Distinguishing impurity concentrations in GaAs and AlGaAs, using very shallow undoped heterostructures

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We demonstrate a method of making a very shallow, gateable, undoped 2-dimensional electron gas. We have developed a method of making very low resistivity contacts to these structures and systematically studied the evolution of the mobility as a function of the depth of the 2DEG (from 300nm to 30nm). We demonstrate a way of extracting quantitative information about the background impurity concentration in GaAs and AlGaAs, the interface roughness and the charge in the surface states from the data. This information is very useful from the perspective of molecular beam epitaxy (MBE) growth. It is difficult to fabricate such shallow high-mobility 2DEGs using modulation doping due to the need to have a large enough spacer layer to reduce scattering and switching noise from remote ionised dopants.

Keywords: undoped heterostructure, shallow ohmics, surface states

Identifying the sources of mobility limiting scattering and relating them to growth conditions is an important practical problem in semiconductor physics. Minimising the background impurity concentration is crucial for achieving high mobility 2DEGs (and 2DHGs) as well as for lowering the percolation threshold, below which the 2DEG breaks up into inhomogeneous puddles. It is also important in reducing the probability of a gate defined nanostructure (like point contacts, quantum dots, interferometers) intercepting a defect/impurity. In this context, a specific question, that motivated this work is: how impure is the AlGaAs compared to GaAs?

The paper is organized in three parts. First we describe our method for distinguishing the impurity concentrations in GaAs and AlGaAs layers that form the heterointerface. We present experimental data from a series of wafers where the interface depth was varied from 30 to 300 nm. Intimately connected with the success and applicability of this method is a way of contacting very shallow (30nm) undoped 2DEGs in a series of wafers where the interface depth was varied from 300nm to 30nm. We demonstrate a way of extracting quantitative information about the fabrication of shallow nanostructures as well as studying the effect of surface states.

Consider first the structure shown in Fig. 1. If a 2DEG is induced by a topgate $d \approx 300$nm below the surface, at low temperature (typically 1.5K or lower) the mobility limiting scattering would come from two sources. First is the Coulomb scattering from the (charged) impurities incorporated during MBE growth. The effect of this is stronger at lower densities and this background also determines a threshold below which the 2DEG would break up into inhomogenous puddles. There are no modulation doped or delta-doped layers, but the surface states have some bound charge and these will affect the 2DEG if the AlGaAs layer is less than $d \sim 80$nm deep, in a manner similar to a delta-doped layer. Secondly the GaAs-AlGaAs interface is not perfectly smooth. The interface roughness can be modelled as a perturbation, that affects the 2DEG more at higher densities than at lower densities, giving rise to a scattering rate $\tau_{IR}$. Between the percolation threshold and near complete occupancy of the first subband, the effect of these two scattering processes can quantitatively explain the observed variation of mobility with density (see Fig.2 and eqn. 11). Observe however that the scattering rate due to background impurities can be written as a sum of two parts: $1/\tau_{IR}$ arising from impurities in AlGaAs ($N_{AlGaAs}^B$) and $1/\tau_{IR}$ arising from impurities in GaAs ($N_{GaAs}^B$). From a single wafer we can know the sum of the two, but cannot determine how the impurities are distributed between GaAs and AlGaAs. Consider now a second wafer grown at the same time (in a sequence), in the same chamber but with a lesser thickness of AlGaAs. The background and the interface roughness should remain the same. We then measure the density-mobility trace for the shallower wafer. The contributions $\tau_{IR}$ for AlGaAs, $\tau_{IR}$ for GaAs can change only marginally. $1/\tau_{IR}^{AlGaAs}$ must decrease because the integration over the thickness of the AlGaAs now has a lesser span (eqn. 6). If we assign a wrong value to $N_{AlGaAs}^B$, then the decrement in $1/\tau_{IR}^{AlGaAs}$ would also be wrong. $1/\tau_{IR}^{SURF}$ should however increase in a predictable way, because the surface charges are now closer.

We grew a series of wafers (as in Fig. 3) and fabricated heterostructure insulated gate field effect transistors (HIGFET) on each and modelled the $\mu(N)$ curves with the following constraints:

1. $N_{AlGaAs}^B$, $N_{GaAs}^B$ must remain the same for all the traces.
2. $\tau_{IR}$ must remain the same for all the traces.
3. Surface states are modelled as a δ-doped layer at a known distance ($d + 10$nm) away.
observed mobility of 2DEGs in Si-MOSFETs and scattering in a 2DEG[1–4] has been used to explain the heterostructure. Can be used to determine the background levels in both materials can be expected to differ. Our re-

purities such as oxygen the background impurity levels in AlGaAs is harder, because the ohmic contacts and AlGaAs. As Al is more reactive than Ga, with impurities in GaAs and AlGaAs. As Al is more reactive than Ga, with impurities such as oxygen the background impurity levels in the two materials can be expected to differ. Our results have consistently shown (for two MBE chambers) that that $N_{B}^{AlGaAs}$ is about 2–3 times $N_{B}^{GaAs}$. We can also determine quantitatively the amount of charge in the surface states between GaAs and the insulator. It is important to note that data from a sequence of 2–3 progressively shallower structures is crucial for distinguishing the background levels in GaAs and AlGaAs.

