Electrical characteristics simulation of GaAs-based blocked-impurity-band detector for THz application

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Abstract

Electrical characteristics of GaAs-based blocked-impurity-band (BIB) detector are numerically studied. Electron density and electric field distributions of the device are presented with consideration of immaturity of GaAs blocking layer. Temperature-dependent dark current characteristics are then simulated by taking into account impurity-band effects.

I. INTRODUCTION

Terahertz (THz) wave is commonly known as electromagnetic radiation with wavelength ranging from 30μm to 3mm. Background-limited space-based THz detection is especially important for astronomical observations [1]. Moreover, space-based THz detection can achieve extremely high signal-to-noise ratio [2], and has thus attracted a lot of attentions in the field of military applications including ballistic missile defense, and cool target tracking [3].

Unlike room-temperature THz detectors [4-5], space-based THz detectors pursue high sensitivity, high speed, and large format. The earliest space-based THz detector is bolometer, which has extremely high sensitivity all over the THz regime. However, long response time limits its wide applications. Subsequently developed THz detectors based on superconductor technology (e.g., HEB, SIS mixer, STJ detector, and TES) [6] significantly improve response speed and at the same time keep high sensitivity, but these superconducting devices still encounter several drawbacks including requiring complex cryocooler to achieve extreme temperature below 1K, not convenient to fabricate large-format arrays, and not compatible with readout electronics. Blocked-impurity-band (BIB) detector can effectively overcome above drawbacks, and realize high-performance space-based THz detection.

Three classes of BIB detectors (Si-based, Ge-based, and GaAs-based) have been reported previously. Response wavelength of Si-based BIB detector can cover 2-40μm range [7]. Ge-based BIB detector with the capability of extending response wavelength over 200μm has been realized [8]. GaAs-based BIB detector can further extend response wavelength beyond 330μm, and has thus attracted extensive attentions since 2005 when the first prototype device was successfully developed [9]. However, it is still facing serious design and process problems leading to not only large dark current but also low responsivity [9]. Many groups have investigated electrical characteristics of Si-based and Ge-based BIB detectors [10, 11], but few reports have been given to GaAs-based BIB devices due to its relatively immature material system and the lack of proper simulation methods to describe the effects of hopping conduction and impurity-band transition.

In this paper, we present electron density and electric field distributions of GaAs-based BIB device with consideration of immaturity of GaAs blocking layer. Besides, temperature-dependent dark current characteristics are simulated by taking into account impurity-band effects. The results will serve as a good sustentation for realization of high-performance GaAs-based BIB detectors.

II. SIMULATION MODELS AND DISCUSSION

The two-dimensional numerical simulations were performed using Sentaurus Device, a commercial package by Synopsys [12]. For the simulations of electron density and electric field distributions, the plain drift-diffusion model [13] that couples Poisson equation and continuity equations, is adopted. The carrier generation-recombination process consists of SRH, Radiative, and Auger terms [14-15]. Additionally, high-field saturation model is chosen for mobility calculation, incomplete ionization model is utilized for both donors and acceptors to represent the carrier freeze-out effect at low temperature.

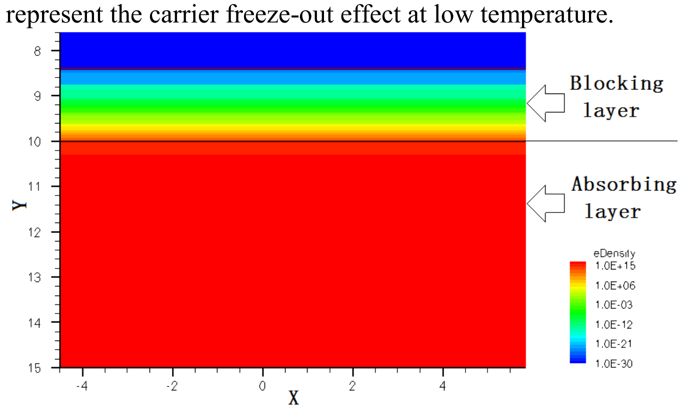

Fig. 1. Contour map of electron density for GaAs:S BIB detector at V_A=0V and T=5K.

