Undoped InSb Schottky Detector for Gamma-Ray Measurements

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***Abstract*—For measuring X-rays and gamma-rays with better energy resolution and higher efficiency than conventional semiconductor detectors such as Si and Ge detectors, we are studying InSb radiation detectors. Previously, we fabricated *p*-InSb Schottky type, *pn*-junction type detectors, and undoped InSb Schottky type detectors with an electrode of 3 mm in diameter, and measured alpha particles of ^{241}Am. For measuring gamma-rays, we fabricated undoped InSb Schottky type detectors with smaller electrode areas. Gamma-ray signals were clearly separated from the background, and differences between energy spectra of ^{241}Am and ^{133}Ba gamma-rays were observed.**

***Index Terms*—Cryogenic detector, depletion layer thickness, gamma-ray, InSb, low temperature, semiconductor detector, Schottky barrier height.**

I. Introduction

In X-RAY fluorescent spectroscopy, detection of light elements such as Be and Li is becoming important in view of their effects on the environment. For measuring characteristic x-rays of heavy elements such as Cd, Pb and U, detector substrates should have a high atomic number and a high density, because the characteristic x-rays are in the range of 10 keV to 100 keV in energy. In short, radiation detectors with better energy resolution and higher efficiency than conventional semiconductor detectors such as Si and Ge detectors are required. Superconducting radiation detectors have the best energy resolution among radiation detectors, however, they are not good at measuring high energy photons.

Table I shows the properties of substrates of radiation detectors. Among semiconductor materials, indium antimonide (InSb) has the smallest band gap energy, i.e., 0.165 eV. This band gap energy predicts the energy resolution of an InSb detector as 60 eV for 6 keV x-rays, comparing the band gap energy to the one of Ge. The high density and the high atomic numbers of InSb bring 10 times higher photon absorption efficiency than that of Ge. Therefore, InSb is a suitable substrate for radiation detectors, especially for measurements of high energy photons.

Until now, we fabricated *p*-type InSb Schottky type [1], *pn*-junction type [2] detectors, and undoped InSb Schottky type detectors [3], and measured alpha particles of ^{241}Am. Moreover, undoped InSb Schottky detector could detect protons with 574 keV created in the nuclear reaction $\mathrm{n} + ^3\mathrm{He} \rightarrow \mathrm{p} + \mathrm{t}$ [4].

In order to measure gamma-rays of ^{241}Am with 59 keV in energy, undoped InSb detectors with smaller electrodes were fabricated. Here, the fabrication method of the detector and the results of gamma-ray measurements are described.

TABLE I
PROPERTIES OF DETECTOR SUBSTRATES

	Semiconductors			Superconductor
	InSb	Si	Ge	Nb
Atomic number	49,51	14	32	41
Density (g·cm^{-3})	5.78	2.33	5.32	8.57
Band gap (eV)	0.165	1.11	0.67	0.002
_E at 6 keV (eV)	60	140	110	2
Operating temp.	<77 K	Room Temp.	77 K	300 mK
Active area	~cm^2	~cm^2	~cm^2	~10^{-4} cm^2

II. Experiments

A. Detector Fabrication

Schottky type detectors were fabricated with undoped InSb wafers (Sumitomo Electric Industries, Japan). The undoped InSb wafer's diameter was 2 inches and the thickness was 0.5 mm. The wafers were cut to dimensions of 5 mm $\times$ 7 mm. Both sides of the InSb substrate were etched using a mixture of nitric and lactic acids (1:10) for 5 min. On one of the InSb substrate surfaces, Au-Pd (60%:40%) alloy was deposited by heat evaporation with a thickness of approximately 5 nm as a Schottky contact. After this process, an electrode area with a diameter of 1.5 mm was defined by a photoresist mask, and the rest of the surface was etched out to fabricate a mesa electrode. The height of the mesa was nearly 10 μm. Finally, the processed wafers were mounted on a Cu plate by In soldering, having an Ohmic contact on the back surface of the InSb wafers. Fig. 1 shows a schematic drawing of the undoped InSb detector.

B. Current-Voltage Curves of InSb Detector

Fig. 2 shows the current-voltage (I-V) curves of the undoped InSb detector with an electrode of 1.5 mm in diameter. The I-V curves were measured at several temperatures from 4.2 K to 300 K. In this detector, nonlinearity was observed even at 77 K. The I-V curves measured at the operating temperature below

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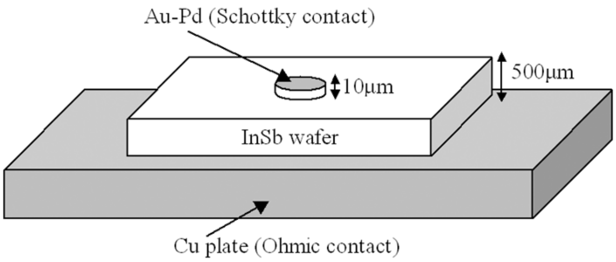

Fig. 1. Schematic drawing of an undoped InSb detector.

