# Non-contact Carrier Density Measurement of Semiconductor Wafers by Terahertz Spectroscopic Ellipsometry

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***Abstract*—We developed a terahertz ellipsometry system that can measure the complex dielectric characteristics of doped semiconductors and evaluate the carrier density and mobility in a non-destructive, non-contact way. The system is constructed of optical-fiber pigtail-coupled terahertz emitter and detector, and delivers high measurement precision and stability. We demonstrated carrier-density measurement of n-type GaAs wafer and n-type SiC epitaxial film using this system, and confirmed a good agreement with conventional measurement methods.**

## I. INTRODUCTION

THE market for power semiconductors that offer better electrical conversion efficiencies has been growing. Wide-gap semiconductors such as GaN and SiC, which have more than 10 times higher breakdown voltage as compared to Si, are expected to be used as materials in next-generation power semiconductors. Accurately measuring the values of electronic properties that affect device properties (carrier density, mobility, etc.) is essential. The Hall measurement method is a destructive testing method that requires preprocessing such as forming electrodes on the samples. However, the need for fast in-process testing has been growing in concert with mass production of power semiconductors, and there has been demand for the development of non-destructive, non-contact, high-precision property evaluation systems. Terahertz technology has attracted attention as an effective means of evaluating these properties.

Since the plasma frequency in doped semiconductor depends on the carrier density and is near the terahertz (THz) band, research has been conducted on evaluating properties such as dielectric function by using THz time-domain spectroscopy. The complex dielectric constant of semiconductors can be expressed using the Drude model, and the carrier density and mobility can then be evaluated by analyzing this. Previously, complex property evaluation using transmission or reflection measurement via THz time-domain spectroscopy required reference measurements obtained using through or mirror, and needed advanced measurement experience, such as requiring that the reference measurement surface was set correctly. To improve this situation, we developed a high-precision property evaluation system by constructing a system that uses a THz emitter and detector with optical-fiber pigtail couplings. The system offers stable measurement by employing reflective THz ellipsometric spectroscopy [1], does not need a reference measurement, and is easy to perform. We report on carrier-density measurements using this THz ellipsometry system, examining n-type GaAs wafer and n-type SiC epitaxial film grown on SiC substrate.

## II. EXPERIMENTS

Figure 1 shows the optical system of the THz ellipsometry system. The THz waves output from the THz emitter are polarized to a 45° linear polarization using a wire grid (WG) polarizer, and are incident upon the sample at an incident angle of 70°. The THz waves reflected from the sample are split into p or s polarization components by a WG polarizer placed in front of the THz emitter, and the amplitude and phase data for each of the polarization components are obtained. Carrier density and mobility are evaluated by performing a model analysis of the obtained data. The THz optical sampling analysis system TAS7500TS (emitter TAS1110 and detector TAS1230) is employed for THz-wave emission, detection, and data acquisition [2]. Since the THz emitter and detector are built into optical-fiber pigtail modules, adjustment of the optical axis is not necessary, and the system is suitable for ellipsometric measurement with various incident angles. Furthermore, since the standard measurement throughput is 8 ms/scan and data can be acquired in a few seconds, even when integration is performed, it offers stable THz spectroscopic measurement that is robust to changes in the ambient environment.

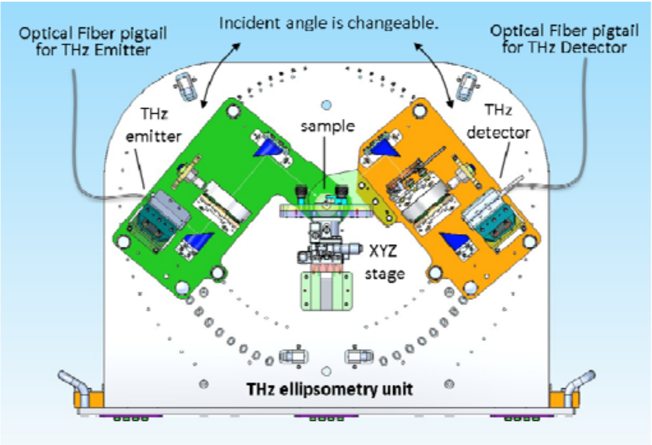

Fig. 1 An optical system of the THz ellipsometry system

Two measurement samples were selected according to differences in the optical model, which depend on the presence or absence of multiple reflections within the thin film: n-type GaAs wafer, which does not produce multiple reflection paths, and n-type SiC epitaxial film, for which multiple reflection paths are a consideration. Since multiple reflection paths have an effect in thin films down to a film thickness of $5d_p$, where $d_p$ is the penetration depth of the THz waves into the thin film, the effect of the underlying substrate needs to be taken into account in the data analysis [3].

## III. RESULTS

First, we report on the carrier-density measurement of n-type GaAs wafer. The external dimensions of the sample were 50 mm in diameter and 150 µm in thickness, and the sample was doped with Si. The values of carrier density and mobility, as found through Hall measurement, were 2 × $10^{18}$ $cm^{-3}$ and 1870 $cm^2V^{-1}s^{-1}$, respectively. Figure 2 shows the amplitude reflection coefficient ratio $\tan\psi(\omega)=|r_p/r_s|$ and phase difference $\Delta(\omega)=\delta_p-\delta_s$, as obtained by measuring this sample using ellipsometric spectroscopy, where $r_p=|r_p|\exp(i\delta_p)$ and $r_s=|r_s|\exp(i\delta_s)$ are the complex amplitude refection coefficients for the p and s polarizations of the THz wave, respectively. Figure 3 shows the complex dielectric constant $\varepsilon=\varepsilon_1-i\varepsilon_2$ as calculated by applying these to the analysis model without multiple reflections [4]. Figure 3 also shows the results of fitting analysis to the Drude model, taking the carrier density and scattering time as variables, as a dashed line. In the analysis, we used a high-frequency dielectric constant $\varepsilon_\infty$ = 13.2 and effective mass $m^*$ = $0.079m_0$, where $m_0$ is the free electron mass. As a result of the analysis, we obtained a carrier density of 1.97 × $10^{18}$ $cm^{-3}$ and a mobility of 1379 $cm^2V^{-1}s^{-1}$. These are good agreement with the Hall measurement values.

