THz帯SIS素子の開発の現状
− 1.5--2.0 GHz帯SISミキサの開発に向けて −

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Requirements for a heterodyne receiver at 1-2 THz band

		HEB	SIS
Operation (center) frequency	$f_0 > 1.5\ \mathrm{THz}$	○	$2f_{Gap} \geq 2\ \mathrm{THz}$ $J_c \geq 50\ \mathrm{kA/cm^2}$
Fractional frequency bandwidth	$\frac{\Delta f}{f_0} > 0.3$	○	$J_c \geq 50\ \mathrm{kA/cm^2}$
IF frequency bandwidth	$\Delta f_{IF} \sim 20\ \mathrm{GHz}$ $(f_{IF} \sim 0 - 20\ \mathrm{GHz})$	×	$J_c \geq 50\ \mathrm{kA/cm^2}$

$$f_{Gap} = \frac{\Delta_1 + \Delta_2}{h}$$

SIS junctions to be used for heterodyne receivers at 1-2 THz band 1

Operating frequency and gap energy

$$2f_{Gap} = \frac{2(\Delta_1 + \Delta_2)}{h} \geq 2\ \mathrm{THz} \implies \Delta_1 + \Delta_2 \geq 4.14\ \mathrm{meV}$$

	Gap energy (meV)	Nb	NbN	Nb3Ge	MgB2
Nb	1.35	2.7 meV 1.30THz			
NbN	2.36	3.71 meV 1,80 THz	4,72 meV 2.28 THz		
Nb3Ge	3.46	4.81 meV 2.33 THz	5.82 meV 2.81 THz	7.92 meV 3.35 THz	
NgB2	~6.5	7.85 meV 3.80 THz	8.86 meV 4.28 THz	9.96 meV 4.82 THz	13 meV 6.3 THz

Current density of SIS junctions

$$\frac{1}{\omega R_N C_J} = 0.1 - 0.3 \;:\; \text{Fractional bandwidth}$$

$$I_C R_N = V_C \;:\; \text{Material constant}$$

$$C_J = C_s A$$

A : Junction area

C_s : Specific capacitance $40 - 80\ \text{fF}/\mu\text{m}^2$

$$\frac{\Delta f}{f} = \frac{1}{\omega R_N C_J} = \frac{1}{\omega}\frac{I_C}{V_C}\frac{1}{C_s A} = \frac{1}{2\pi}\frac{j_C}{f}\frac{1}{V_C C_s}$$

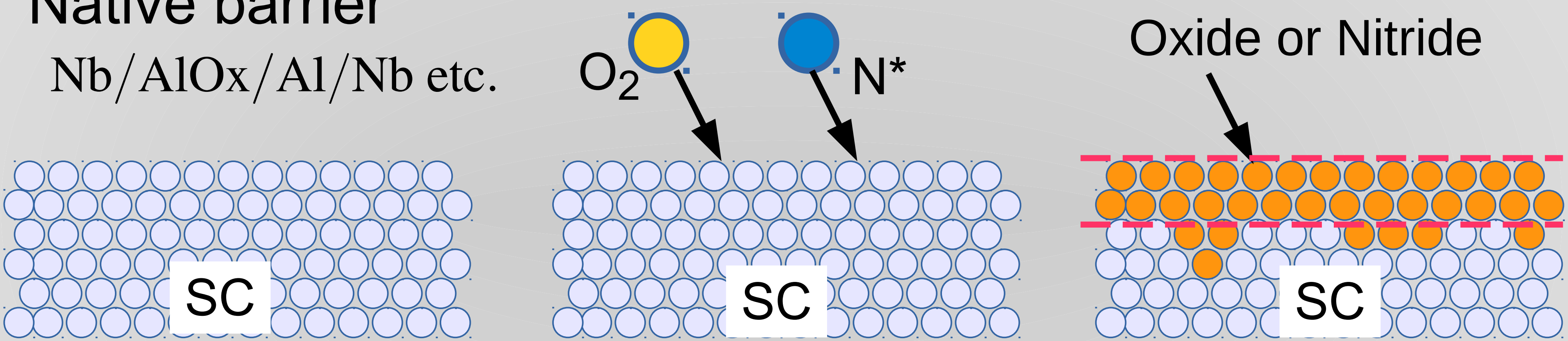
Increase f keeping $\frac{\Delta f}{f}$ constant, j_C must be increased

Increase $\frac{\Delta f}{f}$ keeping f constant, j_C must be increased

SIS junctions to be used for heterodyne receivers at 1-2 THz band 2

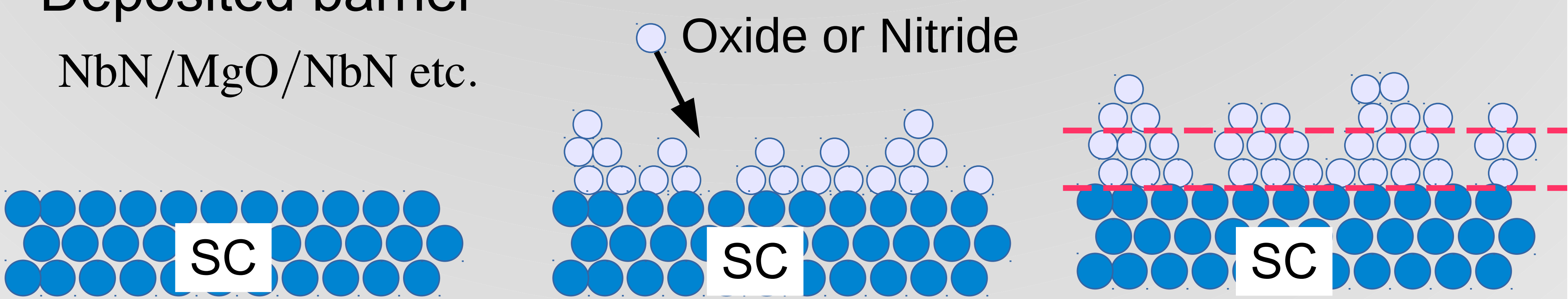
Native barrier

Nb/AlOx/Al/Nb etc.



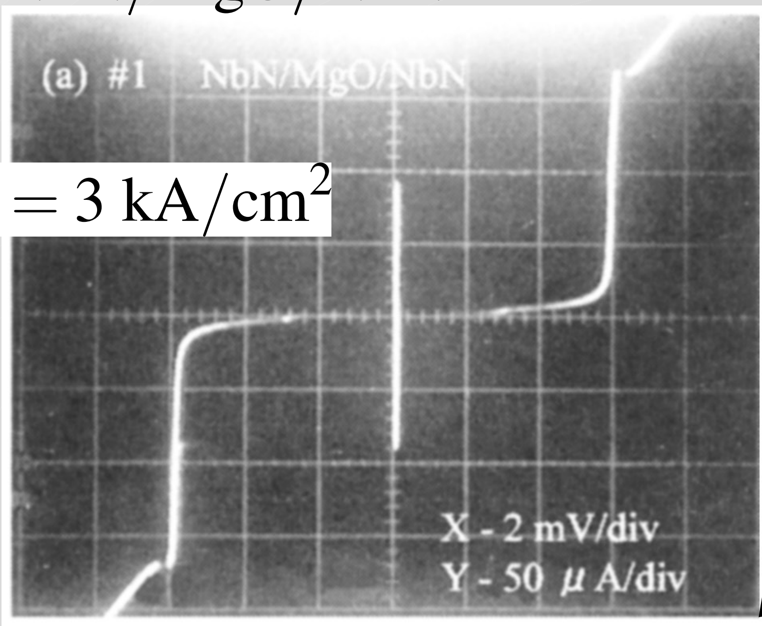
Deposited barrier

NbN/MgO/NbN etc.

