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Terahertz emission from a large-area GaInAsN emitter

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A large-area interdigitated terahertz emitter based on molecular-beam epitaxy grown GaInAsN with an additional AlGaAs heterostructure is investigated as a terahertz source for excitation wavelengths between 1.1 and 1.5 μm. The optical and electrical properties of the emitter material exhibit absorption up to a wavelength of 1.5 μm and have a resistivity of 550 kΩ cm. Terahertz waves were detected by electro-optical sampling with a bandwidth exceeding 2 THz. Best performance is found for excitation wavelengths below 1.35 μm. Furthermore the emission properties for several excitation powers are investigated, showing a linear increase in terahertz emission. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2978398]

Photoconductive (PC) antennas are key elements of many terahertz systems. Over the past years, significant improvements in emitter efficiency have been achieved by large-area emitters based on GaAs with interdigitated electrodes.[1,2] These structures prevent carrier excitation in every second spacing by additional metallization[1,2] or by etching of the substrate.[3,4] Hereby the excited elementary terahertz waves interfere constructively in the far field. These emitter designs combine the advantages of high bias fields and large active areas. Furthermore detection with elements with similar electrode geometry based on GaAs substrates with subpicosecond carrier lifetimes and resistivity in the 10^6 Ω cm range has been demonstrated.[5,6] The availability of low-cost, stable, and compact fiber lasers has stimulated research on PC antennas based on substrates that allow interband excitation with wavelengths up to 1.55 μm. The challenge is to find small-gap materials with photoexcited carriers with high resistivities and short lifetimes.[7] Low-temperature-grown GaInAs and ion-irradiated GaInAs, both grown lattice matched on InP, have been used as substrate materials for dipole emitter antennas.[8,9] However, the resistivity of these materials is still too low for large-area emitters with interdigitated electrodes.

In this letter we discuss such large-area emitters based on 1000 nm quaternary $Ga_{0.89}In_{0.11}As_{0.96}N_{0.04}$ on (001) semi-insulating (SI) GaAs grown in a Varian Gen II modular molecular-beam epitaxy (MBE) system using Al, Ga, In, and As solid sources and a rf nitrogen plasma source. The optimum growth temperature, which depends on the In content of the structure, was in the range of 530–580 °C.[10]

GaInAsN based emitters show efficient terahertz emission for excitation wavelengths up to 1.35 μm. While the indium lowers the bandgap, the nitrogen reduces lattice strains, resulting in a nearly lattice matched compound. Further optimization is achieved by an additional $Al_{0.3}Ga_{0.7}As/GaAs$ heterostructure layer (60 nm AlGaAs and 5 nm GaAs) as barrier on top, resulting in a higher resistivity of the substrate.

We compare the optical and electrical properties of the MBE grown substrate materials. As reference we compare the terahertz performance of SI-GaAs at 800 nm with the best MBE grown material.

The active area of the processed emitter is 1×1 mm^2. The interdigitated metallization consists of 5 μm wide metal stripes with 5 μm spacing. A second gold layer separated from the first one by a Si_3N_4 layer blocks the excitation in every second spacing.

For our experiments we used an optical parametric oscillator (OPO) which is driven by a mode-locked femtosecond Ti:sapphire laser with a central wavelength of 820 nm, a pulse duration of 80 fs, and a repetition rate of 78 MHz. The signal beam of the OPO is tunable between 1.1 and 1.5 μm. The pulse width is in the order of 250 fs. While the signal from the OPO excites the emitter, a small part of the 820 nm beam is split off before entering the OPO and is used for electro-optic sampling in a 1 mm thick (110) oriented ZnTe crystal. The emitter is driven with a bias of 15 V. The terahertz signal and the sampling beam are combined by a tin doped indium oxide coated mirror and focused on the ZnTe crystal by a pair of off-axis parabolic mirrors. The transmitted sampling beam was separated in its vertical and horizontal components by a polarization sensitive beamsplitter cube. Balanced detection is performed using two photodiodes and a quarter-wave-plate. The change of this balanced signal is proportional to the terahertz field reaching the ZnTe crystal

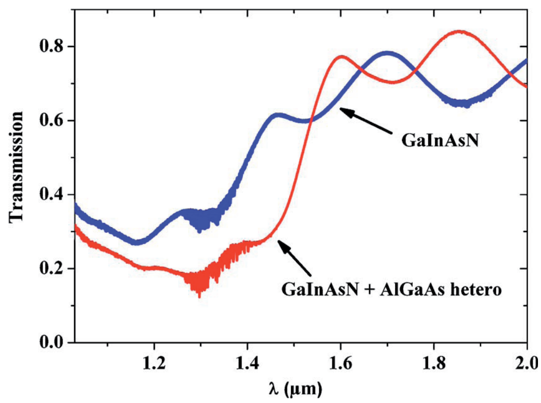

FIG. 1. (Color online) Transmission spectra of the emitters for different substrate materials: GaInAsN (blue) and GaInAsN with AlGaAs heterostructure (red).

