ID: 27-51

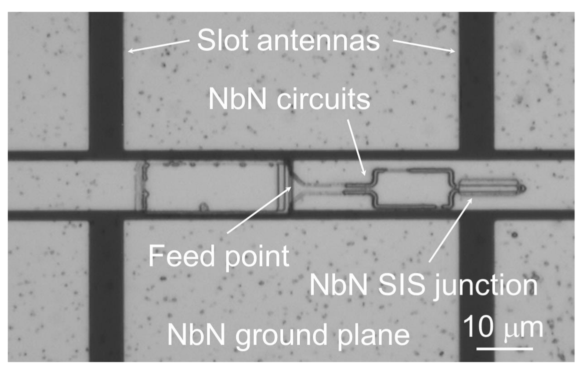
Optical and Tunneling Studies of Energy Gap in Superconducting Niobium Nitride Films

Y. Uzawa[1], S. Saito[2], Wei Qiu[2], K. Makise[3], T. Kojima[1], and Z. Wang[4]

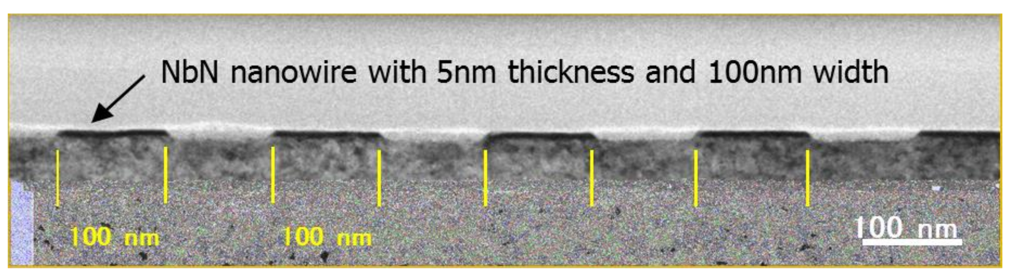
[1] National Astronomical Observatory of Japan, [2] National Institute of Information and Communications Technology, [3] National Institute of Advanced Industrial Science and Technology, [4] Shanghai Institute of Microsystem and Information Technology

Motivation

- **Importance of NbN devices for**
  - Practical applications for High frequency, high speed, and high temperature operations
    - Large gap frequency, high critical temperature



