AIP Applied Physics Letters

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Citation: Applied Physics Letters **74**, 475 (1999); doi: 10.1063/1.123040
View online: http://dx.doi.org/10.1063/1.123040
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/74/3?ver=pdfcov
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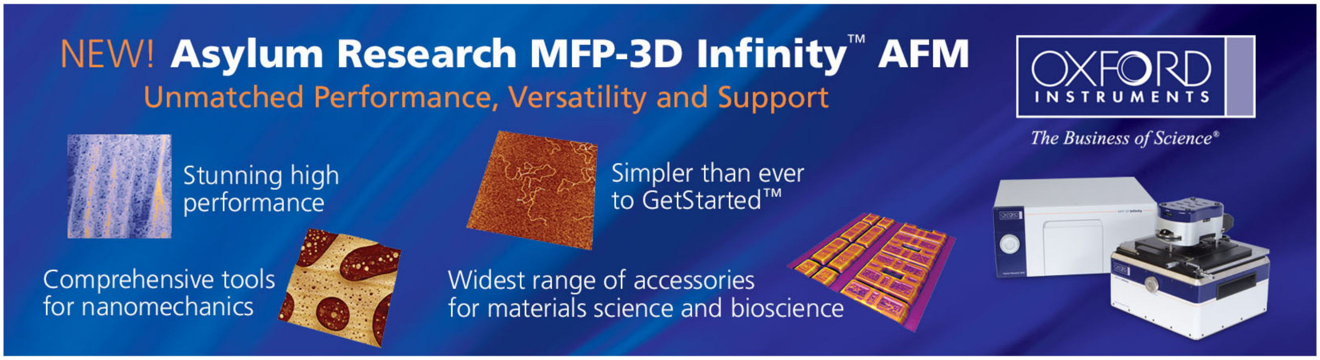

APPLIED PHYSICS LETTERS VOLUME 74, NUMBER 3 18 JANUARY 1999

Determination of built-in field by applying fast Fourier transform to the photoreflectance of surface-intrinsic n^+-type doped GaAs

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(Received 6 July 1998; accepted for publication 10 November 1998)

Photoreflectance spectroscopy of surface-intrinsic n^+-doped (s-i-n^+) GaAs has been measured at various power densities (P_{pu}) of a pump beam. Many Franz–Keldysh oscillations (FKOs) were observed above the band-gap energy, which will enable the electric-field strength *(F)* to be determined from the periods of the FKOs. Field F thus obtained is subject to photovoltaic effects. In order to reduce the photovoltaic effects from the pump beam, P_{pu} was kept below 10 μW/cm^2 in the previous experiments. Here, we demonstrate that the built-in field can be determined at a larger P_{pu} by using fast Fourier transform techniques. © *1999 American Institute of Physics.* [S0003-6951(99)02803-X]

Modulation spectroscopy[1–4] 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 surface or interface electric fields. Photoreflectance (PR) uses a laser as a pump beam to modulate the electric-field strength of samples and is thought to be a form of contactless electroreflectance (ER). Compared with ER, PR has the advantage of not needing to fabricate Ohmic contacts and Schottky barriers to make electrical contacts.

For a medium field strength, the PR 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.[5] It is known that the PR of surface-intrinsic n^+-type doped (s-i-n^+) GaAs exhibit many FKOs, which were attributed to the existence of a uniform F in the undoped layer.[6–10] The F of the s-i-n^+ sample can thus be more accurately determined.

Although PR has the advantage of being contactless, it cannot exclude the photovoltaic effect from the pump and probe beams,[6,10] especially from the pump beam, for its higher intensity. The photovoltage, which was produced by electron–hole pairs generated by the pump and probe beams, will oppose the original built-in voltage. Hence, the F in the depletion region is reduced and almost equal to $F_{\mathrm{bi}} - \delta F/2$ when $\delta F \ll F_{\mathrm{bi}}$, where δF is the strength of the modulating field and F_{bi} is the built-in field of the sample.[10] Therefore, in order to reduce the photovoltaic effect, the power densities of the pump and probe beams were kept below 10 μW/cm^2 in the previous measurements.[7] However, when using such low power density, a long time is required to accumulate enough signal.

