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Simultaneous Determination of the Carrier Concentration, Mobility and Thickness of SiC Homo-Epilayers Using Terahertz Reflectance Spectroscopy

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Abstract. We have simultaneously determined the carrier concentration, mobility, and thickness of 4H-SiC homo-epilayers with carrier concentration of 10^{16}–10^{18} cm^{-3} from reflectance spectroscopy in the wavenumber range of 20–2000 cm^{-1}. The spectra at 20–100 cm^{-1} and at 80–2000 cm^{-1} were measured by using the terahertz time domain spectrometer (THz-TDS) and the Fourier-transform infrared (FTIR) spectrometer, respectively. A modified classical dielectric function (MDF) model was employed for the curve fitting. We have compared the values of free carrier concentrations estimated from the reflectance spectroscopy with the net doping concentrations obtained from *C*–*V* measurements, and have discussed the validity of the electrical properties estimated from the reflectance spectroscopy.

Introduction

SiC homo-epilayers are used for the fabrication of SiC electronic devices in general. Hence, the electrical properties of the epilayers as well as the thickness are required to be monitored in the device fabrication processes. In order to characterize the electrical properties of semiconductors, electrical measurement techniques, such as Hall effect measurements and capacitance-voltage (*C*–*V*) measurements, have been widely used. For the device process monitoring, however, Hall effect measurements cannot be used because they require the formation of electrodes on samples, and *C*–*V* measurements can determine only a net doping concentration and give no information for mobility. In contrast, as a nondestructive and contactless method, we have proposed the method for the simultaneous determination of the free carrier concentration, mobility, and thickness of SiC epilayers grown on SiC substrates from infrared reflectance spectroscopy using Fourier-transform infrared (FTIR) spectrometers in the range of 80–2000 cm^{-1} [1]. We have compared the electrical properties derived from the infrared reflectance analyses with those from Hall effect measurements for *n*-type epilayers grown on *p*-type substrates, and with those from *C*–*V* measurements for *n*-type epilayers on *n*-type substrates, and have found good agreement with each value. We have also found that the thickness of epilayers estimated from infrared reflectance is in good agreement with that from scanning electron microscope (SEM) observation of the cleaved facet of the samples. From these results, we have confirmed the validity of the values of the carrier concentration, mobility and epilayer thickness estimated from infrared reflectance spectra. However, it was difficult to estimate the electrical properties of homo-epilayers with carrier concentrations less than 1×10^{17} cm^{-3} without IR reflectance spectra less than 80 cm^{-1} in wavenumber.

In this work, we have extended the spectral range of the reflectance measurements down to 20 cm^{-1} (0.6 THz) by using terahertz reflectance spectroscopy to be able to apply the method for epilayers with the carrier concentrations in the range of 10^{16} cm^{-3}. Also we have compared the free carrier concentrations estimated from reflectance measurements with the net doping concentrations obtained from *C*–*V* measurements to discuss the validity of this characterization method.

Experiments

Samples used in this study were nitrogen doped *n*-type 4H-SiC epilayers grown on *n*-type 4H-SiC substrates by chemical vapor deposition (CVD). The details of the epilayer growth have been described elsewhere [2]. The net doping concentration ($N_D - N_A$) of the epilayers was in the range between 5×10^{16} and 1×10^{18} cm^{-3}, and that of the substrates was typically 5×10^{18} cm^{-3}. The thickness of the epilayers was 6–7 μm, measured by SEM observation. *C*–*V* measurements were performed using gold electrodes evaporated on the samples as Schottky contacts.

The reflectance spectra were measured at room temperature for the spectral region of 20–100 cm^{-1}, 80–600 cm^{-1} and 540–2000 cm^{-1} using terahertz time-domain spectroscopy (THz-TDS) (*Aispec*: pulse IRS 1000/2000), FTIR spectrometers (*JASCO*: IR-VM7) and (*JASCO*: Irtron IRT-30), respectively.

