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2016 Semicond. Sci. Technol. 31 065013

(http://iopscience.iop.org/0268-1242/31/6/065013)

OPEN ACCESS
IOP Publishing

Semiconductor Science and Technology

Semicond. Sci. Technol. **31** (2016) 065013 (7pp)

doi:10.1088/0268-1242/31/6/065013

N-type ohmic contacts to undoped GaAs/AlGaAs quantum wells using only front-sided processing: application to ambipolar FETs

D Taneja[1], **F Sfigakis**[1], **A F Croxall**[1], **K Das Gupta**[1,2], **V Narayan**[1], **J Waldie**[1], **I Farrer**[1,3] **and D A Ritchie**[1]

[1] Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge CB3 0HE, UK
[2] Department of Physics, Indian Institute of Technology Bombay, Mumbai 400 076, India
[3] Department of Electronic and Electrical Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, UK

E-mail: dt357@cam.ac.uk

Received 24 September 2015, revised 14 February 2016
Accepted for publication 29 March 2016
Published 28 April 2016

Abstract

We report the development of a simple and reliable, front-sided-only fabrication technique for n-type ohmic contacts to two-dimensional electron gases (2DEGs) in undoped GaAs/AlGaAs quantum wells. We have adapted the well-established recessed ohmic contacts/insulated metal gate technique for inducing a 2DEG in an undoped triangular well to also work reliably for undoped square quantum wells. Our adaptation involves a change in the procedure for etching the ohmic contact pits to optimise the etch side-wall profile and depth. As an application of our technique, we present a front-side-gated ambipolar field effect transistor (FET), where both 2D electron and hole gases can be induced in the same quantum well. We present results of low-temperature (0.3 K - 4 K) transport measurements of this device, including assessment of the n-type ohmic contact quality. On the basis of our findings, we discuss why the fabrication of these contacts is difficult and how our technique circumvents the challenges.

Keywords: undoped, GaAs/AlGaAs, quantum wells, ohmic contacts, etching, etch profiles

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

1. Introduction

Field-effect-induced two-dimensional electron gases (2DEGs) and two-dimensional hole gases (2DHGs) in undoped GaAs/AlGaAs heterostructures offer a number of advantages over their modulation-doped counterparts. The absence of doping results in higher carrier mobilities at low carrier densities [1] and more reliable control of the carrier density by an applied gate voltage [2, 3]. 2DEGs and quantum dots can be formed as shallow as 30 nm below the surface [4, 5], and it becomes possible to define finer features using surface gates, as a spacer layer (between the 2DEG and the dopants) is no longer needed. Quantum dots and quantum point contacts in undoped systems can benefit from reduced coupling to nearby charged impurities, giving higher device yields [6, 7], reduced charge noise and longer spin-coherence lifetimes, as required for quantum-dot-based spin qubits [8]. Additionally, undoped systems lend themselves to ambipolar devices, where a 2DEG and a 2DHG can be defined in the same channel [9, 10].

However, the majority of undoped GaAs/AlGaAs devices have been based on a simple heterointerface, where the 2DEG(HG) is confined in a triangular quantum well (TW). Relatively few reports exist of undoped 2DEGs formed in a

GaAs quantum well (QW) confined between AlGaAs layers. The QW structure can enable several new types of devices. Using the ambipolar technology already demonstrated in undoped GaAs/AlGaAs systems [9, 10], it is relatively easy to form a lateral p-n junction, where electrons and holes recombine to emit photons [11, 12]. However, for efficient photon emission the electrons and holes must be confined in a QW; in a TW device the carrier confinement will be lost at the junction. Coupled with single-electron transport devices such as surface-acoustic waves or electron pumps [13, 14], this could form the basis of a single-photon source for use in quantum information processing. The QW geometry is also required for the formation of vertically coupled low-dimensional bilayer systems, where interlayer interactions can lead to the formation of novel quantum phases [15–17]. Fully ambipolar bilayers, where each layer can be populated with either electrons or holes, are of great interest for exploring the differences between attractive (electron–hole) or repulsive (electron–electron or hole–hole) interactions [18].

