Terahertz emission from silicon and magnesium doped indium nitride

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We report an experimental study of femtosecond optically excited emission of terahertz frequency electromagnetic radiation from as-grown n-type InN, silicon doped InN, and magnesium doped InN. We have measured the terahertz emission from these materials as function of dc Hall mobility and carrier concentrations. Terahertz emission from InN:Si and native n-type InN increases with mobility as expected for transient photocurrents as primary mechanism of terahertz emission from InN. InN:Mg exhibits enhanced terahertz emission compared to InN:Si. This is experimental evidence for Mg being electrically active as an acceptor in InN. Terahertz emission from InN:Si is less strong than terahertz emission from native n-type InN because of an increased electron concentration due to silicon being an electrically active donor in InN. © 2008 American Institute of Physics. [DOI: 10.1063/1.3043450]

Excitation of semiconductor surfaces with femtosecond laser pulses at near-infrared (NIR) wavelengths is an important method to generate very short (<1 ps) terahertz radiation pulses. This type of terahertz radiation source has enabled the development of time-domain terahertz spectroscopy and time-domain terahertz imaging for the otherwise difficult to access frequency range between 0.1 and 10 THz.1 Narrow direct band gap semiconductors are particularly promising sources of terahertz radiation because they are strong candidates for compact and lightweight time-domain terahertz spectroscopy and terahertz imaging systems powered by femtosecond fiber lasers with emission wavelengths between 800 nm and 1.6 μm.2–4

Among narrow band gap semiconductors, indium nitride (InN) is considered an exciting source of terahertz radiation. The emission of terahertz radiation pulses from InN thin films was observed initially by Ascazubi et al.5 This observation was confirmed by Chern et al.,6 Pradurutti et al.7 and Mu et al.8 Recently, Ahn et al.9 reported that terahertz emission from InN nanorods can be three times stronger than terahertz emission from InN thin films. Analysis of the electronic and optical properties of InN and comparison with other narrow band gap semiconductors demonstrate that InN has a great potential to perform superior to previously investigated narrow band gap semiconductors.

Terahertz radiation emission from narrow band gap semiconductors exposed to femtosecond NIR laser pulses originates either from a nonlinear optical process or ultrafast photocurrents. Nonlinear optical processes in semiconductors resulting in terahertz-radiation emission are bulk or surface-field induced optical rectification of the incident femtosecond NIR laser pulses.1 Terahertz radiation emission due to ultrafast photocurrents can be achieved through acceleration of photocarriers by intrinsic electric fields. Intrinsic electric fields occurring at a semiconductor surface are surface depletion/accumulation fields or the photo-Dember field.2 Strong advantages of InN as terahertz emitter are strong intrinsic electric fields, potentially low intrinsic carrier concentrations, and a very low probability of intervalley scattering.

Previous research was focused entirely on terahertz emission from as-grown n-type InN. However, impurity doping of a semiconductor strongly affects the electronic and optical properties of the material and consequently the terahertz emission from the material. In our letter, we present an experimental study of terahertz emission from silicon (Si) doped InN and magnesium (Mg) doped InN. Si is a group IV element and an electrically active donor in InN. Mg is a group II element and expected to act as an acceptor in InN. Hitherto, dc Hall effect measurements of in InN:Mg did not demonstrate p-type conductivity because of an n-type inversion layer existing at the InN:Mg surface. However, indirect experimental evidence of p-type doping in the bulk region of InN:Mg was found by capacitance-voltage measurements,10 variable magnetic field Hall effect measurements,11 and photoelectron spectroscopy.12,13 Based on these experiments, it was proposed that Mg-doped InN thin films consist of a thin n-type inversion layer at the surface and a bulk p-type region. The n-type inversion layer and the p-type bulk are separated by a charge depletion region (Fig. 1). The thickness of the n-type inversion layer and depletion region is estimated to be 5–15 and 2–60 nm, respectively.10,12,13

The penetration depth of the femtosecond NIR (800 nm) laser pulses in InN is 208 nm.5 Therefore, the absorption of laser photons and generation of terahertz radiation occur across the surface electron accumulation layer, charge depletion region, and bulk p-type region in InN:Mg. Since terahertz emission from narrow band gap semiconductors is sensitive to doping of the material, we expect that doped and undoped InN thin films exhibit different terahertz emissions.

Our InN thin films are grown by molecular beam epitaxy on c-plane sapphire with AlN nucleation layers and GaN buffer layers. Carrier concentrations are obtained from dc Hall measurements. The as grown n-type InN thin films have electron concentrations ranging from $7 \times 10^{17}$ to $1 \times 10^{19}$ cm$^{-3}$ and electron mobilities ranging from 400 to 2000 cm$^{2}$/V s. InN:Si samples have higher electron concentration ranging from $2 \times 10^{19}$ to $3 \times 10^{20}$ cm$^{-3}$, and the electron mobility of the silicon doped samples was

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measured from 200 to 650 cm²/V s. Magnesium doped InN samples (GS1810, GS1906, GS1909, and GS1920) exhibit electron mobilities ranging from 18 to 80 cm²/V s. Experimental evidence of $p$-type doping in GS1810 has been demonstrated by capacitance-voltage measurements and photoelectron spectroscopy. The Mg concentration of GS1810 as measured by secondary ion mass spectroscopy is $10^{20}$–$10^{21}$ cm⁻³, and the ionized acceptor concentration of GS1810 is $10^{19}$ cm⁻³. InN:Mg samples GS1906, GS1909, and GS1920 are expected to exhibit similar properties than GS1810.

