Superconducting Tunnel Junction Detectors

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Contents

• Introduction to Superconducting tunnel Junction (STJ)
• Cryogenic amplifier development using silicon-on-insulator for STJ signal amplification.
• Application of low energy threshold STJ
  – COBAND (cosmic background neutrino decay search)
In superconducting state, a pair of electrons around $\epsilon_F$ forms Cooper pair with binding energy of $2\Delta$. $\Rightarrow$ DOS has a gap energy.

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Nb</th>
<th>Ta</th>
<th>Al</th>
<th>Hf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tc[K]</td>
<td>9.23</td>
<td>4.48</td>
<td>1.20</td>
<td>0.165</td>
<td></td>
</tr>
<tr>
<td>$\Delta$[meV]</td>
<td>1100</td>
<td>1.550</td>
<td>0.7</td>
<td>0.172</td>
<td>0.020</td>
</tr>
</tbody>
</table>

$\Delta \sim 1.8k_B T_C$ (BCS theory)
Superconducting Tunnel Junction (STJ) Detector

Superconductor / Insulator /Superconductor
Josephson junction device

- A constant bias voltage ($|V|<2\Delta/e$) is applied across the junction.
- An energy absorbed in the superconductor breaks Cooper pairs and creates tunneling current of quasi-particles proportional to the deposited energy.

$\Delta$: Superconducting gap energy
Tunnel current of Cooper pairs (Josephson current) is seen at $V=0$
Tunnel current of Cooper pairs (Josephson current) is suppressed by applying magnetic field.
STJ current-voltage curve

Signal readout

- Apply a constant bias voltage ($|V|<2\Delta/e$) across the junction and collect tunnel current of quasi particles created by energy deposition

✓ Leak current causes background noise
STJ back-tunneling effect

- Bi-layer fabricated with superconductors of different gaps $\Delta_{\text{Nb}} > \Delta_{\text{Al}}$ to enhance quasi-particle density near the barrier
  - Quasi-particle near the barrier can mediate **multiple Cooper pairs**
- Nb/Al-STJ Nb(200nm)/Al(70nm)/AlOx/Al(70nm)/Nb(200nm)
- Gain: >10
Nb/Al-STJ development at AIST/CRAVITY

50μm sq. Nb/Al-STJ fabricated at CRAVITY

- \( I_{\text{leak}} \sim 200\text{pA} \) for 50μm sq. STJ, and achieved 50pA for 20μm sq.

Need \( \sim 1/10T_c \) for practical operation
Nb/Al-STJ response to pulsed laser

• Nb/Al-STJ has \(~1\mu s\) response time.

Nb/Al-STJ has faster response than other superconductor based detectors

⇒ suitable for single photon (single particle) detection
STJ energy resolution

Signal = Number of quasi-particles created by cooper pair breakings

\[
\frac{E_y}{1.7\Delta}
\]

Resolution = Statistical fluctuation in number of quasi-particles

\[
\sigma_E \sim \sqrt{(1.7\Delta)FE}
\]

⇒ Smaller superconducting gap energy \(\Delta\) yields better energy resolution, but need smaller Tc

Δ: Superconducting gap energy
F: fano factor
E: Deposited energy
STJ energy resolution for X-ray

- 100-pixel Nb/Al-STJ of 200µm sq. size (4mm² in total) fabricated at CRAVITY
- X-ray Absorption Fine Structure (XAFS) Spectrometry in Synchrotron Radiation Facilities
- X-ray fluorescence spectra for BN sample with C and O contamination by the STJ

In this energy region, however, transition edge sensor (TES) gives best energy resolution: $\Delta E = 1.6\text{eV} @ E = 6\text{keV}$
STJ energy resolution for near infrared photon

P. Verhoeve et. al 1997

- 30μm sq. Ta/Al-STJ
- ΔE~130meV @ E=620meV(λ=2μm)
- Charge sensitive amplifier at room temp.
  - Electronic noise ~ 100meV

In sub-eV ~ several-eV region, STJ gives the best energy resolution among superconductor based detectors, but limited by readout electronic noise.
STJ summary

- Typical size: 10\(\mu\)m~200\(\mu\)m square size \(\times\) 100nm~1\(\mu\)m thickness per pixel
  - AIST group achieved 100-pixel STJ sensor
- Need magnetic field \(\sim\)100 gauss
- Operate typically at \(1/10 \times T_c\)
- Superconductor with smaller \(\Delta\) is better, but it has smaller \(T_c\)
- Wide energy range: meV \(\sim\) keV
  - Suitable usage of the STJ is single photon/particle detection in sub-eV \(\sim\) several-eV
- In sub-eV range, the energy resolution is limited by readout electronic noise
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COBAND collaboration is developing cryogenic amplifier to amplify STJ signal at cold stage
FD-SOI-MOSFET at cryogenic temperature

**FD-SOI**: Fully Depleted – Silicon On Insulator

- Very thin channel layer in MOSFET on SiO₂
- No floating body effect caused by charge accumulation in the body
- FD-SOI-MOSFET is reported to work at 4K

Id-Vg curve of W/L=10μm/0.4μm at |Vds|=1.8V

Both p-MOS and n-MOS show excellent performance at 3K and below.