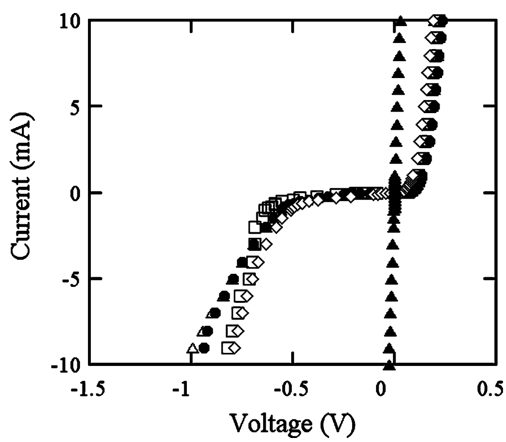

Fig. 2. Current-voltage curves of the undoped InSb detector with the electrode of 1.5 mm in diameter. Operating temperatures are 4.2 K (solid circles), 20 K (open triangles), 40 K (open squares), 77 K (open diamonds) and room temperature (solid triangles).

20 K were nearly the same. Resistance of the detector at 4.2 K was estimated to be 4.6 kΩ.

C. Gamma-Ray Measurements

The InSb detector with an electrode of 1.5 mm in diameter was mounted on a 0.3 K stage of a refrigerator (Infrared Co.). The detector was exposed to gamma-rays of the electro-deposited ^{241}Am and ^{133}Ba sources in the air through two Be windows on the outer and inner vessels of the refrigerator, respectively. Measurements were performed at 4.2 K.

Fig. 3 shows a block diagram for the measurements of gamma-rays. The output pulses of the preamplifier and the main amplifier were observed by a digital storage oscilloscope (DSO), and the pulse height spectra were measured by a multi-channel analyzer (MCA). The resistance of the preamplifier was changed from 100 MΩ to 2.2 MΩ, because the resistance of the InSb detector was smaller by some orders of magnitude than the one of general Si detectors. All the measurements were carried out without applying any bias voltage: large electrical noise was induced when the bias voltage was applied.

Both the foreground and background measurements were performed for 5 min and repeated several times. Obtained gamma-ray energy spectra are shown in Fig. 4 as well as background. An example of output pulses of the preamplifier is shown in Fig. 5.

Gamma-ray signals were clearly separated from the background. Differences between the energy spectra of gamma-rays of ^{241}Am and ^{133}Ba were observed.

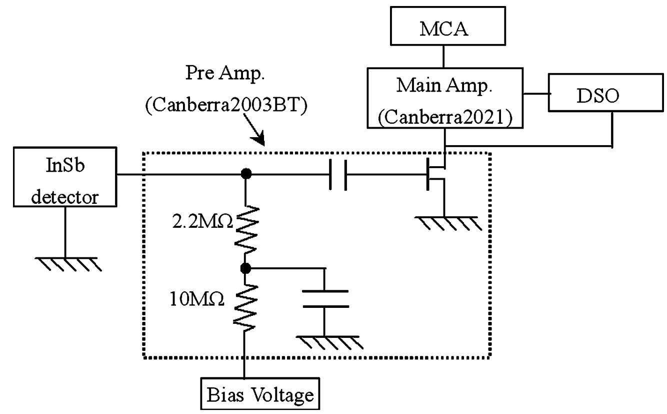

Fig. 3. Block diagram for gamma-ray measurements (MCA: multichannel analyzer, DSO: digital storage oscilloscope).

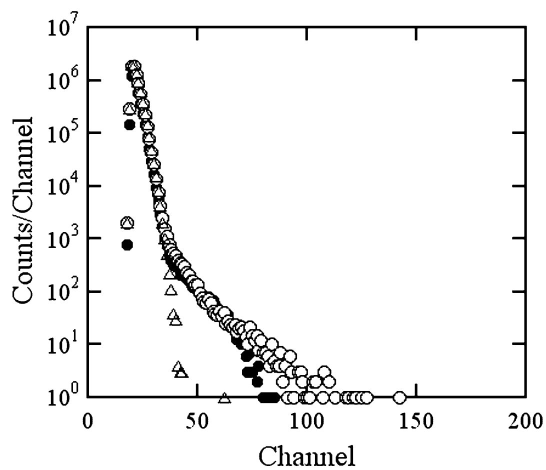

Fig. 4. Gamma-ray energy spectra of ^{241}Am (solid circles) and ^{133}Ba (open circles) measured by the undoped InSb Schottky detector with the electrode of 1.5 mm in diameter at 4.2 K, as well as background (open triangles).

