Liquid phase epitaxy regrowth of two-dimensional electron gas on GaAs patterned by *in situ* meltback

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Selective *in situ* meltback of V-groove channels followed by liquid phase epitaxial regrowth of a modulation-doping AlGaAs layer is used to produce a two-dimensional electron gas on a patterned GaAs substrate. The *in situ* meltback patterning of the substrate forms channels made up of definite crystallographic planes. Characterization of the two-dimensional electron gas by magnetotransport measurements in a tilted magnetic field at 4.2 K confirms that the electron gas exists on all the planes that comprise the channels. Since the regrowth surface is exposed neither to air nor chemical etchants, this technique holds promise of producing high quality interfaces on patterned GaAs.

The formation of a two-dimensional electron gas (2DEG) in a direction other than that resulting from the usual planar growth can give rise to new physical phenomena resulting from electron confinement in directions inaccessible by planar growth and is also a requirement for a number of promising novel devices.[1,2] Various techniques have been tried to achieve 2DEG on a nonplanar surface, including regrowth on the edge of a GaAs substrate cleaved mechanically inside the high-vacuum molecular beam epitaxy (MBE) chamber[3] and metalorganic chemical vapor deposition in which the plane of the 2DEG is selected by controlling which of the crystallographic facets grows preferentially.[4] Recently, liquid phase epitaxy (LPE) regrowth has been employed to create a 2DEG on the V-groove sidewalls of a GaAs substrate patterned by chemical etching.[5] Unless the chemical etching is performed inside the growth chamber, however, this last technique exposes the patterned surface to air, leading to probable degradation of the regrown interface. Moreover, chemical processing can be expected to leave undesirable oxides on the regrowth surface. For these reasons, in Ref. 5 2DEG was observed only on the sidewalls of the chemically etched V-groove channels and not on the bottoms of these channels. In the present work the patterning of the GaAs substrate is accomplished by selective *in situ* meltback inside the growth chamber,[6-8] which is followed by regrowth of the modulation-doping *n*-AlGaAs layer on the clean surface. The meltback produces channels with [111] sidewalls and flat bottoms; the subsequent regrowth creates a 2DEG on both the sidewalls and the bottoms, as confirmed by low-temperature magnetotransport measurements with the sample tilted in a magnetic field.

The LPE system employed for this work has been described previously.[5] Undoped GaAs epilayers grown by LPE on a (100) semi-insulating GaAs substrates served as the initial material for the meltback and regrowth steps. Typically, the LPE-grown epilayers were 15–20 μm thick and contained background impurity concentrations in the low 10^{15} cm^{-3} range. After etching the surface in a 1:8:10 solution (H_2SO_4:H_2O_2:H_2O) to remove surface contamination, the epilayers were covered with ~ 5000 Å of SiO_2 by plasma chemical vapor deposition. Prior to regrowth, the SiO_2 masking layer was patterned by conventional photolithography and buffered oxide etchant to produce a 40 μm period grating (20 μm stripes and spaces) along the $[\bar{1}10]$ direction. The stripes were interrupted at 1 mm length with 1 mm spaces to produce unpatterned regions where both meltback and regrowth would be planar. After chemical degreasing the patterned epilayer was loaded into the chamber behind a sacrificial GaAs precursor piece.

The meltback and regrowth sequence utilized two melts. The first (etchback) melt contained no As, while the second (regrowth) melt contained an excess amount of GaAs source material, 150 mg of Sn for doping, and sufficient Al to produce a solid mole fraction $x \simeq 0.35$ at the growth temperature T_g. After the etchback melt was saturated at 731.5 °C by contact with the GaAs precursor for 1 h, the precursor was removed and the temperature ramped up to produce a melt undersaturated by ΔT. The epilayer was then brought into contact with the undersaturated melt with $\Delta T = 5$ °C for 90 s. Upon the completion of the meltback step, the epilayer was removed and the temperature was ramped down, with the epilayer waiting between the two melts. When the cooling rate reached a constant 0.7 °C/min at $T_g = 729.5$ °C the epilayer was brought into contact with the regrowth melt for 8 min to grow ~ 5 μm of modulation-doping *n*-AlGaAs.