We believe the lack of undoped 2DEG devices in QWs is due to the relative difficulty of establishing reliable ohmic contacts to 2DEGs in undoped QWs. In section 2 we review the methods that have been used so far, and explain why these methods are either more complex than those used for TWs and/or not suited to ambipolar devices. In section 3, we present the development of a simpler and more reliable procedure for forming n-type ohmic contacts to 2DEGs in undoped QWs, which could be easily used in the applications described above. We describe our ambipolar device fabrication procedure and the results of systematic optimisation of key n-type ohmic contact fabrication parameters. Section 4 presents low-temperature transport studies of a front-side-gated ambipolar field effect transistor (FET), fabricated using our procedure, along with some results which demonstrate the quality of our n-type ohmic contacts. Finally, in section 5, based on our results, we discuss why n-type ohmic contacts to undoped QWs are more difficult to fabricate than either n-type contacts to undoped TWs or p-type contacts to TWs and QWs, and how our fabrication method circumvents these difficulties.

2. Overview of ohmic contacts to undoped GaAs/AlGaAs 2D systems

Fabrication and operation of ohmic contacts in undoped heterostructures is distinctly different from doped structures, where the ohmic contact metal is deposited on the surface of the sample and subsequently annealed to diffuse vertically down to the interface and make contact to the 2DEG or 2DHG that already exists [19]. For undoped structures, the 2DEG(HG) needs to be induced in the GaAs channel by electric field effect, and contacted through ohmic contact metal that has diffused laterally into the channel (see figure 1).

Several methods of forming contacts to undoped TWs have been established. In the self-aligned ohmic contacts scheme [20–22], a heavily doped n+ GaAs cap (acting as a gate) pins the Fermi level in the conduction band and induces electrons in the TW upon the application of a gate bias. The ohmic contacts are deposited in regions where the n+ cap has been selectively etched away, and hence self-align to it. This technique can also be used to induce a 2DHG [20, 23]. In the recessed ohmic contacts/insulated metal gate technique [1, 4, 24, 25], ohmic pits are etched down to the GaAs/AlGaAs interface and ohmic contact metal is deposited in them at an angle (figure 1). The recessed nature of the ohmic contacts enables lateral diffusion of the metal. A metal gate, separated from the ohmic contacts by a layer of insulator, is biased to induce the 2DEG(HG).

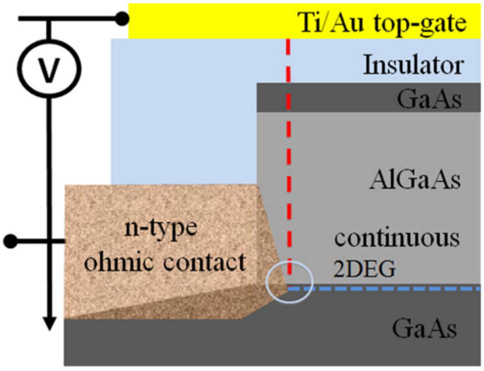

Figure 1. (a) Schematic showing an induced 2DEG in an undoped GaAs/AlGaAs TW. A positive voltage is applied between the metal gate and the n-type ohmic contact to induce the 2DEG. This cross-section is representative of the recessed ohmic contacts/insulated metal gate technique [4].

The self-aligned contacting scheme has been demonstrated for 2DEG(HG)s in both a TW and a QW geometry [20, 26]. However, the requirement of a doped GaAs cap makes it difficult to fabricate ambipolar devices [23]. It is also difficult to avoid short circuiting between the doped cap and the self-aligned contact when the 2DEG(HG) is very shallow. Therefore, we focus on the recessed ohmic contacts/insulated metal gate technique. We note that it is also possible to fabricate field-effect-induced 2D systems from modulation-doped structures by removing/etching away the doped layers in all except the ohmic contact regions [8]. However, this technique would also be difficult to extend to ambipolar devices, since the dopant can aid only one polarity of the contacts.

