Microwave Reflection Measurements on Doped Semiconductors with Picosecond Transient Radiation

W. M. Robertson, G. Arjavalingam, G. V. Kopcsay, and J.-M. Halbout

Abstract—**Broad-band microwave reflection spectroscopy is demonstrated with picosecond transient radiation from optoelectronically pulsed antennas. The validity of the technique is verified by reflection measurements on isotropic and anisotropic dielectrics. Reflection studies on a series of doped silicon samples demonstrate that the carrier dynamics in the 15–140 GHz frequency range are well described by a simple Drude model.**

THE development of microwave techniques based on optoelectronically-generated electromagnetic pulses has permitted experiments in microwave optics and materials characterization with much broader frequency coverage than is possible using traditional microwave methods [1]–[2]. Materials measurements in this frequency range are of particular technological interest to the microelectronics industry because the fastest electrical devices have risetimes on the order of 10 ps and thus possess frequency components out to 100 GHz [3], [4]. Most previous materials measurements using microwave transient spectroscopy have been performed in a transmission configuration and thus were limited to very thin samples or to those with low loss. Reflection spectroscopy, however, has no such limitation. In this letter we present the first measurements of dielectric and conducting material properties obtained using the coherent microwave transient spectroscopy (COMITS) technique in reflection. We first compare the measured reflectivities of insulating materials, whose dielectric constants are well known, to calculations using Fresnel's equation for reflection from a single boundary. We then present the measured reflection spectra of a series of silicon samples ranging from undoped (5000 Ω-cm) to highly doped (0.012 Ω-cm) and show that the carrier dynamics over the 15–140 GHz frequency range are described well by a simple Drude model.

COMITS is based on the radiation and detection of ultrashort electromagnetic transients by optoelectronically pulsed antennas. The radiated transients contain usable frequency components in the range 15–140 GHz. A complete description of the COMITS technique and its application to transmission and reflection measurements is given in [1], [2], and [5]. It is worth noting that the interpretation of data from a reflection experiment requires knowledge of the exact polarization of the incident radiation. For transmission experiments on isotropic samples at normal incidence the polarization state of the microwave radiation is irrelevant. In contrast, reflection from an isotropic sample is markedly different for radiation polarized parallel or perpendicular to the plane of incidence, particularly for reflection near Brewster's angle.

The experimental configuration for reflection measurements is shown in Fig. 1. The transmitting and receiving elements are exponentially tapered coplanar strip antennas photolithographically fabricated on photoconducting silicon-on-sapphire. The dc-biased transmitter is excited and the received signal photoconductively sampled by 1.5 ps optical pulses from a mode-locked pulsed-compressed, and frequency-doubled Nd:YLF laser [2]. The optical pulses are arranged in a pump-probe configuration such that the signal arriving at the receiver is measured as a function of the relative time delay between the pump and probe. As shown in the figure, hemispherical fused silica lenses (diameter 3 cm) are used to collimate the radiation from the transmitter and to refocus the reflected pulse onto the receiver. The transient electromagnetic pulses are linearly polarized with the E-field in the plane of the antenna. In these experiments, the antennas were configured such that the E-field was in the plane of incidence (TM or p-polarized).

The absolute reflectivity of the sample is determined by recording time-domain waveforms first with the sample and then with a gold mirror as the reflecting element. The gold mirror is essentially a perfect reflector at microwave frequencies and provides a reference signal. The two time-domain waveforms are numerically Fourier transformed. The sample spectrum is divided by the reference spectrum to determine the frequency-dependent amplitude reflectivity of the sample. The results of a reflectivity measurement on fused silica are shown as the lower set of points in Fig. 2. Using the Fresnel expression for p-polarized reflection and the dielectric constant of fused silica ($\epsilon = 3.78$), which is well known from transmission measurements, the reflectivity was calculated and is plotted as the lowest dotted line in Fig. 2 [6]. There is good agreement between the calculated and measured values within the experimental resolution, which for amplitude reflection measurements is $\pm 2\%$.

As indicated in the introduction, linearly-polarized radiation is essential for making reflectivity measurements that can be analyzed. A further benefit of a polarized source, both for transmission and reflection experiments, is that measure-

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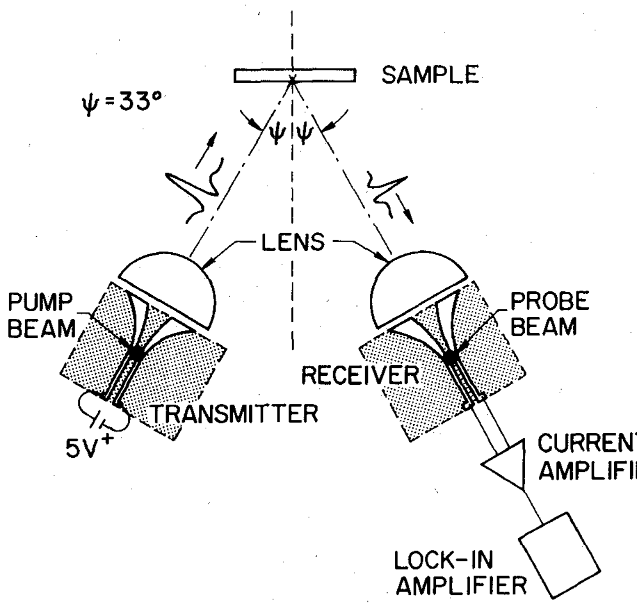

Fig. 1. COMITS configuration for reflection measurements.