The optical constants used for the calculation of the reflectance spectrum of SiC in the infrared region were derived from a modified classical dielectric function (MDF) model [3] as,

$$\varepsilon(\omega) = \varepsilon_\infty \left(\frac{\omega_L^2 - \omega^2 - i\Gamma_L \omega}{\omega_T^2 - \omega^2 - i\Gamma_T \omega} - \frac{\omega_p^2}{\omega^2 + i\gamma_p \omega} \right), \tag{1}$$

where ε_∞ is the high frequency dielectric constant, ω_T and ω_L are TO and LO phonon frequency, Γ_T and Γ_L are the TO and LO phonon damping constants, respectively. The first term in eq. (1) is the contribution from the lattice vibration, where the contributions from the TO-phonon damping constant and the LO-phonon damping constant are independent from each other. The second term in the equation is that from the plasma oscillation of free carriers. We fitted the calculated spectrum to the measured one by adjusting the values of ω_p, γ_p, Γ_T and Γ_L of the epilayer and those of the substrate, and the epilayer thickness *d*. From these values, we have derived the carrier concentration *N* and mobility μ of the epilayer and substrate. We adopted the values ε_∞=6.56, ω_T=798cm^{-1}, ω_L=970cm^{-1}, and $m^*_{M\Gamma}=0.58m_0$, $m^*_{MK}=0.31m_0$, obtained from the Raman scattering measurements [4] and optical detection of cyclotron resonance (ODCR) [5], respectively.

Results and Discussion

We have estimated the values of carrier concentration and mobility for the samples of *n*-type epilayers on *n*-type substrates from the infrared reflectance spectra measured. Fig. 1 shows the measured and calculated reflectance spectra of the epilayer with a net doping concentration around 5×10^{16} cm^{-3} at room temperature. As shown in the figure, the reflectance spectrum measured by THz reflectance spectroscopy is well connected with that measured by IR reflectance spectroscopy at around 100 cm^{-1}, and we obtained a good fit between the measured and the calculated spectrum. From the values of fitting parameters, the values $N_{epi} = 3.2\times10^{16}$ cm^{-3}, $\mu_{epi} = 562$ $cm^2/(V\cdot s)$ and $d = 6.14$ μm, and $N_{sub} = 6.8\times10^{18}$ cm^{-3}, $\mu_{sub} = 63$ $cm^2/(V\cdot s)$ were obtained.

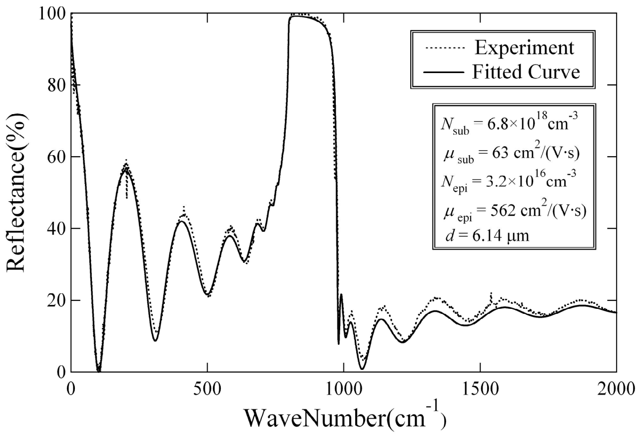

Fig. 1. Measured and calculated reflectance spectra of the *n*-type epilayer on *n*-type substrate at room temperature.

