Characterization of optically dense, doped semiconductors by reflection THz time domain spectroscopy

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We present reflection THz-time domain spectroscopy measurements of the complex conductivity of n-type, 0.038 Ω cm GaAs and n-type, 0.22 Ω cm Si wafers. These measurements clearly demonstrate the efficacy of the reflection technique on highly conductive, optically dense samples and approach the precision of THz–TDS transmission measurements. Because the THz-bandwidth, reflection measurements extend beyond the carrier collision frequency, we obtain direct measures of the mobility and the carrier number density. © *1998 American Institute of Physics.* [S0003-6951(98)04223-5]

The frequency-dependent complex conductivity of doped semiconductors is one of their most important technical properties. However, due to the difficulty of reaching the THz frequency region with conventional sources, complete experimental characterizations to frequencies of several THz have only started to be performed.[1–5] The relatively new technique of THz time domain spectroscopy (THz-TDS)[6] has enabled such experimental studies.[1,2,4] In this technique subpicosecond pulses of THz radiation are transmitted through the sample, and then compared in the frequency domain with the corresponding pulses for no sample in place. THz-TDS has the additional advantage that it bypasses the complications of ohmic contact to the semiconductor. The most recent THz-TDS characterization of doped silicon was of sufficient precision to test the alternative theories of conductivity.[4] Via the THz Hall effect, spatially resolved mobility measurements have been made by measuring the polarization rotation of a focused beam of THz pulses transmitted through a semiconductor sample in a magnetic field.[5]

However, depending on the doping level and the thickness of the sample, the transmitted pulse may be so severely attenuated that THz-TDS cannot be used. For this case a reflection type adaptation of THz-TDS would be desirable, if the precision could be preserved. The initial demonstration of such an approach showed its potential by measuring the reflection from undoped InSb from 0.1 to 1.1 THz, as a function of temperature from 80 to 260 K and thereby obtained values of the mobility and carrier concentration over this temperature range.[3]

Here we present reflection THz-TDS measurements of the complex conductivity from 0.1 to 2.5 THz on doped n-type, 0.038 Ω cm GaAs and from 0.1 to 1.5 THz on n-type, 0.22 Ω cm Si wafers. These measurements approach the precision of transmission measurements and clearly demonstrate the efficacy of the reflection technique on highly conductive, optically dense samples. Because our measurements extend beyond the THz carrier collision frequency, we obtain independent measures of the carrier number density and the mobility. Our results are in good agreement with the Drude theory of conductivity.

The optoelectronic setup used to generate and detect the subpicosecond pulses of freely propagating THz electromagnetic radiation is shown in Fig. 1(a); with the deflecting mirrors removed the setup is the same as that described previously.[1,2,4,6] The angle of incidence of the THz beam on the sample is 19°, and the THz beam is polarized in the plane of the diagram. A GaAs transmitting antenna with a simple coplanar transmission line geometry and a silicon on sapphire receiving antenna consisting of a micron size dipole antenna embedded in a coplanar transmission line are both optoelectronically driven by 8 mW average power beams of

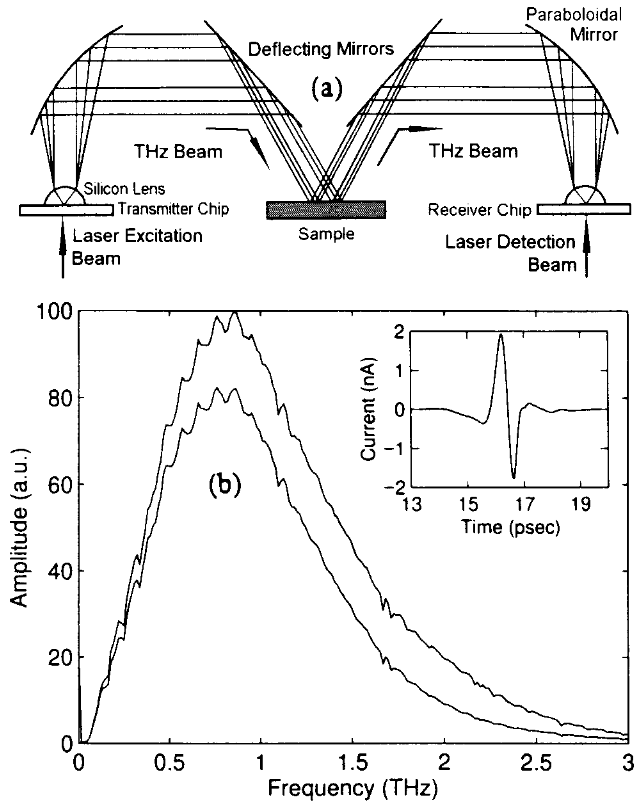

FIG. 1. (a) Schematic diagram for reflection THz-TDS. (b) An expanded view (inset) of the measured reference THz pulse from an aluminum mirror at the sample position. The upper amplitude spectrum is for the reference THz pulse. The lower spectrum is obtained with the n-type, 0.038 Ω cm GaAs sample in place.

