A New X-ray Microcalorimeter Based on a Pixel-lated TES Array

Daiji Fukuda, Masashi Ohno, Hiroyuki Takahashi, Tadashi Inou, Yuichi Kunieda, Manabu Ataka, Masataka Ohkubo, and Masaharu Nakazawa

Abstract— We are developing a new x-ray microcalorimeter based on superconducting transition edge sensors (TES) as an imaging sensor. This device has ten pixel-lated transition edge sensors with Iridium superconductive films. When a constant bias voltage is applied to all pixels, each pixel is operated at slightly different equilibrium temperature. This arises from the different thermal responses between pixels, so that response signal shapes would vary according to the position of the incident x-ray. We have fabricated a prototype of the pixel-lated array and examined its performance. The position dependency measurements by scanning the collimated x-ray over the device have successfully shown that the device is able to resolve its pixel position. The energy resolution of a test device was 13.1 eV (FWHM) for 3 keV x-rays.

I. INTRODUCTION

MICROCALORIMETERS with superconducting transition edge sensors (TES) have shown an excellent performance in energy resolution [1], [2]. The success of the single TES is now leading to a demand for large detecting arrays for material and astromonal applications [3]. For this purpose arrayed TESs and their readout circuits are being developed. Readout circuits using Superconducting Quantum Interference Device (SQUID) multiplexers are promising for such an array. Currently, two multiplexing methods are proposed; a time domain approach [4] and a frequency domain approach [5]. Minimal crosstalks and very high signal-to-noise ratios are required for those readout devices in order to achieve very high energy resolution.

Apart from the ideas of arrayed TES and multiplexing readout, a new detector concept has been proposed that is based on a position-dependent thermal diffusion process of the incident x-ray energy [6]. In Goddard/NASA group, a position sensitive TES (PoST) has been developed and successfully shown its position sensitive performance and 32 eV energy resolution at 1.5 keV x-ray energy. This device requires only two SQUID current amplifiers to readout 7 pixels. Thus, these intelligent microcalorimeters such as PoST are very useful for simplifying the readout circuits.

Here, we have proposed another detector concept to realize a position-sensitive TES microcalorimeter. This device consists of an 1-dimensional array of ten pixel-lated TESs. When a constant bias voltage is applied to pixels in parallel, each TES is biased at a different equilibrium temperature, so that response signals would reflect a different thermal response of each TES pixel. This means that we can obtain position information of the incident x-ray from the pulse shape. This device, in principle, needs only one SQUID amplifier for reading out the signal.

We have fabricated this pixel-lated TES array with a superconductor iridium and analyzed its signal properties. In this paper, we present the design and the results of a pixel-lated TES array.

II. THE DEVICE DESIGN

Figure 1 shows a photograph of a pixel-lated TES array. The one-dimensional TES array is wide along the x direction, and the total TES area is $800 \times 160 \, \mu \text{m}^2$. The array is divided into 10 pixels with nine thin slits of $6 \, \mu \text{m}$ wide and $140 \mu \text{m}$ long. Each pixel is $74 \times 160 \, \mu \text{m}^2$. The TES was fabricated with iridium and no absorber was used. We believe the thermo-dynamical and electrical properties such as a transition temperature, local resistivity and thickness of each pixel, are uniform over the entire area because the iridium is sputtered with a large target of 4 inches. The voltage bias is applied in parallel to each TES pixel through superconducting niobium electrode. Our Ir films have a transition temperature of 139 mK, transition width of 0.5 mK, a resistivity at 4.2 K of $100 \times 10^{-9} \Omega \text{m}$, and a RRR of 1.6 [7], [8]. The membrane size is $1400 \, \mu \text{m}$ square and 400 nm thickness. The device is not centered on the membrane, slightly shifted to 10$\mu \text{m}$ right. This shift will influence the unsymmetrical temperature distribution inside the pixel array. The device is mounted on a cold stage in a dilution refrigerator, operating the base temperature at 50 mK. Current signals are read-out by the 200 series SQUID current amplifier [9]. The normal resistance $R_n$ of the device is 194 m$\Omega$ from the measurement of current voltage characteristics. The thermal conductance is 320 pW/K at the base temperature of 50 mK.

