AIP Journal of Applied Physics

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Citation: Journal of Applied Physics **91**, 4101 (2002); doi: 10.1063/1.1453492
View online: http://dx.doi.org/10.1063/1.1453492
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/91/7?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS VOLUME 91, NUMBER 7 1 APRIL 2002

Evaluation of modulating field of photoreflectance of surface-intrinsic-n^+ type doped GaAs by using photoinduced voltage

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(Received 1 October 2001; accepted for publication 19 December 2001)

Photoreflectance (PR) of surface-intrinsic-n^+ type doped GaAs has been measured for various power densities of pump laser. The spectra exhibited many Franz–Keldysh oscillations, whereby the strength of electric field F in the undoped layer can be determined. The thus obtained Fs are subject to photovoltaic effect and are less than built-in field F_{bi}. In the previous work we have obtained the relation $F \approx F_{\mathrm{bi}} - \delta F/2$ when $\delta F \ll F_{\mathrm{bi}}$ by using electroreflectance to simulate PR, where δF is the modulating field of the pump beam. In this work a method was devised to evaluate δF by using photoinduced voltages V_s and, hence, the relation can be verified by PR itself. The δFs obtained by V_s are also consistent with those of using imaginary part of fast Fourier transform of PR spectra. [DOI: 10.1063/1.1453492]

I. INTRODUCTION

Modulation spectroscopy[1–5] 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 photoreflectance (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] 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.[7–11] The F of the s-i-n^+ sample can thus be determined by using the fast Fourier transform technique (FFT).[12,13]

Although PR has the advantage of being contactless, it cannot exclude the photovoltaic effect from the pump and probe beams,[7,14] especially from the pump beam for its higher intensity. The photoinduced voltage V_s, which was produced by electron-hole pairs generated by the pump and probe beams, will oppose the original built-in voltage. Hence, the strength of F in the depletion region is reduced. However, it is generally difficult to determine modulating field δF in the PR measurements. The previous method of obtaining δF is comparing PR spectra at various power of the pump beam P_{pu}.[9,15] Since V_s and, hence, δF is proportional to logarithm of P_{pu}, P_{pu} needs to be reduced by several orders to neglect the effect of pump beam. In such a low power, it needs to take long time to accumulate the signal to increase the signal to noise ratio.

In the previous work we have obtained relation $F \approx F_{\mathrm{bi}} - \delta F/2$ when $\delta F \ll F_{\mathrm{bi}}$ by using ER to simulate PR,[16] where F_{bi} is the built-in field of the sample. In this work the relation will be verified by PR itself. A method was devised to obtain the strength of δF in the PR by using V_s, which was measured directly with a lock-in amplifier through electrical contacts on the sample. Due to uniformity of F in the undoped layer of s-i-n^+ GaAs, δF is evaluated as V_s/d, where d is the thickness of the undoped layer.

Furthermore, the δFs obtained from V_s were verified by the method of Alperovich's,[17] which uses imaginary part of FFT to determine the strength of δF in the ER measurements.

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 μm n^+ doped GaAs buffer layer was first grown on this substrate, followed by a 1200 Å 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 Å. The ohmic contact was fabricated on the rear side of the sample by depositing Au–Ge alloy.

The experimental setup for the PR or ER measurements, which was similar to that previously described in the 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. An Ar ion laser of the 488 nm line was used as the pump beam in the PR measurements. A combination of a square wave and a dc bias was applied to the sample in the ER measurements.

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III. THEORY

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

$$\frac{\Delta R}{R}=\alpha(\varepsilon_1,\varepsilon_2)\,\delta\varepsilon_1+\beta(\varepsilon_1,\varepsilon_2)\,\delta\varepsilon_2, \tag{1}$$

in which α and β are the Seraphin coefficients, and $\delta\varepsilon_1$ and $\delta\varepsilon_2$ are the modulation induced changes in the real and imaginary parts, respectively, of the complex dielectric function. Near the band edge, E_0, of GaAs, $\beta\approx 0$ and $\Delta R/R \approx \alpha\delta\varepsilon_1$.

