Novel Fermi-Level Managed Barrier Diode For Broadband and Sensitive Terahertz-Wave Detection

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***Abstract*—A novel Fermi-level managed barrier (FMB) diode was developed to enable fabrication of a broadband and low noise THz-wave detector. The fabricated quasi-optical FMB diode module could detect signals at frequencies from 200 GHz to 1 THz. The typical measured voltage sensitivity was 1020 V/W and the current sensitivity for a 50-Ω load was 4.5 A/W at 300 GHz under the zero-biased condition. Square-low detection with good linearity was confirmed at 300 GHz with an output current density of up to over 10^3 A/cm^2.**

I. Introduction

A terahertz (THz) wave detector is an indispensable component for various sensing and measurement systems. A typical device is the Schottky barrier diode (SBD), which has been widely used because it can be operated at room temperature and has a fast response and relatively high sensitivity up to the THz range. However, the characteristics of the SBD are generally unstable and irreproducible because the barrier height is determined by less controllable surface states in semiconductors. Moreover, the barrier height is rather large, so the differential resistance of the small-size (high-frequency) SBD is usually high. This makes it difficult to achieve impedance matching [1] among the input antenna, SBD, and output read-out circuit. Although use of a resonant matching circuit [2] can relax this restriction, it considerably deteriorates the bandwidth of the detector. A small barrier height is also important for zero-biased operation, which is required for low noise detection [1].

As a solution for these problems, a semimetal/semiconductor diode [1] was developed. This diode does not use the metal/semiconductor interface, and it can vary the barrier height from about 150 meV to 610 meV by changing the composition of the InAlGaAs layer. However, the differential resistance is still rather large so that the barrier height should be further decreased for operation in higher frequency ranges with a small area device. In this study, we fabricated a novel Fermi-level managed barrier (FMB) diode to achieve broadband and low noise THz-wave detection.

II. Device Configuration And Fabrication

Figure 1 shows a schematic band diagram of the proposed FMB diode. The barrier is formed as a semiconductor hetero-structure consisting of undoped-InP/n-doped-InGaAs layers. The Fermi-level in relatively highly doped n-InGaAs is known to be above the conduction band edge depending on the doping concentration [3, 4]. By taking advantage of this phenomenon, we can control the barrier height at the hetero-interface (ϕBn) by simply changing the doping concentration in the n-InGaAs layer. The energy difference between the Fermi level (E_f) and the conduction band edge is reported to be increased up to more than 380 meV [4] with a doping concentration of 4×10^{19} cm^{-3}. Thus, using this technique, we can manage the barrier height at the hetero-interface from 0 to a value larger than the conduction-band discontinuity (about 250 meV). The ability to make the barrier height very small is important for realizing a small differential resistance (and thus small noise equivalent power [NEP]). The barrier height is determined at the stage of epitaxial growth so that it is stable and controllable.

The FMB design allows us to adjust the barrier height precisely for the best rectification characteristics. We performed a numerical analysis on the NEP against the barrier height and found that an unusually small barrier height of about 90 meV results in an optimum NEP as small as 2 pW/$\sqrt{\text{Hz}}$ over a wide frequency range in the millimeter and sub-millimeter-wave regions. On the basis of these considerations, we selected a doping concentration of 5×10^{18} cm^{-3} for the n-InGaAs layer and fabricated a mesa-structure device having a small junction area of about 0.5 μm^2. We then integrated it with a self-complementary broadband bowtie antenna [5, 6] with a radius of 180 μm and assembled a compact quasi-optical package using a high-resistivity Si lens, as shown in Fig. 2.

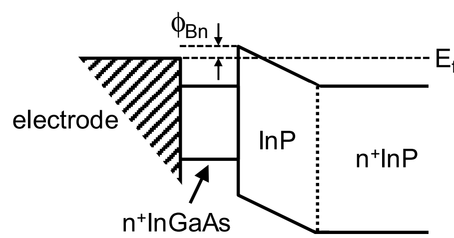

Fig. 1. Band diagram of Fermi-level managed barrier (FMB) diode.

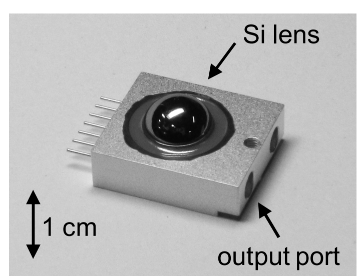

Fig. 2. Photograph of fabricated FMB diode module.

