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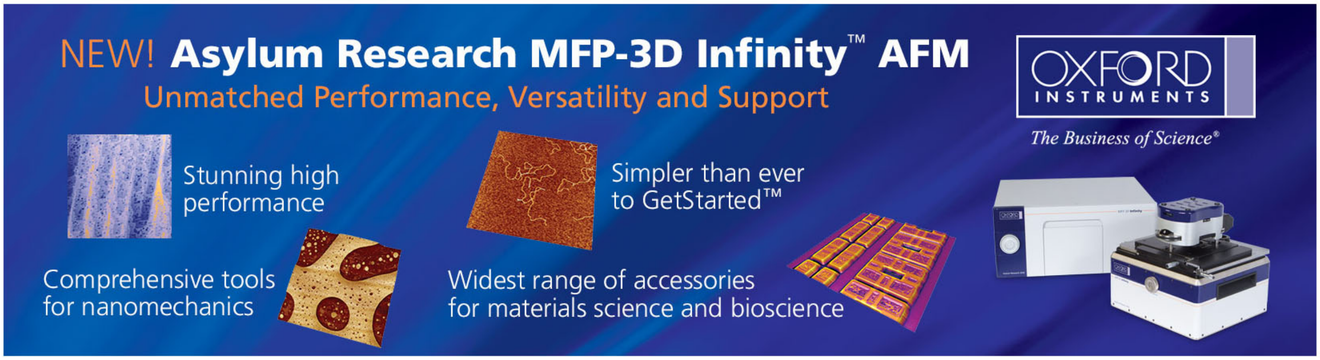

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Critical point energy as a function of electric field determined by electroreflectance of surface-intrinsic-n^+ type doped GaAs

Y. S. Chen, K. S. Wu, and D. P. Wang[a]
Department of Physics, National Sun Yat-Sen University, Kaohsiung, 80424, Taiwan, Republic of China

K. F. Huang and T. C. Huang
Department of Electro-Physics, National Chiao-Tung University, Hsinchu, Taiwan, Republic of China

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Electroreflectance of surface-intrinsic-n^+ type doped GaAs has been measured over a various biased voltage. The spectra have exhibited many Franz–Keldysh oscillations (FKOs) above band gap energy E_g. The electric field F and critical point energy E_c can be determined from the slope and intercept of FKOs fitting. Hence, we can obtain E_c as a function of F. In most of previous works, E_c is taken as E_g. However, it was found that E_c increases with F in this work. In order to explain this, the gain of energy of electron and hole in F was discussed. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1814794]

Modulation spectroscopy[1–5] is an important technique for the study and characterization of semiconductor properties. 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. They can yield sharp structures around the critical points, where the joint densities of states are singular. In most cases, the energy of the critical point, E_c, is taken as band gap energy, E_g. In this work, we will show that E_c is not necessarily equal to E_g but it is dependent on the strength of electric field, F.

For a medium field strength, the PR or ER spectra exhibit Franz–Keldysh oscillations (FKOs) above E_g. The electric-field strength F in the depletion region can be deduced from 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.[7–12] The value of F and E_c of the s-i-n^+ sample can thus be determined more precisely by the slope and intercept of linear fitting. Hence, the value of E_c as a function of F can be obtained.

The s-i-n^+ GaAs sample used in this experiment was grown on an 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 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. A combination of a square wave V_{ac} and a dc biased voltage V_{bias} was applied to the sample in the ER measurements.

In the intermediate field region, the FKO becomes prominent. The oscillatory behavior at $E > E_g$ can be described by an electro-optic function, whose asymptotic form can be written as[12]

$$\Delta R/R \approx \frac{B(\hbar\theta)^{3/2}}{E^2(E-E_c)}\exp\left[-2\frac{(E-E_c)^{1/2}}{(\hbar\theta)^{3/2}}\Gamma\right] \times\cos\left[\pi\frac{d-1}{4}+\frac{4}{3}\left(\frac{E-E_c}{\hbar\theta}\right)^{3/2}\right], \tag{1}$$

where $(\hbar\theta)^3 = e^2\hbar^2F^2/2\mu$, μ is the reduced mass of hole and electron in the direction of F, E is the photon energy, Γ is the broadening parameter, and d is the dimensionality of the critical point.

The nth extrema in FKOs from Eq. (1) are given by

$$\pi\frac{d-1}{4}+\frac{4}{3}\left(\frac{E_n-E_c}{\hbar\theta}\right)^{3/2} = n\pi, \tag{2}$$

where $d=3$ for the three-dimensional critical point and n is the index number of the nth extremum, and E_n is the energy of the nth oscillation extremum.

