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Photoellipsometry Characterization of $In_{0.46}Ga_{0.54}P/n^+$-GaAs Heterostructures

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Photoellipsometry was used for the characterization of $In_{0.46}Ga_{0.54}P/n^+$-GaAs heterostructures. Two samples were investigated, each containing an undoped $In_{0.46}Ga_{0.54}P$ layer of thickness L (L = 40 and 100 nm) grown on top of a heavily doped (100) GaAs substrate by metal-organic chemical vapor deposition. The measured spectra were analyzed using the Franz-Keldysh theory, with inclusion of broadening effects. Our results clearly show the layer thickness dependence of built-in electric field in each sample. In addition, we observed a downward shift of the band-gap energy in the $In_{0.46}Ga_{0.54}P$ layers believed to be related to the phenomenon of ordering.

1. INTRODUCTION

Photoellipsometry, a non-destructive and contactless optical method, has proved useful in the study of *n*-GaAs substrates[1], δ-doped GaAs structures[2], and modulation-doped AlGaAs/GaAs heterostructures[3]. PE utilizes spectroscopic ellipsometry[4] (SE) with the addition of an above-band-gap pump beam directed at near-normal incidence onto the sample surface. It combines the features of both SE and photoreflectance[5,6] (PR), providing more complete information not available in separate applications. A major advantage of PE over reflectance methods such as PR is that it allows direct measurements of built-in electric field-induced changes in both the real and imaginary parts of the pseudodielectric function $\langle\varepsilon\rangle$, *i.e.*, $\delta\varepsilon_1$ and $\delta\varepsilon_2$, on a wavelength-by-wavelength basis without requiring a Kramers-Kronig transformation. This feature makes it possible for tighter constraints to be imposed on the models representing more complicated structures, thereby increasing confidence in the data analysis. The measured PE spectra from a chosen sample can be analyzed using an appropriate theory and model for the determination of such parameters as built-in field strength, broadening, and critical point (CP) energies.

$In_xGa_{1-x}P$ has received increased attention[7-9], because of the direct band-gap attainable up to about 2.2 eV at 300 K, making it technologically attractive in many optoelectronic applications. In this research, we demonstrate the effectiveness of PE by applying it to $In_{0.46}Ga_{0.54}P/n^+$-GaAs heterostructure. Similar to GaAs/n^+-GaAs structure, which has been studied by several groups using PR[6], the presence of a large, almost uniform electric field in the undoped layer of $In_{0.46}Ga_{0.54}P/n^+$-GaAs heterostructure makes it ideal for PE study. To this end, two samples were investigated, each featuring a thin $In_{0.46}Ga_{0.54}P$ layer of different thickness. Our main objective was to determine the built-in field strength in the top layer for each given sample.

2. EXPERIMENT AND THEORY

Each of the two samples used contained an undoped $In_{0.46}Ga_{0.54}P$ layer of thickness L (L = 40 and 100 nm) grown on top of a heavily doped (100) GaAs substrate (with the same Si doping density of 2×10^{18} cm^{-3}) by metal-organic chemical vapor deposition (MOCVD). The indium composition of each layer was confirmed by x-ray diffraction. The layer thickness of each sample was checked and confirmed by SE.

The PE apparatus used in this research consisted of a rotating analyzer spectroscopic ellipsometer similar to that described in the literature[4] and a 10 mW HeNe laser (with a wavelength of 632.8 nm) used as the pump beam light source. All measurements were taken in room air, with the probe beam angle of incidence set at 75^o. The spectral range was from 1.77 to 2.0 eV near the band-gap of $In_{0.46}Ga_{0.54}P$.

In SE, two parameters, ψ and Δ, are measured as a function of wavelength (or photon energy). These two parameters are related to the sample's optical properties through[4]

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

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 $\langle\varepsilon\rangle$, using a two-phase (ambient-substrate) model, from the following expression[4]

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

where ε_a is the dielectric constant of the ambient ($\varepsilon_a \approx 1$ in air) and ϕ is the probe beam angle of incidence.

PE operates on a similar principle to that of PR, in which an above-band-gap pump beam photogenerates free carriers, which in turn are redistributed so as to reduce the built-in field(s) near the sample's surface and/or interface(s). The field-induced change in $\langle\varepsilon\rangle$ can be obtained by[3]

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

where $\langle\varepsilon(\text{pump off})\rangle$ and $\langle\varepsilon(\text{pump on})\rangle$ can be acquired from Eq. (2). Note that Eq. (3) was the means by which the PE spectra were obtained in this research.

