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# Determination of surface state density for GaAs and InAlAs by room temperature photoreflectance

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Room temperature photoreflectance (PR) was used to investigate the surface state densities of GaAs and $In_{0.52}Al_{0.48}As$ surface intrinsic-$n^+$ structures. The built-in electric field and thus the surface barrier height are evaluated using the observed Franz–Keldysh oscillations in the PR spectra. Based on the thermionic emission theory and current-transport theory, the surface state density as well as the pinning position of the Fermi level can be determined from the dependence of the surface barrier height on the pump beam intensity. Even though this method is significantly simpler, easier to perform, and time efficient compared with other approaches, the results obtained agree with the literature. © *1999 American Institute of Physics.* [S0021-8979(99)03815-3]

In this article, we introduce an approach using photoreflectance (PR) to investigate the surface state density by measuring the surface barrier height as a function of pump beam intensity. The built-in electric field and then the surface barrier height as a function of pump beam intensity were evaluated using the observed Franz–Keldysh oscillations (FKO) in the PR spectra. Based on the current-transport theory and thermionic emission theory, the surface state density as well as the pinning position can be obtained. Hwang *et al.* in their earlier reports[1,2] have studied the surface state density and surface state distribution function of InAlAs surface intrinsic-$n^+$ structures by measuring the surface barrier height $V_b$ as a function of the thickness of the top layer. Yin *et al.*[3] calculated the surface state density by fitting the surface barrier as a function of temperature. In this work we determined the surface state density by fitting the surface barrier as a function of pump beam intensity. Since the pump beam intensity can be adjusted by simply inserting a gradient neutral density filter in its beam path, this approach is much simpler and less time consuming compared with other methods.

GaAs and InAlAs $SIN^+$ structures were grown by conventional molecular beam epitaxy. These heterostructures possessed a common structure consisting of a 1000 Å undoped layer on top of 1 $\mu$m of a Si-doped, $n$-type buffer layer grown on a semi-insulating (001) GaAs substrate for GaAs $SIN^+$ structure or on an Fe-doped semi-insulating InP for an InAlAs $SIN^+$ structure. In InAlAs $SIN^+$ structures, both the undoped and the buffer layers share the same AlAs mole fraction. The doping concentration in the buffer layer was approximately $1\times10^{18}\,\text{cm}^{-3}$ for all samples studied.

A standard PR apparatus was used in this study.[4] A He–Ne laser served as the pump beam. The probe beam was defocused on the sample and its intensity was kept at 0.1 $\mu$W/cm$^2$ to reduce the photovotaic effect. PR spectra were measured at room temperature with the intensity of the pump beam, controlled by a neutral density filter, varying from 0.05 to 270 $\mu$W/cm$^2$.

Figure 1 shows the PR spectra of the GaAs $SIN^+$ structure with various pump beam intensities. All the spectra exhibit a large number of FKO originated from the uniform built-in electric field in the undoped region. The plot of $(4/3\pi)[(E_n-E_g)^{3/2}]$ as a function of the FKO extrema index $n$ is a straight line where $E_n$ and $E_g$ are the photon energy of the $n$th extrema and the energy gap, respectively. The built-in electric field $F$ as well as the surface barrier height $V_b$ can be determined from the slope of the straight line using equations in Refs. 1 and 2. The surface Fermi level $V_F$, measured from the conduction band edge, is related to $V_b$ by $V_F=V_b+V_s$, where $V_s$ is the photovoltage induced by the probe beam as well as the pump beam. During our experiments, the probe beam was defocused on the sample and kept at 0.10 $\mu$W/cm$^2$ so that the photovoltage induced by the probe beam is very small and can be neglected. At constant temperature, the photovoltage induced and hence $V_b$ is a function of pump beam intensity only. The surface barrier height $V_b$ as a function of pump beam intensity is shown in Fig. 2.

