X-ray pulse-shape analysis on bridge-type microcalorimeters with Ti-Au transition-edge sensors

Masahiro Ukibe\textsuperscript{a}, Keiichi Tanaka \textsuperscript{b}, Fuminori Hirayama \textsuperscript{a}, Taku Mizuki \textsuperscript{c}, Tomotaka Hikosaka \textsuperscript{d}, Toshimitsu Morooka \textsuperscript{b}, Kazuo Chinone \textsuperscript{b}, Ushio Kawabe \textsuperscript{d}, Toshio Nemoto \textsuperscript{c}, Masao Koyanagi \textsuperscript{a}, Masataka Ohkubo \textsuperscript{a}, Naoto Kobayashi \textsuperscript{a}

\textsuperscript{a} Electrotechnical laboratory, \textsuperscript{b} Seiko Instruments Inc., \textsuperscript{c} Univ. of Meiji, \textsuperscript{d} Chiba Inst. of Tech.
Story

• Introduction
• Experiment
  1) Fabrication of the bridge-type membrane
  2) Fabrication of the TES
  3) Characteristics of TES microcalorimeter
  4) Setup for X-ray measurement
• Results and Discussion
• Summary
**ETL**

*Introduction - 1*

1. **Industry**
   - Microanalysis (EDAX)

2. **Astronomy**
   - Satellite mission
     - (Astro-E, Constellation-X, XEUS)

3. **Biology**
   - Optical spectroscopy

*Advanced ED spectrometer*
- High energy resolution, Fast response time,
- Large detection area
Introduction - 2
Candidate of advanced X-ray detectors
- Microcalorimeter of Transition Edge Sensor (TES)

The status of the art
- Energy resolution: 4.5 eV for 5.89 keV x-ray
- Response time: ~ $10^2$ cps
- Detection area: ~ 0.1 mm$^2$

Goal
- Energy resolution: < 5 eV for 6 keV x-ray
- Response time: > $10^2$ cps
- Detection area: > 50 mm$^2$ (7.5 mm x 7.5 mm)

Increasing the detection area
Array of the TES microcalorimeters
**Introduction - 3**

Array of the TES microcalorimeters

**Conventional TES**

- Frangible structure
  1. Thin membrane < 1µm
  2. Open space under the membrane

Difficult to make large scale array of TESs

Improving the robustness

New membrane structure - **Bridge type membrane**
**Experiment - 1**

1) Fabrication of bridge type membrane

1. Cleaning of a SOI wafer to remove a oxide layer in buffered HF.
2. Deposition of SiNx layer (<1 µm) on the front side of the SOI by plasma-CVD in SH₄ and N₂ gases.
3. Deposition and patterning of Al layer on the SiNx layer.
4. RIE etching of SiNx with SF₆ and O₂ gases, and then removing of the Al mask.
5. After the making the TES, absorber, and wires, anisotropic etching of the SOI layer from the front side in Hydrazine monohydrate solution at 73 ºC for about 4 hours.
Experiment - 2

2) Fabrication of TES

1. Deposition of Ti(70 nm) and Au(30 nm) films on the SOI wafer by RF-sputtering and patterning by 1% HF and KI+I solutions, respectively.

2. Deposition of 300 nm-thick Au absorber layer on the Ti/Au bilayer by RF-sputtering and patterning by lift-off technique.

3. Deposition of 200 nm-thick Nb film by RF-sputtering and forming of electric leads with lift-off technique.
**Experiment - 3**  
**TES microcalorimeter**

**Membrane**

Size TES : 500 µm x 1000 µm  
Absorber : 300 µm x 300 µm  
Membrane : 2100 µm x 700 µm  
Membrane Thickness : 1 µm  
SOI wafer : Si(30-50)/SiO$_2$(1)/Si(525) in µm, (100) orientation
Experiment - 4

3) Characteristics of TES microcalorimeter

Normal resistance
\[ R_N : 0.27 \, \Omega \]

Transition temperature
\[ T_C : 0.43 \, \text{K} \]

Thermal conductance
\[ G : 13 \, \text{nW/K} \]
\[ K : 41 \, \text{nW/K} \]
4) Setup for X-ray measurement

Bias resistance
\[ R_{\text{bisa}} : 0.1 \, \Omega \]
SQUID amp gain
\[ A_{\text{SQUID}} : 600 \, \text{V/A} \]
RT amp gain
\[ A_{\text{RT}} : 100 \]
X-ray source : \(^{55}\text{Fe}\)
\[ K_\alpha : 5.89 \, \text{keV} \]
\[ K_\beta : 6.49 \, \text{keV} \]
### Experiment - 6