Conventionally one can measure the background doping levels ($N_{B}$) by growing a very thick layer ($t$ ~ few microns) and measuring the areal carrier concentration ($N = N_{HT}$). However this method becomes harder as the background level drops to $\sim 10^{14}$cm$^{-3}$ and lower, which is the typical level found in chambers capable of growing very high mobility structures. Additionally to reach a regime where the measured carrier concentration per unit area ($N$) scales with thickness, one has to first overcome the surface depletion regime. If the free surface takes up $10^{11} - 10^{12}$cm$^{-2}$ carriers, then it is easy to see that to reach measurable areal densities, one would have to use a layer at least 15-20 microns in thickness. Whereas in realistic wafers, the MBE grown region is typically not more than 1-2 microns thick, including any buffer regions. Determining the impurity levels in AlGaAs is harder, because the ohmic contacts to AlGaAs are more difficult and the free surface of AlGaAs oxidizes rapidly. Our transport based method can be used to determine the background levels in both GaAs and AlGaAs which are grown as part of the same heterostructure.

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yielding a scattering cross-section $\nu(q, z)$ due to a charged impurity at a distance, $z$, from the interface

$$\nu(\theta, z) = \frac{m e^4}{8\pi^2 \hbar^3 e^2 \epsilon_r} \left| F_1(q, z) \right|^2$$

where $q = 2k_F \sin \frac{\theta}{2}$. The scattering rates are then:

$$\frac{1}{\tau_{\text{GaAs}}} = N_{\text{GaAs}} \int_0^\theta dz \int_0^\pi d\theta (1 - \cos \theta) \nu(\theta, z) \quad (5)$$

$$\frac{1}{\tau_{\text{AlGaAs}}} = N_{\text{AlGaAs}} \int_0^\pi dz \int_0^\pi d\theta (1 - \cos \theta) \nu(\theta, z) \quad (6)$$

$$\frac{1}{\tau_{\text{SURF}}} = \sigma_{\text{SURF}} \int_0^\pi d\theta (1 - \cos \theta) \nu(\theta, z) \quad (7)$$

The contribution of the interface roughness increases with increasing electron concentration at the heterointerface [2]. This (somewhat counter-intuitive) result arises due to a faster growth of the electric field at the interface compared to the intrinsic screening by the 2DEG itself which reduces the effect. The roughness is described statistically by a correlation

$$\langle \Delta(r) \Delta(r') \rangle = \Delta^2 e^{-\frac{(r-r')^2}{\xi^2}}$$

$$\frac{1}{\tau_{\text{IR}}} = \frac{m}{\hbar^3} (\Delta^2) \int_0^\pi d\theta (1 - \cos \theta) \left| \frac{e^2}{2\epsilon_0 \epsilon_r} \frac{N}{2\epsilon(q)} \right|^2 e^{-\frac{x^2}{\xi^2}}$$

Finally we obtain

$$\frac{1}{\tau_{\text{TOTAL}}} = \frac{1}{\tau_{\text{GaAs}}} + \frac{1}{\tau_{\text{AlGaAs}}} + \frac{1}{\tau_{\text{SURF}}} + \frac{1}{\tau_{\text{IR}}} \quad (10)$$

$$\mu(N) = \frac{e}{m} \frac{1}{\tau_{\text{TOTAL}}} \quad (11)$$

Fig.4 shows how the parameters can be extracted from a set of measurements, satisfying the three consistency conditions mentioned earlier. Note that for a 2DEG deeper than 100nm, the mobility hardly changes with depth. This is fully consistent with the predictions of the analysis mentioned in the preceding paragraph. The flattening of the curves at higher density is a consequence of the interface roughness scattering, the lower density regions are dominated by the effect of the charged background and in shallow devices the charged surface states. The charge in the surface state is found to remain constant over the entire range of gate voltage used. The typical density of the surface charge that we obtain ($\sigma_{\text{SURF}} \approx 1 - 5 \times 10^{11} \text{cm}^{-2}$) is considerably less than the typical charge in a delta doped layer - typically in the $10^{13} \text{cm}^{-2}$ range. The very shallow undoped 2DEG not only offers a way to extract information about the wafer characteristics but also considerable advantages over shallow doped wafers in terms of mobility, absence of parallel conduction and most likely much reduced switching noise.

Note that for a 2DEG, even at $n = 1 \times 10^{10} \text{cm}^{-2}$, $T/T_F \approx 0.3$ at the temperature of measurement $T = 5K$ and we can consider the scattering at the Fermi surface only, hence no thermal (Boltzmann) averaging needs to be done to get the scattering rates. While we have also been able to induce a 2DHG in the same wafers (by using a negative top gate bias and p-type ohmic contacts), the higher effective mass of the holes leads to a lower Fermi temperature, so the assumption $T/T_F \ll 1$ is no longer valid. Larger correlations also make the simple calculation of $\epsilon(q)$ invalid. Thus it remains much more convenient to use a 2DEG to extract the background, surface charge and interface roughness parameters.