A photograph of a cross section through the patterned region and a schematic diagram are shown in Fig. 1. The meltback etches V-groove channels ~ 8 μm deep. The sidewalls consist of [111] planes that are tilted $\sim 54°$ from the horizontal. They become rounded near the flat bottom and almost vertical near the SiO_2 with no visible undercut. The uniformity of the meltback channels is very good over the entire sample area (~ 1.5 cm^2), with only a small fraction of the channels exhibiting sidewall irregularities. Calibration meltback runs without regrowth indicate that the *n*-AlGaAs regrowth does not visibly alter the channel profile and that the depth of the channels scales linearly with meltback duration in this range (meltback of 60 s at $\Delta T = 5$ °C produces ~ 5 μm channels). The regrown material fills the channels without affecting the SiO_2 stripes.

In order to confirm the existence of a 2DEG and determine its location we performed magnetotransport mea-

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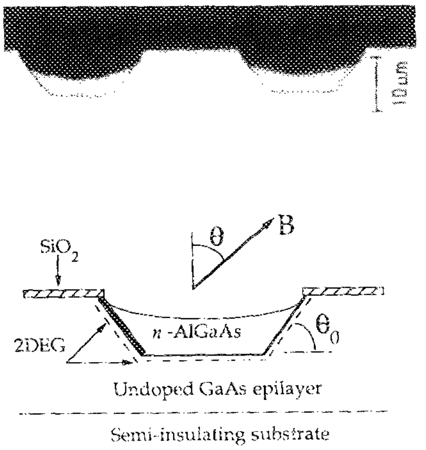

FIG. 1. Cross-sectional photograph and schematic diagram of the V-groove channels formed by selective *in situ* meltback and regrown with n-AlGaAs. Angle $\theta_0 \sim 54°$, corresponding to [111] planes. The tilted field geometry is shown in the diagram; the active sidewall [which sees the larger normal component of $B(\theta)$ in the $0° < \theta < 90°$ range] is shown in bold face.

surements at 4.2 K in tilted magnetic fields. The measurent geometry is shown in Fig. 1. Cleaved samples from both the unpatterned regions, where the meltback and regrowth were planar, and from the patterned regions shown in Fig. 1 were prepared for characterization using alloyed In:Sn contacts. Magnetotransport in the planar samples provided a check on the quality and uniformity of the meltback and regrowth process. Diagonal (R_{xx}) and Hall (R_{xy}) four-point resistance measurements in the van der Pauw geometry are shown in Fig. 2(a). From these data we obtain a 2DEG density of 4.2×10^{11} cm^{-2} and mobility of about 60 000 cm^2/V s. Well-defined Hall plateaus appear down to the $i = 6$ filling factor, while R_{xx} drops to nearly zero at $i = 2$, indicating negligible parallel conductance, and Shubnikov–de Haas (SdH) oscillations are seen down to $i = 18$, indicating good homogeneity. These results are comparable to those obtained earlier by direct epitaxial regrowth.[5,9] Clearly the meltback procedure successfully cleans the surface and does not leave behind a thin layer of intermediate composition[8] that would preclude the formation of 2DEG.[10]

