The absorption enhancement effect of metal gratings integrated Silicon-based Blocked-Impurity-Band (BIB) terahertz detectors

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***Abstract*—High-sensitivity Terahertz (THz) detection technology is widely researched for its potential applications in astronomical observation, human security check, weak signal biomacromolecule detection, etc. In this work, a novel THz detector based on metal gratings/Si-BIB hybrid structure is theoretically simulated and successfully fabricated. From FDTD simulation results, the optical field is localized in the absorbing-layer region due to the waveguide resonance effect of metal gratings with 7μm period, 5μm depth and 2/7 duty ratio. Then, the experimental results show that its spectral response is 223% higher than that of the device without metal gratings at the peak wavelength of 17μm. Our work successfully proposed a practical hybrid structure device for the biomacromolecule detection application as well as the weak signal detection in other THz applications.**

Keywords—Terahertz detector, metal gratings/Si-BIB, absorption enhancement

I. INTRODUCTION

Terahertz (THz, electromagnetic wave between 30μm and 3mm) detection technology gets wide attention due to its potential applications in astronomical observation, human security check, nondestructive flaw detection and biomacromolecule detection [1]. The Si-based Blocked-Impurity-Band (BIB) detector, as an extrinsic photoconductive THz device, takes advantage of a heavily doped absorbing layer to extend wavelength response to longer cut-off wavelength and a high purity blocking layer to suppress the generation of the dark current. It has already been carried to astronomical exploration by IRAS, WISE, SPICA satellites and etc., which can reach 1024×1024 pixels, 5~40 μm wavelength range and 10^{-16} $W/Hz^{1/2}$ noise equivalent power [2].

However, for the biological research and medical science application like biomacromolecule detection, cancer diagnosis and biomedical detection, the THz radiation signal of target is so weak that the response characteristics of BIB detector need to be largely improved. With the development of integrated detection technology, it's reported that optical microstructures can be integrated into the conventional devices. In our previous work, we theoretically designed GaAs photoconductive detectors integrated with metamaterial structure. By split ring resonator (SRR) structure, the optical field can be localized in the absorption area. Finite-difference-time-domain (FDTD) simulation results show a significant enhancement at the wavelength of 142 and 367μm compared with the conventional GaAs photoconductive detector. The enhancement was caused by the resonant cavity and the SRR dipole resonance effect [3]. However, the SRR structure is complicated to fabricate and restricts the reduction of detector pixel size. It is difficult to be used in mature fabrication of focal plane detector. Therefore, how to utilize fabrication technology to make simple and micro structure to realize the light field localization becomes a hot research topic.

In this work, a novel THz detector based on metal gratings/Si-BIB hybrid structure is theoretically simulated and successfully fabricated. The hybrid structure is designed with metal gratings of parameters (period: 7μm, depth: 5μm, duty ratio: 2/3). Its spectral response is 223% higher than that of the device without metal gratings. According to the FDTD simulation results, the optical field is localized in highly doped absorbing region due to the waveguide resonance effect of metal gratings. The theoretical and experimental results are in good agreement. Our work successfully realize the spectral response enhancement and provide a feasible approach to realize high-sensitivity detection for the biomacromolecule detection application as well as the weak signal detection in other THz applications.

II. SIMULATION AND EXPERIMENT

Fig.1. shows the schematic diagram of metal gratings/Silicon-based BIB. Specifically, the detector consists of cathode, high-conductivity Silicon substrate (doping with Arsenic), Silicon absorption layer (doping with Phosphorus), intrinsic Si blocking layer, anode and metal gratings from the bottom to up.

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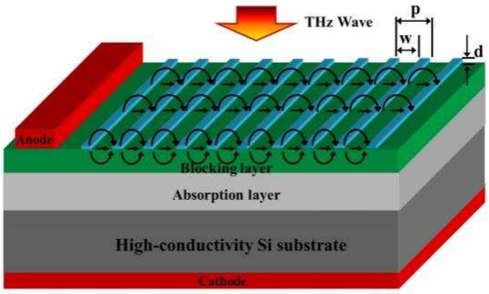

Fig.1. The schematic diagram of metal gratings/Silicon-based BIB THz detector.

