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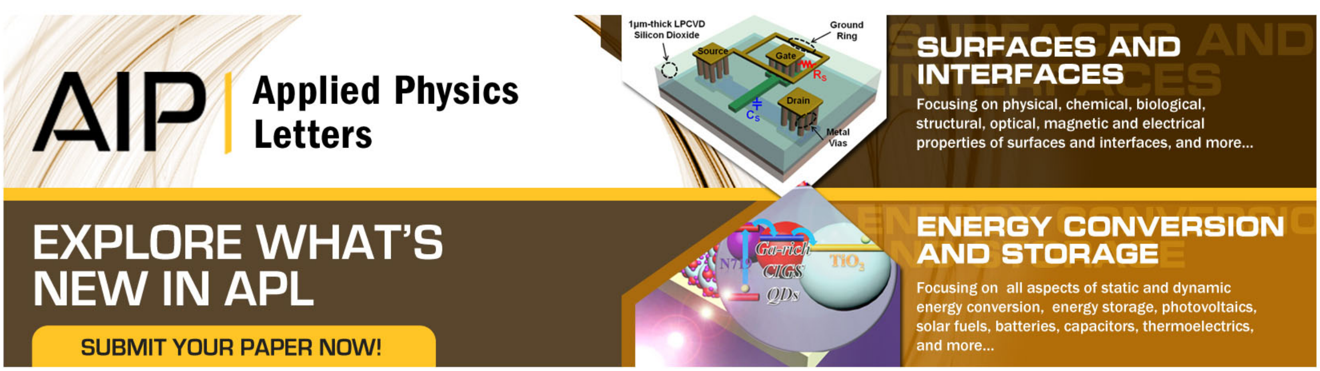

Photoreflectance study of surface Fermi level in GaAs and GaAlAs

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Franz–Keldysh oscillations from GaAs and AlGaAs structures have been studied and we find that the electric field obtained from the oscillations is in agreement with that derived from electrostatic calculations. Our results show that illumination from pump and probe beams in a normal photoreflectance experiment can significantly affect the measurement and thus erroneously lead to a reduced value of the electric field. The Fermi level on the bare surface of AlGaAs with different Al mole fraction has also been determined.

Photoreflectance (PR)[1–3] is used extensively in the study of semiconductor microstructures. There has recently been growing interest in the use of Franz–Keldysh oscillations (FKOs)[1,4] to determine the surface and or interface electric field,[4–7] crystal quality,[7,8] doping concentration,[4] surface Fermi level (E_{pin}), and/or its relative changes ($\Delta E_{\text{pin}}/E_{\text{pin}}$) under different surface treatments.[9,10] While $\Delta E_{\text{pin}}/E_{\text{pin}}$ can be accurately determined,[10] the determination of the absolute value of the E_{pin} is difficult as it depends on doping concentration and its distribution. Recently Van Hoof *et al.*[11] have used a special structure with a surface electric field almost independent of doping concentration. In their report, however, the electric field deduced from FKO is only half the value of the "real field" derived from an electrostatic calculation using $E_{\text{pin}} = 0.7$–0.8 eV. Other studies[10,12] measuring E_{pin} using PR report values less than 0.7 eV. A reexamination of the FKO technique for measuring built-in field thus appears necessary.

Here we report measurements on GaAs structures similar to those in Ref. 11 which reaffirm the usefulness of FKO. Our experiments demonstrate that illumination in a normal PR experiment can significantly affect the measurement, leading to an erroneously reduced value of electric field. Extreme caution must be exercised in the determination of the low field condition and previous anomalous results reassessed. The surface Fermi level pinning (E_{pin}) of bare GaAlAs surface as a function of Al mole concentration will also be presented. The Schottky barrier height of Au on GaAlAs has been measured by Best,[13] but to the best of our knowledge this is the first measurement in GaAlAs using a contactless method.

An undoped top layer of GaAs (or $Ga_{1-x}Al_xAs$) of thickness d was grown by molecular beam epitaxy (MBE) on n^+-(100) GaAs substrates with an n^+-doped 1.0-μm-thick GaAs (or $Ga_{1-x}Al_xAs$) buffer layer. Samples with different thicknesses and Al mole fractions as well as different growth conditions were studied. The conduction-band configuration is schematically shown in Fig. 1. The electric field in the top undoped layer given by the slope of the band edge is created by positive charges in the depleted region of the n^+ layer and negative charges trapped in the surface states. Neglecting the deviation from constant slope due to small background doping in the undoped layer, the field is E_{pin}/qd, where q is the electron charge. The small band bending in the n^+ layer was calculated from the measured electric field and found to be small. The major advantages of surface-insulating-n^+ (SIN$^+$) structure are (a) a combination of high electric field and small broadening parameter, leading to a slow damping[2] of FKO and allowing more accurate determination of the electric field; (b) the surface Fermi level derived from the field is insensitive to the n^+ concentration; (c) the field in the top layer, the major cause of error in E_{pin} determination, is controllable by the thickness d which is known to better than 3% from RHEED.

