Formation of a high quality two-dimensional electron gas on cleaved GaAs

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We have succeeded in fabricating a two-dimensional electron gas (2DEG) on the cleaved (110) edge of a GaAs wafer by molecular beam epitaxy (MBE). A (100) wafer previously prepared by MBE growth is reinstalled in the MBE chamber so that an *in situ* cleave exposes a fresh (110) GaAs edge for further MBE overgrowth. A sequence of Si-doped AlGaAs layers completes the modulation-doped structure at the cleaved edge. Mobilities as high as 6.1×10^5 cm^2/V s are measured in the 2DEG at the cleaved interface.

The study of lower-dimensional systems has become an increasingly important research field in semiconductor physics. Such lower dimensional structures reveal novel physical phenomena[1] and, at the same time, provide a basis for modern device concepts.[2] Today, the predominant fabrication process for lower dimensional semiconductor systems relies on a combination of molecular beam epitaxy (MBE) and electron beam lithography. The layered materials of MBE are inherently two dimensional (2D). The control of layer thickness and smoothness has reached the atomic level and is unrivaled by any other technique. For this reason the MBE process is the method of choice to produce today's preeminent 2D electron system with electron mobilities beyond 10^7 cm^2/V s.[3] Further reduction of the dimensionality to one or zero dimension (1D or 0D) relies on processing of these high quality 2D systems.[2] Such quantum wires or quantum dots are generally printed onto the layered MBE material by a lithographic technique. Lateral confinement is then achieved by subsequent electrostatic gating, removal of material (etching), or damaging (ion beams). While these techniques enjoy a high degree of flexibility for pattern formation in the 2D plane, they lag far behind the atomic precision that can be achieved in the vertical dimension by the MBE process. Ideally, one would like to achieve equivalent atomic control in the definition of all dimensions of a lower dimensional structure.

There is an obvious way of extending the atomic precision of the inherently 2D MBE process to the fabrication of 1D wires. This technique relies on the MBE overgrowth of a cleaved multilayer MBE sample.[4] In this modulation-doping process on a cleaved edge, the carriers of the (AlGa)As overgrowth cannot transfer uniformly to form a 2D electron gas. Instead, they are confined to narrow 1D channels whose width is defined to atomic precision by the thickness chosen for the multilayers grown before cleaving, and whose depth is controlled by the homogeneous electric field arising from the remote positively charged Si doping ions.

This conceptually simple scheme has until now suffered two decisive drawbacks: (i) GaAs-(AlGa)As materials cleave naturally in the (110) direction, and the MBE growth process onto this lattice plane is believed to be very poor. And (ii) sample cleavage would have to be performed *in situ* since exposure to the atmosphere would irreversibly damage the fresh surface particularly of those layers containing Al. We have been able to overcome both these difficulties. We report the fabrication of a high-mobility $\mu = 6\times10^5$ cm^2/V s 2D electron gas at a cleaved (110) interface overgrown by (AlGa)As via MBE as shown in Fig. 1. The demonstration of this novel growth procedure should enable future fabrication of novel lower dimensional structures with unprecedented atomic precision.

As implied above, the problem of MBE overgrowth on the cleaved edge of a previously prepared sample is divisible into two parts: (i) Preparing an atomically clean surface that preserves the epitaxial information of both the GaAs and the (AlGa)As or AlAs layers; (ii) establishing growth conditions for good epitaxy on the (110) atomic surfaces exposed by the cleave.

We discuss first MBE growth on a (110) GaAs surface independently of the issues of edge growth or cleaving. The literature of III-V epitaxy contains very few accounts of growth on any surfaces other than (100), and only a handful[5-8] that discuss GaAs growth on or near (110). However, these references make it clear that good epitaxy on an exact (110) surface is very difficult, because As_4 does not readily stick to the nonpolar (110) surface even in a Ga flux. The proposed solutions include increasing the As_4 overpressure, lowering the substrate temperature, using As_2 in lieu of As_4, or choosing a surface misaligned by a degree or so from exact (110) GaAs. Our work confirms these ideas.