Or it can be reduced to

$$E_n = E_c + \left[\frac{3\pi}{2}\left(n+\frac{1}{2}\right)\right]^{2/3}\left(\frac{e^2F^2\hbar^2}{8\mu}\right)^{1/3}, \tag{3}$$

where $n=0,1,2,\ldots$ The plot of E_n vs $\{(3\pi/2)[n+(1/2)]\}^{2/3}$ yields a straight line whose slope is proportional to $F^{2/3}$ and y-axis intercept is equal to E_c. Due to the contributions of both heavy and light holes, the value of μ is taken as $0.55\ m_0$.

The lifetime of electron-hole is estimated to be $\hbar/\Gamma$ from uncertainty principle. The mean momentum gained by the electron or hole in the electric field F is $eF(\hbar/2\Gamma)$ or $-eF(\hbar/2\Gamma)$, respectively ($e<0$). The plus or minus sign comes from the negative or positive charges of electron or hole. The momentum of electron or hole will be $\hbar k + eF(\hbar/2\Gamma)$ or $\hbar k - eF(\hbar/2\Gamma)$, and their energy $E_c(k)=E_g$

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[a] Electronic mail: wang@mail.phys.nsysu.edu.tw

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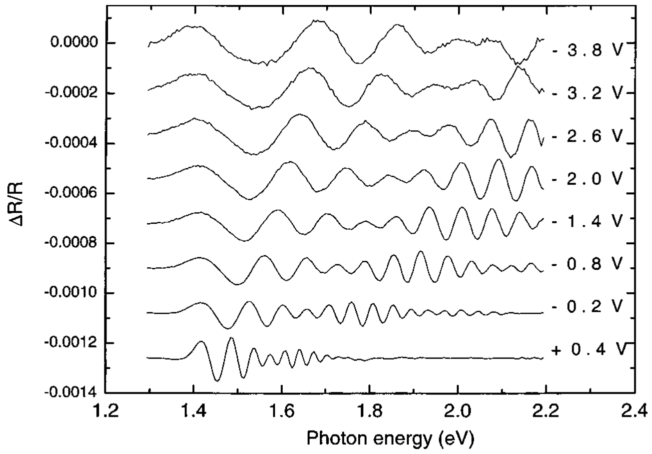

FIG. 1. The ER spectra of *s-i-n*$^+$ GaAs for $V_{ac}=50$ mV of various V_{bias}.

$+[\hbar k+eF(\hbar/2\Gamma)]^2/2m_e$ or $E_v(k)=-[\hbar k-eF(\hbar/2\Gamma)]^2/2m_h$ around $k\approx 0$, respectively. Hence, the energy difference between conduction and valence bands is

$$\Delta E(k) = E_g + \left(\hbar k + eF\frac{\hbar}{2\Gamma}\right)^2 \Big/ 2m_e + \left(\hbar k - \frac{eF\hbar}{2\Gamma}\right)^2 \Big/ 2m_h. \qquad (4)$$

The critical point, where $d\Delta E(k)/k=0$, will no longer be at point $k=0$. Taking the derivative of $\Delta E(k)$ with respect to k, the zeros will be at $k_0=\mu(eF/\Gamma)[(1/m_h)-(1/m_e)]$. The value of ΔE at this point is equal to $\Delta E(k_0)$.

The ER spectra of *s-i-n*$^+$ GaAs of various V_{bias} are shown in Fig. 1. 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 Γ in the undoped layer. The beat in the FKOs results from the different oscillation frequencies associated with the transitions of the heavy and light holes, due to different μ values.

According to Eq. (3), the conventional FKOs fitting are shown in Fig. 2. The values of F's can be evaluated from the slopes of the fitting lines. The thus obtained F's are plotted against V_{bias} as shown in Fig. 3. This relation is nearly linear to confirm the uniformity of F in the undoped layer. The equation of fitting line is

