Effect of acceptor concentration on the dark current characteristics for GaAs-based blocked impurity band (BIB) terahertz detectors

Xiaodong Wang[1,*], Yulu Chen[1], Bingbing Wang[1], Xiaoyao Chen[2], Fangmin Guo[3], and Ming Pan[1]
[1]No. 50 Research Institute of China Electronics Technology Group Corporation, 318 Chang He Road, Shanghai, China 200331
[2]Laboratory of Advanced Material, Fudan University, Shanghai, China 200438
[3]Laboratory of Polar Materials & Devices, East China Normal University, Shanghai, China 200062

Abstract

In this paper, the structural model and the physical model of GaAs-based BIB THz detectors are constructed by means of numerical simulation. The effect of acceptor concentration on the dark current characteristics is investigated. Additionally, the optimal acceptor concentration corresponding to the maximum detectivity has been discussed from the application point of view.

I. Introduction

Terahertz (THz) radiation is commonly known as the electromagnetic wave with frequency range from 0.3 to 10THz. Within the electromagnetic spectrum, it lies in the spectral band between the microwave and the infrared. The importance of THz technology [1,2] has been recognized by more and more people due to the following advantages: strong penetration, good safety, high resolution, and excellent directionality. Nowadays, the THz technology can be widely used in the imaging and spectrum application area [3,4], especially in the security check, nondestructive testing, material identification, atmospheric monitoring, and astronomical observation. The key which determines the application of THz application is high-performance THz detectors, and thus the development of high-performance THz detectors has become the leading force driving the THz technology forward. Blocked impurity band (BIB) detector is a member in the family of opto-electronic detectors, and it can be classified into Si-based, Ge-based and GaAs-based BIB detectors. Si-based BIB detectors have the advantages including high response sensitivity, large array scale, and wide detection spectrum, and have realized a certain degree of application in the field of space-based, and high altitude land-based, and air-borne THz detection systems. For examples, The ISO satellite launched by the ESA has adopted the 1×12 Si-based BIB detectors in 1995, SIRTF satellite launched by the NASA has adopted the 128×128 Si-based BIB detectors in 2003, and ASTRO-F satellite launched by Japan has adopted the 256×256 Si-based BIB detectors in 2004.

GaAs-based BIB detectors [5] can response the THz wavelength beyond 500 μm (corresponding to 0.6 THz), and thus it has attracted worldwide attentions since the first prototype of GaAs-based BIB detector has been successfully developed. However, due to the restriction from the material crystalline quality and device processing technique, the research on GaAs-based BIB detector is still on the initial stage. Until now, GaAs-based BIB focal plane arrays haven't been reported yet, and the problems of poor reproducibility, large dark current, and low responsivity are still encountered by the single-element detector, blocking the application of GaAs-based BIB detectors.

Therefore, it is worthwhile determining the bottlenecks to restrict the device performance from achieving a higher level. This paper focuses on the effect of acceptor concentration on the dark current characteristics of GaAs-based BIB THz detectors. On one hand, dark current is a key parameter to characterize the device performance, which can directly determine the dynamic range of the detector. On the other hand, Reichertz et al. [6] in the UC Berkeley has reported that the depletion width is a monotonically decreasing function of accept concentration (N_A), and thus it seems that a lower N_A is preferred. However, the effect of acceptor concentration on the dark current characteristics has not been reported yet. Therefore, a comprehensive design consideration for the optimal N_A is still missing, which is also the motivation of this work.

II. Device Structure And Processing Technique

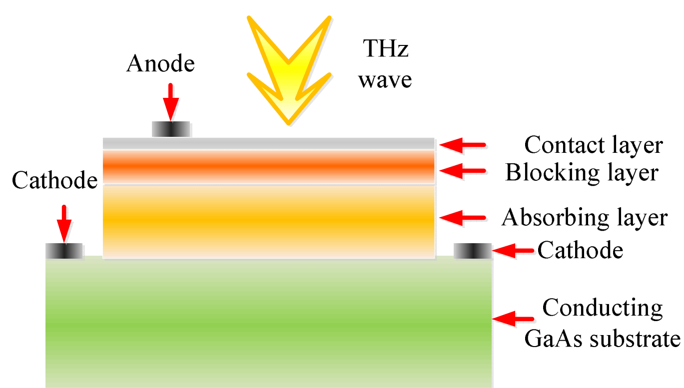

Fig. 1. Schematic cross-section of the GaAs-based BIB THz detector.

