS material application to active devices
- Expectation for RTS materials for electronic applications
- Request for RTS materials from the viewpoint of an electronic device researcher

ISTEC

Role of LTS, HTS and RTS devices

LTS (T=4.2K)	HTS (T=77K)	RTS (T=300K)
Key feature: High-speed, high-sensitivity and extremely low-noise	Key feature: Compact system, high-speed, and high-sensitivity	Key feature: Refrigerator free and improvement of metal conductivity
▪High-speed digital circuit for computers and routers ▪High-sensitive SQUID ▪SIS mixers	▪Digital receiver system for telecommunication ▪Compact SQUID ▪Measurement systems such as a sampling oscilloscope	▪Microwave components ▪Wirings ▪Magnetic shielding ▪Handheld SQUID (?) ▪Voltage standards (?)

Lower temperature operation, such as 4.2K operation of HTS devices and 77K operation of RTS active devices, may be possible to improve their performance.

ISTEC

RTS world

★ : RTS electronic device

Ubiquitous Superconductive Electronics !!!

ISTEC

Contents

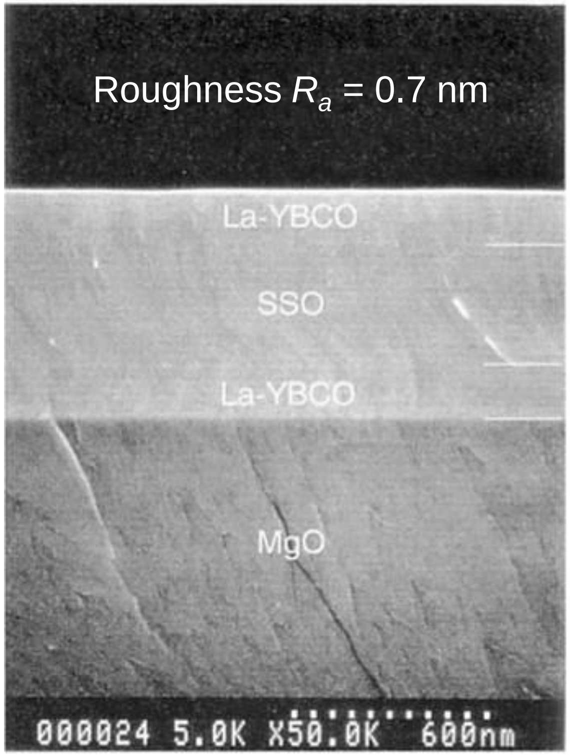
- Classification of superconductive electronic devices
- Examples of LTS and HTS devices
- RTS material application to passive devices
- RTS material application to active devices
- Expectation for RTS materials for electronic applications
- Request for RTS materials from the viewpoint of an electronic device researcher

ISTEC

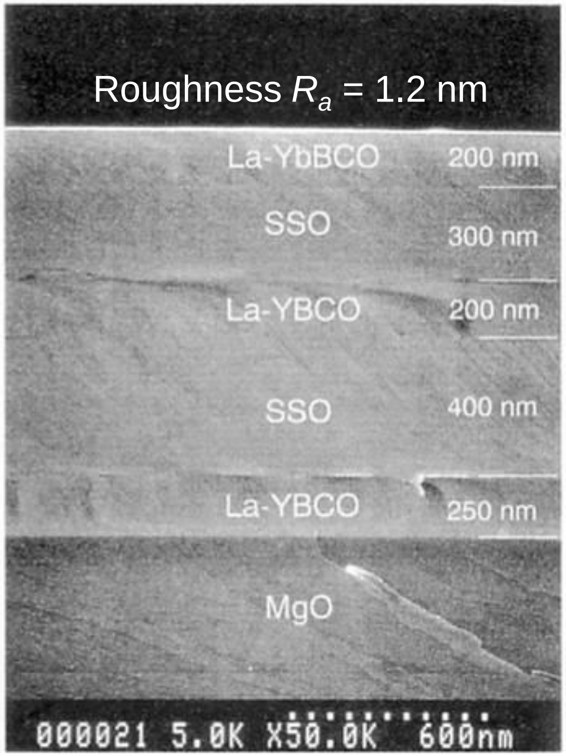
RTS material should be ･･･

- easy to process with physical and/or chemical treatment.
- deposited on any substrate at low temperature (<200℃).
- stable for long term preservation.
- uniform in nm-scale in the case of active device application.

3 HTS layer structure with smooth surface



2-layer structure



3-layer structure

- Optimization of deposition condition with $SrSnO_3$(SSO) insulation layer
- Reproducible deposition of smooth layer with surface roughness less than 2 nm

ISTEC

RTS material should be ···

- easy to process with physical and/or chemical treatment.
- deposited on any substrate at low temperature (<200℃).
- stable for long term preservation.
- uniform in nm-scale in the case of active device application.
- able to carry high current density as high as 10^7 A/cm^2 .

