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# Built-in Electric Field Strength in InP/n$^+$-InP Determined by Photoellipsometry and Photoreflectance

Yi-Ming XIONG and Tadashi SAITOH
*Division of Electronic and Information Engineering*
*Tokyo University of Agriculture and Technology, Koganei, Tokyo 184, Japan*

Hiroyuki YAGUCHI and Yasuhiro SHIRAKI
*Research Center for Advanced Science and Technology*
*University of Tokyo, Meguro-ku, Tokyo 153, Japan*

Built-in electric field strength in InP/n$^+$-InP was evaluated by photoellipsometry (PE) and photoreflectance (PR), respectively. Two samples were investigated, each having an undoped (100) InP layer of thickness L (L = 100 and 150 nm, respectively) epitaxially grown on top of a heavily doped n-type (100) InP substrate. The measured PE spectra were analyzed using the Franz-Keldysh (FK) theory, taking into account the photovoltage effect induced by the pump beam illumination and the broadening effects due to free-carrier scattering. The PR spectra measured under the low pump beam illumination, on the other hand, were analyzed using the asymptotic form of an Airy function for the FK oscillations. The results of our analysis show good agreement between the field strengths determined by PE and PR, respectively, for each sample investigated, which in turn demonstrates the effectiveness of the two methods in the characterization of the chosen samples.

## 1. INTRODUCTION

Photoellipsometry[1,2] (PE) incorporates spectroscopic ellipsometry[3] (SE) with the addition of an above-bandgap $E_g$ laser pump beam directed at near-normal incidence onto the sample surface, combining the features of both SE and photoreflectance[4] (PR) and providing more complete information in a single experiment. PR, on the other hand, is a well-established modulation method. The contactless nature and relatively sharper features produced in the measured spectrum make this method very attractive in the characterization of band structure and built-in field in a given semiconductor sample.

Similar to the case of GaAs/n$^+$-GaAs, which has been studied using PR,[4] a major advantage for a sample with InP/n$^+$-InP structure is that it ensures the presence of an almost uniform built-in electric field in the top undoped layer, leading to the measured spectra that are characterized with large Franz-Keldysh oscillations[4] (FKO) in the above-$E_g$ region and small broadening effects. These features also make it possible for accurate evaluation of the built-in field in the given sample. It was based on this motivation that we applied PE and PR to InP/n$^+$-InP. Two samples were investigated, each featuring an undoped InP layer of different thickness epitaxially grown on a heavily doped n-type InP substrate. Our main goal was to determine the built-in field strength in the top layer for each sample.

## 2. EXPERIMENTS AND THEORIES

The two samples used were prepared by organometallic vapor-phase deposition, each having an undoped (100) InP layer of thickness L (L = 100 and 150 nm, respectively) on top of a heavily doped (100) InP substrate with the S doping density of $5.4 \times 10^{18}$ cm$^{-3}$. All the SE and PR measurements were carried out in room air, near the InP $E_g$ region.

The PE apparatus used consisted of a rotating analyzer SE similar to that described in the literature[3] and a 10 mW HeNe laser (with a wavelength of 632.8 nm) used as the pump beam light source. The PR apparatus used was a standard one,[4)] in which a 0.4 mW Ar ion laser (with a wavelength of 514.5 nm) chopped at a modulation frequency of 210 Hz was used as the pump beam light source.

The FK theory[4)] was used in the analysis of the measured PE spectra, *i.e.*, the $\delta\varepsilon_1$ and $\delta\varepsilon_2$ spectra, for each sample. According to this theory, the change in $\varepsilon$ near the $E_g$ region induced by a uniform field F is given by:[4)]

$$\delta\varepsilon(F, E) = \delta\varepsilon_1(F, E) + i\delta\varepsilon_2(F, E) = (C\theta^{1/2}/E^2)[G(\eta) + iF(\eta)], \quad (1)$$

where E is the photon energy, $C$ contains the interband transition matrix element, and $\theta$ and $\eta$ are defined by $(\pi e^2F^2/\mu h)^{1/3}$ and $2\pi(E_g-E)/h\theta$, respectively, where $\mu$ 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 in the measured spectra, such as broadening induced by free-carrier scattering, were assumed to be Lorentzian type. Consequently, the field induced change in $\varepsilon$ with inclusion of broadening effects can be obtained from:[4)]

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

where $\Gamma$ is the broadening energy and $\delta\varepsilon(F, E')$ is the unbroadened change given by Eq. (1).

