Cryogenic InSb detector for radiation measurements

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The energy spectra of ^{241}Am alpha particles were measured by a detector employing the compound semiconductor InSb at an operating temperature below 4.2 K. The fabrication method and current–voltage curves are shown. Though the energy resolution of the detector is not discussed in this article, this is the first report on an InSb radiation detector. [DOI: 10.1063/1.1484238]

I. INTRODUCTION

Radiation detectors, especially detectors for x rays and gamma rays with very high energy resolutions, are required in the research fields of pure physics such as x-ray astronomy and those of industrial applications. The requirement for energy resolution is some eV for 6 keV x-rays, an energy resolution that cannot be achieved by conventional semiconductor detectors such as Si(Li) and Ge detectors, their theoretical limits of energy resolutions being nearly 120 eV for 6 keV x rays.

To meet the requirement described above, detectors employing superconducting materials have been under extensive study. Theoretically, the energy resolution of superconducting radiation detectors should be only some eV for 6 keV x rays. In practice, this energy resolution can be achieved only by superconducting radiation detectors with small active areas of which the typical dimension of the active area is 100 μm$\times$100 μm, an active area of less than 1/10 000 of that of conventional semiconductor detectors.

Inherently, superconducting radiation detectors cannot have large active areas. This is due to the high capacitance per unit area for superconductor–insulator–superconductor (SIS) tunnel junction detectors, and the heat capacitance-energy resolution relationship for normal metal–insulator–superconductor (NIS) tunnel junction detectors and transition edge sensors (TESs).[1] Another disadvantage of superconducting radiation detectors is their small absorber thickness. With a submicrometer superconducting layer in SIS detectors, and with some micrometers of a normal metal layer in NIS detectors and TESs, x rays and gamma rays with energies higher than some tens of keVs cannot be absorbed efficiently.

However, for measurements of 6 keV x rays in an astronomical application, superconducting radiation detectors with a small active area and thin absorbers can be excellent detectors. In industrial applications, which require detection of higher energy x rays and gamma rays in short time periods, superconducting radiation detectors do not appear to be promising. We need, therefore, to develop other types of radiation detectors with larger active areas, and with energy resolutions higher than conventional semiconductor ones for advanced x-ray applications in industry.

McHarris[2] showed the possibility of the compound semiconductor InSb as a substrate for a radiation detector with high energy resolution. The band gap energy of InSb is 0.165 eV, 1/6 of that of Si, and 1/4 of that of Ge, while the mobility of its electrons is 78 000 cm^2 V^{-1} s^{-1}, 40 and 20 times greater than those of Si and Ge, respectively. The mobility of holes is 750 cm^2 V^{-1} s^{-1}, which while not very outstanding is 1.5 times greater than that of Si. The high atomic numbers of In (49) and Sb (51), and its high density (5.78 g cm^{-3}) make InSb very attractive for photon detection. Although McHarris pointed out these favorable features of InSb, and it has been employed in devices for Hall resistivity measurement, and for detectors of infrared, no work has been reported on using InSb for a radiation detector, except as an absorber in superconducting detectors.[3,4]

In this article, our first attempt to make an InSb radiation detector is described. The method of fabricating an InSb detector and the current–voltage curves of the detector are noted. Energy spectra of ^{241}Am alpha particles measured by this InSb detector are shown as functions of the operating temperature, the shaping time of the main amplifier, and the applied bias voltage. Our goal here is to show the use of an InSb detector to measure x rays with a high energy resolution. However, this is just the first report on radiation measurement by a detector made of InSb, and for ease of use in this we employed alpha particles for radiation measurements to judge if the detector actually works or not. The energy resolution of the InSb detector is not discussed at this point, this being just our first attempt at such a fabrication.