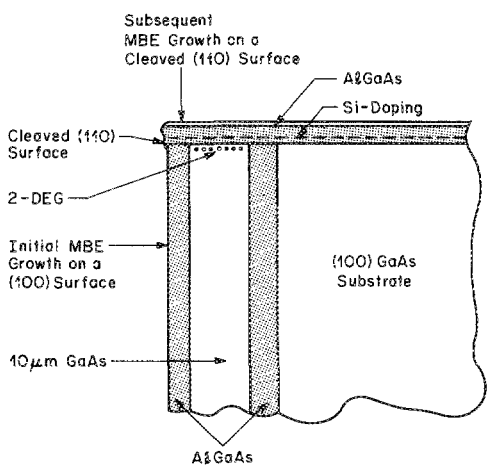

FIG. 1. Schematic diagram of MBE overgrowth of a modulation-doped structure on a cleaved interface. Grey areas indicate AlGaAs; dots locate the 2-DEG.

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We cannot, of course, use misaligned (110) surfaces because the cleave is expected to expose an exact (110) GaAs surface. We found use of an As_2 beam did improve the morphology of the overgrowth, but so far we have been unable to find suitable conditions for good (110) epitaxy using As_2. Using 5-cm-diam GaAs wafers polished on exact (110) surfaces we generally confirm the conditions found by Zhou *et al.*[8] We use a beam-equivalent As_4 ion gauge pressure of 1.6×10^{-5} Torr measured at the substrate position, and a substrate temperature of 480–500 °C measured using an Ircon Type V infrared pyrometer[9] calibrated assuming a congruent sublimation temperature for GaAs of 640 °C. Undoped quantum wells grown on (110) wafers under these conditions at a rate of 0.5 monolayers/s routinely show smooth featureless morphology free of excess Ga and well-resolved luminescence features. Modulation-doped 250-Å-wide quantum wells show clean four-point Shubnikov-de-Haas and quantum Hall effect spectra, and two-dimensional electron gas (2DEG) mobilities in the range $3–5\times10^5$ cm^2/V s in the dark, after exposure to light at 1 K. This mobility is an order of magnitude better than the best previous reported[8] of (110) epitaxy. The degree to which these conditions are tailored to (110) growth is pointed up by noting that (100) GaAs substrates overgrown under these conditions showed generally good morphology, but had transport properties actually inferior to (110) films simultaneously grown on adjacent substrates.

The motivation of using a cleave as opposed to *ex situ* lapping or etching is to provide the cleanest possible surface on which to proceed with further epitaxial growth. But, because a clean surface can only degrade with time and handling, it is obvious that ideally the sample should be in the MBE growth chamber, at the proper growth temperature, with the proper orientation, and in the proper molecular fluxes before the cleave. In this way the cleave becomes the last step accomplished prior to the overgrowth on the newly exposed (110) edge. We modified our Varian Gen II MBE equipment[10] to accomplish this.

The samples to be cleaved are prepared as follows. A GaAs (100) wafer is overgrown by conventional MBE with the layer structure desired. In the present work this consisted of 1000 Å of undoped GaAs, then 7 μm of superlattice consisting of alternating layers of 100 Å $Al_{0.33}Ga_{0.67}As$ and 30 Å GaAs, then 10 μm of GaAs, followed by 7 μm of superlattice cap. The 10-μm-thick GaAs layer will become the 10-μm-wide 2DEG. After growth the wafer is removed from the machine, lapped from the backside to a thickness of 150 μm, and cleaved into rectangular pieces 5 mm$\times$10 mm. A scratch 0.5 mm long is made where the future cleave is to occur. After cleaning these pieces are mounted using Ga metal solder on a special Ta metal substrate holder. The pieces are soldered against a 3-mm-high Ta bracket so that their 10 mm length extends in free space normal to the plane of the sample holder's front surface. To monitor the quality of the growth, and to provide a surface of proper emissivity for the pyrometer, a (110) wafer is mounted conventionally with Ga solder on the front surface of the holder not occupied by the edge growth samples. The holder is in all other respects compatible with the Varian Gen II sample transfer equipment. Thus the sample is loaded into the load-lock of the MBE machine, vacuum outgassed, and loaded into the growth chamber in the usual way.

