Linear non-hysteretic gating of a very high density 2DEG in an undoped metal–semiconductor–metal sandwich structure

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Abstract
Modulation-doped GaAs–AlGaAs quantum-well-based structures are usually used to achieve very high mobility two-dimensional electron (or hole) gases. Usually high mobilities (>107 cm2 V−1 s−1) are achieved at high densities. A loss of linear gateability is often associated with the highest mobilities, on account of some residual hopping or parallel conduction in the doped regions. We have developed a method of using fully undoped GaAs–AlGaAs quantum wells, where densities ≈6 × 1011 cm−2 can be achieved while maintaining linear and non-hysteretic gateability. The conducting channel of our device is induced entirely by a field-effect mechanism, when suitable voltages are applied to the top and bottom gates. We do not use any intentional dopants at all. Our method overcomes the problem of gating very high density two-dimensional electronic system. We show how these devices are useful for understanding mobility limiting mechanisms at very high densities and indicate the likely future applications.

(Some figures may appear in colour only in the online journal)

1. Introduction

The ability to tune the carrier density of a two-dimensional electronic system (2DES) over large ranges with a linear and non-hysteretic gate is one of the most desirable and generic aspects in experiments that involve a 2DES. Fundamental aspects of a 2DES, like the ratio of Coulomb and kinetic energies, screening, relative importance of various scattering mechanisms are all functions of the carrier density. The low density end (∼109 cm−2 and lower) is of great interest because the very dilute 2DES is a strongly interacting system [1], where the Coulomb interaction energy outweighs the kinetic energy. One the other hand, the very high density end (1011–1012 cm−2) is of interest because the highest electron mobilities [2] can be achieved at these densities. Qualitatively, this happens because the effect of ionized impurity scattering diminishes as kF (the Fermi wavevector) becomes larger compared to the Fourier components of the impurity potential (∼e−qd/q, where q is the scattering wavevector and d is the distance of the ionized impurity from the plane of the 2DES). Study of several other phenomena like non-parabolic effects and anti-crossing of hole bands [3], mobility limiting effect of interface roughness [4], study of novel fractional quantum hall (FQHE) states [5, 6] also require single sub-band, parallel-conduction free, linearly gateable, non-hysteretic 2DES in the density range (1011–1012 cm−2).

The advent of the quantum well structure with modulation doping [7] and an undoped spacer allowed higher densities and mobilities to be reached compared to what was possible with a heterostructure. Such structures have been the workhorse for 2DES-based devices for last 30 years. But a limitation of this scheme becomes apparent at high densities (figure 1 (a) and (b)). As the (as grown) carrier density is increased by increasing the doping concentration, the slope of the...
The envelope of the wavefunction in the quantum well for obtaining the maximum mobility.

2. Devices and experimental methods

We describe the growth, fabrication and initial measurements on devices where linear gating is demonstrated from $< 4 \times 10^{10}$ to $\sim 6 \times 10^{11} \text{cm}^{-2}$ in a 20 nm wide (GaAs–AlGaAs) quantum well. The highest electron mobility we achieve is $\mu_e \approx 9 \times 10^6 \text{cm}^2\text{V}^{-1}\text{s}^{-1}$ at $T = 1.5 \text{K}$. We present some data indicative of the mobility limiting scattering mechanism at the highest density. Finally, we discuss how the control over the shape of the wavefunction is important for achieving very high mobilities.

Figures 1(c) and (d) show the basic idea behind our method. If a very thin (1–2 $\mu$m), completely undoped AlGaAs–GaAs–AlGaAs can be sandwiched between two layers of metals, then the back- and top-gate biases on these plates ($V_{BG}$ and $V_{TG}$ w.r.t. the ohmics which connect to the quantum well) can be used to attract carriers into the well. There is no intentional dopant layer anywhere. The electrochemical potential itself goes down as one moves out from the quantum well, because the positive voltage bias on the gates is set to attract electrons (positive bias lowers the electrochemical potential). The combination of these two ensures that there is no place for parallel conduction to develop. Also, the relative bias on the two gates can be adjusted to tune the shape and tilt of the wavefunction in the quantum well. Two practical considerations are however needed at this point. First, there must be ohmic contacts going into the quantum well. Second, the 1–2 $\mu$m thick sandwiched structure cannot be self-supporting. Thus, the fabrication method has to ensure alignment of the topside and bottom-side features, as well as stress-free embedding of this structure in a suitably rigid base. Our fabrication method achieves these. The packaged devices showed no cracking after several thermal cycles from room temperature to 1.5 K. The densities and mobilities obtained from measurements in two different cryostats agreed within $\sim 10\%$.