II. EXPERIMENT

A. Device fabrication

We fabricated a surface barrier-type detector, with a rectifying Schottky contact on the front surface of an InSb sub-

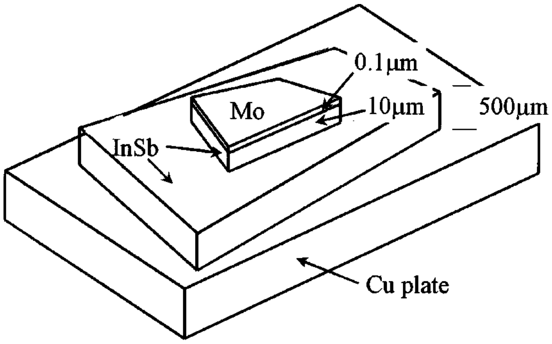

FIG. 1. Schematic drawing of the InSb detector.

strate, and an Ohmic contact on the back side. The InSb employed was a *p*-type wafer (Wafer Technology Ltd., England) a diameter of 2 in., thickness of 500 μm, and with a Ge dopant concentration of $3.5\times10^{15}\,\mathrm{cm}^{-3}$. The resistivity of the InSb substrate at 77 K was 0.29 Ω cm.

The InSb substrate (nearly 4 mm×6 mm) was etched using a mixture of nitric and lactic acids (1:10) for 5 min. On this etched surface, a Schottky electrode was made by evaporating Mo with a thickness of 0.1 μm. Next, a mesa electrode was defined using a photoresist mask, and formed by etching Mo and InSb with suitable etchants with mixtures of nitric and phosphoric acids and of nitric and lactic acids for Mo and InSb, respectively. The dimensions of the mesa were nearly 2 mm×3 mm, with a thickness of 10 μm. Finally, the processed wafer was mounted by In solder on a Cu plate having an Ohmic contact on the back surface. A schematic drawing of the detector is shown in Fig. 1.

B. Measurement of current–voltage curves

Current–voltage ($I-V$) curves were measured by the usual method of connecting the InSb detector, a voltage supply (Yokogawa 7651), and a digital multimeter (Keithley 197A) in series. The $I-V$ curves were measured at several temperatures from 4.2 to 77 K. Measured $I-V$ curves, double Schottky-like, are shown in Fig. 2, where a positive x value corresponds to the positive applied voltage on the Cu electrode. The resistivity at the voltage around 0 V, and the voltage range for which the same resistivity holds, were estimated for each $I-V$ curve. The summarized results are shown in Fig. 3.

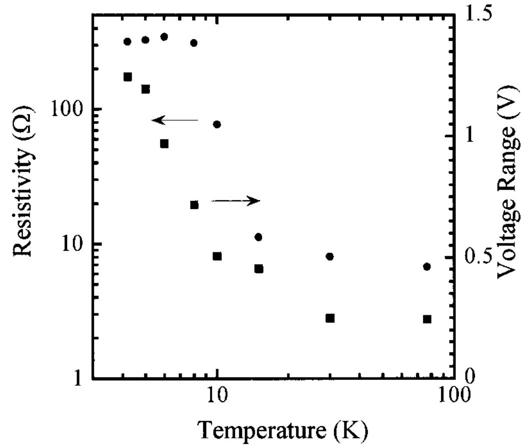

FIG. 3. Resistivity (solid circles) and voltage range (solid squares) of the center regions of the $I-V$ curves of Fig. 2.

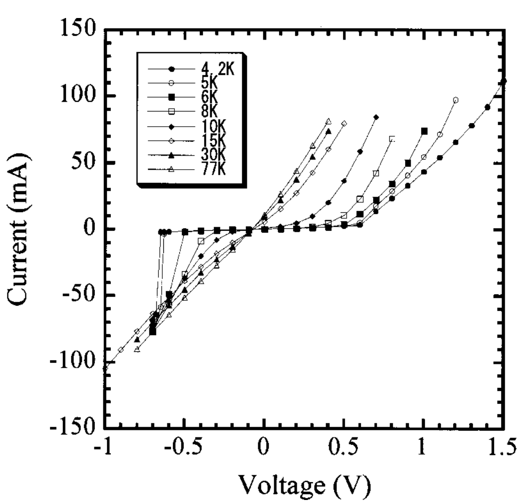

FIG. 2. Current–voltage curves of the InSb detector. The operating temperatures are shown in the figure.

