Broadband Terahertz Emission Based on the Femtosecond Laser Pulses

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ABSTRACT: The characteristics of terahertz (THz) radiation from the surface of InN excited by the femtosecond laser pulses are presented. The effect of intensity and central wavelength of the excited laser pulse on THz emission are studied experimentally. THz radiations from the surface emission of Mg-doped InN and InAs are compared. The results show the stronger dependence of THz radiation on the different intensity and central wavelength of the excitation pulses. THz radiation from InAs than InN has higher emission efficiency. However, the strong enhancement of THz emission is observed from InN with appropriate Mg concentrations. The mechanism of THz emission from InN is found to be the photo-Dember effect and the emission intensity is inversely proportional to the conductivity, which is beneficial to investigate THz source based on InN.

INTRODUCTION

The terahertz (THz) region of the electromagnetic spectrum (0.1-10THz) has potential applications in many fields of science and technology, including imaging, time-domain spectroscopy, and nondestructive materials identification and so on [1-3]. It was found by Zhang et al. in 1990 that ultrashort THz pulses can be generated by illuminating semiconductor surfaces with femtosecond laser pulses [4]. Due to the low effective mass and the high mobility and saturation velocities of III nitrides [5], InN is considered to be an exciting source of terahertz radiation. The emission of THz pulses from InN thin films was observed firstly by Asazubi et al. [6]. After that, several groups reported the THz emission from InN films with different growth orientations [7-11]. Others reported Mg-doped InN samples can greatly enhance the THz radiation intensity [12-14]. Recently, Ahn et al. reported that THz emission from InN nanorods can be three times stronger than THz emission from InN thin films [15]. Chern et al. reported excitation wavelength dependence of THz emission from InN and InAs [16]. In that letter, they used a ultrafast laser pulses at wavelengths tuned between 800 and 1500nm. The THz amplitude, normalized to pump and probe power, from both narrow bandgap semiconductors remains relatively constant over the excitation wavelength range.

Semiconductor surface irradiated with femtosecond fs laser pulses generates terahertz THz radiation pulses which are of great importance for time-resolved spectroscopy in condensed matter, chemical spectroscopy, imaging in medicine and material science. Owing to strong photo-absorption and high electron mobility, narrow band gap semiconductors are promising sources of optically excited THz irradiation. Among them, indium nitride (InN) is considered as one of the best candidates due to the large difference between the diffusion lengths of electrons and holes and very low probability of intervalley scattering [2,6] Several groups have reported THz emission from InN films and nanostructures until now [5-8,17] It has been reported recently that the emission intensity from InN is even higher than that from InAs which was found to show the highest emission efficiency [18]. Since the native InN layer is seriously defective and shows high electron concentration ranging from 10^{17}–10^{20} cm^{-3}, which degrades the emission efficiency, the THz emission can be further enhanced by compensating the donors through doping.

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In this paper, we present THz emission from InN excited by the ultrafast laser pulses at central wavelengths from 750 nm to 840 nm in the same pump and probe power. THz radiation generated from InN exhibits greatly dependence on the excitation wavelength and intensity. Its amplitude, radiation efficiency and the effective spectral width are greatly different. On the other hand, the strong enhancement of THz emission from InN with appropriate Mg concentrations is shown. The mechanism of THz emission from InN is found to be the photo-Dember effect and the emission intensity is inversely proportional to the conductivity, which is beneficial to investigate THz source based on InN.

EXPERIMENT AND SAMPLES

Our measurements are performed using a Ti:sapphire laser, which operates at a center wavelength of 800 nm, and has a pulse duration of 100 fs and a repetition rate of 82 MHz. Its average output power is about 930 mW. The laser is split into two beams. The stronger beam used as pump beam is focused on the sample surface with a diameter of 2 mm and incident angle of 45° from normal. The pump power is ~250 mW while the detect power is ~25 mW for all excitation wavelengths. The THz signal was detected by free-space electro-optic sampling in a 2 mm thick ZnTe crystal.

InN films with both In- and N-polarities were grown by molecular beam epitaxy. [12,13] For the series of InN:Mg films in In-/N-polarity regimes, the typical thickness is 450/600 nm with Mg concentration \([\text{Mg}] \) at \(10^{16} - 10^{22} \text{cm}^{-3} \). [13] Other samples are either undoped or Mg-doped with the thickness up to 3 \(\mu\text{m} \). Some InN:Mg layers showed p-type conduction in electrolyte capacitance-voltage measurement. [13,19] Hall effect measurement was performed to investigate the conductivity, carrier concentrations and mobility. Here, it should be noticed that the measured carrier concentrations and mobility are apparent ones. Since the surface electron accumulation layer with the density as high as \(2\times10^{13} \text{cm}^{-2} \) exists in both n- and p-type InN due to the surface Fermi level pinning above the conduction band minimum, [20] the apparent conduction is n-type even for p-type InN and this is the reason why it is called the “buried p-type.”

