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BY ION IMPLANTATION**

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LONG-WAVELENGTH GERMANIUM PHOTODETECTORS BY ION IMPLANTATION

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ABSTRACT

Extrinsic far-infrared photoconductivity in thin high-purity germanium wafers implanted with multiple-energy boron ions has been investigated. Initial results from Fourier transform spectrometer(FTS) measurements have demonstrated that photodetectors fabricated from this material have an extended long-wavelength threshold near $192\mu\text{m}$. Due to the high-purity substrate, the ability to block the hopping conduction in the implanted IR-active layer yields dark currents of less than 100 electrons/sec at temperatures below 1.3K under an operating bias of up to 70mV. Optimum peak responsivity and noise equivalent power(NEP) for these sensitive detectors are 0.9A/W and $5 \times 10^{-16} \text{ W/Hz}^{1/2}$ at $99\mu\text{m}$, respectively. The dependence of the performance of devices on the residual donor concentration in the implanted layer will be discussed.

INTRODUCTION

Because of the potential technological importance of high performance far infrared detectors for space-born telescope applications, the development of far infrared Ge detectors using a two-layer structure based on the Blocked-Impurity-Band(BIB) concept is being extensively studied¹⁻⁵. In contrast to normal photoconductors^{1,3}, BIB photodetectors have a number of desirable features: 1. extension of the cutoff wavelength limit from the dopant photoconductive onset to longer wavelengths, 2. a decrease in interference from cosmic radiation because of volume reduction, and 3. a reduction in the noise due to fixed unity gain.

These improvements have been realized to a large extent with Si BIB detectors for wavelengths up to $30\mu\text{m}$ ^{6,7}. Furthermore, these novel devices have the capability of achieving background limited performance at the very low infrared levels encountered in space-based observations⁸. In addition, two-dimensional monolithic BIB detector arrays have been fabricated using IC process technologies^{6,7}.

Conventional BIB detectors consist of a thin, undoped intrinsic blocking layer grown homo-epitaxially on an intermediately doped substrate. Incident photons absorbed in this intermediately doped region generate free carriers which pass through the pure layer, and are collected as photocurrent when the device is properly biased. The ionized impurity state travels via successive bound carriers to the opposite electrode. The intrinsic layer serves to block the large currents which would arise from hopping conduction within the impurity band in the intermediately doped layer. The device derives improved performance from the fact that the presence of the blocking layers makes it possible to dope the IR-active layer more heavily than in conventional photoconductive detectors, without the corresponding increase in dark current

due to hopping conduction. The higher doping also allows a reduction in device volume without compromising quantum efficiency of the device.

In view of considerable success of Si BIB detectors, it appears worthwhile to try to develop Ge detectors with similar structure. Because of the much smaller ionization energies of shallow impurities in Ge as compared with Si, Ge BIB detectors are expected to have a longer wavelength cutoff around 200 μm and perhaps beyond. A Ge BIB detector of conventional design consists of a pure Ge epitaxial layer which is grown on an intermediately doped IR-active substrate. Early devices fabricated by chemical vapor deposition (CVD)⁹ indeed showed an extended long-wavelength threshold at 190 μm and had a promising peak responsivity of 5 A/W. However, data on Ge BIB devices which exhibit such characteristics as well as low dark currents ($< 100 \text{ e}^-/\text{s}$) and NEP^{10,11} which are necessary for future satellite born applications have not been published so far.

In this paper, we present a new approach of fabricating two layer Ge far-IR photoconductors which show BIB device characteristics. In this new approach, the IR active layer is formed in an ultra-pure Ge substrate using ion implantation. The high-purity substrate serves as the blocking layer. Since the substrate can be selected from very high quality bulk crystals ($|N_A - N_D| < 2 \times 10^{10} \text{ cm}^{-3}$)^{12,13}, its ability to block hopping conduction is assured. The thickness and dopant concentration of the IR-active layer can be controlled by varying ion energies and doses. Since complete analysis of BIB device physics and applications have been published elsewhere¹⁻⁵, we will confine ourselves to describing the processes required to make the new structure and to their characterization. Preliminary experimental results of the discrete far-IR Ge detectors will be presented and discussed.

