Diffusion and drift in terahertz emission at GaAs surfaces

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We study terahertz (THz) emission from GaAs as a function of photon energy and electric field. THz radiation arises from transport of photogenerated charge in an electric field and by hot carrier diffusion (the photo-Dember effect). These mechanisms can be separated by experiments in which either the electric field or the kinetic energy of the carriers is varied. For electric fields $E \sim 4$ kV/cm, we find that the electric field controls THz emission for carrier temperatures $k_B T_C \leqslant 0.1$ eV, while hot-carrier diffusion dominates for $k_B T_C \approx 1$ eV. Both mechanisms contribute at intermediate fields and carrier temperatures. Our results are consistent with estimates of the relative magnitudes of these two effects.
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Photoexcitation of a semiconductor surface by femtosecond laser pulses can generate pulses of terahertz frequency (THz) radiation.[1] This process is an important practical source of pulsed THz radiation for time-domain THz spectroscopy[2] and THz imaging.[3] Analysis of the electric-field transients of the pulses can also probe the carrier dynamics in the semiconductor with subpicosecond time resolution. While ultrafast optical techniques such as time-resolved luminescence probe single-particle properties, THz techniques probe collective properties such as conductivity or transient center-of-mass motion of carriers. These global properties are important for determining the performance of ultrafast electronic and electro-optic devices. THz emission has been used to study, e.g., ballistic acceleration and velocity overshoot,[4–6] plasma oscillations[7,8] and cyclotron motion[9,10] of free carriers. In this letter we show that THz techniques can be used to distinguish drift and diffusive transport of photoexcited carriers.

Optically pumped THz emission has been observed in a wide range of semiconductors.[1] THz generation can proceed by difference-frequency mixing of the pump beam[11] (optical rectification), or by the coherent transport of photoexcited free carriers (the current–surge effect). At *n*-type and *p*-type GaAs, GaSb and InP surfaces, where the surface depletion fields are typically relatively large (10^4–10^5 V/cm), the current–surge effect is primarily powered by the acceleration of free photocarriers in the surface electric field.[1] This impulsive excitation can also couple to other excitations of the material, such as plasma oscillations[8] and optical phonons[12] to produce radiation. The polarity of the THz wave forms is opposite in *n*-type and *p*-type samples, indicating that the direction of the initial acceleration of the charge is controlled by the surface field. THz emission has also been observed from narrow-gap semiconductors in which the surface electric fields are absent[12] (InAs, Te) or very weak (InSb), and Gu *et al.*,[13] showed that the signal polarity in InAs and InSb does not change between *n*-type and *p*-type samples. In these cases it was proposed that hot-carrier diffusion powers the transient photocurrent (the photo-Dember effect). Here, the density gradient of the photogenerated carriers drives diffusion of electrons and holes into the material from the surface. A transient electrical current results because the electron mobility is higher than that of the holes. Dekorsky *et al.*,[12] measured THz emission in Te, and concluded that diffusion dominated THz generation in this material. Monte-Carlo simulations by Johnston *et al.*,[14] of THz emission from GaAs and InAs found that for a 1 nJ optical pump pulse at $\lambda \sim 800$ nm, THz emission from GaAs is powered by the surface field, while THz emission in InAs is driven by hot-carrier diffusion. Simulated THz wave forms in GaAs showed inversion of polarity between *n*-type and *p*-type samples, but no inversion between *n*-type and *p*-type InAs.

To date, there have been no experimental studies showing both drift- and diffusion-dominated THz emission from a single sample. However, such results would be valuable to more tightly constrain theoretical simulations of hot-carrier dynamics. In this letter we show that both surface electric field and hot-carrier diffusion contribute to drive optically pumped THz emission in GaAs, and that either process can dominate under the appropriate experimental conditions.

We measured optically pumped THz emission from epitaxial GaAs samples at room temperature. Sample G606 [1 μm undoped GaAs on 1 μm *n*-GaAs ($n = 10^{17}$ cm^{-3})] and G601 [1 μm undoped GaAs grown on 1 μm *p*-GaAs 1($p = 10^{17}$ cm^{-3})], were grown on [100] semi-insulating substrates. As the absorption length $L \leqslant 1$ μm in our experiments, pump radiation is primarily absorbed in the undoped layer where the electric field is uniform. Energy band diagrams of the samples are sketched in Fig. 1. Measurements were performed both on as-grown samples, and on diode structures to measure *E*-field dependence.

