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Electroreflectance of surface-intrinsic- n^+ -type-doped GaAs by using a large modulating field

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It is known that electroreflectance of surface-intrinsic- n^+ -type-doped GaAs has exhibited many Franz-Keldysh oscillations to enable the application of fast Fourier transform to separate the heavy- and light-hole transitions. However, each peak still contains two components, which belong to $F + \delta F/2$ and $F - \delta F/2$, respectively, where F is the electric-field strength in the undoped layer and δF is the modulating field of applied ac voltage (V_{ac}). In order to resolve the heavy- and light-hole transitions, δF was kept much smaller than F in the previous works. In this work, we have used a larger V_{ac} and, hence, a larger δF , to further separate the peaks. The peaks can be divided into two groups which belong to $F + \delta F/2$ and $F - \delta F/2$, respectively. The peak belonging to the heavy-hole transition and $F - \delta F/2$ can be singled out to compare with the Airy function theory. © 2003 American Institute of Physics. [DOI: 10.1063/1.1625098]

I. INTRODUCTION

Modulation spectroscopy¹⁻⁵ is an important technique for the study and characterization of semiconductor properties. It can yield sharp structures around the critical points and is sensitive to the surface or interface electric fields. Among them, electroreflectance (ER) is used to modulate the electric-field strength of samples and photorefectance (PR) is thought of as a form of contactless ER.

For a medium-field strength, the PR or ER spectra exhibit Franz-Keldysh oscillations (FKOs) above the band-gap energy. The electric-field strength F in the depletion region can be deduced from the periods of FKOs.⁶ The larger modulating field δF will enhance signals to shorten the collection time. However, a larger δF will make the determination of F uncertain. This is the reason that in most of the previous works, the strengths of δF 's are much smaller than that of F so that the strength of F can be determined from periods of FKOs.⁷

It is known that the PR or ER of surface-intrinsic n^+ -type-doped ($s-i-n^+$) GaAs exhibit many FKOs and they were attributed to the existence of a uniform F and a small broadening parameter in the undoped layer.⁸⁻¹² The value of F of the $s-i-n^+$ sample can thus be determined by using the fast Fourier transform (FFT) technique.^{13,14}

By using the FFT, the heavy- and light-hole transitions can be separated to some degrees. In order to resolve the heavy- and light-hole transitions, δF was kept much smaller than F in the previous works. However, each peak still contains two components, which belong to $F + \delta F/2$ and $F - \delta F/2$ for ER (F and $F - \delta F$ for PR), respectively. When the larger δF was used, the peaks will become broader so that the determination of F become uncertain.¹⁵ In this work,

we have used an even larger applied ac voltage (V_{ac}), hence, a larger δF , to further separate those components and single out the one belonging to the heavy-hole transition and $F - \delta F/2$.

II. EXPERIMENT

The $s-i-n^+$ GaAs sample used in this experiment was grown on a n^+ -type GaAs (100) substrate by molecular-beam epitaxy. A $1.0 \mu\text{m}$ n^+ -doped GaAs buffer layer was first grown on this substrate, followed by a 1200 \AA undoped GaAs cap layer. The gold film was deposited on the front side of the sample by hot filament evaporation and the thickness estimated to be about 70 \AA . The ohmic contact was fabricated on the rear side of the sample by depositing a Au-Ge alloy.

The experimental setup for the ER measurements, which was similar to that previously described in literature,⁵ will be described briefly. Light from a 200 W tungsten lamp was passed through a 500 mm monochromator. 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. A combination of a square wave V_{ac} and a dc voltage V_{dc} was applied to the sample in the ER measurements.

III. THEORY

The line shape of electromodulation is a response of the field-induced change of the reflectivity, which is written as^{2,3}

$$\frac{\Delta R}{R} = \alpha(\epsilon_1, \epsilon_2) \delta\epsilon_1 + \beta(\epsilon_1, \epsilon_2) \delta\epsilon_2, \quad (1)$$

in which α and β are the Seraphin coefficients, and $\delta\epsilon_1$ and $\delta\epsilon_2$ are the modulation-induced changes in the real and

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imaginary parts, respectively, of the complex dielectric function. Near the band edge, E_0 , of GaAs, $\beta \approx 0$ and $\Delta R/R \approx \alpha \delta \epsilon_1$.

In the case of a flat-band condition under an electric field F , $\Delta \epsilon$ is defined as

$$\Delta \epsilon(E, F) = \epsilon(E, F) - \epsilon(E, 0), \quad (2)$$

where E is the photon energy.