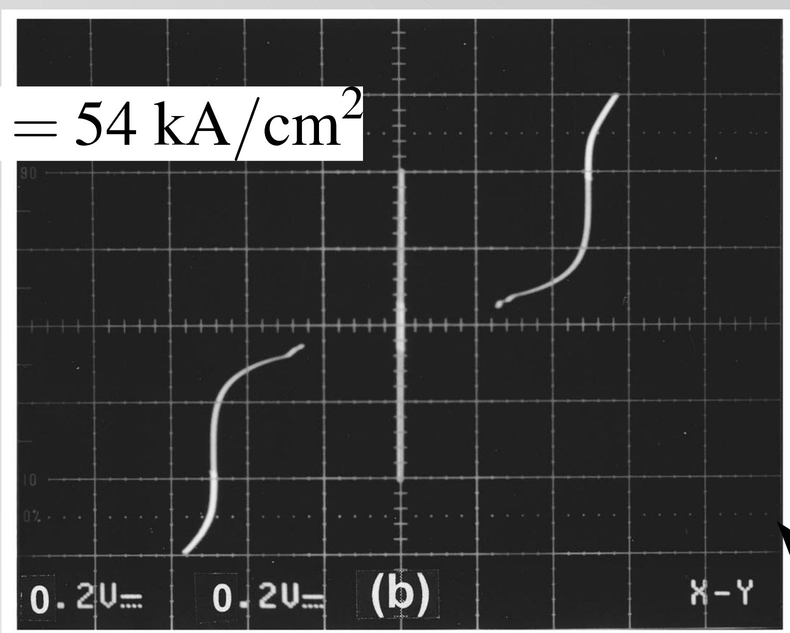


Current density of SIS junctions

NbN/MgO/NbN

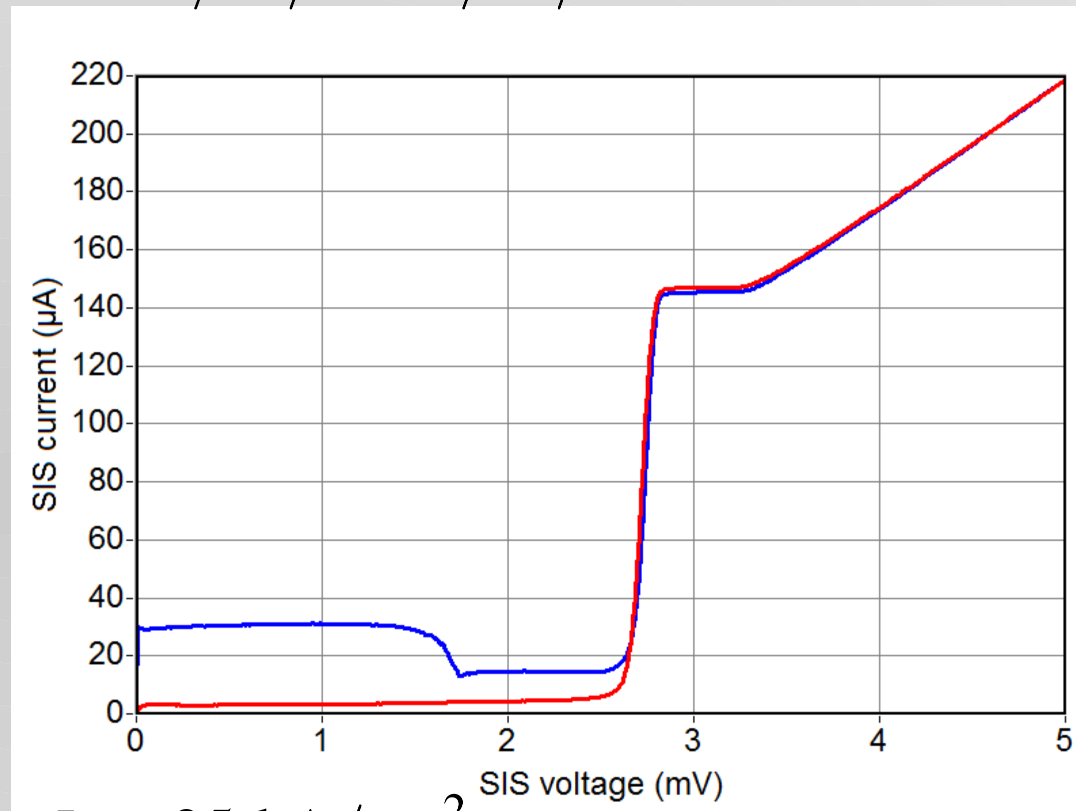


$J_c = 3\ \mathrm{kA/cm^2}$



$J_c = 54\ \mathrm{kA/cm^2}$

Nb/Al/AlOx/Al/Nb



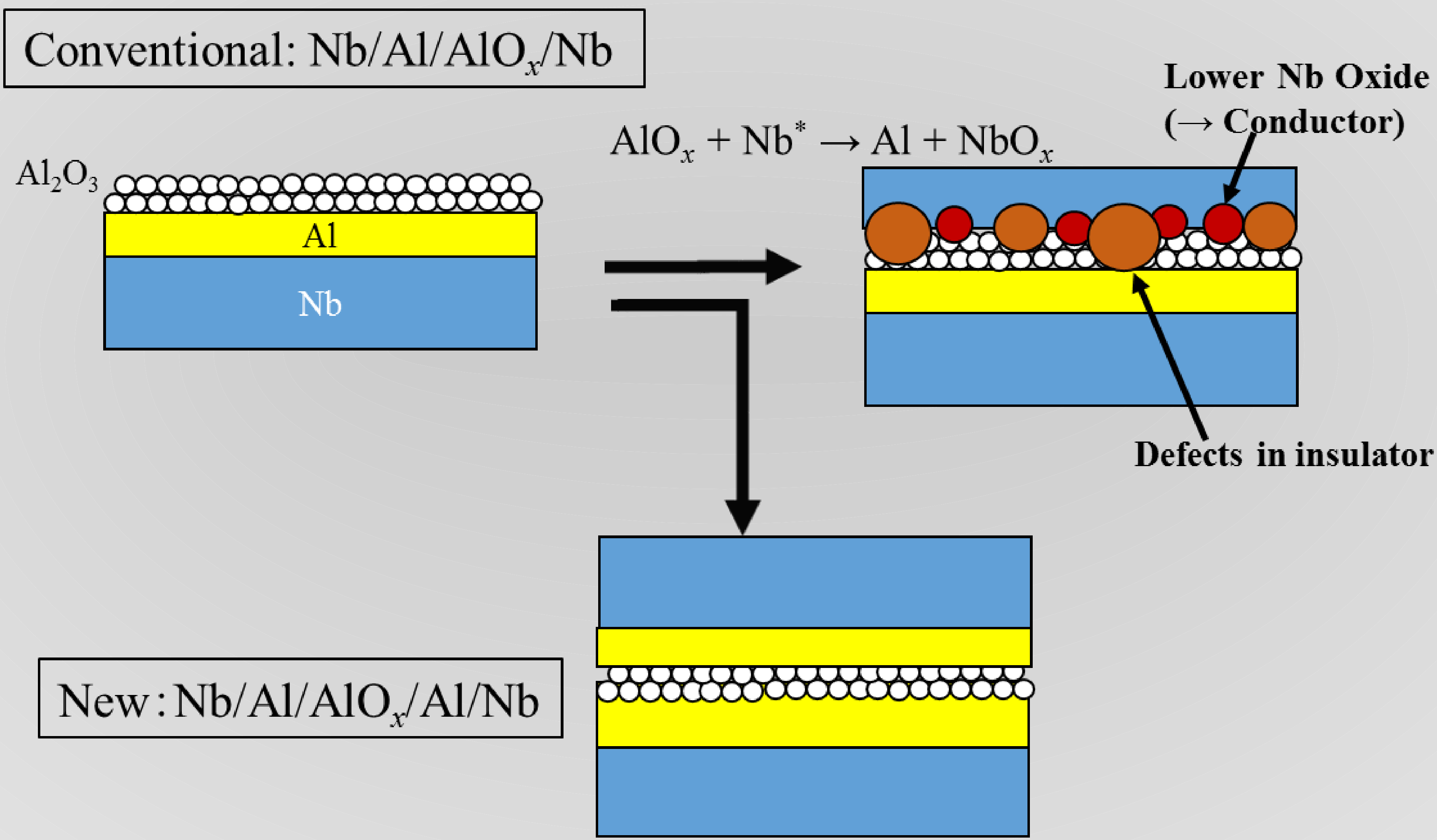
$J_c = 25\ \mathrm{kA/cm^2}$

M. Kroug et al., to be published.

H. Ishida et al., Electronics and Communications in Japan, Part 2, Vol. 88, No. 12, 2005

Z. Wang et al., Appl. Phys. Lett. 70, 114 (1997).

Nb/Al接合のサブギャップ電流について

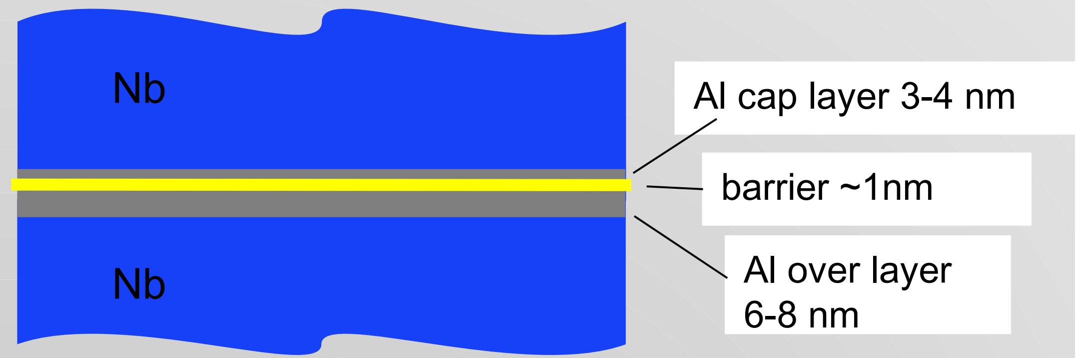


Niobium SIS Junctions with Al Cap Layer

- previously reported:

  SIS Junctions Based on AlN_x Barrier

  - j_c = 10 – 45 kA/cm^2
  - sharp non-linearity and low leakage with $q > 20$
  - several devices successfully tested in the 400 – 500 GHz range (including a j_c ~ 45 kA/cm^2 mixer)