Next, we report on carrier-density measurement of n-type SiC epitaxial film. The external dimensions of the sample were 76.2 mm in diameter and 280 µm in thickness. A 6.2 µm film was grown homo-epitaxially on n-type 4H-SiC substrate, and the carrier density as measured by mercury probe CV/IV measurement was 3.2 × $10^{18}$ $cm^{-3}$. During the measurement, the complex refractive index N=n-iκ of SiC substrate was obtained by ellipsometric measurement of the substrate, as shown in Fig. 4. Next, ellipsometric measurement of the SiC epitaxial film was performed and the amplitude reflection coefficient ratio $\tan\psi(\omega)$ and phase difference $\Delta(\omega)$ were obtained. The results are shown in Fig. 5. The inflection point that can be seen near 3 THz arises due to multiple reflections inside the epitaxial film. The results of analysis by fitting this data with the model, which considers multiple reflection paths, are shown by dashed lines in Fig. 5. The values obtained in the analysis were carrier density of 3.4 × $10^{18}$ $cm^{-3}$, mobility of 277 $cm^2V^{-1}s^{-1}$, and film thickness of 5 µm. These results are good agreement with the measurement results from CV/IV measurement and optical thickness meter.

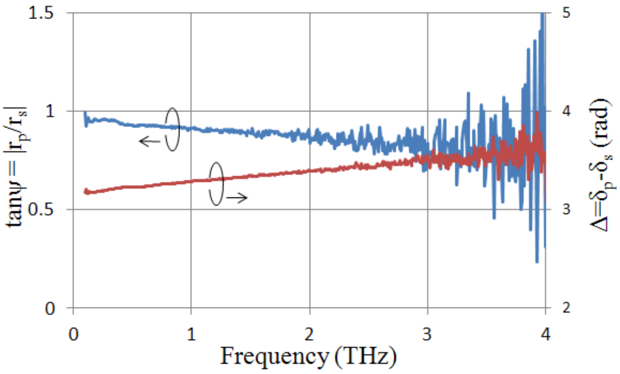

Fig. 2 Complex amplitude reflection coefficient ratio $\rho=\tan\psi\exp(i\Delta)$ of n-type GaAs wafer

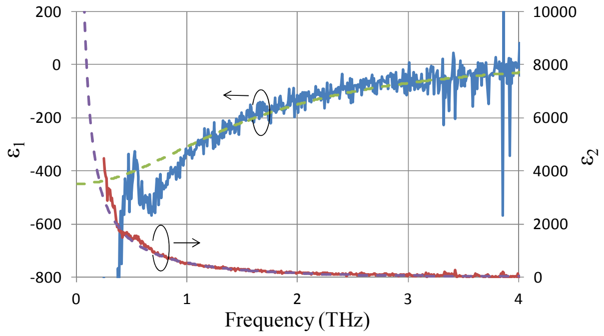

Fig. 3 Complex dielectric constant $\varepsilon=\varepsilon_1-i\varepsilon_2$ of n-type GaAs wafer

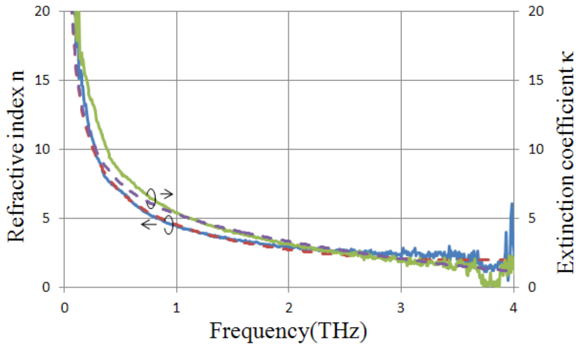

Fig. 4 Complex refractive index N=n-iκ of n-type 4H-SiC substrate

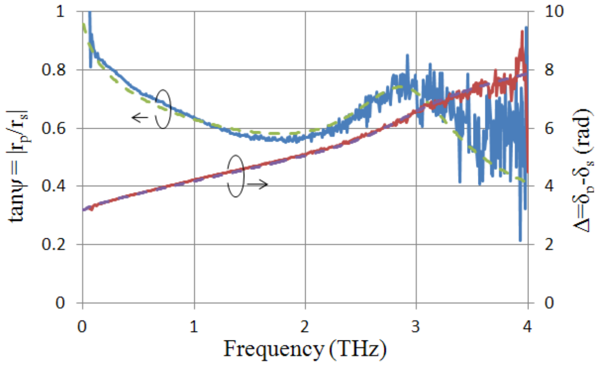

Fig. 5 Complex amplitude reflection coefficient ratio $\rho=\tan\psi\exp(i\Delta)$ of n-type SiC epitaxial film

## IV. SUMMARY

We demonstrated carrier-density measurement of n-type GaAs wafer and n-type SiC epitaxial film on SiC substrate, using a THz ellipsometry system that we developed, and obtained a good agreement with conventional measurement methods. Since this system is able to perform electronic property evaluation of semiconductor materials in a rapid, non-destructive, and non-contact way, it is expected to find applications in process management and inspection processes.

## REFERENCES

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