While the recessed ohmic contacts/insulated metal gate technique is well-established for 2DEG(HG)s in TWs, and also 2DHGs in QWs [18], there are few reports of a 2DEG being induced in an undoped QW using insulated gates [27, 28], and these often require specialist techniques such as reactive-ion etching, which might affect electronic quality [29]. Croxall *et al* fabricated an ambipolar device based on an undoped GaAs/AlGaAs QW [9]. However, the 2DEG in this device had to be induced using a back-gate overlapping the n-type contacts. This involved a challenging flip-chip technique [3, 30], where the device must be thinned to only a few micrometers thick before the back-gate is deposited. The flip-chip technique could induce strain in the finished devices. It will, therefore, be advantageous to have a front-side-only process, where the possibility of depositing an MBE-grown buried back-gate could also be explored.

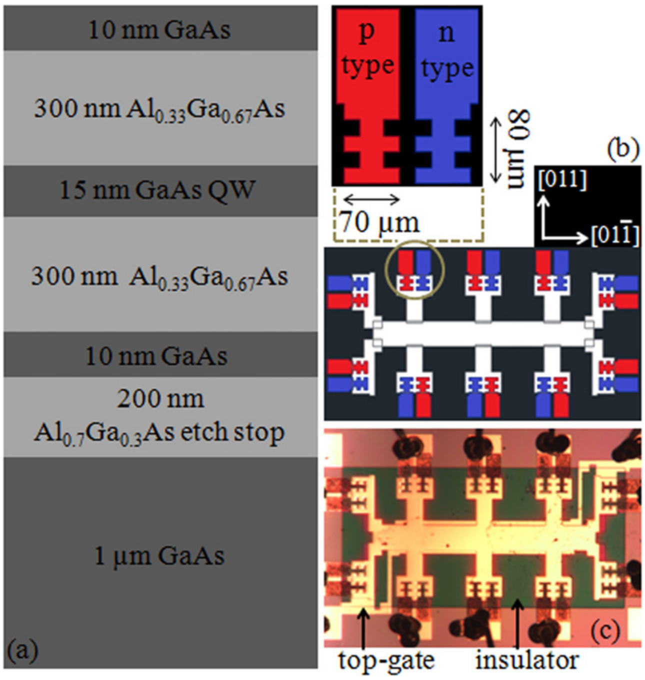

Figure 2. Schematic showing the (a) generic quantum well wafer structure in use, and (b) Hall-bar-shaped mesa and ambipolar ohmic contacts, with zoomed-in contacts pattern. The indicated crystallographic directions in (b) are the as-represented directions in the 2D plane of the paper. (c) An optical image of a fabricated ambipolar device.

One of the primary requirements for an undoped device is that the ohmic contact metal and the inducing gate must overlap vertically without short circuiting, to ensure that the 2DEG(HG) is continuous right up to the ohmic contact (see figure 1). Therefore, lateral diffusion of the ohmic contact metal is extremely important. In the work presented here, we look to adapt the recessed ohmic contacts/insulated metal gate technique to induce a 2DEG in an undoped QW with simple, front-side-only fabrication. Our adaptation involves a change in the procedure for etching the ohmic contact pits, to modify the side-wall profile of the etch, in a way such that the vertical overlap requirement between the ohmic metal and the inducing gate is more easily met.

3. Experimental methods and results

For our studies we used a range of GaAs/AlGaAs heterostructures, grown by molecular-beam epitaxy on the (100) GaAs surface, with the generic layer structure shown in figure 2(a). The QW lies at a depth of 310 nm below the surface and the QW width varies from 15 nm to 60 nm. There are no intentional dopants anywhere in the system. The etch stop in the wafer structure can be used for thinning and back-gating devices [3, 9].

Ambipolar device fabrication begins with the processing of p-type ohmic contacts as these require a higher annealing temperature than the n-type contacts. Both types of contacts are patterned by photolithography, using a positive 1.2-μm thick resist (Microposit S1813). Following resist development, samples are given a 40 s RF oxygen plasma etch to remove any residual resist from the developed regions. The ohmic contact pits for the p-type contacts are then etched to a depth of ≈ 250-300 nm, using the standard H_3PO_4:H_2O_2:$H_2O \equiv 1$:1:20 solution, used for TWs [4]. This is followed by a 5 min RF oxygen plasma etch to remove the resist overhang left after etching [4] and a dip for 25 s in a 20% HCl solution to remove GaAs surface oxides. Approximately 160 nm of AuBe (Au(99):Be(1) by weight%) is deposited by thermal evaporation at pressures not exceeding 2×10^{-6} mbar, at an angle of 45° with the sample rotating. After lift-off of unwanted metal in acetone, the contacts are annealed in forming gas (N_2/5% H_2) in a rapid thermal annealer at 520 °C for 90 s.