The F deduced from FKOs can be obtained either by the conventional method or by applying the fast Fourier transform (FFT) technique to the PR spectra.[11,12] The method of FFT has several advantages over the conventional method. The first is the unambiguous reduced mass in the determination of F. The second is that even if the signal was too poor to be analyzed by the conventional method, the FFT transformed spectra can still be resolved into two clearly separated peaks. The third is that if there are more than one field existing in the signals, they can be resolved in the transformed spectra. Besides those, it will be demonstrated here that F can be determined at a larger power density (P_{pu}) of the pump beam by using the FFT technique.

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 μm 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 hot filament evaporation and the thickness estimated to be about 70 Å.

The experimental setup for the PR measurements, which was similar to that previously described in the literature,[13] 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. The sample was modulated at 400 Hz by a He–Ne laser, which was also defocused. The photodiode signal was composed of a dc component (R) and an alternating current (ac) component (ΔR). The direct current (dc) component (R) was measured by an analog-to-digital converter card of an IBM compatible personal computer. The output of the photodiode was also fed into a lock-in amplifier to measure the modulated ac signal *(*ΔR*)*. The entire system was controlled by the personal computer.

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

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

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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 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 flatband condition under an electric-field F, $\Delta\epsilon$ is defined as

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

where E is the photon energy.

Near the E_0 transition of GaAs, $\Delta\epsilon$ is given by[14]

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

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

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

in which μ_{hh} and μ_{lh} are the reduced masses of heavy holes, light holes, and electrons in the direction of F, respectively.

In the case of a uniform built-in electric-field F_{bi} and a modulation field δF, it was proposed that[13]

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

The conventional method for determining F from FKOs is to use asymptotic expressions of the Airy function in Eq. (3). The extrema of FKOs are given by

$$n\pi=\varphi+\tfrac{4}{3}[(E_n-E_g)/\hbar\theta]^{3/2}, \tag{6}$$

in which n is the index number of the nth extremum, φ is an arbitrary phase factor, E_n is the corresponding energy, and $\hbar\theta=(e^2\hbar^2F^2/2\mu)^{1/3}$. Here, μ is also the reduced mass of electrons and holes, but needs to take into consideration the contributions of both heavy and light holes. A plot of $(E_n-E_g)^{3/2}$ vs n yields a straight line with a slope proportional to F.

An alternative way to obtain electric fields is to apply the FFT to the PR spectra. This approach has the advantage of determining F without the ambiguity of choosing reduced mass. The frequency f_i evaluated from the Fourier transform is related to F by

$$f_i=\frac{2}{3\pi}(2\mu_i)^{1/2}\left(\frac{1}{e\hbar F}\right), \tag{7}$$

where $i=$hh or lh, respectively.

The PR spectra were measured at various P_{pu} ranging from 10 μW/cm^2 to 30 mW/cm^2, and the corresponding FFTs are shown in Figs. 1 and 2, respectively. There are many FKOs observed above the band-gap energy and this is due to a uniform field existing in the undoped layer. The beat in the FKOs, especially apparent in the PR spectra of low P_{pu}, results from the different oscillation frequencies associated with the transitions of the heavy and light holes, due to the different μ values.