Near the E_0 transition of GaAs, $\Delta \epsilon$ is given by¹⁶

$$\Delta \epsilon(E, F) = \sum_i \frac{B_i (\hbar \theta_i)^{1/2}}{E^2} G \left(\frac{E_g - E}{\hbar \theta_i} \right), \quad (3)$$

where $i = h$ or ℓ , standing for the heavy- and light-hole contributions, respectively, the B_i are parameters which contain the interband optical transition matrix elements, E_g is the energy gap, and $\hbar \theta_i$ is the electro-optic energy as given by

$$(\hbar \theta_i)^3 = e^2 \hbar^2 F^2 / 2 \mu_i, \quad (4)$$

in which μ_h (μ_ℓ) is the reduced mass of heavy (light) hole and electron in the direction of F .

In the case of a uniform electric field F in the undoped layer and a modulation field δF , it was proposed that⁵

$$\begin{aligned} \delta \epsilon^{\text{ER}}(E, F) &= \epsilon \left(E, F + \frac{\delta F}{2} \right) - \epsilon \left(E, F - \frac{\delta F}{2} \right) \\ &= \Delta \epsilon \left(E, F + \frac{\delta F}{2} \right) - \Delta \epsilon \left(E, F - \frac{\delta F}{2} \right). \end{aligned} \quad (5)$$

The electric fields can be obtained by applying the FFT to the ER spectra. This approach has the advantage of determining F without the ambiguity of choosing μ . The frequency, f , evaluated from the FFT is related to F by

$$f_i = \frac{2}{3\pi} (2\mu_i)^{1/2} \left(\frac{1}{e\hbar F} \right), \quad (6)$$

The asymptotic form of $\Delta \epsilon_i$ of heavy hole ($E - E_g > 2\hbar \theta_i$) can be expressed as¹⁷

$$\begin{aligned} \Delta \epsilon_i(E, F) &= \frac{B_i (\hbar \theta_i)^{3/2}}{E^2 (E - E_g)} \exp \left(-2 \frac{(E - E_g)^{1/2}}{(\hbar \theta_i)^{3/2}} \Gamma \right) \\ &\times \cos \left(\phi + \frac{4}{3} \left(\frac{E - E_g}{\hbar \theta_i} \right)^{3/2} \right), \end{aligned} \quad (7)$$

where B_i stands for the intensities of heavy and light hole transitions, respectively, the Γ is broadening parameter.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

The ER spectra of $s-i-n^+$ GaAs and their FFT for $V_{ac} = 50$ mV of various V_{dc} are shown in Figs. 1 and 2, respectively. There are many FKO's observed above the band-gap energy and they were attributed to the existence of a uniform F and a small broadening parameter in the undoped layer. The beat in the FKO's results from the different oscillation frequencies associated with the transitions of the heavy and light holes, due to different μ values. Their FFT spectra are resolved into two peaks, which correspond to heavy- and

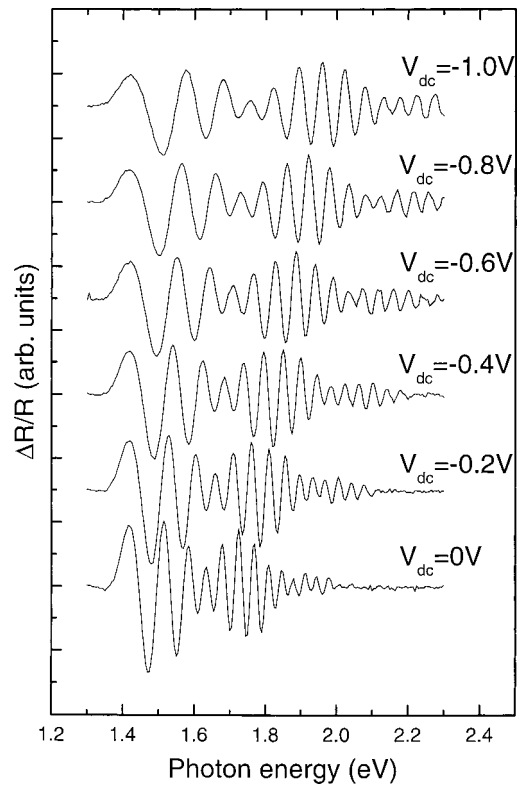


FIG. 1. The ER spectra of $s-i-n^+$ GaAs for $V_{ac} = 50$ mV of various V_{dc} .