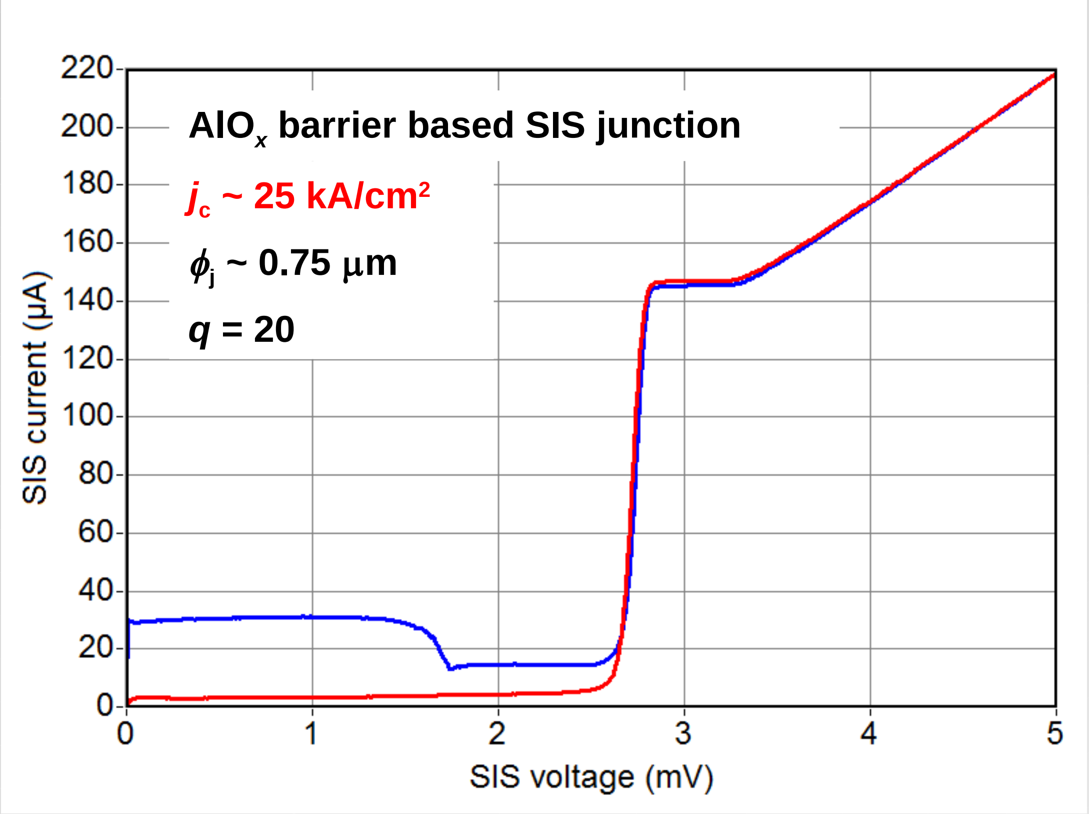


- same approach recently used for:

  SIS Junctions Based on AlO_x Barrier

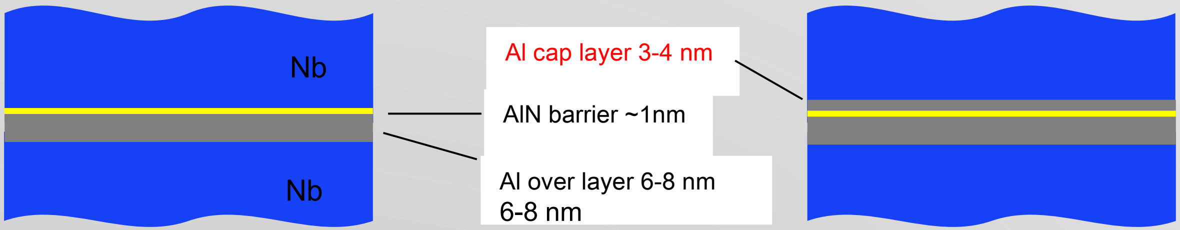
  - junction quality comparable for current density up to 25 kA/cm^2
  - fabrication not optimized yet

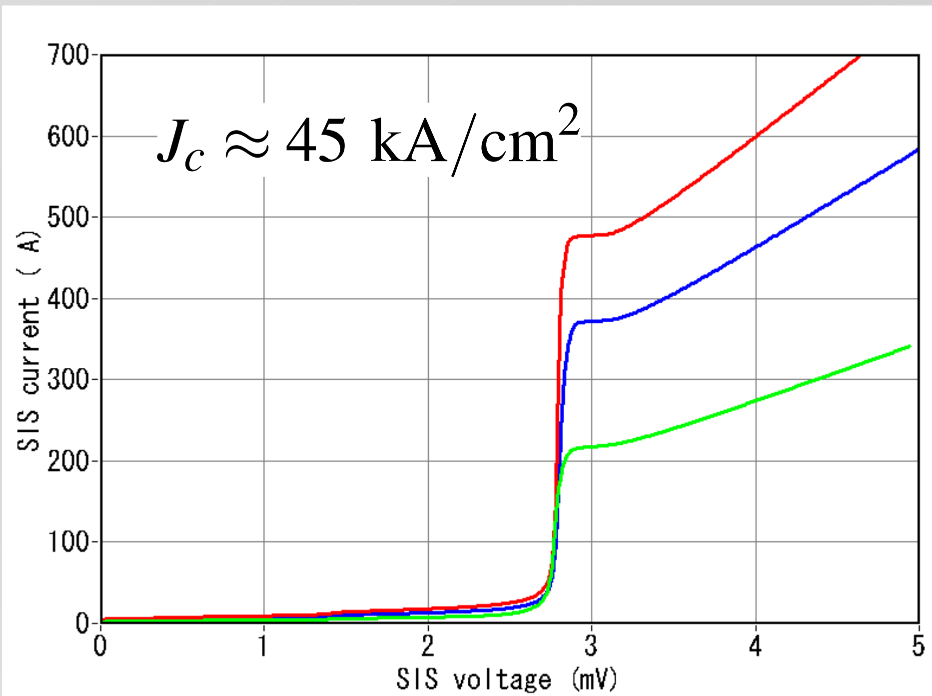
- we have a promising *additional* option for fabricating high-j_c SIS mixers