70 fs pulses from a mode-locked Ti:sapphire laser with an 86 MHz repetition rate.

A measured reference THz pulse with an aluminum mirror placed in the sample position is shown as the inset in Fig. 1(b). The corresponding amplitude spectrum is the upper curve, obtained by a numerical Fourier transform of the complete reference pulse measurement extending from 0 to 70 ps. When the mirror is replaced by the n type, 0.038 Ω cm GaAs sample, the measured THz pulse is slightly reshaped compared to the reference pulse; the amplitude spectrum for the sample is the lower curve. The small, sharp spectral features on both curves are due to a slight amount of residual water vapor in the experimental enclosure, which is purged with dry air. From such data we obtain the complex amplitude reflectivity of the sample, referenced to the 100% reflectivity aluminum mirror. From the measured reflectivity, we then obtain the absorption and index of refraction of the sample and the complex conductivity. For measuring the relative phase shift a significant experimental requirement is the precise positioning of the sample with respect to the reference mirror. Their orientations should be the same to within mrads and their surface positions the same within microns. To achieve our best fits the relative positions were theoretically adjusted by typically ±15 μm, corresponding to a time shift of the sample pulse by ±100 fs. This is similar to the problem in transmission THz-TDS, involving the precision of the sample thickness.

The magnitude of the measured amplitude reflectivity for the n-type GaAs wafer is shown as the open circles in Fig. 2(a). The excellent signal-to-noise-ratio (S/N) measurements show an unusual frequency dependence, decreasing from unity at low frequencies and with a break in the slope at 1.2 THz compared to the collision frequency of 1.0 THz. After reaching the minimum value at 2.3 THz the reflectivity begins a monotonic climb expected to reach the value of 0.55 corresponding to our angle of incidence and the index of refraction of 3.60 for intrinsic GaAs.[6] The relative phase of the sample pulse with respect to that of the reference is shown as the solid dots. The phase shows a simple frequency dependence, increasing almost linearly to the rounded peak at 1.7 THz then falling off linearly, but with a steeper slope. Independent of the theoretical model of conductivity, from these data we directly obtain the corresponding absorption and index of refraction shown in Fig. 2(b).[2,7] The absorption is quite high, indicating the extreme difficulty of a transmission measurement through this optically dense sample. The absorption peak is almost at the 1 THz collision frequency. The index of refraction shows a smooth frequency dependence with the maximum measured value of 12 at the lowest frequency of our system, a broad minimum of 2.0 centered at 1.7 THz, and then a slow monotonic increase. The conductivity has significantly lowered the index, compared to the value of 3.60 for intrinsic GaAs.[6] Finally, from these data and the previously measured power absorption and index of refraction data of intrinsic GaAs,[6] we obtain the real σ_r and imaginary σ_i parts of the complex conductivity as shown in Fig. 2(c), with a good S/N approaching that of the early transmission measurements.[1] It is to be emphasized again that the data as presented in different forms in Fig. 2, do not depend on the theoretical model of conductivity.[2,7]