ISTEC

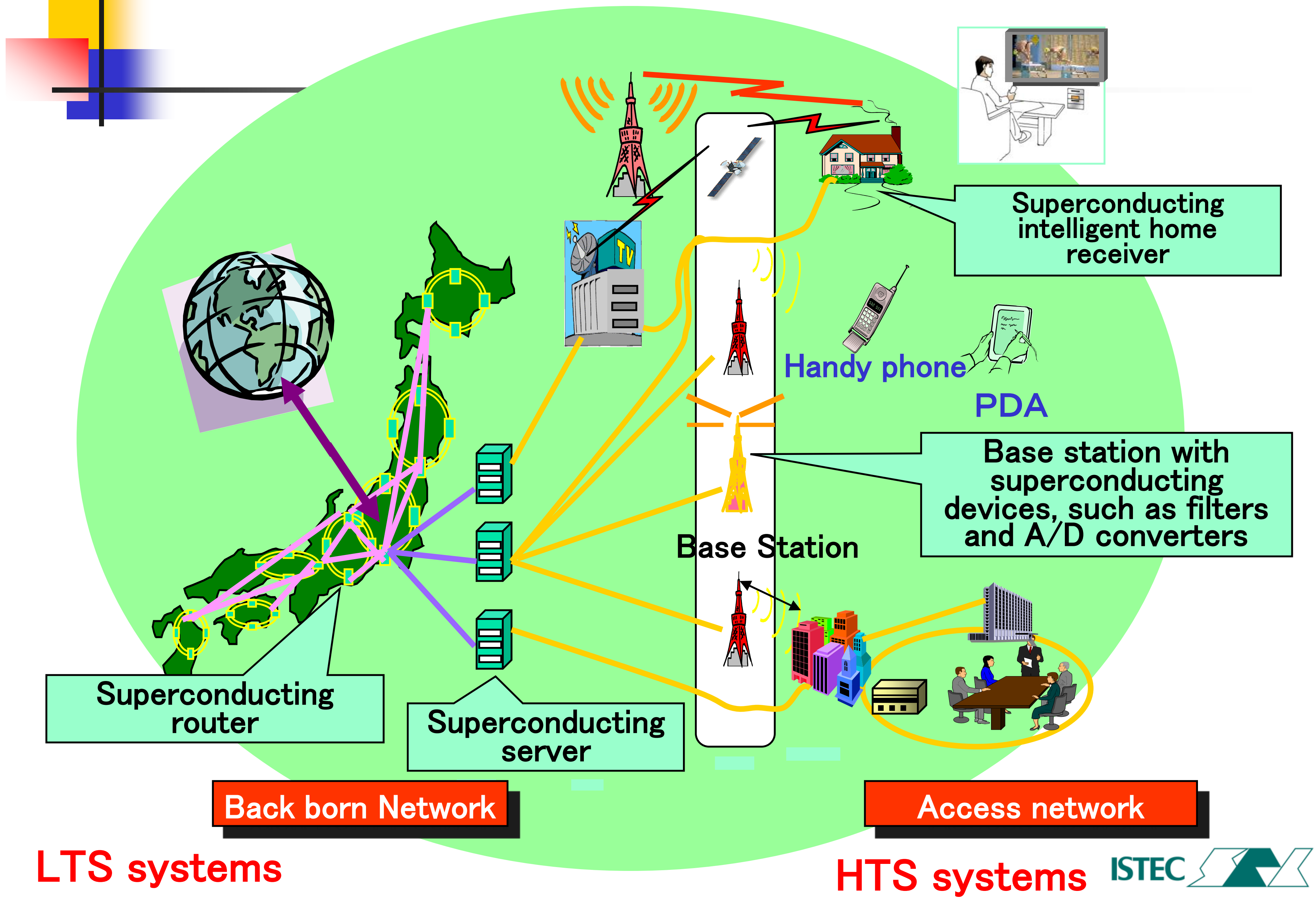
Conclusion

- Refrigeration free is the most important nature of RTS materials for electronic applications.
- Passive device applications are quite hopeful in various field of electronics, especially in consumer market.
- Active device applications are doubtful.   But, if RTS Josephson junction characteristics exhibit high-quality and uniformity, active devices may be practical.

ISTEC

Supplements

Image of HTS and LTS applications



Difference of HTS and LTS systems from the view point of users

Big difference is cooling scale !

- HTS systems
  - Operated in a small cooler (sometimes in a palm-top cooler)
  - Suitable for small scale system
  - Competitors are conventional low-end systems, such as high-speed measurement systems

- LTS systems
  - Suitable for large scale system
  - Competitors are conventional high-end systems
  - The larger the system becomes, such as supercomputers, the better the performance

ISTEC

Comparison of HTS and LTS applications referring semiconductors

Semiconductors

Si vs Compound semiconductors (GaAs, InP, GaN, InAs, InGaAs, etc)

Applications of Si

Supercomputer
High-speed processor
(Large scale systems)

Applications of Compound Semiconductors

・Optical communication system
・Satellite communication system
(Small scale high-speed systems)

Superconductors

Nb vs HTS (Y, Bi, Tl, Hg-systems, etc)