C. Alpha particle measurement

The InSb detector was mounted on the 0.3 K stage of a refrigerator (Infrared Co.) and an electrodeposited ^{241}Am alpha particle source placed some millimeters from the surface of the detector. The alpha particles (mainly 5.4 MeV in energy) were collimated at nearly 4 mm diam.

The electronic circuit was a conventional one as shown in Fig. 4. The preamplifier used was a Canberra 2004 with the originally connected 100 MΩ resistor replaced by a 2 MΩ resistor.

In this electronic circuit, the voltage applied to the detector V_d was calculated by the following equation:

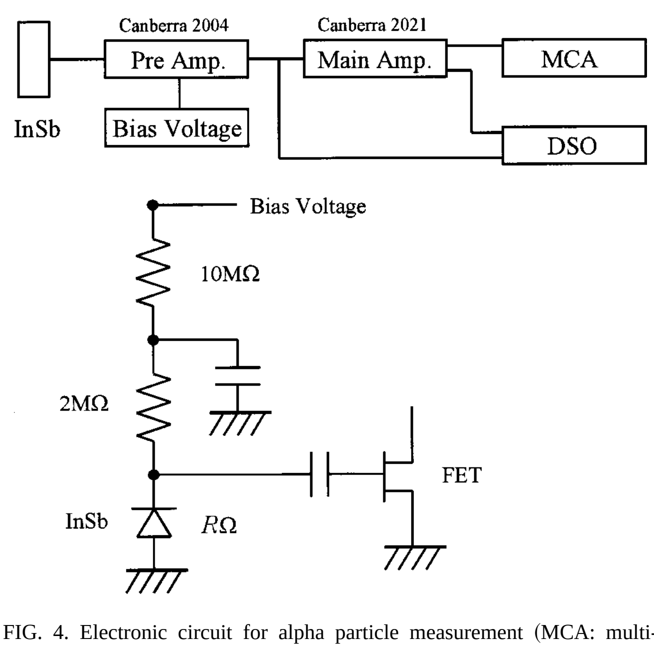

FIG. 4. Electronic circuit for alpha particle measurement (MCA: multichannel analyzer, DSO: digital storage oscilloscope). Details of the input part of the preamplifier are shown.

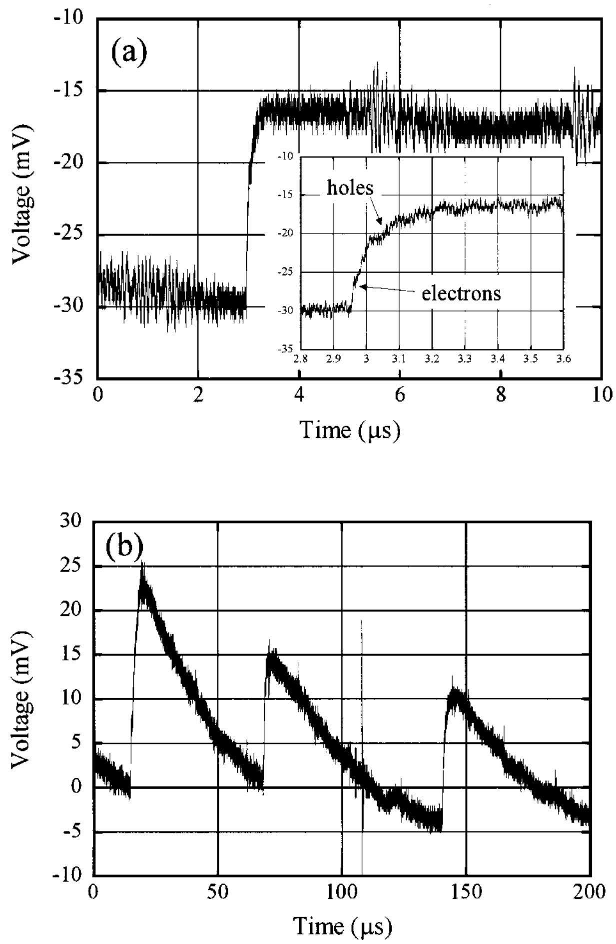

FIG. 5. Preamplifier output pulses at temperatures (a) 0.5 K and (b) 4.2 K.

