

Development of Far-Infrared Germanium Photoconductors with Surface Activated Wafer Bonding Technology

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ABSTRACT

We present our recent activities on the development of new Ge photoconductors for far-infrared (far-IR) astronomy. Using the surface-activated wafer bonding (SAB) method provided by Mitsubishi Heavy Industries, we fabricated a Ge $p^+ - i - p^+ - i$ junction device with clean abrupt junction, which basically possesses a Blocked-Impurity-Band-type (BIB-type) structure. We measured the far-IR sensitivity of the device at 1.7 K using a blackbody source and spectral response curves at 2.8 K using a Fourier transform spectrometer. The device shows considerably higher sensitivity and wider spectral coverage than a conventional bulk Ge:Ga device, demonstrating promising applicability of SAB Ge $p^+ - i$ junction devices to BIB-type Ge detectors.

1. INTRODUCTION

For future far-IR astronomy in the *SPICA* era, improvements in the detector technology are crucial. There are two main streams for the development of detectors covering the far-IR region (50–200 μm): photoconductor and bolometer. Ge:Ga photoconductors have been widely used for instruments carried on major IR astronomical satellites ever launched. For *SPICA*, superconducting bolometer technology is being developed to be adopted for the far-IR instrument, SAFARI. Although the superconducting bolometer is expected to possess unprecedentedly high sensitivity, a photoconductor is still advantageous in achieving a wide dynamic range of signal detection, reducing the size of a pixel of an array, and most importantly not requiring sub-Kelvin coolers.

We are developing new Ge photoconductors which possess a Blocked-Impurity-Band-type structure. BIB-type Ge detectors are known to mitigate problems, such as cosmic-ray-induced fluctuations of detector sensitivity and non-linear slow transient responses, which are notorious problems for conventional Ge:Ga photoconductors. They can also cover a relatively wide spectral range with a longer cutoff wavelength because of shallow energy levels of heavily-doped impurities. We are developing layered extrinsic photoconductors using the room-temperature, surface-activated wafer bonding (SAB) technology provided by Mitsubishi Heavy Industries (Takagi et al. 1996; Takagi & Maeda 2006). In the SAB method, two wafers are attached in a high vacuum chamber at a room temperature after activation of their contact surface by an Ar ion beam. Since the SAB method is a non-thermal process, the layered photoconductors obtain clean abrupt junction with almost no thermal contamination by impurities from a heavily-doped layer to an intrinsic layer. Recently, Watanabe et al. (2011) tested SAB-processed Ge:Ga devices at temperatures of 300 and 77 K; they bonded two Ge:Ga layers, both with the same Ga concentration of $2 \times 10^{14} \text{ cm}^{-3}$. They demonstrated that there was no degradation in electrical properties at the bonded interface, although there was a crystallographic discontinuity.

Using the same process as described in Watanabe et al. (2011), we have fabricated SAB Ge $p^+ - i$ junction devices consisting of a heavily-doped Ge:Ga layer (p^+ layer) and a non-doped intrinsic Ge layer (i layer). The initial results of evaluating the electric and photoconductive properties of the devices under dark conditions were reported in Kaneda et al. (2011), where the derived properties were found to be physically reasonable for BIB-type devices. In this paper, we report further results of the evaluation to demonstrate applicability of the device to BIB-type Ge detectors.

2. MEASUREMENTS

Using the SAB method, we have fabricated a Ge $p^+ - i$ junction device with the size of $1 \times 1 \times 0.55 \text{ mm}^3$. The device consists of two layers; a heavily-doped Ge:Ga layer of thickness 0.5 mm with a Ga concentration of $1 \times 10^{16} \text{ cm}^{-3}$ and a non-doped intrinsic Ge layer of thickness 0.05 mm. In order to evaluate the properties of each layer independently, we fabricated a non-doped bulk Ge device and a heavily-doped bulk Ge:Ga device with a Ga concentration of $1 \times 10^{16} \text{ cm}^{-3}$. The former basically has the same properties as the i layer, and the latter has the same properties as the p^+ layer. As a reference sample, we also fabricated a conventional bulk Ge:Ga device with a Ga concentration of $2 \times 10^{14} \text{ cm}^{-3}$.