The measured PR spectrum, *i.e.*, the $\Delta R/R$ spectrum, in the above-$E_g$ region from each sample, was analyzed using the following expression:[4)]

$$m\pi = (4/3)[2\pi(E_m - E_g)/h\theta]^{3/2} + \phi, \quad (3)$$

where $E_m$ is the photon energy of the mth extrema, $\theta$ has the same meaning as the one in Eq. (1), and $\phi$ is an arbitrary phase factor. Note that Eq. (3) was obtained based on the asymptotic form of an Airy function for the FKO.

## 3. RESULTS AND DISCUSSION

As an example, we show in Fig. 1 the measured PE spectra from the sample with L = 100 nm, together with the calculated spectra obtained via model calculations using Eqs. (1) and (2), in which a uniform field of $3.35 \times 10^4$ V/cm was assumed in the top layer, a broadening energy of 2 meV was used, contributions from both the heavy- and light-holes were included, and the photovoltage effect was taken into account. Very good agreement between the measured and calculated spectra suggests that the theories used in the model calculations were appropriate and that the calculated results were reliable for the chosen sample. Figure 2 illustrates the measured $(4/3\pi)(E_m-E_g)^{3/2}$ as a function of the FKO index m, in which the slope of a least squares fit using Eq. (3) to the measured data yielded a field of $3.16 \times 10^4$ V/cm in the top layer for the same sample as in Fig. 1. The inset in Fig. 2 shows the measured PR spectrum, from which the measured data in this figure were acquired. The above results show good agreement between the field strengths determined, respectively, by PE and PR, thereby demonstrating the effectiveness of the two methods in the characterization of the chosen sample. It should be mentioned that similarly good agreement between the field strengths obtained by the two methods was also found for the thicker layered sample with L = 150 nm. More details will be presented, including the modeling procedure used in the analysis of the measured PE spectra as well as the surface Fermi level for each sample obtained from its built-in field strength and layer thickness.

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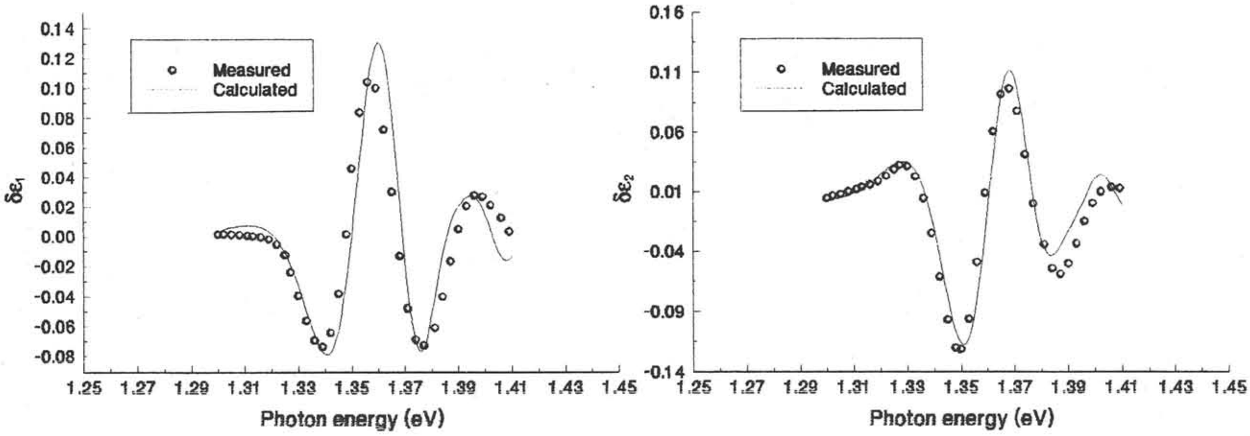


Fig.1 Measured PE spectra from an InP/$n^+$-InP sample with the top layer thickness of 100 nm, together with the calculated spectra obtained via model calculations using a uniform field of $3.35 \times 10^4$ V/cm in the top layer and a broadening energy of 2 meV.