The wafer used in this study was grown on a 500 $\mu$m [1 0 0] GaAs substrate as shown in figure 2(a). The quantum well was located approximately 100 nm below the surface and the etch stop (Al$_{0.3}$Ga$_{0.7}$As) was approximately 1500 nm below the surface. The topside processing consisted of four main steps. A Hall bar shaped mesa was etched (150–200 nm) and ohmics were lithographically defined. AuGeNi contacts were annealed at 450 °C for 180 s in a reducing atmosphere (N$_2$/H$_2$) after lift-off. A layer of polyimide (HD 4104, HD microsystems) was then spin-coated on the sample. The polyimide layer was 400–500 nm thick after curing at 250 °C. A metal top gate (Ti/Au) was patterned and deposited on top of the polyimide layer. After this, the sample was embedded topside down on a host (GaAs wafer) with a thin layer of epoxy. The GaAs substrate was then removed from the back using a combination of abrasive mechanical polishing and selective etching (in citric-acid+H$_2$O$_2$) etch to expose the Al$_{0.3}$Ga$_{0.7}$As etch stop. In our procedure, a 1:1 solution was prepared by mixing equal weight of de-ionized water and citric acid —1/5 of its volume...
of H$_2$O$_2$ was then added. The etch stop was then removed using hydrofluoric acid (HF). The HF removes the etch stop due to its high Al concentration but does not attack the GaAs layer below. At this stage a smooth mirror finish is obtained. A careful inspection is done for any cracks and deformations. The sample is then coated with another layer of polyimide and the back gate is deposited on top of the cured polyimide. During this last stage the bond pads to the sample are also defined, which are then used to connect the ohmics and the gates to a leadless chip carrier using an ultrasonic wire bonder. A similar use (with some differences) of epoxy embedding and etch-stop layer was introduced by Weckworth et al [12] for fabricating back gates on a bilayer 2DES.

3. Results

Figure 3(a) shows that combination of the top-gate voltage ($V_{TG}$) and bottom-gate voltage ($V_{BG}$) induces a two-dimensional electron gas (2DEG) in the quantum well. The proof that the channel indeed forms in the quantum well and not somewhere else is provided by the clean quantum Hall traces. It is impossible to have a high mobility (close to $10^7 \text{cm}^2\text{V}^{-1}\text{s}^{-1}$) single-sub-band 2DEG anywhere else (e.g. the superlattice). The single-sub-band nature of the 2DEG is established by the excellent agreement (better than 1 part in 100) of the densities calculated from the slope of the Hall voltage and the period of the oscillations. From the slope of the density of the 2DEG ($n$) versus $V_{TG}$ and $V_{BG}$, we can calculate the capacitance of the gates to the 2DEG. This agrees well with the calculated values obtained using the known thickness of the semiconductor and polyimide layers:

$$n = \frac{C_{TG}}{e}V_{TG} + \frac{C_{BG}}{e}(V_{BG} - V_0)$$

where $C_{TG}$ and $C_{BG}$ denote the top- and back-gate capacitances. We associate a threshold voltage ($V_0$) with the back gate because the specific design of our device uses the back gate to activate the ohmics $V_0 \sim 4 \text{ V}$ in our devices.

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The density of the 2DES in the channel depends only on the two gate voltages and not the past history of the voltage
cycles. We also verified that the mobility of the 2DES is also a function of the two gate voltages only—thus mobility versus density curves have no ambiguity associated with them. Within operating limits (figure 3(a)), the behaviour of the device is thus independent of how a certain configuration was reached.