In the case of a flatband condition under an electric field F, $\Delta\varepsilon$ is defined as

$$\Delta\varepsilon(E,F)=\varepsilon(E,F)-\varepsilon(E,0), \tag{2}$$

where E is the photon energy.

Near the E_0 transition of GaAs, $\Delta\varepsilon$ is given by[7]

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

where $i=$hh or lh, 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

$$\eta\theta_i=(e^2\hbar^2F^2/2\mu_i)^{1/3}, \tag{4}$$

in which $\mu_{\mathrm{hh}}(\mu_{\mathrm{lh}})$ is the reduced mass of heavy (light) hole and electron in the direction of F.

In the case of a uniform built-in electric field F_{bi} and a modulation field δF, it was proposed that[5]

$$\begin{aligned}\delta\varepsilon^{\mathrm{PR}}(E,F_{\mathrm{bi}})&=\varepsilon(E,F_{\mathrm{bi}})-\varepsilon(E,F_{\mathrm{bi}}-\delta F)\\&=\Delta\varepsilon(E,F_{\mathrm{bi}})-\Delta\varepsilon(E,F_{\mathrm{bi}}-\delta F).\end{aligned} \tag{5}$$

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

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

where $i=$hh or lh, respectively.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

The PR spectra of s-i-n^+ GaAs and their corresponding FFT for various V_s are shown in Figs. 1 and 2, respectively. There are many FKOs 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 FKOs, especially apparent in the PR spectra of low values of V_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 light-hole transitions, respectively.

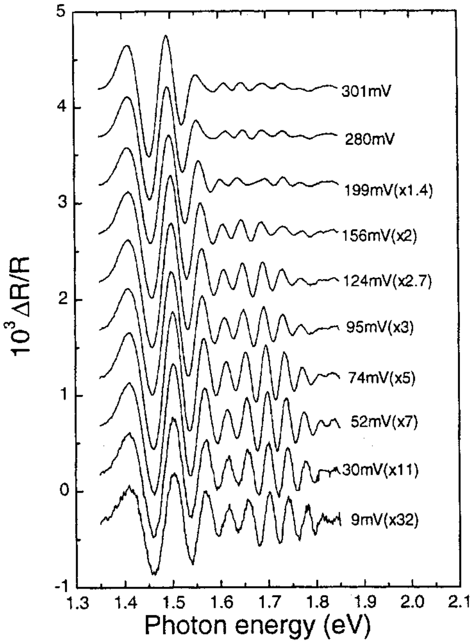

FIG. 1. Photoreflectance spectra at various photoinduced voltages (V_s) of the pump beam.

We have used ER to simulate PR to study the relation between F and δF, i.e., $F\approx F_{\mathrm{bi}}-\delta F/2$ when $\delta F \ll F_{\mathrm{bi}}$,[16] where δF was determined from the magnitude of applied ac voltage divided by the undoped layer thickness. In this work, we will verify this relation by using PR itself instead of using ER to simulate PR. Here a method was devised to obtain δF in the PR measurements. By making electrical contacts on the front and rear sides of the sample, V_s of the pump beam was measured directly with a lock-in amplifier. Because of

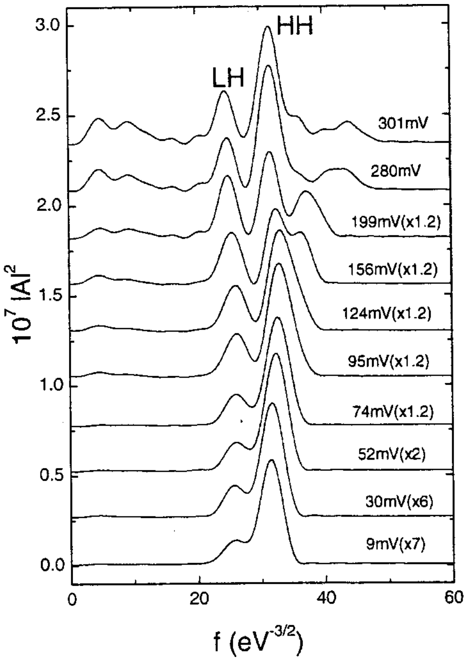

FIG. 2. The fast Fourier transform of Fig. 1, where HH and LH denote heavy and light hole transitions, respectively.