THz NbN SIS mixer



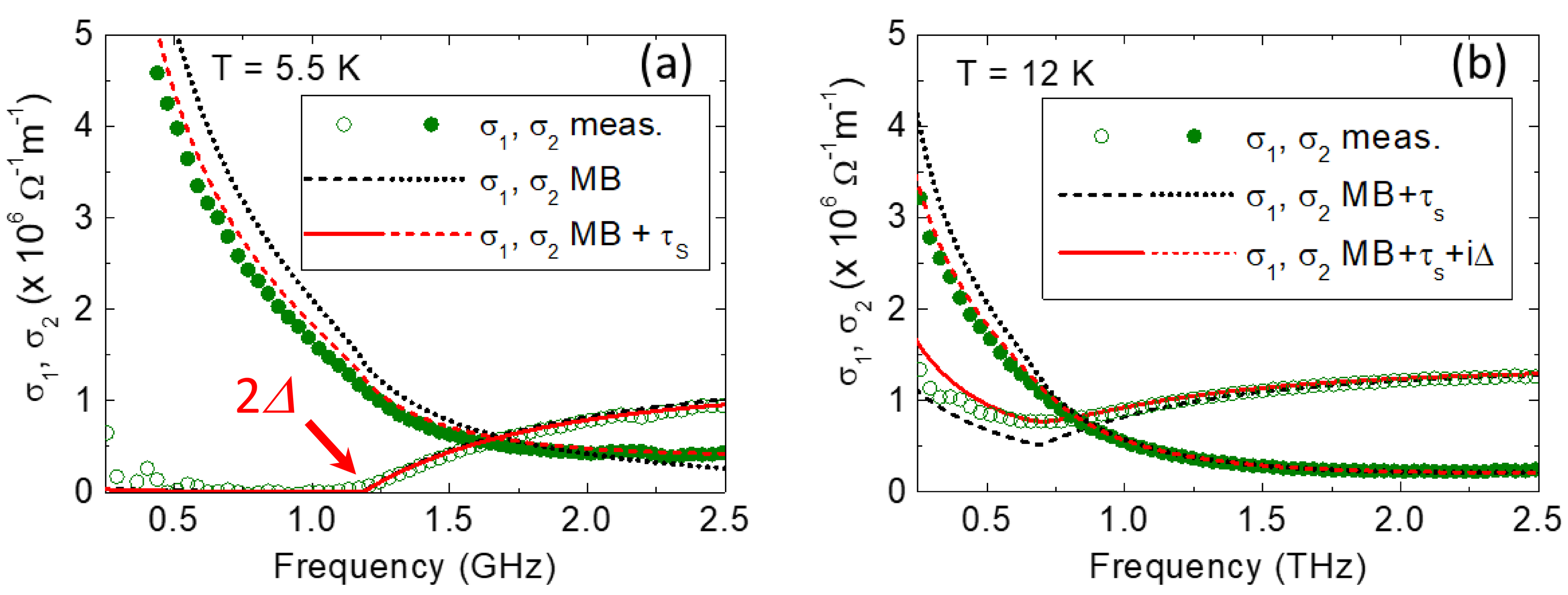
TEM photograph of NbN SSPD

- **Understanding of fundamental properties**
  - Superconducting energy gap, Density of states, etc.

Optical and Tunneling Spectroscopy Studies

Results

Derived optical conductivity



Mattis-Bardeen (MB) theory with arbitrary electron scattering time τ_S explains the measured conductivity at 5.5 K, but not enough at 12 K. Introducing an imaginary energy gap into the gap energy ($\Delta=\Delta_1+i\Delta_2$), a good agreement was obtained (red line in the right figure), where Δ_1 = 1.42 meV, Δ_2 = 0.107 meV.

Calculation: ρ_{20K}(DC) = $1/\sigma_0$ = 69.1 μΩcm, T_C = 14 K, $2\Delta(0)$ = 4.96 meV, τ_S = 15 fs (5.5 K), 7 fs (12 K)

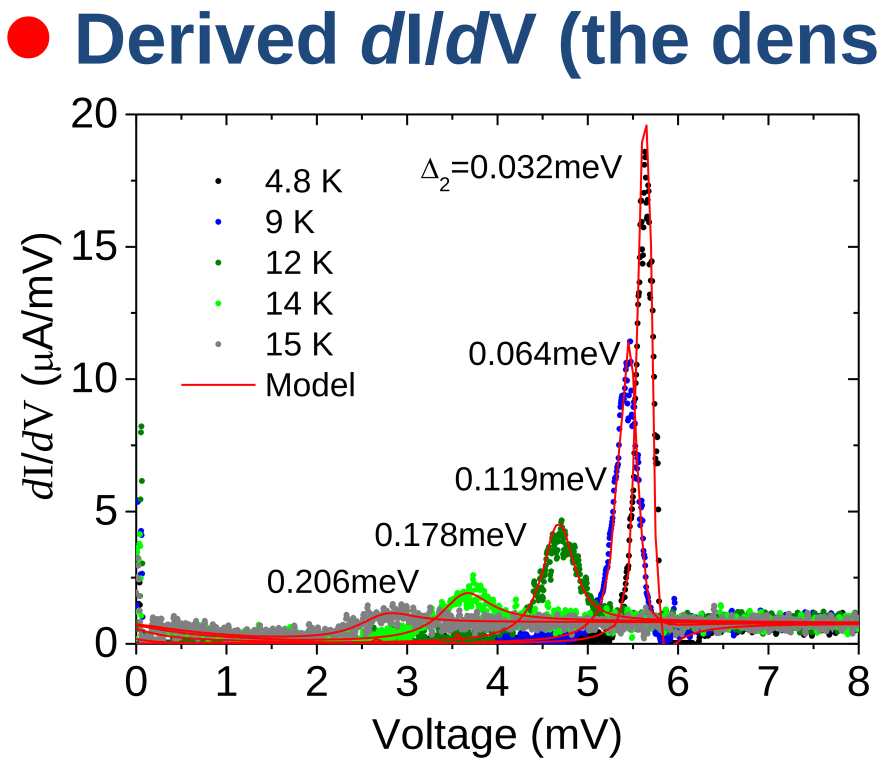
$$\frac{\sigma_1^{MB}(\omega)}{\sigma_0}=\frac{2}{\hbar\omega}\int_{\Delta}^{\infty}[f(E)-f(E+\hbar\omega)]g(E)dE+\frac{1}{\hbar\omega}\int_{\Delta-\hbar\omega}^{-\Delta}[1-2f(E+\hbar\omega)]g(E)dE$$

