Abstract—In this paper, alternative operational mode (AOM) of Si-based blocked impurity band (BIB) detectors is thoroughly investigated. The basic structure of the detector evolves from the prototype of the ion-implanted BIB detector, which is potentially compatible with CMOS processes. Benefiting from lower dark current, the detectivity of ion-implanted devices studied in this work is comparable with the Si BIB detectors ever reported. For ion implantation devices, a peak blackbody detectivity of $5 \times 10^{12}\text{cm-Hz}^{1/2}/\text{W}$ (background temperature $T = 40\text{K}$) occurs at 2 V under AOM. These merits make the ion-implanted device a powerful candidate for a wide range of applications from infrared to terahertz band. By analyzing the carrier distribution and the band structure in different functional regions of the device at the measured temperature, depletion junction formed in the region of active layer near active layer/cathode interface side is deduced when the device is operated under AOM. The theory is successfully used to interpret experimental data, including the detectivity comparable to the epitaxial device, significantly reduced dark current.

Index Terms—Blocking impurity band, diode, planar device.

I. INTRODUCTION

THE electromagnetic spectrum, covering far-infrared band to terahertz (THz) band ($\sim 14–300 \mu\text{m}$), has become a powerful tool in an imaging application, security application, astronomical application, and chemical spectroscopy, etc. [1]–[5]. Various kinds of infrared and THz detectors have been developed to discover the novel physical phenomenon in this band [6]–[10]. For example, large-scale observing facilities built to work in this range have become the engine of astronomical science by supplying valuable data related to the origin and evolution of the universe [11]–[14]. As a core component in those facilities, the detector experiences brutal elimination mechanism. Extrinsic photoconductors, bolometers, and superconductor-insulator-superconductor detectors were chosen to take responsibility as the core detector in different eras. However, they are quickly replaced without exception due to different disadvantages until the invention of blocked impurity band (BIB) detectors. BIB detectors have become the state-of-the-art choice for astronomical and imaging application from far-infrared to THz region in the last several decades based on the following merits [15]. First, the most mature BIB detectors, namely Si:As detectors covering $3–28 \mu\text{m}$ [14] and Si:Sb detectors covering $3–40 \mu\text{m}$ [16], are silicon-based devices with the feasibility of mass production, CMOS compatibility [17], [18] and excellent uniformity [14], [16]. Second, the covering band of photoresponse of BIB detectors is determined by the ionization energy of doped impurity atoms in the absorption layer (AL). Theoretically, BIB could cover 3 to $300-\mu\text{m}$ range by adopting a combination of different material and impurity atoms [19]–[23].

In order to provide an alternative development approach for BIB detectors except for epitaxial method, Haegel proposed a theoretical solution in 2005 [24]–[26]. However, there has been limited experimental work. The theoretical operation mode, namely alternative operation mode (AOM) with a reverse bias, predicted by Haegel spurs our passion to further explore device physics of BIB detectors.

The traditional theory believes that BIB works like a diode with reverse-blocking property [27]. Since the resistivity of blocking layer (BL) is several orders of magnitudes larger than AL, a voltage drop occurs almost entirely in BL under AOM with this assumption. Consequently, the electrical field in AL is neglected under AOM, which means that the photo-generated carriers are unable to be separated, not to mention drift to individual contacts. In this paper, the traditional theory is proven to need correction since Si-based BIB detectors are demonstrated to be capable of operating under AOM as Haegel predicted. The basic structure of the detector is based on the prototype of a CMOS compatible ion-implanted BIB detector [28], [29]. The dominant performances operated at AOM are comparable with the conventional operation mode (COM), including detectivity and responsivity. The peak blackbody detectivity at $-2 \text{ V}$ reaches $5 \times 10^{12} \text{ cm-Hz}^{1/2}/\text{W}$, which is remarkably improved compared to the reported value in Si-based BIB detectors.

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Optimized Si-Based Blocked Impurity Band Detector Under Alternative Operational Mode

He Zhu, Chao Wang, Peng Wang, Jiale He, and Weida Hu

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Abstract—In this paper, alternative operational mode (AOM) of Si-based blocked impurity band (BIB) detectors is thoroughly investigated. The basic structure of the detector evolves from the prototype of the ion-implanted BIB detector, which is potentially compatible with CMOS processes. Benefiting from lower dark current, the detectivity of ion-implanted devices studied in this work is comparable with the Si BIB detectors ever reported. For ion implantation devices, a peak blackbody detectivity of $5 \times 10^{12}\text{cm-Hz}^{1/2}/\text{W}$ (background temperature $T = 40\text{K}$) occurs at 2 V under AOM. These merits make the ion-implanted device a powerful candidate for a wide range of applications from infrared to terahertz band. By analyzing the carrier distribution and the band structure in different functional regions of the device at the measured temperature, depletion junction formed in the region of active layer near active layer/cathode interface side is deduced when the device is operated under AOM. The theory is successfully used to interpret experimental data, including the detectivity comparable to the epitaxial device, significantly reduced dark current.