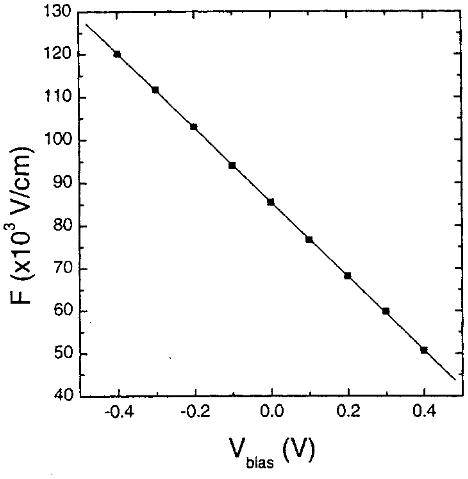

FIG. 3. The strengths of the electric field (F) in the undoped layer are plotted against V_{bias}. The solid line is a linear fitting to the equation, $F = F_{\mathrm{bi}} - V_{\mathrm{bias}}/d$ and the value of d is 1151 Å.

uniformity of F in the undoped layer, the strength of δF can be evaluated as $\delta F = V_s/d$, where d is the thickness of the undoped layer.

The value of d can be determined in the following way. The ER spectra for various biased voltage V_{bias} were measured and their Fs were deduced from the periods of FKOs of ER spectra. The thus obtained Fs are plotted against V_{bias} as shown in Fig. 3. The relation between them is very linear to confirm the uniformity of F in the undoped layer. From the fitting line $[F = F_{\mathrm{bi}} - V_{\mathrm{bias}}/d]$, the value of d was determined to be 1151 Å.

According to Eq. (6), the evaluated F vs δF is shown in Fig. 4. In region when $\delta F \ll F_{\mathrm{bi}}$, the data are fitted by a line whose equation is expressed as $F = 84043\ \mathrm{V/cm} - 0.53 \times \delta F$. This is consistent with the previous result of using ER to simulate PR. If this relation does not hold, it is either because this relation does not exist in the PR measurements or the use of V_s/d as δF is not appropriate. On the contrary, this relation does hold within the error of our experimental results and hence the use of V_s/d as δF is acceptable. For the other regions of δF, the relation between F and δF is similar to the previous result.

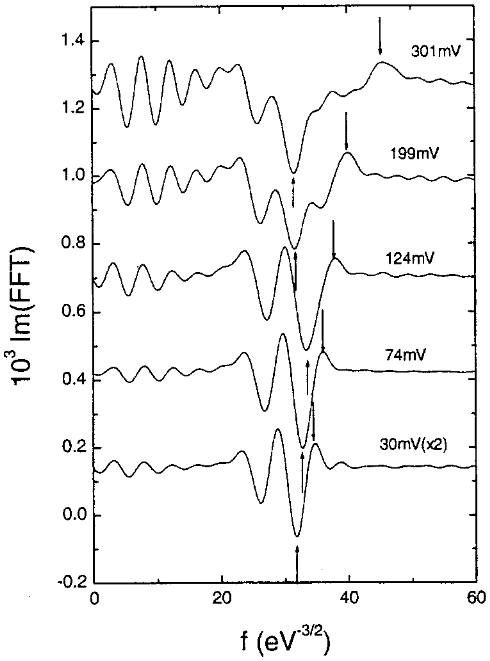

FIG. 5. The imaginary part of the FFT of PR spectra at various photovoltage with amplitude V_s. The up and down arrows indicate the positions of peaks corresponding to F and $F - \delta F$ of heavy-hole transitions, respectively.