For n-type ohmic contacts, following lithography and a 30 s RF oxygen plasma etch, and preceding the ohmic pits etch, the samples are subjected to an additional 25 s dip in 20% HCl solution to ensure that the ohmic contact area is free of any GaAs surface oxides. For etching the ohmic pits, a variety of etchants and etch depths were tested. The etchants included the H_3PO_4, H_2SO_4 and HCl families with different concentrations of acid, hydrogen peroxide and water. The mixed etch solutions were allowed to stabilise overnight, and HCl-based solutions were agitated to remove any bubbles that formed during this time [29], to ensure a uniform etching across the sample. Immediately after etching, 470-490 mg of AuGeNi alloy (Au(83)/Ge(12)/Ni(5) by weight%) is deposited by thermal evaporation at pressures not exceeding 5×10^{-6} mbar, at an angle of 45° with the sample rotating, giving a thickness of ≈ 250 nm. Approximately 80 nm of Pd is then deposited in the same way, to smooth the surface of the ohmic contacts and minimise the possibility of leakage currents between the contacts and the metal gate. We note that in reference [4] for TWs, the ohmic contact metal is deposited at an angle of 60°, in addition to performing a short microwave ash before metal deposition (similar to the 5 min RF oxygen plasma etch for our p-type contacts to the QW), as this enables a good side-wall wetting of the ohmic pit required for good quality n-type contacts to TWs. However, for our n-type ohmic contacts to QWs, an angle of 45° is chosen, along with a bypassing of the ashing step. This ensures that the ohmic metal is deposited right up to the edge of the ohmic pit, but does not wet the side-walls. Wetting of the side-walls was found to lead to a degradation or complete failure of the n-type ohmic contacts to QWs. Further studies are required to determine whether wetting of the side-walls affects the quality of p-type contacts to TWs or QWs. Following lift-off, our n-type ohmic contacts to QWs are annealed at 470 °C for 40 s in the rapid thermal annealer in forming gas. These parameters for annealing have been adopted from an optimised recipe for TWs and are also found to work well for QWs. A Hall-bar-shaped mesa (see figure 2(b)) is etched down to 500 nm. A photo-definable polyimide insulator (HD Microsystems HD4104, ≈ 800 nm) is overlaid and a metal gate (30 nm Ti and 150 nm Au, evaporated at an angle of 45° to climb the mesa) is deposited. Figure 2(c) shows an optical image of a completed device.

We have studied the etch profiles of ohmic contact pits along different crystallographic planes with various oxidising

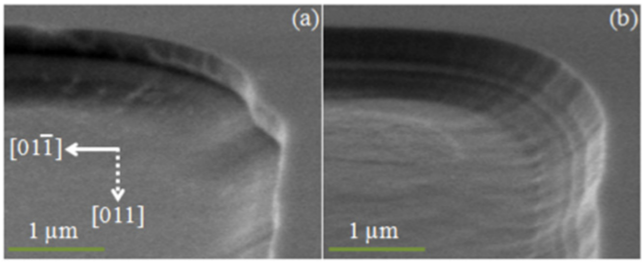

Figure 3. Scanning electron micrographs of ohmic contact pits etched with a H_3PO_4:H_2O_2:H_2O $\equiv$ 1:1:20 etching solution for (a) a TW, and (b) a QW. The depth of both the TW and the QW is 310 nm. The directions corresponding to the two visible side-walls of the etched pits are indicated. The direction labelled [01$\bar{1}$] (solid line) indicates the as-represented direction in the plane of the paper, whereas [011] (dashed line) indicates the direction coming out of the plane of the paper, towards the reader.