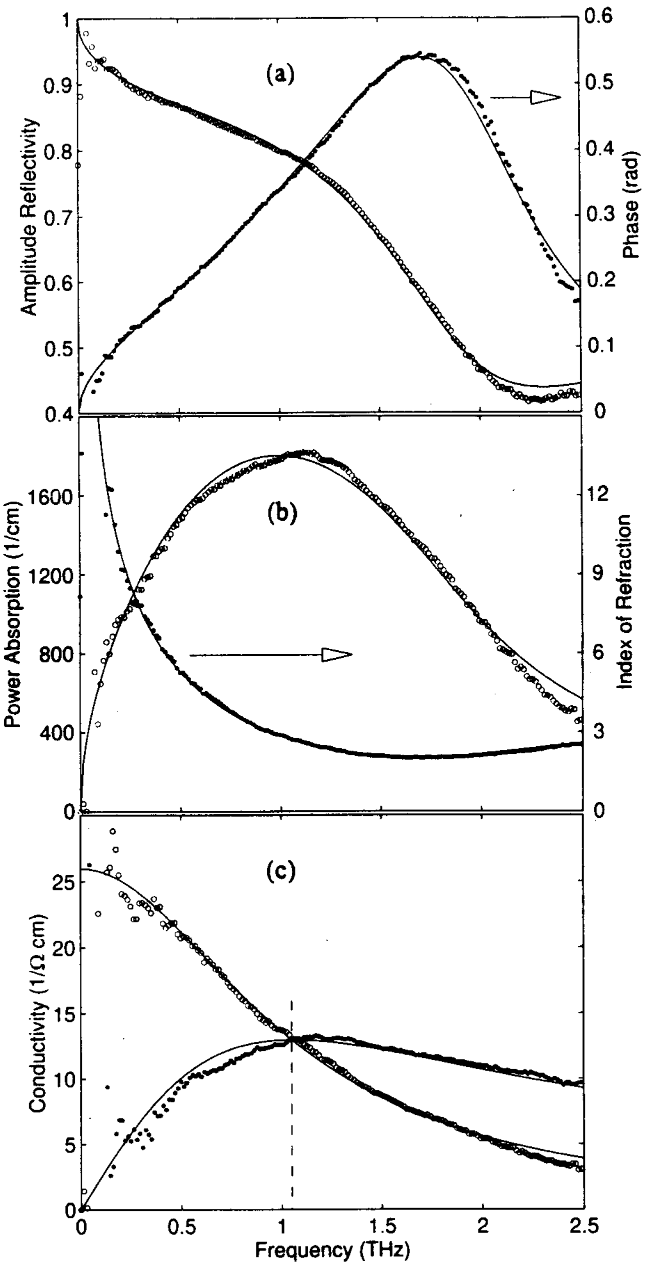

FIG. 2. Reflection THz-TDS measurements of n type, 0.038 Ω cm GaAs compared with Drude theory (solid line). (a) Amplitude reflection (open circles) and relative phase (dots); (b) power absorption coefficient (open circles) and index of refraction (dots); (c) real part of the conductivity σ_r (open circles) and imaginary part of the conductivity (dots). The vertical dashed line indicates Δf, the HWHM of σ_r.

Given the measurements shown in Fig. 2, we then favorably compare these results with a Drude theory analysis, which has been experimentally shown to provide a good description of the conductivity at high carrier densities,[1,2,4] The definitive comparison is with the conductivity curves in Fig. 2(c); the other comparisons are shown to demonstrate self-consistency. Within the framework of the Drude theory, the half-width at half-maximum (HWHM) Δf of the measured real conductivity is equal to the collision frequency $\Gamma/(2\pi)=\Delta f$. In addition, the Drude σ_r and σ_i curves cross at the frequency $\Gamma/2\pi$, where σ_i also has its maximum value equal to one-half the dc conductivity σ_0. The crossing of the σ_r and σ_i curves is clearly shown by both the theory and measurements and is marked by the vertical dashed line. Δf