* Corresponding author: wxd06296@163.com

978-1-5090-5323-0/17/$31.00 ©2017 IEEE

Figure 1 shows the structural model of GaAs-based BIB THz detector. From the bottom to the top, the detailed device structure is as follows: (1) the conducting GaAs substrate with donor concentration of 5×10^{18} cm^{-3}; (2) the absorbing layer and the blocking layer sequentially formed by epitaxial technique with donor concentration of 5×10^{15} cm^{-3}, and 1×10^{13} cm^{-3}, respectively; (3) the contact layer formed by ion implantation with donor concentration of 3×10^{19} cm^{-3}; (4) the anode is formed upon the contact layer; (5) the cathode is formed upon the substrate. Besides, the physical model has been described elsewhere [7, 8], and the response mechanism of GaAs-based BIB detector is as follows: (1) THz wave is front-illuminated at the detector; (2) THz wave pass through the contact layer and the blocking layer, and then is absorbed by the absorbing layer; (3) Photo-generated carriers are transmitted through the bent conduction band, and eventually are collected by the electrodes.

III. Result And Discussion

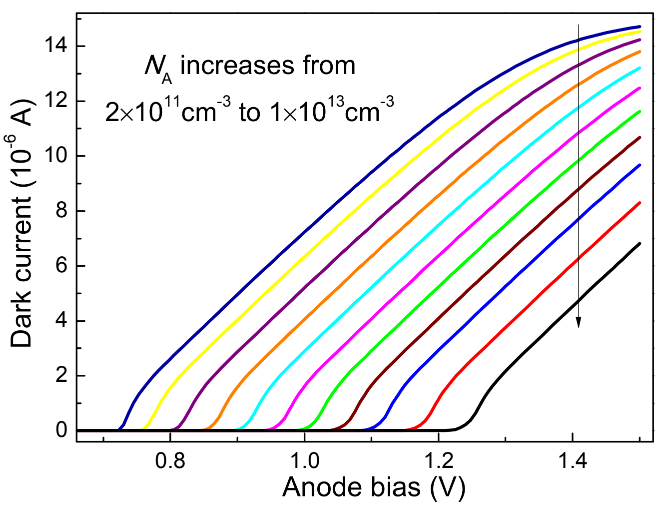

Fig. 2. Anode-dependent dark current characteristics with different values of N_A. From the top to the bottom, N_A is 2×10^{11} cm^{-3}, 1×10^{12} cm^{-3}, 2×10^{12} cm^{-3}, 3×10^{12} cm^{-3}, 4×10^{12} cm^{-3}, 5×10^{12} cm^{-3}, 6×10^{12} cm^{-3}, 7×10^{12} cm^{-3}, 8×10^{12} cm^{-3}, 9.3×10^{12} cm^{-3}, 1×10^{13} cm^{-3}, respectively.

