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# Effects of polarization on electroreflectance spectroscopy of surface-intrinsic $n^+$-type doped GaAs

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The electroreflectance (ER) spectra of a surface-intrinsic $n^+$-type doped (100) GaAs have been measured at various polarization angles of the probe beam. Several Franz–Keldysh oscillations were observed above the band-gap energy, thus enabling heavy- and light-hole transitions to be separated by the application of the fast Fourier transform to the ER spectra. From this, the ratios of the amplitudes of the light- to heavy-hole transitions versus angle of polarization were obtained. At a large incident angle (80°), the strength of the field of the probe beam in the normal direction of the sample ($F_z$) was varied from zero to a larger component. It was found that the ratios increased with increasing $F_z$ which is consistent with the theory that the light-hole transition becomes more enhanced with $z$-polarized light.
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## I. INTRODUCTION

The effect of an electric field on the optical properties of a semiconductor is one of the basic problems of optoelectronics. In bulk medium, the Franz–Keldysh effect (FKE) can be observed,[1,2] that is, the absorption has an exponential tail for photon energy ($E$) smaller than the gap energy ($E_g$), and has Franz–Keldysh oscillations (FKO) for energy above $E_g$.

Most of the experiments on the polarization dependence of the FKE have been investigated for $E<E_g$.[3–5] There has been only one report[6] of an experiment dealing with $E>E_g$ for low-temperature-grown GaAs. Although the difference in the FKO between transverse-electric and transverse-magnetic polarization was observed, the beat due to heavy- and light-hole contributions was not visible. This has, however, been observed in many photoreflectance (PR) or electroreflectance (ER) experiments.[7–11]

Many FKO for $E>E_g$ have been observed[7–11] in the PR or ER spectra of surface-intrinsic $n^+$-type doped (s-i-n$^+$) GaAs. The beat observed in the FKO results from the different oscillation frequencies associated with the transitions of the heavy and light holes, and is due to the different values of reduced masses. The contributions of heavy and light holes can be separated by applying the fast Fourier Transform (FFT) to the FKO[12,13]

In this work, we investigate the polarization dependence of FKO by using ER. The ER spectra of s-i-n$^+$ GaAs have been measured over a range of polarization angles of the probe beam. At a large incident angle, the strength of the field of the probe beam in the normal direction of sample ($F_z$) can be varied from zero to a larger component. We study the ratio of the intensity of the light-hole to heavy-hole transitions as a function of $F_z$.

## II. EXPERIMENT

The s-i-n$^+$ GaAs sample used in this experiment was grown on an $n^+$-type GaAs (100) substrate by molecular beam epitaxy (MBE). A 1.0 $\mu$m $n^+$-doped GaAs buffer layer was first grown on this substrate, followed by a 1200 Å undoped GaAs cap layer. Gold film was deposited by a hot filament evaporation, and the thickness was estimated to be about 70 Å.

The experimental setup for the ER measurements is similar to that described in the literature.[14] Light from a 200 W tungsten lamp passed through a 500 mm monochromator (Acton spectra Pro-500). The exit light was defocused onto the sample by a lens. The reflected light was collected by a lens to focus onto a Si photodiode detector. The incident angle was 80°, and a polarizer was placed between the lens and the sample. The polarization angle was varied by rotating the polarizer. The sample was modulated at 400 Hz by an ac sine wave. The photodiode signal was composed of a dc component ($R$) and an ac component ($\Delta R$), the output of which was also fed into a lock-in amplifier (Stanford Research System SR 830) to measure the modulated ac signal ($\Delta R$). The entire system was controlled by a personal computer.

## III. THEORY

Because of the different frequencies of FKO associated with heavy- and light-hole transitions, the contributions can be separated by the application of FFT to the ER spectra.[12,13]

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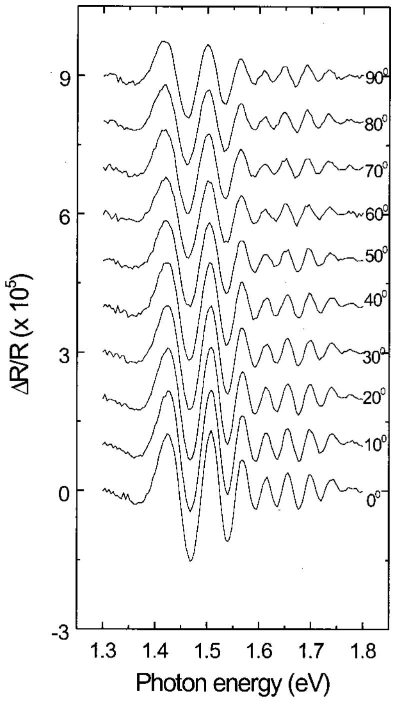

FIG. 1. Measured electroreflectance spectra of the s-i-n$^+$ GaAs at several angles of polarizer ($\theta_{pol}$).