The Franz-Keldysh (FK) theory formulated by Aspnes[5,6] describes electric field-induced effects near CPs in semiconductors. According to this theory, the change in the dielectric function ε near an M_0 CP (*e.g.*, the band-gap E_0 CP) induced by a uniform field F is given by[5,6]

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

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

In this research, all broadening effects, such as collision-induced life-time broadening, were assumed to be Lorentzian type. Accordingly, the field-induced change in ε with inclusion of broadening effects can be obtained using the following expression[6]

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

where Γ is the broadening parameter and $\delta\varepsilon(F, E')$ is the unbroadened change given by Eq. (4).

3. RESULTS AND DISCUSSION

Shown in Fig. 1 are the measured spectra (circles) from the sample of layer thickness L = 40 nm, together with the calculated spectra (solid lines). From the measured spectra in this figure, all the characteristics of the FK effect can be clearly observed, as illustrated, for example, in the $\delta\varepsilon_2$ spectrum by the oscillations in the above E_0 ($E_0 \approx 1.85$ eV for $In_{0.46}Ga_{0.54}P$) region and the exponentially decaying tail in the below E_0 region. To quantitatively describe the measured spectra for this sample, Eqs. (4) and (5) were used for the model calculations, in which a uniform field was assumed in the $In_{0.46}Ga_{0.54}P$ layer and the contributions from both heavy- and light-holes were included. The calculated spectra shown by the solid lines in Fig. 1 were obtained using a field of 2.35×10^5 V/cm, a band-gap energy of 1.845 eV, and a broadening parameter of 5 meV. Good agreement between the measured spectra and model calculations indicates that the theory and model employed are appropriate and that the calculated results are reliable for the chosen sample. Here, it should be mentioned that the contributions from split-off holes and fields in the $In_{0.46}Ga_{0.54}P/n^+$-GaAs interface region were not included in the model calculations, as they were assumed too small to generate significant effects in the measured spectra. Using Eqs. (4) and (5) and making the same assumptions as those used for the first sample, we obtained similarly good agreement between the measured and calculated spectra for the thicker layer sample (with L = 100 nm). Our model calculations for this sample show that a weaker field of 8.65×10^4 V/cm was present in the top layer, indicating that, for the type of sample structure studied here, the field strength was dependent on the layer thickness. The same phenomenon was observed elsewhere in similar structures[2,6]. Note that, from the calculated results, we found the band-gap energy for MOCVD grown $In_{0.46}Ga_{0.54}P$ layer to be around 1.85 eV for both samples, as opposed to be the expected value[7] of about 1.92 eV. This type of band-gap reduction is believed to be related to the phenomenon of ordering and the amount of it is often used to measure the degree of ordering, which have been described in the literature[8,9].

4. SUMMARY

We have demonstrated that PE is a useful tool in the study of $In_{0.46}Ga_{0.54}P/n^+$-GaAs heterostructure. The analysis of the measured spectra clearly shows the layer thickness dependence of built-in electric field in each sample. In addition, we observed a downward shift of the band-gap energy in the $In_{0.46}Ga_{0.54}P$ layers believed to be related to the phenomenon of ordering.

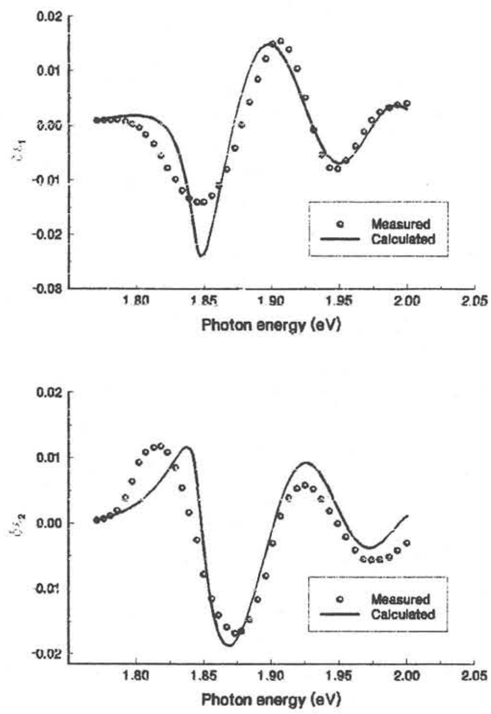

Fig. 1 Measured and calculated PE spectra for an $In_{0.46}Ga_{0.54}P/n^+$-GaAs heterostructure, in which the $In_{0.46}Ga_{0.54}P$ layer thickness was 40 nm.

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