Terahertz generation from Si_3N_4 covered photoconductive dipole antenna

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We observe enhanced terahertz (THz) radiation generated from a Si_3N_4 film-coated GaAs photoconductive dipole antenna. Compared to an uncoated antenna with identical electrode geometry and optical excitation power, the Si_3N_4 film-coated antenna has a higher effective DC resistance and larger breakdown voltage. As a result, the peak amplitude of generated THz radiation is significantly enhanced due to the Si_3N_4 film-coated layer.

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A photoconductive dipole antenna (PDA) based on a semi-insulating (SI) GaAs substrate is a widely used terahertz (THz) radiation source[1] for both THz time-domain spectroscopy (THz-TDS)[2] and THz imaging applications[3]. Because of its significant applications, the study to improve PDA performance is an active topic[4,5]. In a PDA, a high resistant semiconductor is used to generate transient photocarriers by a femtosecond laser pulse, and two metallic electrodes are used to supply the biased field, which accelerates the photocarriers (mostly electrons) inside the gap. The THz electric field E_{THz} is emitted by the rapidly changing photocurrent, and at far field, it is described by

$$E_{\mathrm{THz}} \propto e\mu E_{\mathrm{B}} \frac{\mathrm{d}}{\mathrm{d}t} n(t), \tag{1}$$

where e is the electron charge, μ is the photoelectron mobility, $n(t)$ is the carrier concentration, and E_{B} is the biased electric field.

The THz radiation originates from the stored electrical energy in the PDA. The output THz radiation power is determined by the static-electric field and the optical excitation power. The biased electric field and excited photocarriers are limited to a very thin layer along the surface of the semiconductor. As a result, the breakdown field along the surface of the semiconductor becomes an important factor for improving the performance of a PDA emitter because the breakdown field limits the highest possible external electric field.

The breakdown field of SI GaAs is limited by the presence of high-density surface states, which are induced by the absorption of impurities, such as oxygen atoms or metallic elements[6]. It was reported that the deposit of an isolator layer, such as Si_3N_4, on the surface of the SI GaAs wafer will suppress the density of surface states, and thereby, increase the breakdown voltage of the wafer[7]. We demonstrate THz generation from a SI GaAs PDA coated with a Si_3N_4 layer. The electric field of the THz radiation generated from the covered PDA is enhanced in comparison with a bare PDA.

The schematic of the coated PDA is shown in Fig. 1. Two Au/Ge/Ni parallel electrodes are deposited on a 0.6-mm-thick SI GaAs wafer, and the gap between the electrodes is 3 mm. Following the Au/Ge/Ni ohmic contacts, an 800-nm-thick Si_3N_4 layer is coated on the PDA. A PDA with the identical structure, but without the Si_3N_4 layer coating, is used as a reference sample.

A Ti-sapphire laser (800-nm wavelength, 120-fs pulse duration, 82-MHz repetition rate, and 1.2-W average power) is used to generate THz radiation from the PDA. An adjustable optical attenuator is used to control the optical excitation power on the PDA gap from 10 to 250 mW (after being modulated by an optical chopper). The diameter of the laser spot incident on the PDA is 1.2 mm and the laser beam illuminates in the center of the gap by carefully adjusting the position of the PDA. THz radiation generated from the PDAs is collected and focused onto the THz detection crystal by using two pairs of parabolic mirrors. The THz radiation electric field is detected by modulating the polarization of a probe optical beam (part of the same femtosecond laser) in an electro-optic (EO) crystal (2-mm-thick, (110) orientation ZnTe crystal)[8]. Scanning the time difference between

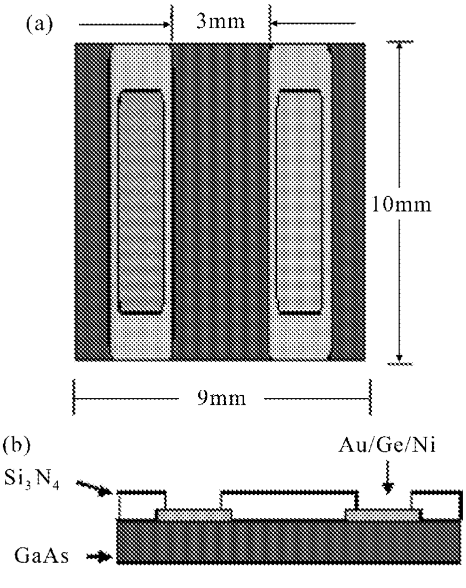

Fig. 1. Schematic of a GaAs photoconductive dipole antenna coated with Si_3N_4 layer. (a) Top view; (b) side view.

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the pump and probe pulses to sample the THz pulse provides the temporal waveform of the THz pulse.

The electric field breakdown in a PDA THz emitter is due mainly to the Joule heating effect. When a femtosecond laser pulse with photon energy larger than the energy gap of the semiconductor is illuminated onto the surface of the semiconductor, free-carriers are generated in the illuminated area. The free-carriers are then accelerated by the biased electric field and form the photocurrent between the two electrodes. Both the input optical energy and the electric energy will transform into thermal energy via the trapping of free-carriers and collision between the free-carriers and the crystal lattices. The temperature of the semiconductor will increase until the thermal diffusion rate is reached, which is enhanced as the temperature increases, and equals the thermal generation rate. Consequently, the DC effective resistance of the semiconductor will be reduced because of the thermal effect. If the photocurrent or the electric field applied to the PDA is very high, and the semiconductor cannot support the consistent high voltage because of low resistance, then the electric field applied on the semiconductor will crash. The electric field, which causes the crash in the PDA, is the breakdown field of the PDA. According to the discussion above, the breakdown field will be affected by the optical excitation power.