The photovoltage $V_s$ derived from the thermionic emission theory is[5]

$$V_s=(\eta kT/e)\ln(I_{pc}/I_0+1), \qquad (1)$$

where $\eta$ is an ideality factor,[6] $I_{pc}$ equals the photocurrent density $J_{pc}$ times the surface area $A_{pc}$, $I_0(T)$ is the saturation current which depends on the dominant current flow mechanism and equals the saturation current density $J_0(T)$ times some effective area $A_0$. The photocurrent density $J_{pc}$, according to current-transport theory in the case where the diffusion length is much larger than the penetration depth of the pump beam, can be written as[7]

$$J_{pc}=eP_m\gamma(1-R_0)/\hbar\omega, \qquad (2)$$

where $P_m$ is the pump beam intensity, $\gamma$ is the quantum efficiency, $R_0$ the reflectivity of sample surface, and $\hbar\omega$ the photon energy of the pump beam.

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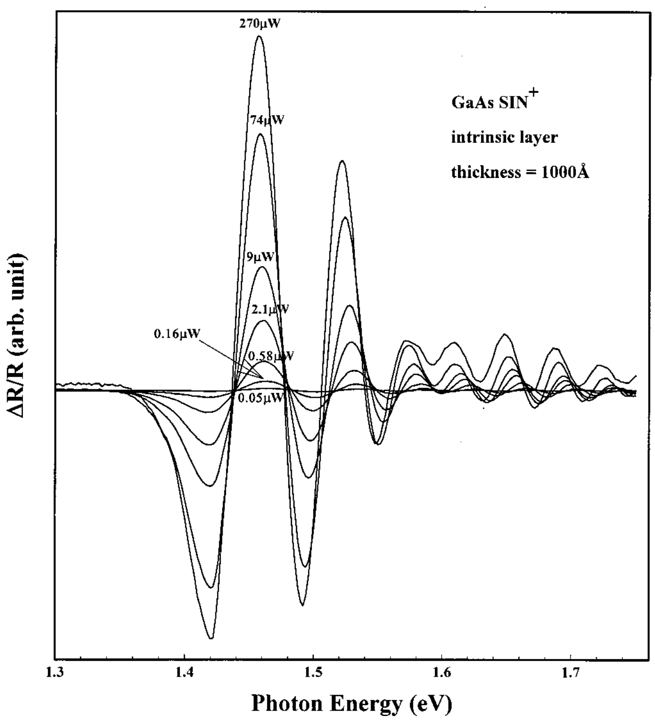


FIG. 1. The PR spectra of the GaAs $SIN^+$ structure with the pump beam intensity varying from 0.05 to 270 $\mu W/cm^2$.

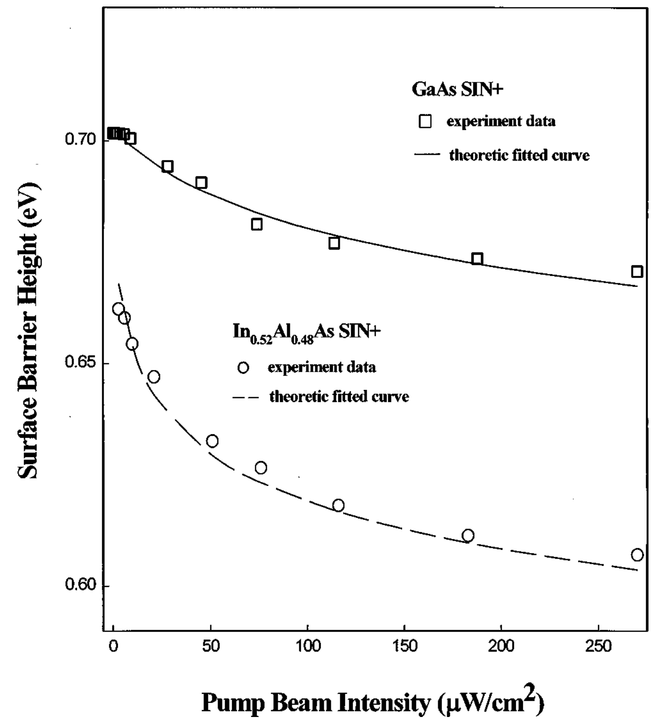


FIG. 2. The measured surface barrier heights $V_b$ of the GaAs and InAlAs $SIN^+$ structures as a function of the pump beam intensity. The solid and dashed lines are least-squares fits of the data of $V_b$ to Eq. (4).

