Opto-electrical characteristics of Si-based blocked-impurity-band detector: Experiment and simulation

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Abstract

Opto-electrical characteristics of Si-based blocked-impurity-band (BIB) detector are investigated by combing experiment with simulation. The measured black-body response characteristics at different temperature are discussed. The simulated dark current characteristics with different thicknesses of blocking layer are also presented by taking into account impurity-band effects.

I. INTRODUCTION

The concept of blocked impurity band was proposed based on extrinsic photoconductivity. Compared with intrinsic photoconductive detector, extrinsic photoconductive detector can improve the photon absorption probability, and extend response to even longer wavelength. However, electrons hopping between impurity centers in the extrinsic photoconductive detector can bring about extremely large dark current and noise, making it difficult to further increase doping concentration and responsivity. To overcome this problem, Petroff and Stapelbroek invented the blocked-impurity-band (BIB) detector in 1986 [1]. The unique feature of the BIB detector is a thin intrinsic blocking layer adjacent to a heavily doped absorbing layer. The thin intrinsic blocking layer can contribute to two advantages: (1) a smaller size of the BIB detector can be allowed to make the detector less susceptible to high energy cosmic rays; (2) a higher doping concentration of the absorbing layer can be allowed to broaden the absorption transition lines and therefore extend the response from infrared into terahertz (THz) regime.

The BIB detectors have been successfully realized with Si [2], Ge [3], and GaAs [4]. Among them, Si-based BIB detector is most mature, and thus has been most widely used. This is because the quality of Si material is far superior to that of either Ge or GaAs. Response wavelength of Si-based BIB detectors can cover 2-40μm range [5], and their performances are excellent in terms of quantum efficiency, dark current, linearity, and operability. Therefore, Si-based BIB detector has become the overwhelming choice for space-based, airborne, and high-altitude ground-based THz detecting and imaging system. For example, Si:As together with Si:Sb BIB detectors have been employed on the infrared spectrograph of Spitzer Space Telescope launched in 2003 [6].

A lot of innovative contributions have been successively made by some outstanding researchers. For instance, Martin *et al*. have substituted the traditional ohmic contact by the PtSi Schottky barrier for blocking the injected electron dark current in a back-illuminated Si:As BIB detector, making the maximum bias as high as 10V [7]. Garcia *et al*. have proposed a new operating mode (i.e., alternate bias mode) for the Si-based BIB detector, allowing for growth of thicker blocking layers without deteriorating photoresponse [8]. Rauter *et al*. have fabricated a novel vertical Si:B BIB detector based on a silicon-on-insulator (SOI) wafer, circumventing the troublesome MBE growth of an ultrapure blocking layer by employing ion implantation [9]. Although many experimental breakthroughs have been made for Si-based BIB detector, a comprehensive description on the photo-electrical characteristics by combining experiment with simulation is still lacking. The key reason lies on that the traditional energy band theory is not applicable to the simulation of electrons hopping and photons absorption in the impurity band.

In order to fill this gap, we present the measured black-body response characteristics of Si-based BIB device. Dark current characteristics with different thicknesses of blocking layer are also simulated by taking into account impurity-band effects. The results would serve as a good basis for optimization of Si-based BIB detectors.

II. EXPERIMENTAL SETUP AND SIMULATION MODELS

The testing system for black-body response consists of a 900^{0}C black-body source (HFY-206B), a low-noise current amplifier (SR570), a direct-current source (YOKOGAWA 7651), and a lock-in amplifier (SR830) with chopper frequency of 317Hz. The fabricated BIB detector was placed at the center of a specially designed PCB board, which was then enclosed by a cryogenic and vacuum Dewar with a TPX window.