$$V_d = V_i + \frac{R\Omega}{(10+2)M\Omega + R\Omega} \cdot V_b, \tag{1}$$

where, V_i is the inherent voltage, V_b is the output voltage of the bias voltage, and R is the resistivity of the InSb detector at the operating temperature. When a bias voltage of 100 V was applied to the InSb detector at an operating temperature of 4.2 K, Eq. (1) gives a very small voltage, such as $V_i + 2.5\,\mathrm{mV}$, substituting R with 300 Ω as shown in Fig. 3. The determination of V_i was difficult, however, it was estimated as less than 1 V, following a number of examples of semiconductor devices.

The preamplifier and main amplifier output pulses of InSb were observed by digital storage oscilloscope, and the pulse height spectra measured by multichannel analyzer (MCA).

The output pulses of the preamplifier at the operating temperatures of (a) 0.5 K and (b) 4.2 K are shown in Fig. 5. At 0.5 K the rise time of the pulse was nearly 250 ns, but with a very long decay time. In the inset of Fig. 5(a), fast and slow components, which we think correspond to the contributions of electrons and holes, respectively, can be observed in the rising part of the pulse. At 4.2 K, the rise time was nearly 1 μs, and the pulse decay shorter than that at 0.5 K. As the operating temperature rose from 0.5 to 4.2 K, the slow component of the output pulse became dominant.

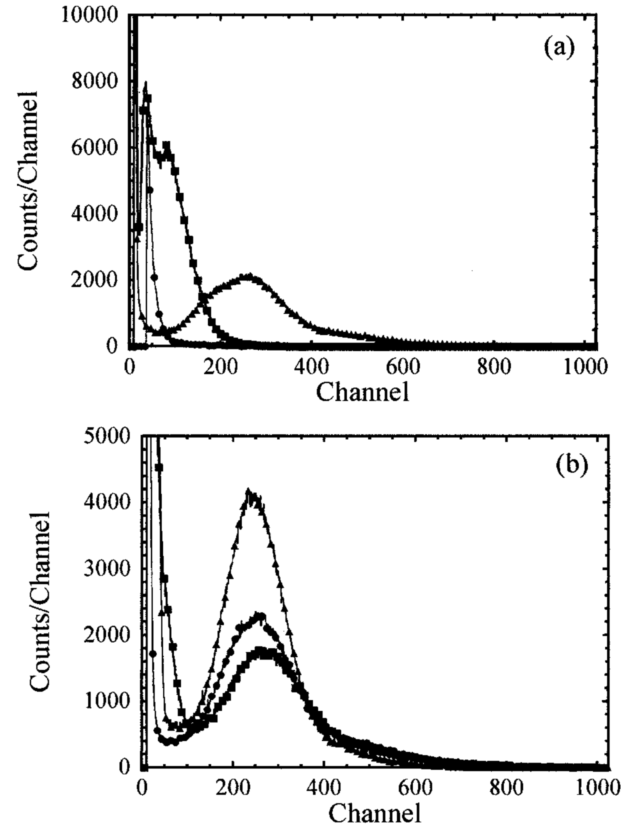

FIG. 6. Energy spectra of ^{241}Am alpha particles measured at operating temperature, shaping time, and applied bias voltage V_b of (a) 0.5 K, 0.25 μs, 1 V (solid circles), 3.5 K, 0.25 μs, 0 V (solid squares), and 3.5 K, 4 μs, 0 V (solid triangles); (b) 4.2 K, 4 μs, 0.5 V (solid circles), 4.2 K, 4 μs, 50 V (solid squares), and 4.2 K, 1 μs, 50 V (solid triangles), respectively. The voltage actually applied to the detector V_d is calculated by Eq. (1).