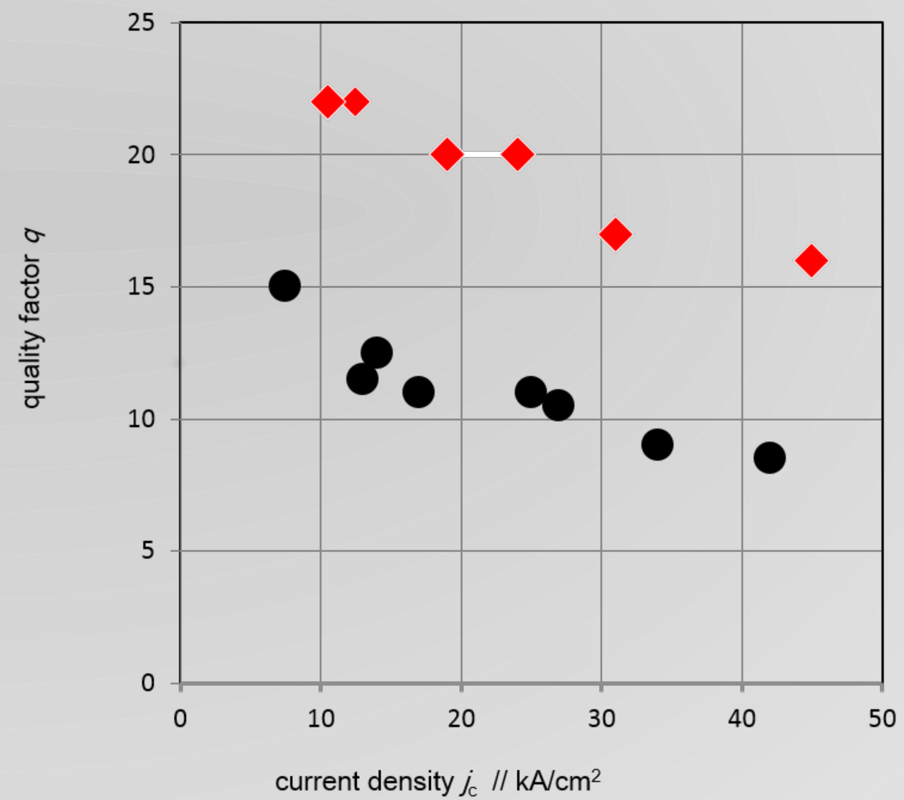
Ultra high current density SIS junction

Nb/Al/AlN/Al/Nb

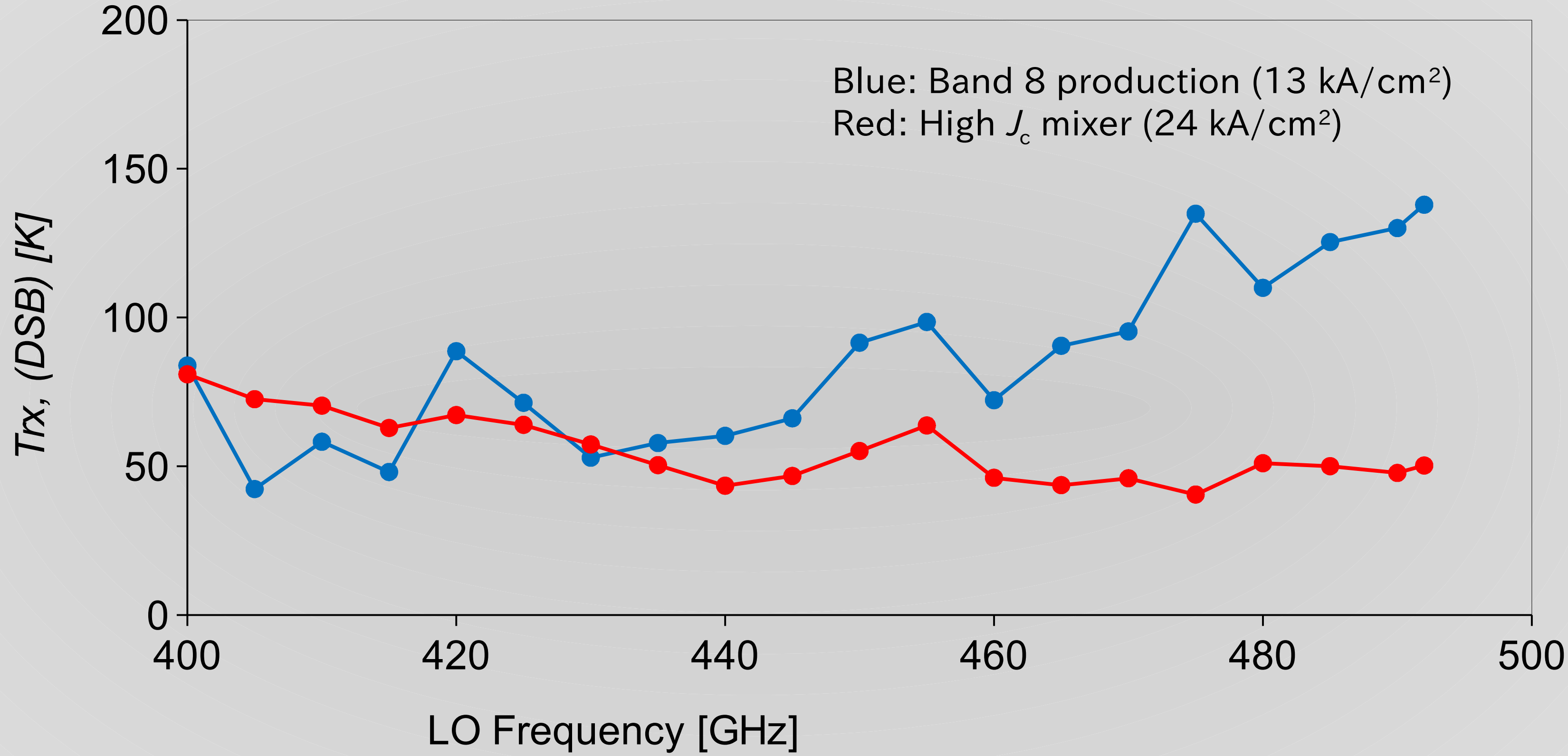




IV characteristics of three junctions, nominal diameter ϕ_j = 1.0, 0.9 and 0.8 μm, made from the layer stack Nb/Al,AlN_x/Al/Nb.



High Critical Current Density (J_c)
SIS Junction Device Development

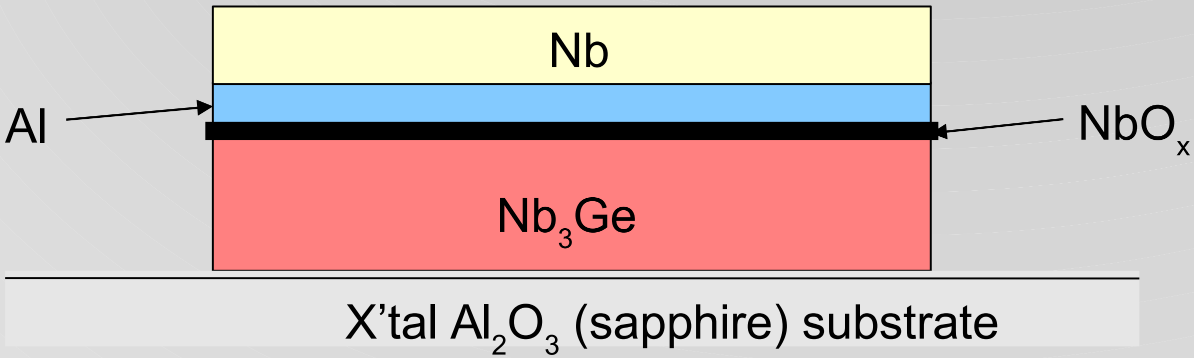


Band 7 275 – 370 GHz
Band 8 385 – 500 GHz
} Unification !

本研究の目指す技術開発

Nb_3Ge/NbOx/Al/Nb接合の新規性、利点

- Nb_3Ge/NbOx/Al/Nb接合自体が新規な構造
- Pbに代えて、化学的、機械的に安定なNbを利用
  →SIS素子の安定性、信頼性の向上
  →実用的なSIS素子へ
- Alバッファ層の活用
  →酸化層のNbとの反応による劣化を低減、防止→リーク電流の低減
  →超高電流密度接合の実現
- 同一真空中で、Nb_3Ge/NbOx/Al/Nb接合構造を作成
  →素子製造の再現性、安定性の向上

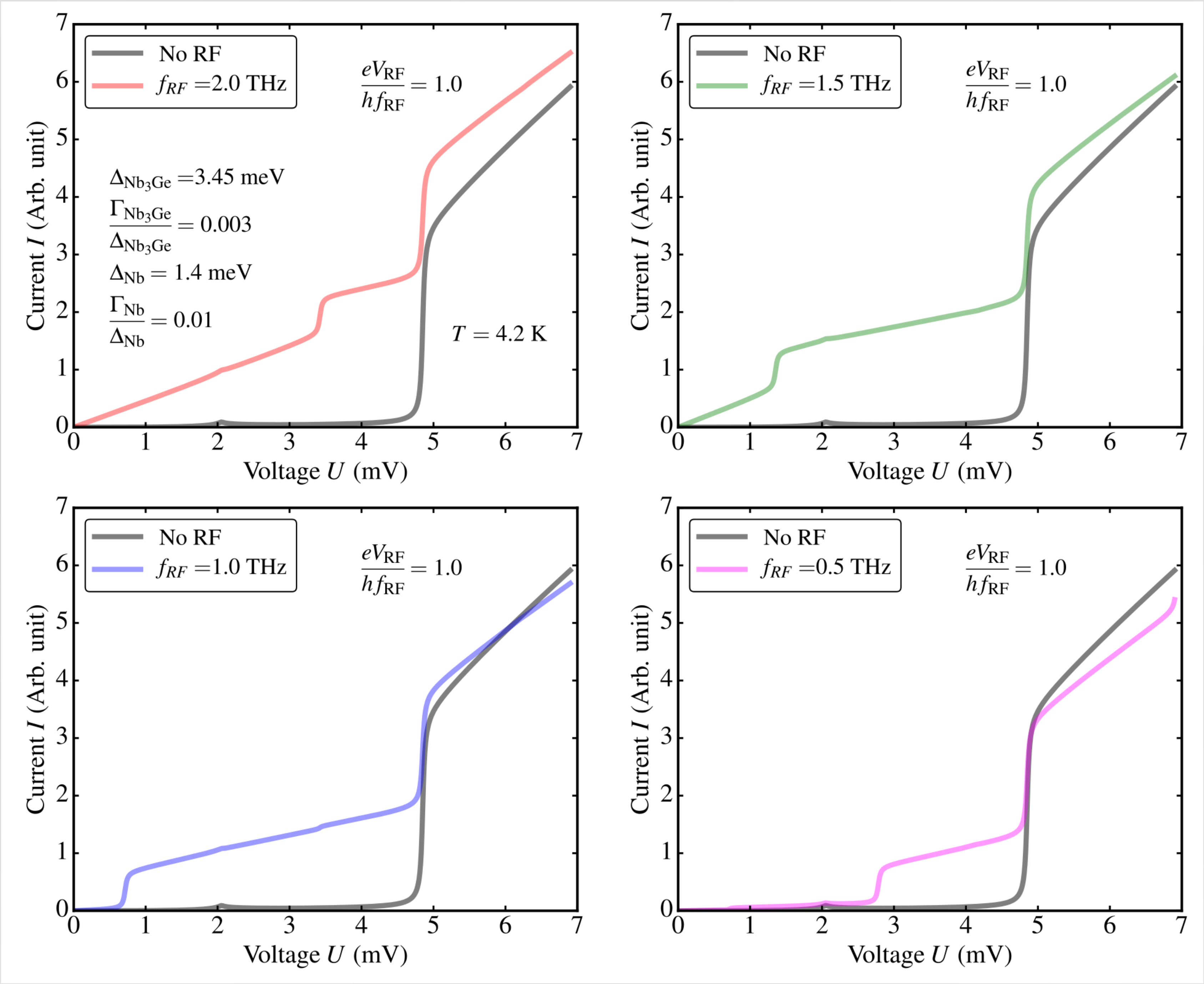


$$\Delta_{Nb_3Ge} \approx 3.46 \text{ meV}$$
$$f_{GAP} \approx 1.7 \text{ THz}$$

$$\Delta_{Nb} \approx 1.35 \text{ meV}$$
$$f_{GAP} \approx 0.7 \text{ THz}$$

$$\Delta_{Nb_3Ge} + \Delta_{Nb} \approx 4.81 \text{ meV} \Longrightarrow f_{GAP} \approx 1.2 \text{ THz}$$
$$\Longrightarrow f_{MAX} \approx 2 f_{GAP} = 2.4 \text{ THz}$$

Simulated RF response of a Nb3Ge/barrier/Nb junction



Nb_3Ge/SiO2/Pb junction

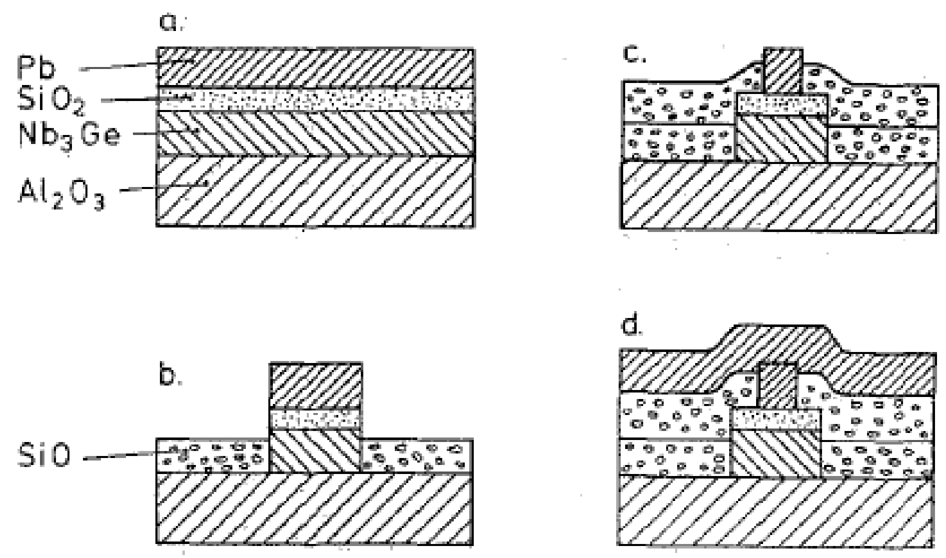


Fig.1 Different steps during structuring of a tunneljunction sandwich (cf. text).