For samples of $SIN^+$ structure, thermionic emission and diffusion are the main contributions to $J_0(T)$ so that $J_0$ can be expressed as[3,8]

$$J_0(T)=[A^*T^2/(1+BT^{3/2})]\exp[-eV_F(T)/kT], \qquad (3)$$

where $A^*$ is the modified Richardson constant defined as[9] $m^*ek^2/(2\pi^2\hbar^3)$ and $B=(k/2\pi m^*)^{1/2}(300/\nu_0)$, where $m^*$ is the effective mass of the electron. By substituting Eqs. (1) and (2) into Eq. (4) with $I_{pc}=A_{pc}-J_{pc}$ and $I_0=A_0J_0$, the surface barrier height is then

$$V_b=V_F-(\eta kT/e)\ln[1+eP_m\gamma(1-R_0)(1+BT^{3/2}) \times\exp(eV_F/kT)/\hbar\omega rA^*T^2], \qquad (4)$$

where $r\equiv A_0/A_{pc}$ is defined as the geometry factor introduced first by Yin *et al.*[3]

At constant temperature, the only variable in Eq. (4) is the pump beam intensity $P_m$. When the experimental data of $V_b$ at various pump beam intensity is least-squares fitted to Eq. (4), $V_F$, $\eta$, and $r$ can be obtained from the fitting parameters. The solid line in Fig. 2 is a least-squares fit of the experimental data to Eq. (4). For GaAs sample, where $A^*=8.0\ A/cm^2K^2$, $B=3.3\times10^{-4}\ K^{-3/2}$, $\gamma\cong1$, $N_0=6.3\times10^{14}\ cm^{-2}$, and $R_0=0.34$, the fitting parameters obtained are $V_F=0.70\pm0.02$ eV, $\eta=0.80\pm0.05$ and $r=0.040\pm0.005$. Assuming one state per atom on the (001) GaAs surface,[3] the surface state density can be calculated from $D_s=rN_0$ and is $(2.52\pm0.32)\times10^{13}\ cm^{-2}$. These results are listed in Table I. Yin *et al.*[3] measured the barrier height as a function of temperature. By fitting the measured $V_b(T)$ as a function of $T$ to Eq. (4), they obtained $V_F=0.77\pm0.02$ eV, $\eta=0.93\pm0.05$, and $D_s=(1.26\pm0.63)\times10^{13}\ cm^{-2}$ for GaAs. Their results are in agreement with our study shown in Table I.

Figure 3 displays a series of PR spectra of an $In_{0.52}Al_{0.48}As$ $SIN^+$ structure with 1000 Å undoped top layer under various pump beam intensities. The surface barrier height is also plotted as a function of the pump beam inten-

TABLE I. The surface Fermi level, ideality factor $\eta$, geometry factor $r$, and the surface state denties of GaAs and $In_{0.52}Al_{0.48}As$ $SIN^+$ structures obtained in various studies.

| | (300 k) | $V_F$(eV) | $\eta$ | $r$ | $D_s$ ($cm^{-2}$) |
|---|---|---|---|---|---|
| GaAs | Present work | $0.70\pm0.02$ | $0.80\pm0.05$ | $0.040\pm0.005$ | $(2.52\pm0.32)\times10^{13}$ |
| | Yin *et al.*[a] | $0.77\pm0.02$ | $0.93\pm0.05$ | $0.02\pm0.01$ | $(1.26\pm0.63)\times10^{13}$ |
| $In_{0.52}Al_{0.48}As$ | Present work | $0.66\pm0.02$ | $0.80\pm0.05$ | $(2.0\pm0.5)\times10^{-3}$ | $(5.8\pm1.45)\times10^{11}$ |
| | Hwang *et al.*[b,c] | $0.62\pm0.01$ | | | $(3.31\pm0.05)\times10^{11}$ |

[a]Reference 3.
[b]Reference 1.
[c]Reference 2.