Applications of LTS

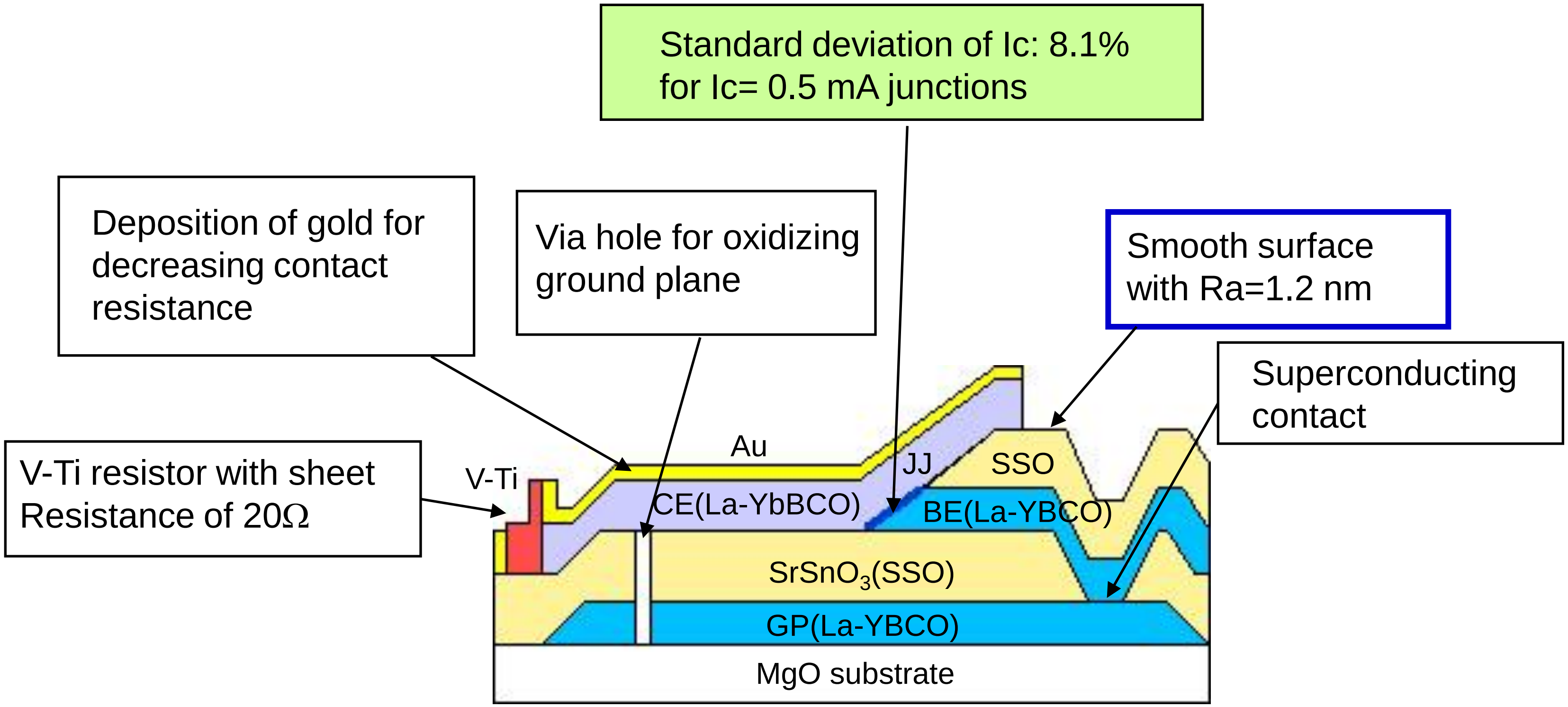
High-speed router
Large scale low power server
(Large scale systems)

Applications of HTS

・A/D converter system
・High-speed measurement system
(Small scale systems)

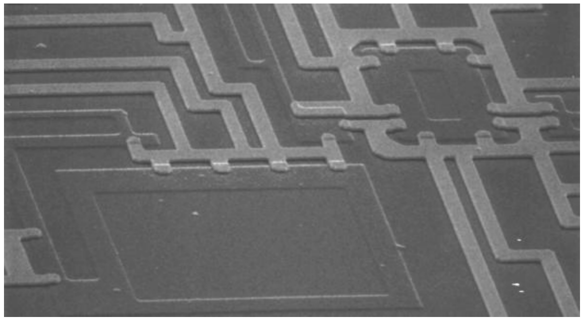
ISTEC

HTS device structure

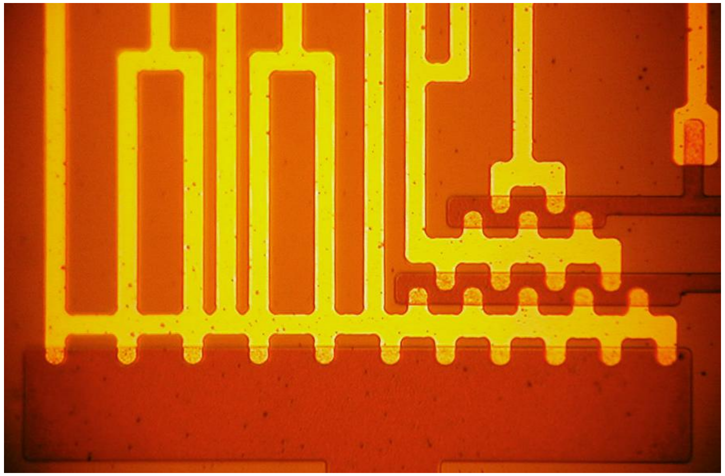


ISTEC

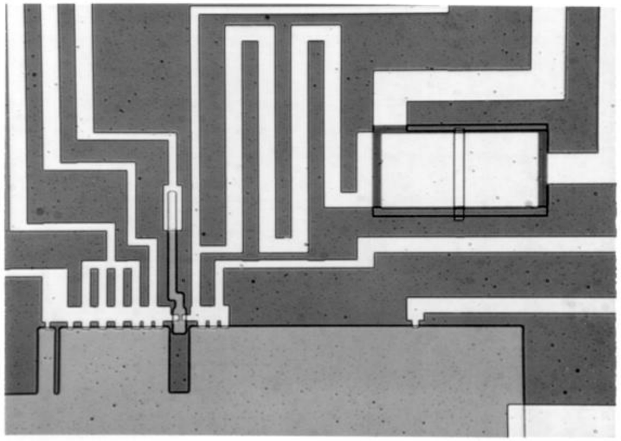
Demonstration of elementary SFQ circuits



Ring Oscillator (21 JJ, Toshiba) 57 GHz @20K



SQUID-array interface (25 JJ, SRL)