JAXA/ISIS AIPC 1185,286-289(2009)
J Low Temp Phys 167, 602 (2012)
SOI prototype amplifier for demonstration test

Test pulse input through C=1nF at T=350mK
- Power consumption: ~100μW
- Output load: 1MΩ and ~0.5nF
Connect 20μm sq. Nb/Al-STJ and SOI amplifier on the cold stage through a capacitance.
STJ response to laser pulse amplified by Cold amplifier

Demonstrated to show amplification of Nb/Al-STJ response to laser pulse by SOI amplifier situated close to STJ at T=350mK

Development of SOI cryogenic amplifier for STJ signal readout is now moving to the stage of design for practical usage!
Search for Neutrino decay in Cosmic background neutrino ➔ To be observed as far infrared photons of $\lambda \sim 50 \mu m$ (E~ 25meV)
Search for Neutrino decay in Cosmic background neutrino

→ To be observed as far infrared photons of $\lambda \sim 50\mu m$ (E~ 25meV)

$\tau = 1 \times 10^{14} \text{ yrs}$

$m_3 = 50 \text{ meV}$
Search for Neutrino decay in Cosmic background neutrino

⇒ To be observed as far infrared photons of $\lambda \sim 50 \mu m$ (E~ 25meV)

COBAND Rocket Experiment

• 200-sec measurement at an altitude of 200~300km
• Aiming at a sensitivity to $10^{14}$ years for the neutrino lifetime
COBAND rocket experiment sensitivity

- 200-sec measurements with a sounding rocket
- 15cm dia. and 1m focal length telescope and grating in 40~80µm range
- Each pixel in 100µm×100µm×8×50pix. array counts number of photons

\[ \Delta m_{31}^2 = 2.5 \times 10^{-3} \text{eV}^2 \]

\[ \Sigma m_i < 0.23 \text{eV} \]

L-R SM \( \zeta = 0.02 \), \( M(W_2) = 715 \text{GeV} \)

COBAND rocket
200sec meas.

\[ x_{100} \text{ improvement!} \]

S.H. Kim et. al (2012)
Mirizzi et. al (2007)
Sub-GeV Dark Matter Search

- Target: $^{93}\text{Nb}$ (92.9u) $100\mu\text{m} \times 100\mu\text{m} \times 1\mu\text{m} \times 10\text{pix}$
- Measurement time: 10000 sec (~2.8 hours)
- Assume negligible dark count above 350meV threshold

![Graph showing cross-section versus dark matter mass](image)

Sensitive down to 0.1GeV/c^2 DM
Summary

- STJ is the most powerful detector for energy detection in sub-eV ~ several-eV, though it has weakness in its small sensitive area.
- SOI Cryogenic amplifiers for STJ readout is under development and we performed demonstration of STJ signal amplification by a prototype SOI amplifier at T~350mK.
  - SOI cryogenic amplifier is expected to extract maximum potential of STJ.
- COBAND collaboration propose an experimental search for neutrino radiative decay in cosmic neutrino background using STJ.

STJ with SOI cryogenic amplifier has a potential to be the most powerful low energy threshold detector.
Backup
SOI増幅回路一体型STJ検出器(SOI-STJ)

STJ layers are fabricated directly on a SOI pre-amplifier board and cooled down together with the STJ

• Potential to large pixel array integration
FD-SOI on which STJ is fabricated

- Both nMOS and pMOS-FET in FD-SOI wafer on which a STJ is fabricated work fine at temperature down below 1K
- Nb/Al-STJ fabricated at KEK on FD-SOI works fine
- We are also developing SOI-STJ where STJ is fabricated at CRAVITY
Cosmic neutrino background (CνB)

The universe is filled with neutrinos. However, they have not been detected yet!