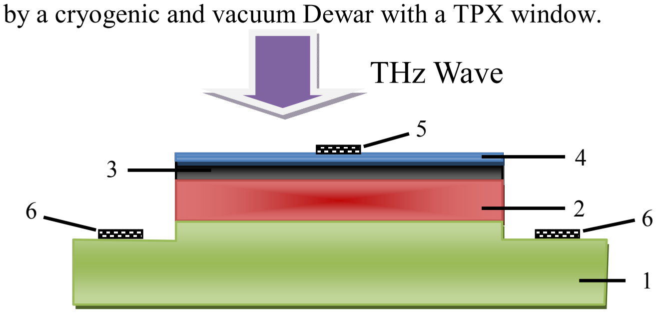

Fig. 1. Schematic cross-section of fabricated front-illuminated Si:P BIB detector.

As shown in Fig. 1, the experimental structure of front-illuminated Si:P BIB detector is composed of (1) a 450-μm-thick Si substrate degenerately doped with As, (2) a 30-μm-

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thick Si absorbing layer highly doped with P, (3) a 8-μm-thick unintentionally doped Si blocking layer, (4) a P-ion-implanted ultrathin contact layer, (5) a circular anode formed upon the contact layer, and (6) an annular cathode formed upon the substrate. Sentaurus Device, a commercial package by Synopsys [10] was used to perform the two-dimensional numerical simulations for the Si:P BIB detector. The drift-diffusion model [11] that couples Poisson and continuity equations is selected. Shockley-Read-Hall, Radiative, and Auger terms [12] constitute the carrier generation-recombination process. High-field saturation model is adopted for mobility simulation. Additionally, incomplete ionization has been taken into account for both donors and acceptors to describe the carrier freeze-out effects at low temperatures.

III. Results And Discussion

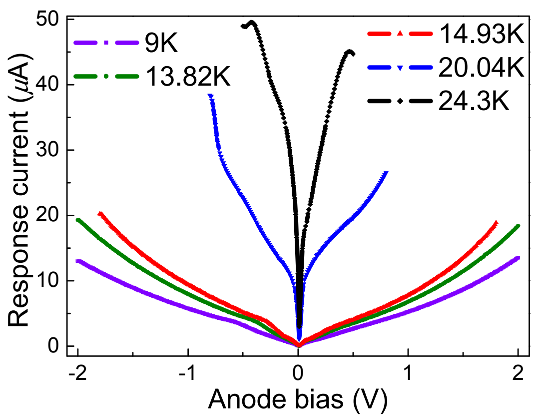

Fig. 2. Measured black-body response characteristics of Si:P BIB detector at different temperatures.

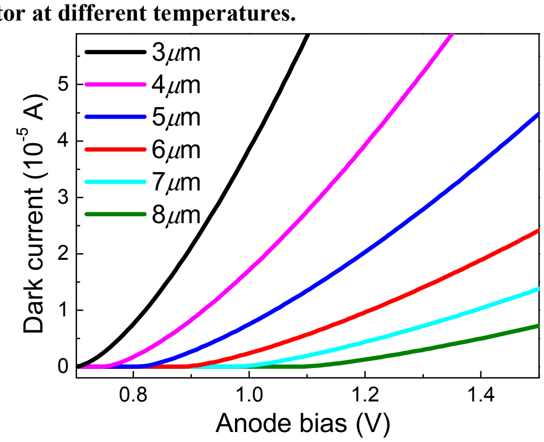

Fig. 3. Simulated dark current characteristics of Si:P BIB detector with different thicknesses of the blocking layer at *T*=5K.

Figure 2 illustrates the measured black-body response current versus anode bias at different temperatures. As indicated, the black-body response current is on the order of μA. It is found that photoresponse is a strong function of anode bias and temperature. Specifically, either a larger anode bias or a higher temperature will contribute to a larger response. It is worthwhile to point out that if the absolute value of anode bias is fixed, the negative bias will give rise to a larger response compared with the positive bias. The phenomenon can be well interpreted by the theory of Carcia *et al* [8]. However, this does not imply that the negative bias will be a more favorable operating mode than the positive bias because the dark current and noise at the negative bias will also be larger than those at the positive bias.