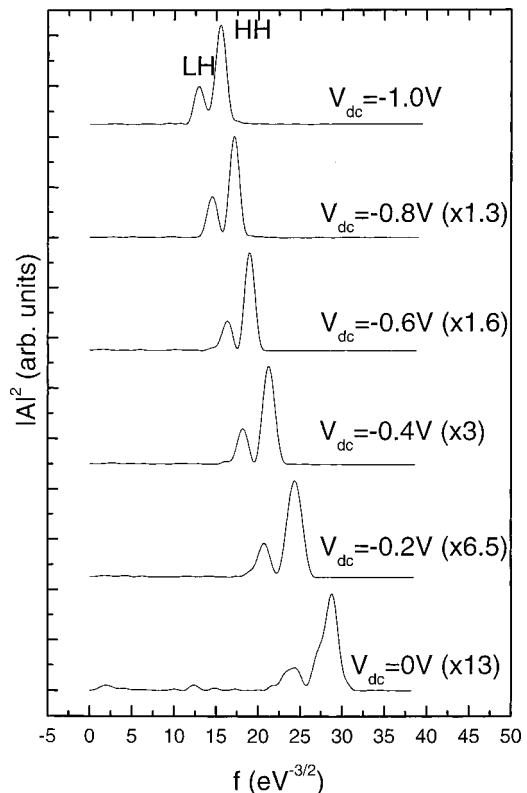


FIG. 2. The FFT of Fig. 1 after transforming the x variable from E to $(E - E_g)^{3/2}$, where HH and LH denote heavy- and light-hole transitions, respectively.

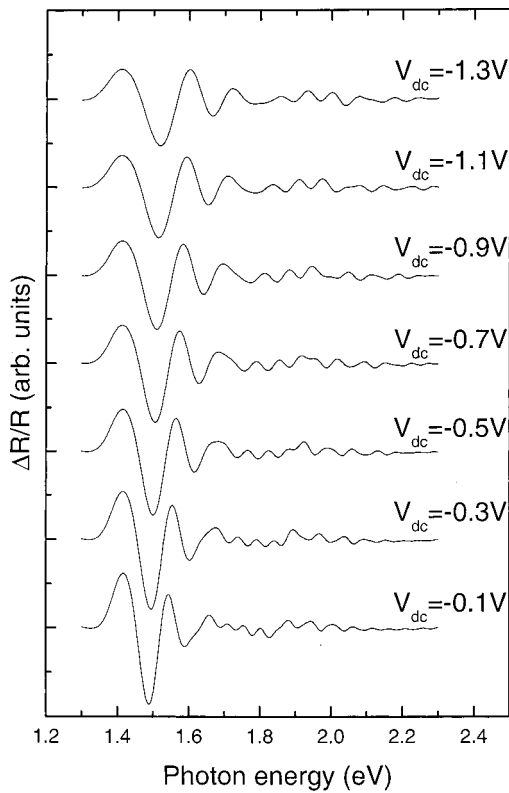


FIG. 3. The ER spectra of $s-i-n^+$ GaAs for $V_{ac}=1.0$ V of various V_{bias} , where V_{bias} is taken as $V_{dc}-V_{ac}/2$.

light-hole transitions, respectively. Although they can be resolved into two peaks, each peak still contains components belonging to $F + \delta F/2$ and $F - \delta F/2$.

In order to further separate the components belonging to $F + \delta F/2$ and $F - \delta F/2$, a larger $V_{ac}=1.0$ V was used. The measured ER spectra of various V_{dc} and their corresponding FFT spectra are shown in Figs. 3 and 4, respectively. They are different from those of Figs. 1 and 2. The beats are not so obvious and their FFT spectra can be clearly resolved into two groups which correspond to $F + \delta F/2$ and $F - \delta F/2$, re-

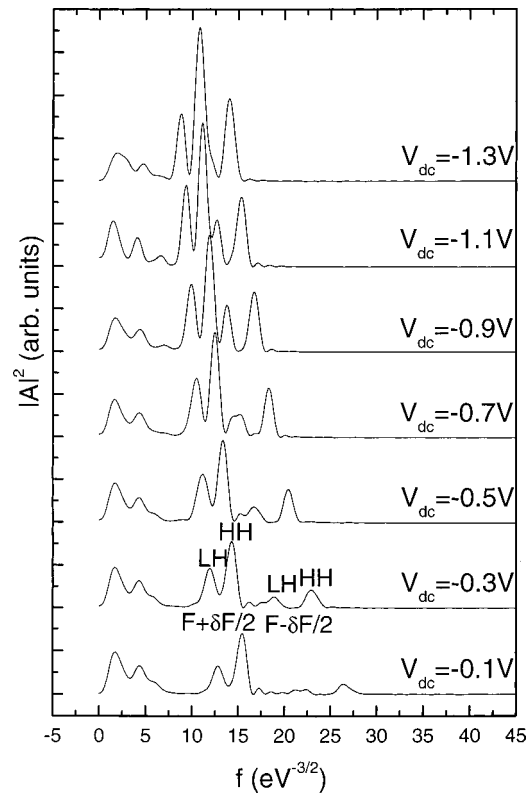


FIG. 4. The FFT of Fig. 3 after transforming the x variable from E to $(E - E_g)^{3/2}$, can be clearly resolved into two groups, which correspond to $F + \delta F/2$ and $F - \delta F/2$, respectively. Each group can be further separated into two peaks corresponding to heavy- and light-hole transitions, respectively.

