Invited paper

Fabrication of antenna integrated UTC-PDs as THz sources

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Abstract: We report the design, fabrication and characterization of an antenna integrated, waveguide-fed, traveling-wave uni-traveling carrier photodiodes (TW-UTC-PDs). In the device, a dilute passive waveguide structure, which is easy to be coupled with a single mode fiber, is adopted. Measurement results show that broad band THz emission can be obtained for frequencies up to 700 *GHz*.

Keywords: Terahertz source, UTC-PD, Antenna

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1. Introduction

Terahertz (THz) waves, which are in the range from 100 *GHz* to 10 *THz*, have been arousing great interests for decades. They have many unique properties including ability to penetrate nonmetallic materials and spectroscopic fingerprints of molecules. As a result, applications can be expected in a variety of fields such as wireless communications, sensing, security, imaging, biology and medicine [1]. For these applications, several different types of THz signal sources have been studied in recent years including quantum cascade laser (QCL) [2], frequency multiplier chain [3], and THz transistors [4]. Another widely studied THz source is uni-traveling carrier photodiodes (UTC-PD) integrated with antenna [5]. In the device, two laser emissions with different frequencies are photomixed to produce THz radiation. Compared with other types of THz sources such as quantum cascade lasers [6] and photomixing in low-temperature grown GaAs photoconductors [7], UTC-PD based THz sources have many advantages including room temperature working, high output power, wide THz frequency tuning range and high spectral purity. In the paper we report the design, fabrication and characterization of an antenna integrated, waveguide-fed, traveling-wave UTC-PD (TW-UTC-PD). In the device, a traveling wave UTC-PD having a reduced p type doping in the absorption layer is combined with a dilute input waveguide structure, which is easy to be coupled with a single mode fiber.

2. Device design and fabrication

The UTC-PD material was grown by metal-organic chemical vapor deposition (MOCVD) on a semi-insulating InP substrate. Zn and Si are used for p and n type doping, respectively. The schematic material structure is shown in Fig. 1(a). The PD structure consists of a diluted waveguide, which is composed of six InGaAsP layers interspersed between the InP layers, a 200 *nm* InGaAsP coupling guide, a 200 *nm* unintentionally doped InP collector layer, a 70 *nm* p type $In_{0.53}Ga_{0.47}As$ absorption layer, a 200 *nm* p type InGaAsP electron diffusion blocking layer and a 200 *nm* p^+ InGaAs contact layer. Additionally, there are two 10 *nm* thick InGaAsP matching layer inserted between absorber layer and collector layer to eliminate the conduction band peak caused by energy band discontinuity. The doping level of the absorber layer is decreased gradually from the InGaAsP blocking layer side to the InP collector layer side in a 50 *nm* distance to generate a self-build electric field [8], which enhances the transmission of electrons in absorption layer. In the 20 *nm* absorption layer near the InP collector, the doping level is less than $1\times10^{17}/cm^3$, forming a composite PIN structure, which was shown to enhance the PD performance [9].

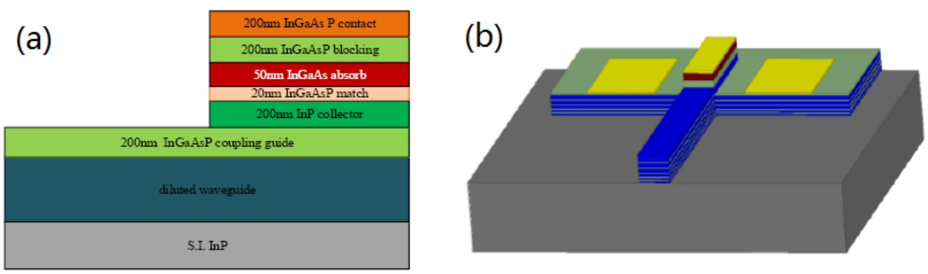

Fig. 1 Schematic structure of the PD.