III. Characterization

The static I-V characteristics measurements suggest that the effective barrier height be as small as 70 meV, which is apparently smaller than the conduction band discontinuity at the InP/InGaAs hetero-interface. The intrinsic differential resistance of the fabricated diode at zero-bias was evaluated to be about 80 Ω. These results clearly demonstrate that a small barrier height with a small differential resistance was successfully implemented in the fabricated device in accordance with the FMB design.

Figure 3 shows the measured current sensitivity (responsivity) of the FMB diode module for a 50-Ω load against frequency under zero-biased condition. The fabricated module could detect signals at frequencies from 200 GHz to 1 THz. For this measurement, the RF input signal was generated by photomixing using a quasi-optical uni-traveling-carrier photodiode module [6]. The peak current sensitivity obtained was as large as 4.5 A/W at 300 GHz. The detection sensitivity at high frequency is generally much smaller than its DC value due to the influence of the bandwidth. Thus, the obtained result indicates that the fabricated device has a large intrinsic (low frequency) current sensitivity and a large operational bandwidth at the same time. The zero-biased voltage sensitivity for a 10-MΩ load was 1020 V/W at 300 GHz, which is comparable to the reported best results for InP-based zero-biased broadband SBDs [2].

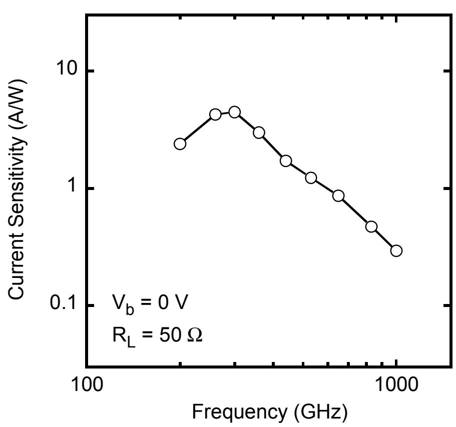

Fig. 3. Dependence of current sensitivity on frequency for fabricated FMB diode module.

Figure 4 shows the dependence of output current against the input power for a fabricated FMB diode module at 300 GHz with a 50-Ω load under zero-bias condition. The output current increased almost linearly with increasing input power according to the square-low detection scheme and then showed a slight saturation when the input power was larger than about 3 μW. The maximum output current density in the linear region is higher than 10^3 A/cm^2, which clearly indicates that the FMB diode is capable of large current output even if the device area is very small (for the high frequency operation). The large output current of the diode is suitable for applying it to the low-noise current-input amplifier (generally referred to as a trans-impedance amplifier [TIA]). Thus, the combination of the FMB diode with a low-noise TIA is a promising solution for the broadband and low NEP THz wave detector.

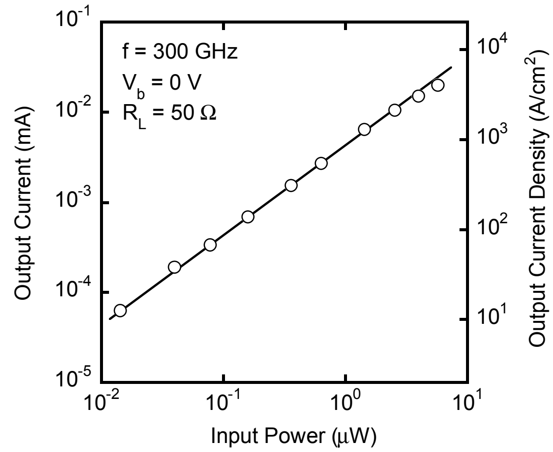

Fig. 4. Dependence of output current on input power for fabricated FMB diode module at 300 GHz.

IV. Summary

We developed a novel Fermi-level managed barrier (FMB) diode to realize broadband and low noise THz-wave detection. The fabricated quasi-optical module could detect signals at frequencies from 200 GHz to 1 THz. A large current sensitivity of 4.5 A/W was obtained at 300 GHz for a 50-Ω load under zero-biased condition. A high voltage sensitivity of 1020 V/W was also obtained at 300 GHz for a 10-MΩ load. Square-low detection with good linearity was demonstrated at 300 GHz with an output current density of up to over 10^3 A/cm^2.

Acknowledgments

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