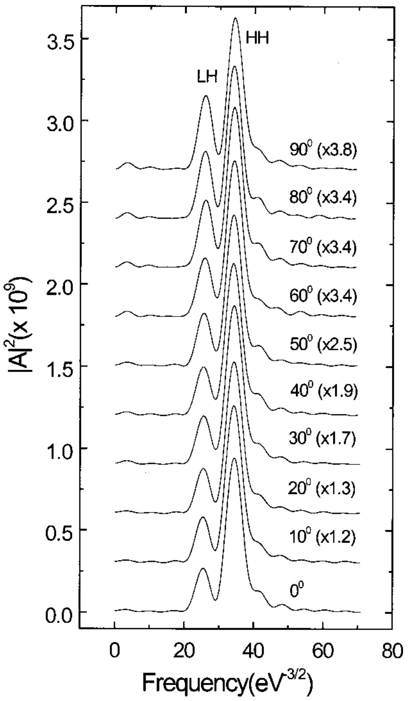

FIG. 2. Fast Fourier transform of Fig. 1 after transforming the $x$ variable from $E$ to $(E-E_g)^{3/2}$.

The frequencies $f_i$ evaluated from the FFT are related to the strength of the electric field $F$ in the undoped layer by the following:

$$f_i=\frac{2}{3\pi}(2\mu_i)^{1/2}\left(\frac{1}{e\hbar F}\right), \tag{1}$$

where $i(=\text{HH,LH})$ stands for the heavy- and light-hole contributions, $\mu_i$ is the reduced mass of the electron and heavy or light holes, respectively.

The intensity of the heavy or light hole to the conduction band transition is given by

$$B_i \propto |\langle c|e\cdot p|v\rangle|^2 \mu_i^{3/2}, \tag{2a}$$

where $<c|$ and $|v>$ are the conduction and valence states, respectively. The heavy (light)-hole states are $|3/2, \pm 3/2\rangle(|3/2, \pm 1/2\rangle)$ in the $|J.m_J\rangle$ representation, where

$$\begin{aligned}|3/2,3/2\rangle &= (1/\sqrt{2})(x+iy)\uparrow\\ |3/2,1/2\rangle &= (1/\sqrt{6})(x+iy)\downarrow-\sqrt{2/3}z\downarrow.\end{aligned} \tag{2b}$$

According to Eqs. (2a) and (2b), the intensity of the light-hole transition becomes larger when the probe beam is polarized more in the $z$ direction, where $z$ direction is in the normal of the sample.

## IV. RESULTS AND DISCUSSION

Figure 1 shows the measured ER spectra of s-i-n$^+$ GaAs for the angle ($\theta_{pol}$) of the polarizer, where $\theta_{pol}=0°$ indicates that the polarization of the probe beam is perpendicular to the incident plane and $\theta_{pol}=\pm 90°$, in the incident plane. The spectra exhibit many FKO above $E_g$, which is due to a uniform field and a small broadening parameter in the undoped layer. The beat in the FKO results from different oscillation frequencies associated with different $\mu_i$ values in the transitions of the heavy and light holes.

The FFTs of the ER spectra in Fig. 1 are shown in Fig. 2. The spectra can be clearly resolved into two peaks corresponding to heavy- and light-hole transitions. The values of $|A_{LH}|/|A_{HH}|$ are plotted versus $\theta_{pol}$ in Fig. 3. The ratios increase with $\theta_{pol}$. It will be shown later that $F_z$ also increases with $\theta_{pol}$. Hence the light hole transition becomes more enhanced with $z$-polarized light.

For our experimental setup, where the incident angle ($\theta_{in}$) is 80°, the electric and magnetic fields inside the sample can be calculated by using the condition that the tangential components of the electric and magnetic fields across the air-sample boundary are continuous. The calculated ratios $F_z/F$ as a function of $\theta_{pol}$ are shown in Fig. 4, where $F$ is the total strength of the electric field of the probe beam. $F_z$ is equal to zero at $\theta_{pol}=0°$ and becomes larger when $\theta_{pol}$ approaches ±90°. But even for $\theta_{pol}=\pm 90°$, $F_z$ is still less than 30% of $F$. This is due to the high index of refraction ($n=3.6$ was used) of the sample such that the angle of the refraction is small even for $\theta_{in}=80°$. If the geometry of total internal reflection (TIR)[15,16] could be employed, the $F_z$ component would be larger. However, TIR for $E>E_g$ cannot be used because the light will then be totally absorbed in the sample.