Time-domain THz emission measurements were performed by using a Ti:sapphire fs laser with a center wavelength of 800 nm, a pulse duration of 100 fs and a repetition rate of 82 MHz. [21] THz radiation is generated by the pump beam focused on the InN surface in p-polarization with a diameter of 0.2 mm and an incident angle of 45°. The energy of the pump beam was 4 nJ per pulse. THz signal was detected by the free-space electro-optic sampling in a 1 mm thickness of ZnTe crystal.

RESULTS AND DISCUSSION

The wavelength and intensity dependence of THz emission from InN on the excitation laser pulse are studied experimentally. By keeping at the intensity of pump and probe laser pulses and adjusting the central wavelength of excitation laser pulse, the THz emission efficiency of InN by the different central wavelength of excitation pulses is measured. At the same way, the intensity dependence of THz emission is investigated at 800 nm of central wavelength of excitation pulse. Finally, THz emission from the different InN with undoped and Mg-doped samples are compared and analyzed in detail.

Figure 1 shows the THz peak-peak amplitude as a function of wavelength of excitation laser pulse. from 750 nm to 840 nm at the same pump and probe power. The obvious change of THz emission efficiency for the different wavelength of excitation laser pulse is observed experimentally. It is clear that there exist a minimum of THz emission at 770 nm of excitation wavelength. THz emission from InN excited by the femtosecond laser pulse at more than 800 nm of wavelength shows a great enhancement of radiation efficiency.
Fig. 1 THz peak-peak amplitude as a function of wavelength of excitation pulse

Figure 2 illuminates the relationship of THz emission spectra of InN and the pump intensity of femtosecond laser pulse. In the experiment, we kept the probe intensity as a constant and measured THz emission spectra at different pump power of excitation laser pulse. With increasing of pump power, THz emission intensity shows an obvious increase which is almost linear proportional to the pump power. At the same time, it is noticed that the half-maximum-full width of THz spectra increased firstly and reached saturation at a critical pump power.

Fig. 2 THz emission spectra for the different pump power of excitation pulses

Figure 3 shows the typical time-domain waveforms of THz emission from nondoped and Mg-doped InN layers with In- and N-polarities and $p$-InAs ($p=1\times10^{16}$ cm$^{-3}$). In our measurement, more than 40 samples including undoped and Mg-doped ones in different lattice polarity regimes were investigated. No azimuthal angle dependence of THz radiation was observed in all these samples, indicating that THz emission is not related to the optical rectification effect. As shown in Fig.1, time-domain waveforms of THz emission from all InN layers show the same polarity as $p$-type InAs, which is independent of conduction and lattice polarities. It is known that the electric field of the THz waveform in the far field is given by $E_{THz} \sim \frac{\partial J}{\partial t}$, where $J$ is the transient current induced by photoexcitation and originated from the photo-Dember effect due to the difference between the diffusion lengths of electrons and holes and the acceleration of photoexcited carriers by the surface depletion or accumulation field. At lower carrier densities, the optical rectification contribution is no longer the main THz generation mechanism in InN due to the effects of the difference of the electron and hole diffusion coefficients, which is so called photo-Dember effect. The same THz wave polarity of all InN layers and $p$-type InAs contradicts the second origin. It has been reported that $p$-type InAs showed the same THz wave
polarity as the $n$-type GaAs, indicating the same wave polarity of InN and $n$-type GaAs. Since the surface electron accumulation layer exists in both $n$- and $p$-type InN, the surface band bending is downward, which is opposite to that of $n$-type GaAs, where the surface band bending is upward. InN would show opposite wave polarity to the $n$-type GaAs if the second origin is correct, which does not coincide with our experimental observation. Thus, the dominant mechanism for THz emission from InN is the photo-Dember effect.

![THz waveform comparison](image)

**Fig. 3** The typical THz time-domain waveforms generated from nondoped InN and Mg-doped InN in In- and N-polarity, respectively. The THz waveform generated from $p$-type InAs ($p=1\times10^{16}$ cm$^{-3}$) is also shown for comparison.

Figure 4 shows the magnitude of THz emission from InN layers as a function of [Mg] in both In- and N-polarity regimes. It is obvious that the intensity of THz emission is greatly affected by Mg doping. With increasing [Mg], the intensity first increases and then decreases with the maximum intensity at [Mg] of $\sim1\times10^{18}$ and $6\times10^{18}$ cm$^{-3}$ for In- and N-polar InN films, respectively. In addition, the $p$-type InN samples generally shows stronger THz emission than the $n$-type ones.