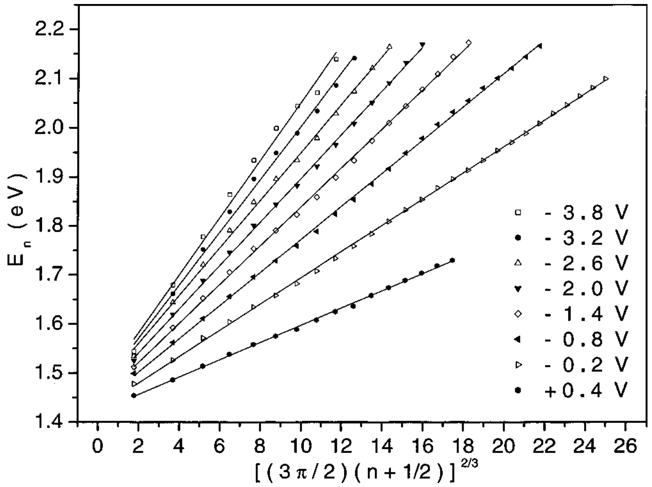

FIG. 2. Plot of E_n as a function of $\{(3\pi/2)[n+(1/2)]\}^{2/3}$, the values of E_c and F can be evaluated from the intercepts at the y axis and the slopes of the fitting lines.

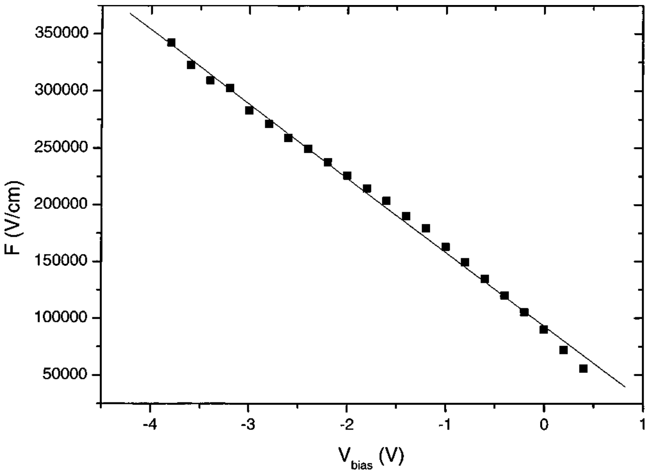

FIG. 3. The strengths of the electric field (F) in the undoped layer are plotted against V_{bias}. The solid line is a linear fitting to the data.

$$F(\text{V/cm}) = -65131V_{bias}(V) + 93142. \qquad (5)$$

In addition to F, the value of E_c can be obtained by the y-axis intercepts of the fitting lines in Fig. 2. The thus obtained values of E_c are plotted against F as shown in Fig. 4. Instead of being a constant, which was taken as E_g in previous works, the value of E_c increases with F. In order to explain the dependence, the momentum gained in F was considered. They are calculated according to Eq. (4) and the result is shown in Fig. 4 for $\Gamma=20$, 30, and 40 meV, respectively. The larger Γ is, the lifetime of electron and hole becomes shorter so that the gain of energy becomes smaller. The agreement between experimental and theoretical result of $\Gamma=30$ meV is good except in the higher F region, where experimental result does not increase as much as that of theoretical ones. This discrepancy can be attributed to assuming the constant value of Γ, which will become larger in the higher F region because of shorter lifetime. In addition, the value of $\Gamma=30$ meV is larger than those obtained from PR line shape fitting, which in general give a result around 10 meV.[13] This is reasonable because only the order of lifetime can be estimated from uncertainty principle.

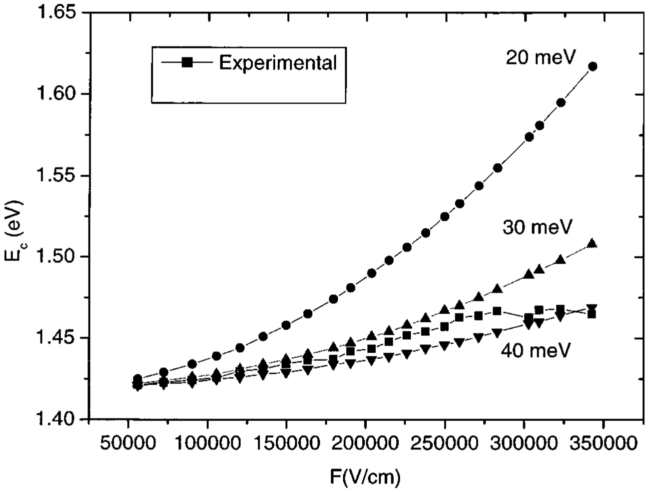

FIG. 4. The values of E_c as a function of F for various Γ.

In summary, we have measured ER of various V_{bias}. The critical point energy E_c and the strengths of field F can be deduced from the conventional FKOs fitting. Hence, we can obtain E_c as a function of F. It shows an increase with F. This can be explained by including the effect of the gain of energy in the electric field F.

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