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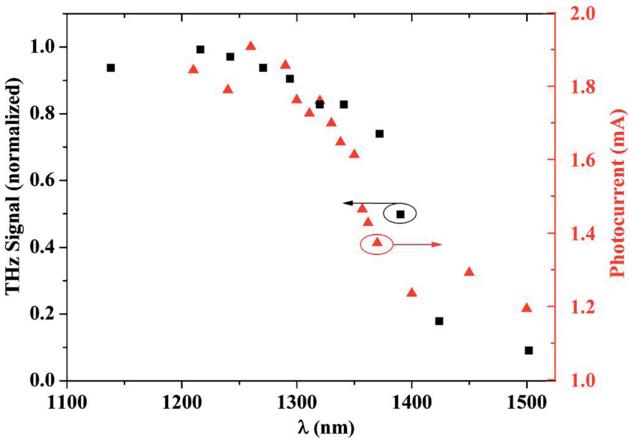

FIG. 2. (Color online) Terahertz signal and photocurrent vs excitation wavelength (black squares and red triangles, respectively) of the GaInAsN device with AlGaAs heterostructure at a 25 mW excitation power.

as described in Ref. 11. To prevent water absorption, the whole setup is purged with dry nitrogen. Temporal resolution is achieved by mechanical delay of the sampling beam.

Figure 1 shows the transmission spectra of the emitters with different MBE grown layers on SI-GaAs. The large oscillations are due to Fabry-Perot oscillations on the Si_3N_4 layer of the device; the smaller ones are from water absorption. The blue curve corresponds to the spectrum for the GaInAsN without and the red to the sample with AlGaAs/GaAs heterostructure. Both substrates show a strong absorption below 1.4 and 1.5 μm, respectively. This step in the transmission spectra is linked to the bandgap[12] and therefore to the excitation of free carriers in the substrate. The resistivity in the GaInAsN substrate is only 150 Ω cm. The absorption coefficient in the GaInAsN substrate with AlGaAs barrier at a 1.3 μm wavelength is 1.5×10^4 cm^{-1}, which is comparable to the absorption coefficient for SI-GaAs at 800 nm. The GaInAsN device with AlGaAs heterostructure shows a resistivity of 500 kΩ cm, which is almost three orders of magnitude higher than previously reported for high resistivity GaInAs material grown on InP substrate.[13] After

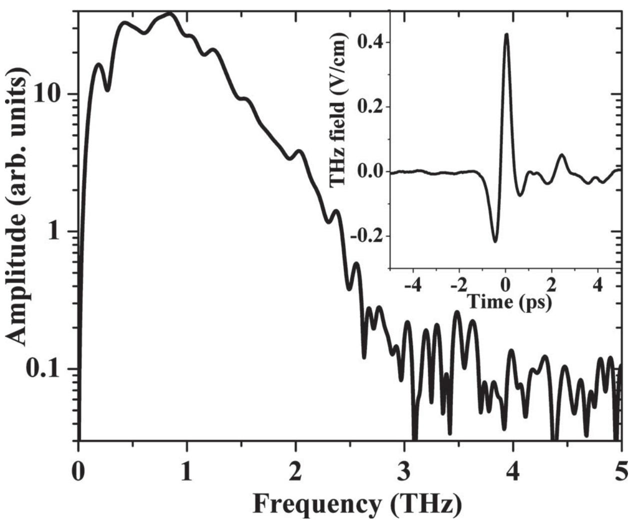

FIG. 3. Terahertz spectrum obtained by Fourier transformation of time-domain data as shown in the inset. The emitter was excited at 1.3 μm and 50 mW average power.