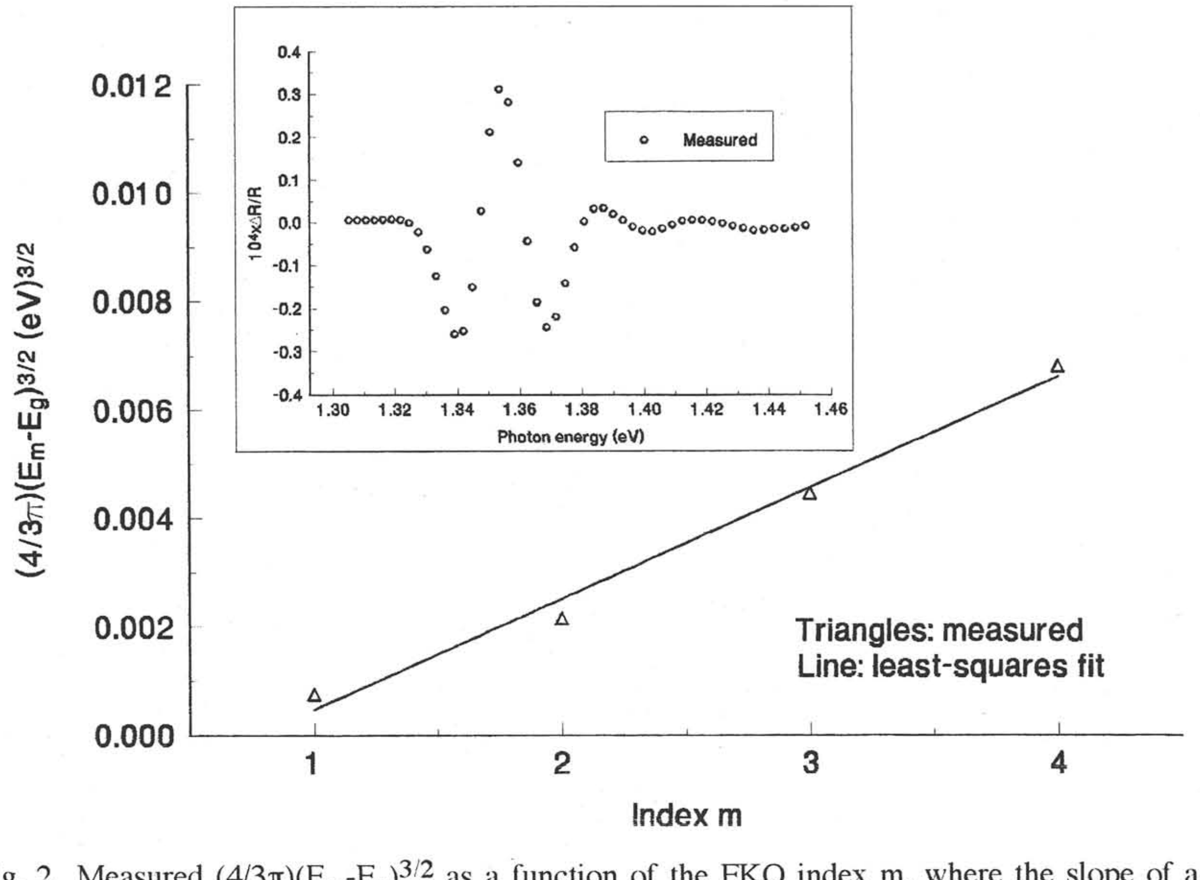


Fig. 2 Measured $(4/3\pi)(E_m-E_g)^{3/2}$ as a function of the FKO index m, where the slope of a least squares fit to the measured data (triangles) yielded a field of $3.16 \times 10^4$ V/cm in the top layer for the same sample as in Fig. 1. The inset shows the PR spectrum, from which the measured data in this figure were obtained.