The samples were excited with a mode-locked Ti–sapphire laser oscillator ($\tau \leqslant 12$ fs, $\lambda = 800$ nm, $\Delta\lambda = 110$ nm) and the THz emission was sampled using electro-optic detection[15] with a 1 mm ZnTe detector. Tunable pulses in the energy range $h\nu = 1.45$–1.65 eV were obtained by fil-

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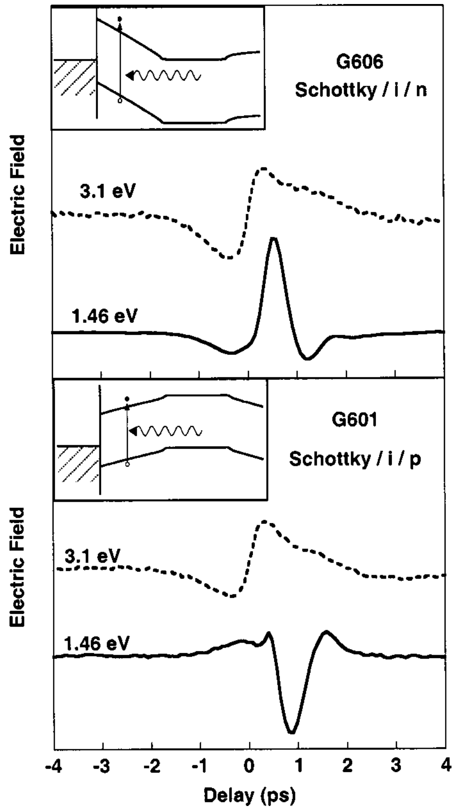

FIG. 1. THz emission from samples G606 and G601 for pump energies $h\nu = 1.46$ and 3.1 eV. Wave forms are normalized and offset for clarity. Insets show energy band diagrams of the two samples.

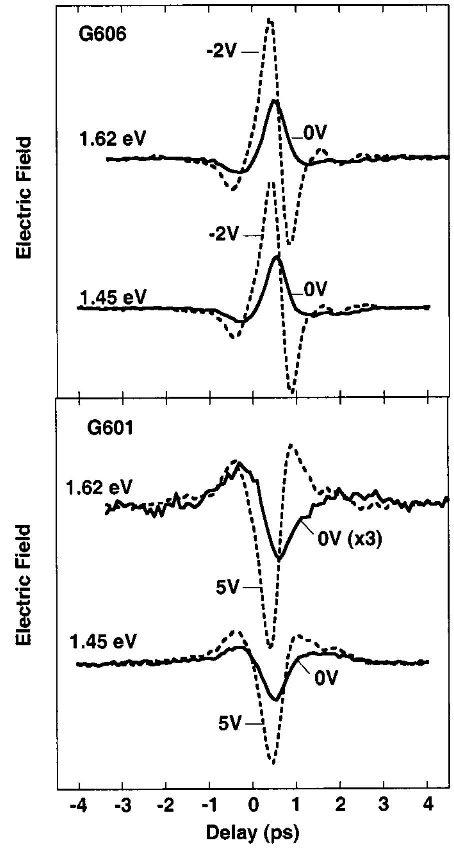

FIG. 2. THz emission from samples G606 and G601 vs gate bias and pump energy. Measurements performed on diode structures with transparent metallic gate contacts.

tering the pump beam, while $h\nu = 3.1$ eV pulses were obtained by frequency doubling the pump laser in a 0.5 mm BBO crystal. The effect of filtering and of the finite detector thickness was to lower the temporal resolution to ~150 fs, as measured by optical crosscorrelation. The excitation density at the sample was sufficiently low (~10 nJ/cm^2) that THz electric field amplitudes were proportional to excitation intensity, and the pulse shapes were independent of intensity.

Our samples produce measurable THz emission from the current–surge effect and from optical rectification. Optical rectification is orientation dependent, and vanishes for our samples when the in-plane component of the pump-laser polarization is parallel to the [010] crystallographic direction.[16] We used this orientation dependence to suppress this effect to negligible levels in our measurements.

Figure 1 shows THz emission from G606 and G601 obtained using near band gap excitation ($h\nu = 1.46$ eV), and excitation far above band gap ($h\nu = 3.1$ eV). The pump laser was incident on the as-grown samples at 45° and THz radiation was collected in the pseudoreflection geometry. Under photoexcitation with near band edge radiation, the polarity of the THz signal is opposite in G606 vs G601. Similar dependence of THz pulse polarity on sample type has been observed in bulk GaAs as well. The amplitude of the THz wave form from G601 is approximately 20 times weaker than that from G606.

In contrast, the THz emission obtained with far-above band gap excitation ($h\nu = 3.1$ eV) is qualitatively different. First, the wave form of the THz pulses from the two samples are nearly identical in shape and magnitude. THz emission is clearly *not* controlled by the surface electric field under these conditions. Second, the pulses are both broader and weaker than those obtained with near band gap radiation. We note that in this case, the photoexcited electrons have sufficient excess energy to scatter to the *L* and *X* conduction band valleys, so that their average effective mass will be much higher. This is qualitatively consistent with the observed change in the THz wave forms. We have also measured THz emission from bulk *n*-InAs and *p*-InAs, and our results are consistent with those of Gu *et al.*[13] In InAs we see no substantial difference between THz wave forms measured with excitation energy $h\nu = 3.1$ eV and $h\nu = 1.5$ eV. We suggest that due to the large energy barrier for intervalley scattering in InAs (1.2 eV), and the rapid thermalization of photoexcited carriers with extrinsic carriers in these heavily doped samples, intervalley scattering is suppressed.