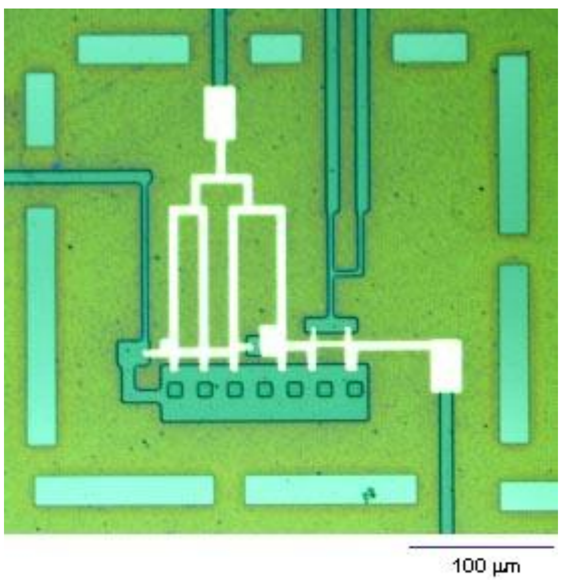


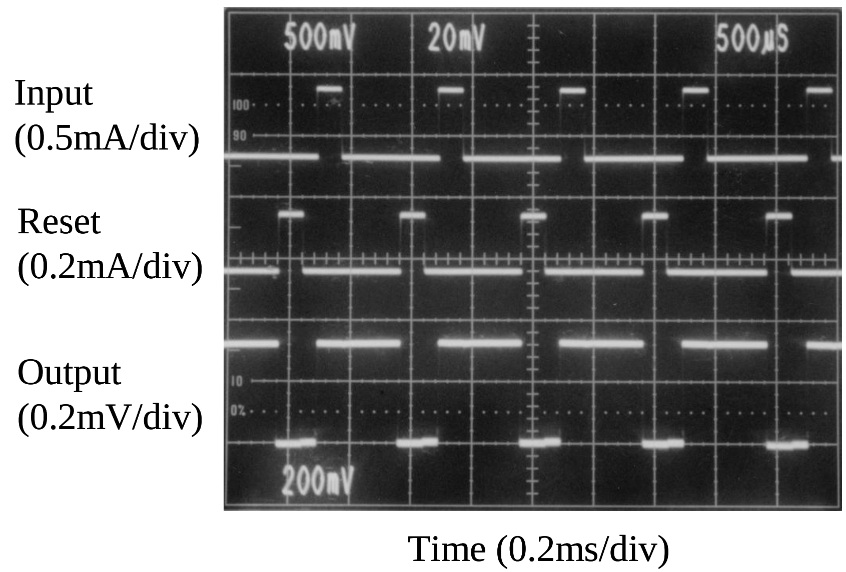
Σ-Δ AD modulator (13 JJ, Hitachi) 100 GHz @20K

- Latch-type interface (10 JJ, Fujitsu)
  >I mV output @30 K
- Sampler circuit with JTL buffer (25 JJ, NEC)
  20 GHz signal observation @35 K
- QOS comparator (10 JJ, SRL)
  82 GHz @40 K

ISTEC

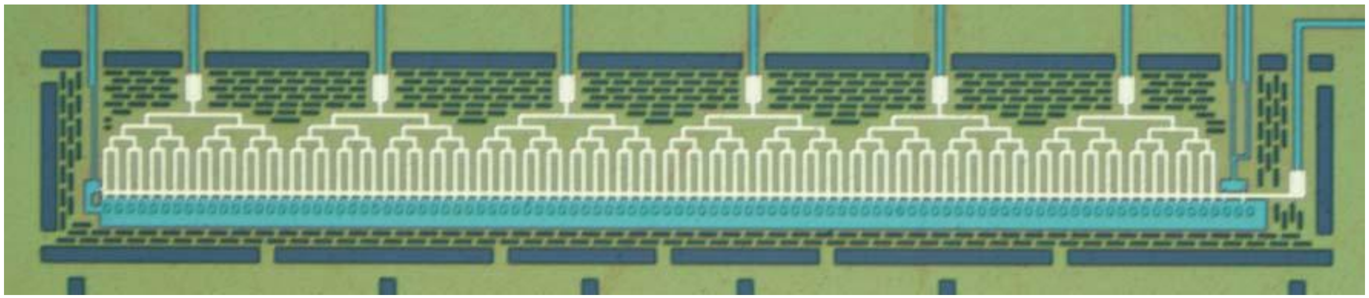
Design of HTS circuits



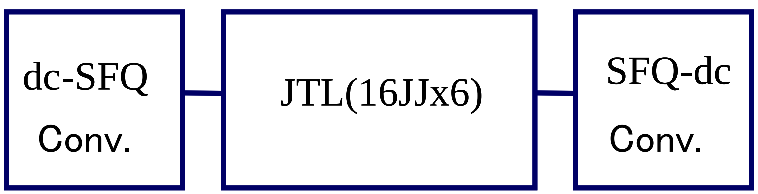


- SFQ-dc circuit suitable for HTS devices was designed.
- Operating margin was increased twice (±22%)@22K operation.
- Confluence buffer, splitter, and RS-flip flop circuits were also operated.

