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Fermi energy pinning at the surface of high mobility $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ modulation doped field effect transistor structures

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Fermi level pinning at the surface of the undoped $In_{0.52}Al_{0.48}As$ Schottky layer in high mobility $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ modulation doped field effect transistor structures has been studied. The electron subband densities for samples prepared with different Schottky layer thicknesses have been deduced from fast Fourier transform analyses of 1.5 K Shubnikov-de Haas data. These results have been compared with densities calculated self-consistently using the free surface potential Φ_S as the only fitting parameter. Good agreement between theory and experiment is achieved for a surface Fermi energy pinned 0.65 ± 0.05 eV below the $In_{0.52}Al_{0.48}As$ Γ-conduction band minimum. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2716844]

High electron mobility transistors (HEMTs) based on $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/InP$ have shown cutoff frequencies (f_T) up to 550 GHz for devices with 50 nm long T gates.[1] Optimization of the HEMT requires the fabrication of devices with short gate lengths and also the correct scaling of the epitaxial layer thicknesses and doping levels.[2] Another key parameter is the surface potential Φ_S of the undoped $In_{0.52}Al_{0.48}As$ layer (un-$In_{0.52}Al_{0.48}As$ or Schottky layer) on which the gate contact is deposited, since this influences the degree to which shallow channels are naturally depleted of charge. We have described previously the application of the Shubnikov-de Haas (SdH) effect to obtain a value for Φ_S at the free surface of un-$In_{0.52}Al_{0.48}As$.[3] Samples were prepared by wet etching to realize different Schottky layer thicknesses W_S from the as-grown value of 40 nm down to ~10 nm. The total electron densities at the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ interface were deduced from fast Fourier transform (FFT) analyses of 1.5 K SdH data, and then compared with values calculated by solving the Schrödinger and Poisson equations self-consistently.[4] Φ_S was the only fitting parameter, together with the appropriate value of W_S, for the sample under evaluation. A value $\Phi_S = 0.6 \pm 0.1$ eV was obtained, close to that reported for un-$In_{0.52}Al_{0.48}As$ epitaxial layers of similar thickness.[5] However, the self-consistent calculations (SCC) took no account of conduction band nonparabolicity which impacts on $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ when the total electron density in the channel (N_S) exceeds $\sim 1 \times 10^{12}$ cm^{-2}, and becomes significant for $N_S \geqslant 2 \times 10^{12}$ cm^{-2},[6,7] values lower than those normally required for practical HEMTs. We report here SdH and SCC results for an $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructure δ doped with Si to give $N_S < 1 \times 10^{12}$ cm^{-2} and thus avoiding any nonparabolicity effects which might have been present in the earlier experiments. Our analyses show that Φ_S can be found to an accuracy of ±0.05 eV.

The heterostructure shown in Fig. 1 was grown by molecular beam epitaxy (MBE) under conditions summarized in Ref. 3. The 30 nm thick $In_{0.52}Al_{0.48}As$ layer separating the Si δ doping (density of 2×10^{12} cm^{-2}) and the $In_{0.53}Ga_{0.47}As$ channel was designed for a low total electron density in the channel. The choice of 40 nm for the total Schottky layer thickness allowed us to compare directly our quantum transport data with photoreflectance measurements.[5] This thickness also permitted the partial removal of the Schottky layer by wet etching while leaving an un-$In_{0.52}Al_{0.48}As$ surface layer at least 20 nm thick. Si δ doping was used because a narrow dopant profile is required in the thin $In_{0.52}Al_{0.48}As$ barrier layer of a shallow $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ HEMT designed for ultrahigh frequency devices.

The SdH data were recorded from two sets of Hall bars, fabricated on separate quarters of a 2 in. diameter Fe–InP wafer on different occasions. Following preparation of the Hall bars, individual samples were wet etched in $H_3PO_4-H_2O_2-H_2O$ (1:1:100) held at 23 °C for different lengths of time to remove the $Si^+-In_{0.53}Ga_{0.47}As$ cap layer and a proportion of the un-$In_{0.52}Al_{0.48}As$ Schottky layer. Residual Schottky layer thicknesses from 20 to 40 nm were prepared, where the amount of material removed was determined by measuring the spacing between the etched and the

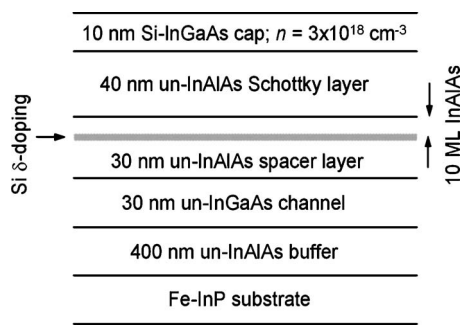

FIG. 1. Schematic diagram of lightly doped $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ HEMT structure grown by molecular beam epitaxy (ML—monolayer).

