Numerical simulation of the temperature dependent dark current characteristics for GaAs-based blocked impurity band (BIB) terahertz detectors

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***Abstract*—Dark current as a critical parameter to evaluate the performance of Gallium Arsenide (GaAs) blocked-impurity-and (BIB) terahertz detector has attracted a lot of attentions from theoretical and experimental researchers. Accordingly, several methods have been developed to measure the dark current of BIB detectors. In this paper, the temperature dependent dark current characteristics of GaAs-based BIB detectors have been simulated. As a new analysis method, information about the carrier transition and transport mechanism can be easily extracted.**

Keywords—Numerical simulation, Gallium Arsenide (GaAs), Blocked-impurity-band (BIB), Terahertz, Detector, Temperature

I. INTRODUCTION

Terahertz (THz) wave lies in the spectral band between the microwave and the infrared. The special feature of THz wave includes safety, penetrability, fingerprint characteristics and wide distribution. Additionally, THz wave has tremendous application potentials in the area of electronics, information, biochemistry, national defense, and space technologies. Therefore, THz science and technology have become the top priority many governments support and develop.

At present, hot topics of the THz science and technology [1] include the high-performance THz detectors and THz sources, among which the current THz detectors are mostly based on the electronic technology. They can realize THz detection by extending spectral response from the microwave to a higher frequency. Blocked-impurity-band (BIB) detector is a new type of THz detector, whose detection mechanism is completely different from that based on the electronic technology. They can realize THz detection by extending spectral response from the infrared to a lower frequency. BIB detectors possess distinct advantages including high sensitivity, large array scale, and broad frequency range, and thus have been widely applied in the field of air monitoring, astronomical observation, and contraband testing.

BIB detectors can be realized using different material systems [i.e., Silicon (Si), Germanium (Ge), and Gallium Arsenide (GaAs)]. Among them, Si-based BIB detector [2] presenting a cut-off frequency of 6THz is the relatively mature and widely used THz technology at present. Due to the lower bonding energy of shallow impurity level in the Ge than that in the Si, Ge-based BIB detectors can response photon with cut-off frequency of 1.4THz. GaAs-based BIB detectors can further extend cut-off frequency to 0.6THz, and thus has been regarded as a very promising substitute technology for Schottky diode in the application of security check and drug inspection.

At present, research and development on GaAs-based BIB detectors are still on the initial stage, and no focal plane array has been reported all over the world. Dark current as a critical parameter to evaluate the performance of GaAs BIB terahertz detectors, has attracted a lot of attentions from theoretical and experimental researchers. Accordingly, several methods have been developed to measure the dark current. For example, Reichertz et al. [3] in UC Berkeley have adopted a transimpedance amplifier with a cold low noise JFET stage and $10^9\Omega$ feedback resistor inside the cryostat for readout, and have measured the dark current of GaAs:S BIB detectors at the temperature of 1.3K. In this experiment, both experimental equipment and testing process are quite complicated, while the physics-based numerical simulation can provide an efficient and economical way for complementing the experiment. In this paper, the temperature dependent dark current characteristics of GaAs-based BIB detectors have been simulated. As a new analysis method, information about the carrier transition and transport mechanisms can be easily extracted.

II. STRUCTRAL AND PHYSICAL MODELS

Figure 1 shows the structural model of GaAs-based BIB THz detector. Specifically, (2) the absorbing layer, (3) the blocking layer, and (4) the contact layer are formed sequentially on the (1) GaAs conducting substrate; (5) the anode is formed on (4) the contact layer; (6) the cathode is formed on (1) the GaAs conducting substrate. THz wave is front-illuminated on (4) the contact layer, and can be almost completely absorbed by (2) the absorbing layer because (4)

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the contact layer and (3) the blocking layer are nearly transparent for the incident THz wave. For the structural model shown in Fig. 1, back-illumination of THz wave on (1) GaAs conducting substrate is forbidden due to the absorption of THz wave by the substrate where the transportation of photo-generated carriers is suppressed.

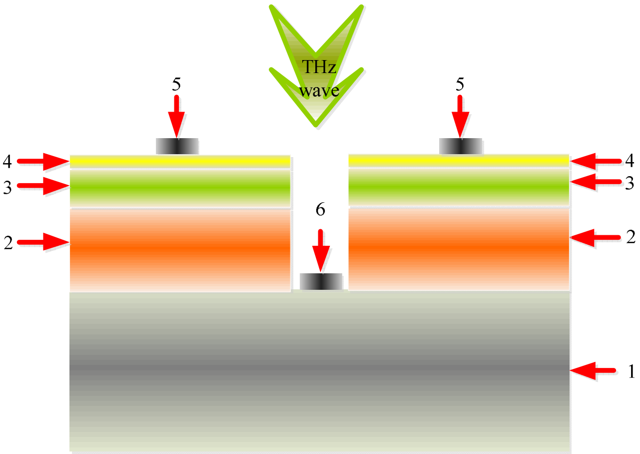

Fig. 1. Structural model of GaAs BIB THz detector.