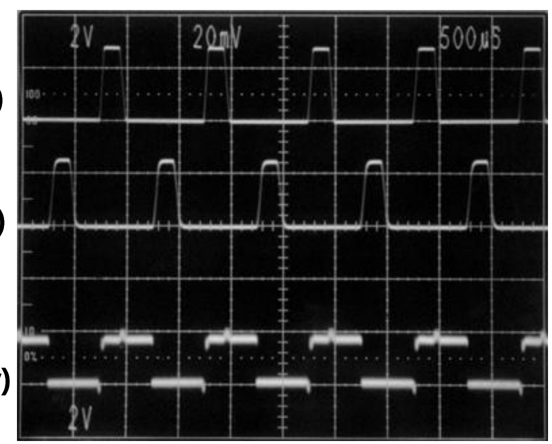
HTS 100 JJ circuit



Circuit including 101 JJs



Circuit



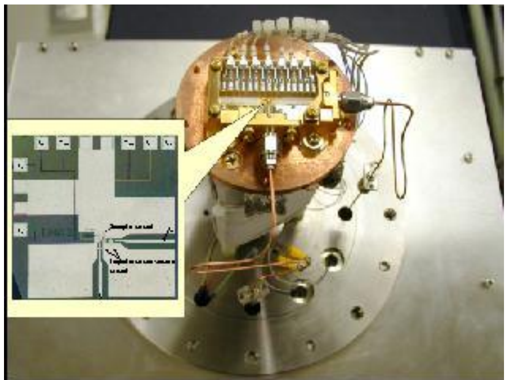
Ref: H.Wakana et al （ISTEC), ISS2004

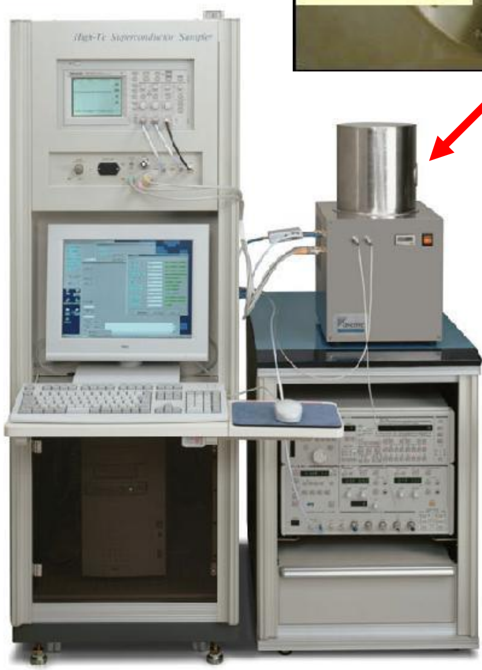
Operation at 29 K

ISTEC

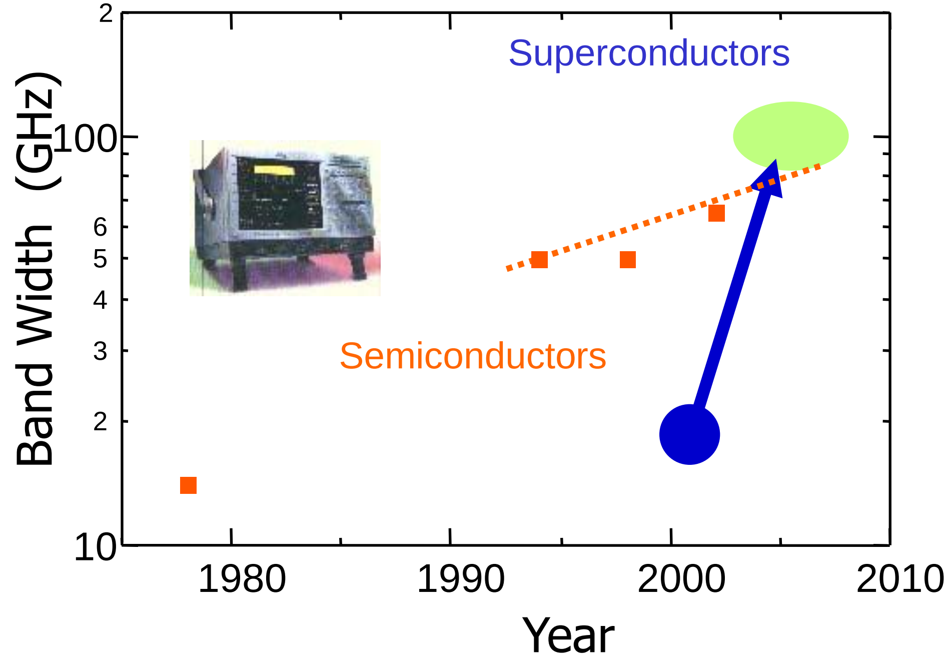
Superconducting sampling oscilloscope

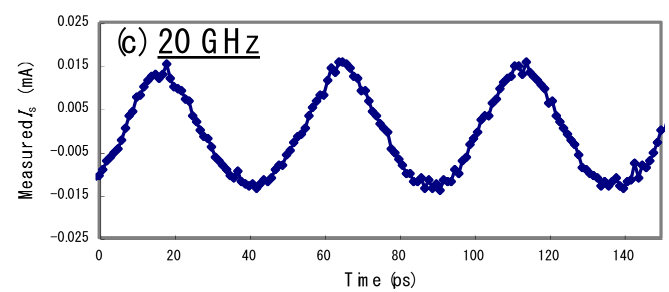
Sampling Oscilloscope Prototype





Chip and Package





Waveform of 20GHz

Ref: M.Hidaka (NEC) et al., ASC2000

ISTEC

Research items for low temperature packaging

- Signal conversion from semiconductor to SFQ
- Multi-chip module (MCM)
- Signal conversion from SFQ to semiconductor
- Low temperature cooling
- Latency between low temperature and room temperature