etchants. Figures 3(a) and 3(b) show the scanning electron microscopy (SEM) images of ohmic pits etched with a H_3PO_4:H_2O_2:H_2O $\equiv$ 1:1:20 solution for a 310-nm-deep TW and a 310-nm-deep QW, respectively. The etch profile obtained for the TW structure is almost vertical in the AlGaAs region followed by a sharp over-cut in the GaAs region, and is suitable for forming n-type ohmic contacts to TWs, as demonstrated by Mak *et al* [4]. In contrast, a very rounded and pronounced over-cut profile is obtained in the QW structure with the same etching solution. We have fabricated numerous devices based on a QW structure with the ohmic pits etched with a H_3PO_4:H_2O_2:H_2O $\equiv$ 1:1:20 solution but were unable to induce a 2DEG with an insulated top-gate. We believe that the failure of the ohmic contacts in these devices could be related to the pronounced over-cut etch profile shown in figure 3(b), which is very different to the TW case (figure 3(a)). Therefore, we believe that the key to successful fabrication of n-type ohmic contacts to undoped QWs may lie in adapting the etching procedure to reduce the over-cut in the side-wall profile above the QW, and achieve a profile similar to that in figure 3(a).

Figures 4(a) and 4(b) show SEM images of the ohmic pits for QW samples etched with H_3PO_4:H_2O_2:H_2O $\equiv$ 1:1:20 and H_2SO_4:H_2O_2:H_2O $\equiv$ 1:1:8 solutions respectively. For this imaging, the samples are cleaved and rotated through an angle of $\approx 90°$ from horizontal to allow for complete visibility of the side-wall profile. The shown etched facets (i.e. side-walls) are along the (01$\bar{1}$) plane. The ohmic contact metal (before annealing) deposited with the angled evaporation is also shown for these two images. On comparing the two images, it is clear that the shape of the etch profile obtained with the H_3PO_4 solution leads to the deposition of the ohmic contact metal (in the QW region) horizontally further away from the top of the etched pit. The etch profile obtained with the H_2SO_4 solution, on the other hand, has a much smaller over-cut, with a slight under-cut at very shallow depths, leading to closer horizontal proximity between the ohmic contact metal and the top of the etched pit. A similar side-wall profile is also obtained with a HCl:H_2O_2:H_2O $\equiv$ 1:1:9 solution (figure 4(c)), where the over-cut in the side-wall profile is significantly reduced as compared to figure 4(a). Such a profile was never obtained with the range of concentrations explored for H_3PO_4.

We have found that the side-wall along the (011) crystallographic plane for H_2SO_4:H_2O_2:H_2O $\equiv$ 1:1:8 and HCl:H_2O_2:H_2O $\equiv$ 1:1:9 etching solutions has a large over-cut profile [31], which may not be suitable for forming ohmic contacts. The lithographic shape of the ohmic contacts (see figures 2(b) and 2(c)) is, therefore, such that there is always some etched side-wall along the (01$\bar{1}$) plane, where the over-cut profile is reduced.

We have fabricated devices on different wafers employing H_3PO_4:H_2O_2:H_2O $\equiv$ 1:1:20, H_2SO_4:H_2O_2:H_2O $\equiv$ 1:1:8, and HCl:H_2O_2:H_2O $\equiv$ 1:1:9 etching solutions. We also tried etchants with various other concentrations of H_3PO_4/H_2SO_4/HCl, H_2O_2 and H_2O. In agreement with reference [31], we found that the etch profile depends on the acid: peroxide ratio and dilution. The only devices in which a 2DEG could be induced with an insulated top-gate were those made with the H_2SO_4:H_2O_2:H_2O $\equiv$ 1:1:8 and HCl:H_2O_2:H_2O $\equiv$ 1:1:9 etching solutions, which also reduced the over-cut in the ohmic pit etch profile (figures 4(b) and 4(c)).

In addition to the etch profile, we have observed that the etch depth of the ohmic pit is crucial. We were reliably able to fabricate ohmic contacts to the 2DEG when the etch depths of the ohmic contact pits were in the range 290-330 nm for the