Figure 2 shows THz emission from gated samples of G606 and G601 for two values of the surface electric field and for two photon energies. Gated samples had semitransparent metallic Schottky contacts and diffused indium ohmic contacts. THz emission measurements were performed in the pseudotransmitted geometry and the pump laser was incident on the samples at Brewster's angle. For both samples, the amplitude of the THz wave forms initially increase with reverse bias, reach a maximum at $V_{ext} \sim 2$ V (G606) and $V_{ext} \sim 5$ V (G601) and then decrease, qualitatively consistent with the high-field saturation of drift velocity. Figure 2 shows the THz emission from each sample near the maximum signal point.

In G601 we see a clear dependence of the THz wave

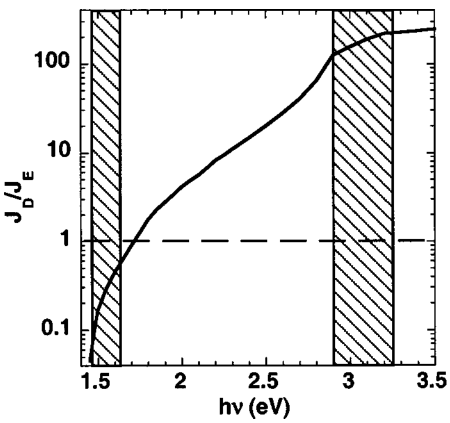

FIG. 3. Ratio of the diffusion current to the drift current, calculated from Eq. (2) for GaAs with $E=4$ kV/cm. Shaded regions are experimentally accessible with our laser system.

form with photon energy at zero applied bias. The nearly symmetric wave form obtained with $h\nu=1.45$ eV becomes asymmetric, and the amplitude decreases at $h\nu=1.62$ eV. We obtain similar results from the as-grown sample. Application of an electric field ($E_{ext}\leqslant 50$ kV/cm)[17] renders the emitted THz wave form from G601 nearly symmetric and independent of photon energy. In contrast, the THz emission from G606 is nearly independent of photon energy in this range. The signal is nearly symmetric at zero applied bias, but becomes asymmetric for $E_{ext}=20$ kV/cm.

We have constructed a simple model to describe our results. Rapid carrier–carrier scattering establishes a thermal carrier distribution on a time scale shorter than our 0.1 ps temporal resolution, and we describe the carriers with an effective temperature (T_c) and effective mobility (μ_n and μ_p). The current of photoexcited carriers due to drift (J_E) and to diffusion (J_D) becomes

$$J=J_E+J_D=eE(n\mu_n+p\mu_p)+e(D_n\nabla n-D_p\nabla p). \quad (1)$$

Using $D_i=\mu_i kT_i/e$, and approximating $n/\nabla n=p/\nabla p=L$ the optical absorption length, we have

$$\frac{J_D}{J_E}=\frac{k_B}{eLE}\left[\frac{T_e\mu_n-T_p\mu_p}{\mu_n+\mu_p}\right]\approx\frac{k_BT_e}{eLE}, \quad (2)$$

where the approximation holds when $\mu_n\gg\mu_p$, as for Γ-valley electrons and holes in GaAs and InAs. We further approximate the carrier temperature from the excess energy per carrier $3/2\,k_BT_e\sim(h\nu-\varepsilon_G)$. Then the ratio J_D/J_E can be estimated for any specific electric field and pump photon energy (see Fig. 3).

Our model predicts that transport is dominated by the electric field for $h\nu=1.45$ eV and $E\approx4\times10^3$ V/cm. This is supported by the observation that the polarity of the THz wave form is opposite for G606 and G601 for this pump photon energy. For $h\nu=3.1$ eV, $J_D/J_E\sim200$, and transport should be completely dominated by hot-carrier diffusion. This is consistent with the experimental result that the THz wave form is independent of electric field under these conditions. For $h\nu=1.6$ eV the drift and diffusion currents are comparable for small electric fields. We expect the drift contribution will substantially modify the THz wave form in G601, where the drift and diffusion currents are in opposite directions. The change should be less significant in G606 where the two effects add. Increasing the electric field to ~50 kV/cm causes the transport to be drift-dominated again, in agreement with experiment.

In summary, THz emission via the current surge effect at semiconductor surfaces can driven by carrier drift in the surface electric field or by hot-carrier diffusion. We have investigated THz emission from undoped GaAs epitaxial samples, and find that either mechanism can dominate THz emission under appropriate experimental conditions. For moderate electric fields $E\sim4$ kV/cm, the drift current dominates THz emission for carrier excess energies $h\nu-E_g\leqslant0.1$ eV. Both drift and diffusion contribute for $h\nu-E_g\approx0.2$ eV and $E\sim4$ kV/cm, but drift dominates THz emission at higher electric fields. Hot-carrier diffusion drives THz emission in GaAs for $k_BT_C\approx1$ eV. Our results are consistent with estimates of the relative magnitudes of the drift and diffusion currents under these conditions.

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