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THz Probe Studies of MBE Grown Epitaxial GaAs

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Abstract. We have built a THz time-domain spectrometer driven by a sub-15fs pulse duration mode-locked Ti:Al_2O_3 laser. Using THz time-domain spectroscopy with photoconductive antenna for THz generation and electro-optic sampling for detection as well as photoexcited THz spectroscopy, we measured the carrier concentrations and mobilities of epitaxially grown undoped GaAs samples to be used in photoconductive antenna production. The samples were grown at 600 ^{o}C to 1 μm effective layer thickness on top of a 650 μm SI-GaAs wafer. The resistivities, mobilities and the carrier concentrations were measured and calculated by the van der Pauw method under the magnetic field. These Hall effect measurements and the THz probe studies were compared with each other. The measurements and calculations obtained electronically are compared optically using the Drude Model for the conductivity and mobility.

1. Introduction

One of the major applications of THz time-domain spectroscopy (THz-TDS) is in material characterization. THz spectroscopy has been used to determine ultrafast carrier dynamics of doped semiconductors such as GaAs and silicon wafers.[1 2, 3, 4] An important focus is on the measurement of the dielectric constant of thin films[6]. Epitaxially grown GaAs films using MBE methods have attracted much attraction due to their projected use in the infrared detection systems.

In this study, we have demonstrated the efficiency of THz-TDS to measure the electron and hole mobilities and the carrier number densities of MBE grown GaAs. From the photoexcitation measurements, we found that the photoexcitation increases the conductivity of the GaAs samples in addition to changes in the refractive index. This paper is organized as follows: In section 2, we describe the experimental setups and procedure as well as the data collected by the Hall effect and THz spectroscopy measurements. In the section 3, we present the analysis of data, and the critical parameters of the epitaxial grown GaAs. In the section 4, the results are discussed.

2. Experiment

The epitaxial nominally undoped GaAs samples were grown at 600 ^{o}C to a 1 μm effective layer thickness on top of a 650 μm thick SI-GaAs wafer. The resistivity measurements were done by the van der Pauw technique along with the standard Hall Effect measurements[5, 6] to determine mobilities and the carrier concentrations. To obtain accurate data, very small (less than 1 mm^2) AuGe Ohmic contacts were devised at the corners of the square shaped (1.4 cm x 1.4 cm) GaAs sample. The resistivity, conductivity, Hall coefficient, charge carrier concentration, and mobility of the p-type GaAs samples were calculated to be 10.4 Ω.cm, 0.096 $\Omega.cm^{-1}$, 5800 $cm^3.C^{-1}$, $1.1x10^{15}$ cm^{-3}, and 550 $cm^2.V^{-1}.s^{-1}$ respectively.

The THz spectroscopy techniques, on the other hand, provide noncontact measurements with subpicosecond temporal resolution as an alternative method in the field of solid state electronics where it is difficult to use traditional probes. This makes THz spectroscopy an ideal tool for measuring the conductivities and obtaining data on charge carrier dynamics without use of electrical contacts.

THz-TDS is driven by a mode-locked $Ti:Al_2O_3$ laser with a center wavelength of λ = 800 nm and a pulse duration of τ = 15 fs at a repetition rate of 75 MHz. 180 mW of the average beam power is split into two optical lines, where 36 mW is fed through to a LT-GaAs based photoconductive antenna (PCA) with a dipole gap of 6 µm is used for generation. The antenna bias was AC modulated at 2.5 kHz with V_{p-p} = 10 V. For the detection of the THz beam, the electro-optic method is performed by use of a 2 mm thick <110> oriented ZnTe crystal, a quarter wave-plate, Wollaston prism (WP) and a balanced photodetector. The amplitude and phase of the signal was detected with the aid of a digital dual channel lock-in amplifier (Model SR830 DSP). The photoexcited measurements were made with the aid of 750 mW continuous laser at 808 nm pump wavelength. The sample was placed at 45° to the THz and probe beam. The THz beam was focused on the sample by using 10 cm focal length TPX lenses. The system shown is Figure 1.