To approach the breakdown voltage of the PDA at a certain excitation power in the experiment, a high-voltage DC power supply (0 to 5000 V) is used to provide the biased voltage on the electrodes. A DC ampere meter is serially connected with the PDA to monitor the DC current passing through the PDA. At each excitation power, the applied voltage is increased at a step of 10 V until the breakdown voltage is reached. The maximum voltage, which can be applied on the PDA at a certain excitation power and will not cause breakdown, is defined as U_{max} of the PDA at this excitation power.

The U_{max} versus the excitation optical power is plotted in Fig. 2. For both coated and uncoated PDAs, the U_{max} reduces with the increase of the excitation power due to the higher free-carrier density at higher excitation power as well as more optical power transfers to thermal power. When comparing the U_{max} of coated and uncoated PDAs, the U_{max} of a coated PDA is significantly higher than the uncoated PDA at the same excitation power. To have the biased voltage divided by the DC current in the PDA, the DC effective resistance of the PDA is obtained. When employing the same excitation power and biased voltage, the DC effective resistance of the coated PDA is two times higher than that of the uncoated PDA. The higher effective resistance of the coated PDA causes lower electrical-thermal transformation and thereby leads to a higher breakdown voltage.

The THz electric field generated from a large aperture PDA is proportional to the moderate biased electric field, or is proportional to the moderate excitation power[9]. As a result, the higher breakdown voltage of the coated PDA enables greater THz radiation power than the uncoated PDA at the same excitation power. The THz temporal waveform is recorded at various excitation powers and biased voltages in the experiment. The amplitude of the THz electrical field (E_{THz}) is defined as the peak-to-peak difference in the THz temporal waveform.

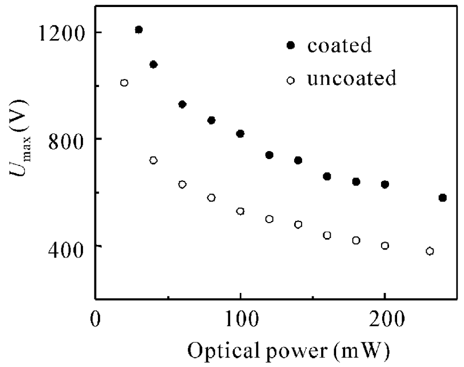

Fig. 2. U_{max} versus optical excitation power.

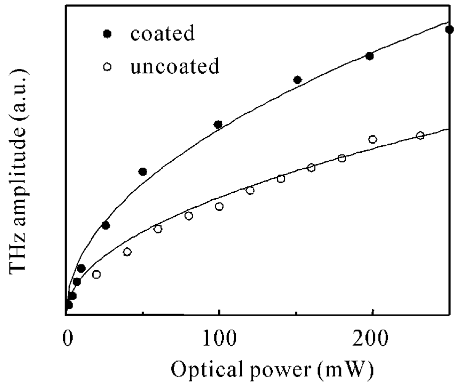

Fig. 3. THz electrical field amplitude versus optical excitation power. The solid curves are fitted by $I_O^{1/2}$ and normalized to the data of coated and uncoated, respectively.

Figure 3 shows the dependence of E_{THz} on the excitation power, where the biased voltage is set at the U_{max} for each excitation power. The measured THz field from the coated PDA is stronger than the uncoated PDA, due to the higher voltage. For each PDA, the higher excitation power leads to a higher THz field, yet the relationship between the THz field and the excitation power is not linear.

Two factors affect the THz wave generation from a PDA type emitter. The first is the optical excitation power and the second is the biased electric field. According to expression (1), the THz field increases with the optical power when the biased voltage is fixed; this is due to an increased release of stored electric energy from the static potential to the THz radiation. On the other hand, the THz field is also proportional to the biased voltage at a certain excitation power, because of higher static potential being stored. However, for a certain PDA the excitation power and the biased voltage cannot be independently enlarged. As shown in Fig. 2, the higher excitation power leads to the lower maximum biased electrical field on the PDA. When the optical excitation power is low, the optical thermal transformation can be ignored, and thereby, the electrical power is the only thermal source, which will affect the DC effective resistance of the semiconductor.

In this condition, the breakdown point requires that the electrical power consumed in the PDA is a constant for different excitation powers. This condition leads to a $U_B^2 \propto \frac{1}{I_O}$ relationship because the conductivity of the semiconductor is proportional to the excitation power, where U_B is the biased voltage, and I_O is the optical intensity. According to Ref. [9], E_{THz} is proportional to U_B and I_O at this optical excitation power, and then one has

$$E_{THz} \propto \sqrt{I_O}. \tag{2}$$

At a high excitation power condition, when the optical input power is comparable to the electrical power, and the optical thermal load cannot be ignored, the generated THz electrical field should be lower than the prediction with expression (2).

The dependence of the THz electrical field on the biased voltage when the optical excitation is fixed at 200 mW, and the dependence of THz electrical field on the excitation power when the biased voltage is fixed at 300 V are investigated. We note that for both cases the THz field generated from the uncoated PDA is higher than the THz field generated from the coated PDA when the same excitation power and biased voltage are applied because of the Fresnel loss from the Si_3N_4 layer. Only when the biased voltage is higher than the breakdown voltage of the uncoated PDA, the coated PDA benefits from the coated layer and provides a stronger THz field. As a comparison, the electrical field of the THz radiation from the covered PDA still linearly increases with the increase of biased voltage, until it reaches the breakdown voltage. The spectra of the THz radiation from the coated and uncoated antenna are obtained by fast Fourier transformation and do not have a significant difference.

In conclusion, the breakdown voltage of the Si_3N_4 coated PDA is higher than that from the uncoated PDA, therefore the Si_3N_4 layer covered PDA enhances the generated THz electric field.

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