Photoreflectance spectra[14] are taken at room temperature. The probe beam is from a tungsten lamp and quarter-meter monochromator combination attenuated by neutral density filters. This beam is DEFOCUSED on the sample to further reduce the power density. The pump beam is from an air-cooled Ar^+ laser with attenuation and defocusing. The power density for the probe and pump beam is less than 0.1 $\mu W/cm^2$. Use of such low-power density reduces photon-induced flattening of band bending and allows determination of E_{pin} under the unperturbed condition.

Shown in Fig. 2 (a) are the PR spectra from a SIN$^+$ GaAs structure with $d = 2000$ Å. FKO from E_0 and $E_0 + \Delta_0$ gap are observed up to the 20$^{\text{th}}$ extrema. The reduction of the amplitude at the 6$^{\text{th}}$ extrema is due to the interference between the oscillations arising from heavy and light hole subbands. The large number of extrema enables accurate determination of the electric field. We do not fit the experimental spectra with published theoretical line shapes, unlike Ref. 11, since functions G and F in Refs. 1–3 are derived for modulation from flatband condition and functions G and F in Ref. 4 are for nonuniform field from depletion layer under small modulation; neither line shape being suitable for our experiments on SIN$^+$ struc-

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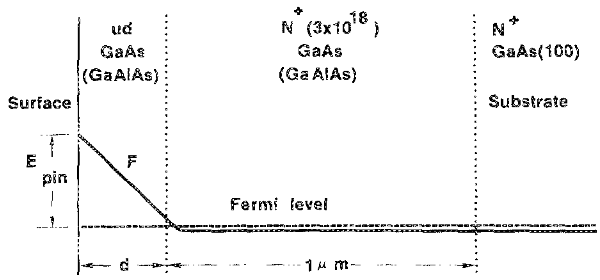

FIG. 1. Schematic representation of the conduction-band configuration in a SIN$^+$ structure.

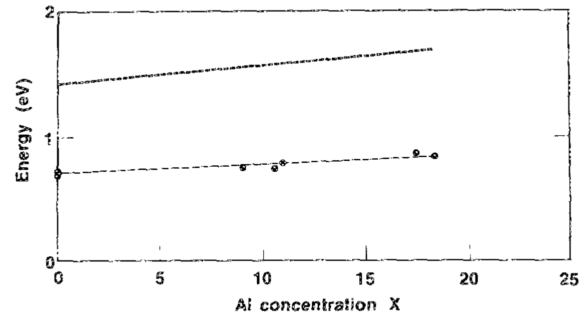

FIG. 3. Energy gap E_0 (dotted line) and the surface Fermi level (dashed line) from bare $Ga_{1-x}Al_xAs$ surface as a function of Al mole fraction x.

tures in which the FKO comes from a small modulation on a uniform built-in field. The correct line shape is the first derivative of G and F with respect to the electric field. A detailed derivation[15] proved rigorously that the period of FKO under such a condition is a function of the built-in electric field. The extrema in FKO are given by[4]

$$m\pi=\phi+(4/3)[(E_m-E_g)/\hbar\theta]^{3/2}, \tag{1}$$

and can be used to determine the electric field. Here m is the index of the mth extrema, ϕ is an arbitrary phase factor, E_g is the energy gap, E_m is the photon energy of the mth extrema, and $\hbar\theta$ is the electro-optical energy:

$$(\hbar\theta)^3=e^2\hbar^2F^2/2\mu, \tag{2}$$

with μ the reduced interband effective mass for electron and heavy hole pair in the direction of electric field F. Plotted in Fig. 2(b) by squares is the quantity $(4/3\pi)(E_m-E_g)^{3/2}$ as a function of m for the spectrum Fig. 2(a). The solid line is a linear fit to Eq. (1), which yields $\hbar\theta$ from which the electric field can be deduced. The surface Fermi level for all GaAs samples was 0.72 ± 0.05 eV, in good agreement with other determinations.[16] Therefore, the electric field measured from FKO in our samples, under our experimental conditions, is in agreement with the value derived from electrostatic calculations.

Photoreflectance has also been performed on SIN$^+$ GaAlAs structures with different Al mole concentrations. Similar spectra with FKO from E_0 and $E_0+\Delta_0$ are observed. The built-in electric field is deduced from Eq. (1) using[17] $m_{el}^*=0.067+0.083x$ and $m_{hh}^*=0.45+0.014x$, where m_{el}^*, m_{hh}^* are the effective masses for electron and heavy hole. The surface Fermi level $E_{pin}(x)$ and the energy gap $E_g(x)$ as a function of Al mole concentration x is plotted in Fig. 3. We find $E_{pin}(x)=E_g(x)/2$, i.e., the surface Fermi level on bare AlGaAs surface is at midgap.