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TABLE I. Material parameters used in the self-consistent calculations.

Parameter	Value	Reference
$In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ conduction band offset, ΔE_C (eV)	0.520	[a]
1.5 K band gap (eV)		
$In_{0.53}Ga_{0.47}As$	0.810	[b]
$In_{0.52}Al_{0.48}As$	1.540	[c]
Electron effective mass at Γ-conduction band minimum		
$In_{0.53}Ga_{0.47}As$	$0.043m_0$	[d]
$In_{0.52}Al_{0.48}As$	$0.072m_0$	[e]

[a]Reference 8.
[b]Reference 9.
[c]Reference 10.
[d]Reference 11.
[e]Reference 12.

original, unetched (masked) surfaces to an accuracy of ±1 nm with a Dektak surface profiler and a Nanoscope atomic force microscope (AFM). The electron concentrations of the occupied subbands N_i at the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ interface were deduced from FFTs of SdH measurements carried out in the dark at a temperature of 1.5 K with magnetic flux densities B up to 13 T. In practice, the upper (N_1) subband depopulated at $B<2.0–2.5$ T due to its low initial population; consequently, the data presented is restricted to $B<2.5$ T.

The electron density of the i^{th} occupied subband is given by $N_i=2e\nu_i/h$ (ν_i are the frequencies of the peaks in the FFT spectra, e is the electron charge, and h is Planck's constant) and the total free electron concentration in the channel is $N_S=\Sigma_i N_i=\Sigma_i 2e\nu_i/h$. The measured concentrations N_i for each Hall bar sample were compared with those calculated self-consistently for a structure with matching un-$In_{0.52}Al_{0.48}As$ Schottky layer thickness, using the parameters listed in Table I (Refs. 8–12) and employing Φ_S as the *only* variable parameter. The Si δ doping was assumed to be distributed uniformly through 1 nm of $In_{0.52}Al_{0.48}As$ to enable satisfactory convergence in the SCC,[3] even though spreading of Si by surface segregation was probably less than this under the growth conditions employed here.[13] A distribution thickness of 2 nm results in a change to the calculated subband densities smaller than the measurement error of $\pm 1.0\times10^{10}$ cm^{-2}. Similarly, SCC based on increasing the $In_{0.53}Ga_{0.47}As$ electron effective mass from $0.043m_0$ (Ref. 11) to $0.046m_0$ also predict an immeasureable change in the electron subband densities. The influence of the two main deep electron traps reported for $In_{0.52}Al_{0.48}As$ (Ref. 14) has not been included here since their total density of $\sim5\times10^{15}$ cm^{-3} translates to a maximum sheet density of $<1\times10^{10}$ cm^{-2} within the combined thickness of our $In_{0.52}Al_{0.48}As$ Schottky and spacer layers. This is negligible when compared to the Si dopant density of 2×10^{12} cm^{-2}.

A summary of the SCC for $W_S=35$ and 24 nm with $\Phi_S=0.65$ eV is given in Table II. E_F-E_C is the energy difference between the Fermi energy and the conduction band minimum at the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ interface, and E_F-E_0 and E_F-E_1 are the differences between the Fermi energy and the $n=0$ and $n=1$ subband energies, respectively. These energies support the assumption that nonparabolicity effects can be ignored.

TABLE II. Data from self-consistent calculations; un-$In_{0.52}Al_{0.48}As$ surface pinned at $\Phi_S=0.65$ eV below its Γ-conduction band minimum.

Value calculated when	$W_S=35$ nm	$W_S=24$ nm
Total electron density in channel, N_S ($\times10^{11}$ cm^{-2})	8.12	6.03
$n=0$ subband density, N_0 ($\times10^{11}$ cm^{-2})	6.91	5.46
$n=1$ subband density, N_1 ($\times10^{11}$ cm^{-2})	1.21	0.57
E_F-E_C (meV)	111.0	91.0
E_F-E_0 (meV)	38.4	30.4
E_F-E_1 (meV)	6.76	3.20

Curve (a) of Fig. 2 shows the SdH oscillations for a sample with $W_S\sim39$ nm. Two occupied subbands are observed in the corresponding FFT spectrum, giving electron densities $N_0=7.37\times10^{11}$ cm^{-2} and $N_1=1.36\times10^{11}$ cm^{-2}. No parallel conduction associated with the δ-doped layer was detected in the dark.[15,16] The two sets of oscillations observed for this sample represent the lower and upper occupied subbands (also seen for $W_S=35$, 32, 28, and 24 nm—not shown in Fig. 2). The absence of beat frequencies in the SdH data indicates that the wet etching of un-$In_{0.52}Al_{0.48}As$ produces a smooth surface, as verified by the profiles recorded using the surface profiler and the AFM.