CνB (=neutrino decoupling) ~1s after the big bang

\[ T_\nu = \left( \frac{4}{11} \right)^{\frac{1}{3}} T_\gamma = 1.95 \text{K} \]
\[ \langle p_\nu \rangle = 0.5 \text{meV} / c \]

\[ n_\nu + n_\overline{\nu} = \frac{3}{4} \left( \frac{T_\nu}{T_\gamma} \right)^3 n_\gamma = 110 / \text{cm}^3 \]

\[ n_\gamma = 411 / \text{cm}^3 \quad T_\gamma = 2.73 \text{K} \]
Motivation of $\nu$-decay search in C$\nu$B

- Search for $\nu_3 \to \nu_{1,2} + \gamma$ in cosmic neutrino background (C$\nu$B)
  - Search for anomalous magnetic moment of neutrino
  - Direct detection of C$\nu$B
  - Determination of neutrino mass: $m_3 = (m_3^2 - m_{1,2}^2)/2E_\gamma$

- Aiming at a sensitivity to $\nu$ lifetime for $\tau(\nu_3) = 0(10^{17}\text{ yrs})$
  - Standard Model expectation: $\tau = 0(10^{43}\text{ yrs})$
  - Experimental lower limit: $\tau > 0(10^{12}\text{ yrs})$
  - L-R symmetric model (for Dirac neutrino) predicts down to $\tau = 0(10^{17}\text{ yrs})$ for $W_L$-$W_R$ mixing angle $\zeta < 0.02$

\[ \nu_{jL} i \sigma_{\mu \nu} q^\nu \nu_{iR} \]

SM: $\text{SU}(2)_L \times \text{U}(1)_Y$

LRS: $\text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1)_{B-L}$

$\Gamma \sim (10^{43} \text{ yr})^{-1}$ Suppressed by $m_\nu$ and GIM

$\Gamma \sim (10^{17} \text{ yr})^{-1}$ Only suppressed by L-R mixing ($\zeta$)
Photon Energy (Wavelength) in Neutrino Decay

\[ \nu_3 \rightarrow \nu_{1,2} + \gamma \]

in the \( \nu_3 \) rest frame

\[ E_\gamma = \frac{m_3^2 - m_{1,2}^2}{2m_3} \]

Two body decay

\( m_3 = 50 \text{ meV} \)

\( E_\gamma = 24.8 \text{ meV} \)  
(\( \lambda = 50 \mu\text{m} \))

\( m_2 = 8.7 \text{ meV} \)
\( m_1 = 1 \text{ meV} \)

\( E_\gamma = 4.4 \text{ meV} \)  
(\( \lambda = 282 \mu\text{m} \))

\( E_\gamma \) distribution in \( \nu_3 \rightarrow \nu_2 + \gamma \)

- From neutrino oscillation
  - \( |\Delta m_{23}^2| = |m_3^2 - m_2^2| \approx 2.4 \times 10^{-3} \text{ eV}^2 \)
  - \( \Delta m_{12}^2 \approx 7.65 \times 10^{-5} \text{ eV}^2 \)
- From Planck+WP+highL+BAO
  - \( \sum m_i < 0.23 \text{ eV} \)

\( \Rightarrow \) \( 50 \text{ meV} < m_3 < 87 \text{ meV} \)

\( E_{\gamma\text{rest}} = 14 \sim 24 \text{ meV} \)  
(\( \lambda_\gamma = 51 \sim 89 \mu\text{m} \))

\[ \lambda_\gamma \] distribution in \( \nu_3 \rightarrow \nu_2 + \gamma \)

Red Shift effect

Sharp Edge

with 1.9K smearing

\( m_3 = 50 \text{ meV} \)

\( 50 \mu\text{m} (25 \text{ meV}) \)
CνB decay signal and Backgrounds

- **Zodiacal Emission (ZE)**
  - \( I_\nu \sim 8 \text{ MJy/sr} \)

- **CIB**
  - \( \lambda I_\lambda \sim 0.1-0.5 \text{ MJy/sr} \)

- **Expected \( E_\gamma \) spectrum**
  - \( m_3 = 50 \text{ meV} \)
  - \( \tau = 3 \times 10^{12} \text{ yrs} \)
  - \( I_\nu \sim 0.8 \text{ MJy/sr} \)
  - Excluded by S.H. Kim et al. 2012

- **CνB decay**
  - \( \lambda = 50 \mu\text{m} \)
  - \( E_\gamma = 25 \text{ meV} \)
  - \( \tau = 1 \times 10^{14} \text{ yrs} \)
  - \( I_\nu \sim 25 \text{ kJy/sr} \)

CIB summary from Matsuura et al. (2011)