We measured, 5 min for each measurement, the energy spectra of alpha particles with the rising of the operating temperature. The measured pulse height spectra are shown in Figs. 6(a) and 6(b) and the applied bias voltage and shaping time of the main amplifier are in the legend.

III. DISCUSSION

A. Current–voltage curve of the InSb detector

Double-Schottky-like $I-V$ curves were obtained at temperatures below 10 K, Fig. 2. We think this was the result of an incomplete Ohmic electrode showing Schottky-like characteristics at these lower temperatures.

Estimations of resistivity and voltage range became difficult at temperatures above 15 K, Fig. 3, and could have had large errors. However, we note the drastic change of resistivity between 10 and 15 K. That the resistivity showed a saturated behavior below 8 K is encouraging for the practical application of InSb detectors. In the future, with a better Schottky electrode, resistivity and voltage range at low temperatures would increase and a thicker depletion layer could be achieved.

B. Energy deposition of alpha particles

According to the semi-empirical formula of Ziegler *et al.* related to the range and energy loss of ions,[5] the energy of alpha particles with an initial energy of 5.4 MeV after passing the Mo layer was 5.36 MeV. The range of the alpha particles in the InSb substrate was calculated as 0.19 μm. On the other hand, the thickness of the depletion layer of the InSb detector was estimated as 0.14 μm, using a resistivity of the InSb substrate of 0.29 Ω cm at 77 K the hole mobility as 750 $cm^2 V^{-1} s^{-1}$, and assuming the inherent voltage as 0.5 V.[6] We could not tell if the depletion layer thickness was greater than the range of alpha particles at a lower temperature, at which resistivity of the substrate could be greater than that at 77 K.

In practical use for x-ray measurements, a thick depletion layer is necessary for efficient detection. The fabrication of an InSb substrate with high resistivity is a key technology in detector development.

C. Charge collection process in the InSb detector

On the digital storage oscilloscope, we observed a strong electronic noise in the preamplifier output when a bias voltage was applied to the InSb detector at 0.5 K. This phenomenon was taken as being the electron avalanche due to energetic electrons under a stronger electric field with a long mean free path and high mobility at low temperature. To avoid this phenomenon, an *n*-type substrate should be employed; in an *n*-type semiconductor detector with a rectifying electrode, electrons experience a weaker electric field as they approach the positive electrode. The velocity they would obtain has limitations, which is not enough to induce an electronic avalanche. On the other hand, holes will have a stronger electric field as they move to the negative electrode. However, the hole velocity will not be too high due to their mobility, less than 1/100 of that of an electron.

The difference of preamplifier outputs at 0.5 and at 4.2 K, as shown in Figs. 5(a) and 5(b), was due to the movement of electrons and holes. At 0.5 K, electrons quickly arrived at the positive electrode due to their greater mobility at low temperatures, and holes were captured and released very slowly. At higher temperatures, the movement of electrons became slower, while the release of holes occurred soon after they were captured.

The pulse height spectrum measured at 0.5 K was in the smaller channels of MCA as shown in Fig. 6(a). At a low temperature such as 0.5 K, most of the electrons and holes created by the energy deposition of the alpha particles froze out. This is closely related to the output pulse of the preamplifier. At a temperature of 3.5 K, a slow component of the carriers appeared and had a higher pulse height with a shaping time of 4 μs. The pulse height with an applied voltage of 50 V was slightly higher than that with 0.5 V, Fig. 6(b). According to Eq. (1) the difference of V_d between these two bias voltages was nearly 1.2 mV. This indicated that the electrons and holes created by the alpha particles were under the influence of an electric field, i.e., the InSb detector behaved as a semiconductor detector. While the shaping time of 1 μs may be a better condition for measurement, we still have to fabricate InSb detectors with better rectifying characteristics to study their operating conditions, and their charge collection process.

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