We measured the electric and photoconductive properties of the devices at temperatures of 1.7–77 K. Figure 1 Left shows a measurement system on a cold stage which consists of a blackbody source with a cold shutter and a housing where

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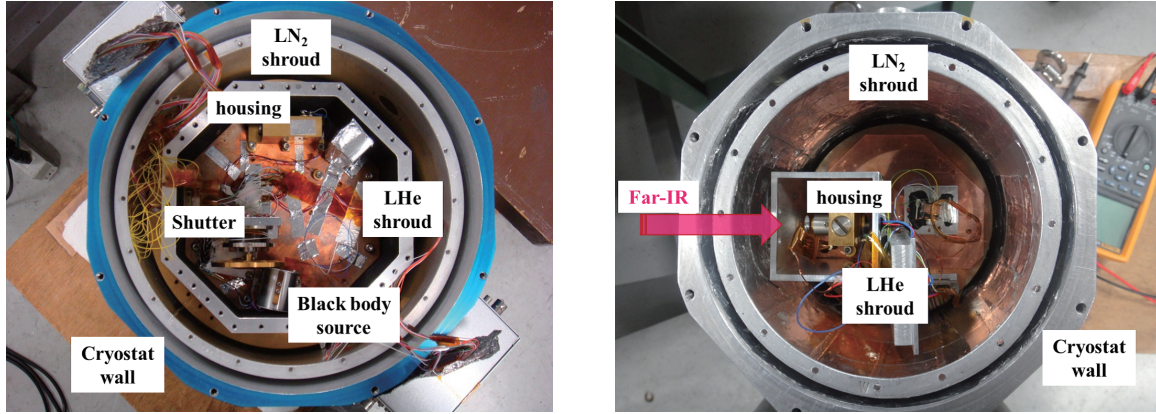


Figure 1. *Left:* Configuration for measurement of sensitivity and thermal current under dark condition. *Right:* Configuration for measurement of spectral response curves using an external FT-IR spectrometer.

Table 1. Responsivity of the p^+-i junction device and the bulk Ge:Ga device, both measured at 1.7 K with $V_{\text{bias}} = 100$ mV.

| Device | R (A/W) |
|--------------|-----------|
| bulk Ge:Ga | 0.37 |
| p^+-i type | 13 |

the test device is installed. This system provides dark conditions, so that we can precisely measure the far-IR sensitivity of the test device. To evaluate the sensitivity, we measured the output photo current of the device against the illumination of far-IR photons by the 40 K internal blackbody source. Additionally, we evaluated the temperature dependence of the thermal current of the device at a fixed voltage bias; we controlled the operational temperature of the device by changing the internal pressure of the liquid-He tank of the cryostat.

Figure 1 *Right* shows a measurement system for spectral response, which consists of a device housing and optical filters on a cryostat wall and cold shrouds. Illuminating far-IR light from an external Fourier transform infrared (FT-IR) spectrometer to the device through the filters, we obtained spectral response curves of each device. For the curves, we removed the wavelength dependences of the emission of the light source and the transmission of the optical filters.

3. RESULTS

Table 1 shows the responsivity of the Ge p^+-i junction device and the conventional bulk Ge:Ga device with a Ga concentration of $2 \times 10^{14} \text{ cm}^{-3}$. Both devices are measured at temperature of 1.7 K with a bias voltage of 100 mV. From Table 1, we find that the Ge p^+-i junction device has sensitivity much higher than the conventional Ge:Ga bulk device.

Figure 2 *Left* shows spectral response curves of the Ge p^+-i junction device and the conventional bulk Ge:Ga device at temperature of 2.8 K with bias voltages of 1 V and 25 mV, respectively. The peak sensitivity of each device is normalized to a unity. From Figure 2 *Left*, we find that the cutoff wavelength of the Ge p^+-i junction device is extended to $160 \mu\text{m}$, significantly longer than that of the bulk Ge:Ga device without mechanical stress.

