

Theory of magnetic-field enhancement of surface-field terahertz emission

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We present a theoretical treatment of surface-field THz generation in semiconductors, which explains the power enhancement observed when a magnetic field is applied. Our model consists of two parts: a Monte Carlo simulation of the dynamics of carriers generated by a subpicosecond optical pulse, and a calculation of the resulting THz radiation emitted through the semiconductor surface. The magnetic field deflects the motion of the carriers, producing a component of the THz dipole parallel to the surface. This causes the power transmitted through the surface to be increased by more than one order of magnitude. © 2002 American Institute of Physics.
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INTRODUCTION

The generation of terahertz (THz) radiation is important for the study of hot carrier dynamics¹ and collective processes² in semiconductors. However, emerging applications of coherent THz radiation spectroscopy^{3,4} and imaging⁵ are at present limited by the lack of compact, high power THz emitters. Research into the development of higher power semiconductor THz emitters is thus of considerable practical significance.

Surface-field THz generation occurs when a semiconductor is illuminated by a subpicosecond laser pulse with photon energy greater than the semiconductor band gap.⁶ The electric field within the surface depletion region accelerates electrons and holes in opposite directions.⁷ The resulting charge separation, which occurs on a picosecond timescale, forms a dipole that emits a coherent THz transient.

Over the last 3 years, several groups have observed a large magnetic field induced enhancement in surface-field THz emission from a variety of semiconducting materials (GaAs, InAs, InP, GaSb and InSb).^{8–12} Until now, no convincing theoretical explanation of this enhancement effect has been proposed. Some authors^{8,9} have suggested that the power enhancement is due to the additional charge acceleration produced by the Lorentz force. However, Meinert *et al.*¹³ have presented a theoretical treatment of emission from GaAs in crossed electric and magnetic fields, which does not predict a significant increase in the THz dipole strength.

Here we show, using a semiclassical Monte Carlo model, that the main effect of the Lorentz force is to reorientate the THz dipole with respect to the surface of the semiconductor, with little change to the dipole strength. The observed increase in emitted THz power is due to the increased transmission of THz radiation through the surface of the semiconductor in the new dipole orientation. This effect can be understood in terms of the Fresnel refraction theory. We show the reorientation of the THz dipole can result in an

over 1 order of magnitude increase in the coupling of radiation out of the semiconductor.

Very recently Shan *et al.*¹⁴ have presented a similar explanation of the importance of the dielectric interface in the magnetic field enhancement mechanism. They describe the carrier dynamics as cyclotron motion with a phenomenological damping term. Hence their theory does not reproduce the experimental magnetic field dependence and saturation of THz power, which is explained by our Monte Carlo treatment. Heyman *et al.*¹⁵ have also discussed magnetic field enhancement of THz emission from GaAs and InAs, but without including the effect of the dielectric interface, which we show to be critical.

The particular sample we discuss, both theoretically and experimentally, is an *n*-doped ($2 \times 10^{15} \text{ cm}^{-3}$) piece of GaAs, illuminated with a 150 fs full width half maximum, 2 nJ pulse of 1.6 eV photons focused to a 0.5 mm diam spot. The lattice temperature is set to 200 K. The magnetic field is applied at an angle of 45° to the surface, as shown in the inset to Fig. 1. In the experiments, transverse electric (TE) and transverse magnetic (TM) polarized THz emission are measured in the direction of the magnetic field, for fields ranging from 0 to 8 T. More experimental details are given in Ref. 9.

THE MODEL

In order to describe the carrier dynamics following the absorption of the optical pulse, we have developed a three-dimensional semiclassical Monte Carlo simulation.¹⁶ Briefly, the model follows the trajectories of an ensemble of electrons and holes over a series of short time steps. The initial carrier distribution is created randomly according to the absorption profile of the subpicosecond optical pulse. The carrier motion is then calculated, over time steps much less than the scattering time, using the solutions of

$$\ddot{\mathbf{r}}_i(t) = \frac{q_i}{m_i^*} [\mathbf{E}(\mathbf{r}_i, t) + \dot{\mathbf{r}}_i(t) \times \mathbf{B}], \quad (1)$$

where $\mathbf{r}_i(t)$ is the position of the carrier, with charge q_i and effective mass m_i^* , in an electric field $\mathbf{E}(\mathbf{r}_i, t)$ and applied

