Development of the multi-pixel x-ray microcalorimeters

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ABSTRACT

An x-ray microcalorimeter is a promising x-ray spectrometer for its extremely good energy resolution and its good detecting efficiency. We are developing an x-ray microcalorimeter for high energy resolution x-ray imaging application.

The energy resolution of 43eV(FWHM) at 5.9keV is obtained with our x-ray microcalorimeter.

The intrinsic performance of our x-ray microcalorimeter was estimated to be 10.4eV(FWHM) at 5.9keV. This value is more than 10 times better than that of the conventional x-ray CCD.

Keywords: x-ray, calorimeter, spectrometer, low temperature, temperature sensor.

1 INTRODUCTION

An x-ray microcalorimeter is a kind of x-ray sensors, which measures the incident energy of a single photon as a temperature change. The energy resolution can be expected to be ~1eV at low temperature and it is sensitive in wide energy range of ~several tens eV.

In the field of the x-ray astronomy, an extremely good energy resolution x-ray spectrometer is strongly requested. Through x-ray observation of astronomical objects with a high energy resolution x-ray spectrometer, we can learn more about high-energy phenomena in the universe. Particularly, an x-ray of the energy range of 0.3-8 keV, there exist K and L emission- and absorption-lines from various elements (e.g., O, Mg, Si, S, Ar, Fe, and Ni). These lines contain much information about high-energy phenomena. A high energy resolution of 1-10eV is essential to resolve these absorption- and emission- lines.[1][2]

In terms of industrial or another academic use, such an x-ray spectrometers of high performance have a potential to obtain a new information by material or chemical analysis through x-ray observations.

Thus, we are developing an x-ray microcalorimeter of ~10eV in energy resolution and the x-ray microcalorimeter is also expected to be realized to be 1000 pixel array for imaging. In our previous work, an x-ray microcalorimeter, which can be fabricated by wafer level process was reported. [3] For a single pixel x-ray microcalorimeter, ΔE ~4 eV at 5.9keV has been reported so far. [4][5]

2 WORKING PRINCIPLES

2.1 Pulse Shape

A typical x-ray microcalorimeter consists of three important functional elements; an x-ray absorber which changes the incident energy to a temperature rise, a temperature sensor to observe the resulting temperature change of the absorbing event and the microstructure to thermally isolate the pixel and the substrate.

As shown in Fig.1, the energy of the absorbed photon is converted to heat in the x-ray absorber. Then, the temperature of the calorimeter pixel rises rapidly. The temperature change T is given as $T=E/C$, where E is the incident energy and C is the heat capacity of the pixel. This temperature change is transfered into the resistance change at the temperature sensor, which is located below the absorber. Due to the pixel is coupled to the substrate by a weak thermal link, the temperature of the pixel decays to the initial operating temperature with a time constant τ_0. The time constant is given as follows.

$$\tau_0=C/G \quad (1)$$

Where G is the thermal conductance between the substrate and the calorimeter pixel. The resulting temperature change of the calorimeter pixel is shown in Fig.2.

2.2 Energy Resolution

The theoretical energy resolution of an x-ray microcalorimeter is limited by intrinsic noises such as the phonon noise due to thermal fluctuation and the Johnson noise of the temperature sensor. Considering these intrinsic noises and the sensitivity of the temperature sensor, the energy resolution of an x-ray microcalorimeter is given as following equation.

$$E_{FWHM} = 2.35\xi\sqrt{k_B T^2 C} \quad (2)$$

Where k_B is the Boltzmann constant and is a parameter depends on the sensitivity of the temperature sensor . and are written as follows.

$$\xi = \frac{1}{\sqrt{\alpha}} \quad (3)$$

$$\alpha = \frac{d\log R}{d\log T} \quad (4)$$

Where R is the resistance of the temperature sensor and T is the temperature of the pixel.