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I. INTRODUCTION

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II. FABRICATION AND TEST DETAILS

Fig. 1 shows the basic structure of the device. The top view in Fig. 1(a) illustrates the detailed structure of the device, corresponding to the cell in the box enclosed by the dashed line in Fig. 1(b). The device consists of four different functional regions with a consistent length of 1 mm, including 40-μm-width AL, unintentionally doped BL, anode contact adjacent to BL, and cathode contact adjacent to AL. Three different BL width \(l_{BL}\) parameters were adopted here, including 3, 5, and 10 μm. The side view in Fig. 1(b) depicts the cross-sectional view of the device from the right side of the dashed line in the planar view. Most of the functional regions in the device were achieved by ion implantation on a high-purity (100) Si wafer, including AL (1-μm thick), the anode, and cathode contact region. The residual part of the silicon wafer between AL and the anode contact plays the role of BL. Ion implantation with different energy and dose parameters was implemented step by step in order to achieve a uniform distribution of dopant atoms (phosphorus-P) in AL and the contacts. The doped concentration \(N_D\) in AL is \(2 \times 10^{17} \text{ cm}^3\), while the value in the contact regions is two magnitudes higher than that in the AL.

The blackbody response \(R_{bb}\) was measured with an 800-K blackbody source. Dark current is collected with three layers of cold shield to ensure thermal insulation. The temperature of the innermost cold shield is about 40 K. The field of view (FOV) of the optical system is 0.3 rad. The photocurrent spectra are measured in a Bruker 80v Fourier-transform infrared spectrometer. Details of the measurements are described in our preliminary work (see [16]). The noise spectrum is measured with Keysight 35670A dynamic signal analyzer while collecting its dark current. Therefore, the blackbody detectivity of the device is calculated with the formula

\[
D = \left( \frac{R_{bb}}{\sqrt{i_n}} \right) \sqrt{\frac{A_d \Delta f}{i_n f}}
\]

in which \(i_n\), \(A_d\), \(\Delta f\) represents noise current, detector size, and bandwidth, respectively. Without specific statement thereafter, the characterizations of the detectors were performed at liquid helium temperature (4 K).

III. RESULT AND DISCUSSION

Since the silicon wafer is slightly p-doped, the small concentration of acceptors is more than likely to be the boron doped. The Fermi level \(E_F\) shifts far away from the intrinsic Fermi level due to the high dopant concentration. Therefore, the acceptors are assumed to be totally activated as \(N_A^- = N_A\). There are four types of charge particles in AL, including ionized acceptor \((N_A^-)\), ionized donor \((N_D^+)\), electron \((n)\), and hole \((p)\). Due to the relation \(p \ll n \ll N_D^+\) between those charge particles under the measured temperature, the hole can be neglected. The residual positive charge particle is the ionized donor indubitably. The band structure in thermal equilibrium is illustrated in Fig. 2(a). An impurity band is formed in AL due to the degeneration of
donor level between dopant atoms. The positive vacancy of ionized donor behaves like a charge carrier that transports the impurity band through hopping conductance, as depicted in Fig. 2(b). The mobile positive vacancy is considered as meta-hole when investigating the carrier transportation phenomenon. Therefore, AL is regarded as p-type since the major carrier in AL is meta-hole and could form a p-i-n-junction under COM with the BL and anode. Since most of the depletion region is established in AL adjacent to AL/BL interface, the theory inferred by Szmulowicz is still applicable. However, the region is established in AL adjacent to AL/BL interface, which is depicted in Fig. 2(b). The mobile positive vacancy is considered as meta-hole through hopping conductance, as depicted in Fig. 2(c). The mobile positive vacancy is considered as meta-hole through hopping conductance, as depicted in Fig. 2(d).

![Image](https://example.com/image.png)

**Fig. 2.** (b) Relationship between experimental responsivity $R_{bb}$ and external bias $V_{ex}$ for devices with multiple $l_{BL}$. (b) Relationship between $R_{bb}$ and $l_{BL}$ with $V_{ex} = 2$ V under AOM for both experimental result and simulation result. (c) Evolutionary tendency of $R_{bb}$ with measured temperature. (d) Relationship between experiment detectivity $D_{bb}$ and $V_{ex}$ for devices with multiple $l_{BL}$. $l_{BL} = 5\mu$m in (b) and (c).