The SdH data for the $W_S=20$ nm sample is also shown in Fig. 2 [curve (b)]. A slight modification of the envelope function of the oscillations corresponding to the N_0 subband is observed, indicating that the upper subband is almost depopulated. Depending on the exact value of Φ_S, complete depopulation of the upper subband will occur once W_S is below a critical thickness, and one period only will then be observed in the SdH data. This is the case experimentally for $W_S<20$ nm. Low field ($B=0.3$ T) Hall measurements taken at 1.5 K in the dark for the $W_S=20$ nm sample gave a mobility of 73 400 cm^2 V^{-1} s^{-1} and a total sheet electron density of 4.98×10^{11} cm^{-2}.

The experimental subband densities and those derived from the SCC for values of Φ_S equal to 0.60 eV (■), 0.65 eV (▲), and 0.70 eV (▼) are shown in Fig. 3 as a function of W_S. The minimum electron subband density detectable from SdH measurements is $\sim2\times10^{10}$ cm^{-2}, although this figure depends both on the proximity of the energy level of the upper occupied subband to the Fermi energy and the subband mobility. For $W_S=20$ nm and $\Phi_S=0.65$ eV, SCC predict a value $N_1=0.25\times10^{11}$ cm^{-2}. Inspection of Fig. 3 shows that the best fit between theory and experiment is for Φ_S pinned 0.65 eV below the $In_{0.52}Al_{0.48}As$ Γ-conduction

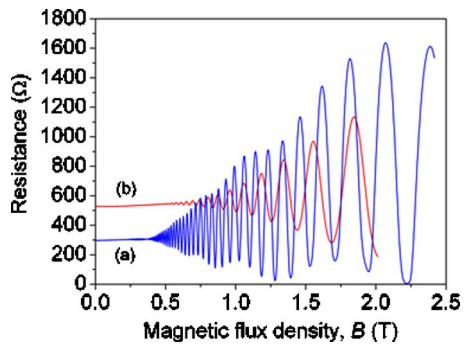

FIG. 2. (Color online) 1.5 K Shubnikov-de Haas oscillations recorded in the dark for residual un-$In_{0.52}Al_{0.48}As$ Schottky layer thicknesses W_S of (a) 39 nm and (b) 20 nm.

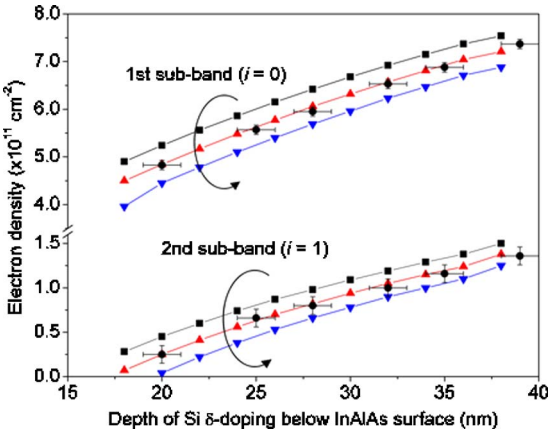

FIG. 3. (Color online) Electron subband densities N_0 and N_1 for three values of the surface potential Φ_S as a function of the un-$In_{0.52}Al_{0.48}As$ Schottky layer thickness W_S. The symbols for the SCC data correspond to (■) Φ_S =0.60 eV, (▲) Φ_S=0.65 eV, and (▼) Φ_S=0.70 eV. Error bars on both axes of the experimental SdH data (●) show the uncertainties in determining the thickness of the $In_{0.52}Al_{0.48}As$ Schottky layer after wet etching (±1 nm) and measuring the electron subband densities ($\pm 1 \times 10^{10}$ cm^{-2}). Note the change in the vertical scale to add clarity to the two sets of data.

band minimum. Note the excellent match between the experimental results (shown as ● with error bars) and theoretical calculations for *both* occupied subbands across all the values of W_S. Errors of ±1 nm in determining the etched depth of the un-$In_{0.52}Al_{0.48}As$ Schottky layer and $\pm 1.0 \times 10^{10}$ cm^{-2} in measuring the electron density of an occupied subband are the main factors contributing to the uncertainty of ±0.05 eV in the value of Φ_S.

