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

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Motivation

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

Understanding of fundamental properties

- Superconducting energy gap, Density of states, etc.

Optical and Tunneling Spectroscopy Studies

Results

- Derived optical conductivity

  \[ T = 5.5 \text{ K} \quad 10.5 \quad 20 \text{ K} \]

  \[ T = 12 \text{ K} \quad 10.5 \quad 20 \text{ K} \]

  \[ \sigma \]

  \[ 2 \Delta \]

  \[ \Delta \]

- 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 \( \Delta_i \) becomes larger with increasing temperature.

  \[ 2 \Delta \]

  \[ \Delta \]

  \[ \Delta_0 \]

  \[ \Delta_\text{eff} \]

  \[ \Delta_\text{g} \]

  \[ \Delta_\text{t} \]

- Sample preparation

  - Epitaxial NbN film and NbN/AIN/NbN junctions

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

  Cross-sectional STEM image of the NbN/AIN/NbN junction with a 2 nm thick AIW 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

  \[ E_{\text{Super}}(\omega) \]

  \[ E_{\text{Normal}}(\omega) \]

  \[ n_{\text{sub}} + 1 + Z_0 d f_{\text{film}}^{\text{Normal}}(\omega) \]

  \[ n_{\text{sub}} + 1 + Z_0 d f_{\text{film}}^{\text{Super}}(\omega) \]

  where \( E \) : electrical field, \( r \) : refractive index, \( n \) : thickness, \( Z_0 \) : 377 \( \Omega \)

  \( \sigma_{\text{Super}} \) can be numerically derived.

Discussion

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

  The density of states can be derived by numerical differentiation of I-V curves \( (dI/dV) \).

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

  \[ 4.8 \text{ K} \quad 9 \text{ K} \quad 12 \text{ K} \quad 14 \text{ K} \quad 15 \text{ K} \]

  \[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \]

  \[ V \text{ (mV)} \]

  \[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \]

  \[ I \text{ (mA)} \]

- Quasi-particle (QP) lifetime = \( h/\Delta_2 \)

  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.