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M. Hanaoka · **H. Kaneda** · **S. Oyabu** ·
M. Yamagishi · **Y. Hattori** · **S. Ukai** ·
K. Shichi · **T. Wada** · **T. Suzuki** ·
K. Watanabe · **K. Nagase** · **S. Baba** ·
C. Kochi

Development of Blocked-Impurity-Band-type Ge detectors fabricated with the surface-activated wafer bonding method for far-infrared astronomy

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Abstract We report the current status of the development of our new detectors for far-infrared (FIR) astronomy. We develop Blocked-Impurity-Band (BIB)-type Ge detectors to realize large-format compact arrays covering a wide FIR wavelength range up to 200 μm. We fabricated Ge junction devices of different physical parameters with a BIB-type structure, using the room-temperature, surface-activated wafer bonding (SAB) method. We measured the absolute responsivity and the spectral response curve of each device at low temperatures, using an internal blackbody source in a cryostat and a Fourier transform spectrometer, respectively. The results show that the SAB Ge junction devices have significantly higher absolute responsivities and longer cut-off wavelengths of the spectral response than the conventional bulk Ge:Ga device. Based upon the results, we discuss the optimum parameters of SAB Ge junction devices for FIR detectors. We conclude that SAB Ge junction devices possess a promising applicability to next-generation FIR detectors covering wavelengths up to $\sim$ 200 μm with high responsivity. As a next step, we plan to fabricate a BIB-type Ge array device in combination with a low-power cryogenic readout integrated circuit.

Keywords instrument: far-infrared detector, Ge photoconductor, Blocked-Impurity-Band detector

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M. Hanaoka · H. Kaneda · S. Oyabu · M. Yamagishi · Y. Hattori · S. Ukai · K. Shichi
Nagoya University, Nagoya, Aichi, 464-8602, Japan
Tel.: 052-789-3540
E-mail: hanaoka@u.phys.nagoya-u.ac.jp
T. Wada · T. Suzuki · K. Nagase · S. Baba · C. Kochi
Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 252-5210, Japan
K. Watanabe
Research Center for Advanced Science and Technology, University of Tokyo, Meguro-ku, Tokyo 153-8904, Japan

1 Introduction

In far-infrared (FIR) astronomy, gallium-doped germanium (Ge:Ga) photoconductors with the Ga concentration of $\sim 10^{14}$ cm^{-3} have been widely used at temperatures of $1.8-4$ K. Those conventional Ge:Ga photoconductors cover a wavelength range from ~ 50 μm to ~ 120 μm. In order to cover wavelengths longer than 120 μm, we need to apply a large mechanical stress to the detector and thus require a huge mechanical system compared to detectors [1]. However it is difficult to realize large-format compact arrays because of the complexity of the mechanical system. The Blocked-Impurity-Band (BIB) detectors overcome the difficulty in covering a wide range of FIR wavelengths up to 200 μm without applying a mechanical stress [2].

The BIB-type Ge detectors consist of a heavily-doped Ge:Ga with the Ga concentration of $\sim 10^{16}$ cm^{-3} (hereafter called heavily-doped Ge:Ga layer) and a non-doped intrinsic Ge or a lightly-doped Ge:Ga (blocking layer). The Ga concentration of the heavily-doped Ge:Ga layer is high enough to form an impurity band. The impurity band has a shallower energy level and thus can extend FIR wavelength coverage up to ~ 200 μm. However the impurity band also produces large leakage current. In order to block the current, the blocking layer is inserted between the heavily-doped Ge:Ga layer and an electrode. Attempts to develop BIB Ge detectors have started since the 1980s, but they were not very successful in achieving both high responsivity and low dark current because of the difficulty in producing a clean abrupt junction between a highly-doped Ge:Ga layer and a blocking layer [3,4]. We fabricate the detectors with the room-temperature, surface-activated wafer bonding (SAB) method; the surfaces of two wafers are activated by sputter etching with an Ar beam and bonded at room temperature in the vacuum environment [5-7]. This method does not require thermal treatment and therefore we can expect clean abrupt junctions.

2 Measurements

We fabricated SAB Ge junction devices with the sizes of $1\times1\times1$ mm^3 or $1\times1\times0.55$ mm^3; which have the electric contact area of 1×1 mm^2 and the intercontact length of 1 mm or 0.55 mm. A schematic image of the structure of the SAB Ge junction devices is shown in Fig. 1a. The device is installed in the cavity of the detector housing (Fig. 1b) and is illuminated on the lateral side by signal FIR photons, as shown in Fig. 1a. The Ga concentrations of the heavily-doped Ge:Ga layers and blocking layers of the SAB Ge junction devices are summarized in Table 1, which are estimated by the measurement of the Hall effect independently. We measured three types with different impurity concentrations in the heavily-doped Ge:Ga layer and the blocking layer. We tested the lightly Ga-doped blocking layer, considering potential difficulty in securing ohmic contacts to pure Ge. The thickness of both layers is 0.5 mm except for SAB Ge junction device (2), where the blocking layer is thinned to 50 μm. As a reference sample, we also fabricated a conventional Ge:Ga photoconductor with the Ga concentration of 2×10^{14} cm^{-3} and the size of $1\times1\times1$ mm^3. Hereafter we call this a bulk Ge:Ga device and compare the performance between the SAB Ge junction devices and the bulk Ge:Ga device.