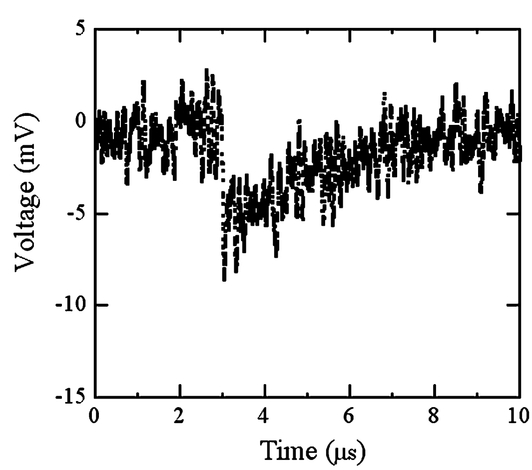

Fig. 5. A preamplifier output pulse of gamma-rays of ^{133}Ba measured by the undoped InSb Schottky detector with an electrode of 1.5 mm in diameter at 4.2 K.

D. Depletion Layer Thickness of an Undoped InSb Detector

For high efficiency photon detection, a thicker depletion layer is desirable. In this section, depletion layer thickness is estimated.

The depletion layer thickness [5], d, is given by

$$d \cong \sqrt{\frac{2\varepsilon V}{eN}}. \quad (1)$$

Here ε is the semiconductor permittivity, V is the reverse bias voltage, e is the unit charge and N is the carrier concentration of the InSb wafer. Since we take V as 1 V as was estimated in [2], and ε as a constant, it is necessary to know the carrier concentration of the InSb wafer for estimating the depletion layer thickness.

The carrier concentration of undoped InSb was measured by a capacitance-voltage (C-V) method using an undoped InSb Schottky detector. The capacitance is related to the carrier concentration by the following equation:

$$C \cong \frac{\varepsilon S}{d} = S\sqrt{\frac{e\varepsilon N}{2V}} \quad (2)$$

$$N = \left(\frac{C}{S}\right)^2 \frac{2V}{e\varepsilon}. \quad (3)$$

Here C is the capacitance of the detector and S is the area of an electrode. From (3), the carrier concentration was calculated from the slope of $(1/C^2)$ versus V curve. The capacitance of the detector was measured with frequencies from 120 Hz to 100 kHz and showed no big differences according to frequency. Fig. 6 shows the carrier concentration of the undoped InSb (solid circles) and the depletion layer thickness of the undoped InSb Schottky detector (open circles) as a function of operating temperature.

Depletion layer thickness is calculated using the measured values of the carrier concentration. As shown in Fig. 6, the depletion layer thickness was nearly constant between 10 K and 30 K. Depletion layer thickness of the undoped InSb detector at 4.2 K was estimated to be 9 μm. This estimated result agrees fairly well with the conclusion reached earlier in [4] that the depletion layer thickness was greater than 6 μm, which corresponded to the range of protons with 574 keV in InSb.

The depletion layer thickness of the compound semiconductor detector has not been extensively reported at low temperatures. We could only find one example on the depletion layer thickness of a GaAs detector [6]: nearly 4 μm at $-54°$C with no applied bias voltage. The carrier concentration of the GaAs was almost the same as the one of InSb discussed in this paper.

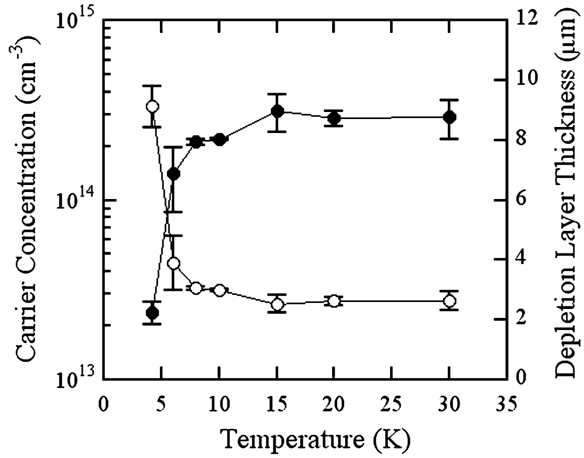

Fig. 6. Temperature dependence of the carrier concentration of undoped InSb (solid circles) and the depletion layer thickness of an undoped InSb detector (open circles). Solid lines are eye-guides.

