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Highly efficient THz emission from differently grown InN at 800 nm and 1060 nm excitation

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Abstract

A detailed study on differently molecular-beam epitaxy (MBE) grown InN wavers as THz surface emitters is reported. The samples were excited using 120 fs and 100 fs short laser pulses delivered by a Ti:Sapphire oscillator at 800 nm and a fiber laser amplifier at 1060 nm, respectively. The InN emission properties are compared to a p-type InAs reference sample. At 800 nm, atomically smooth InN with low background electron concentration exhibits slightly stronger THz emission than the well-established p-InAs emitter. This high THz efficiency of InN is reported for the first time. The strong emission of InN is caused by the absence of any intervalley scattering, which in the case of InAs, increases the effective mass of the photogenerated electrons and, thus, reduces the photo-Dember effect, which is most responsible for THz emission. Consequently, InN is a reliable material for strong THz emission.

Keywords: Terahertz; Surface emitter; InN; Ultrafast lasers

1. Introduction

The terahertz (THz) region of the electromagnetic spectrum (10^{11}–10^{13} Hz) has potential applications in many fields of science and technology, extending from spectroscopy, medical imaging, nondestructive materials testing through homeland security [1–5]. It was found by Zhang et al. [6] in 1990 that ultrashort THz pulses can be generated by illuminating semiconductor surfaces with femtosecond laser pulses. Typically InAs is used as the emitter material, however, also the emission of THz radiation from InN using a common Ti:Sapphire laser has been demonstrated [7]. The potential of these narrow band gap semiconductors (note that the band gap for InN has been revised from 1.9–2 eV to less than 0.8 eV, recently [8]) is the use of powerful fiber laser systems working at longer wavelengths, in particular at 1060 nm [9] or 1550 nm (the telecommunication regime) [10]. In contrast to conventional Ti:Sapphire systems, fiber lasers offer higher average power and can be designed as most compact systems [11].

InN provides a very strong absorption coefficient ($\approx 10^4$ cm^{-1}, [12]), a high saturation velocity ($>1.5 \times 10^7$ cm/s, [13]) and has an extraordinary energy band structure yielding high electron mobilities ($\mu_n \approx 3500$ cm/Vs, [14]) over a wide range of excitation wavelengths. Hence, a more efficient InN-based THz source compared to the commonly established arsenides like GaAs or InAs could be expected.

Here, we present a detailed investigation of differently MBE grown InN layers as THz surface emitters excited at 800 and 1060 nm. We compare the InN measurements to a p-doped InAs emitter, which is known as the strongest surface emitter [15]. All InN layers show significant THz

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emission. One sample even slightly exceeds the emission of our InAs reference sample.

The discussion of the origin of the strong surface emission is based on an ultrafast charge transport phenomena in an intrinsic surface field or due to the photo-Dember effect. However, these two models can not sufficiently explain the peculiar high THz emission from InN.

In this paper, we present a detailed study of the dependence of THz emission on the InN film properties. Moreover, we provide an extension of the theoretical models by taking into account the peculiarities of the InN band structure. It considers the low band gap, the high electron mobility and the reduced probability of intervalley scattering.

2. Experiment

The InN layers were grown by plasma-induced MBE on various epitaxial templates as described in [16]. The thickness of the InN layers have been varied from 0.35 to 2.20 μm. The according layer properties are summarized in Table 1.

For the detection of the InN surface emission we used a common THz time domain system (TDS, see Fig. 1). More details on the setup can be found in [9].

For pumping the InN samples at 800 nm we used a Ti:Sapphire oscillator, delivering 120 fs short pulses at a repetition rate of 75 MHz. The maximum average output power was about 1.2 W. The pump source at 1060 nm, a self developed parabolic fiber amplifier system [17], delivered 100 fs pulses at the same repetition rate with a maximum average output power of about 12 W. In the experiment only 1.5 W were used in order to have similar experimental conditions compared to the Ti:Sapphire system. The excitation was performed at an angle of 45° with a laser spot size of approximately 2 mm at the semiconductor surface. The polarization was parallel to the plane of incidence for best pump absorption. As a detector we used a photoconductive antenna on low-temperature grown GaAs. To overcome the band gap of GaAs (≈1.4 eV) during 1060 nm excitation we frequency doubled the gate beam via second harmonic generation (SHG) using a BBO crystal.

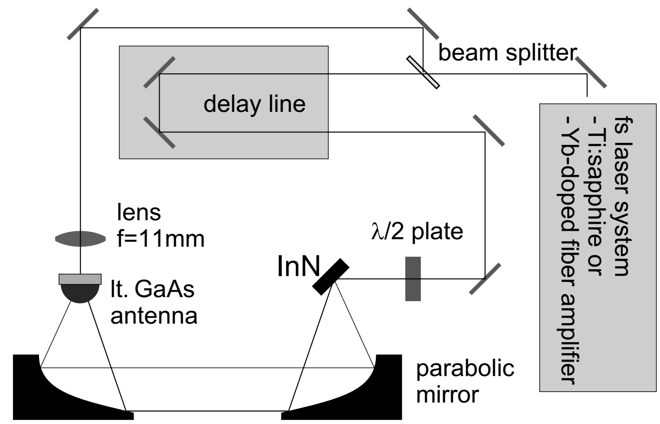

Fig. 1. Schematic for the THz-TDS.

3. Results

Fig. 2 and 3 show the measured THz signal of three InN samples excited at 800 and 1060 nm, respectively. All THz amplitudes were normalized to the emission of p-doped InAs, measured under identical experimental conditions. The highest THz efficiency was obtained from sample 207 (see Table 1). At 800 nm excitation it even revealed a slightly higher THz emission than p-InAs. Such a high THz emission of InN is observed for the first time. Until now, the highest investigated THz emission of InN was only reported to be about the same order of magnitude or less compared to InAs [7,10].

However, the InN samples also show multiple negative echoes with a delay of about 7 ps (Figs. 2a and 3a). Zhang

Table 1
InN layer properties

Structure	No.	Th. (nm)	μ_n (cm^2/Vs)	n (cm^{-3})	Morphology (nm)	rms	FWHM (XRD)	THz amplitude for 800 nm excitation (%)	THz amplitude for 1060 nm excitation (%)
InN/AlN/SiC,Si	199	195	473	5.1×10^{18}	Columns	43	0.835°	31	64
InN/GaN/AlN/SiC,Si	204	760	1150	1.6×10^{18}	Columns	13	0.356°	10	12
InN/GaN/Sapphire	186	170	221	5.1×10^{18}	Columns	34	–	3	19
	188	450	503	5.1×10^{18}	Columns	15	0.355°	11	44
	189	650	671	5.1×10^{18}	columns	12	0.273°	9	28
InN/GaN/AlN/SiC,Si	205	796	910	1.3×10^{18}	3D	34	0.317°	19	60
InN/AlN/Sapphire	202	120	91	2.2×10^{20}	Pits	8	0.835°	4	11
	203	170	212	2.2×10^{19}	Deep pits	2.3	1.379°	9	8
	206	2000	1240	9.5×10^{17}	Pits	8	0.461°	23	36
InN/GaN/AlN/Sapphire	207	700	1300	1.6×10^{18}	2D, Small pits	2.3	0.446°	108	75

Layerthickness Th., electron mobility μ_n, electron concentration n, surface roughness (rms), full width at half maximum value (FWHM) of the (0002) InN reflection in X-ray-diffraction (XRD), THz peak amplitude excited at 800 nm and 1060 nm (normalized to InAs peak).