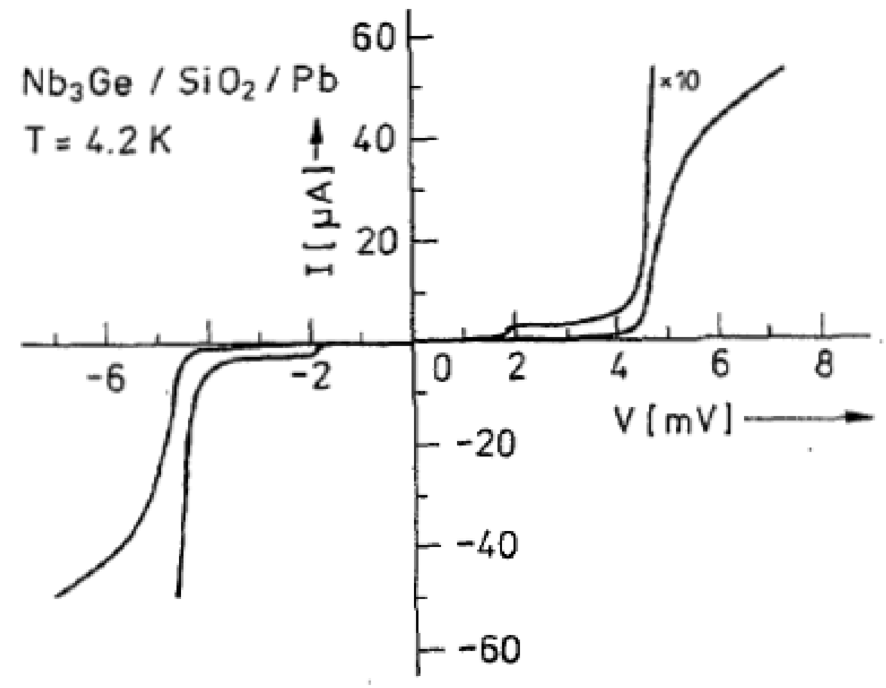
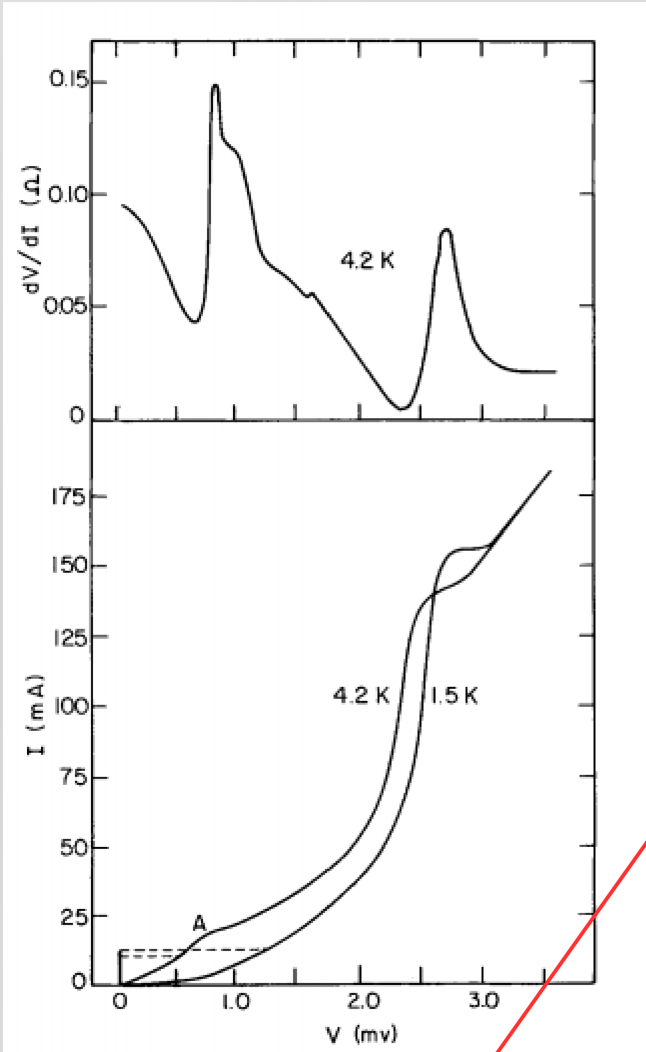


Fig.2 I-V characteristic of a Nb_3Ge-SiO_2-Pb tunnel junction.

M. Muck et al., IEEE Trans. Magn., Vol. 23(2), 1493 – 1496, 1987.

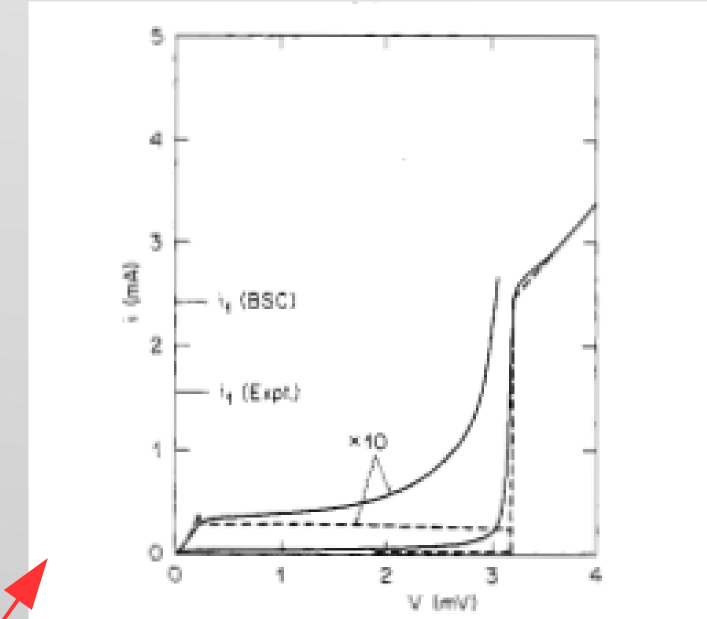
Note:
Pb was etched by $FeCl_3$ solution, whereas Nb_3Ge was etched reactively in an SF_6 plasma.