EXPERIMENTAL DETAILS

The starting material for these devices investigated in the present work was prepared from ultra-pure Ge with extremely low impurity concentration (about $2 \times 10^{10} \text{ cm}^{-3}$) and essentially perfect crystalline quality¹³. Wafers of 200 μm thickness were cut from large boules with a diamond saw, then lapped and polish etched to remove all mechanical damage. Boron ions were implanted using several energies to approximate a flat impurity concentration profile of $3 \times 10^{16} \text{ cm}^{-3}$ from the surface to a depth of 0.5 μm . The wafers were then annealed for one hour at 400°C in argon to remove any implantation damage and to fully activate the boron¹⁴. Boron was used for implantation doping because it is the shallowest elemental acceptor in Ge and it is active as implanted at room temperature. These two characteristics guarantee the longest wavelength response and circumvent very high temperature annealing which might introduce other impurities into the wafer. Furthermore, boron is the lowest mass acceptor thus reaching the greatest implantation depth for a given ion energy.

A schematic diagram of a prototype ion implantation Ge BIB device described in this work is demonstrated in Fig. 1. Square samples of 1x1 or 2x2 mm^2 were cut from an implanted and annealed wafer with a dicing saw. The small samples were mounted with the implanted side down onto a glass slide using wax. The device was then further thinned by chemically etching the unimplanted side to reach a final sample thickness of 50 μm . The sides were

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Fig.1 Schematic cross section of a ion implanted Ge far-IR detector.

also etched to remove any residual saw damage, which could contribute to excess surface leakage currents⁸. A final implantation of B⁺ ions formed a degenerately doped p⁺⁺ contact on the top face without any post-implant annealing. We chose an implant dose of 2×10^{13} B/cm² at an energy of 25 keV. This produces ohmic, semi-transparent contact layers.¹⁵

Finally, a strip of copper was attached to the bottom surface of the detector using pure indium solder. The specimens were then mounted on copper heatsinks in an integrating cavity for photocurrent response and NEP tests. A copper wire was pressure-welded to the top surface by using a pure indium pad. Measurements of dark current were obtained using an integrating JFET amplifier JF-4 (Infrared Labs.) which has a read noise of less than 20 electrons.¹⁶

EXPERIMENTAL RESULTS AND DISCUSSIONS

Various detector figures of merit, including spectral response, responsivity, noise equivalent power, and dark current, were measured from several specimens. Because all the devices showed very uniform response, we chose to restrict ourselves to reporting results from just one of these specimens. The two spectral responses of this detector under different bias are shown in Fig.2. It was obtained using a Fourier transform spectrometer (FTS). The periodic variation in the current response resulted from the Fabry-Perot interference between the front and the back surfaces of the detector. When the applied bias was varied from 10 to 25 mV with the detector operating at a temperature of 1.5K, the long-wavelength cutoff moved from 140 to 192 μm, significantly beyond the 120 μm onset of a standard boron-doped Ge photoconductors¹⁷. Such a shift does not occur in the very pure blocking layer. It must be due to photoexcitation in the moderately doped ion-implanted layer.

BIB device structure can be compared to a metal-insulator-semiconductor (MIS) photodiode. A positive bias applied to the detector surface contact (Fig. 1) will deplete the moderately doped detection layer of ionized acceptors to some depth. The positively charged minority donors constitute the space charge. By solving Poisson's equation, we find that the width of depletion layer W relates to the applied bias V_a and minority donor concentration N_d as follows:

$$W = \sqrt{\frac{2 \epsilon_0 \epsilon V_a}{e N_d} + t^2} - t$$

where ϵ is the dielectric constant of Ge, t the thickness of blocking layer, and e the electronic charge. It is desirable to increase the applied bias to widen of the depletion layer W from the tail of the implant profile into the intermediately doped plateau so as to extend the cutoffs to the longest possible wavelengths and also to increase the quantum efficiency of the detector. However, for our ion implanted BIB detectors, no further increase in both cutoff wavelength and photoresponse were observed when the bias voltage exceeded 25mV. Beyond 25mV, the detector noise level increased sharply with the increase of the applied bias.

It should be mentioned that photocurrent could be also measured under reverse bias operation. This response has been found to be due to the implanted contact on the back side of the device as shown in Fig.1. However, the spectral response (Fig.2) generated from the back single-implant contact is different from that the front multiple-implant side. The former always lacks a sharp long wavelength threshold and shows a lower value of the peak responsivity at about 60 μm . For a conventional extrinsic photoconductor, the spectral response is completely symmetric with respect to applied bias polarity. However, for these implanted detectors, the asymmetry of performance in regard to bias polarity is a strong indication that the spectral response (Fig.2) of the detector comes primarily from the front multiple-implant layer.