In addition, the results were verified by Alperovchi's method,[17] that is, the peaks corresponding to $F + \delta F/2$ and $F - \delta F/2$ can be specified in the imaginary part of FFT of PR spectra. The imaginary part of FFT of PR spectra for various P_{pu} are shown in Fig. 5. The strengths of $F + \delta F/2$ and $F - \delta F/2$ can be evaluated according to Eq. (6) and their difference is equal to modulating field δF_{im}. The thus obtained

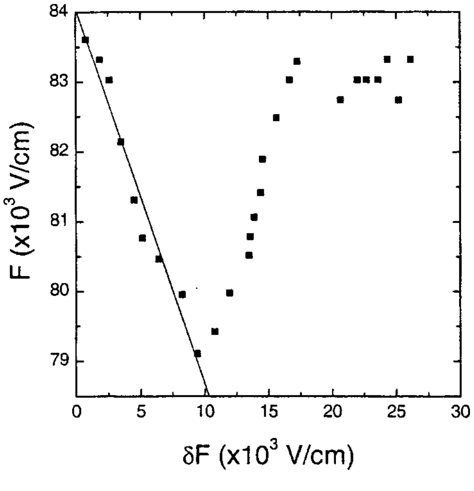

FIG. 4. The strengths of the electric field (F) in the undoped layer are plotted against δF, where δF is taken from V_s/d. The straight line is a linear fitting to the data for $\delta F < 10\,000$ V/cm and its slope is 0.53.

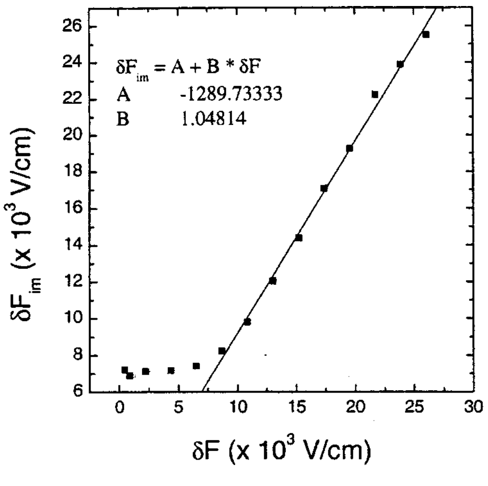

FIG. 6. δF_{im} were evaluated from the peak positions in Fig. 5 according to Eq. (6). δF were evaluated from V_s/d. The solid line is a linear fitting to the data for $\delta F > 8000$ V/cm and its slope is 1.05.

δF_{im} vs δF obtained from photovoltage measurements is shown in Fig. 6. The slope of the fitting line is 1.05 for $\delta F > 8000\ \mathrm{V/cm}$. This means that δF obtained from V_s/d agrees well with that obtained from imaginary part of FFT of PR spectrum in this region. When $\delta F < 8000\ \mathrm{V/cm}$, the evaluated δF_{im} becomes almost unchanged and is larger than δF. This can be explained by that all peaks in the imaginary part of FFT have an intrinsic width due to finite range of PR spectra. When δF becomes smaller, the relative contribution of intrinsic width becomes larger.[16]

V. CONCLUSIONS

In summary, we have verified the relation between F and δF by using PR itself. A method was devised to evaluate δF by using photoinduced voltages V_s. The δF can be evaluated as V_s/d because of uniformity of F in the undoped layer. The thus obtained δFs were consistent with those obtained by imaginary part of FFT of PR spectra.

ACKNOWLEDGMENT

The authors acknowledge the support of the National Science Council of Taiwan, Republic of China, under Contract No. NSC 89-2112-M-110-022.

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