The expected capacitances $C_{TG}$ and $C_{BG}$ can be estimated by using a simple parallel plate model of capacitors with two dielectrics stacked vertically on one another. Here, the capacitor is formed between the 2DES and the top (bottom) gate. The intervening dielectrics are GaAs/AlGaAs (thickness $d_1$, relative dielectric constant $\kappa_1 = 13$) and the cured polyimide (thickness $d_2$, relative dielectric constant $\kappa_2 = 3$ from manufacturer’s datasheet). We then obtain

$$\frac{\partial n}{\partial V} = \frac{C}{e} = \frac{e_0/e}{d_1/\kappa_1 + d_2/\kappa_2},$$

where $C$ can be either $C_{TG}$ or $C_{BG}$.

Using the data obtained from figure 3(a), we find a slope of $\partial n/\partial V_{BG} = 3.5 \times 10^{10}$ cm$^{-2}$ V$^{-1}$ for all the traces. Taking $d_1 = 100$ nm (as grown by MBE, see figure 2(a)) and $d_2 \approx 500$ nm (measured by a profilometer), we calculate an expected slope of $3.1 \times 10^{10}$ cm$^{-2}$ V$^{-1}$. The change in carrier density due to change $V_{BG}$, while keeping $V_{TG}$ fixed can be read off from the same data as the vertical distance between the set of straight lines and the corresponding change in $V_{BG}$. The observed slope $\partial n/\partial V_{BG} = 2.2 \times 10^{10}$ cm$^{-2}$ V$^{-1}$ and the calculated value with $d_1 = 1200$ nm (as grown by MBE, see figure 2(a)) and $d_2 \approx 500$ nm (measured by a profilometer) $2.3 \times 10^{10}$ cm$^{-2}$ V$^{-1}$ agree sufficiently well, given that there is some (5–10%) variation in the thickness of the polyimide layer over the full extent of the device. The leakage current was monitored by applying gate voltages with a source of the type that continuously measures the current flowing out of the source. Over the entire operating range shown, the leakage remained below 50 picoamperes. However, near the high voltage end of the operating range, above $V_{BG} \gtrsim 10$ V and above $V_{TG} \gtrsim 15$ V small deviations from linear change in the density could be noted. We did not operate the device in this region. Although the corresponding electric field is considerably less than the expected dielectric breakdown voltage of cured polyimide ($\sim 100$ V/\(\mu\)m), it is possible that the interfacial trapped charge at the interfaces are becoming active beyond this. The interfacial states between a polymer and GaAs can indeed be complex, and is not very well understood. The large slope of the conduction band around the quantum well itself may also aid some amount tunnelling. These two factors are likely to set a physical limit to the operating range of the device. However, at the highest densities reached, there was no evidence of a second sub-band in the Shubnikov-de Haas traces—like the one shown in figure 3(c).

Since both $V_{TG}$ and $V_{BG}$ may be used to tune the carrier density, it is possible to obtain the same density for a number of combinations of the two voltages. In these different combinations, $n$ is the same but the shape of the wavefunction is different. See figure 4 for a schematic of how the ‘tilt’ of the wavefunction towards the top or bottom interface can be controlled by the top- and bottom-gate voltages. Figure 3(b) shows that the mobility of the electron gas can vary by nearly 50% depending on the choice of the two gate voltages for the same $n$. For example if we examine the four traces in figure 3(a), we find that the density of $n = 4 \times 10^{11}$ cm$^{-2}$ may be obtained by setting $V_{BG}$ equals; 6 V and $V_{BG} = 8.25$ V, (green filled square) or $V_{BG} = 15$ V and $V_{BG} = 3.0$ V (blue empty square). Figure 3(b) shows that the mobility in the first case is $7.2 \times 10^{6}$ cm$^{2}$ V$^{-1}$ s$^{-1}$ but in the second case it is only $5.0 \times 10^{6}$ cm$^{2}$ V$^{-1}$ s$^{-1}$. Indeed the large difference in the four traces in figure 3(b) indicates that in the highest mobility regime the ionized background is not necessarily the dominant factor determining the mobility. In a quantum well, we necessarily have two GaAs–AlGaAs interfaces. Inevitably the first of the interfaces (in order of growth) is ‘inverted’ (GaAs is grown on top of AlGaAs) and is thought to have more interface roughness than the other interface in which AlGaAs is grown on GaAs. A rough interface is known to affect transport mobility in MOSFETs [14], heterostructures [4, 15, 16], thin metal films [18] and quantum wells. However, the perturbative term introduced in the problem due to a rough interface is essentially a perturbation of the boundary condition. Usually, the change in boundary conditions is transformed to an effective ‘extra’ electric field and the perturbative analysis is carried out [18, 15]. This fundamental fact makes the treatment of the effect of roughness on mobility more complex than the effect of impurities, traps and defects. Progress in MBE growth has now led to very high quality heterostructures where the mobility of the 2DES (at least in the high density range) may be primarily limited by the interface roughness for electrons [4] as well as hole gases [16]. Thus, it appears that the achievement of even higher mobilities in a 2DES may well depend on our ability to analyse and control the interfacial roughness. Interestingly, recent experimental data and efforts to understand the transport mobility of electrons and holes using similar numbers for the background impurity and (Gaussian) interface roughness have shown that the apparent ‘disorder’ seen by the electrons and the holes is somewhat different [17, 19]. However, in these experiments it was not possible to control the position (shape) of the wavefunction independent of the electron density. The metal–semiconductor–metal sandwich structure proposed in our paper makes this possible over a very wide range of densities.

