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Photoellipsometry Study of δ-Doped GaAs

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In this work, photoellipsometry, a new optical method, was used to study δ-doped GaAs. Four δ-doped samples, each having an undoped cap layer of different thickness, were measured. The objective was to determine the build-in electric field strength in the cap layer. Data analysis was made using the Franz-Keldysh theory, in which the effect of broadening and the contributions from heavy- and light-holes were included. Good agreement found between the measured and calculated spectra indicates the effectiveness of the method used.

1. Introduction

Photoellipsometry (PE), a new optical method, has proved valuable in the characterization of n-type GaAs [1,2]. PE incorporates spectroscopic ellipsometry (SE) [3] with the addition of a laser pump beam directed at near-normal incidence onto the sample surface. It combines the features of both SE and photoreflectance (PR) [4], thus providing more complete information not available in separate applications. A major advantage of PE is that it allows the direct measurements of two types of data: the real and imaginary parts of the pseudodielectric function $<\varepsilon>$ (note that $<\varepsilon>$ includes all the surface effects possibly presented in the dielectric function ε), *i.e.*, $<\varepsilon_1>$ and $<\varepsilon_2>$, and the built-in field induced changes in $<\varepsilon>$, *i.e.*, $\delta<\varepsilon_1>$ and $\delta<\varepsilon_2>$, on a wavelength-by-wavelength basis without requiring a Kramers-Kronig transformation. This feature also permits the truly direct observation of the Franz-Keldysh (FK) effect [4] from a given semiconductor.

Si δ-doped GaAs structures grown by molecular-beam-epitaxy (MBE) have been studied in the recent past by PR, which yielded useful information about the electronic properties of the samples under investigation [5,6]. In particular, the oscillations observed near the above-the-bandgap region in the measured data have been identified to be from the FK effect due to the presence of a built-in field in the region between the δ-doped layer and the sample surface. Like PR, PE is also sensitive to the built-in field and thus should be useful in the study of δ-doped semiconductors. In this work, we demonstrate the first application of PE to δ-doped GaAs. To this end, four samples were studied, each containing the following structure: a 500 nm undoped MBE GaAs buffer layer grown on top of a semi-insulating GaAs (100) substrate followed by a Si δ-doped thin layer and an undoped MBE GaAs cap layer of thickness L (L = 30, 100, 150, and 200 nm). The sheet doping density in the δ-doped layer was about 4.4×10^{12} cm^{-2} for each sample. The cap layer thickness was confirmed by *C-V* measurements. Our objective was to determine the built-in field strength in the cap layer for each given sample.

2. Experiment and Theory

Figure 1 shows the schematic diagram of the PE apparatus used in this work. It consisted of a rotating analyzer variable angle spectroscopic ellipsometer and a HeNe laser (with a wavelength of 632.8 nm) used as the pump beam light source. The pump beam power density was about 7mW/cm^2. All the measurements were taken in room air at 75° for the probe beam angle of incidence. The spectral range was from 1.3 to 1.7eV near the bandgap of GaAs.

In SE, one measures ψ and Δ, as a function of wavelength (or photon energy), which are related to the sample's optical properties by [3]

$$\rho \equiv \tan\psi \exp(i\Delta) = R_p/R_s, \qquad (1)$$

where R_p and R_s are, respectively, the complex reflection coefficients for light polarized parallel (p) and perpendicular (s) to the plane of incidence.

With each pair of ψ and Δ measured, one can obtain $<\varepsilon>$ using a two-phase (ambient-substrate) model [3]

$$
\begin{aligned}
<\varepsilon> &= <\varepsilon_1>+i<\varepsilon_2> \\
&= \sin^2\phi\{1+[(1-\rho)/(1+\rho)]^2\tan^2\phi\}, \qquad (2)
\end{aligned}
$$

where ϕ is the probe beam angle of incidence.