According to eq.2, the energy resolution is improved under extremely low temperature circumstance. Specific heat of the most kinds of materials is propotional to T^3 (for lattices) or T (for electrons). This fact also indicates that the energy resolution of the x-ray microcalorimeter is improved when it is used under low temperature. Thus, it is typically operated about 0.1K or lower.[6]

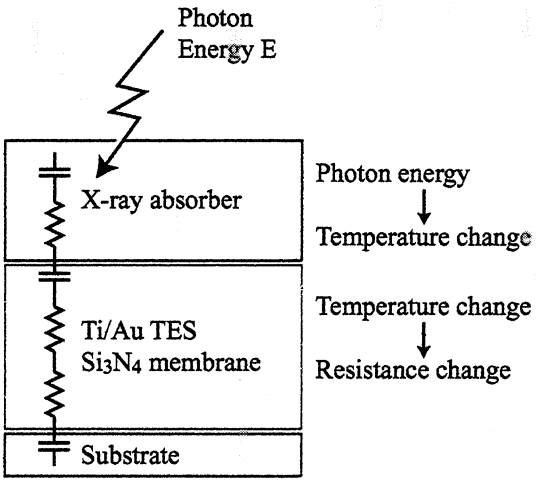


Figure 1: A thermal equivalent circuit of an x-ray microcalorimeter.

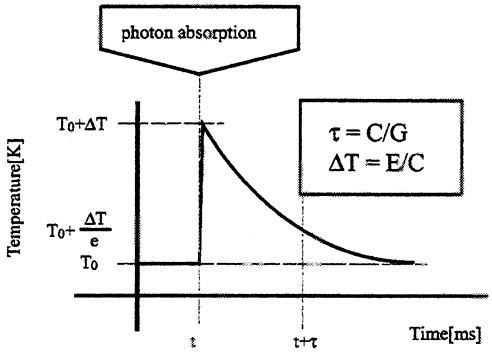


Figure 2: A typical pulse shape of an x-ray microcalorimter

2.3 Transition-edge Sensor (TES)

The temperature rise (ΔT) caused by the photon absorption event is calculated to be several mK by $\Delta T = E/C$. E is the incidental energy and C is the heat capacitance of the x-ray microcalorimeter pixel. And ΔT is propotional to the energy of the incident photon. This indicates that the temperature sensor is required very high sensitivity during the narrow range of several mK for an x-ray microcalorimeter application.

By using the sharp resistance change from normal state to superconducting state transition of the superconducting material, significantly large α is obtained. This kind of the temperature sensor is called transition-edge sensor (TES). Under a constant voltage-bias circuit, a strong negative electro-thermal feedback (ETF) is applied to the TES. The resistance of the TES rapidly follows to the heat input. Due to the constant voltage-bias operation, the current decreases when the resistance rises and the Joule power also decreases. Thus, the operating point of the TES is self-regulated within the narrow transition edge. Applying the ETF, the thermal time constant given as $\tau_0 = C/G$ is reduced by a factor of α. By reducing α, the x-ray microcalorimeter can achieve higher count rate.[2]

We have developed titanium-gold bilayer as a TES for our x-ray microcalorimeter. According to eq.1, the energy resolution of the x-ray microcalorimeter is determined by the operating temperature T and the sensitivity of the temperature sensor α. In case of the TES x-ray microcalorimeters, the operating temperature is equal to the transition temperature T_c of the TES. To obtain low transition temperature of the Ti-Au TES, the thickness of Ti and Au are optimized to 100nm and 200nm. Under this condition, the transition temperature is reduced to 0.194mK by the proximity effect. Usually, the sharpness of the transition edge is degraded when the superconducting material is patterned into fine microstructure because the

effect of the current at the sidewall becomes dominant. So far, it is reported that the overhang of the normal conducting layer can dissolve this effect with a good reproducibility [6]. We have applied this method to our TES and obtained sharp transition of $\alpha \sim 600$. Figure 3 shows the resistance temperature characteristics.