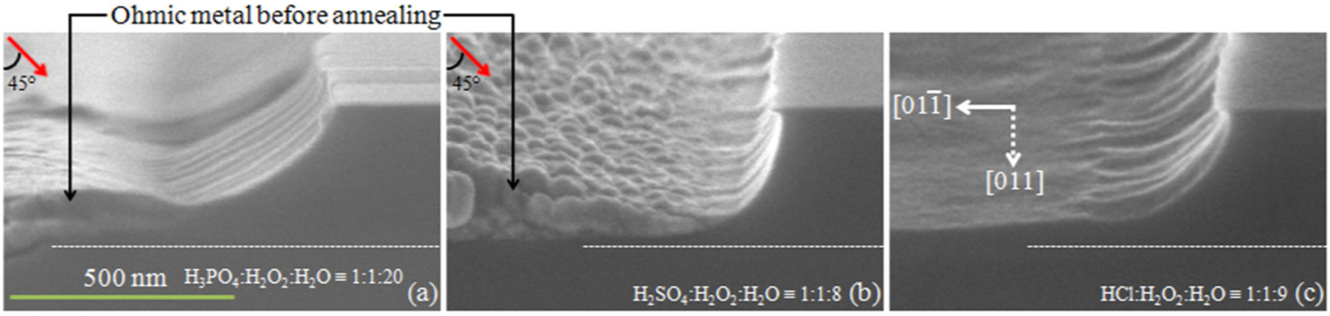

Figure 4. Scanning electron micrographs of ohmic contact pits in QW samples etched with (a) H_3PO_4:H_2O_2:H_2O $\equiv$ 1:1:20, (b) H_2SO_4:H_2O_2:H_2O $\equiv$ 1:1:8, and (c) HCl:H_2O_2:H_2O $\equiv$ 1:1:9 etching solutions. As in figure 3, the direction labelled [01$\bar{1}$] indicates the as-represented direction in the plane of the paper, and corresponds to the direction of the shown side-walls. The direction labelled [011] points out of the plane of the paper. The horizontal dotted lines indicate the position of the 310-nm-deep QW on each image. The red arrows in (a) and (b) indicate the direction of metal evaporation. Note that image (c) is shown without the ohmic metal.

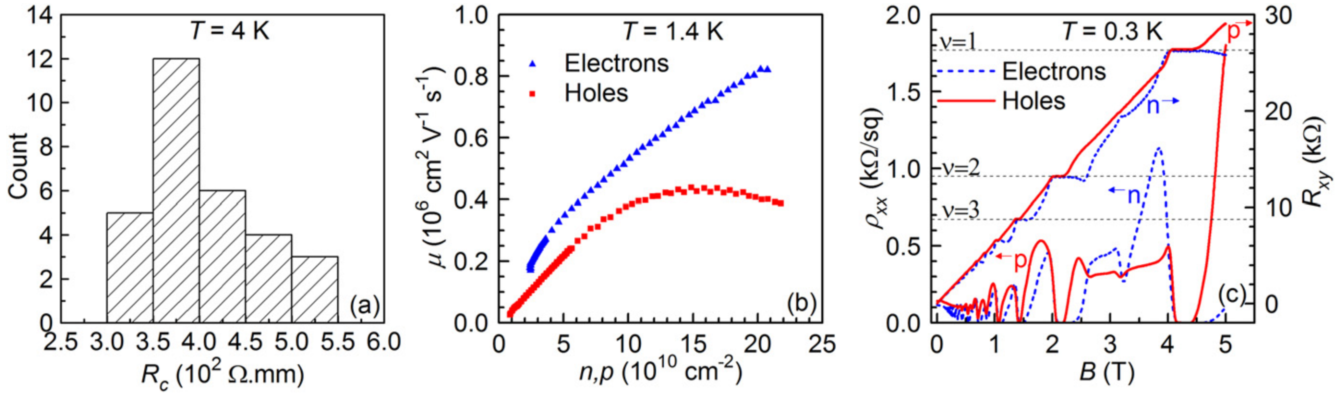

Figure 5. (a) Histogram showing the spread of the contact resistances (R_c) for n-type ohmic contacts. (b) Electron and hole mobilities (μ_e and μ_h) as a function of carrier concentrations (n and p). (c) Magnetoresistivity (ρ_{xx}) and Hall resistance (R_{xy}) for electrons and holes at $n = p = 1 \times 10^{11}$ cm^{-2}.