I-V curves of Nb-based SIS junctions



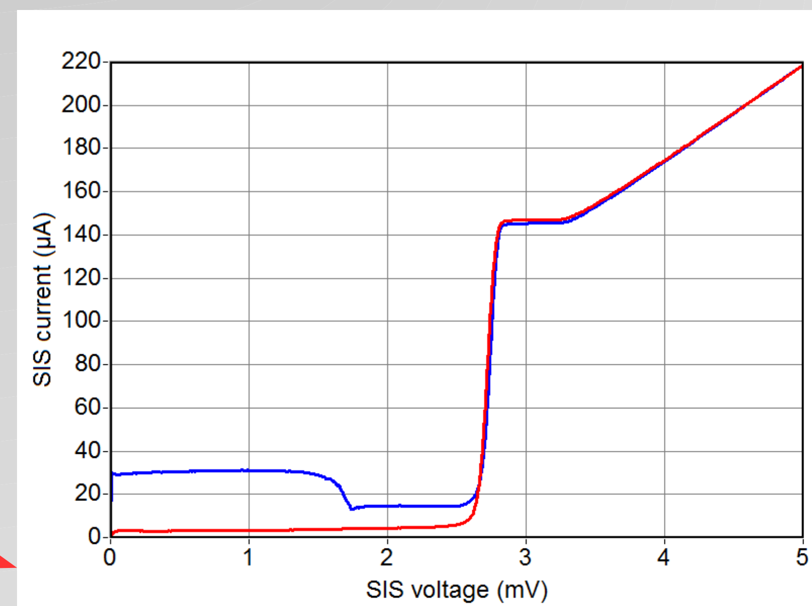
High V_G material ← $Nb/NbO_x/Nb$

G. Hawkins and J. Clarke.
J. Appl. Phys., 47, 1616 (1976)



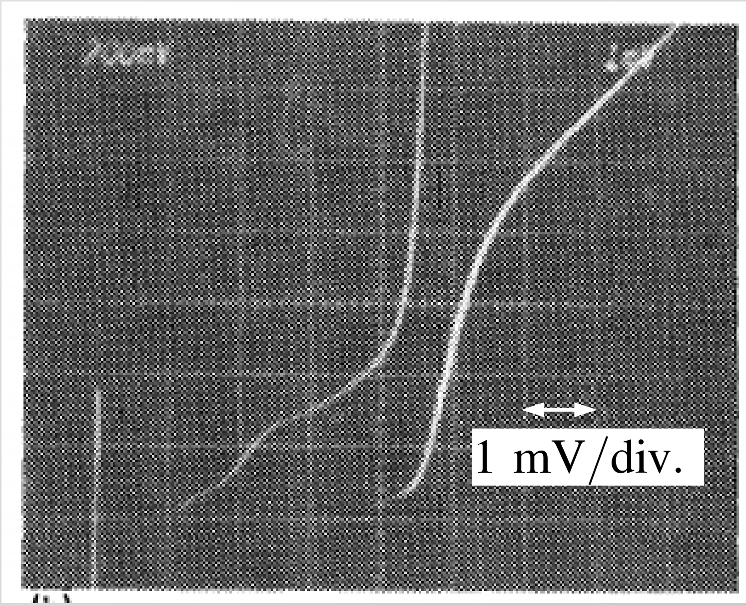
$Nb/NbO_x/PbBi$

R. F. Broom et al., IEEE Trans.
Electron Dev., ED-27, 1998, (1980).



$Nb/Al/AlO_x/Al/Nb$

Nb_3Ge/NbOx/Pb junction



Nb_3Ge/Oxide/Pb

K. Tanabe and O. Michikami, J. Appl. Phys., vol.58(9), 3519-3528, 1985.

$Pb : T_c = 7.2$ K

Substrate: ($1\bar{1}02$) Sapphire (R plane)
Nb_3Ge preparation:
- DC magnetron sputtering
- Target: Arc melted $Nb_{0.742}Ge_{0.258}$
- Subst. Temp.: ~700 ℃
- Sputt. Rate: ~20 nm/min.
- Thickness: 300-400 nm
- Tc : 21.3 K

(Breaking vacuum)
Base electrode patterning: Chemical etching
(Breaking vacuum)
Base electrode cleaning: Ar + 9.7vol%CF_4
Oxidation: Plasma oxidation, Ar + 8.1vol%O_2
- 4 Pa, 60 V, 1-30 min. (typcal)

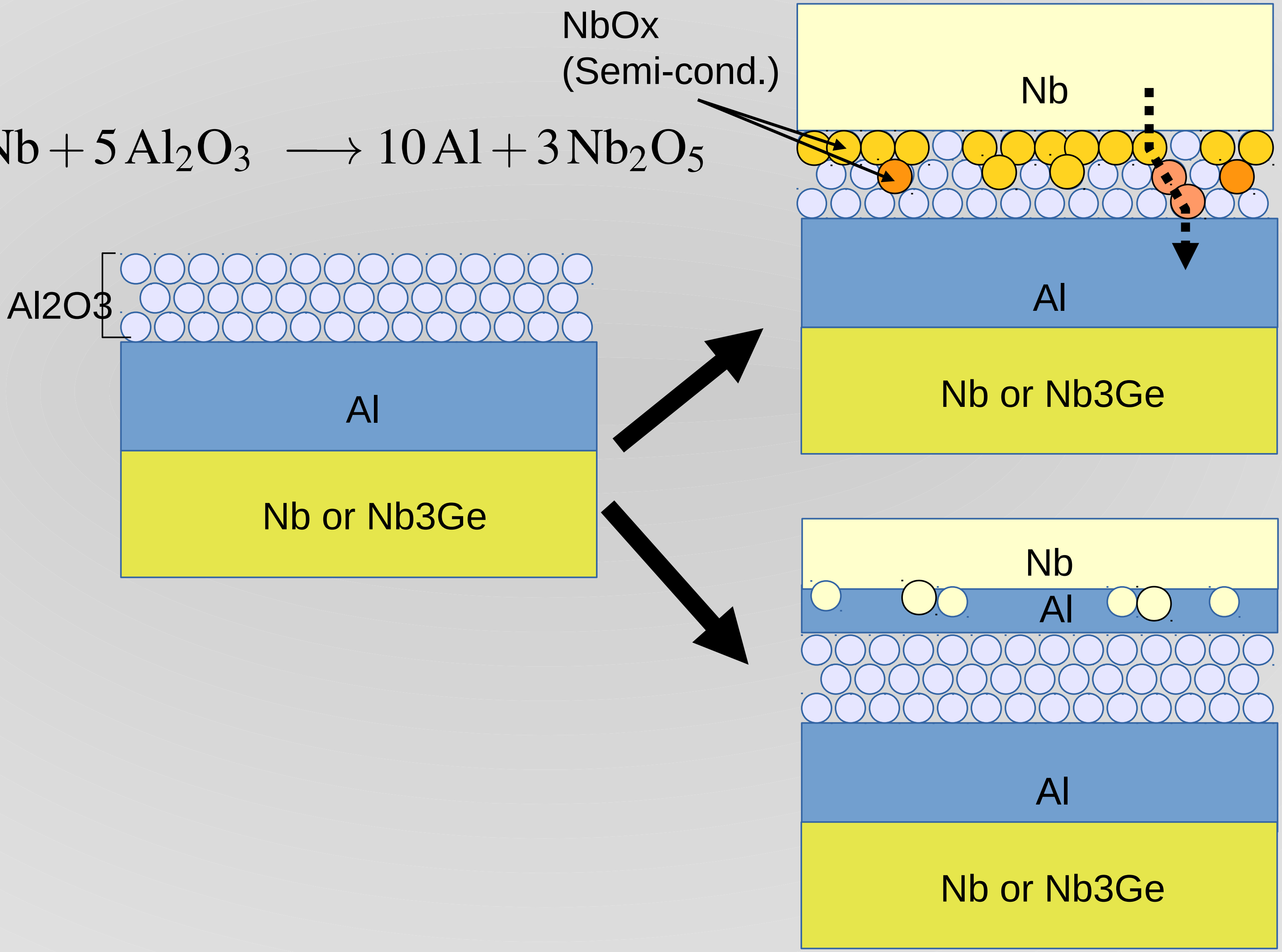
Pb deposition:
- Thermal deposition, 400-600 nm

$Pb \longrightarrow Nb$

- 物理的、化学的に安定
- ドライエッチングが可能 → 写真製版による微細加工が可能

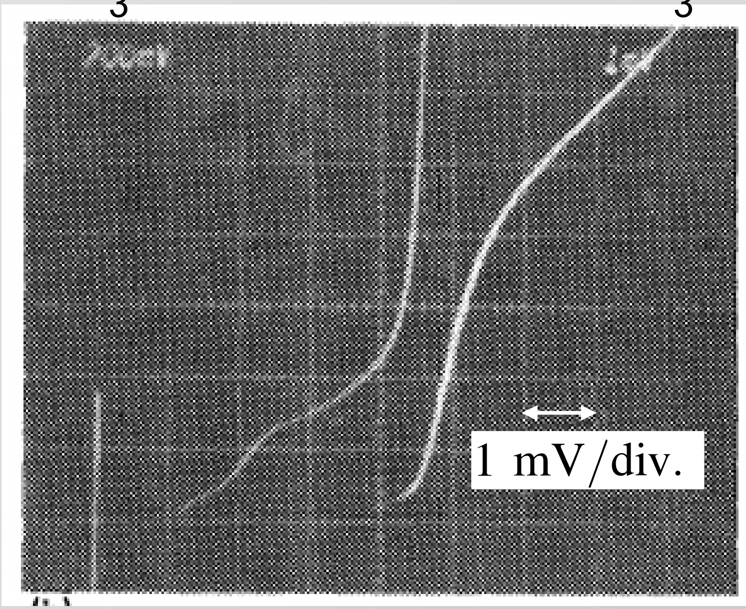
Suppression of leakage current

$$6\,\mathrm{Nb} + 5\,\mathrm{Al_2O_3} \longrightarrow 10\,\mathrm{Al} + 3\,\mathrm{Nb_2O_5}$$



従来技術の拡張

Nb_3Ge/NbOx/Pb → Nb_3Ge/NbOx/Al/Nb



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Base electrode cleaning: Ar + 9.7vol%CF_4

Oxidation: Plasma oxidation, Ar + 8.1vol%O_2

4 Pa, 60 V, 1-30 min. (typcal)

Pb deposition:

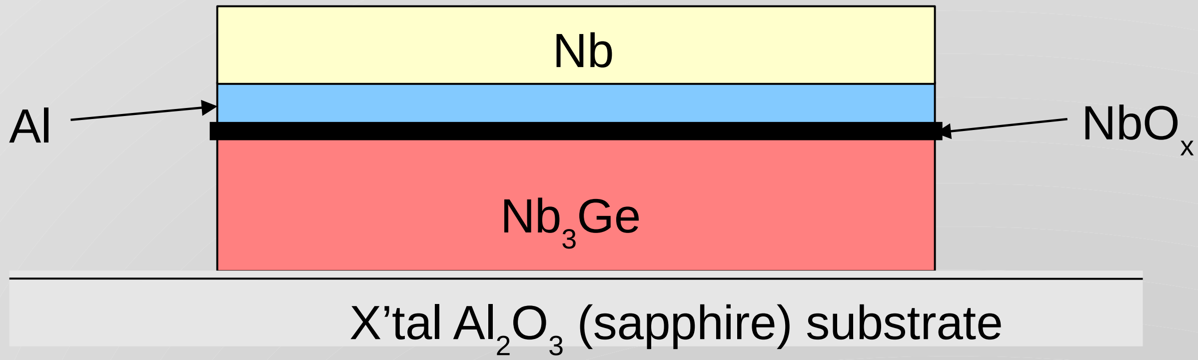
Thermal deposition, 400-600 nm

↓

Al/Nb deposition:

E-beam deposition, 400-600 nm

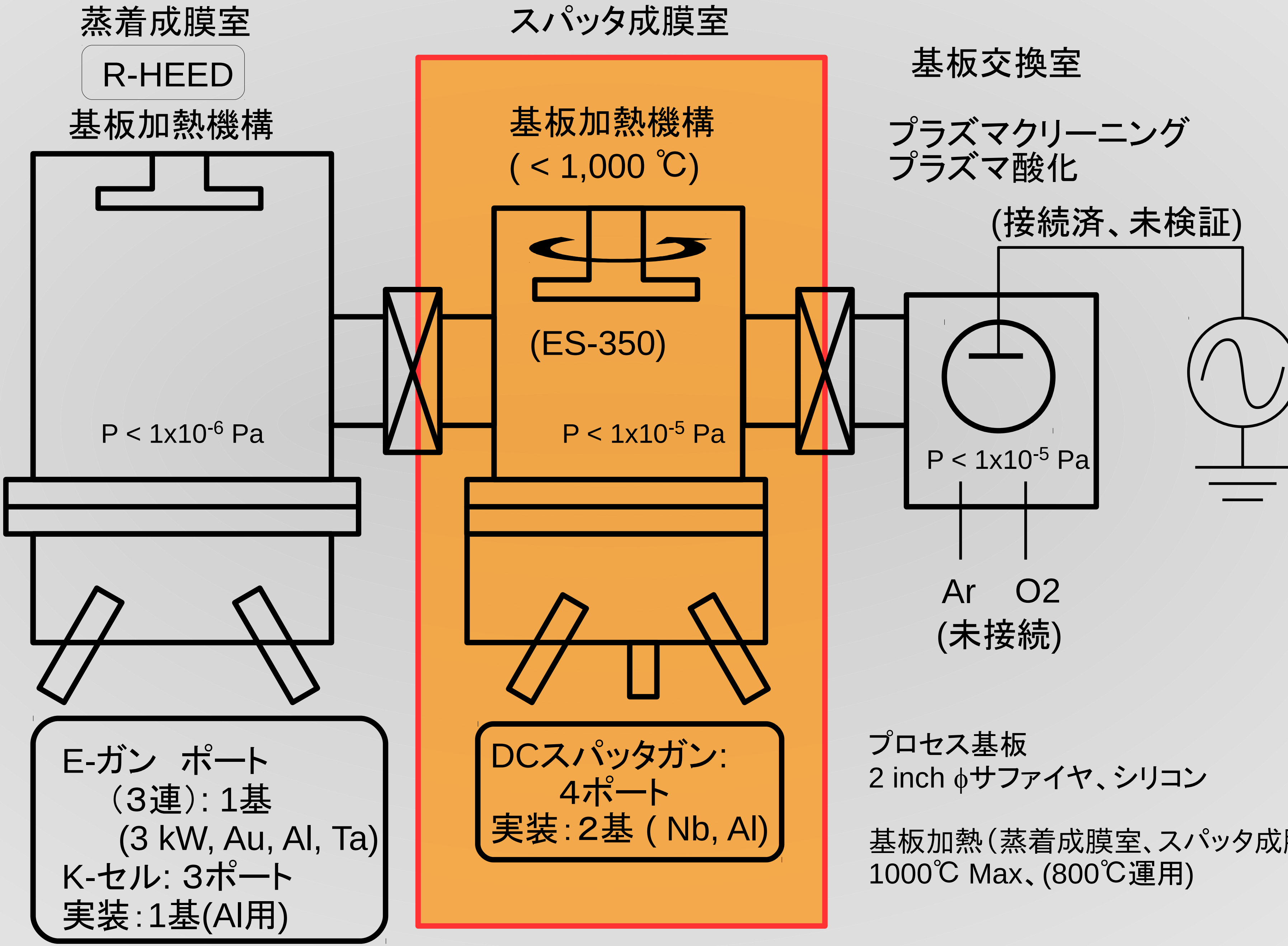
Fabricaton of a SIS junction with a Nb_3Ge base electrode



$$\Delta_{Nb_3Ge} \approx 3.46 \text{ meV}$$
$$\Delta_{Nb} \approx 1.35 \text{ meV}$$
$$f_{GAP} \approx 1.2 \text{ THz}$$
$$f_{MAX} \approx 2.4 \text{ THz}$$

Procedure of the growth of the quadruple-layers （同一真空中で真空を破らずに実施）			
1	Substrate temperature elevation	Up to 950 ℃	Sputter chamber
2	Nb3Ge sputter	Φ2 inch target, confocal config.	Sputter chamber
3	Substrate temperature cool down	Down to room temperature	Sputter chamber
4	Plasma oxidation (NbOx)	10%O2/Ar	Load locked chamber
5	Al deposition	< 10 nm thick	Sputter chamber or evaporation chamber
6	Nb deposition	100 nm	Sputter chamber

MBE/スパッタ成膜システム構成図

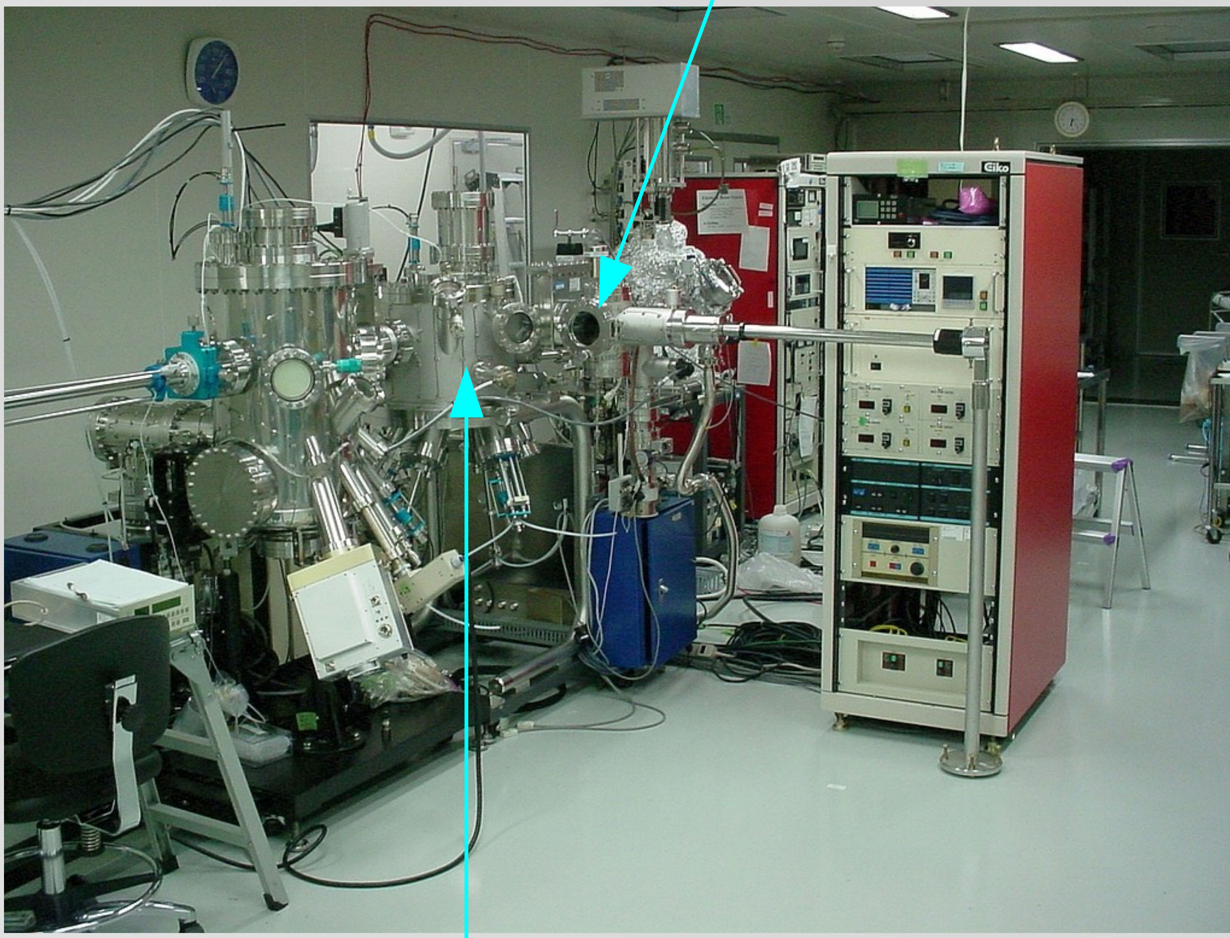


プロセス基板
2 inch ϕサファイヤ、シリコン

基板加熱（蒸着成膜室、スパッタ成膜室)
1000℃ Max、(800℃運用)