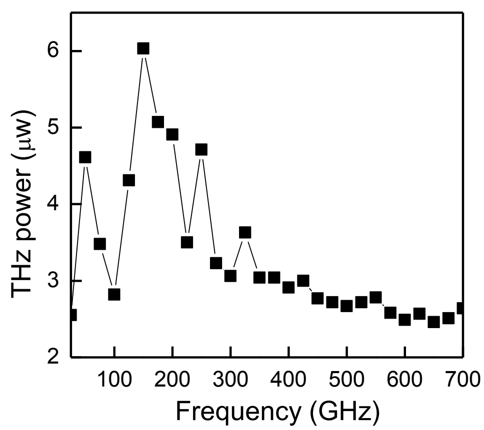

Fig. 2 Calculated bandwidth of UTC-PDs

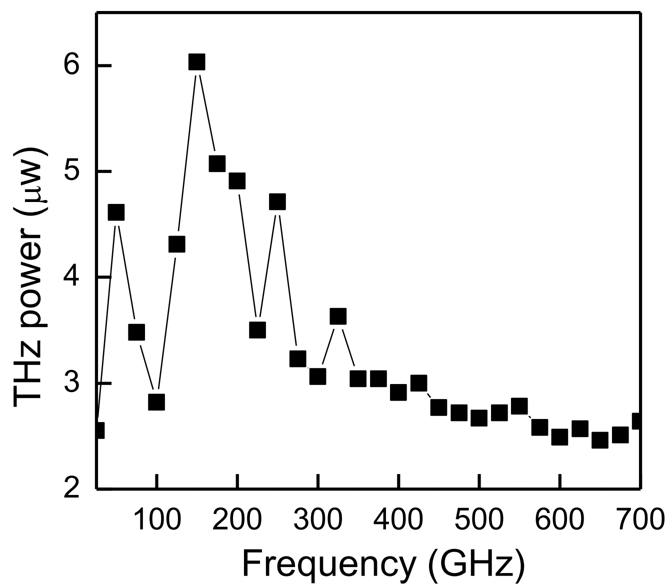

Fig. 3 simulated light propagation in the device

For a UTC-PD, the response bandwidth f3dB can be given by:

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where,

$$f_{RC} = 1/2\pi RC = D/2\pi R\varepsilon_0\varepsilon_r s$$
$$f_t = 1/\left(2\pi\left(t_{drift} + t_{diff}\right)\right) = 1/[2\pi(W_a^2/2D_e + W_a/v_{th} + D/v_{es})]$$

In the equations, W_a and D are the thicknesses of the absorber and collector, respectively. R, D_e, V_{th} and V_{es} are the resistance, electron diffusion coefficient, electron emission velocity in the absorber, and electron overshoot velocity in the collector, respectively. Calculated from the equations, the bandwidths of UTC-PDs as functions of W_a and collector thickness are shown in Fig. 2. The length and width of the PD absorber are 15 and 4 *μm*, respectively. It can be seen from these results that the designed bandwidth of our UTC-PD is about 75 *GHz*. The light propagation through the PD structure is simulated by beam propagation method (BPM) and is shown in Fig. 3. The length of the passive waveguide is 150 *μm*. The responsivity is 0.25 *A/W* when the passive waveguide loss and coupling loss are not considered. A broad band Bow-Tie antenna is adopted for the device. The simulated return loss of the antenna is simulated by HFSS. Better than -10 *dB* return loss is suggested between 250 *GHz* and 1000 *GHz*. After the material growth, the wafer is fabricated into devices as shown schematically in Fig. 1(b). AuZn and TiAu are used as p and n contact metals, respectively. Au is used as the antenna metal.

