Directional terahertz emission from diffusion-engineered InAs structures

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We have designed and fabricated a new type of terahertz (THz) emitter that radiates THz waves along the surface-normal direction because of the lateral distributions of the transient electric dipoles. The excitation and measurements were performed using a conventional THz time-domain spectroscopy scheme with femtosecond optical pulses. The corrugated mirror patterns on the InAs layers made the radiation directional along the surface-normal direction, and the emission efficiency was controlled by adjustment of the pattern width.

As an important practical source of pulsed electromagnetic radiation at terahertz (THz) frequencies, the photo-excitation of semiconductor surfaces by femtosecond (fs) laser pulses has been widely used over the past two decades. A vast array of compound semiconductors have been examined with regard to their material parameters, including InAs, InSb, GaAs and InP.1 The THz radiation emitted from these materials has been attributed to either photo-carrier acceleration caused by band-bending near the semiconductor surface or to the large diffusion velocity difference between electrons and holes (the photo-Dember effect). These drift and diffusive transport mechanisms of the photo-excited carriers are identified separately from those of the different bulk compound semiconductors: In the case of GaAs, the THz radiation is known to be produced mainly by the surface electric field,2 whereas the radiation from InAs is mainly governed by the photo-Dember effect.3,5 Comparison studies were also performed on the THz radiation from GaAs and InAs,4 while a detailed explanation of the THz radiation processes from InAs was provided in terms of drift and diffusion.5,6

Further technological advances have been made toward efficient radiation sources with higher output powers and/or tunability7 and with better spatial resolution that is sometimes beyond the diffraction limit.8 Recently, THz waves with increased amplitude and bandwidth have been reported in periodically metal-patterned In0.53Ga0.47As (and GaAs) by breaking lateral symmetry in their diffusion currents,9,10 while the transfer of THz waves over long distances was demonstrated by using either a laser-plasma filament11 or an optical fiber coupled with tilted InAs tips, while retaining superior spatial resolution.12

From the materials viewpoint, InAs is known to be one of the most intense sources among the various candidate semiconductors because it has an electron mobility (reaching up to 30,000 cm2/V·s) that is much higher than the hole mobility (∼240 cm2/V·s), leading to efficient photo-Dember current generation. Also, the 800 nm excitation at the central wavelength of Ti:sapphire-based laser technologies provides a large photo-Dember field because of the short absorption depth (∼140 nm) and large excess energy (∼1.2 eV), when considering the narrow band-gap (Eg = 0.35 eV at 300 K).13 Despite the moderate efficiency of InAs-based transmitters, significant obstacles to the materials use remain, particularly with regard to the control of the propagation direction of the THz waves. In conventional THz time-domain spectroscopy (THz-TDS) systems with fs laser illumination, for example, InAs sources are tilted with an angle of 45° to the incident beam to be coordinated with the guiding components; the generated THz waves are therefore inevitably spatially dispersed. We also note that the diffusion-controlled currents in InAs, with a larger photo-Dember field than in any other semiconductor, could offer THz emitters that are aligned in a line-of-sight configuration for prospective THz applications in imaging and communications. In this work, we have implemented micro-scale groove patterns in InAs-based structures, with the aim of producing enhanced directional emission of THz waves, as measured using various detection geometries.

The photo-Dember currents feature prominently along the [100] growth direction of conventional InAs epilayers, as shown in Fig. 1(a). The 1 µm-thick InAs epilayers used here were processed to have grating patterns, acting either as 45° reflectors with a gap width W (as shown in Fig. 1(b)) or as parabolic apertures with W of 2.5 µm. The grooves in Fig. 1(b) were proposed to produce enhanced lateral diffusion by generation of abrupt photocarrier gradients at the air-(010) interfaces, together with the enhanced THz radiation along the surface-normal direction, as depicted by a large green cone along the [100] direction. The grating grid (with W=0.5, 1.2 µm, or 2.5 µm) was fabricated by the shot-modulation technique and dry etching on InAs epitaxial layers (containing p-type doping of 1.5 × 1019 cm−3 with Be) grown on 500 µm-thick GaAs substrates; scanning electron microscopy (SEM) images of the structure are shown in Fig. 1(c). A 2.5 µm-thick GaSb layer was inserted to compensate for the lattice mismatch between InAs and GaAs. The gap width W was designed to have a similar scale to the
FIG. 1. Illustrations of the THz generation processes (a) without and (b) with the groove patterns. The incident IR laser beams (shaded red cone) are assumed to be normal to the surface ($\theta=90^\circ$), and the diffusion directions of the photo-generated electrons (blue dots) and holes (red dots) determine the radiation patterns (green dumbbell-like cones) accordingly. (c) SEM images of the fabricated patterns with $W$ of 0.5 $\mu$m, 1.2 $\mu$m and 2.5 $\mu$m.