Figure 2 *Right* shows the output current plotted against the reciprocal of the operating temperature for the heavily-doped bulk Ge:Ga device with a Ga concentration of $1 \times 10^{16} \text{ cm}^{-3}$, measured under dark conditions. The current is measured with a bias voltage of 100 mV. At low temperatures, output current is dominated by the thermal excitation of carriers, and hence the current is almost proportional to the Boltzmann factor, $\exp(-E_A/kT)$, where E_A is the depth of the Ga energy level. By fitting the temperature dependence of the current at $20 \leq T \leq 40$ K while avoiding the influence of the hopping current, we obtain $E_A = 7.2$ meV, which corresponds to the cutoff wavelength of $165 \mu\text{m}$. This result is consistent with the cutoff wavelength derived from the measurement of the spectral response curve.

4. SUMMARY

We have fabricated the Ge p^+-i junction device consisting of a heavily-doped Ge:Ga layer and a non-doped Ge layer, using the SAB method. We evaluated the sensitivity and spectral response curves of the device and compared them with those of the conventional bulk Ge:Ga device at temperatures of 1.7–77 K. As a result, we find that the Ge p^+-i junction device has sensitivity considerably higher than that of the Ge:Ga bulk device. We also find that spectral response curves of the Ge p^+-i junction device are extended to the cutoff wavelength of $\sim 160 \mu\text{m}$, significantly longer than that of the Ge:Ga bulk device without mechanical stress. Our overall results suggest promising applicability of SAB Ge p^+-i junction

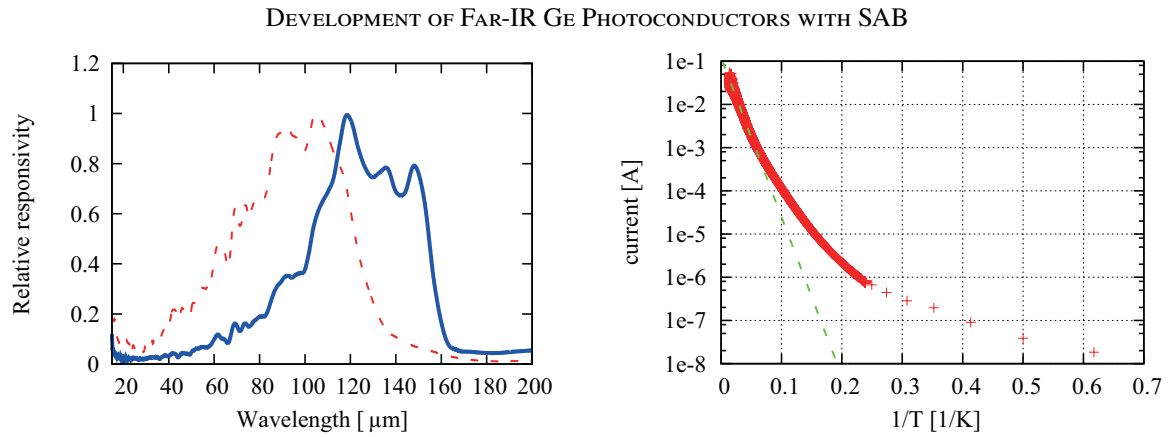


Figure 2. *Left:* Spectral response curves. The blue solid line is the spectral response curve of the Ge p^+-i junction device while the red dashed line is that of the conventional bulk Ge:Ga device without mechanical stress. The vertical axis shows the responsivity, the peak of which is normalized to a unity for each device. *Right:* Output thermal current plotted against the reciprocal of the operating temperature for the heavily-doped bulk Ge:Ga device, measured under dark conditions. The green dashed line is the result of fitting to the data in a range of 20 K to 40 K.

devices to BIB-type Ge detectors. In a future work, the Ga concentration of the p^+ layer will be further increased to extend the cutoff wavelength up to 200 μm .

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