The measured responsivities are shown in Fig. 3. As depicted in Fig. 3(a), the responsivity is always positively correlated with the absolute bias value $|V_{ex}|$ for both operation modes. The responsivity under AOM is barely influenced by $l_{BL}$ when $|V_{ex}|$ is below 1.5 V. The difference of $R_{bb}$ for distinct $l_{BL}$ value increases with $|V_{ex}|$ when $|V_{ex}|$ exceed 1.5 V. However, the difference of $R_{bb}$ for distinct $l_{BL}$ is obvious under COM even if $|V_{ex}|$ is below 1 V. The relation between $l_{BL}$ and $R_{bb}$ for $|V_{ex}| = 2$ V under AOM is illustrated in Fig. 3(b). The responsivity is negatively correlated with $l_{BL}$ when $V_{ex}$ equates $-2$ V. The electrical field $E_{AL}$ differ with each other for distinct $l_{BL}$ when $V_{ex}$ equates $-2$ V since AL is totally depleted. With the theoretical electrical field, the calculated simulation fits well with the experimental result. The relationship between responsivity and temperature is shown in Fig. 3(c). It is obvious that responsivity is positively correlated with temperature, which could be explained as follows. Electrons bounded by impurity atoms are easier to be activated into conduction band with the assistant of phonons. The calculated blackbody detectivity $D_{bb}$ versus $V_{ex}$ are presented in Fig. 3(d). The detectivity of various devices discriminates from each other, besides the detectivity decreases significantly as the $l_{BL}$ increases. The symmetric characteristics in Fig. 3(a) and (d) enables the device to work both under forward bias and reverse bias. It is the unique advantage of this kind of devices, while normal photodiode can only work under one mode, and normal photoconductors do not have a depletion region.

The ratio between the responsivity under AOM ($R_{AOM}$) and COM ($R_{COM}$) is presented in Fig. 4(a). The simulation result is in good consistent with experiment. The graph obviously

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\epsilon}$</td>
<td>3.1 kV/cm</td>
<td>$N_{A}$</td>
<td>$2 \times 10^{17}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$R_{1}$</td>
<td>0.3</td>
<td>$N_{D}$</td>
<td>$1 \times 10^{12}$ cm$^{-3}$</td>
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<td>$l_{BL}$</td>
<td>$3.5,10\mu$m</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>$10^{6}$ ph.cm$^{-2}$. s$^{-1}$</td>
<td>$l_{AL}$</td>
<td>$40\mu$m</td>
</tr>
</tbody>
</table>

**Table I**

PARAMETERS ADOPTED IN THE SIMULATION
occurs at the maximum detectivity value of the ion-implanted device. The spectrum of the ion-implanted device is depicted in Fig. 4(d). Two types of devices are comparable. The relative response of the epitaxial device degrades rapidly in the range from $-1.5$ to $2$ V, while the detectivity of the epitaxial device degrades rapidly in the range from $-1.5$ to $-2$ V. The maximum detectivity value of the ion-implanted device occurs at $-2$ V with a value of $5 \times 10^{12}$ cm-Hz$^{1/2}$/W. The dark current of the ion-implanted device is remarkably lower than the epitaxial device. According to Liao’s theory [31], the dark current could be regarded as the responsivity with a low flux density. The effective thickness of AL($E_{AL}$) in the epitaxial device is $1 \mu$m. In the epitaxial device, $E_{AL} = 40\mu$m. Since the absorptivity of the radiation is positively correlated with $H_{AL}$, the responsivity and the dark current of the ion-implanted device are both smaller than the epitaxial device. Consequently, the detectivities of these two types of devices are comparable. The relative response spectrum of the ion-implanted device is depicted in Fig. 4(d). The spectrum covers $15 \sim 28 \mu$m with its peak located at $25.3 \mu$m. The peak location corresponds to activation energy ($E_a$) of the impurity atom. The calculated value of $E_a$ is $49$ meV, which is larger than a $45$-meV theoretical value.

**IV. Conclusion**

In this paper, the AOM of Si-based BIB detectors is demonstrated. The basic structure of the detector is based on a prototype of the ion-implanted BIB detector. The dominant performance operated at AOM is better than the COM, including $R_{bb}$ and $D_{bb}^*$. The theory of Haegeland is consummated in this paper to explain these physics phenomena. By analyzing the carrier distribution and the band structure in different functional regions of the device, the depletion junction formed in the region of active layer near AL/cathode interface side is deduced when the device is operated under AOM. The linear electrical field is established in AL, while a constant electrical field $E_{BL}$ much weaker than $E_{AL}$ is established in BL. On the contrary, the constant electrical field $E_{BL}$ is stronger than $E_{AL}$ under COM. The spectrum under AOM covers $15 \sim 28 \mu$m, which is consistent with the impurity activation energy $E_a$. Benefiting from lower dark current, the performance of the ion-implanted device is comparable with the traditional epitaxial device. The peak blackbody detectivity of the ion-implanted device occurs at $-2$ V with a value at $5 \times 10^{12}$ cm-Hz$^{1/2}$/W. In conclusion, the excellent performance of the ion-implanted device makes itself a powerful candidate for various applications from infrared to THz band.

**Appendix**

Optical generation in the epitaxial device can be expressed as (see [23])

$$G(z) = \frac{\alpha \Phi (1 - R_1) (e^{-az} + R_2 e^{az} e^{-2ad})}{1 - R_1 R_2 e^{-2ad}}.$$  

Since the wafer is not thinned and no back reflective layer is deposited, $R_2$ can be neglected.

The optical generation in the ion-implanted device could adopt the average value through the thickness of the active layer

$$G(z) = \int_0^{H_{AL}} \alpha \Phi (1 - R_1) e^{-az} dz.$$  

The value used in the simulation is listed below.

**Acknowledgment**

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**References**