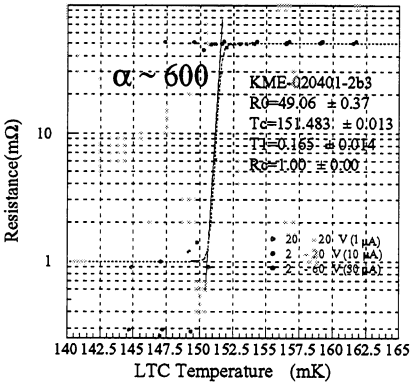


Figure 3: Resintance-Temperature characteristics of the Ti-Au TES

3 DESIGN AND FBRICATION

The structure of our x-ray microcalorimeter is shown in fig.4. The size of the pixel is determined to 500μm x 500μm. The Ti-Au TES (Ti: 100nm, Au: 200nm) is located on the Si_3N_4 and SiO_2 membrane. The SiO_2 layer compensates the stress of Si_3N_4 and also it is used as an etch-stop layer. The Ti-Au TES is 300μm x 300μm.

This x-ray microcalorimeter is designed to be able to form an x-ray microabsorber using electrodeposition. The x-ray microabsorber is so-called a 'mushroom-shaped' x-ray microabsorber.

A 100nm thick SiO_2 and a 200nm thick Si_3N_4 are deposited on a 300μm thick n-type silicon wafer using LPCVD. Then, a Ti (100nm) and Au (200nm) are evaporated on the Si_3N_4 membrane. The TES is etched using ion milling and Ti is over etched by wet etching (Fig.5). The Al superconducting interconnections are sputtered and patterned by ion milling. After that, the tin x-ray microabsorber is fabricated on the TES and finally, the backside etching is applied using deep ICP RIE (DRIE)

Figure.5 shows the photomicrograph of the fabricated x-ray microcalorimeters.

Figure 5: The photomicrograph of our x-ray micromater.

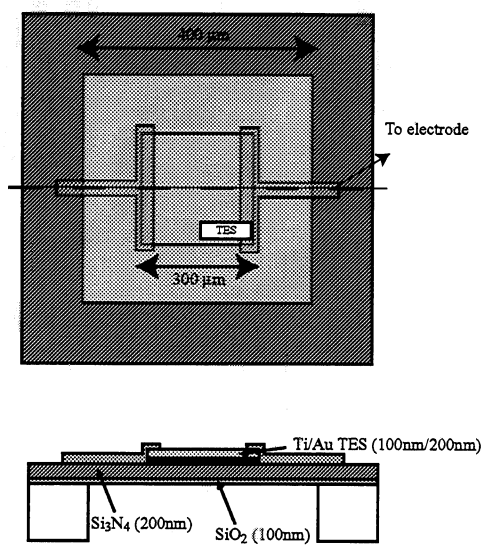
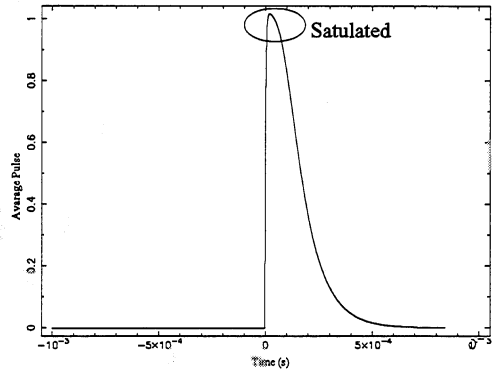


Figure 4: A schematic design of our x-ray microcalorimter

4 EXPERIMENTAL RESULT

The x-ray microcalorimeter is installed in the dilution refrigerator with a collimator of 200μm diameter attached on it. Then, ^{55}Fe radiation source was illuminated. The x-ray pulse was obtained as shown in figure 6. The TES is used as both an x-ray absorber and a temperature sensor in this case.

The thermal time constant $\tau_0 \sim 200\mu s$ was obtained. The heat capacity was too small that the pulse is saturated with an incidental input. This is because the temperature of the TES was piled up to out of the transition edge. The obtained pulses were corrected using optimal filters and the energy spectrum as shown in figure.7 is obtained. The energy resolution $\Delta E_{FWHM} = 43eV$ was obtained.