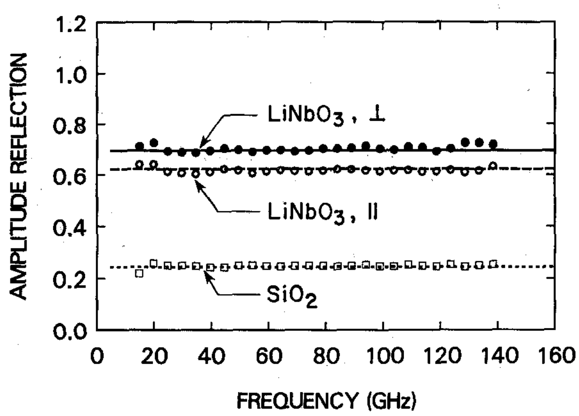

Fig. 2. Measured amplitude reflectivity from fused silica [open squares] and from the orthogonal axes of $LiNbO_3$ [open and filled circles]. Lines are calculated reflectivities using the known dielectric constants and Fresnel's equation.

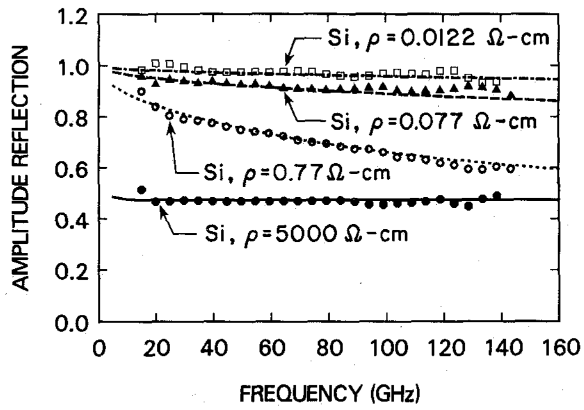

Fig. 3. Amplitude reflection from a series of Si samples of different resistivities as detailed in the figure. Lines are calculated using a simple Drude model for the dielectric constant as described in the text.

ments can be made on anisotropic materials. Reflectivity measurements of the two orthogonal axes of crystalline $LiNbO_3$ are shown as the upper two sets of points in Fig. 2. The measurements were made by aligning the optical axis of the sample either parallel or perpendicular to the plane of reflection. In the latter case, the reflection is determined solely by the ordinary microwave index, whereas in the former, the reflection depends on both the ordinary and the extraordinary microwave indices. The reflection in the perpendicular case is larger, as shown in Fig. 2, because $LiNbO_3$ is a negative uniaxial crystal [7]. Again, the lines, calculated from Fresnel's equation and the known ordinary and extraordinary microwave indices of $LiNbO_3$, agree well with the measured values.

The foregoing results on dielectrics establish the ability of the COMITS technique to make accurate reflection measurements. We now present results of reflection experiments on a series of silicon samples covering the doping range from semi-insulating (5000 Ω-cm) to highly conducting (0.012 Ω-cm). This range of resistivities spans the doping spectrum of silicon (10^{13}–10^{18}) used as substrates in microelectronics fabrication [8]. The higher resistivity (100 Ω-cm–1 Ω-cm) substrates are used in the fabrication of bipolar transistors, whereas CMOS circuits are made with more conducting (1 Ω-cm–0.01 Ω-cm) wafers. Although transmission experiments are possible for moderately doped samples [9], the loss introduced by free carriers in heavily doped semiconductors makes transmission measurements either very difficult or impossible. In contrast, using reflection spectroscopy it is possible to characterize samples over the entire doping range.

Float-zone and Czochralski grown silicon samples were cut from boules into circular disks 10 cm in diameter and 0.7 cm thick, and the reflecting surfaces were polished to a mirror finish. The results of the reflection measurements are plotted as points in Fig. 3. The high resistivity sample behaves as a low loss dielectric (lowest curve in Fig. 3) with a reflection spectrum that is constant over the entire frequency range. With Si of progressively higher doping, the reflected amplitude increases and exhibits dispersion over the 15 GHz–140 GHz frequency range due to the increased importance of free carriers in the reflection process. To describe the effect of free carriers on the dielectric function, a simple Drude model [10] was used:

$$\epsilon(\omega) = \epsilon_\infty + \frac{i\sigma_{dc}}{\omega\epsilon_o(1 - i\omega\tau)}, \tag{1}$$

where $\epsilon(\omega)$ is the frequency dependent dielectric constant, ω the frequency, ϵ_0 the permittivity of free space, and τ the carrier scattering time. The dc-conductivity, σ_{dc}, is given by

$$\sigma_{dc} = \frac{ne^2\tau}{m}, \tag{2}$$

where m is the effective carrier mass, e the electronic charge, and n the number density of carriers. Because the carrier scattering times are of the order of a picosecond or less, the product $\omega\tau$ in (1) is much less than 1 in the frequency range of our measurements and does not produce observable effects. With the measured values for σ_{dc}, (1) was used to determine $\epsilon(\omega)$. The reflectivity was then calculated from Fresnel's equation and is plotted as lines in Fig. 3.

Clearly, at room temperature and over the 15-140 GHz frequency range, there is excellent agreement between the measured and theoretical spectra.

In conclusion, we have demonstrated the capability of performing broad-band microwave reflection measurements on dielectric and semiconductor materials using the technique of coherent microwave transient spectroscopy. COMITS is particularly suited to reflection studies because the transient radiation emitted by the planar antenna structures is strongly linearly polarized. The reflection spectra of isotropic and anisotropic dielectrics and a series of doped silicon samples covering a wide range of resistivities were presented. In all cases, good agreement was found between measured data and theoretical predictions.

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