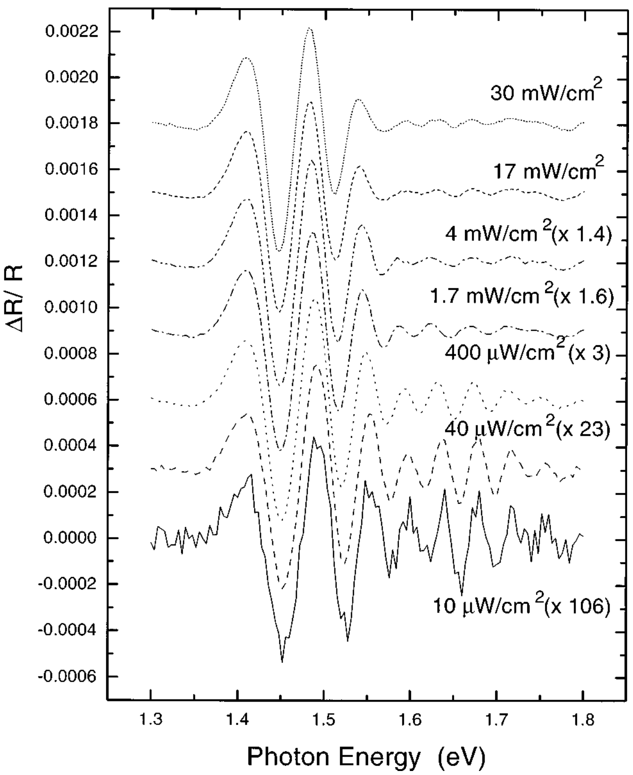

FIG. 1. Photoreflectance spectra of the s-i-n^+ GaAs sample at various pump power density (P_{pu}).

The F's obtained from the conventional and FFT methods are shown in Fig. 3. Those obtained from the conventional method show a decrease as P_{pu} is increased. This is known as the photovoltaic effect. While those obtained from FFT also decrease with increasing P_{pu} when P_{pu} is less than 4 mW/cm^2, as P_{pu} becomes larger than 4 mW/cm^2, F is

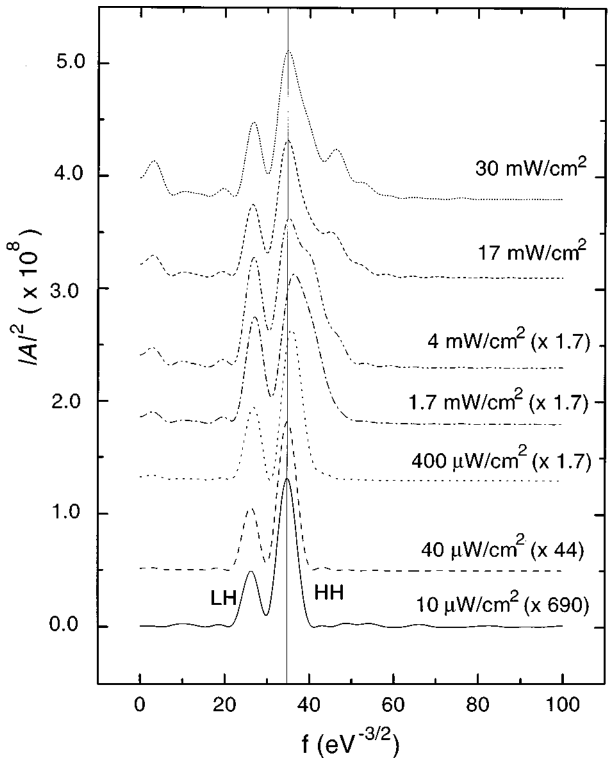

FIG. 2. The fast Fourier transformed spectra of Fig. 1.

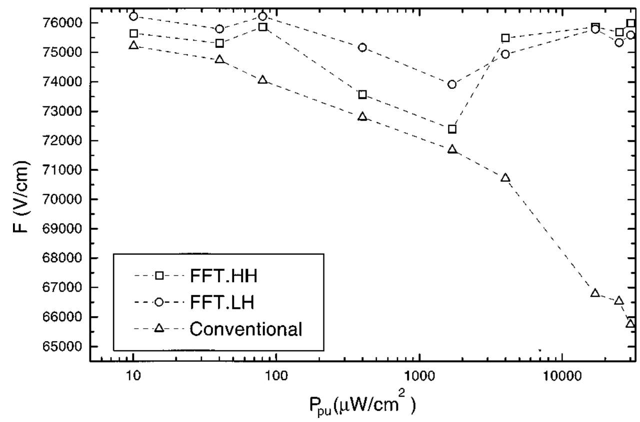

FIG. 3. The experimentally obtained strength of the electric-field *(F)* vs the pump power density (P_{pu}). The squares, circles, and the triangles represent the data obtained by the technique of FFT using the heavy- and light-hole transitions and the conventional method, respectively. The reduced masses, μ_{hh}, μ_{lh}, and μ used to calculate F are 0.0585, 0.034, and 0.055 m_0, respectively, where m_0 is the mass of free electrons.

increased and becomes almost equal to that of the lowest P_{pu}.