Figure 3 compares the simulated dark current characteristics for different thicknesses of the blocking layer at the temperature of 5K (*T*=5K). It is clear that the dark current decreases with increasing the thickness of the blocking layer as for a fixed anode bias. Furthermore, the breakdown voltage of the device is a monotonic increasing function of anode bias.

IV. Conclusion

Opto-electrical characteristics of Si:P BIB detector are investigated. Our results show that either a larger anode bias or a higher temperature will contribute to a larger response. Moreover, if the absolute value of anode bias is fixed, the negative bias will give rise to a larger response compared with the positive bias. It is demonstrated that the breakdown voltage of the device is a monotonic increasing function of anode bias.

Acknowledgements

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References

[1] M. D. Petroff, and M. G. Stapelbroek, "Blocked impurity band detectors," *US patent*, No. 4,568,960, 1986.
[2] K S. Liao, N. Li, C. Wang, L. Li, Y. L. Jing, J. Wen, M. Y. Li, H. Wang, X. H. Zhou, Z. F. Li, and W. Lu, "Extended mode in blocked impurity band detectors for terahertz radiation detection," *Appl. Phys. Lett.*, Vol. 105, pp. 143501, 2014.
[3] D. M. Watson, and J. E. Huffman, "Germanium blocked-impurity-band far-infrared detectors," *Appl. Phys. Lett.*, Vol. 52, pp. 1602, 1988.
[4] L. A. Reichertz, B. L. Cardozo, J. W. Beeman, D. I. Larsen, S. Tschanz, G. Jakob, R. Katterloher, N. M. Haegel, and E. E. Haller, "First result on GaAs blocked impurity band (BIB) structures for far-infrared detector arrays", *Proc. SPIE*, Vol. 5883, pp. 58830Q, 2005.
[5] V. Khalap, and H. Hogue, "Antimony doped silicon blocked impurity band (BIB) arrays for low flux applications," *Proc. SPIE*, Vol. 8512, pp. 85120O, 2012.
[6] J. R. Houck, T. L. Roellig, J. V. Cleve, B. Brandl, and K. Ulchida, IRS: the spectrograph on SIRTF; its fabrication and testing, *Proc. SPIE*, Vol. 4131, pp. 70, 2000.
[7] B. G. Martin, R. W. Fathauer, E. W. Jones, T. N. Krabach, and S. M. Dejewski, "Blocking injected dark current in impurity-band-conduction photodetectors using PtSi Schottky barrier," *Appl. Phys. Lett.*, Vol. 67, pp. 774, 1995.
[8] J. C. Garcia, N. M. Haegel, and E. A. Zagorski, "Alternate operating mode for long wavelength blocked impurity band detectors," *Appl. Phys. Lett.*, Vol. 87, pp. 43502, 2005.
[9] P. Rauter, T. Fromherz, S. Winnerl, M. Zier, A. Kolitsch, M. Helm, and G. Bauer, "Terahertz Si:B blocked-impurity-band detectors defined by nonepitaxial methods," *Appl. Phys. Lett.*, Vol. 93, pp. 261104, 2008.
[10] Synopsys: Sentaurus Device User Guide, Synopsys Inc., USA, 2008.
[11] X. D. Wang, W. D. Hu, X. S. Chen, and W. Lu, "The study of self-heating and hot-electron effects for AlGaN/GaN double-channel HEMTs," *IEEE Trans. Electron Devices*, Vol. 59, pp. 1393, 2012.
[12] W. D. Hu, X. S. Chen, Z. H. Ye, A. L. Feng, F. Yin, B. Zhang, L. Liao, and W. Lu, "Dependence of ion-implant-induced LBIC novel characteristics on excitation intensity for long-wavelength HgCdTe-based photovoltaic infrared detector pixel arrays", *IEEE J. Sel. Top. Quantum Electon.*, Vol. 19, pp. 4100107, 2013.