310-nm-deep QW. Shallower as well as deeper ohmic pits reduced the yield and the quality of the ohmic contacts. The etch rate of the H_2SO_4:H_2O_2:H_2O $\equiv$ 1:1:8 solution is quite fast ($\approx$ 20 nm.s^{-1}), and varies greatly with etching conditions such as temperature and solution agitation, making precise control of the etch depth difficult. Alternatively, the etch rate of the HCl:H_2O_2:H_2O $\equiv$ 1:1:9 solution is $\approx$ 5-7 nm.s^{-1}, which lends itself to an easier achievement of the desired etch depths for making successful ohmic contacts.

4. Transport experiments

We have fabricated devices with successful ohmic contacts using our fabrication recipe on 5 different wafers with both single and double QWs of varying widths (15 nm to 60 nm). In this section, we present results from an ambipolar device based on a 15-nm-wide undoped single QW (see figure 2), including data for the n-type ohmic contact resistances and showing the types of low-temperature transport studies enabled by these contacts. The ohmic contact pits for the n-type contacts on this device were etched with a HCl:H_2O_2:H_2O $\equiv$ 1:1:9 solution. The device was characterised using standard low-frequency ac lock-in techniques at temperatures between 0.3 K and 4 K. A 2DEG(HG) could be induced in the device by the application of a positive(negative) bias on the top-gate relative to the n-(p-)type contacts.

We determined the average contact resistance of the n-type ohmic contacts using two-terminal measurements at 4 K. For this, the known resistance of the measurement wiring, and the 2DEG resistance, determined from the 2D resistivity and the device geometry, are subtracted from the measured two-terminal resistance, followed by dividing by two. The results from 30 distinct pairs of contacts on two different samples are shown in figure 5(a). The average contact resistance is approximately 410 Ω.mm. We observe a large spread of contact resistances, which range from $\approx$ 320 Ω.mm to $\approx$ 540 Ω.mm. Estimations of the contact resistance using a transmission line method (TLM) device geometry could reduce the measurement uncertainties. The average contact resistance of the standard p-type contacts is approximately 590 Ω.mm. Both the n- and p-type contact resistances are quite high compared to those achieved in doped GaAs/AlGaAs devices [19]. Further work is required to reduce the contact resistances. However, our contact resistances are suitably low to enable low-temperature transport studies, such as the following examples.

Figure 5(b) shows the electron mobility μ_e and the hole mobility μ_h as a function of the electron density n and the hole density p respectively at temperature T = 1.4 K. For low n (below 3 × 10^{10} cm^{-2}), μ_e can be observed to drop rapidly, indicating a transition to the percolating regime of the 2DEG at low density [32]. This shows that the lowest measured n is limited by the disorder in the 2DEG and not the ohmic contacts. The observed density dependence of the electron and the hole mobilities is in qualitative agreement with reference [9], where the devices were fabricated using a flip-chip technique. However, the mobilities are suppressed because the asymmetric nature of the gating in our top-gate-only device pulls the wavefunction against the upper AlGaAs layer, increasing the amount of interface roughness scattering, particularly at higher densities.

Magnetotransport data for matched $n = p = 1 \times 10^{11}$ cm^{-2} at $T = 0.3$ K (figure 5(c)) demonstrates a clean, parallel-conduction-free 2DEG(HG) in the QW. The observation of well-developed Shubnikov-de-Haas (SdH) oscillations and Integer Quantum Hall Effect (IQHE) plateaux shows that our ohmic contacts work well in a quantising magnetic field. The different shapes of the SdH minima for electrons and holes may be due to the different disorder environments experienced by the electrons and the holes [33, 34]. Our n-type ohmic contacts have also been subjected to temperatures down to 0.07 K and are found to work well without exhibiting odd behaviour or freezing out at lowest temperatures. These contacts are, therefore, reliable for low-temperature transport studies.