The nonrotated sample holder is oriented in the growth chamber so the multilayer side of the yet-to-be-cleaved sample pieces does not see any flux from the Si furnace. The oxide from the (110) planar sample is then desorbed at $\sim$630 °C in the As_4 flux. Subsequently, the substrate temperature is lowered to 485 °C, and the precleave growth on the (110) planar substrate begins. The precleave layer sequence is as follows: 3000 Å GaAs, a 1300 Å superlattice consisting of alternating layers of 100 Å $Al_{0.25}Ga_{0.75}As$ and 30 Å GaAs, and finally a 1000 Å GaAs wide layer which will become the 2DEG channel in the (110) planar sample.

All growth is then stopped for a few seconds during the cleave. The cleave is accomplished by moving a Ta metal bar against the upright uncleaved pieces along a path parallel to and $\sim$7 mm above the front surface of the substrate holder. Within about 1–2 s after the cleave, the MBE growth resumes. But now the growth proceeds on both the newly exposed cleave as well as the (110) planar wafer. The postcleave layer sequence is as follows: 300 Å $Al_{0.25}Ga_{0.75}As$ undoped setback, Si δ doping at 10^{12} cm^{-2}, 3000 Å $Al_{0.25}Ga_{0.75}As$, completed by a 50 Å GaAs cap.

We verify the existence of a 2DEG on the (110) planar wafer (A) by standard magnetotransport measurements. The specimen consists of a 4$\times$4 mm square with eight symmetrically placed diffused In contacts. The experiments are performed with standard lock-in techniques at a temperature of 0.3 K. Figure 2 shows the results of four-probe magnetoresistance measurements (4-prb R_{xx}) and Hall measurements (R_{xy}). The plateaus of the integral quantum Hall

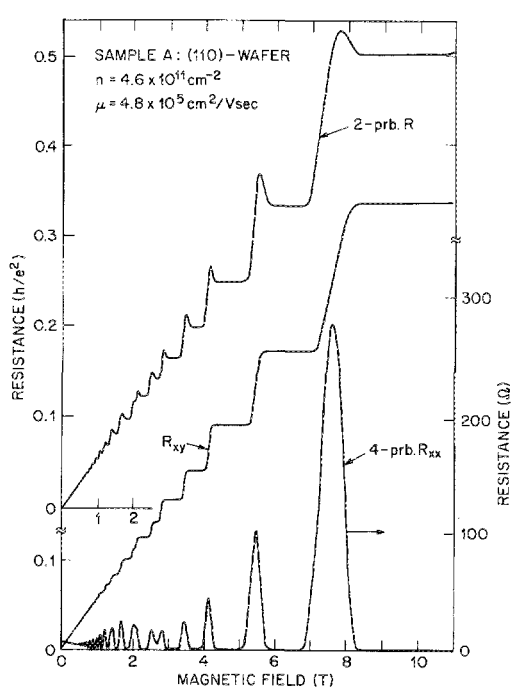

FIG. 2. Four-probe magnetoresistance (4-prb R_{xx}), two-probe magnetoresistance (2-prb R), and Hall resistance R_{xy} of a two-dimensional electron gas in a 4 mm$\times$4 mm planar (110) modulation-doped sample grown at the same time as the edge cleaved sample of Fig. 3.