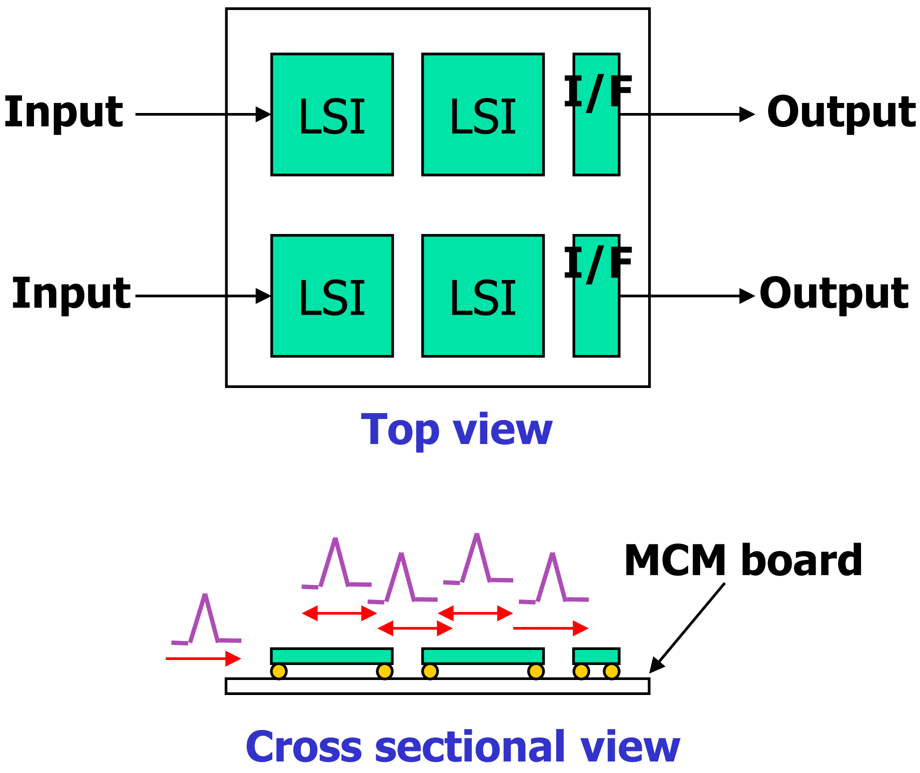
ISTEC

Superconducting MCM

Multi Chip Module

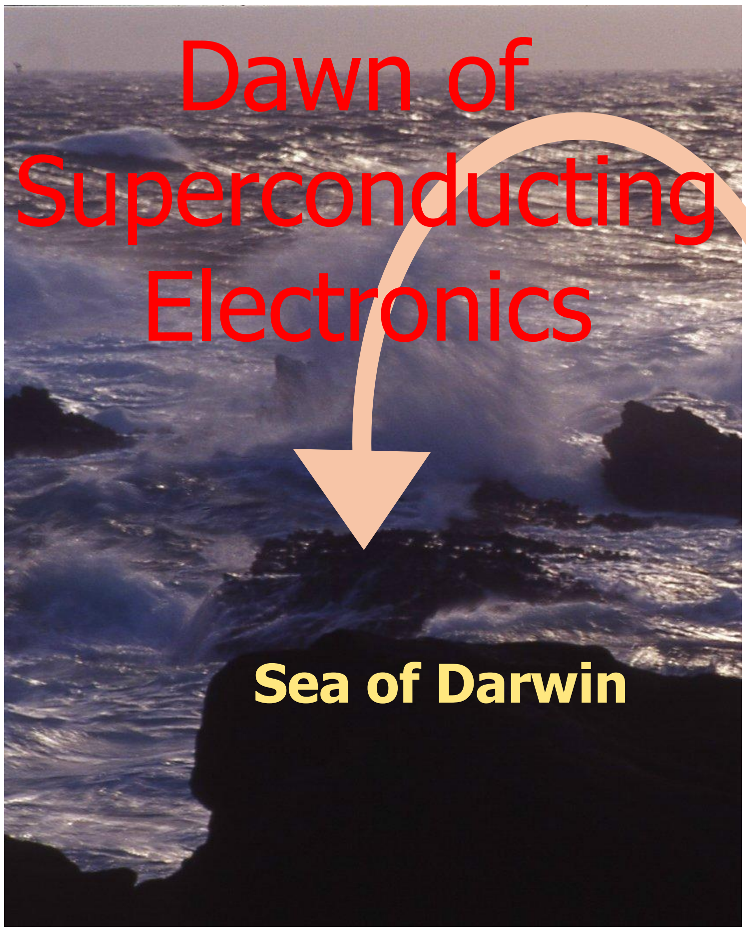
SFQ signal can propagate

in between LSIs.