diffusion length of the electrons along the vertical [100] direction ($\sim$ 1 $\mu$m). We performed THz-TDS measurements under excitation with a pulsed Ti:sapphire laser at 300 K (pulse duration $\sim$ 150 fs, centered at 800 nm).

The incident angle $\theta$ of the IR beam was either 45$^\circ$ or 90$^\circ$. When $\theta=90^\circ$, for comparison purposes, the photo-conductive antenna (PCA) was either placed along the IR laser in the normal detection geometry or along the surface in the lateral detection geometry. The pump beam supplies an excitation fluence of about 0.9 $\mu$J/cm$^2$ on a 800 $\mu$m beam diameter; under this regime, the optical rectification is negligible when compared to the photo-Dember effect.

THz-TDS measurements, similar to those conducted previously in InAs epilayers without the groove structures, were conducted in as shown in Fig. 2(a), in both the conventional 45$^\circ$ reflection geometry and in the surface-normal transmissive geometry (or normal detection geometry). The experimental setups used for the two geometries are depicted in the inset figures. The emission along the surface-normal direction (solid line) in Fig. 2(a) was relatively suppressed, which can be attributed to the combined effects of longitudinal diffusion and the reduced radiation out-coupling efficiency caused by the refractive index mismatch at the interfaces. The slight and slow oscillations shown in Fig. 2(a) are related to the Fabry-Perot effect, for which the period of 12.5 ps is well matched with the round-trip time in the GaAs substrate.

The lateral photo-carrier density modulation for surface-normal incidence could remove a major hindrance that affected the transmissive emission suppression, as shown in Fig. 2(a). When the wedge-shaped groove patterns were configured for lateral diffusion, as shown in Fig. 2(b), and the IR pump beam was orthogonally polarized relative to the groove axis, the THz amplitude increased with evident pattern scale ($W$) dependence. The results from these patterned structures were compared to the radiation from a bare sample (short dotted line), indicating the enhanced lateral diffusion. The strongest amplitude was observed in a sample with $W$ of 1.2 $\mu$m, which was similar to the reported value of the maximum diffusion length of 1.3 $\mu$m and could possibly be associated with the optimized lateral diffusion. On the other hand, the out-coupling efficiency in the groove-patterned samples could be similar to that in the epilayer, as inferred from the persistently observed Fabry-Perot oscillations. The ratios of the peak amplitudes to the Fabry-Perot peaks were almost the same among the samples shown in Fig. 2(b). These results are somewhat intuitive, because the wavelength of the THz waves is much larger than the groove scale, such that we would not expect enhanced scattering at the interfaces of the patterned samples along the surface-normal direction. In
FIG. 3. THz measurements of (a) InAs layers with and without groove patterns in the lateral detection geometry. (b) Fourier transformed spectra. (c) Emission amplitude enhancement ratios for comparison of the patterned samples to the bare sample for both detection geometries.

In conclusion, we have developed a new method of implementing groove patterns to act as reflectors for incident laser pulses in the IR range. The amplitude of the associated THz waves along the surface-normal direction was alternated, depending on the period and shape of the groove patterns. The mirror-like patterns that were separated by a gap width of 1.2 μm were found to be the most efficient among our samples, whereas periodic aperture patterns with a gap width of 2.5 μm did not assist with the directionality when compared to the bare bulk sample. The lateral emission signals, in contrast, did not show many differences among the samples, which means that the longitudinal diffusion was persistent with or without the groove patterns. These results
show that, under excitation with IR laser pulses, the optimization and controllability of the lateral carrier diffusion in InAs could be useful for alignment-free THz applications in imaging and communications. The groove emission patterns could possibly be optimized by using low-cost methodologies such as echelon gratings\textsuperscript{21} and pattern imprinting.\textsuperscript{22}

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