In our devices, a larger $V_{BG}$ leads to lower mobilities because the wavefunction is then tilted more towards the inverted interface. In both cases, the electrons see that a similar ionized background resulting from the unintentional impurities incorporated during MBE growth remains the same. The small change in the form factor of the wavefunction resulting from the change in tilt cannot account for the large change in screening (or the dielectric function) that would be required to account for a large change in mobility. Coulomb scattering arising from ionized impurities cannot account for this change, leaving the roughness of the interface and the ‘alloy scattering’ as possible sources of the observed change in mobility.

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3 Using methods developed by us earlier [4], we estimated the background in the growth chamber to be approximately $7 \times 10^{13}$ cm$^{-3}$ in GaAs and $1.4 \times 10^{14}$ cm$^{-3}$ in Al$_{0.3}$Ga$_{0.7}$As.
Figure 4. Schematic of the self-consistent solutions of the wavefunction in a quantum well for different top- and bottom-gate voltages. The parameters used in this plot are close to the actual values for the wafer used in our experiments. However, the presence of the polyimide on both surfaces was not taken into account.

4. Summary

Undoped heterostructures have been known to be particularly useful for maintaining high mobility at low densities [1, 9, 11, 13], making very shallow gateable 2DEGs [4]. Similar devices have been used to study the two-dimensional metal insulator transition problem [13] and more recently the effect of long- and short-ranged scattering on the 5/2 FQHE state [21]. In this paper, we have shown that the field-effect mechanism of pulling carriers from the ohmics into the conducting channel can be useful in reaching very high densities as well. Our method has several useful features and possibilities. First, this applies equally well for creating an electron or a hole type channel. The MBE chamber used for growth needs to be optimized for the lowest possible unintentional background and interface roughness once—and not separately for n-type/p-type dopants (which is essential if modulation doping, or any of its variants, is used). Second, the experimenter can decide whether to fabricate n-type or p-type ohmic contacts. It is clearly possible to make these sandwich structures fully ambipolar by fabricating both n-type and p-type ohmics on the same Hall-bar [20]. Third, in several data published in the literature so far, the mobility of a 2DEG in undoped heterostructures [11, 13, 21] is seen to saturate around a density \( n = 1 - 2 \times 10^{11} \, \text{cm}^{-2} \). This happens because at the triangular confining potential at a heterointerface, the strength of the roughness scattering increases rapidly with density. Since the shape of the wavefunction gets self-consistently determined with the confining potential, the experimenter does not have independent control over the shape. By using a quantum well and controlling the position of the wavefunction using top and bottom gates with comparable capacitance to the 2DEG, we are able to overcome this saturation at relatively low densities. We anticipate that the method of achieving gateable higher densities could also possibly be used to increase the energy gaps of fragile FQHE states by forcing the same filling factor to occur at higher magnetic fields in future.

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