PE operates on the similar principle to that of PR, in which an above-the-bandgap pump beam photo-generates free carriers, which in turn redistribute so as to reduce the built-in fields near the sample surface and interfaces. The change in the built-in field alters $<\varepsilon>$ near the bandgap via the FK effect, which can be obtained by [1,2]

$$
\delta<\varepsilon> = <\varepsilon(\text{pump off})>-<\varepsilon(\text{pump on})>, \qquad (3)
$$

where $<\varepsilon(\text{pump off})>$ and $<\varepsilon(\text{pump on})>$ can be found from Eq. (2). Note that Eq. (3) was the means by which the PE data were obtained in this work.

For a uniform field F, the field induced change in ε due to the FK effect near the bandgap E_0 is given by [4]

$$
\begin{aligned}
\delta\varepsilon(F, E) &= \delta\varepsilon_1(F, E)+i\delta\varepsilon_2(F,E) \\
&= (C\theta^{1/2}/E^2)[G(\eta)+iF(\eta)], \qquad (4)
\end{aligned}
$$

where E is the photon energy, C is the interband transition matrix element, and θ and η are defined by $(\pi e^2F^2/\mu h)^{1/3}$ and $2\pi(E-E_0)/h\theta$, respectively, where μ is the interband reduced effective mass. $G(\eta)$ and $F(\eta)$ are given by the combinations of the complex Airy functions, their derivatives, and a unit step function.

If the broadening is Lorentzian type, which was assumed to be in this work, the field induced change in ε in the presence of broadening can be obtained from the unbroadened term $\delta\varepsilon(F, E)$ given by Eq. (4) using the following expression [4]

$$
\begin{aligned}
&\delta\varepsilon(F, E+i\Gamma) \\
&= 1/\pi\int_0^\infty \{\delta\varepsilon(F, E')\Gamma/[(E-E')^2+\Gamma^2]\}dE', \qquad (5)
\end{aligned}
$$

where Γ is the broadening parameter.

3. Results and Discussion

Due to the limited space, we only present here the data and results from one of the samples studied. In Figs. 2(a) and 2(b), we show the SE spectra $<\varepsilon_1>$ and $<\varepsilon_2>$ measured with the pump beam off and on, respectively, from a δ-doped GaAs sample (L = 100 nm). The variations seen near the above-the-bandgap region in both the $<\varepsilon_1>$ and $<\varepsilon_2>$ spectra are mainly due to the FK effect. For the same sample, much more distinctive FK oscillations can be clearly observed in the above-the-bandgap region in the PE spectra $\delta<\varepsilon_1>$ and $\delta<\varepsilon_2>$, as shown by the dotted lines in Figs. 3(a) and 3(b), thereby suggesting the presence of a built-in field in the cap layer. To quantitatively interpret these measured spectra, a lineshape analysis was carried out, in which Eqs. (4) and (5) were used and the contributions from both heavy- and light-holes were included. Shown by the solid lines in Figs. 3(a) and 3(b) are the calculated spectra, obtained assuming a uniform field of 8.5 kV/cm in the cap layer and a broadening parameter of 8 meV. Reasonably good agreement found between the measured spectra and the calculations indicates that the model used was fairly adequate. The discrepancy seen in the above-the-bandgap region in these figures is believed to be mainly due to the interference effect of light reflected from the sample surface and the interface between the cap layer and the δ-doped layer, which was not included in the model calculations. Also not included in the calculations was the electron subband filling effect, which might be responsible for the first-derivative-like lineshape observed in the bandgap region [7]. Detailed lineshape analysis together with the results of thickness dependence of PE spectra will be presented for the given samples, including the lineshape change from the first-derivative-like to the third-derivative-like observed from the sample with the cap layer thickness of 30 nm.

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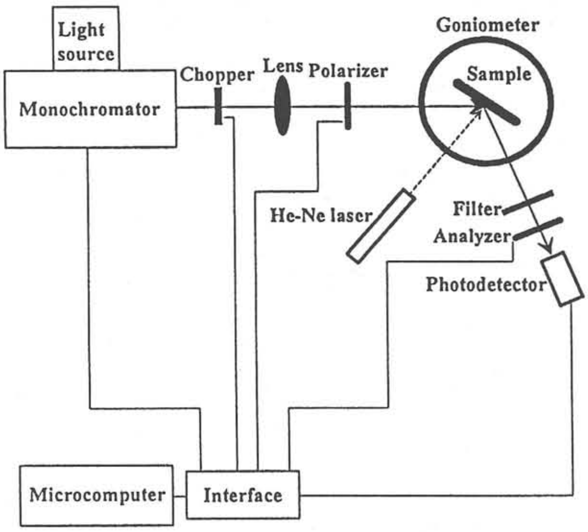

Fig.1 Schematic diagram of Photoellipsometry set-up.