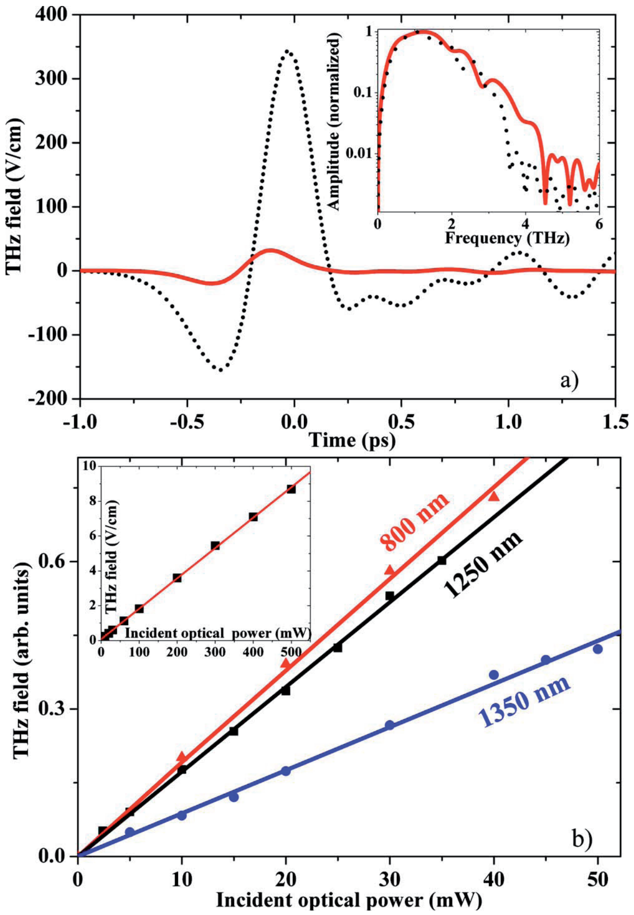

FIG. 4. (Color online) (a) Terahertz transient of a SI-GaAs emitter (black dotted) in comparison to a GaInAsN/AlGaAs emitter (red solid) excited at 800 nm. The inset shows the Fourier transformed spectra obtained from time-domain data. (b) Terahertz field from the GaInAsN/AlGaAs emitter as a function of excitation power for 800, 1250, and 1350 nm (red triangles, black squares, and blue circles respectively). Solid lines are fits to the experimental data. The inset shows higher optical excitation powers reached at 800 nm.

processing the interdigitated electrodes, the whole device resistance is 280 kΩ, enabling a high bias field of up to 60 kV/cm. Therefore we investigate the terahertz emission from emitters which are fabricated on the GaInAsN/AlGaAs substrate.

Figure 2 shows the dependency of the terahertz signal on the excitation wavelength while keeping the excitation power constant. Between 1.1 and 1.34 μm the terahertz emission remains constant. For excitation wavelengths above 1.4 μm the signals are about five times smaller as compared to the shorter wavelength. This is consistent with the dependency in the measured photocurrents of the emitter. Based on the transmission spectra in Fig. 1 where absorption is observed up to an excitation wavelength of 1.5 μm, we would expect the decrease in terahertz emission at longer excitation wavelengths. We attribute this to the lower mobility of the electrons due the modified band structure in $GaInAs_{1-x}N_x$.[14,15]

Figure 3 displays the Fourier transform amplitude of the temporal waveform, which is also shown in the inset. The spectral maximum is around 1 THz and the usable bandwidth exceeds 2 THz. The terahertz transient is measured with lock-in technique and has a signal to noise ratio of 400 with a 100 ms lock-in time constant. The bandwidth of the emitted terahertz radiation is limited by the pulse duration of the OPO. For a 250 fs pulse the bandwidth is limited to about 2 THz.

Figure 4(a) shows a comparison between a normal SI-GaAs emitter and the GaInAsN/AlGaAs emitter at 800 nm excited with a 500 mW optical power and an 80 fs pulse duration and focused to a spot of 300 μm. For SI-GaAs the signal is eight times higher than that for GaInAsN/AlGaAs. In principle the emitted terahertz field is proportional to the mobility times the excited carrier density. Since the number of excited carriers at 800 nm in GaInAsN/AlGaAs is at least equal to that in SI-GaAs, we conclude from our data that the mobility in GaInAsN/AlGaAs is at least a factor of 8 lower than in SI-GaAs (6000 $cm^2\,V^{-1}\,s^{-1}$). The inset shows the spectra obtained from a Fourier transform of the time-domain data. The bandwidth exceeds 3 THz, which is consistent with the assumption that the long pulse duration of the OPO (250 fs) limits the terahertz bandwidth at excitations above 1 μm.

Figure 4(b) shows the terahertz signal versus excitation power for 800, 1250, and 1350 nm wavelengths. For the whole optical power range of the OPO up to a fluence of 1 $\mu J/cm^2$ we observe a linear dependence of the emitted terahertz field. The inset shows even higher optical powers obtained from direct excitation by the Ti:sapphire laser at 800 nm and up to 500 mW, corresponding to a carrier density of 10^{17} cm^{-3}. This behavior is in contrast to low-temperature-grown GaInAs emitters on InP with smaller active areas operating at 1.56 μm, where saturation behavior already occurs at a few milliwatt optical excitation power.[9]

In conclusion, we have demonstrated a large-area PC terahertz source operating at excitation wavelengths up to 1.5 μm, while best performance is achieved for wavelengths below 1.35 μm. A high resistivity substrate, which is a key prerequisite for a large-area device, can be realized by MBE grown GaInAsN on GaAs with an additional AlGaAs heterostructure. Based on the scalability of the device, no saturation behavior over the available range of excitation powers was observed. The limited bandwidth of the emitted terahertz radiation of 2 THz is attributed to the relatively large pulse duration of the OPO. Further optimization of the balance between the high resistivity and high mobility of the substrate material should increase the performance in bandwidth and excitation wavelength toward the 1.55 μm range. In addition the presented device shows an interesting opportunity for fiber lasers operating around 1.1 μm, as described in Ref. 16.

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