Figre 6: The temperature change of the x-ray microcalorimeter by the photon absorption

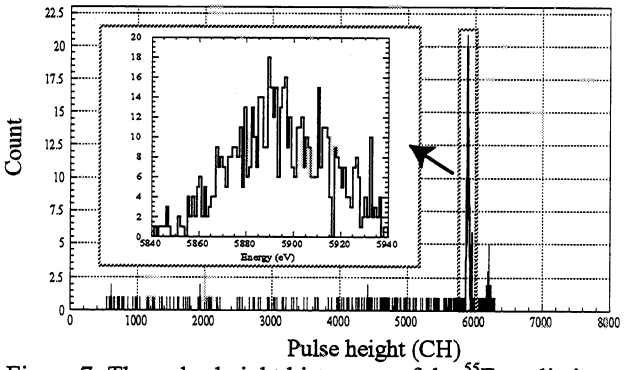


Figure 7: The pulse height histogram of the ^{55}Fe radiation obtained using the x-ray microcalorimeter

5 DISCUSSION AND CONCLUSION

The x-ray microcalorimeter is fabricated and tested. The energy resolution of 43eV(FWHM) at 5.9keV was obtained. But the value was still poor compared to that of expected.

The white noise equivalent energy spectrum, which is calculated by the Johnson noise and the phonon noise, is shown in Fig. 8. This spectrum indicates that x-ray microcalorimeter has a potential to achieve ~10eV of energy resolution.

The gap between the obtained energy resolution and the estimated one is due to what we call the *excess* noise. The *excess* noise might exist in the voltage fluctuation inside the TES [2].

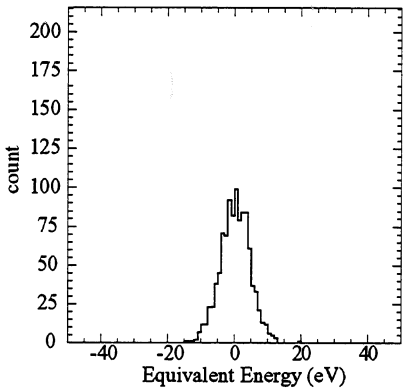


Figure 8: The estimated energy spectrum calculated by the white noise.

To improve the energy resolution, we are going to reduce the *excess* noise by further optimization of the process condition. Also, we are developing the wafer level fabrication process of an x-ray microabsorber using electrodeposition. The x-ray microabsorber has a so-called 'mushroom-shaped' microstructure. Using this x-ray microabsorber, the photon energy to temperature translation process is separated from the TES. Also, the large filling factor to the pixel can be realized. The SEM photomicrograph of the test device of mushroom-shaped x-ray microcalorimeter array is shown in figure.9. We are going to realize x-ray imaging with a high energy resolution by 32x32 pixel x-ray microcalorimeter array.

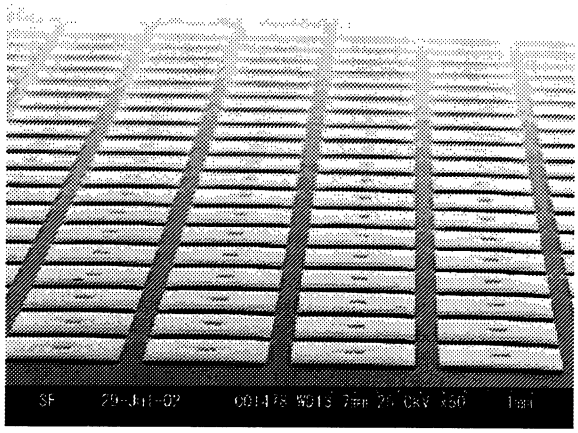


Figure 9: A SEM photomicrograph of an x-ray microabsorber array fabricated using electrodeposition.

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