![Mg concentration vs THz amplitude](image)

**FIG. 4** THz emission intensity and resistivity of InN layers with N-polarity as a function of Mg doping concentrations.
It is known that origins of transient currents in semiconductors induced by photo-excitation come from (1) the photo-Dember effect originating from the difference between the diffusion constants of electrons and holes and (2) the acceleration of photo-excited carriers by a surface depletion field or accumulation field. In the case of InN, which is similar as InAs, a surface electron accumulation layer exists. This surface electron accumulation layer is independent of conduction polarity and thus it’s electric field has the same direction for both n- and p-type InN layers. However, this electric field should lead to negative polarity time-domain wave forms, which is different from the experimental observation shown in Fig. 3. Therefore, the contribution from the surface field should not be the dominant one. This is probably because the thickness of surface accumulation layer is less than 10 nm, which is much smaller than the penetration depth of ∼200 nm for a 800 nm laser beam. As for the depletion layer, its contribution is also small due the small thickness as reported previously. In addition, it has been reported by Lin et al that the dominant radiation mechanism is the drift current induced by the internal electric field due to spontaneous polarization in InN.[22] However, this is only correct at low density excitation and the polarity of time-domain wave forms should be different for InN layers with different lattice polarities, which does not coincide with our experimental results as shown in Fig. 3. Thus, it is suggested that that the dominant mechanism of THz emission from our InN samples is the photo-Dember effect. In this case, the intensity of THz emission greatly depends on the concentration and mobility of carriers. However, for InN:Mg, it is difficult to precisely determine the carrier concentration due to the surface electron accumulation, in particular for p-type sample. In our measurements, it was found that the dependence of THz emission intensity on [Mg] shows almost the same tendency as that of the resistivity (inverse of conductivity), as shown in figure 5. This is reasonable since the dominant mechanism for THz emission is the photo-Dember effect, where drift and diffusion currents of electrons $J_n$ and hole $J_p$ in an optical pumped semiconductor are described by the following equations [23]:

\[
J_n = eE(\mu_n n + \mu_n \Delta n) + \mu_n k_B T (\partial n / \partial z + \partial \Delta n / \partial z) \\
J_p = eE(\mu_p p + \mu_p \Delta p) - \mu_p k_B T (\partial p / \partial z + \partial \Delta p / \partial z)
\]

(1) (2)

Where the $E$ is electric field, $T$ is carrier temperature, $\mu_n$ and $\mu_p$ are mobilities of electrons and holes, $n / \Delta n$ and $p / \Delta p$ are bulk/photo-generated electron and hole concentrations, $\partial n / \partial z$, $\partial \Delta n / \partial z$, $\partial p / \partial z$, $\partial \Delta p / \partial z$ are the
gradients of bulk carrier concentrations and photocarrier concentrations. Thus, the photo-Dember field can be deduced according to the Dember hypothesis that the total current equals to zero:

\[
E_D = \frac{k_B T}{e} \frac{\partial \Delta \sigma_p / \partial z - \partial \Delta \sigma_n / \partial z}{\sigma_n + \sigma_p + \Delta \sigma_p + \Delta \sigma_n} = \frac{k_B T}{e} \frac{\partial \Delta \sigma_p / \partial z - \partial \Delta \sigma_n / \partial z}{\sigma_{\text{total}} + \Delta \sigma_{\text{total}}}
\] (3)

**FIG. 6** The THz emission intensity generated from undoped and Mg-doped InN layers at both In- and N-polarities as a function of conductivity.

Where \(\sigma_n = ne\mu_n\), \(\sigma_p = pe\mu_p\), \(\sigma_{\text{total}} = \sigma_n + \sigma_p\) are conductivities contributed from electrons and holes, and the both carriers, the \(\Delta \sigma_n\), \(\Delta \sigma_p\) are photoconductivity. The \(\partial \sigma_n / \partial z\) and \(\partial \sigma_p / \partial z\) are negligible. It is obvious from Eq. (3) that the intensity of THz emission is strong for InN layer with low conductivity since the \(\Delta \sigma_{\text{total}}\) is smaller than the \(\sigma_{\text{total}}\) in our measurement condition. This relationship is true for both Mg-doped and undoped InN samples as shown in figure 6. It can be seen that the intensity of THz emission decreases with increasing conductivity, which is independent of conduction polarity. The p-type samples exhibit stronger intensity due to its lower apparent conductivity. Meanwhile, the undoped InN samples with low conductivity also show stronger THz emission. Thus it is suggested that it is more reasonable to correlate the THz intensity with the conductivity than with carrier concentration since (1) the conductivity includes contribution from electrons and holes and (2) it is very difficult to precisely determine the bulk carrier concentration for InN, in particular for p-type InN. The dependence of THz intensity on conductivity also confirms that the dominant mechanism of THz emission of InN is photo-Dember effect under our measurement condition. It can be suggested from Fig. 6 that it is necessary to decrease the conductivity of InN samples by improving crystalline quality or carrier compensation.

**SUMMARY**

In summary, the THz emission from InN excited by the femtosecond laser pulse is studied experimentally. THz radiations from the surface emission of Mg-doped InN and InAs are compared. The effect of intensity and central wavelength of the excited laser pulse on THz emission are studied experimentally. The results show the stronger dependence of THz radiation on the different intensity and central wavelength of the excitation pulses. THz radiation from InAs than InN has higher emission efficiency. However, the strong enhancement of THz emission is observed from InN with appropriate Mg concentrations. The mechanism of THz emission from InN is found to be the photo-
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