As shown in Fig. 2, for the low value of P_{pu} ($P_{\mathrm{pu}} < 4$ mW/cm^2), the FFT spectra exhibit two well-separated peaks corresponding to heavy- and light-hole transitions, respectively. However, as P_{pu} is increased, the peaks become broadened, and the value of the center of the heavy hole peak shifts to a larger value. According to Eq. (7), this means that F becomes smaller as P_{pu} is increased. However, when P_{pu} is larger than 4 mW/cm^2, the heavy-hole transition of FFT spectra becomes separated into two peaks, and the position of the main peak is almost equal to that of the lowest P_{pu}. If the value of the center of the main peak was used to calculate F, then the evaluated value will be close to that of the lowest P_{pu}.

According to Eq. (5), $\delta\epsilon^{\mathrm{PR}}$ is the difference between $\Delta\epsilon_1(E,F_{\mathrm{bi}})$ and $\Delta\epsilon_1(E,F_{\mathrm{bi}}-\delta F)$. When $\delta F \ll F_{\mathrm{bi}}$, the FKOs have slightly different frequencies. Hence, the peaks corresponding to $\Delta\epsilon_1(E,F_{\mathrm{bi}})$ and $\Delta\epsilon_1(E,F_{\mathrm{bi}}-\delta F)$ will be merged into one peak, but as δF is increased, the merged peak will become broadened. The value of the center of the merged peak will be close to the one corresponding to $\Delta\epsilon_1(E,F_{\mathrm{bi}}-\delta F/2)$. Hence, F is almost equal to $F_{\mathrm{bi}}-\delta F/2$ when $\delta F \ll F_{\mathrm{bi}}$. When δF is large enough ($P > 4$ mW/cm^2), the frequencies of $\Delta\epsilon_1(E,F_{\mathrm{bi}})$ and $\Delta\epsilon_1(E,F_{\mathrm{bi}}-\delta F)$ are so different that they become separated. Also, the amplitude of $\Delta\epsilon_1(E,F_{\mathrm{bi}})$ becomes much larger than that of $\Delta\epsilon_1(E,F_{\mathrm{bi}}-\delta F)$ so that $\Delta\epsilon_1(E,F_{\mathrm{bi}})$ will be more dominant as δF is increased. Hence, if δF is large enough that the heavy-hole transition can be separated into two peaks, the F evaluated from FFT is close to that of the lowest P_{pu}.

In contrast to the splitting of the heavy-hole transition, no separation of the light-hole transition is seen in Fig. 2. This is because when δF is increased, the overlap between the heavy- and light-hole transitions is increased and also the amplitude of $\Delta\epsilon_1(E,F_{\mathrm{bi}}-\delta F)$ of the light-hole transition is much smaller than that of $\Delta\epsilon_1(E,F_{\mathrm{bi}})$ of the heavy-hole transition. Hence, the former is buried in the latter so that no splitting of the light-hole transition can be observed.

In conclusion, the PR of $s-i-n^+$ GaAs has been measured at various P_{pu}. The F evaluated from the conventional method shows a decrease as P_{pu} increases. This is known as the photovoltaic effect. We have demonstrated that if P_{pu} is so large that the heavy-hole transition of FFT can be separated into two peaks, F is obtained to be equal to that of the lowest P_{pu}. Hence, F_{bi} can be obtained by using larger P_{pu}.

The authors acknowledge the support of the National Science Council of Taiwan, Republic of China, under the Contract No. NSC 88-2112-M-110-003.

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