Estimation of Carrier Density of Wide Bandgap Semiconductor β-Ga_2O_3 Single Crystals by THz Reflectance Measurement

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***Abstract*—In order to estimate carrier density on wide bandgap semiconductor β-Ga_2O_3, we made a measurement of THz reflectance spectra of β-Ga_2O_3 samples by using a THz time-domain spectroscopic method. The tails of reflectance structures were shifted to higher energy side with increasing the carrier density. We treated the structure was caused by plasmon, and calculated the carrier density of each samples. The carrier densities obtained by the THz reflection measurements showed a good agreement with the results by Hall-effect measurements. These results indicated that THz spectroscopy is a useful method to estimate the carrier density of β-Ga_2O_3 samples.**

I. INTRODUCTION

THz spectroscopy is a powerful tool for solids, because many fundamental excitations in the solids such as phonon, plasmon, and so on, are lying in the THz frequency region. In particularly, THz time-domain spectroscopy (THz-TDS) has an advantage over other spectroscopies since spectra can be measured without any coolant for detection and optical constants of materials obtained without any assumption. [1-3]

These days, wide-bandgap semiconductors, such as SiC and GaN devices have been intensively developed to deliver the higher breakdown voltage and lower loss than those of Si devices for the energy-saving technology. From the viewpoint of the material properties, β-Ga_2O_3 can be a strong contender for the power electronic devices in the near suture.[4, 5]

In this report, we applied THz-TDS method to intentionally-doped β-Ga_2O_3 single crystals to estimate the carrier density and compared the value obtained by Hall-effect measurements.

II. EXPERIMENTAL

All the measurements in this report were carried out at room temperature. In order to avoid the absorption of THz radiation by water vapor, the transmittance measurements were done in the vacuum condition and reflectance measurements in the dried air atmosphere, respectively. Single-crystal β-Ga_2O_3 bulk substrates were synthesized by the melt-growth methods. Surfaces of samples for THz measeurements were polished by chemical mechanical methods. Carrier densities of samples were determined by Hall-effect measurements.

III. RESULTS

Figure 1 shows the waveforms of the THz radiation transmitted through Fe-doped well-compensated, semi-insulating β-Ga_2O_3 sample (thickness = 0.6mm) and reference. From analysis of these data, we obtained the complex refractive index, n and k of β-Ga_2O_3 single crystal in THz frequency region, ~3.4 and ~0.05, respectively. Figure 2 shows THz reflectance spectra of single-crystal β-Ga_2O_3 samples with various carrier densities.

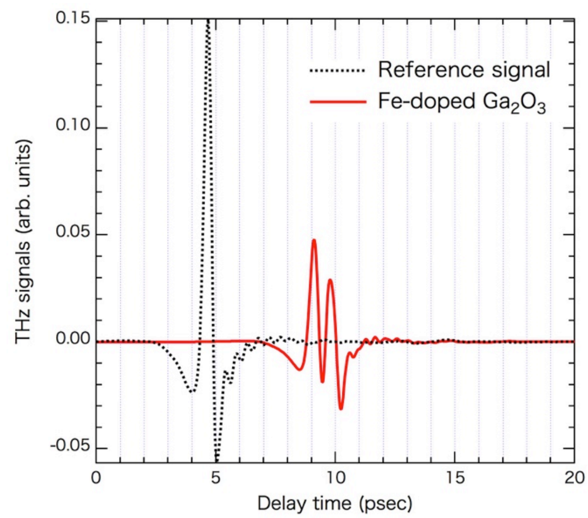

Fig. 1. Waveforms of the THz radiation transmitted through Fe-doped well-compensated, semi-insulating β-Ga_2O_3 bulk substrate and reference.