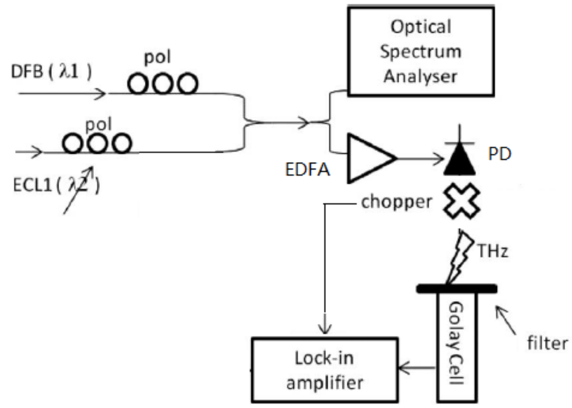

Fig. 4 Measurement setup for the device.

3. Device characterizations

The experimental setup for the characterization of the device is shown schematically in Fig. 4. Lights from a DFB laser and a widely tunable external cavity laser are polarization controlled before combining by a fiber coupler. The combined light is then splitted by another fiber coupler. One part of the light is fed through a fiber into a spectrum analyzer to determine the frequency difference. The other part of the signal is amplified with an Er doped fiber amplifier (EDFA) before being coupled into the PD device, which is mounted on a high-resistivity silicon lens. The THz signal from the device is modulated with an optical chopper at 15 *Hz* and measured by a Golay cell at room temperature. The obtained electrical signal is fed into a lock-in amplifier with a reference from the chopper.

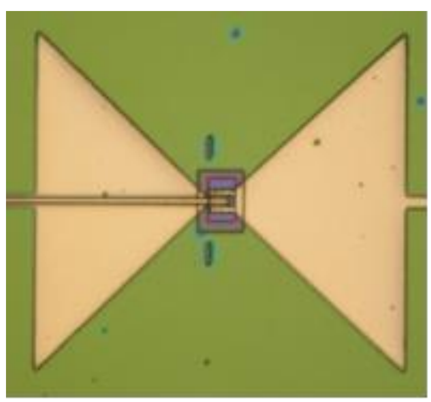

Fig. 5 Optical graph of a fabricated antenna integrated device

Fig. 5 shows an optical graph of a fabricated antenna integrated device. The responsivity of the device is 0.1 *A/W* at -1 *V* reverse bias when 1550 *nm* light is coupled into the device by a lensed single mode fiber. The dark current at 0 *V* is about 1 *nA* and rises gradually with the reverse voltage. When the reverse voltage is -2 *V*, the dark current is 40 *uA*.

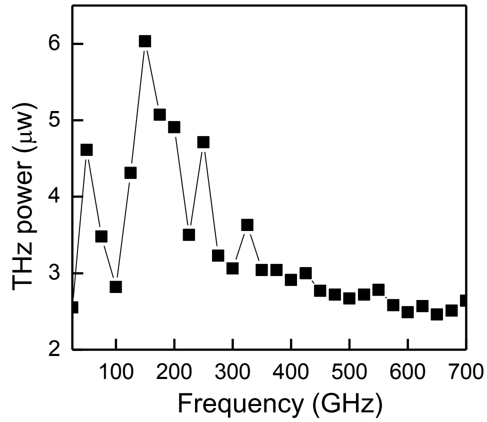

Fig. 6 Measured THz power

Fig. 6 shows the measured THz power with -1 *V* reverse bias and 3.6 *mA* photocurrent. Broad band emission is obtained for frequencies up to 700 *GHz* with 4.6 μW at 50 *GHz*, 6 μW at 150 *GHz*, 4.7 μW at 250 *GHz* and 2.6 μW at 700 *GHz*. To enhance the THz emission, both the design and the fabrication of the PD can be further optimized. As shown in Fig. 2, the bandwidth can be increased notably by proper design of the PD structure. Then, the leak current can be reduced by appropriate surface passivation, as well as surface cleaning and optimized photolithography technique. Related works are still ongoing.

4. Conclusions

Antenna integrated TW-UTC-PDs have been fabricated. In the device, a reduced p type doping in the absorption layer is adopted. A dilute waveguide structure, which is easy to be coupled with a single mode fiber, is integrated. Broad band THz emission can be obtained for frequencies up to 700 *GHz* with 6 μW at 150 *GHz* and 2.6 μW at 700 *GHz*.

Acknowledgment

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