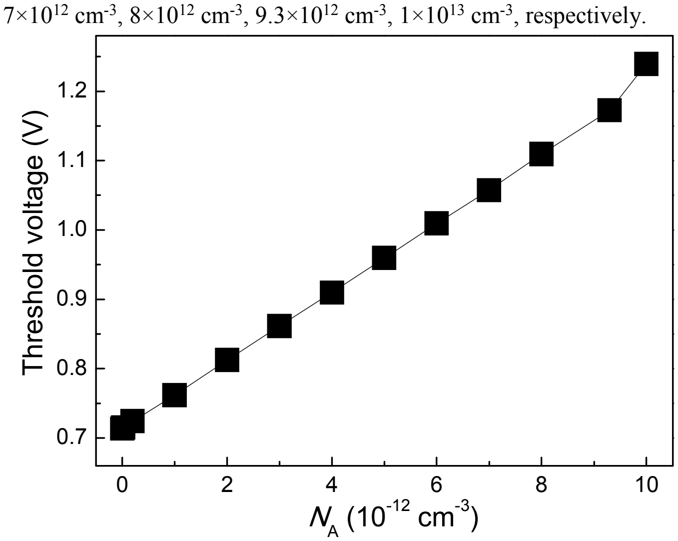

Fig. 3. Threshold voltage of GaAs-based BIB detector as a function of N_A.

Figure 2 shows the anode-dependent dark current characteristics with N_A increasing from 2×10^{11} cm^{-3} to 1×10^{13} cm^{-3}. It is found that dark current keeps a relatively small value when the anode bias (V_A) is below the threshold voltage, which is represented by V_T in the manuscript. When $V_A>V_T$, the dark current is exponentially increasing with V_A first, and then is linearly increasing with V_A, and finally is independent of V_A and saturated to a certain value. According to Fig. 2, it is interesting to note that dark current is a monotonically decreasing function of N_A. It has been mentioned above that the responsivity is also a decreasing function of N_A. Therefore, the optimal N_A corresponding to the maximum detectivity can be achieved, and the detailed procedure of pursuing the optimal N_A will be discussed in our future work.

Figure 3 illustrates the dependence of V_T on N_A. Our results reveal that V_T is almost a linear increasing function of N_A with N_A changing from 2×10^{11} to 1×10^{13} cm^{-3}, further indicating that a larger N_A can give rise to a larger dynamic range, which is also preferred from the application point of view.

IV. Conclusion

The structural model and the physical model of GaAs-based BIB THz detectors are constructed by means of numerical simulation. The effect of acceptor concentration on the dark current characteristics is investigated. It is found that dark current is a monotonically decreasing function of acceptor concentration. Besides, our results reveal that the threshold voltage is almost a linear increasing function of acceptor concentration, and a larger acceptor concentration is preferred from the dynamic range point of view.

Acknowledgements

This work was sponsored by Shanghai Rising-Star Program (No. 17QB1403900), the National Natural Science Foundation of China (No. 61404120), and Shanghai Sailing Program (No. 17YF1418100).

References

[1] M. Tonouchi, "Cutting-edge terahertz technology," *Nature Photonics*, Vol. 1, pp. 97-105, 2007.
[2] P. H. Siegel, "Terahertz technology," *Nature*, Vol. 50, pp. 910-928, 2002.
[3] D. M. Mittleman, R. H. Jacobsen, and M. C. Nuss, "T-ray imaing," *IEEE J. Sel. Top. Quantum Electon*, Vol. 2, pp. 679-692, 1996.
[4] H. B. Liu, H. Zhong, N. Karpowicz, Y. Q. Chen, and X. C. Zhang, "Terahertz spectroscopy and imaging for defense and security applications," *Proceedings of the IEEE*, Vol. 95, pp. 1514-1527, 2007.
[5] L. A. Reichertz, et al., "Development of a GaAs based BIB detector for sub-mm wavelenghts," *Proc. SPIE*, Vol 6275, pp. 62751S-1-8, 2006.
[6] L. A. Reichertz, B. L. Cardozo, J. W. Beeman, D. I. Larsen, et al., "First results on GaAs blocked impurity band (BIB) structures for far-infrared detector arrays," *Proc. SPIE*, Vol 5883, pp. 58830Q-1-8, 2005.
[7] Xiaodong Wang, et al., "Analysis of dark current and spectral response mechanisms for Si-based block-impurity-band detectors operating at terahertz regime," *Opt. Quantum Electron.*, Vol. 48, pp. 100-1-10, 2016.
[8] Xiaodong Wang, et al., "Spectral response characteristics of novel ion-implanted planar GaAs blocked-impurity-band detectors in the terahertz domain," *Opt. Quantum Electron.*, Vol. 48, pp. 518-1-10, 2016.