According to Eqs. (2a) and (2b), the theoretical values of $B_i$ are evaluated and their ratios are also shown in Fig. 3. The result shows that the light-hole transition becomes more enhanced relative to the heavy-hole transition when $\theta_{pol}$ becomes larger. This is consistent with the experimental result obtained by using FFT, except that the values of the latter are too large. In order to solve this discrepancy, the amplitudes

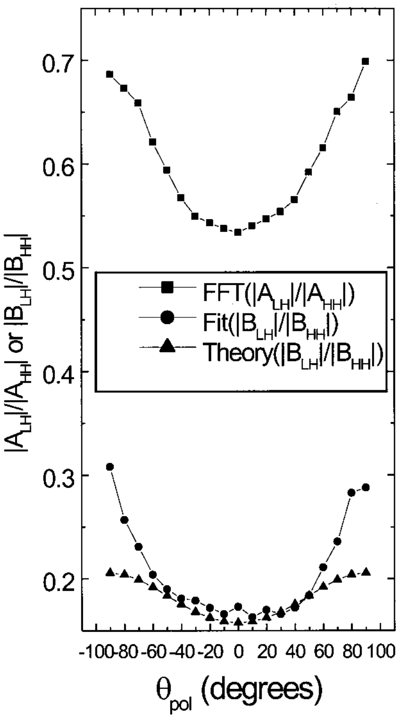

FIG. 3. The ratios of intensity of the light-hole transition to that of heavy-hole as a function of the angle of polarizer ($\theta_{pol}$). The circle is the result obtained by using FFT. The square is the result obtained by using Eq. (3) to fit the ER line shape. The triangle is the theoretical result calculated by using Eqs. (2a) and (2b).

obtained by FFT need to be discussed more. The asymptotic form of line shape of $\Delta R/R$ can be expressed as[17]

$$\frac{\Delta R}{R}\approx\sum_i \frac{B_i(\hbar\theta_i)^{3/2}}{E^2(E-E_g)}\exp\left[-2\frac{(E-E_g)^{1/2}}{(\hbar\theta_i)^{3/2}}\Gamma\right]\times\cos\left[\phi+\frac{4}{3}\left(\frac{E-E_g}{\hbar\theta_i}\right)^{3/2}\right], \tag{3}$$

where $E$ is the photon energy, $E_g$ is the energy, gap, $\hbar\theta_i=(e^2\hbar^2F^2/2\mu_i)^{1/3}$, and $\Gamma$ is the broadening parameter.

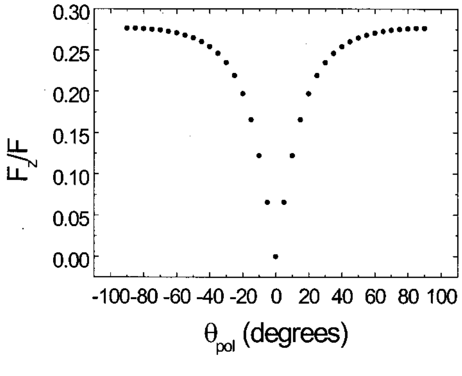

FIG. 4. The ratios of $F_z/F$ as a function of the angle of the polarizer ($\theta_{pol}$).

According to Eq. (3), the nonzero broadening parameter ($\Gamma\neq 0$) will make the FKO damp out with $E$. In addition, the FKO of the heavy-hole transition will damp out faster than those of the light-hole transition because $\hbar\theta_{HH}<\hbar\theta_{LH}$. Therefore, by using FFT to determine $A_{HH}$ or $A_{LH}$, $A_{LH}$ will be overestimated relative to $A_{HH}$. In order to compare with theoretical values, the $B_i$ need to be used instead of the $A_i$. We have obtained $B_i$ by using Eq. (3) to fit the experimental spectra, and the ratios of $B_i$ are shown in Fig. 3. It is better than the FFT method, but there are still some disagreements. This might be due to the mixing of heavy- and light-hole states. The representation of $|J.m_J>$ holds only at the $\Gamma$ point where the wave vector, $k=0$. When $E>E_g$ the transition occurs at $k\neq 0$; hence this representation will no longer be suitable.

## V. CONCLUSION

We have measured the ER spectra of a surface-intrinsic $n^+$-type doped (100) GaAs at several polarization angles, which can vary $F_z$ from zero to a larger component. The heavy- and light-hole transitions were separated by applying fast Fourier transforms to the ER spectra. We have found that the value of $|A_{LH}|/|A_{HH}|$ increases with increasing $F_z$. This is consistent with the theory that the light-hole transition is enhanced with $z$-polarized light. But the values of $|A_{LH}|/|A_{HH}|$ obtained by FFT are much larger than theory would predict. To further explain the discrepancy, the nonzero broadening parameter needs to be taken into consideration.

## ACKNOWLEDGMENT

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