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Magnetic-field-induced enhancement of terahertz emission from III–V semiconductor surfaces

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Abstract

We discuss the origins of the magnetic-field-induced enhancement of terahertz (THz) emission from bulk semiconductor surfaces. The principal effect of the magnetic field is to rotate the THz dipole and hence dramatically increase the THz power radiated through the semiconductor surface. It also significantly affects the ability of the photo-created carriers to screen surface electric fields. The sensitivity of THz emission to the motion of photo-created carriers makes this an ideal probe of hot carrier dynamics both in bulk semiconductors and sophisticated heterostructures. © 2002 Elsevier Science B.V. All rights reserved.

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The terahertz (THz) frequency range, usually defined as 100 GHz–10 THz, represents a significant portion of the electro-magnetic spectrum for which compact, solid-state sources are still not available. Neither transit time devices (e.g. HEMTs and Gunn diodes) operating up to a few hundred GHz, nor optical sources lying on the higher frequency side (e.g. infra-red lasers and LEDs) can efficiently span the ‘THz gap’. Recently, though, the need for such sources has been significantly emphasised by the demonstration of promising biomedical applications of THz spectroscopy and imaging [1], which stand together with traditional and well-developed applications within solid-state physics.

One method for generating THz radiation involves illuminating a semiconductor with a sub-picosecond laser pulse, which has a photon energy greater than the semiconductor band gap [2]. The electric field at the semiconductor surface accelerates the photo-created electrons and holes in opposite directions, thereby forming a changing dipole that emits a coherent THz transient. Recent results have shown that the THz power emitted from a range of semiconductor surfaces (e.g. GaAs, InAs, InP, GaSb and InSb) after photo-excitation can be significantly enhanced by placing the semiconductor in a magnetic field (see for e.g. Ref. [3]). The exact origin of this enhancement has, however, been the source of debate and forms the basis for our discussion here.

Fig. 1 shows the typical THz emission as a function of magnetic field for three semiconductors: GaAs, InAs and InSb. 2 nJ pulses of 1.6 eV photons from

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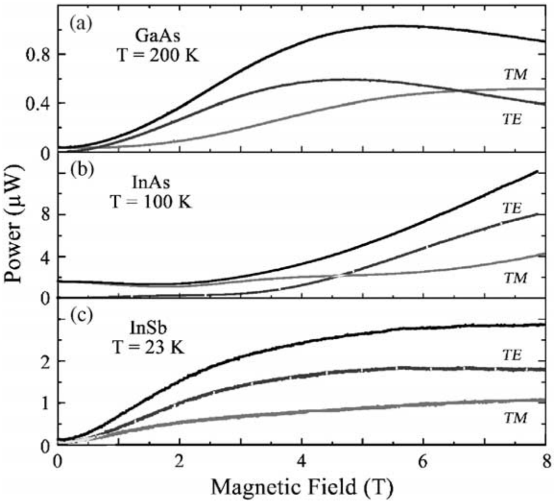

Fig. 1. Emitted THz power as a function of applied magnetic field for bulk GaAs, InAs and InSb. The TE and TM components of the radiation (labelled) are given together with the total radiated power. The measurement temperature is chosen to maximise the THz power. Wafer details are given in Table 1.

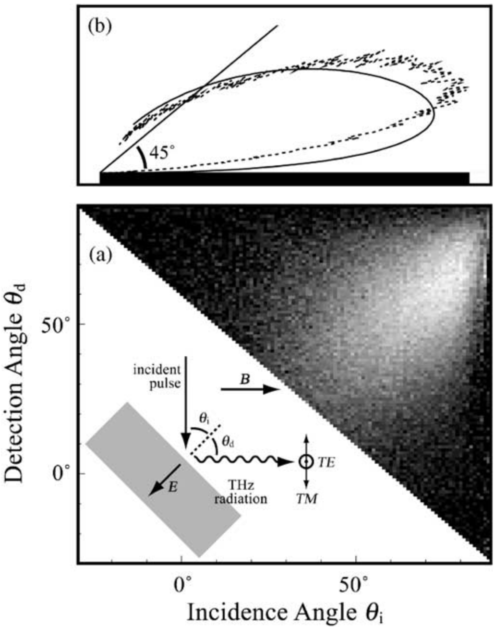

Fig. 2. (a) Emitted THz power as a function of the optical pulse incidence angle (θ_i) and the THz detection angle (θ_d) for bulk InAs at 300 K. The incident optical pulse was focused into an 80 μm spot. White and black represent high- and low-power levels, respectively. Inset: Geometry of the experimental arrangement. Also shown is the direction of the applied magnetic field used for taking the data in Fig. 1. (b) Polar plot showing the experimental (dashed line) and theoretical (solid line) emission intensity for $\theta_i = \theta_d$. The line at 45° represents the detection direction used in magnetic field studies (Fig. 1).

a mode-locked Ti-Sapphire laser (80 MHz repetition rate) excited each semiconductor at an angle of 45° to the surface normal, and the emitted THz radiation was collected parallel to the applied magnetic field and perpendicular to the incident beam (see inset Fig. 2(a)). Emission was measured both by an incoherent bolometeric detection scheme and also by coherent electro-optic sampling. As expected from the geometry of the experiment, in the absence of a magnetic field the emitted THz radiation is completely TM-polarised. This is because the acceleration of the photo-created carriers is restricted to being perpendicular to the plane of the semiconductor surface i.e. in the direction of the surface electric field (see inset Fig. 2(a)). However, as the magnetic field is increased, a TE component is induced and the emitted THz radiation becomes elliptically polarised. Both TE and TM power show significant enhancement in a magnetic field, with electro-optic sampling used to demonstrate that the emitted radiation is coherent.