Table 1 Parameters of the devices tested in the present paper.

	Impurity concentration	
Device	Heavily-doped Ge:Ga layer	Blocking layer
SAB Ge junction (1)	1×10^{16} cm^{-3}	4×10^{12} cm^{-3}
SAB Ge junction (2)	1×10^{16} cm^{-3}	4×10^{12} cm^{-3}, thinned
SAB Ge junction (3)	8×10^{16} cm^{-3}	7×10^{13} cm^{-3}
bulk Ge:Ga	2×10^{14} cm^{-3}	N/A

We measured the absolute responsivity of each device under dark conditions using an internal blackbody source with a cold shutter. Figure 1c shows the measurement setup in a liquid-He cryostat. We evaluated the absolute responsivity of each device at 2 K by measuring the photo-current generated by illumination of FIR photons from the blackbody source where the temperature is fixed at 40.0 K. The input power was estimated with the Planck function of 40.0 K multiplied by the spectral response curves which were obtained in the following measurements. The output photo-current was estimated by subtracting the current with the shutter closed from that with the shutter open.

We also measured the spectral response curve of each device with a Fourier transform infrared (FTIR) spectrometer (Fig. 1d). To illuminate the device with the external light source, we use another cryostat which has an entrance window with optical filters. The measurements were performed at 2.5 K. We measured the transmission curves of the optical filter and the vacuum-sealing windows as a function of the wavelength independently, which were used to correct the measured spectral response curves.

3 Results

We first evaluated the absolute responsivity of each SAB Ge junction device and the conventional bulk Ge:Ga device with the measurement setup shown in Fig. 1c. The obtained responsivity is 2 A/W for SAB Ge junction device (1), 15 A/W for (2), and 7 A/W for (3) at an optimal operating bias voltage. The responsivity of the bulk Ge:Ga device is 0.4 A/W, and thus the improvement in the responsivity from the conventional to the new devices is significant. On the other hand, the upper limit of the leakage current (i.e., the current measured with the shutter closed) is estimated to be (1) $\lesssim 10^{-15}$ A, (2) $\lesssim 10^{-11}$ A, (3) $\lesssim 10^{-13}$ A, and (4) $\lesssim 10^{-14}$ A, which suggests relatively large leakage current for device (2).

We then evaluated the spectral response curves of the SAB Ge junction devices and the conventional bulk Ge:Ga device with the measurement setup as shown in Fig. 1d. The obtained spectral response curves are shown in Fig. 2. The figure clearly shows that the SAB Ge junction devices have cut-off wavelengths longer than $120-130$ μm which is the cut-off wavelength of the conventional bulk Ge:Ga device. Thus we confirm that the Ga concentrations higher than 1×10^{16} cm^{-3} form impurity bands with shallower energy levels and thus extend the cut-off wavelength of the spectral response. On the other hand, at wavelengths shorter than 100 μm, the SAB Ge junction devices show lower responsivity than the conventional bulk Ge:Ga device. This is likely to be caused by relative increase in the

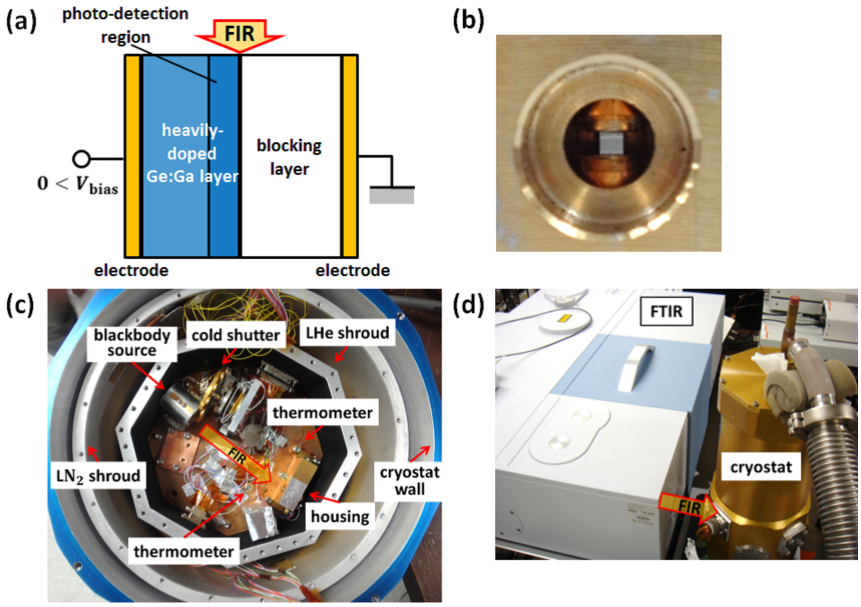

Fig. 1 (a) Schematic image of the structure of the SAB Ge junction device, clarifying the relation of the electrodes, the heavily-doped Ge:Ga layer and blocking layer, the bonded interface, and the direction of the incident FIR light. (b) A photo of the device (a small cube in the center) installed in the cavity of the detector housing. (c) A setup of the measurement of the absolute responsivity under dark conditions on the cold stage of a liquid-He cryostat. (d) A setup of the measurement of the spectral response curves, using a FTIR spectrometer.

phonon absorption of the Ge lattice due to a larger volume of non-photo-detection regions (i.e., blocking layer + non-biased heavily-doped layer) in the SAB Ge junction devices.