5. Discussion and conclusions

The above results show that we have successfully adapted the recessed ohmic contacts/insulated metal gate technique that is often used to induce a 2DEG in an undoped GaAs/AlGaAs TW

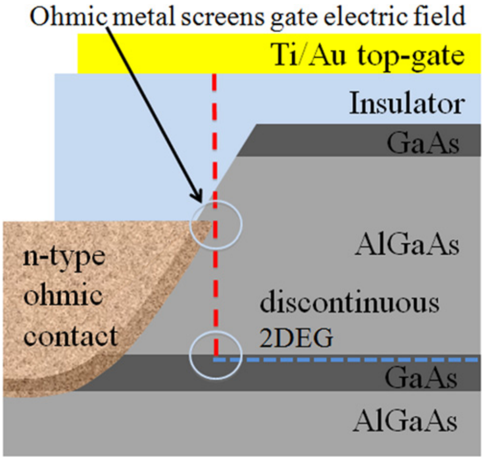

Figure 6. Schematic showing a discontinuous 2DEG in a QW with a large over-cut side-wall profile of the etched ohmic pit.

to induce a 2DEG in an undoped GaAs QW. This was achieved through use of suitable wet chemical etchants to give the etched ohmic pits a less over-cut, more vertical side-wall profile. The depth of the ohmic pits was also found to be critical. In this section, we present some possible reasons for the comparative difficulty of forming n-type ohmic contacts to undoped QWs, and discuss how our method circumvents these problems.

Figure 3 showed that the side-wall profiles for a TW and a QW etched with the same solution of H_3PO_4:H_2O_2:$H_2O \equiv$ 1:1:20 are remarkably different. The pronounced over-cut side-wall profile of the etched ohmic pit obtained for a QW may lead to the vertical overlap requirement between the ohmic metal and the inducing gate not being met, as illustrated in figure 6. With the large over-cut profile, the ohmic metal in the AlGaAs layer above the 2DEG channel could screen the electric field from the gate, leading to a discontinuous 2DEG with no electrical connection to the ohmic contacts. By reducing the over-cut in the side-wall profile with our procedure, this problem could be circumvented. We note that the large over-cut profile does not hinder the successful inducing of the 2DEG in the QW with a gate placed at the back of the (thinned) sample [9], perhaps because then the contact metal in the AlGaAs layer below the QW does not screen the back-gate electric field.

We have found that for successful ohmic contacts it is important to terminate the ohmic pit etch very close to/in the QW. This is in contrast to the method used for contacting TWs, where the ohmic pit etch extends past the TW interface [4]. This suggests that the relative amounts of AlGaAs and GaAs exposed by the ohmic pit etch may be important for n-type contacts to 2DEGs induced in QWs, perhaps because the exposed AlGaAs may oxidise [35] or because the diffusion of Ge into AlGaAs is known to be slower than into GaAs [36–38]. Studies of the composition of the ohmic contacts, by energy-dispersive x-ray (EDX) analysis [39] or Auger electron spectroscopy [40], together with transmission electron microscopy (TEM), could determine whether these effects play a role.

In addition to the above discussed reasons, we cannot rule out other factors that may be relevant, such as the differing carrier depletion depths in GaAs/AlGaAs caused by surface states on the etched side walls for different etching solutions [41].

We note that, in contrast to the n-type case, p-type contacts to undoped QWs have been successfully fabricated using the over-cut etch profile of figure 3(b), using AuBe alloy. It is possible that this is due to the high diffusivity of Be in GaAs/AlGaAs [42], which is linked to the small atomic radius of Be.

In conclusion, we have established a simple and reliable, front-sided-only fabrication method for inducing a 2DEG in an undoped GaAs/AlGaAs QW by successfully adapting the recessed ohmic contacts/insulated metal gate technique. We achieved this through a systematic study and optimisation of etch profiles and depths of the ohmic contact pits. Using our contact fabrication procedure, we have demonstrated a front-side-gated ambipolar FET based on a QW, and performed low-temperature transport studies of this device. Further studies are required for optimising our n-type contacts for shallower quantum wells and reducing the contact resistance. Our contacts will enable the fabrication of fully ambipolar bilayers [18, 43, 44], with the freedom to choose the polarity of the charge carriers in each layer.

Acknowledgments

The authors would like to thank H E Beere and B Zheng for useful discussions. This work was funded by the Engineering and Physical Sciences Research Council (EPSRC), UK. DT acknowledges funding from St. Catharine's College, Cambridge, AFC from Trinity College, Cambridge and IF from Toshiba Research Europe Limited.

Note added. The data presented in this article can be accessed at https://www.repository.cam.ac.uk/handle/1810/254987.

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