Thermal properties of calorimeters with Ti/Au transition-edge sensors on silicon nitride membranes

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Abstract

We are developing X-ray microcalorimeters employing superconducting-transition-edge sensors (TESs) for relatively high operation-temperatures of an \(^3\text{He} \) cryostat. The TESs are proximity bilayers of Ti and Au. An important thermal parameter, the thermal conductance \( G \), of the microcalorimeters on SiN\(_x\) membranes was evaluated by a simple method using \( R-T \) curves at different bias currents. It has been shown that the \( G \) value can be controlled by altering the membrane thickness and size. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Advanced X-ray detectors for energy dispersive spectroscopy should achieve a high-energy resolution and a fast response time. A promising X-ray detector is a microcalorimeter equipped with a superconducting-transition-edge sensor (TES) operated in a strong electrothermal feedback mode. The energy resolution of the TES microcalorimeter has recently reached 7.2 eV for 5.9 keV X-rays with a photon count rate of 150 cps [1]. The theoretical energy resolution (\( \Delta E \)) and response time (\( \tau \)) [2,3] of TES calorimeters are expressed by

\[
\Delta E_{\text{FWHM}} = 2.355 \sqrt{\frac{4k_B T^2 C n/2}{\alpha}}
\]

and

\[
\tau = \frac{C/G}{1 + \alpha \phi/n}
\]

where \( T \) is the operating temperature, \( C \) is the heat capacity, \( G \) is the thermal conductance, \( n \) is the power-law dependence of the thermal impedance between the heat bath and the electrons in the TES, \( \alpha \) is the logarithmic transition sensitivity, \( \Delta \)ln \( R/\Delta \)ln \( T \), and \( \phi \) is related to the temperature of the heat bath \( T_b \) by \( \phi = 1 - (T_b/T)^n \). A straightforward means of achieving a high-energy resolution is to operate the TES calorimeters at as low a temperature as possible. However, it is difficult to obtain a fast response time at low operating temperatures [3]. We are, therefore, developing TES microcalorimeters for operation at high temperatures of about 0.4 K, which can be continuously maintained by using an \(^3\text{He} \) cryostat. For this temperature, a proximity Ti/Au bilayer is a possible combination. Important parameters for obtaining...
Fig. 1. \( R-T \) curves at two bias currents for a TES-A sample on the 500 nm-thick membrane. The \( T_c \) value without the self-heating effects is 0.388 K.

### 2. Experiment

Our X-ray microcalorimeters consist of bilayer TESs of Ti(60 nm) and Au(40 nm), Au absorbers with a thickness of 300 nm, Nb leads, and polycrystalline silicon nitride (SiN\( _x \)) membranes. All layers were deposited by RF-sputtering. The size of the TESs and the absorbers were 1.0 x 0.5 mm\(^2\) and 0.3 x 0.3 mm\(^2\), respectively. The calorimeters were fabricated on two types of membranes with sizes of 1.5 x 1.5 mm\(^2\) (TES-A), and 1.5 x 1.0 mm\(^2\) (TES-B). The \( G \) values of TES-A and TES-B were evaluated at a membrane thicknesses of 500, 750, and 1000 nm.

Resistance versus temperature (\( R-T \)) curves of the TESs were measured in a \( ^3 \)He cryostat by the lock-in technique, sweeping \( T \) at a rate of below 0.5 mK/S. The \( G \) values were obtained by the following procedure. \( T \) is governed by the differential equation of

\[
C \frac{dT}{dt} = RI^2 - K(T^n - T_b^n)
\]

(3)

where \( K \) is a material and geometry-dependent parameter [3]. When the \( T_b \) is close to the \( T \), Eq. (3) can be approximated by

\[
C \frac{dT}{dt} = RI^2 - G(T - T_b)
\]

(4)

where \( G \) is expressed by

\[
G = nKT \left( T_b \right)^{n-1}
\]

In our experiments, the \( C \) value is typically of the order of \( 10^{-12} \), \( dT/dt \) is less than 0.5 mK/S, and \( n \) is 4 for SiN\( _x \) membranes in a surface-scattering dominant case [5]. Therefore, the left-hand side of Eq. (4) leads to a value in the order of between \( 10^{-16} \) and \( 10^{-15} \). This is negligibly small, so that the Joule-heating balances with the heat flow to the bath. As a result, Eq. (4) can be reduced to

\[
RI^2 = G(T - T_b).
\]

(5)

The TES becomes the superconducting state at different \( T_b \) values, depending on bias currents, because of Joule-heating effects. From the \( R-T \) curves at two bias currents, two different \( T_b \) values are obtained at the same \( R \) value just before the superconducting transition. By inserting these \( T_b \) values into Eq. (5), the \( G \) value can be calculated.

### 3. Results and discussion

A typical example of the Joule-heating effects on the \( R-T \) curves of a TES-A sample on the 500 nm-thick membrane is shown in Fig. 1.

It is seen that at 10 \( \mu \)A the TES becomes superconducting at the \( T_b \) lower than that at 900 nA because of the Joule-heating. By using Eq. (5), the \( G \) value of this calorimeter is calculated to be 9.7 n W/K. The \( G \) values of the other calorimeters on the membrane with different thickness were obtained by the same procedure.

Each TES has a slightly different \( G \) value between 0.38 and 0.47 K and the \( G \) depends on \( T \), so that the \( G \) values are not appropriate for representing the influence of the calorimeter geometry on the thermal properties. Therefore, the \( K \) values were hereafter used instead of the \( G \) values. Fig. 2 shows the dependences of \( K \) on the membrane thickness for TES-A and TES-B.

A general trend of \( K \) value to increase with increasing the membrane thickness is observed.
The thickness dependence of $K$ is caused by the reduction of the membrane cross-section. It should be noted that the slope of $K$ with respect to the thickness is greater for the case of TES-B than the case of TES-A. This difference may show the effects of the membrane shapes, but systematic experiments are necessary.

Next, we estimate the performance of our calorimeter. The smallest $G$ and $K$ values were 4 nW/K and 18 nW/K for the TES-B sample on the 500 nm-thick membrane. This TES has a normal resistance $R_n$ of 0.7 $\Omega$, a $T_c$ value of 0.383 K, a $C$ value of 10 pJ/K, and an $\alpha$ value of 500. According to Eq. (1) and (2), this microcalorimeter is expected to have an energy resolution of 7.0 eV and a response time of 65 $\mu$s for the 6-keV X-rays. The intrinsic X-ray detection efficiency is estimated to be more than 20%.

4. Conclusion

We made the TES calorimeters consisting of the Ti/Au bilayer TESs with a thickness of 100 nm, the Au absorbers with a thickness of 300 nm, the Nb leads, and the SiN$_x$ membranes. The $G$ values of the microcalorimeters were evaluated by a simple method using $R$--$T$ curves. The thermal properties of the TESs depend on the membrane thickness and size. However, since even the smallest $G$ value is considerably larger than the value for the proper operation of the calorimeters, the $G$ value should be made smaller. Therefore, we plan to fabricate thinner SiN$_x$ membranes or to create a bridge-like membrane structure to reduce the heat flow to the bath at a relatively high temperature of $\sim$ 0.4 K.

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