SAB Ge junction device (2) with a blocking layer thinned from 0.5 mm to 50 μm shows higher responsivity than SAB Ge junction device (1) at wavelengths of $120 - 160$ μm. This indicates a significant increase in the responsivity of the heavily-doped Ge:Ga layer through thinning the blocking layer, because the bias applied to the heavily-doped Ge:Ga layer becomes relatively large with the decreasing thickness of the blocking layer. On the other hand, SAB Ge junction device (3) shows an even longer cut-off wavelength than the others, but lower responsivity relative to the peak. The former indicates that the Ga concentration of 8×10^{16} cm^{-3} is high enough to extend the wavelength coverage to ~ 200 μm. The latter suggests that the blocking layer with an impurity concentration of 7×10^{13} cm^{-3} makes a significant contribution to the responsivity peak at ~ 110 μm and also requires thinning to 50 μm like SAB Ge junction device (2) to increase relative responsivity at > 130 μm.

Based upon the above results, we conclude that the heavily-doped Ge:Ga layer of the Ga concentration of $\sim 8 \times 10^{16}$ cm^{-3} and the blocking layer of ~ 50 μm in thickness and $\lesssim 1 \times 10^{13}$ cm^{-3} in the impurity concentration are an optimal combination of SAB Ge junction devices for FIR detectors, at least with high back-

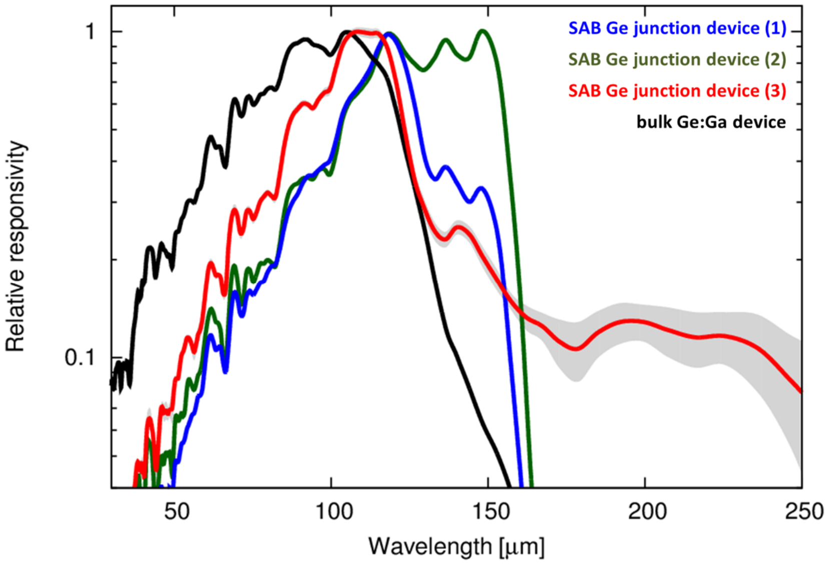

Fig. 2 Spectral response curves of the devices tested in the present paper. The vertical axis shows the relative responsivity where the peak is normalized to a unity for each device. The hatched regions represent the standard deviation of the spectral response curves measured 100 times.

ground conditions. We are yet to investigate the potential problem of relatively large leakage current for the thinned SAB Ge junction device.

4 Future Works

We plan to fabricate a 5 × 5 array SAB Ge junction detector with transparent electrodes in combination with a low-power cryogenic read out integrated circuit (ROIC). The parameters for the SAB Ge junction are determined, considering the results presented in this paper. We have developed the transparent electrodes which have a high FIR transmittance and a high-quality ohmic contact [8]. We have also developed the ROIC operable at cryogenic temperatures [9,10], and successfully demonstrated a trans-impedance amplifier at 4.2 K [11]. Development of a large-format FIR imaging sensor based on the SAB Ge junction device is underway [12].

5 Summary

We have fabricated Ge junction devices which possess a BIB-type structure (i.e., heavily-doped Ge:Ga layer plus blocking layer) with the SAB method for FIR astronomy. We evaluated the absolute responsivities and spectral response curves of the SAB Ge junction devices at ~ 2 K and compared the performance with that of the conventional bulk Ge:Ga device. The results show that the SAB Ge junction devices have significantly higher responsivities than the conventional bulk Ge:Ga device, and cover wavelength ranges up to $\sim 200\ \mu$m. Hence the SAB Ge junction devices possess a promising applicability to next-generation FIR detectors. As a next step, we plan to fabricate a 5×5 array SAB Ge junction detector in combination with the low-power cryogenic ROIC.

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