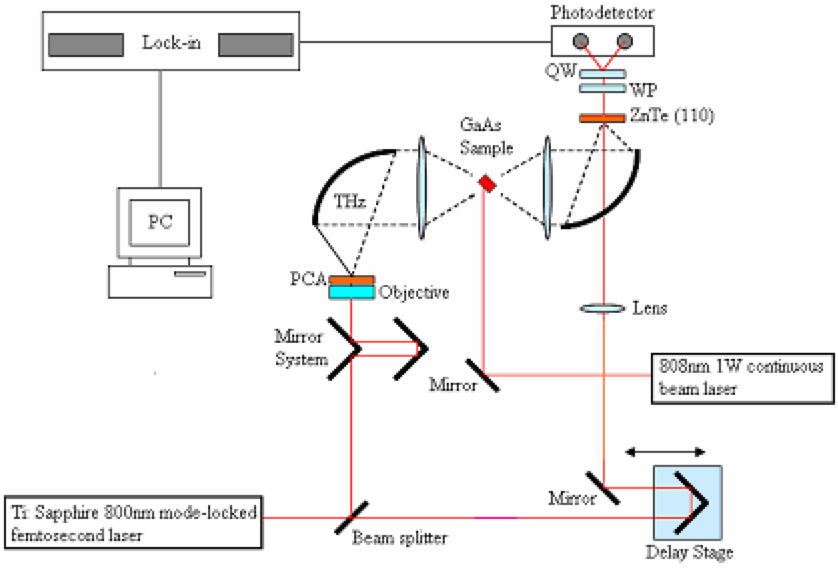

Figure 1: THz spectroscopy system for the probe measurements

The typical THz waveforms measured on the GaAs sample as well as photoexcited data is shown in Figure 2.

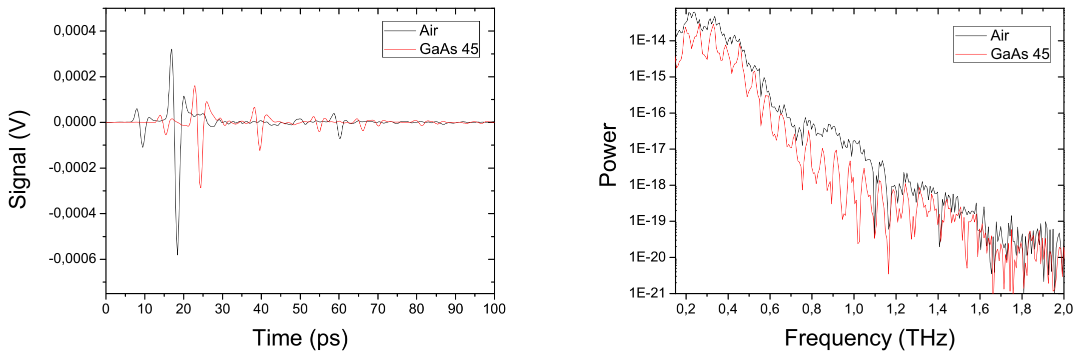

Figure 2a: THz-TDS scan and FFT of the direct spectroscopy of GaAs compared with air.

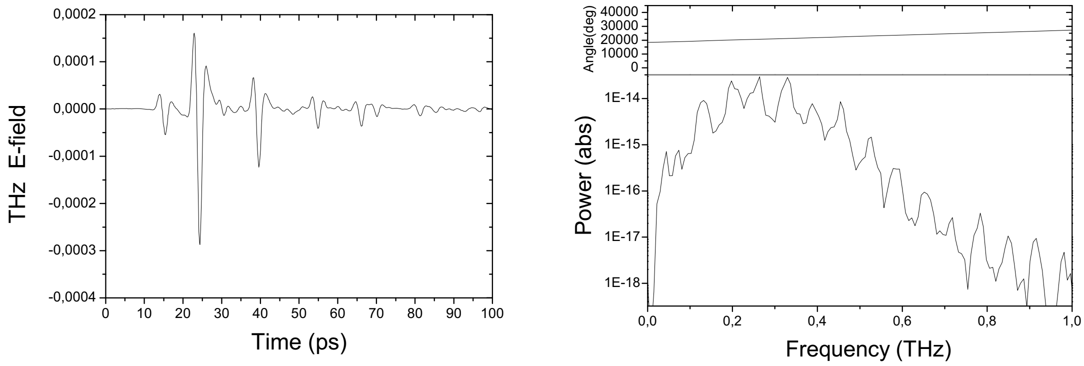

Figure 2b: THz-TDS of Time-Domain scan and FFT of the photoexcited spectroscopy

3. Analysis

Using the experimental data, the real (n_r) and complex (n_ι) components of the refractive index can be calculated by

$$n_r = \frac{1}{kl}\left(\varphi(\omega,l) - \varphi(\omega)\right) \text{ and } n_\iota = \frac{1}{kl}\left(\ln\left(\frac{E(\omega,l)}{E(\omega)}\right)\right)$$

where k is the wave number, l is the thickness of the sample. The results of these calculations are shown in Figure 3.