$$f(\eta)=\frac{1}{1+e^{\eta/k_BT}}\qquad g(E)=\frac{E^2+\Delta^2+\hbar\omega E}{(E^2-\Delta^2)^{1/2}[(E+\hbar\omega)^2-\Delta^2]^{1/2}}$$

$$\sigma_1^{\tau_S}(\omega)=\mathrm{Re}\left[\frac{1}{1+i\omega\tau_S}\right]\sigma_1^{MB}(\omega)$$

$$\sigma_2^{\tau_S}(\omega)=\frac{2}{\pi\omega}\int_0^{\infty}\left(\mathrm{Re}\left[\frac{\sigma_0}{1+i\omega\tau_S}\right]-\sigma_1^{\tau_S}(\omega')\right)d\omega'+\frac{2\omega}{\pi}\int_0^{\infty}\frac{\sigma_1^{\tau_S}(\omega')}{\omega^2-\omega'^2}d\omega'$$

Derived dI/dV (the density of states)



Good agreement in dI/dV curves between the experiment and calculation was obtained assuming that the imaginary gap (Δ_2) becomes larger with increasing the temperature.

Calculation:

$$I(V)=\frac{G_n}{e}\int_{-\infty}^{\infty}N(E-eV)N(E)[f(E-eV)-f(E)]dE$$

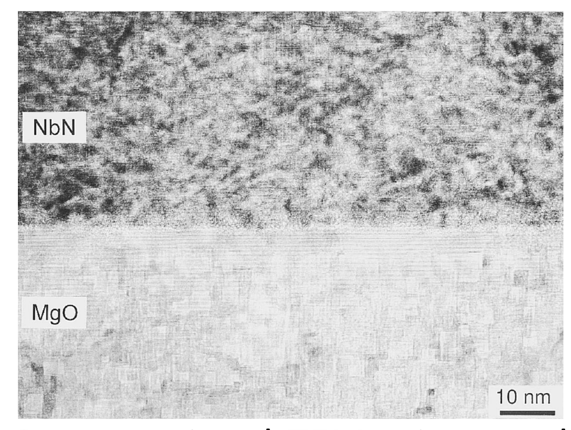
where G_n is the normal-state conductance of the junction

and $N(E)=\mathrm{Re}\{E/[E^2-\Delta^2]^{1/2}\}$: the density of state.