In Fig.3, we show three figures of merit of this device. The absolute responsivity and NEP values at 99 μm as a function of bias were tested at a photon background of 1×10^8 photons/cm²-s and at a typical photon chopping frequency of 23 Hz with a low noise, trans-impedance preamplifier and a spectrum analyzer. Dark currents at this test temperature of 1.3K were found to be independent of the bias up to 40 mV. Operated at 24 mV, the detector has a NEP of 5×10^{-16} W/Hz^{1/2} which is only about an order of magnitude higher than the value of background limited performance (BLIP). Scaled to the measured responsivity at 99 μm , the corresponding peak responsivity in Fig.2 is expected to be about 0.9 A/W at 120 μm .

The thickness of the detection layer for these devices is determined by two parameters, N_d and t . For instance, with an applied bias of 25 mV, a value of $t=50$ μm , and an assumed $N_d=1 \times 10^{11}$ cm⁻³, the depletion width W has a value of 4.2 μm . This is eight times as thick as the range of 150 keV B⁺ ions, i.e., the device is fully depleted except the electrode layer. But, for $N_d=1 \times 10^{12}$ cm⁻³, with

Fig.2 Spectral response of a boron-implanted Ge detector under two different bias 10 and 25 mV.

Fig.3 Responsivity and NEP of low-energy implanted Ge detector active layer depth = 0.5 μm , $[B] = 3 \times 10^{16}/\text{cm}^3$, narrow band filter at 99 μm , chopping frequency = 23Hz.

all other parameters as above, W would be $0.44 \mu\text{m}$ which is close to depth distribution of 150 keV B^+ ions. Therefore, the determination of N_d in the IR-active layer is crucial for device development. Due to the fact that carrier freeze-out does not occur in the intermediately doped layer, both the actual value of N_d and therefore W in the implanted IR-active layer are not known and are still under investigation. We have used variable temperature Hall effect measurements to determine donor concentrations on several low dose B-implanted layers ($[B]=1 \times 10^{15} \text{ cm}^{-3}$). These low dose layers were deliberately utilized to avoid hopping conductivity in the implanted layer at low temperatures. Our preliminary Hall data indicate that 150 keV boron as-implanted layers are highly compensated with donor concentrations in the $1 \times 10^{14} \text{ cm}^{-3}$ range. Post-implant annealing steps for these implanted layers have been found to be necessary to lower donor concentrations to the $1 \times 10^{13} \text{ cm}^{-3}$ range, which is still higher than the expected value of $N_d < 1 \times 10^{12} \text{ cm}^{-3}$. As already mentioned, the lower donor concentration values lead to an increased depletion region thickness, therefore, if the residual donor concentration N_d can be reduced to lower values ($N_d \sim 1 \times 10^{11} \text{ cm}^{-3}$) via optimization of the fabrication processes, then the use of MeV implantation to produce IR-active layer several microns in thickness to improve the detector sensitivity become very desirable.

Finally, low dark current is a key factor which promises the detector performance in low background condition. The far-IR space-based astronomy application requirements for dark current are less than $100 \text{ electrons/sec/pixel}$ with a typical pixel size of less than $0.5 \times 0.5 \text{ mm}^2$. As shown in Figs.3 and 4, even lower dark currents, about $70 \text{ e}^-/\text{s}$, have been achieved with this discrete Ge device $1 \times 1 \text{ mm}^2$ in size at operating temperatures below 1.3K and a bias below 70 mV . The temperature dependence of dark currents under different bias conditions is shown in Fig.4. Indeed, at a temperature of 1.25K , the value of the dark current did not exceed $100 \text{ e}^-/\text{s}$ up to an applied bias of 80 mV . The breakdown voltage in the dark for this operating temperature was about 90 mV .

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Fig.4 Dark currents as a function of temperature. At 1.25K , the values of dark currents are less than $70 \text{ e}^-/\text{s}$ over the applied voltages from 1 to 70 mV .

CONCLUSION

We have fabricated the first far-infrared Ge detectors based on the BIB concept using ion implantation technique. These boron-implanted Ge BIB detectors exhibit operating characteristics compatible with requirements for low background applications. Device parameters such as low dark currents, acceptable sensitivity and extended wavelength threshold, demonstrate that ion-implanted Ge far-IR detectors offer promise for use in astrophysics instrumentation. Further studies are aimed at fully understanding the device operation. In particular, the origin of the residual donor concentration in the ion-implanted IR-active layer needs to be determined. If the lower N_d value can be achieved in boron implanted layers, the use of high-voltage ion implantation to increase the active layer thickness will also be examined in order to optimize the detector performance.

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