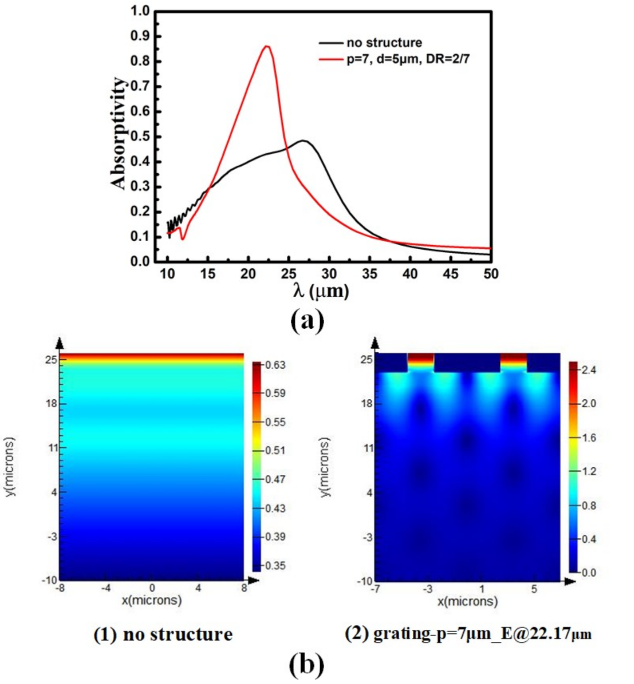

Fig.2. The absorption properties of the Si-based BIB device with metal gratings (parameters: p=7μm, d=5μm, DR=2/7) compared with that of device without metal gratings. (a) The absorption spectrum; (b) The longitudinal profile of of electric field intensity.

Fig.2 (a) shows the absorption spectrum of device with metal gratings (parameters: p=7μm, d=5μm, DR=2/7) compared with the absorption spectrum of device without metal gratings. The absorptivity of the device with metal gratings is 178% higher than that of the device without metal gratings. The longitudinal profile of electric field intensity distribution under the 22.17μm wavelength radiation of the novel structure is showed in Fig. 2 (b). The electric field of the device with metal gratings is localized in absorbing-layer region and is significantly enhanced.

Fig.3 shows experimental spectral response with metal gratings compared with that of device without metal gratings. The spectral response is measured by Fourier Transform Infrared Spectrometer. The operating temperature of device is set at 4.2K. The results show that the spectral response of device with metal gratings is enhanced in the overall compared with that of device without metal gratings, which is consistent with the simulation results. The results show three peaks. The peak_3 at the wavelength of 28.25μm is formed by the heavily doped absorption layer with 0.046eV impurity ionization energy of phosphorus doped in silicon, which is consistent with simulation result. Its spectral response is 223% higher than that of the device without metal gratings. In addition, the other two absorption peaks (Peak_1 and Peak_2) emerge at the wavelength of 16.97μm and 22.11μm. Peak_1 is induced by optical interference, according to the formula $\lambda=4nd/m\approx17\mu m$ (n=3.24, d=12μm, m=5). Peak_2 is caused by the diffusion of arsenic ion (impurity ionization energy in silicon as 0.054eV) from the high conductivity substrate to the absorption layer during the high temperature chemical vapor deposition epitaxial process.

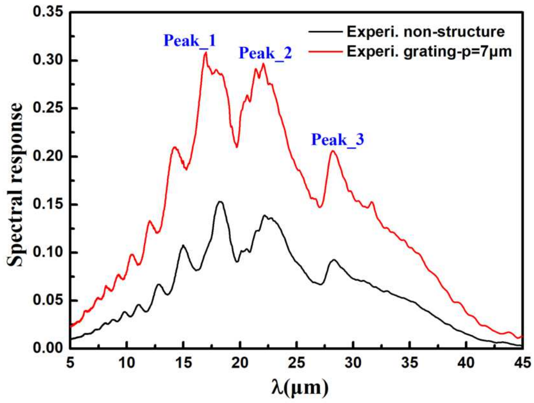

Fig.3. The experimental spectral response of device with metal gratings (parameters: p=7μm, d=5μm, DR=2/7) compared with that of device without metal gratings.

III. Conclusion

In this paper, a novel THz detector based on metal gratings/Si-based BIB is proposed. The simulation and experiment of the detector are carried out. It can be found that metal gratings are useful in localizing the incident radiation and enhancing the THz absorption of the device, induced by the coupling resonance effect of metal gratings. The experimental results show that the spectral response of the device with metal gratings (parameters: p=7μm, d=5μm, DR=2/7) is 223% higher than that of the device without metal gratings. This work provides a novel device to realize high-sensitivity detection for the application of biomacromolecule detection as well as the weak signal detection in other THz applications.

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