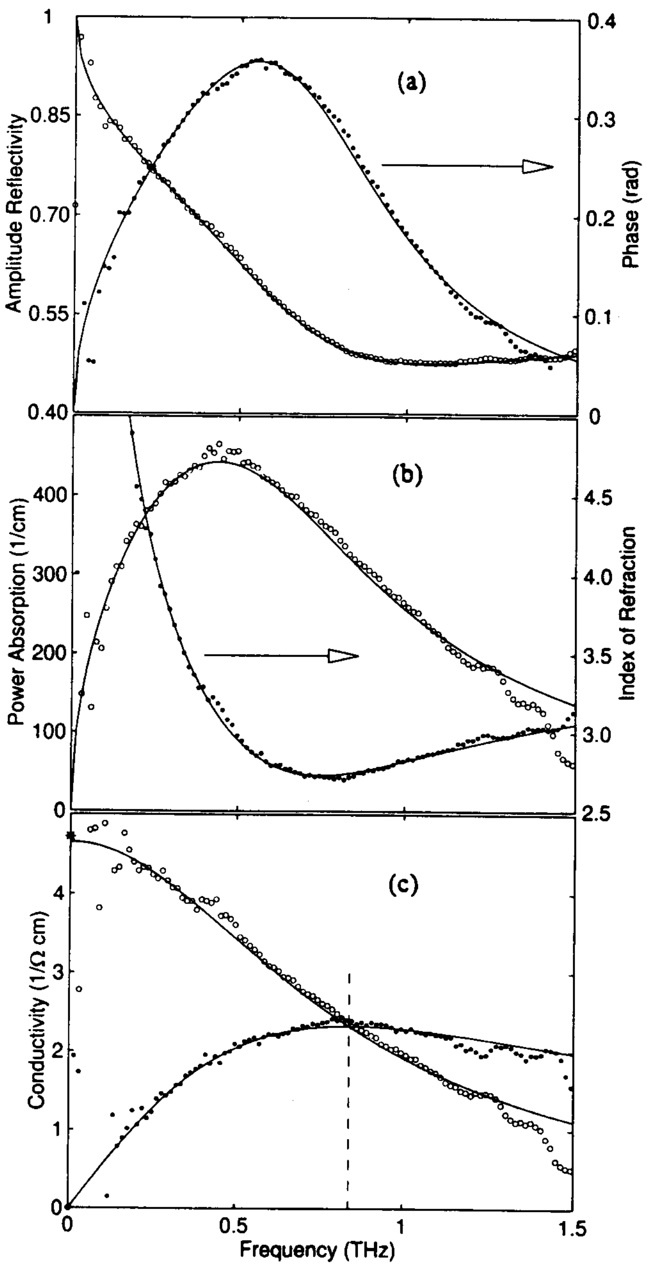

FIG. 3. Reflection THz-TDS measurements of n type, 0.22 Ω cm Si compared with Drude theory (solid line). (a) Amplitude reflection (open circles) and relative phase (dots); (b) power absorption coefficient (open circles) and index of refraction (dots); (c) real part of the conductivity (open circles) and imaginary part of the conductivity (dots). The vertical dashed line indicates Δf, the HWHM of σ_r.

thereby provides a direct measure of the mobility $\mu = e/(m^*\Gamma)$. The carrier damping rate is $\Gamma = 1/\tau$, where τ is the carrier collision time; e is the electron charge, and m^* is the effective mass. For Fig. 2(c), $\Delta f = 1.05$ THz; from this value the corresponding mobility $\mu = 3970\ \mathrm{cm^2/V\,s}$, is obtained. The carrier number density $N = 4.08\times 10^{16}/\mathrm{cm}^3$ is then obtained from the mobility and the extrapolated value of $\sigma_0 = 26.0/(\Omega\ \mathrm{cm})$, as given by $\sigma_0 = eN\mu$. These values are consistent with the previous transmission THz-TDS measurement on a more lightly doped GaAs sample.[2]

A similar measurement for n type, 0.22 Ω cm silicon is shown in Fig. 3. The amplitude reflectivity and relative phase show broad features similar to the GaAs results. However, the magnitudes and details are different; for the silicon sample the knee in the reflectivity curve is absent and the peak in the relative phase occurs below the collision frequency $\Gamma/(2\pi) = 0.84$ THz. The corresponding power absorption and index of refraction are shown in Fig. 3(b), where the shape of the absorption curve is surprisingly similar to that of the phase in Fig. 3(a). The index of refraction shows a strong dependence due to the presence of the carriers, where the maximum measured value of 4.9 and the minimum value of 2.7 differ strongly from the index of intrinsic silicon of 3.42.[6] From our data, and the index of intrinsic silicon (the power absorption is insignificant)[6] we obtain with good S/N the complex conductivity for our silicon sample as shown in Fig. 3(c). The real part of the conductivity provides a good measure of σ_0 as evidenced by the agreement with the four-point probe measurement indicated by the asterisk. From the half-width $\Delta f = 0.84$ THz, we obtain the mobility $\mu = 1280\ \mathrm{cm^2/V\,s}$. From the dc conductivity of $\sigma_0 = 4.65/\Omega$ cm and the mobility, we obtain the carrier number density $N = 2.3\times 10^{16}/\mathrm{cm}^3$. These values are consistent with the expected dependence of μ on N (see Ref. 8), and agree with previous transmission THz-TDS measurements on a series of n-type Si samples.[4]

In summary, we have demonstrated the efficacy of reflection THz-TDS to measure the mobility and carrier number density of optically dense, doped semiconductors. From our numerical fitting process within the Drude theory framework and the scatter of our data, we estimate these parameters were determined to an accuracy of ±5%.

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