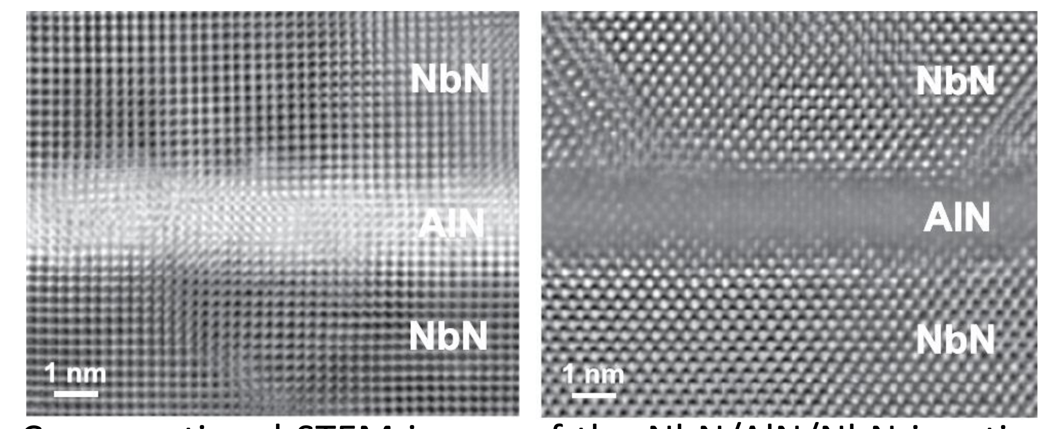
Measurements

Sample preparation

- Epitaxial NbN film and NbN/AlN/NbN junctions

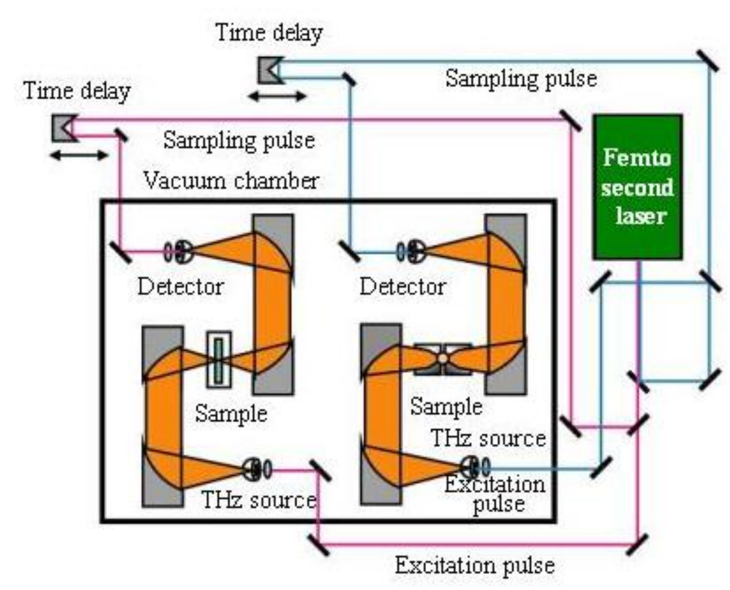


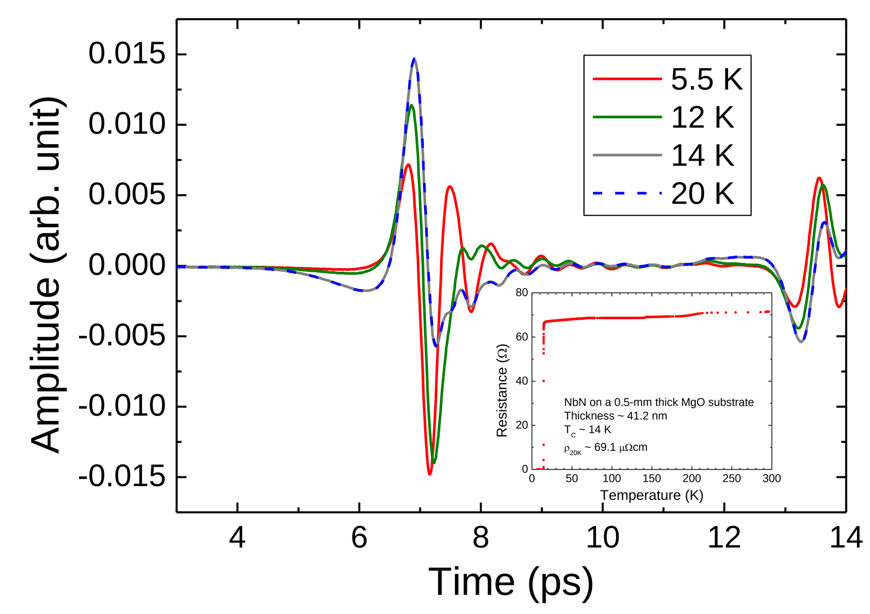
Cross-sectional TEM micrograph of the NbN thin film deposited on MgO substrates.

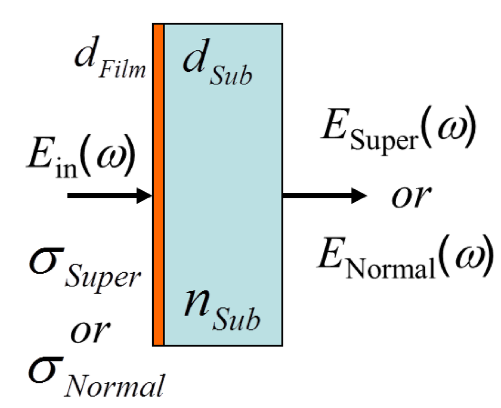


Cross-sectional STEM image of the NbN/AlN/NbN junction with a 2-nm thick AlN barrier. (Left) Bright-field image of (100) surface, and (Right) annular-dark-field image of (110).