Except the structural model described above, the physical model is also required to construct the numerical model of GaAs BIB THz detector. The critical physical models include the carrier recombination model, the carrier generation model, and the carrier low-temperature freeze-out model. Among them, the carrier recombination model takes simultaneously Shockley-Read-Hall recombination, Radiative recombination, and Auger recombination into consideration; the carrier generation model describes the carrier generation rate by coupling GaAs absorption coefficient into ray-tracing model; the carrier low-temperature freeze-out model considers incomplete ionization effects for both donors and acceptors due to environmental temperature close to absolute zero.

III. Results and Discussions

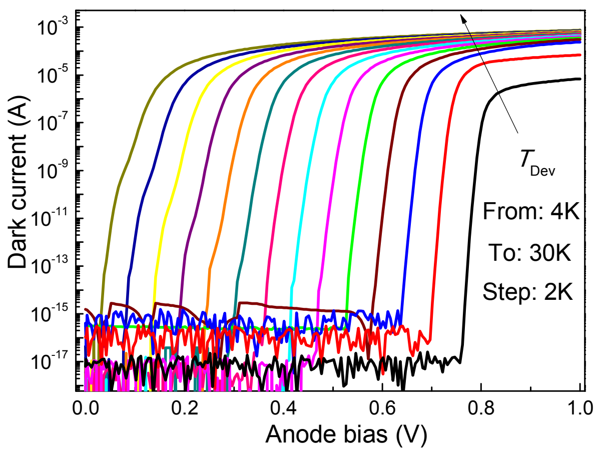

Fig. 2. Temperature-dependent dark current characteristics with device temperature T_{Dev} increasing from 4K to 30K in 2K steps.

Device temperature is a sensitive parameter for dark current of GaAs BIB detector. Useful information can be extracted by analyzing temperature-dependent dark current characteristics. Figure 2 shows the temperature-dependent dark current characteristics with device temperature T_{Dev} increasing from 4K to 30K in 2K steps. Our results show that if T_{Dev} is fixed the relationship between the dark current and anode bias can be classified into three phases: (1) dark current is independent of anode bias; (2) dark current increases rapidly with anode bias; (3) dark current increases slowly with anode bias. For the phase (1), dark current fluctuates around an extremely low level corresponding to the turn-off status of GaAs BIB detector. For the phase (2), GaAs BIB detector turn on rapidly, and the initial voltage contributing to the rapid increase of dark current can be defined as the threshold voltage V_T. For the phase (3), the slope of dark current versus anode bias drops significantly compared with that for the phase (2). Besides, dark current increases monotonically with T_{Dev}. According to Fig. 1, the phase (3) dominates over the phase (2) with the increased T_{Dev}, which means that the turn on of GaAs BIB detector can become earlier when increasing T_{Dev}.

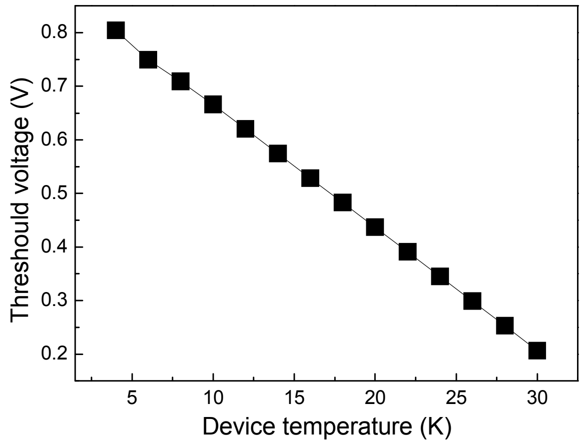

Fig. 3. Threshold voltage V_T of GaAs-based BIB detector as a function of device temperature T_{Dev}.

Figure 3 presents V_T as a function of T_{Dev}, and it is found that V_T a linearly decreasing function of T_{Dev}. Therefore, a simple fitting function about V_T and T_{Dev} can be obtained:

$$V_T = 0.89303 - 0.02285 T_{Dev}$$

IV. Conclusion

Temperature-dependent dark current characteristics of GaAs-based BIB detector have been simulated. It is found that the threshold voltage is a linearly decreasing function of temperature, and a fitting function about the threshold voltage and temperature has been obtained.

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