effect in R_{xy} and vanishing resistance in R_{xx} are well resolved. From these data we deduce a 2D electron density of $n = 4.6\times10^{11}$ cm^{-2}. Van der Pauw measurements reveal a mobility of $\mu = 4.8\times10^{5}$ cm^2/V s. Figure 2 also contains a two-probe measurement (2-prb R) of the same sample for later comparison with the edge grown sample. The characteristic two-probe data of high-mobility 2D electron systems reflect the well-established[11] mixture between R_{xy} and R_{xx}. In the plateau regions R closely matches the quantized vaiues of R_{xy} (apart from contact resistances) while in the transition regions between plateaus, R deviates from R_{xy} due to contributions from R_{xx}. This equivalence between the two-probe data R and the Hall data R^{4}_{xy} allows us to determine the density of a 2D system directly from a two-probe measurement.

This fact has been exploited to facilitate the date acquisition on the 2D electron system of the edge-growth sample. Since in this geometry, the 2D electron system has a width of only 10 μm and, furthermore, is located on a wafer edge of only 150 μm total width, a four-probe configuration is difficult to achieve. We therefore employed the much simpler two-probe method by diffusing two In beads into the edge, separated by 600 μm. The two-probe magnetoresistance measurements R are shown in Fig. 3. The standard result is indicated by the trace marked 0°. In this case the magnetic field is perpendicular to the 2D electron system. We observe the characteristic magnetic field dependence of a 2D electron system which resembles the Hall resistance in a four-probe configuration. As compared to Fig. 2 the mixing of R_{xx} into R_{xy} is much stronger due to the much larger aspect ratio of 10 μm/600 μm of the edge sample as compared to 4 mm/4 mm in planar sample. Nevertheless, in the high-field regime a clear plateau of $R = h/2e^2$ is well resolved from which we can deduce the electron density $n = 3.6\times10^{11}$ cm^{-2}. This is only slightly less than in the simultaneously grown planar sample. From the resistance of the 600-μm-long, 10-μ-wide stripe we infer a mobility of $\mu = 6.1\times10^{5}$ cm^2/V s, slightly in excess of the planar sample. The characteristic two-probe resistance, including plateau formation, is ample proof for the existence of a high-mobility 2D system at the overgrown edge.

However, we performed an additional experiment which unambiguously demonstrates the two-dimensionality of the carrier system. We rotate the sample with respect to the magnetic field and take magnetoresistance traces at various angle Θ up to 70° as indicated in Fig. 3. The magnetoresistance pattern shows the orderly cos Θ shift that is expected from a 2D electron gas located in the plane of the (110) cleave. The lack of any additional oscillations also proves that the 2DEG only exists on the cleaved surface and that no other 2DEG has been grown accidentally on any other of the exposed surfaces.

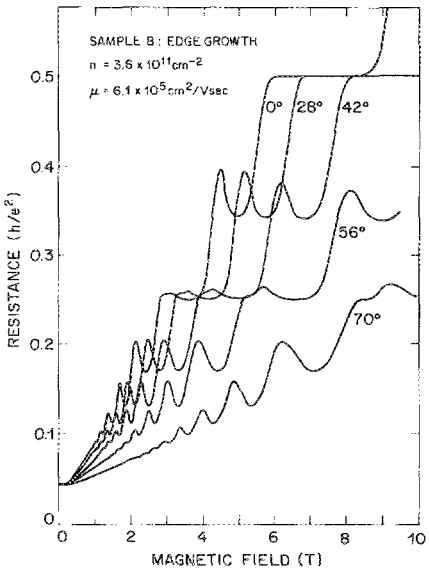

FIG. 3. Two-probe magnetoresistance data of a two-dimensional electron gas in a modulation-doped sample regrown with MBE on a (110) surface after an *in situ* edge cleave.

This demonstration of high quality epitaxy on a cleaved wafer edge adds a new dimension to the capabilities of molecular beam epitaxy, beyond simply the atomic control of multilayer thicknesses. It opens up exciting new possibilities for exotic quantum wire structures of unprecedented atomic precision.

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