4) Setup for X-ray measurement - SQUID array

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{SQUID}}$</td>
<td>200</td>
</tr>
<tr>
<td>$S_{\text{SQUID}}$</td>
<td>5.8 pA/ Hz$^{1/2}$</td>
</tr>
<tr>
<td>$B_{\text{SQUID}}$</td>
<td>1 MHz</td>
</tr>
<tr>
<td>$M_{\text{input}}$</td>
<td>60pH</td>
</tr>
<tr>
<td>$A_{\text{SQUID}}$</td>
<td>600 V/A</td>
</tr>
<tr>
<td>$T_{\text{OPERATE}}$</td>
<td>4.2 K</td>
</tr>
</tbody>
</table>

SQUID array
Results and Discussion - 1

Feedback curve

Narrow plateau region (ETF region) of $P_{JOULE}(V_{Bias})$

Large $R_{bias}$: 0.1 Ω

Residual Resistance($R_{resi}$) of the bias circuit 25 mΩ

Bias current($I_{Bias}$) and Joule power($P_{JOULE}$) as a function of bias Voltage($V_{Bias}$)

TES(Ti:70nm Au:30nm) $R_{Bias} = 0.1\,Ω$ and $R_0 = 0.27\,Ω$
**Results and Discussion - 2**

**X-ray pulse**

**Operation condition**

- $V_{Bisa}$: 18 $\mu$V
- $I_{Bias}$: 70 $\mu$A
- TES resistance $R$: 0.25 $\Omega$
- TES temperature $T_{OPERATE}$: 0.43 K
- Bath temperature $T_{BATH}$: 0.35 K

There are two types of pulses: **Large** and **Small** pulses.


**Results and Discussion - 3**

**Large pulse**

\[ \tau_{rise} : \sim 3 \mu \text{sec} \]

\[ \tau_{decay1} : \sim 10 \mu \text{sec} \]

\[ \tau_{decay2} : \sim 130 \mu \text{sec} \]

**Fitted curve**

\[ a_1 + (a_2 - a_3 \exp(-\frac{t}{\tau_{rise}})) \times (a_4 \exp(-\frac{t}{\tau_{decay1}}) + a_5 \exp(-\frac{t}{\tau_{decay2}})) \]

- **Pulse height (mV)**
- **Time (µsec)**
Results and Discussion - 4

Small pulse

$\tau_{\text{rise}} : \sim 10 \mu\text{sec}$

$\tau_{\text{decay1}} : \sim 130 \mu\text{sec}$

Fitted curve

$$a_1 + (a_2 - a_3 \exp(-\frac{t}{\tau_{\text{rise}}})) \times a_4 \exp(-\frac{t}{\tau_{\text{decay1}}})$$
ETL

Results and Discussion - 5
Estimation of time constants - 1

1. Slow decay time: \( \sim 130 \mu\text{sec} \)

Effective response time (\( \tau_{\text{eff}} \)) of TES

\[
\tau_{\text{eff}} = C / G (1 + \alpha \phi / n) \\
\phi = 1 - (T_{\text{BATH}} / T_{\text{OPERATE}})^n \\
G = n KT_{\text{OPERATE}}^{(n-1)} \\
\alpha \approx 50, \quad T_{\text{OPERATE}} = 0.43 \text{ K}, \quad T_{\text{BATH}} = 0.35 \text{ K} \\
\rightarrow \tau_{\text{eff}} = 115 \mu\text{sec}
\]

2. Rise decay time of large pulses: \( \sim 3 \mu\text{sec} \)

Electrical response time (\( \tau_{\text{ele}} \)) of TES

\[
\tau_{\text{ele}} = L / R \\
R = 0.25 \Omega, \quad L \approx 1 \mu\text{H} \\
\rightarrow \tau_{\text{ele}} = 4 \mu\text{sec}
\]
Results and Discussion - 6
Estimation of time constants - 2

3. Fast decay time of large pulses and rise time of small pulses

\[ \tau_1 \approx 10 \, \mu\text{sec} \]

Time of heat transfer between TES and Absorber

Time constant of large pulses: TES to Absorber
Time constant of small pulses: Absorber to TES
Summary

- We have fabricated the bridge-type TES microcalorimeters. (Ti(70 nm)/Au(30 nm) bilayer TES and Au(300 nm) absorber)
- 5.9 keV X-ray was measurement with 200-series array of SQUIDs.
- X-ray pulses are put into two categories.
  1) Large pulse: Large pulse height, Fast rise and two decay time
  2) Small pulse: Small pulse height, Slow rise and one decay time
  3) Large pulses → X-ray events in the TES
  4) Small pulses ← X-ray events in the absorber
Each TES size
TES: 500 µm x 1000 µm
Absorber: 300 µm x 300 µm
Membrane: 2100 µm x 700 µm

The total 5 x 5 array size
7 mm x 11 mm