The effect of the illumination density on the electric field has been studied using three-beam photoreflectance. Both the probe and the pump beams are kept at low intensity. The third beam from a 20 mW He-Ne laser provides the major illumination on the sample. The intensity of this illumination beam is adjusted by neutral density filters over seven orders of magnitude. The electric field derived from FKO, as a function of illumination power density for two nominally identical SIN$^+$ GaAs structures with $d=1000$ Å, is shown in Fig. 4. Circles represent data from a sample grown on n^+-GaAs (100) substrate using As_4 and indium

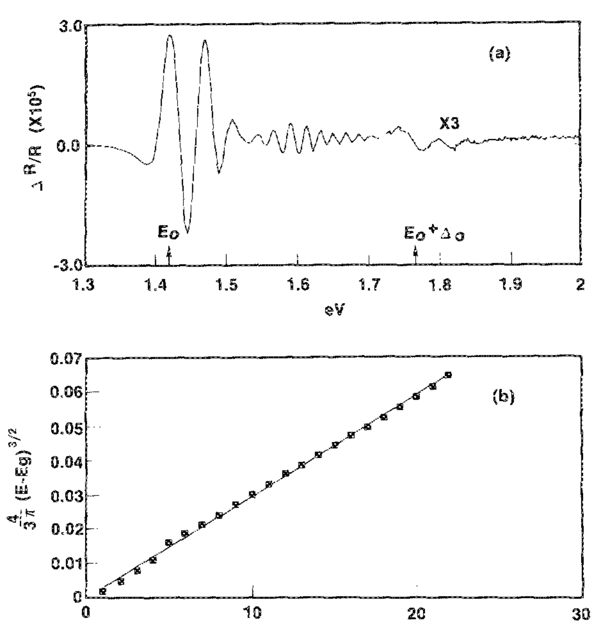

FIG 2. (a) Photoreflectance spectrum from a SIN$^+$ GaAs structure with $d=2000$ Å. (b) The quantity $(4/3\pi)(E_m-E_g)^{3/2}$ as a function of FKO index m for the E_0 transition of spectrum (a). The solid line is a least-squares fit to a linear function.

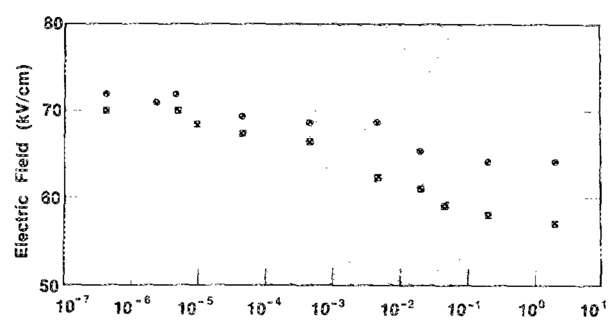

FIG. 4. Electric field measured from FKO as a function of illumination power density from two nominally identical SIN$^+$ structures with $d=1000$ Å. Circles represent data from sample grown on an n^+-GaAs (100) substrate using As_4 and indium mounting, while squares are that from one grown on an n^+-GaAs 2° off (100) towards (110) using As_2 and indium-free mounting. Hatched area represents the power density used in the majority of photoreflectance studies.

mounting, while squares are those from one grown on n^+ GaAs 2° off (100) towards (110) using As_2 and indium-free mounting. The electric field is reduced as the intensity of the illumination beam increases. This is due to light-generated photovoltage similar to that reported recently[18] in low-temperature photoemission experiments. The difference in the photovoltage in the two nominally identical samples may be related to the MBE growth condition.

Increasing the intensity of either the pump or the probe beam has a similar effect. In the majority of the photoreflectance studies, the total power density (both the probe and the pump beam) is about 10^{-4}–10^{-1} W/cm^2, which is indicated in Fig. 4 by the hatched area. The generally accepted criterion for low field modulation is that one obtains identical line shapes by varying the pump beam intensity by one or two orders of magnitude. Our results indicate that a slight change in FKO over one or two orders of magnitude does not always mean that the experiment is in the low field region. Extreme caution must be used when optical techniques are used to study electric field in semiconductor structures.

Very recently Sydor *et al.*[19] have proposed an interpretation to Van Hoof's result.[11] The discrepancy in the measured value is believed to be due to nonuniform field in the top layer. Since up to 20 extrema are observed, we believe that a nonuniform field is unlikely in our SIN^+ structures. The 71 kV/cm electric field reported in Ref. 26 is in good agreement with our result from the $d = 1000$ Å SIN^+ structure, at illumination power of 0.1–5 mW/cm^2, (squares in Fig. 4).

The work presented here demonstrates the usefulness of the SIN^+ (SIP^+) structure for many currently active studies. For example, the effect of surface treatments and preparation can be studied in a contactless way. A heterojunction SIN^+ (SIP^+) structure can be used to study the band offset. Work is under way to explore such possibilities.

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