spectively. Each group can be further separated into two peaks corresponding to heavy- and light-hole transitions, respectively. Here, the component belonging to $F - \delta F/2$ and heavy-hole transition can be singled out.

Using the singled out component, the values of $F - \delta F/2$ can be evaluated from Eq. (6), where $\mu_h = 0.0585m_0$ was used and m_0 is the mass of free electron.

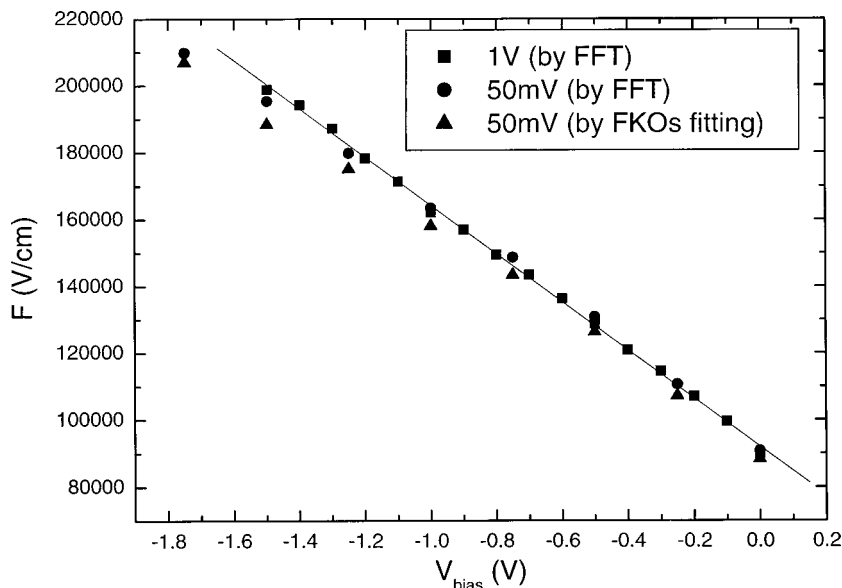


FIG. 5. The strengths of the electric field (F) in the undoped layer are plotted against V_{bias} or V_{dc} . The value of V_{bias} or V_{dc} was used for $V_{ac}=1.0$ V or 50 mV, respectively. The solid line is a linear fitting to the data obtained from $V_{ac}=1.0$ V.

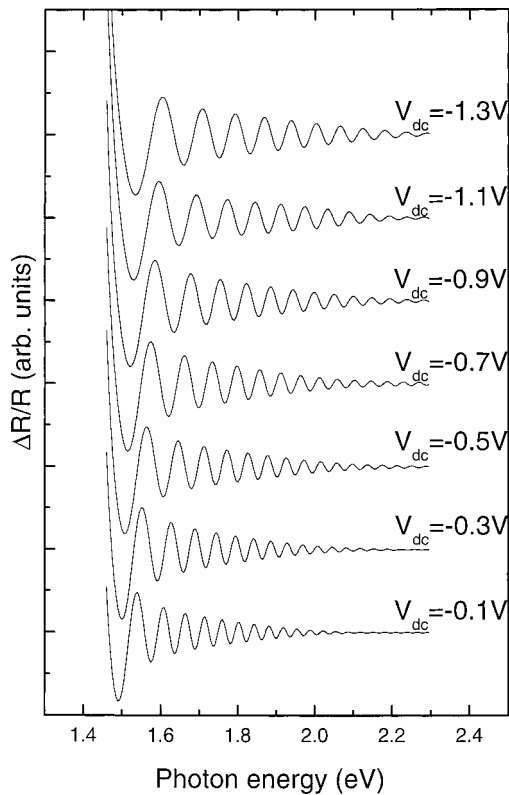


FIG. 6. The ER spectra of various V_{dc} belonging to heavy-hole transition and $F - \delta F/2$, which was obtained by inverse FFT to the singled out component in the Fig. 4.

