Direct characterization of terahertz radiation from the dynamics of the semiconductor surface field

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We report on a time-resolved electro-optic sampling of the photocarrier-induced surface field dynamics by a midband gap probe beam from a femtosecond fiber laser. By measuring the ultrafast surface field variation, we are able to derive the undistorted terahertz wave form radiated from the semiconductor surface that is excited by the femtosecond laser pulses. The derived wave form agrees well with the directly measured terahertz radiation at the far field. The peak frequency of terahertz radiation is found to increase with the carrier density, which can be explained in terms of field dynamics. © 2000 American Institute of Physics. [S0003-6951(00)01944-6]

Coherent terahertz (THz) spectroscopy (generation and detection) and related phenomena has been an area of heavy research due to the rich physical and chemical processes in this frequency region. One important method of generating coherent terahertz radiation is to illuminate semiconductor surfaces with femtosecond (fs) laser pulses. The underlying generation mechanism was attributed to the ultrafast transient current formed from the acceleration of the photoexcited carriers in the surface field. It is very difficult to directly record the temporal behavior of the photocurrent, and subsequently, the undistorted THz wave form. THz spectroscopy is normally used to detect the THz wave form at far field, which is always distorted due to the convolution of the original THz wave form with the detector’s response function. Electric field-induced optical rectification was proposed as another possible mechanism for generating THz radiation from the semiconductor surface; it is found to significantly contribute only under intense illumination. However, there is a lack of the knowledge of the undistorted THz, as well as a clear understanding of the features of THz wave form at its physical origin.

In our experiments, a midband gap probe beam is used to record the transient surface field change induced by an above-band gap pump beam through transmissive electro-optic sampling (TEOS). The surface depletion field is found to be screened at a higher speed with a higher excitation density. A direct study of the physical origin of the THz wave form, which is radiated from the semiconductor surfaces, is conducted from the perspective of field dynamics. An undistorted THz wave form is derived by using the second-order time derivative of the internal field and the result agrees well with those measured by THz spectroscopy.

Figure 1 shows the schematic setup for electro-optic (EO) sampling of the surface field dynamics using a two-color fiber laser. A compact fiber laser delivers 24 mW of a fundamental beam at a wavelength of 1.55 μm with a pulse width of 150 fs and 14 mW of a second harmonic (SH) beam at 780 nm with a pulse width of 140 fs. The SH beam is used as a pump source and is chopped at 1.8 kHz for phase-sensitive detection. Part of the fundamental beam is used as a probe. The probe beam is collinearly combined with the pump beam after passing a dichromatic mirror, which has been coated for high reflection at 780 nm and is transparent for 1.55 μm light. They are normally focused onto a sample by a lens of 63 mm focal length. The vertical surface field change induced by the pump beam yields an anisotropic refractive index change. For EO detection, the probe beam is polarized along the [001] crystal orientation. After transmitting the sample, the probe beam is biased by a quarter waveplate and is split into two orthogonal components along the [0-1-1] and [0-11] crystal orientations by a polarized beamsplitter. The photocurrents from these two components are balanced and sent to a lock-in amplifier. Due to the use of balanced detection, the isotropic refractive index and absorption changes induced by the photoexcited carriers, which have been observed in the conventional pump-probe scheme, are cancelled and will not contribute to the experimental results.

Figure 2 shows the anisotropic transmission changes of the 1.55 μm probe beam induced by the 780 nm pump beam.
in a 1 mm (100)-orientated semi-insulating (SI) GaAs, which has a weakly p-type carrier concentration of about \(4 \times 10^{14} \text{ cm}^{-3}\). The plots are obtained at a photocarrier density of \(5 \times 10^{16} \text{ cm}^{-3}\) (solid curve) and \(1 \times 10^{15} \text{ cm}^{-3}\) (dotted curve), respectively. The curve at the low excitation density is averaged six times to improve signal to noise ratio and appears smoother. The EO signal does not depend on the pump beam polarization. Therefore, optical rectification can be ruled out as a possible contribution to the EO signal. The measured TEOS signal gives a change of the phase of the probe beam, from which the potential change across the sample can be obtained. Then, we can calculate the electric field change by assuming there is a uniform field change within the first absorption length (\(\sim 1 \mu m\)) in the surface, which has a comparable value to the depletion field width (\(\sim 1.3 \mu m\)) of the sample.