The dependence of the TM and TE-polarised THz fields on the applied magnetic field differs significantly between semiconductor surfaces. A nearly monotonic increase in both THz fields is seen in InSb, whilst peaks in the emission are observed in GaAs and InAs. Furthermore, as shown in Table 1, the maximum emitted THz powers are different between these semiconductors. This, however, does not simply reflect the different carrier concentrations or effective masses in these materials. It is known that surface field photo-currents dominate the THz emission process in GaAs [2], whilst the Dember field effect [4], arising from the difference in mobilities between hot electrons and hot holes, is strongest in InAs and InSb. However, the differences between these two generation mechanisms alone are not sufficient to explain the different experimental results in a magnetic field.

In order to understand the carrier dynamics following absorption of an optical pulse, and thereby explain the enhancement of THz emission in magnetic field, we have developed a three-dimensional semi-classical Monte-Carlo simulation. Early work ascribed the strong THz enhancement in a magnetic

Table 1
Characteristics of the bulk wafers used as THz emitters

Wafer	GaAs	InAs	InSb
Orientation	(1 0 0)	(1 0 0)	(1 0 0)
Doping density (cm^{-3})	1×10^{15}	2×10^{16}	3×10^{14}
Electron effective mass	$0.063m_0$	$0.023m_0$	$0.014m_0$
Maximum THz power	1.0 μW at 200 K	12 μW at 100 K	2.7 μW at 23 K

field to additional charge accelerations associated with the Lorentz force. However, our theoretical calculations indicate that this does not produce a significant increase in dipole strength, in agreement with the conclusions of Meinert et al. [5]. Instead the principal reason for the enhancement in radiated THz power is a reorientation of the THz dipole. Owing to the large differences in refractive index between the semiconductor and air, a change in dipole orientation can result in over an order-of-magnitude increase in the efficiency with which radiation couples out of the semiconductor [6]. To confirm this interpretation, we have calculated the expected radiation pattern from (1 0 0) InAs in the absence of an applied magnetic field as the angle of the incident optical pulse and detected THz radiation are altered. Fig. 2(a) shows the experimentally measured THz radiation pattern, obtained by focusing the incident laser beam to an 80 μm spot on the sample. This spot size is of the same order as the wavelength of the emitted THz radiation, and hence the dipole acts as a point source, as assumed in the theoretical simulations. From the data in Fig. 2(a), a polar plot of the experimental data is obtained (Fig. 2(b)), in which the direction of the incident optical pulse and detected THz radiation are altered concurrently to maintain a reflection geometry. Excellent agreement between our theoretical and experimental results is found. Also, shown (for convenience) in Fig. 2(b) is the 45° direction of the applied magnetic field used to collect the data presented in Fig. 1.

Fig. 3 shows the self-consistently simulated potential in GaAs following excitation by an optical pulse. Typical results are shown, both with and without a 5 T magnetic field. Comparing traces at 0.6 ps, the magnetic field is clearly observed to rotate the potential profile. This is consistent with the rotation of the THz dipole, which leads to enhanced coupling of THz radiation out of the semiconductor, as discussed above.

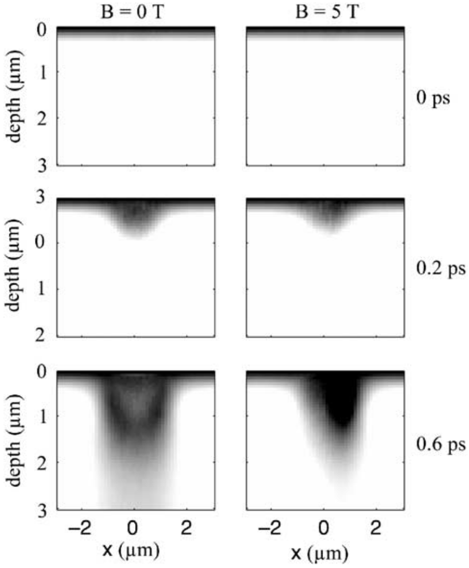

Fig. 3. Electrostatic potential in a GaAs wafer as a function of lateral position and depth (the laser is incident at $x = 0$ μm). Successive plots show the progression of the potential with time following excitation with a pulsed laser; results are shown with and without a 5 T magnetic field applied at an angle of 45° to the sample surface. White and black represent potentials of 0 and −0.7 V, respectively.

Fig. 3 also illustrates a second important point. The applied magnetic field dramatically alters the screening of the surface field by photo-created carriers. On incidence of the optical pulse (0 ps), there is a very strong electric field in the depletion region at the semiconductor surface. Carriers are photo-created in this depletion region, accelerate in the surface electric field, and are scattered by collisions with carriers, impurities, and phonons. The net difference between the movements of the electrons and holes gives rise to the changing dipole, which emits a THz transient. However, this movement of electrons and holes also screens the surface electric field. This is well illustrated at 0.6 ps by the slowly varying electric potential into the semiconductor at $x = 0$ μm for $B = 0$ T. The magnetic field induces cyclotron motion, which has a pronounced effect both on carrier scattering processes and the ability of the carriers to screen the surface field. Fig. 3 shows that the magnetic field suppresses the screening of the depletion region surface field. A much sharper potential gradient is observed compared with the equivalent data at $B = 0$ T.

In summary, we have investigated the variation of total radiated THz power with applied magnetic field in three bulk semiconductors and have demonstrated why there can be a significant increase in emitted THz power in a magnetic field. We note that electro-optic sampling additionally allows the temporal response of the THz electric field, and hence the frequency spectrum of the THz pulses, to be obtained. Given the sensitivity of the generation mechanism to the movement of photo-created carriers, we propose this process as an ideal way to probe hot carrier dynamics and scattering processes in semiconductors and heterostructures.

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