Optical transmission spectra of a 41-nm-thick NbN film by THz Time-Domain Spectroscopy





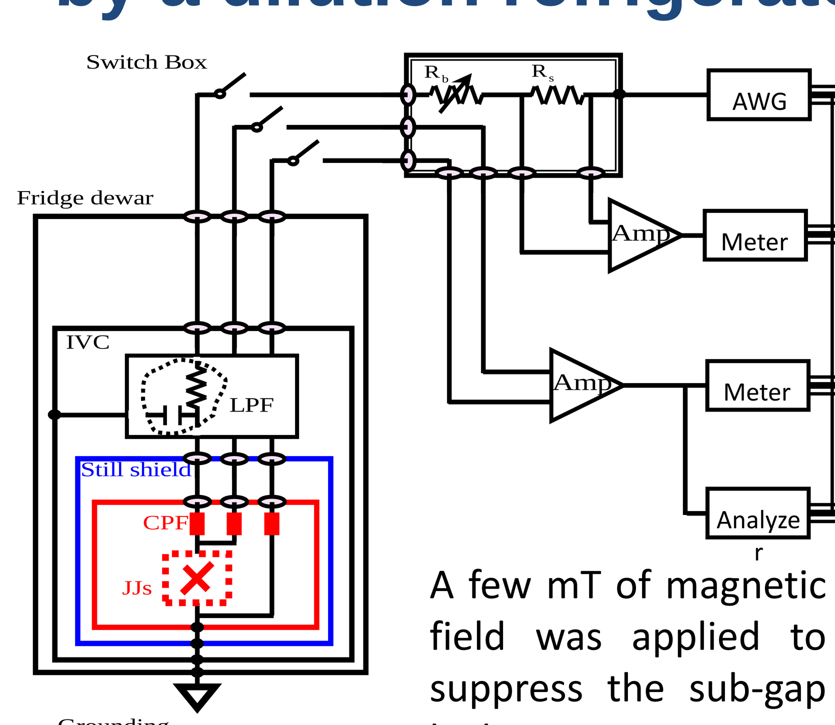


$$\frac{E_{Super}(\omega)}{E_{Normal}(\omega)}\approx\frac{n_{Sub}+1+Z_0 d_{Film}\sigma_{Normal}(\omega)}{n_{Sub}+1+Z_0 d_{Film}\sigma_{Super}(\omega)}$$

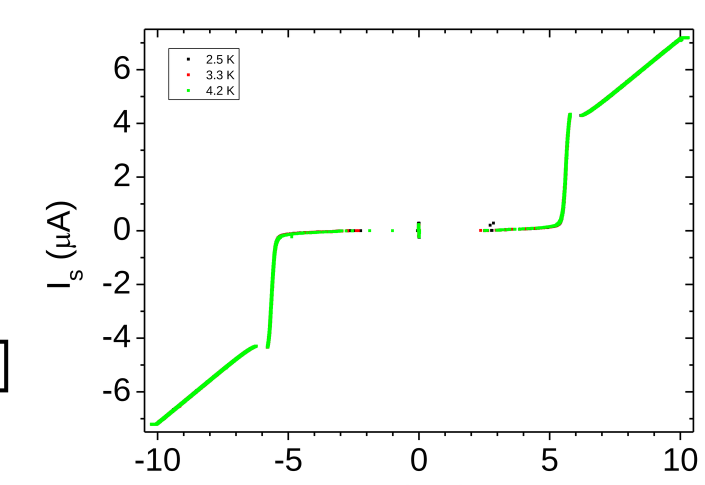
where E: electrical field, σ: conductivity, n: refractive index, d: thickness, Z_0: 377 Ω