Measured field dynamics is decided by an interplay between the surface field and the photocarrier transportation. At the low excitation density of \(1 \times 10^{15} \text{ cm}^{-3}\), the low depletion field is not strong enough to accelerate electrons to energy high enough for intervalley scattering. Carriers undergo ballistic acceleration in the depletion field until they leave the depletion field region. Therefore, surface field screening starts immediately after the carriers are generated. Surface field decreases by 0.5 kV/cm after it reaches equilibrium. Because the surface field is relatively weak and its width is large, the transport of electrons and holes through the field takes a relatively long time. At the higher density of \(5 \times 10^{16} \text{ cm}^{-3}\), field screening happens faster than in the low-density case, as shown by the slope of the curves. In addition, there is a coherent spike, which is caused by nonlinear interaction at the higher power density. However, this coherent spike is nonradiative and does not contribute to THz generation.

It is worthwhile to address the unique features of the two-color EO sampling. Since the probe beam photon is off-resonant (below the band gap), the EO coefficient, as well as the field amplitude, can be accurately determined. With the pump photon energy above the band gap, background-free detection is achieved. Furthermore, the spatial overlap is easily guaranteed with pump and probe beam collinearly incident on the sample. At last, transmissive geometry can probe the potential (field) change across the whole sample.

The ultrafast field change observed from the above experiments can emit THz electromagnetic waves and is directly related to the THz radiation from the semiconductor surfaces. The emitted radiation \(E_{\text{rad}}\) in the far field can be shown as the second time derivative of an internal field \(E_{\text{int}}\):

\[
E_{\text{rad}} = \frac{\sin \theta}{\epsilon \epsilon_0 c} \frac{V}{r} \frac{\partial^2 E_{\text{int}}}{\partial t^2} ,
\]

where \(\theta\) is the radiation angle, \(V\) is the radiation volume, and \(r\) is the distance between source and detector. This equation is equivalent to the one previously derived from the transient current model. The field change distribution can be calculated from Poisson’s equation:

\[
\frac{\partial E}{\partial z} = \frac{q}{\epsilon \epsilon_0} (N_h - N_e) ,
\]

where \(z(t)\) is the average distance between electrons and holes. Assuming there is a uniform carrier distribution within the first absorption length of the sample, we first begin to integrate both sides over \(z\). Then, by taking the second order time derivative of both sides and substituting back into Eq. (1), we get

\[
E_{\text{rad}} = \frac{\sin \theta}{\epsilon \epsilon_0 c} \frac{V}{r} \frac{\partial [q(N_h - N_e) u]}{\partial t} ,
\]

where \(q(N_h - N_e) u\) is the photocurrent. This agrees with the equation that was derived before. We do not consider the contribution from the population decay of photoexcited carriers, since the lifetime of carriers is measured to be over 100 ps by isotropic pump-probe experiments and can be neglected in the subpicosecond regime.

Figure 3 shows the THz temporal wave forms derived from the surface field variation (dotted lines) and measured by direct THz spectroscopy (solid lines), respectively. Due to the dramatic reduction of signal to noise ratio that occurs during the time-derivative process, a smoothing process using binomial algorithm is performed to retain a clear THz wave form from the surface field transient and to facilitate a comparison with the wave form obtained from THz spectroscopy. For the direct THz field generation and detection, a pump beam with 780 nm wavelength is incident onto a SI GaAs surface at a 45° angle. THz radiation in the reflection direction is detected by a 0.25 mm ZnTe EO crystal at far field. The excited carrier density is about \(1 \times 10^{15} \text{ cm}^{-3}\), close to the value used in surface field study. The wave forms obtained from both THz spectroscopy and field dynamical...
The discrepancy mainly comes from the limited spectral response of the ZnTe sensor, as well as the dispersion and absorption in the GaAs and ZnTe. The response of the EO sensor is dramatically reduced for high frequency components. Therefore, we demonstrate a first derivation of undistorted THz wave form radiated from a semiconductor surface. In addition to the far-field wave form, the near field THz wave form can be easily obtained by taking the first time derivative of the surface field variation.

To study the influence of carrier density on THz generation, we measure the THz wave form at different excitation densities from the same SI GaAs, as shown in Fig. 4. The carrier density is varied from $1 \times 10^{17}$ to $1 \times 10^{15} \text{cm}^{-3}$ by changing the average power using a variable attenuator. With the increase of the excitation density, the peak THz frequency shifts to a higher frequency and the bandwidth becomes larger. THz pulse also becomes shorter. This can be explained from the field dynamics. At a higher density, the surface field is screened faster; thus, the THz wave form becomes narrower as the second time derivative of the field variation.

In conclusion, we have provided a method to directly study the ultrafast dynamics of the surface field using mid-band gap EO sampling. The undistorted THz wave form is obtained from the surface field variation and agrees with those from direct THz measurement. The detailed THz generation processes have been analyzed from the comparison.

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