![Fig. 1. The configuration of pixel-lated TES array. The device has 10 TES pixels with the iridium films.](image)
III. PULSE HEIGHT AND RISE TIME ANALYSIS

To analyze the signal property of the pixellated TES array, LTSSM (Low Temperature Scanning Synchrotron Microscope) measurements were performed by using a beam line of an SR facility, TERAS at AIST. Both 1-D and 2-D mapping of response signal properties can be obtained by scanning the collimated x-ray beam on the device and by storing all measured waveforms. We have used 3keV x-rays collimated with a φ20μm pin hole. The details of the LTSSM are described in reference [10].

Figure 2 shows measured 2-D profiles at bias voltage of 1.25 μV. At this bias point, the dynamic resistance R of the device was 57% of Rn. The current integral Pi in figure 2 (a) is defined as the following equation,

\[ P_i = \frac{2\beta}{1+\beta} \int V \Delta I(t) dt, \]  

where \( \beta = (R - R_s)/(R + R_s) \) is a parameter that characterizes the nonideal voltage bias. \( R_b \) is shunt resistance plus residual resistance. In this bias point, \( \beta \) is 0.78 for \( R_b \) of 13.7 mΩ. As shown in figure 2 (a), \( P_i \) is relatively flat over the entire device area.

\[ P_i = \frac{\beta L_0}{1 + \beta L_0} E, \]  

where, \( E \) is an absorbed photon energy. Thus, \( P_i \) approaches to \( E \) with large loop gain \( L_0 \). The current integral \( P_i \) in figure 2 (a) is calculated to be 2830 eV for the incident energy of 3keV. From these, we can deduce the loop gain \( L_0 \) of 21.3 at the bias point. The \( L_0 \) is comparable to that of the other bilayered TES [11].

The pulse height of a current pulse signal \( \Delta I \), on the other hand, depends strongly on the incident x-ray position as shown in figure 2 (b). The observed pulse height should be proportional to the thermal response (\( \alpha = T/R \cdot dR/dT \)) of the pixels around the incident x-ray position. The variation of the pulse height in figure 2 (b) means that the thermal responsivity of each pixel is not uniform over the entire sensitive area. As an extreme case, if the thermal diffusion of the incident energy is localized in the incident pixel, \( \Delta I \) is determined by the resistance change \( \Delta r \) of the incident pixel. Since the saturation resistance \( r_n \) is almost same for each pixel and therefore, provided by \( r_n = R_n \times 10 \). One can know the initial resistance \( r_0 \) of the incident pixel from the signal resistance change \( \Delta r \) by \( r_0 = r_n - \Delta r \). The \( r_0 \) is related to the temperature of the pixel. Therefore one can guess the initial temperature of the pixel from the pulse height of saturated signals. From these observations, the pulse height distribution of saturated signals is related to the initial temperature distribution of each pixel. Figure 3 shows the 1-D scanning results of the pulse height at various bias voltages. The heat diffusion length of the incident x-ray energy of 3 keV is estimated to be 140 μm from the
observed signal rise time of 40 $\mu$s at 1.25 $\mu$V bias. This diffusion length is more than 3 times of one unit pixel width of 80 $\mu$m, however, we ignore possible cross talk effect for simplicity. At the center region in fig. 3, the observed pulse height is smaller than that of the peripheral pixels and gradually increasing at the end. This implies that the pixel was biased at higher $r_0$ so that the temperature of the center pixels would be hotter than that of the peripheral region. On the other hand, at the peripheral region the large $\Delta T$ means the pixel was biased at lower temperature. The thermal responsivity $\alpha$ becomes large when the $r_0$ is biased at low resistance. Therefore, the pixels at the peripheral region has a large $\alpha$. The thermal conductance of the Iridium film is relatively worse compared to that of other bilayered TES. Our recent experiments showed that an iridium microcalorimeter with a large area will split into two phases of a superconducting and a normal conductive state because of a self-heating effect [7], [12]. We think this different equilibrium temperature of each pixel would cause the pulse height differences. A theoretical and numerical analysis of the detail temperature distribution is now in progress.