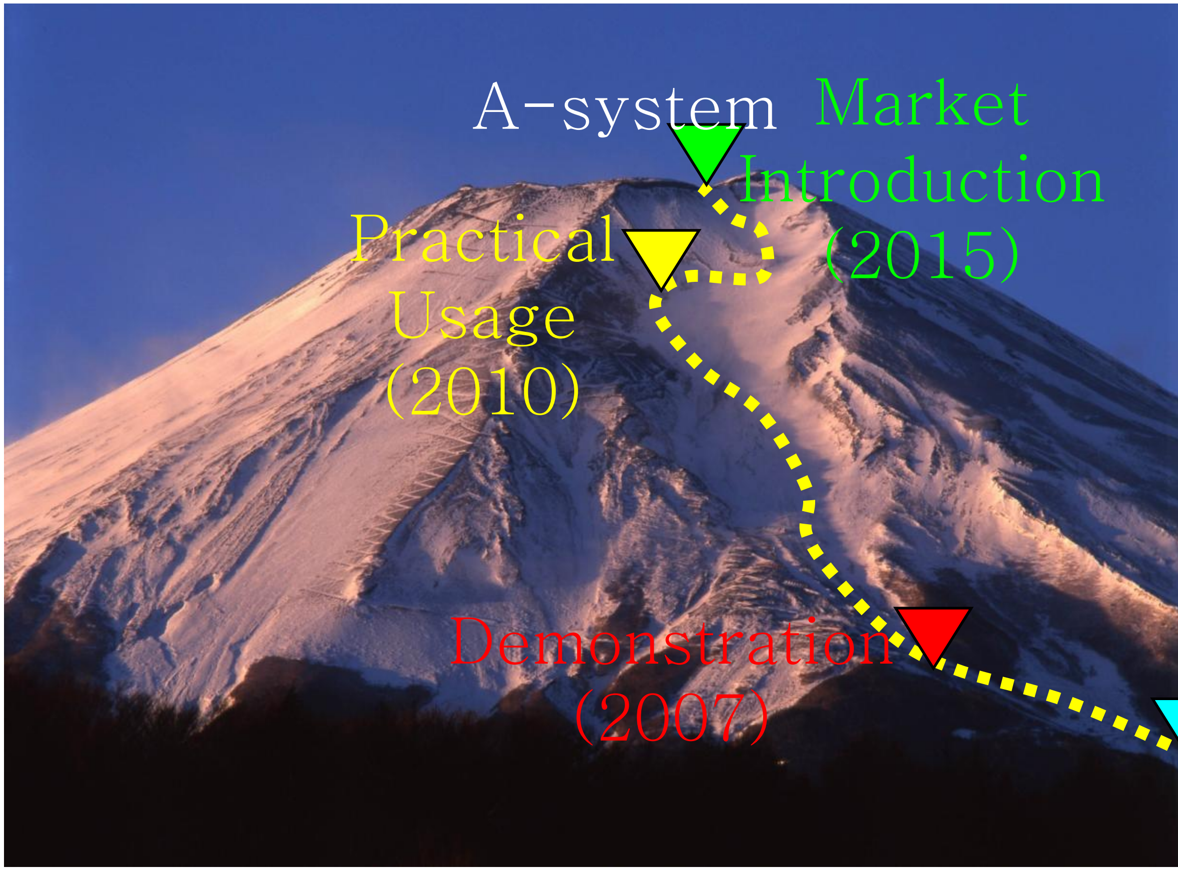
ISTEC

Overcome the difficulties



Filters
SQUIDs

Technology strategic map



(1) Technology r

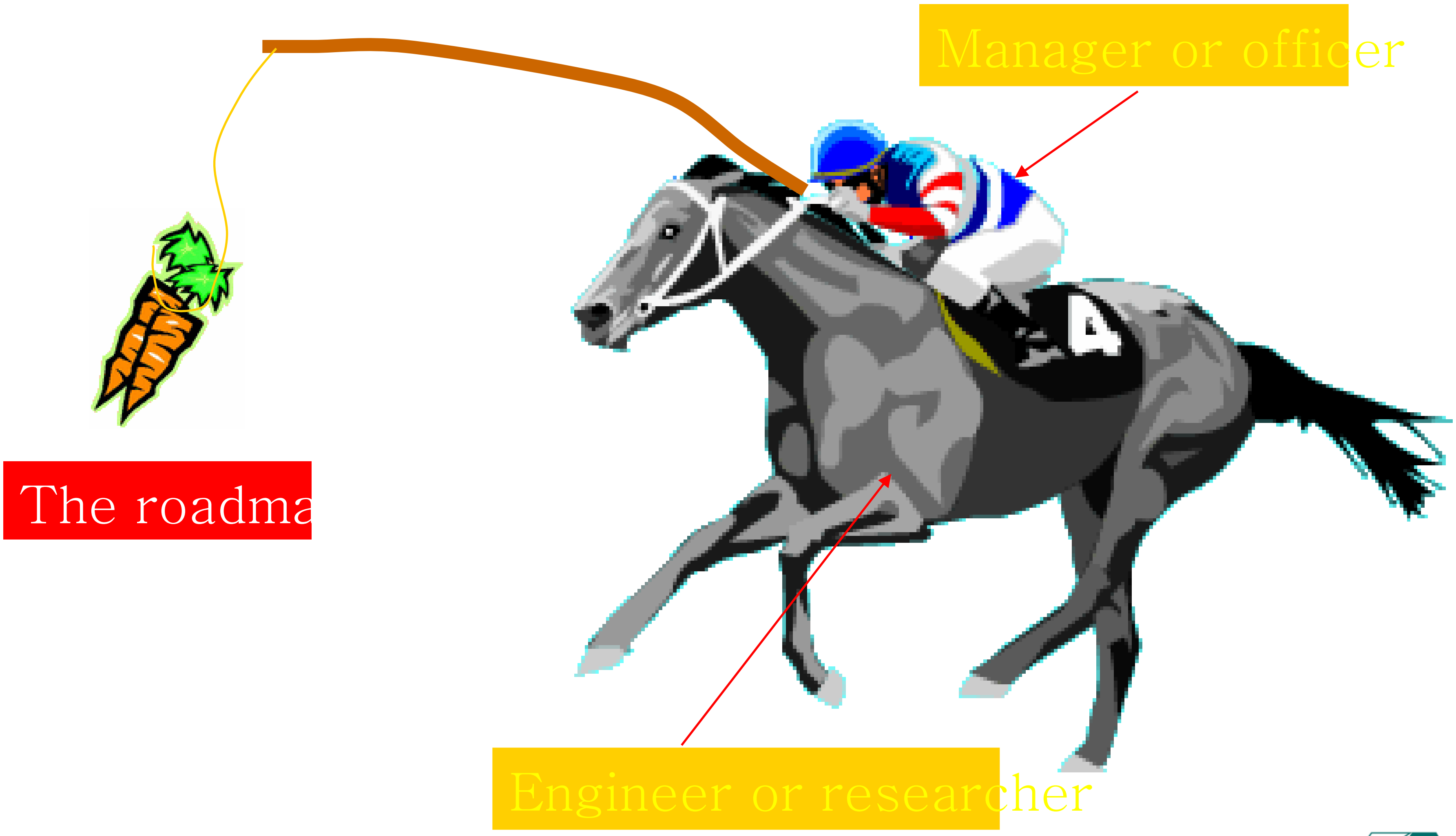
(2) Deployment scenario

(3) Road map

We are here (2006)