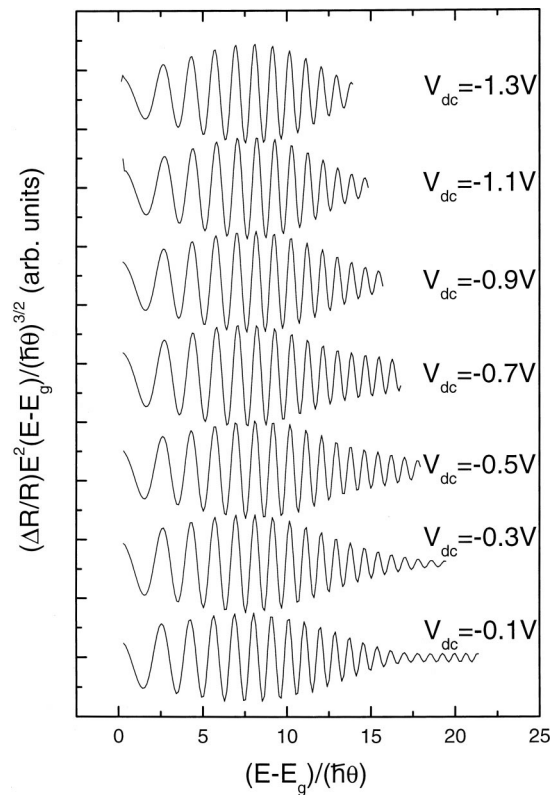


FIG. 7. The spectra of Fig. 6 of various V_{dc} are plotted in the universal variables [according to Eq. (7)].

The, thus obtained F 's are plotted against V_{bias} , where V_{bias} is chosen as $V_{dc} - V_{ac}/2$, as shown in Fig. 5. The relation is linear to confirm the uniformity of F in the undoped layer. The values of δF 's can be evaluated from V_{ac} by using Eq. (6). Also shown in Fig. 5 are the values of F 's evaluated from FFT peaks in Fig. 2 and the slopes of conventional FKOs fitting in Fig. 1, where $\mu = 0.055m_0$ was used in the conventional fitting. The values from both FFT methods are not distinguishable within experimental errors. This is reasonable because the values of F evaluated from the FFT are close to the average of $F + \delta F/2$ and $F - \delta F/2$ when $\delta F \ll F$. The values from conventional fitting are a little bit smaller than those of the FFT. This can be attributed to the choice of μ in the conventional fitting. It is noted that the values from conventional FKOs fitting in Fig. 3 are not marked in Fig. 5. This is because the frequencies corresponding to $F + \delta F/2$ and $F - \delta F/2$ are so different for $V_{ac} = 1.0V$ that only the first few (about three) points can be fitted into a line.

The asymptotic form of ER spectra belonging to heavy-hole transition and $F - \delta F/2$ can be obtained by applying the inverse FFT to the singled out spectra. The results are shown in Fig. 6. The spectra are replotted in the universal variables according to Eq. (7) as shown in Fig. 7. The fact that they are pretty similar means that the asymptotic approximation of Eq. (7) is somewhat correct.

According to Eq. (7), the amplitude of $E^2(E - E_g)\Delta R/R$ becomes a constant when $\Gamma = 0$ and it exhibits a monotonic decrease with E otherwise. The amplitude de-

creases faster when Γ becomes greater. But instead of a monotonic decrease with E , the experimental data in Fig. 7 show an increase and then a decrease with E . The discrepancy at low E may come from the neglect of the excitonic effect, which is important in the range of E close to E_g , in the Airy function theory.

This result can explain the reason that it was not able to obtain accurate values of Γ by using Eq. (7) in the previous works.¹⁶ According to Eq. (7), a plot of $\ln(|\Delta R/R|_n E_n^2 (E_n - E_g))$ versus $2(E_n - E_g)^{1/2}/(\hbar\theta)^{3/2}$ should yield a straight line with slope $-\Gamma$. But our experimental result shows that the asymptotic behavior of $\Delta R/R$ is more complex than that predicted from Airy function theory.

For an ordinary bulk sample, it was shown that the dependence of the amplitude of FKOs on surface electric field, F_s , is $F_s^{1/3}$.¹⁸ This is arguable because the ER spectra are complicated by the fact that they are composed of four components, and the PR is even further complicated by the unknown magnitude of δF . For the bulk samples, there are additional problems that the field is not uniform in the depletion region and the value of Γ cannot be treated as being equal to zero.

V. CONCLUSIONS

In summary, we have measured the ER by using a larger δF . The component belonging to heavy-hole transition and $F - \delta F/2$ has been singled out to compare with the Airy function theory. Instead of a monotonic decrease with E , it

shows an increase and then a decrease with E . The discrepancy at lower E was attributed to the excitonic effect.

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