The temperature difference of each pixel is also responsible for the rise time property of the device. Figure 5 shows the bias-voltage dependence of the rise time profiles along x-direction. It is clearly visible that the profile is symmetric and changing as decreasing the bias voltage. At a higher bias voltage of 1.50 $\mu$V, the rise time becomes shorter at both sides because of a large $\alpha$. The $\alpha$ of the center region is relatively small, which results in a longer rise time. At lowering the bias voltage, the rise time profile becomes flat. A lower bias voltage means smaller Joule heating at the same dynamic resistance. This in turn shifts the bias point to a lower $r_0$, so that $\alpha$ near the center pixels would become larger. These observations are well consistent with the temperature profile shown in fig. 4.

It is worthy to note that the measured spatial dependence of pulse height along the y direction is relatively small. This might be due to a rapid thermal diffusion process within the pixel, compared to the observed signal decay time.

IV. Position Sensitivity and Energy Resolution

Because of the rise time and pulse height differences, we can easily identify the pixel where an x-ray photon is incident. Figure 6 shows the scatter plots for the rise time and the pulse height of each incident position. It is clearly observed that each signal event concentrates at ten regions which correspond to pixel numbers in fig. 1.

This profile was obtained only by one SQUID current amplifier. The effective time constant was 80 $\mu$s at this bias voltage, which ensures reasonably fast response of our detector.

The relation between the rise time and the pulse height is not one to one, so that the identification of each pixel becomes difficult if the various energy of the incident x-ray comes into the device. However this can be solved by changing the temperature distribution inside the device. As an example, figure 6 (b) shows the scatter plots of rise time and the pulse height at the bias voltage of 1.59 $\mu$V. At this voltage, the dynamic resistance of the TES is 180 $\Omega$, that is 93% of the $R_n$. Thus the whole pixels are operated near the normal state, except that the right side of the pixels (number 9,10) have a lower $r_0$ and hence a high thermal sensitivity. The left side pixel is also operated near the normal state because of unsymmetrical thermal conductance $G$ along the x-direction. In this case, the most of heat must diffuse to the right side. Therefore the rise time becomes slower as the incident position is left. The signal to noise ratio is not good.
at the bias voltage, however, the relation in fig 6 (b) shows that the pixel determination can be made only from the rise time information. This suggests that if the temperature of each pixel is different gradually along the x direction, the risetime of signals will change affecting the temperature distribution. This configuration will be realized by optimizing the thermal conductance for each pixel.

The energy resolution of the pixellated TES array is 26.0 eV (FWHM) for 5.9keV x-rays by irradiating the whole device area [13]. This resolution, however, is restricted by the incomplete separation of each pixel. If we irradiate the center of pixel with a collimated x-ray beam of $\phi/20 \mu m$, we have achieved the 13.1 eV for 3 keV x-ray, as shown in figure 7. The energy resolution is close to the base line noise of 10.7 eV. We expect the energy resolution of 26.0 eV will be improved by reducing the position dependency within the pixel.

V. CONCLUSION

We have developed a new position sensitive TES microcalorimeter with a pixellated TES array. The response signals of the device showed the risetime and pulse height depended strongly on the position of the incident pixel. This leaded to be able to determine the incident x-ray position. The energy resolution was 26.0 eV(FWHM) for 5.9keV x-ray of the entire illumination, however, this can be improved to 13.1 eV(FWHM) for 3 keV by irradiating the center of the pixel. Our device successfully showed that the ten pixel readout with only one SQUID current amplifier. This is very useful to simplify the read-out circuits for a future multi-pixel TES microcalorimeter.

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