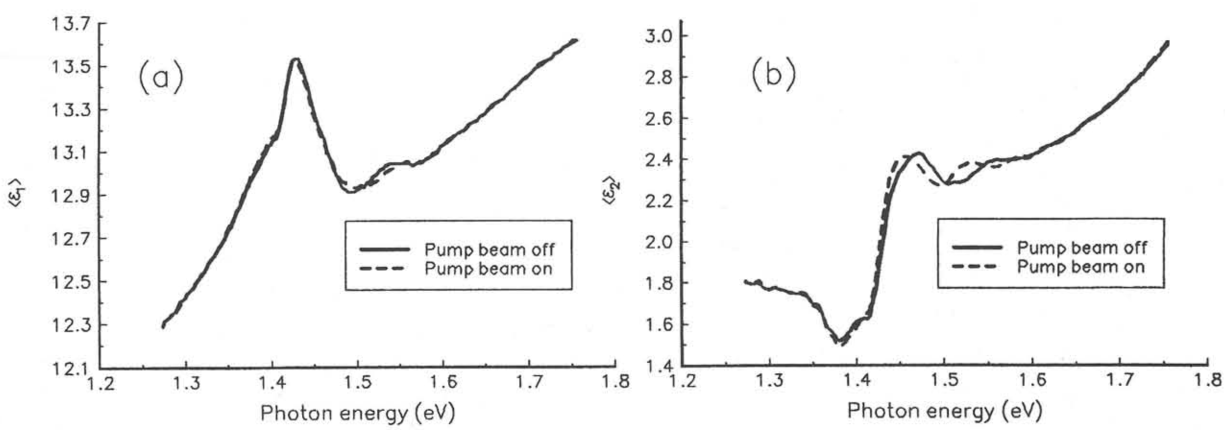

Fig.2 Measured SE spectra from a delta-doped GaAs (L=100nm).

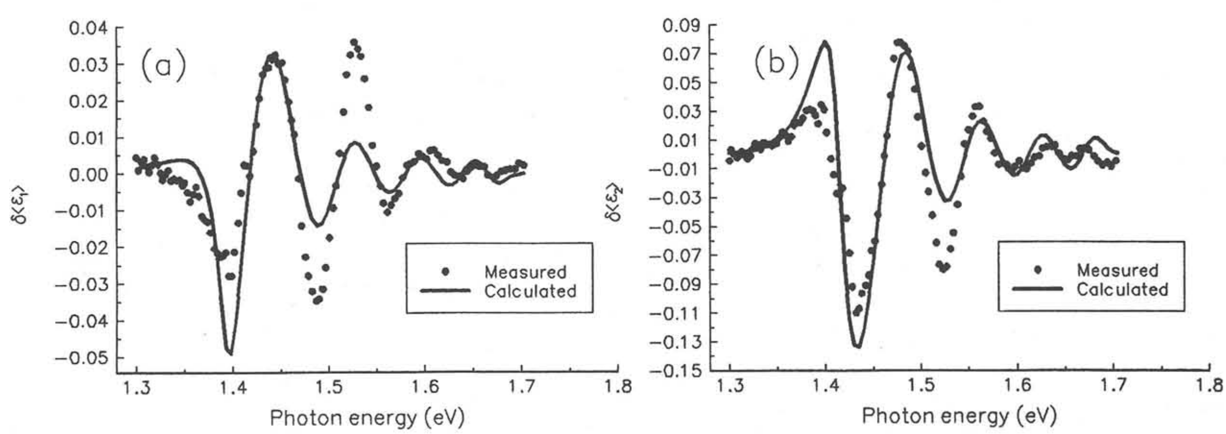

Fig.3 Measured and calculated PE spectra for a delta-doped GaAs (L=100nm).