In Fig. 2, the free carrier concentrations estimated from the infrared reflectance spectra are plotted against the net doping concentrations $N_D - N_A$ derived from *C–V* measurements. We have calculated the free carrier concentrations *n* from the net doping concentrations using the following equations,

$$n(T) + N_A = \frac{N(h)}{1 + \{gn(T)/N_c\}\exp[\Delta E(h)/k_B T]} + \frac{N(k)}{1 + \{gn(T)/N_c\}\exp[\Delta E(k)/k_B T]}, \qquad (2)$$

$$N_c = 2M_c\left(\frac{m^*_{d.s.}k_B T}{2\pi\hbar^2}\right), \qquad (3)$$

where k_B is the Boltzmann constant, *T* is the temperature, N_A is the concentration of acceptors, and $N(h)$ and $N(k)$ are the concentrations of the nitrogen atoms occupied at hexagonal and cubic lattice sites, respectively. Since the number of hexagonal sites are equal to those of cubic sites for 4H-SiC, the donor concentration N_D is given by $N(h) + N(k)$. The values of $\Delta E(h)$ and $\Delta E(k)$ are the ionization energies of the nitrogen donor at hexagonal and cubic lattice sites, respectively, and $g = 2$ is the spin degeneracy factor. Equation (3) gives the effective density of states, where $M_c = 3$ is the number of equivalent conduction band minima, and $m^*_{d.s.}$ is the density of states effective mass. The values of $\Delta E(h)$ and $\Delta E(k)$ were set as 50 meV and 100 meV, respectively. The values of $m^*_{M\Gamma} = 0.58m_0$, $m^*_{MK} = 0.31m_0$, $m^*_{ML} = 0.33m_0$ derived from ODCR measurements [5] were adopted. The solid line in Fig. 2 shows the free carrier concentrations calculated as a function of net doping concentration in the case of $N_A / N_D = 0$ or $N_D / (N_A + N_D) = 1$ because the epilayers we measured are hardly carrier-compensated [6]. The values obtained from the reflectance spectra were in fairly good agreement with the solid line, suggesting the validity of the values of the carrier concentrations estimated from infrared reflectance spectra. However, a careful look confirms that the values of carrier concentration derived from the reflectance measurements are slightly lower than those estimated from the electrical measurements. The same tendency was observed in the comparisons with the Hall effect measurements for the samples of n-type epilayers on p-type substrates [1]. This tendency is considered to be partly because of the adoption of inappropriate effective mass values for the calculation of reflectance spectra. It is also considered as a cause that the part of free carriers trapped in the defects or bounded by dopants cannot follow in the THz frequency range used for the reflectance measurements.

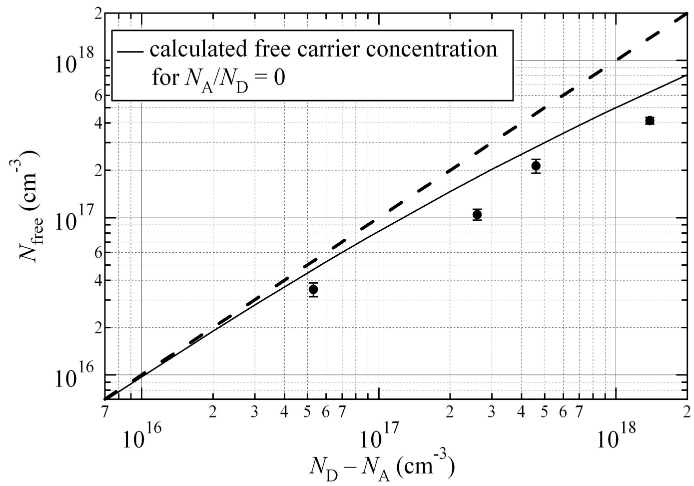

Fig. 2. The carrier concentration estimated from the reflectance spectra as a function of doping concentration obtained from *C-V* measurements.

Summary

We have proposed the method for the simultaneous determination of the carrier concentration, mobility and thickness of SiC homo-epilayers using infrared and THz reflectance spectroscopy. We estimated the carrier concentration and mobility by the curve fitting with the spectra calculated using the MDF model. These values obtained were compared with those obtained from *C–V* measurements. Through these comparisons, we have shown that the characterization method using reflectance spectroscopic measurements can determine the electrical property and the thickness of SiC homo-epilayers simultaneously.

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