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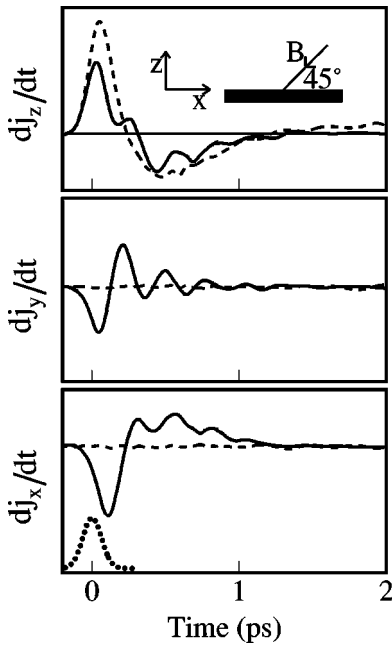


FIG. 1. Time derivatives of the components of the simulated average current, with magnetic fields of 0 T (dashed lines) and 8 T (solid lines). The inset shows the sample and field geometry. The dotted curve in the bottom panel gives the temporal profile of the laser pulse.

magnetic field \mathbf{B} . In each small time interval all fields are assumed to be constant. $\mathbf{E}(\mathbf{r}_i)$ is obtained from the three-dimensional electric potential, calculated by solving Poisson's equation using the charge distribution from the previous time interval.

After every time step, each carrier velocity is updated randomly according to the scattering probability and angular distribution calculated for its local environment. The scattering mechanisms included in the model are longitudinal optical (LO) phonon, impurity and electron-hole scattering. However, for the relatively low excitation densities considered here, LO phonon and impurity scattering are found to dominate.

RESULTS AND DISCUSSION

In Fig. 1, we show the results of our simulation for 0 and 8 T applied magnetic fields. The plotted quantities are the components of the time derivative of the ensemble average current, $\partial\mathbf{J}/\partial t = \sum_i q_i \dot{\mathbf{r}}_i$. This acts as the source term in Maxwell's equations for our calculation of the THz emission. In the absence of any magnetic field there are no x or y components of the average current, because the system has rotational symmetry about the z axis. Hence, a simple linear THz dipole is formed in the z direction. The magnetic field rotates the dipole, producing x and y components of similar magnitude to the z component. An increase in the total dipole strength of approximately 15% is observed. On its own, this would increase the THz power by approximately 30%, significantly less than the 1 order of magnitude enhancement observed experimentally.

It can be seen from Fig. 1 that, at $B = 8$ T, the THz dipole becomes elliptically polarized: the x , y and z components

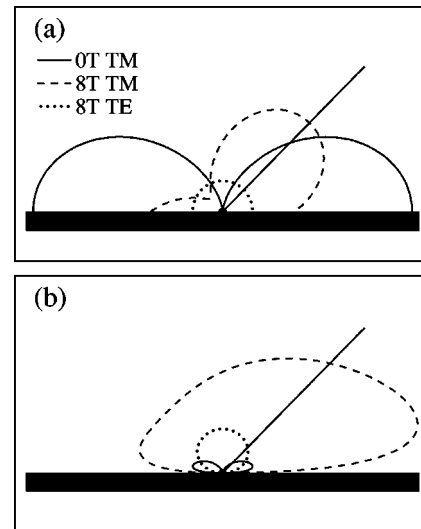


FIG. 2. Calculated THz radiation patterns above the semiconductor surface: (a) in the absence of dielectric contrast ($n_e = n_i = 3.5$), and (b) with dielectric contrast ($n_e = 1.0$, $n_i = 3.5$). The TE and TM patterns are plotted separately, for magnetic fields of 0 and 8 T. The solid line at 45° from the semiconductor surface shows the measurement direction used in our experiments. Plot (b) has been scaled up by a factor of 2 with respect to (a).

cross zero at different times. This is a consequence of the cyclotron motion, which tends to produce a circularly polarized dipole. At high fields, when the cyclotron frequency differs significantly from the plasmon frequency, so magnetoplasmon effects are not important, the motion of the charge distribution can be separated into distinct plasmon and cyclotron parts. Thus the rotated dipole at high fields can be considered as a combination of linearly polarized plasmon and circularly polarized cyclotron contributions.

We now calculate how the THz radiation emitted by the dipole is transmitted through the semiconductor surface, and show that the enhanced power recorded in the experiments is a result of a dramatic increase in transmission when the dipole is rotated. The calculation is straightforward: the TE and TM fields inside the semiconductor are obtained from $\mathbf{J}(t)$, and the external fields computed using the Fresnel transmission coefficients for the two polarizations. We consider here detection directions in the $x-z$ plane, defined by the magnetic field and the surface normal, since this includes the direction of our experimental measurements. For detection at an angle θ_e from the surface normal, the external fields are

$$E_{TE}(\theta_e, t) \propto \frac{2 \sin \theta_e \cos \theta_i}{\sin(\theta_e + \theta_i)} \left[\frac{\partial J_y}{\partial t} \right],$$

$$E_{TM}(\theta_e, t) \propto \frac{4 \sin \theta_e \cos \theta_i}{\sin 2 \theta_e + \sin 2 \theta_i} \left[\frac{\partial J_z}{\partial t} \sin \theta_i - \frac{\partial J_x}{\partial t} \cos \theta_i \right], \tag{2}$$

where θ_i is the corresponding internal angle, given by Snell's law, $n_e \sin \theta_e = n_i \sin \theta_i$, with n_e , n_i the external and internal refractive indices. In these expressions, the prefactors are the Fresnel coefficients and the terms in [. . .] are proportional to the internal fields emitted by the dipole. For this analysis we assume that the THz dipole is a point source.