スパッタ装置　ES-350改

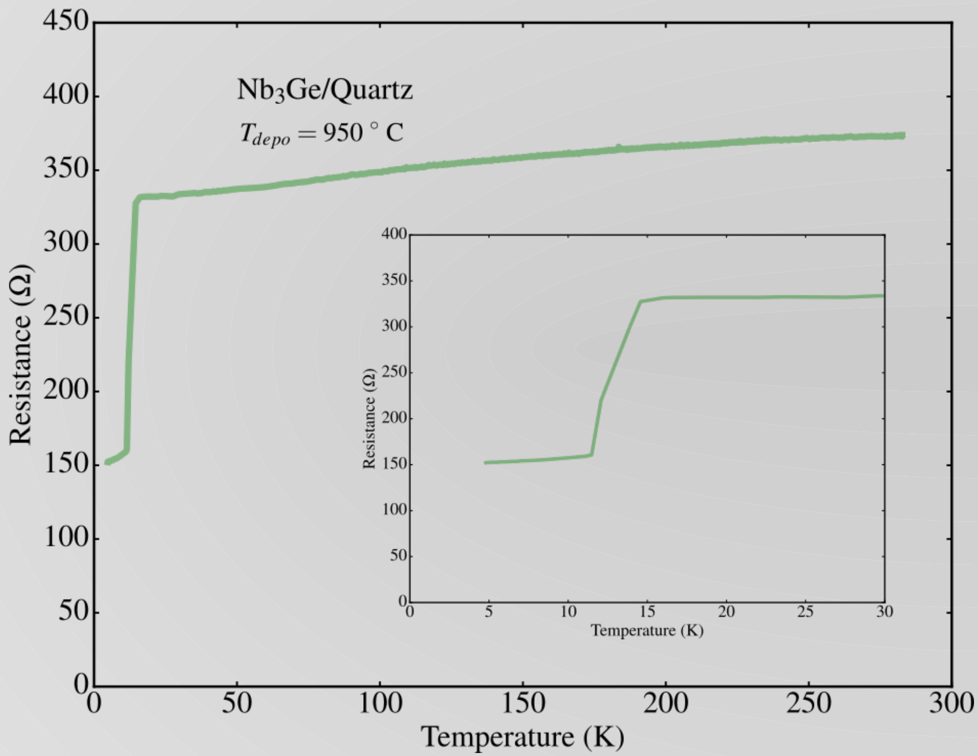
ロードロックチャンバ

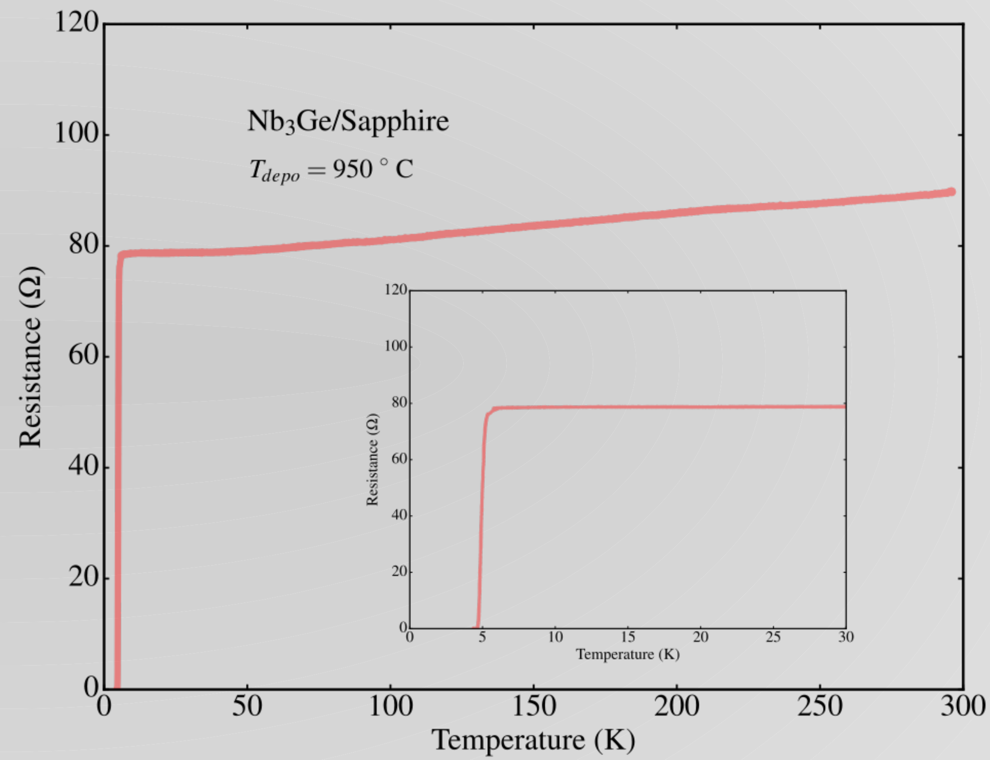


スパッタチャンバ

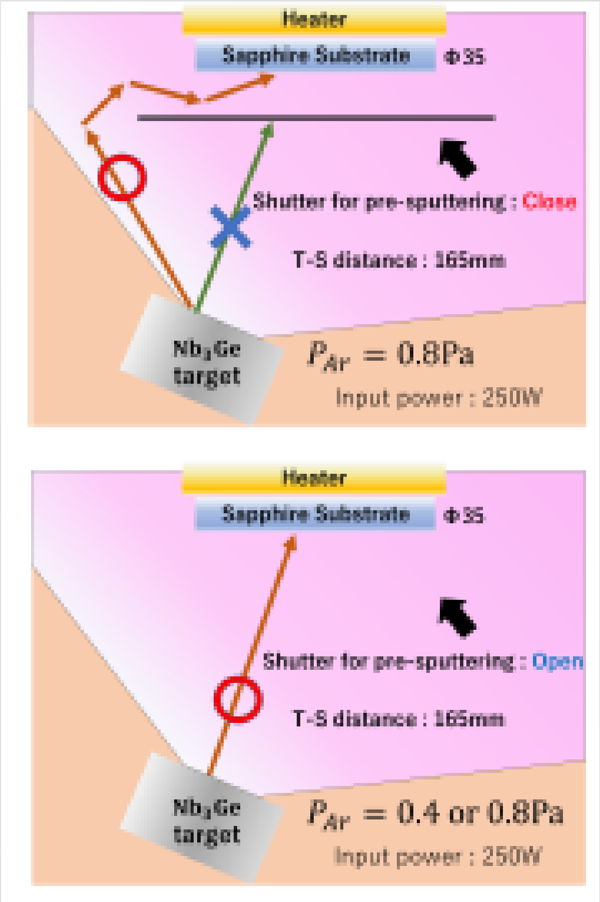
加熱ステージマニピュレータ

Nb3Ge薄膜の試作



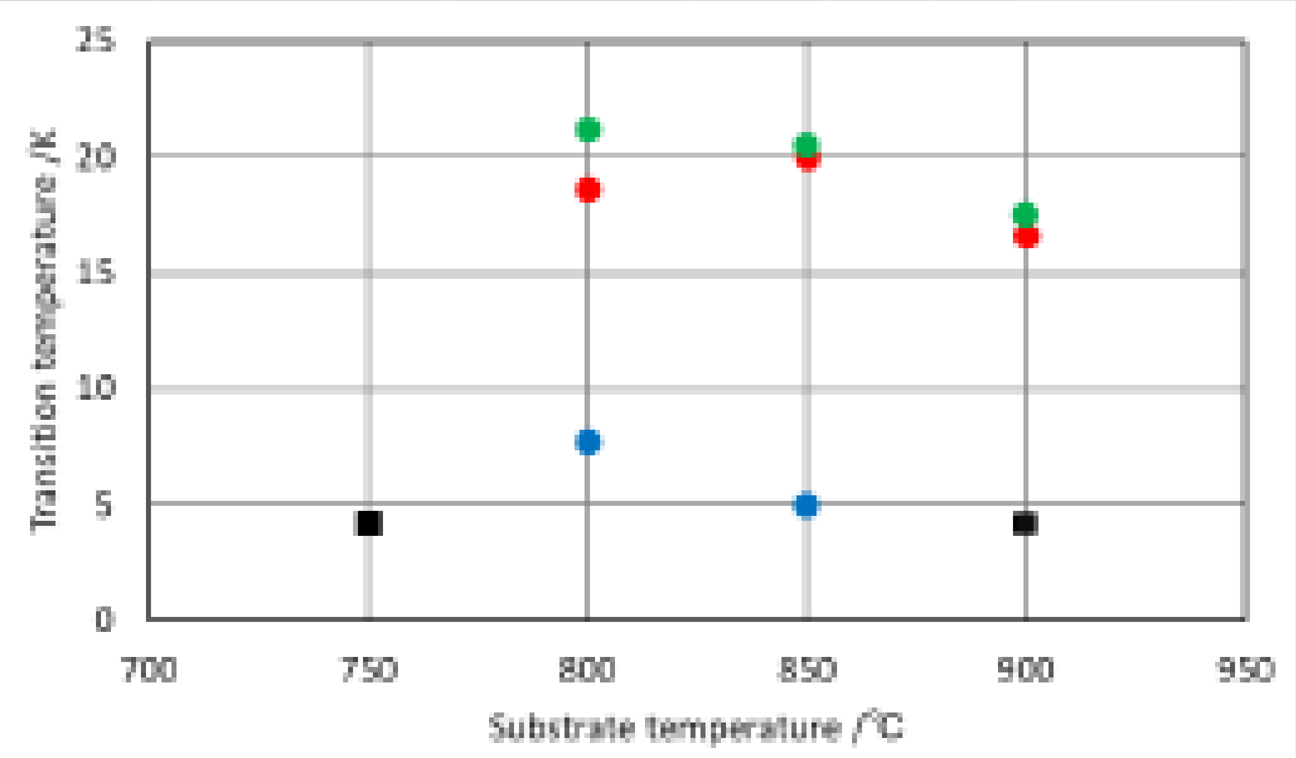


Fabricated and measured by H. Yamashita



Sputtering apparatus

Nb_3Ge film on 35-mmΦ sapphire



● :Ar pressure = 0.4Pa, Shutter: open, 12 nm/min

● : Ar pressure = 0.8Pa, Shutter: open, 7 nm/min

● : Ar pressure = 0.8Pa, Shutter: close, 2 nm/min

■ : No transition

Future work

- 高Tc Nb_3Ge膜の作成条件の確定
- Nb_3Ge/Oxide/Al/Nb SIS接合の作成
  oxide: Al_2O_3 or Nb_2O_5