The figure of $\Phi_S = 0.65 \pm 0.05$ eV is in close agreement with the value obtained from photoreflectance modulation spectroscopy[5] on 20–50 nm thick un-$In_{0.52}Al_{0.48}As$ samples. Although not strictly comparable to a measurement on a free surface, metal (Au or Al)/un-$In_xAl_{1-x}As$ Schottky barrier heights of 0.621 ± 0.05 eV have been determined from *C-V* data for compositions in the range of $0.435 < x < 0.620$,[17] whilst *I-V* curves[18] have yielded barriers of 0.688 eV (Au), 0.640 eV (Ti), and 0.623 eV (Pt) on un-$In_{0.52}Al_{0.48}As$.

In summary, pinning of the Fermi energy at the surface of the un-$In_{0.52}Al_{0.48}As$ Schottky layer in high mobility $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ HEMT structures has been studied for electron subband concentrations where conduction band nonparabolicity effects can be ignored. The best agreement between experiment and theory is for a Fermi level pinned 0.65 ± 0.05 eV below the un-$In_{0.52}Al_{0.48}As$ Γ-conduction band minimum, in agreement with the value derived from photoreflectance spectroscopy measurements.[5]

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[1] K. Elgaid, H. McLelland, C. R. Stanley, and I. T. Thayne, *Proceedings of the 17th International Conference on Indium Phosphide and Related Materials*, Glasgow, U. K. (IEEE, Piscataway, NJ, 2005), pp. 523–525.
[2] A. Asenov, S. Babiker, N. Cameron, S. P. Beaumont, and M. Taylor, *Proceedings of Microwave and Communication Technologies Conference, London, 1997*, London, U. K., (Nexus Media, Swanley, Kent, England, 1997), pp. 198–203.
[3] E. Skuras, G. Pennelli, A. R. Long, and C. R. Stanley, J. Vac. Sci. Technol. B **19**, 1524 (2001).
[4] G. Snider; http://www.nd.edu/~gsnider/
[5] J. S. Hwang, G. S. Chang, W. C. Hwang, and W. J. Chen, J. Appl. Phys. **89**, 1771 (2001).
[6] M. McElhinney, B. Vögele, M. C. Holland, C. R. Stanley, E. Skuras, A. R. Long, and E. A. Johnson, Appl. Phys. Lett. **68**, 940 (1996).
[7] E. A. Johnson and A. MacKinnon, Semicond. Sci. Technol. **5**, S189 (1990).
[8] D. F. Welch, G. W. Wicks, and L. F. Eastman, J. Appl. Phys. **55**, 3176 (1984).
[9] G. Bastard and R. Ferreira, Semicond. Sci. Technol. **5**, 470 (1990).
[10] D. K. Gaskill, N. Bottka, L. Aina, and M. Mattingly, Appl. Phys. Lett. **56**, 1269 (1990).
[11] I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, J. Appl. Phys. **89**, 5815 (2001).
[12] K. L. Chen, H. H. Lin, G. J. Jan, Y. H. Chen, and P. K. Tseng, Appl. Phys. Lett. **66**, 2697 (1995).
[13] E. Skuras, C. R. Stanley, A. R. Long, E. A. Johnson, A. MacKinnon, H. Yaguchi, M. van der Burgt, and J. Singleton, J. Appl. Phys. **86**, 6593 (1999).
[14] P. S. Whitney, W. Lee, and C. G. Fonstad, J. Vac. Sci. Technol. B **5**, 796 (1987).
[15] R. L. Williams, P. Coleridge, Z. R. Wasilewski, M. Dion, A. Sachrajda, and S. Rolfe, Solid State Commun. **78**, 493 (1991).
[16] E. Skuras, A. R. Long, B. Vogele, M. C. Holland, C. R. Stanley, M. van der Burgt, H. Yaguchi, and J. Singleton, Phys. Rev. B **59**, 10712 (1999).
[17] P. Chu, C. L. Lin, and H. H. Wieder, Appl. Phys. Lett. **53**, 2423 (1988).
[18] W. Gao, P. R. Berger, and R. G. Hunsperger, Appl. Phys. Lett. **66**, 3471 (1995).