The emitted power is obtained from Eqs. (2) by calculating the time integrals of $|E(t)|^2$. To obtain the correct flux,

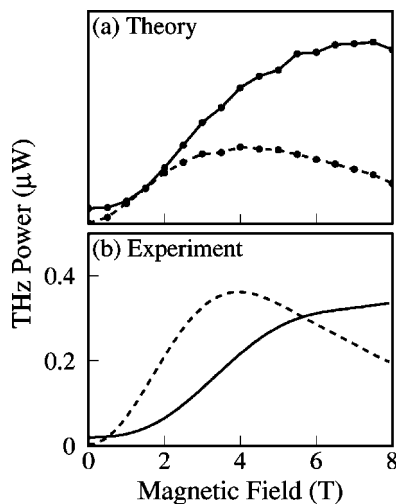


FIG. 3. Magnetic field dependence of THz power emitted at 45° from the surface of photoexcited GaAs. (a) Shows the power calculated using simulation data and (b) the experimentally measured results. The solid and dashed lines represent the TM and TE power components, respectively.

we also scale by a factor $(n_e \cos \theta_e)/(n_i \cos \theta_i)$, which accounts for the differences in the propagation speeds and solid angle elements in the internal and external media.

In Fig. 2, we show polar radiation plots of the angular distribution of emitted power, corresponding to the simulated data of Fig. 1. Figure 2(a) shows the power that would be emitted if there were no dielectric boundary at the surface ($n_e = n_i = 3.5$). In the absence of magnetic field, the characteristic “bow-tie” pattern of a linear dipole emitter is seen, and the radiation is completely TM polarized. At a magnetic field of 8 T the TM emission pattern rotates toward the magnetic field direction, and a TE component appears, as a result of the cyclotron motion. The total THz power emitted in the magnetic field direction is only enhanced by a small amount, $\sim 50\%$.

Figure 2(b) shows the real situation with the THz source radiating below the surface of GaAs ($n_i = 3.5$) into air ($n_e = 1.0$). At 0 T there is strong suppression of the TM polarized bow-tie dipole pattern. This can be readily understood as an effect of refraction: the maximum internal angle, corresponding to $\theta_e = 90^\circ$, is less than 17° so only the small fraction of power emitted close to the dipole axis can pass through the surface. For the 8 T magnetic field, the TM polarized radiation pattern is distorted by the dielectric boundary, but the overall strength, with allowance for the factor of 2 scaling between (a) and (b), is quite comparable to the case without dielectric contrast. Thus the magnetic field enhancement can be seen to be in reality a reduction of the suppression of the emission from the z polarized dipole.

In Fig. 3(a) we plot, as a function of magnetic field, the TE and TM polarized THz power along the direction parallel to the field, indicated by the 45° lines in Fig. 2. For comparison, the experimentally measured THz power is shown in Fig. 3(b). There is good agreement between the forms of the theoretical and experimental curves. In both theory and ex-

periment, a peak is observed in the TE polarized power at 4 T, which confirms that our Monte Carlo calculation correctly reproduces the experimental dipole rotation.

The theory predicts a TM power enhancement of \sim tenfold, and a total enhancement (TE + TM) of ~ 15 -fold. The corresponding experimental enhancements are ~ 20 and 30 times. The calculated peak TE power, relative to the TM, is a factor of ~ 2 smaller than the experimental value. Given the complexities of simulating the carrier dynamics, we regard this as fairly good agreement, but the differences suggest that the theory underestimates the cyclotron contribution to the dipole. This may be explained by inherent inaccuracies in our semiclassical treatment, particularly for the scattering processes, or by uncertainties in the experimental excitation conditions.

CONCLUSION

In conclusion, our Monte Carlo simulations demonstrate that a magnetic field has little effect on the magnitude of the THz dipole of the carrier motion, but it produces a large rotation of the dipole away from the surface normal direction. We have shown that the radiation of THz is significantly affected by the dielectric contrast between semiconductor and air, with external emission strongly suppressed for a dipole normal to the surface. The experimental order of magnitude power enhancement is thus found to be a consequence of the reorientation of the dipole relative to the surface.

ACKNOWLEDGMENTS

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