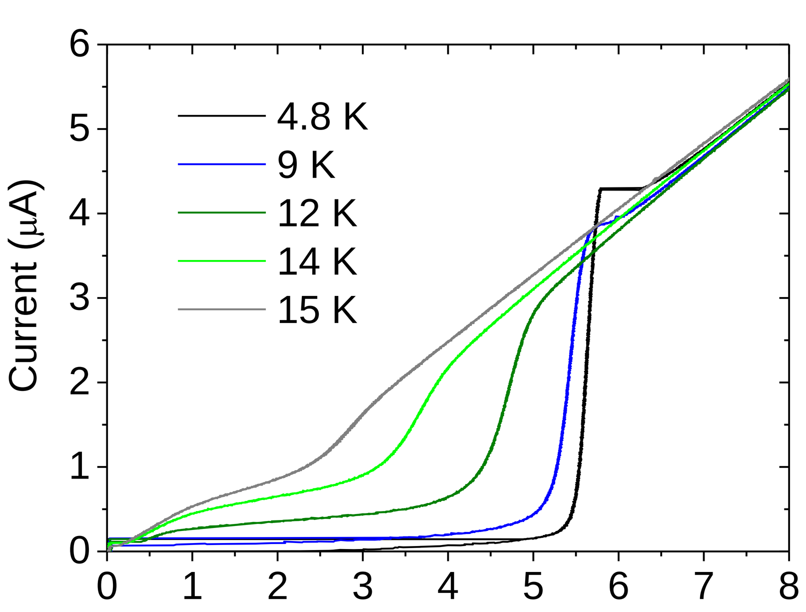
σ_{Super} can be numerically derived.

I-V curve of epitaxial NbN/AlN/NbN junctions by a dilution refrigerator



A few mT of magnetic field was applied to suppress the sub-gap leakage current.

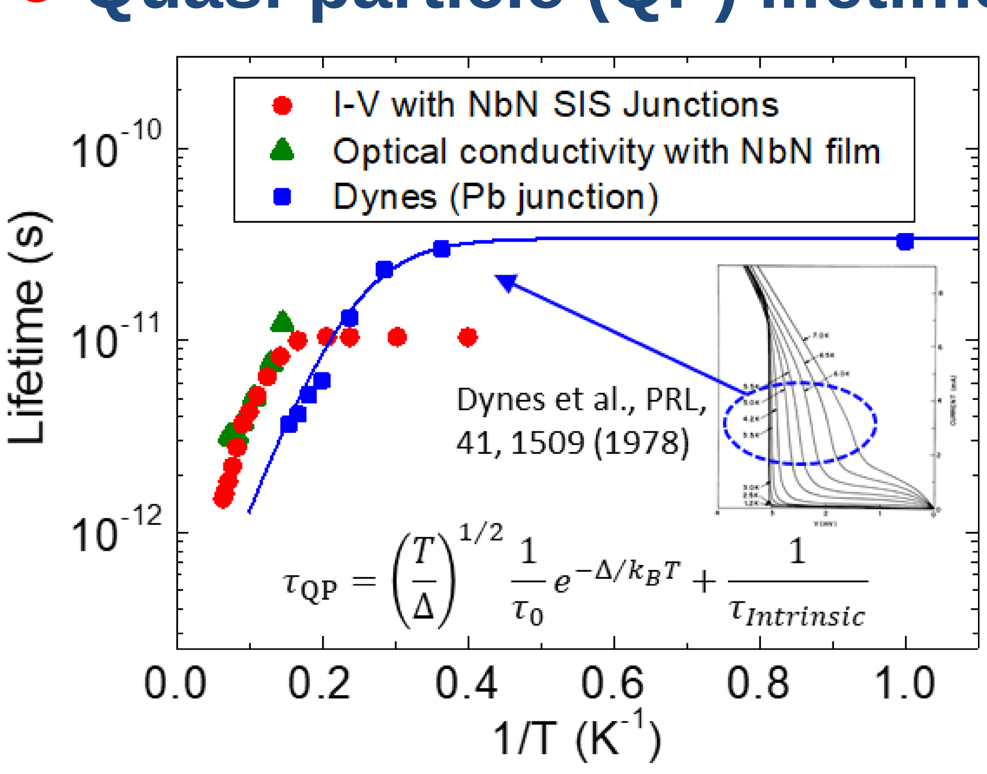




The density of states can be derived by numerical differentiation of *I-V* curves (d*I*/d*V*).

Discussion

Quasi-particle (QP) lifetime = $\hbar/\Delta_2$



A) Near the critical temperatures, the gap broadening may be explained by the QP lifetime in the NbN.

B) At low temperatures, an intrinsic QP lifetime was suggested from I-V curve measurement.

Further investigation is needed to understand a root cause of the intrinsic gap broadening at low temperatures.

Acknowledgement: This work was supported by JSPS KAKENHI Grant Numbers 18H03881 and 19H02205.