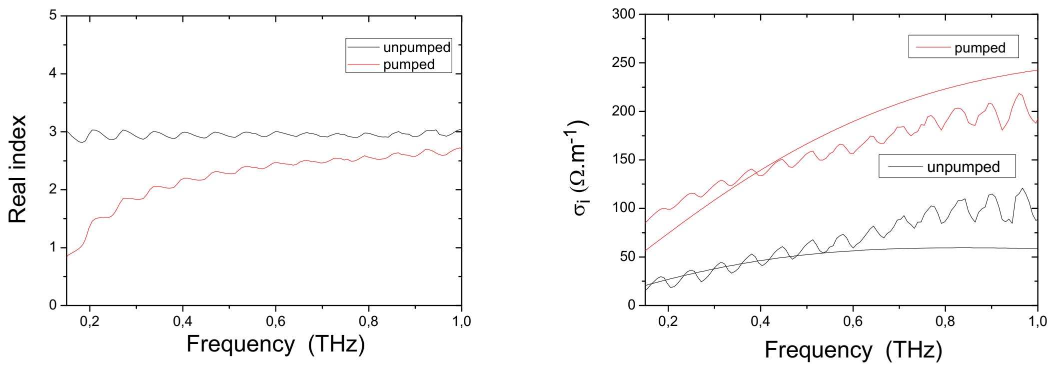

Figure 3a (left): The real part of the refractive index obtained by direct and photoexcited THz spectroscopy
Figure 3b (right): The conductivities obtained by direct and photoexcited THz spectroscopy with their Drude fits

The absorption coefficient of the sample can be obtained as $\alpha = \frac{1}{l}\left(\ln\left(\frac{I}{I_0}\right)\right)$ where I is the intensity after transmission and I_0 is the intensity without sample. The complex absorption spectrum is obtained by the Fourier analysis and the imaginary index can be extracted by $\alpha = \frac{2n_i\omega}{c}$.

Any of the above parameters can be obtained experimentally, however, the other carrier dynamics, such as conductivity and mobility can be extracted from an appropriate conduction model. In order to calculate the conductivity and the mobility, the Drude model for electrical conductivity is appropriate to use in which the charge carriers can move freely, although their motion is subject to damping with time constant τ . From the experimental values, the imaginary and real components of conductivity are calculated by $\sigma_i = \varepsilon_0\omega\left(\varepsilon_{dc} - n_r^2 + n_i^2\right)$ and $\sigma_r = 2n_r n_i \omega\varepsilon_0$. The extracted values for the mobility and carrier density are obtained by a fit to the experimental data shown in Figure 3 where the imaginary conductivity is determined by

$$\sigma_i = \frac{\varepsilon_0\omega\omega_p^2}{\omega^2 + \langle\tau\rangle^{-2}}.$$

In this equation, $1/\tau = \nu_c$ is the collision frequency $\omega_p = \left(\frac{Ne^2}{m\varepsilon_0}\right)^{1/2}$ is the plasma frequency, N is the number density, e is the charge of the free carriers, m is the mass of the free carriers. From this model, the Drude parameters for direct THz spectroscopy are calculated to be N = $1.0\text{x}10^{16}$ cm^{-3}, $\nu_C = 5.26\text{x}10^{12}$ s^{-1} where m = 0.45 m_0 [7] and for the photoexcited THz spectroscopy N = $1.0\text{x}10^{16}$ cm^{-3}, $\nu_C = 8.33\text{x}10^{13}$ s^{-1} where m= 0.067 m_0.

Therefore, using $\mu = \frac{e}{m\nu_c}$, the calculated the mobility values of the GaAs sample from the direct and photo excitation measurements are 740 cm^2 V^{-1} s^{-1} and 3150 cm^2 V^{-1} s^{-1} respectively.

4. Conclusion:

We have demonstrated that linear and photoexcited THz-TDS measurements give an estimate of the carrier densities and both the hole and electron mobility values with good precision. Here we assumed single layer transmission in our calculations, inclusion of multilayer transmissions can improve the accuracy of the results. While Hall effect and van der Pauw measurements are more accurate, THz-TDS coupled with photoexcitation allows for measurement of electron mobilities of p-type samples.

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