TABLE II
SCHOTTKY BARRIER HEIGHT AND RESISTIVITY OF UNDOPED INSB DETECTORS

Diameter of electrode (mm)	Schottky barrier height (V)			Resistance (kΩ)		
	4.2K	40K	77K	4.2K	40K	77K
1.5	0.0030	0.043	0.089	4.6	4.2	3.3
3	0.0043	0.055	0.110	16	13	8.1
1 [8]	-	-	0.114	-	-	-
0.02 mm^2 [9]	-	-	0.118	-	-	-

III. DISCUSSION

A. Schottky Barrier Height and Resistivity of the Undoped InSb Detectors

From the current-voltage (I-V) curves of undoped InSb detectors, Schottky barrier height and resistance were estimated. In Schottky type radiation detectors, Schottky contacts are the key element for device operation. The electronic states of the metal-semiconductor interface were estimated as Schottky barrier heights from the measured I-V curves of the InSb detector. The extrapolated value of the current density at zero voltage is the saturation current J_S and the Schottky barrier height ϕ_{Bn} can be obtained by [7]

$$\phi_{Bn} = \frac{kT}{q} \ln \frac{A^* T^2}{J_S}. \quad (4)$$

Here k is the Boltzmann constant, T is the absolute temperature, q is the unit electrical charge and A^* is the effective Richardson constant.

The estimated Schottky barrier height and resistance are given in Table II for InSb detector with an electrode of (a) 1.5 mm in diameter and (b) 3 mm in diameter, which was used for alpha particle measurements [3]. Additionally, Schottky barrier heights of similar *n*-type InSb Schottky diodes at 77 K are listed [8], [9]. All of the Schottky barrier heights and resistances of detector (a) are smaller than those of detector (b). This indicates that detector (b) has better interface states than detector (a).

B. The Rise Time of the Preamplifier Output Pulses

Fig. 7 shows the rise times of the preamplifier output pulses at each operating temperature for the undoped InSb detector with an electrode of 1.5 mm in diameter (open circles and triangles), as well as for one detector with an electrode of 3 mm in diameter (solid squares), a *p*-type *pn*-junction InSb detector (solid circles), and a *p*-type Schottky InSb detector (solid triangles) employed in previous papers. The error bars show the standard deviation of 1000 pulses at each temperature.

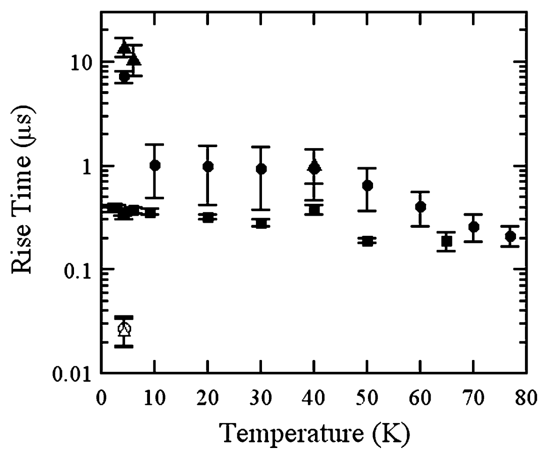

Fig. 7. Temperature dependence of the rise time of the undoped InSb Schottky detector with an electrode of 1.5 mm in diameter in the measurements of gamma-rays of ^{241}Am (open circle) and ^{133}Ba (open triangle). The rise time of undoped InSb Schottky detector with an electrode of 3 mm in diameter (solid squares), *pn*-junction InSb detector (solid circles) and *p*-type InSb Schottky detector (solid triangles) in the measurements of alpha particles are also shown.

In the measurements of alpha particles, the rise times of the undoped InSb Schottky detector are shorter than those of *pn*-junction and *p*-type InSb Schottky detectors. In particular, the rise time of the undoped InSb Schottky detector at 2 K was nearly 350 ns, whereas that of the *p*-type InSb Schottky detector was 13 μs. The shorter rise time of the *p*-type InSb Schottky detector at 40 K is due to the contribution of electrons.

Both the rise times of the output pulses due to photons of ^{241}Am (open circle) and ^{133}Ba (open triangle) measured by the undoped InSb Schottky detector were also nearly 30 ns. The rise times are shorter than the ones of the alpha particle measurement by one order of magnitude. These short rise times might be the result of smaller electron-hole pair densities created by photoelectrons, compared to those created by alpha particles.

C. Energy Spectrum of Gamma-Rays

Gamma-ray signals were clearly separated from the background. Differences between the energy spectra of gamma-rays of ^{241}Am and ^{133}Ba were observed. However, the photo-peak of gamma-rays could not be observed.

In case gamma-rays of ^{241}Am (mainly 59 keV in energy) converted into electrons by photoelectric effects, the range of photoelectrons in InSb substrate was estimated as 20 μm. On the other hand, the depletion layer thickness of the undoped InSb detector was nearly 9 μm at 4.2 K. Therefore, most of the photoelectrons might escape from the depletion layer of the undoped InSb detector.

For the observation of photo-peaks, InSb detectors with thicker depletion layers should be fabricated in future work. InSb crystals with better performance are necessary for having higher resistivity and applying bias voltage to InSb detector.

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