Time-domain terahertz emission measurements were performed with an experimental setup as described in Refs. 2–5. Terahertz emission was excited by a titanium-sapphire (Ti:S) laser. The laser pulses duration, laser pulse repetition rate, laser wavelength, and average laser power were 130 fs, 82 MHz, 800 nm, and 700 mW, respectively. The angle of incidence of the laser beam at the InN surface was 45°. The laser pulses duration, laser pulse repetition rate, laser wavelength, and average laser power were 130 fs, 82 MHz, 800 nm, and 700 mW, respectively. The angle of incidence of the laser beam at the InN surface was 45°. The laser beam was focused at the InN surface to a spot of 1 mm².

We observed terahertz emission from native $n$-type InN, InN:Si, and InN:Mg (Fig. 2). The experiment demonstrates that the strength of terahertz emission from InN thin films is a function of doping of the material. The strongest terahertz emission is observed from native $n$-type InN. The weakest terahertz emission is observed from InN:Si. The strength of terahertz emission from InN:Mg exhibits a large variation. However, the average terahertz emission from InN:Mg thin films is stronger than the average terahertz emission from InN:Si. The InN:Mg thin film with the strongest terahertz emission is comparable in emission strength to the best native $n$-type InN thin films.

Next, the relationship between terahertz emission and mobility is discussed. For this purpose, it is necessary to examine the origin of terahertz emission from InN. As described previously, the primary mechanism of terahertz emission from InN exposed to femtosecond NIR laser pulses with nanomole energies, as in our experiments, is ultrafast transient photocurrents. The absorption of laser radiation generates photocarriers in the material. Subsequently, the photocarriers are accelerated by intrinsic electric fields and emit electromagnetic radiation. Transient currents in semiconductors induced by photoexcitation have the two following sources: (1) the photo-Dember effect originating from the difference between the diffusion constants of electrons and holes and (2) the acceleration of photocarriers by a surface field depletion or accumulation field. Both models of terahertz emission predict a linear dependence between the amplitude of the emitted terahertz radiation and mobility. Figure 2 illustrates that native $n$-type doped InN thin films and InN:Si thin films follow the trend that terahertz emission gets stronger with increasing mobility.

The observation of strong terahertz emission from InN:Mg is well explained by the model that InN:Mg thin films consist of a thin, strongly $n$-type surface layer, a charge depletion region, and a bulk $p$-type region. Previous research on terahertz emission of $n$- and $p$-type narrow band gap semiconductors has demonstrated that terahertz emission from a narrow semiconductor is maximized if the semiconductor is compensated ($N_A = N_D$). This fact applies to terahertz emission due to the photo-Dember effect as well as due to surface field acceleration. The penetration depth of 800 nm laser radiation in InN thin films is approximately 208 nm. Therefore, absorption of laser photons and subsequent generation of photocarriers occur across the $n$-type inversion layer, the depletion region, as well as the bulk $p$-type region. Since the $n$-type inversion layer and the depletion layer are short compared to the penetration depth of the laser radiation, most of the photocarriers are absorbed in the bulk $p$-type region of InN:Mg. The terahertz emission from InN:Mg is strong because electrically active acceptors in the bulk of the InN thin films partially compensate native donors. Our terahertz emission measurements of Mg doped InN provide further experimental evidence that Mg is electrically active.
trically active as an acceptor in InN. The terahertz emission of InN:Mg is enhanced compared to InN:Si because of compensation of native donors by Mg acceptors.

We also investigated terahertz emission from InN thin films as a function of electron concentrations. The terahertz emission from InN decreases as a function of increasing electron concentrations in the material. The terahertz emission from InN is enhanced by a factor of 100 when electron concentrations in the material are reduced from $3 \times 10^{20}$ to $10^{17}$ cm$^{-3}$. High electron concentrations have a negative effect on the terahertz emission process in narrow band gap semiconductors. Fundamentally, the amount of terahertz radiation emitted by a semiconductor is limited by the intrinsic carrier concentration of the material. The intrinsic carrier concentration of InN is unknown because the hole effective mass for InN has not been measured yet. However, lower carrier concentrations than those already achieved in InN are considered possible. Therefore, it is expected that further improvement in InN thin film growth with lower carrier concentrations will lead to stronger terahertz emission. This demonstrates the potential of InN as terahertz emitter.

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$\text{FIG. 3. Terahertz emission measured as a function of electron concentrations in as grown } n\text{-type InN and InN:Si. The data points plotted represent the peak terahertz emission signal measured in the time domain (Ref. 2).}$

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\includegraphics[width=0.5\textwidth]{figure3}
\caption{Terahertz emission measured as a function of electron concentrations in as grown $n$-type InN and InN:Si. The data points plotted represent the peak terahertz emission signal measured in the time domain (Ref. 2).}
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