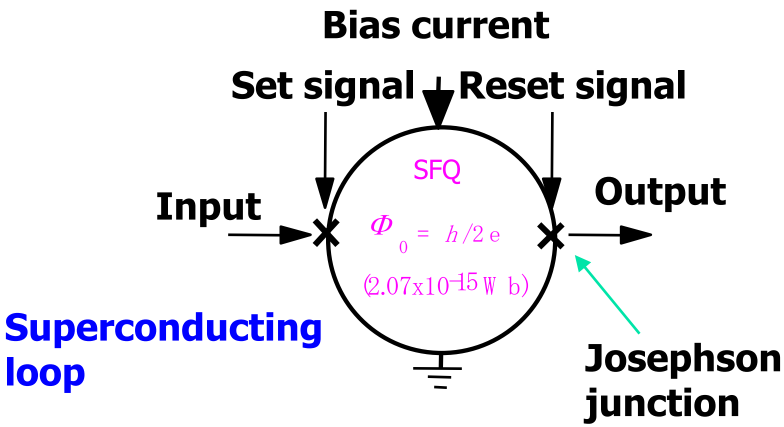
ISTEC

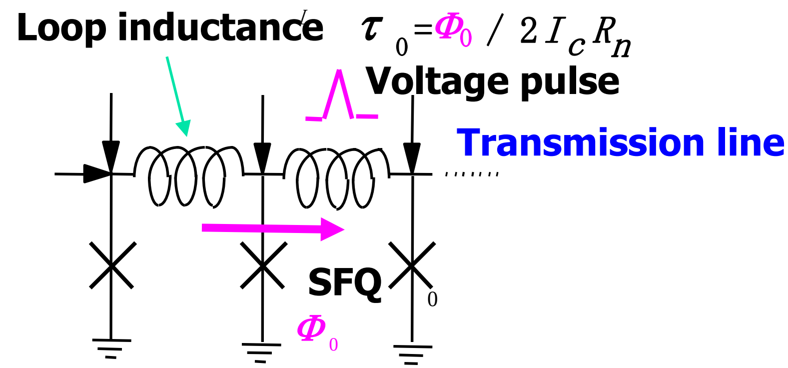
Hurry up!

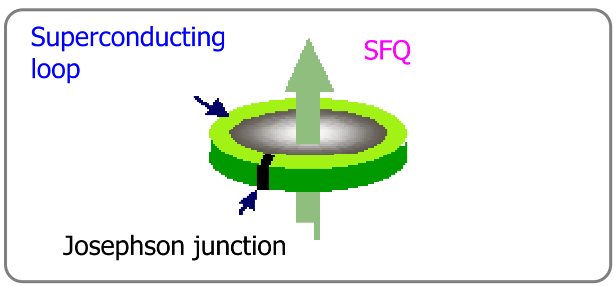


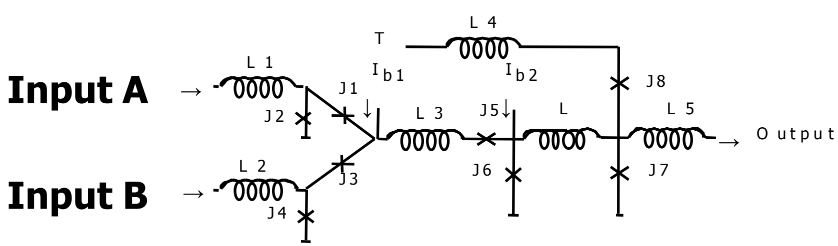
Thank you for your kind attention.

SFQ circuits



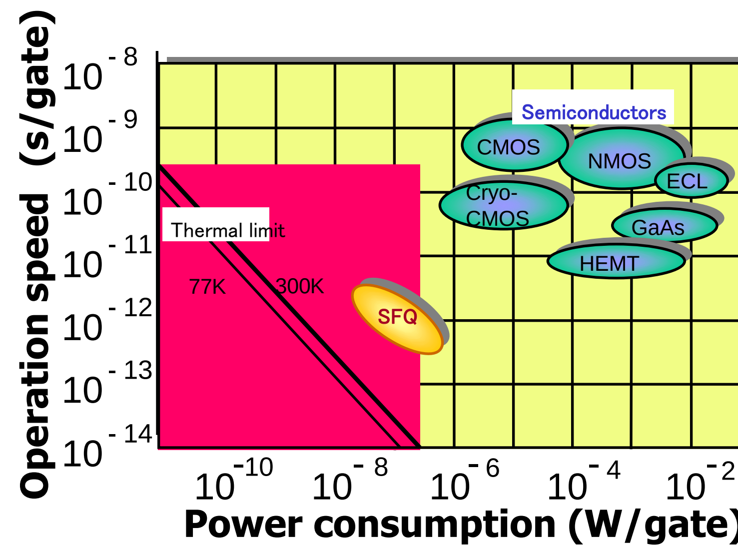






OR Cell

SFQ circuit



Operation Speed vs power consumption