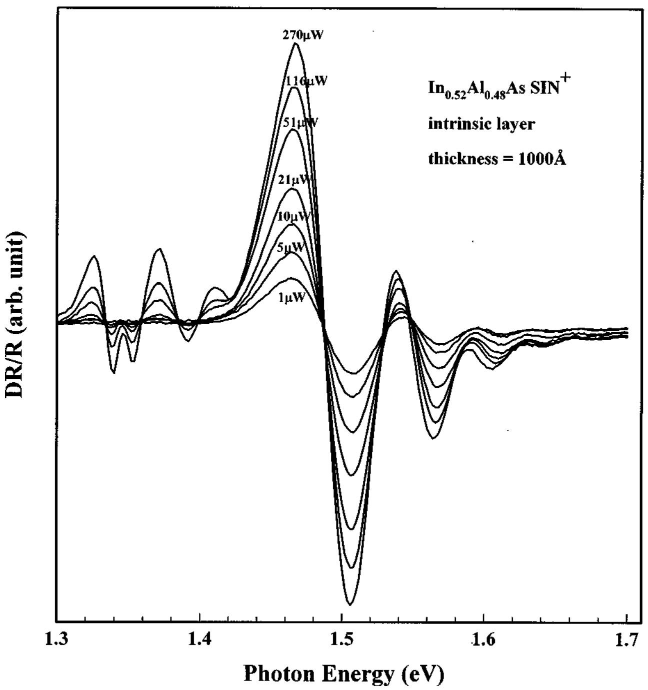


FIG. 3. The PR spectra of an $In_{0.52}Al_{0.48}As$ $SIN^+$ structure with 1000 Å undoped top layer under various pump beam intensities.

sity in Fig. 2. Again, the dashed line in Fig. 2 represents a least-squares fit of the data to Eq. (4). For InAlAs, where $A^*=8.5\,A/cm^2\,K^2$, $B=3.2\times10^{-4}\,K^{-3/2}$, $\gamma\cong1$, $N_0=2.9\times10^{14}\,cm^{-2}$, and $R_0=0.30$, the fitting parameters obtained are $V_F=0.66\pm0.02\,eV$, $\eta=0.80\pm0.05$, and $r=(2.0\pm1.0)\times10^{-3}$. The density of occupied surface states estimated from $D_s=rN_0$ is $(5.8\pm2.9)\times10^{11}\,cm^{-2}$ with $N_0=2.9\times10^{14}\,cm^{-2}$. In our previous studies,[1,2] we found that the surface Fermi level of $In_{1-x}Al_xAs$ $SIN^+$ structures is not pinned at midgap over an aluminum concentration of 0.42–0.57. For each Al composition there exists certain ranges of top layer thickness within which the surface Fermi level is weakly pinned. From the dependence of the electric field and surface Fermi level on the top layer thickness, we concluded that the surface states distribute over two separate regions within the energy band gap and the densities of surface states are as low as $(1.36\pm0.15)\times10^{11}\,cm^{-2}$ for the distribution near the conduction band ($U$) and $(4.38\pm0.50)\times10^{11}\,cm^{-2}$ for the distribution near valence band ($L$). In this study, the top layer thickness of the sample is 1000 Å. Our previous studies showed that the surface Fermi level is pinned within the lower distribution. Therefore the surface state density obtained in this study is the surface state density of the lower distribution occupied by electrons and is comparable with the result obtained in our previous study.

In conclusion, we have introduced an approach to investigate the surface state density and the Fermi level pinning position of a semiconductor by simply changing the intensity of the pump beam in the photoreflectance experiment. Since the intensity of the pump beam can be adjusted simply by inserting a neutral density fitter in the beam path, it is a simple and efficient method to investigate the surface state density of various semiconductor surfaces or interfaces. The surface state densities of GaAs and $In_{0.52}Al_{0.48}As$ obtained using this technique are in good agreement with those obtained from other procedures, which provides further support of its validity.

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