The importance of shallow doped [3, 4] and undoped 2DEGs/2DHGs [3, 8] has recently been noted in the context of surface gate defined nanostructures. However the method of making ohmic contacts to very shallow undoped 2DEGs requires some careful consideration. Fig. 5a & 5b, 10 & 11 show the two known methods of making undoped 2DEGs. However a structure of the type shown in Fig. 5b cannot be made very shallow, because the ohmic material (after
ohmic material in these cases need to be evaporated working above $B = 10$ Tesla. AlGaAs is only 20nm thick with reliable ohmic contacts. We have successfully fabricated devices where this limitation and can be made arbitrarily shallow.

Thick, the structure of Fig. 4b does not suffer from between the ohmic and the doped cap that acts as a topgate. If the AlGaAs layer is any less than 100nm thick. The structure of Fig. 4b does not suffer from this limitation and can be made arbitrarily shallow. We have successfully fabricated devices where the AlGaAs is only 20nm thick with reliable ohmic contacts working above $B = 10$ Tesla and $T < 300$ mK. The ohmic material in these cases need to be evaporated into etched pits (see Fig. 4b) at an angle of 60° to ensure good sidewall wetting. Experimentally we found (from AFM scans) that the annealed ohmic near the AuGeNi-GaAs sidewall tends to be rough and spiky if the sidewalls are not fully wetted. Good diffusion into the sidewalls resulted in a comparatively smoother boundary ensuring good uniform coverage of the polyimide insulator (see Fig. 4b) between the ohmic and the overlapping topgate. The topgate to ohmic bias could be held at 10V with a leakage current of less than 50 μA, with the resistance less than 50 Ω/contact (see Fig. 5).

In conclusion, we have devised a low temperature transport method to determine the background impurities in GaAs and AlGaAs. We also determine that the amount of charge in the surface states is significantly less than what is expected in a typical delta doped layer. The method can be used to determine the backgrounds resulting from growing a wafer at different growth rates, substrate temperatures and cell temperatures. As part of this process we developed a way of making good ohmic contacts to very shallow undoped heterostructures. In structures where modulation doping or delta doping is used a minimum distance from the surface is dictated by the need to have a large enough spacer layer to reduce scattering and switching noise from remote ionised dopants. The undoped 2DEGs do not suffer from these limitations. Shallow, high mobility undoped 2DEGs are expected to be useful in defining smaller lithographic features that conveniently approach the single electron limit.

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[1] T. Ando, A.B. Fowler and F. Stern, Reviews of Modern Physics 54, 437 (1982)  
[2] Y. Matsumoto and Y. Uemura, Japan Journal of Applied Physics Suppl. 2, Part 2, 367 (1974)  
[3] A. Gold, Physical Review B, 38, 10798 (1988)  
[4] K. Hirakawa and H. Sakaki, Physical Review B 33, 8291 (1986)  
[5] D. Laroche, S. Das Sarma, G. Gervais, M. P. Lilly, and J. L. Reno, Applied Physics Letters, 96, 162112 (2010)  
[6] D.A. Kozolov, Z.D. Kvon, A.K. Kalagin and A.I. Toropov, Semiconductors, 41, no 2, 180 (2007). Original Russian text Fizika i Tekhnika Poluprovodnikov, 41, no 2, 186 (2007)  
[7] O. Klochan, J.C.H. Chen, A.P. Micolich, A.R. Hamilton, K. Muraki and Y. Hirayama, Applied Physics Letters, 96, 092103 (2010)  
[8] A.M. See, O. Klochan, A.R. Hamilton, A.P. Micolich, M. Aagesen and P.E. Lindelof, Applied Physics Letters, 96, 112104 (2010)  
[9] B. E. Kane, L. N. Pfeiffer, K. W. West, and C. K. Hartnett, Applied Physics Letters, 63, 2132 (1993)  
[10] R.H. Harrell, K.S. Pyshkin, M.Y. Simmons, D.A. Ritchie, C.J.B. Ford, G.A.C. Jones, and M. Pepper, Applied Physics Letters 74, 2328 (1999)  
[11] R.L. Willett, L.N. Pfeiffer and K. W. West, Applied Physics Letters 89, 242107 (2006)  
[12] S. Sarkozy, K. Das Gupta, C. Siegert, A. Ghosh, M. Pepper, I. Farrer, H. E. Beere, D. A. Ritchie and G. A. C. Jones, 2009, Applied Physics Letters, 94, 172105 (2009)  
[13] S. Sarkozy, F. Sfigakis, K. Das Gupta, I. Farrer, D. A. Ritchie, G. A. C. Jones and M. Pepper, 2009, Physical Review B, 79, 161307 (2009)