The BIB detector area is 50×50μm^2, and its structure consists of a 40-μm-thick absorbing layer and a 10-μm-thick blocking layer. Both layers are sandwiched between two metallic electrodes. The electrodes near the blocking layer and the absorbing layer are named as anode and cathode, respectively. The bias of cathode keeps 0V during our simulation. The effects of anode bias (V_A) and temperature (T) on the electrical characteristics of GaAs:S BIB detector are

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presented as follows. Figure 1 shows the simulated contour map of electron density at V_A=0V and T=5K. As shown in Fig. 1, the 1.6-μm-thick transition area between absorbing layer and blocking layer is formed by electron diffusion.

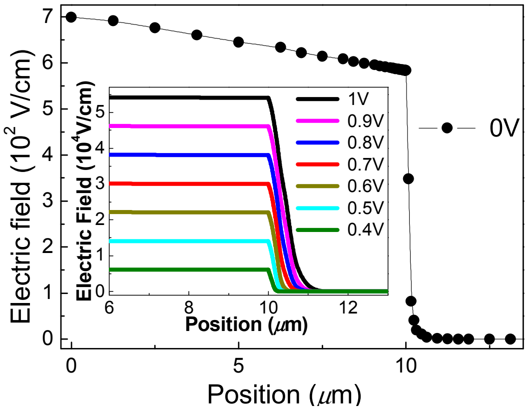

Fig. 2. Vertical electric-field distributions at different V_A, at T=5K.

Most of traditional numerical models for Si-based BIB devices are based on the assumption of charge neutrality in blocking layer, and thus the obtained electric-field intensity in this layer is uniform (e.g., [11]). However, the material quality of GaAs is not as mature as that of Si, and the number of impurities in GaAs is larger than that in Si. Therefore, the assumption mentioned above is not applicable to our GaAs-based BIB detector, and the traditional models need to be revised. Figure 2 presents the simulated equilibrium electric-field distribution using the revised device models. As shown in Fig. 2, the electric-field intensity in the blocking layer is a strong function of vertical position. The inset of Fig. 2 compares electric-field distributions with V_A changing from 0.4 to 1 V in 0.1V steps. It is found that the width of the depletion region increases monotonically with the increased bias.

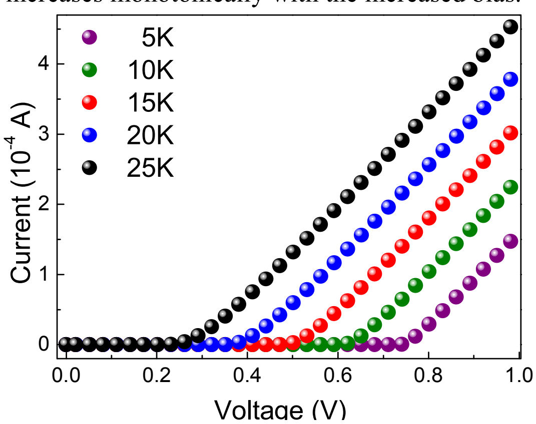

Fig. 3. Dark current characteristics of GaAs:S BIB detector at different temperatures.

Dark current of GaAs:S BIB detector is dominated by two components. One is associated with thermally excited electrons from the impurity band to the conduction band, and the other is linked to electrons hopping between impurity centers. Thus, constructing the impurity band that has proper energy gap with the conduction band is a critical step to simulate temperature-dependent dark current characteristics. In our simulation, the impurity band is directly simulated by the valence band, and the bandgap is set to the excitation energy of S in GaAs (6meV at 0K). The results shown in Fig. 3 closely resemble experimental reports from Ref. [9].

III. Conclusion

Electrical characteristics of GaAs-based BIB detector are numerically studied. At bias of 0V and temperature of 5K, 1.6-μm-thick transition area is observed due to electron diffusion. It is found that the electric-field intensity in the blocking layer is a strong function of vertical position by revising traditional numerical models. Our results show that the width of the depletion region increases monotonically with the increased bias. Additionally, the simulated temperature-dependent dark current characteristics bear a close resemblance to previously reported experimental results.

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