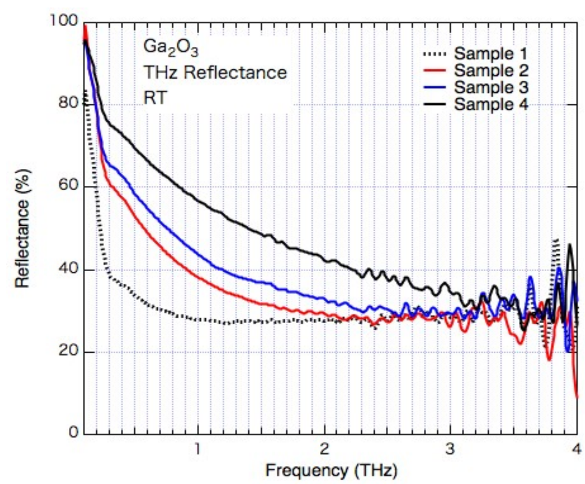

Fig. 2. THz reflectance spectra of single-crystal β-Ga_2O_3 samples with different carrier densities. The carrier density of the samples were estimated to be 7×10^{16} ~ $1\times10^{18}cm^{-3}$ by Hall-effect measurements.

The carrier densities of samples were ranging from 7×10^{16} to 1×10^{18} cm^{-3}. In the reflectance spectra, the tails of the structure were shifted to the higher energy side with increasing a carrier density of the samples. We considered that the reflection structure was affected by plasmon. The plasma frequency, ω_p, in the Drude term is given by

$$\omega_p = \left(\frac{e^2 d}{m^* \varepsilon}\right)^{1/2},$$

where e, d, m^*, and ε are the electron charge, carrier density, carrier effective mass, and dielectric constant, respectively. We calculated the plasma frequency of β-Ga_2O_3 as function of carrier density, using the effective mass parameter, $m^*=0.28m_e$ reported in the literatures [6-8] and the background dielectric constant, $\varepsilon = 11.6$, obtained from the complex refractive index from our results mentioned above.

Figure 3 shows the plasma frequency as a function of carrier density and the experimental results. Red line represents the calculated plasma frequency as a function of carrier density of β-Ga_2O_3 and blue dots the edge frequencies of THz reflectance spectra of β-Ga_2O_3 plotted with the carrier densities obtained from Hall measurements.

In the case of β-Ga_2O_3 single crystals, the carrier densities obtained from the THz reflectance measurements agree with the values of determined from Hall-effect measurements. Therefore, THz reflectance measurement is a convenient method to characterize the carrier density without electrical contacts. Our results have demonstrated the capability of obtaining the carrier density in β-Ga_2O_3 substrate using THz reflectance measurement.

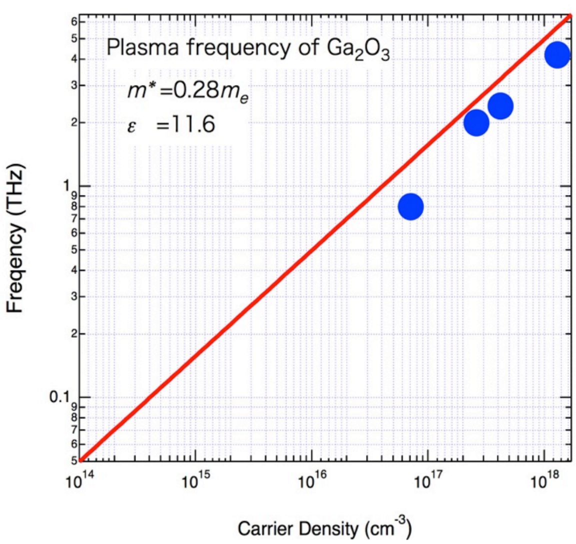

Fig. 3. Comparison of calculated plasma frequency as a function of carrier density and the value obtained from the reflectance and Hall-effect measurements. Red line represents the calculated plasma frequency and blue dots the edge frequencies of THz reflectance spectra plotted with the carrier densities obtained from Hall-effect measurements.

IV. SUMMARY

THz reflectance spectra measurements were performed for β-Ga_2O_3 single crystals with various carrier densities at room temperature by using a THz time domain spectroscopic method. The reflectance spectra were analyzed as structure caused by plasmon, and we estimated the carrier densities based on them. The results were consistent with the values by Hall-effect measurements, indicating that THz spectroscopy is useful tool for estimation of carrier density in β-Ga_2O_3 samples, which can be done without any damage on the sample.

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