Samples from the patterned regions were prepared by alloying pairs of contacts along the direction of the channels. At 4.2 K the resistance between contacts from different pairs (separated by material covered with SiO$_2$ where no 2DEG could be created by regrowth) increased to the MΩ range, while the resistance between contacts in the same pair remained below 1 kΩ. This indicates that the bulk carriers in the epilayer freeze out and the current between contacts in the same pair is carried by 2DEG. In Fig. 2 (b) the two-point magnetoresistance R for the patterned sample at 4.2 K in a tilted magnetic field $B(\theta)$ is plotted versus B for $\theta = 0°$, 50°, 90°. When the field is perpendicular to the sample ($\theta = 0°$, see Fig. 1) R clearly contains two sets of SdH oscillations. The two-point geometry of measurement and the existence of more than one 2DEG channel prevent the SdH minima from going to zero as in the data on the planar region [Fig. 2 (a)], but the oscillations are still sufficiently strong to be clearly discernible down to $i = 14$. As the sample is tilted with respect to the field, the positions of the SdH minima shift in B and the oscillation amplitude changes. One set of SdH minima retains a nearly constant amplitude, while the other set of oscillations decays as θ increases from 0°. Finally, at $\theta = 90°$ only one set of oscillations exists [see Fig. 2 (b)]. From the cross section of the patterned region in Fig. 1(a), we observe that 2DEG can be present on the sidewalls, tilted $\theta_0 \sim 54°$ from the horizontal, and on the flat bottom. By following the positions of the SdH minima as a function of θ we can determine the location of the 2DEG, as well as estimate the sheet density n_s. In Fig. 3 we plot the positions B_i of $i = 4$, 6, and 10 SdH minima ($i = 8$ series has been omitted for clarity) for the sidewall 2DEG and the $i = 4$, 6, and 8 minima for the bottom 2DEG. The expected positions of these minima B_i can be easily calculated from the formula

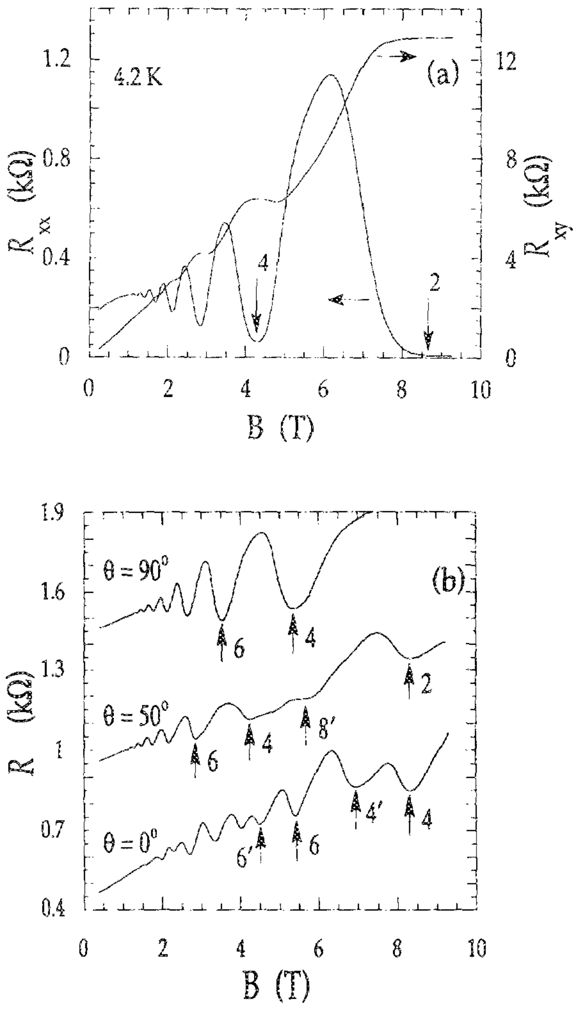

FIG. 2. (a) Diagonal (R_{xx}) and Hall (R_{xy}) resistance measurements of the planar 2DEG in the unpatterned region (van der Pauw geometry). Arrows mark R_{xx} minima corresponding to the filling factor i of the planar 2DEG. (b) Two-point magnetoresistance R along the V-groove channels in the selectively patterned region in a tilted magnetic field at $\theta = 0°$, 50°, 90°. For clarity, the $\theta = 50°$ and $\theta = 90°$ traces are displaced by 0.5 and 1.0 kΩ, respectively. Arrows mark the minima positions B_i corresponding to the filling factors i of the 2DEG at the active sidewall (unprimed numbers) and of the 2DEG at the bottom (primed numbers).

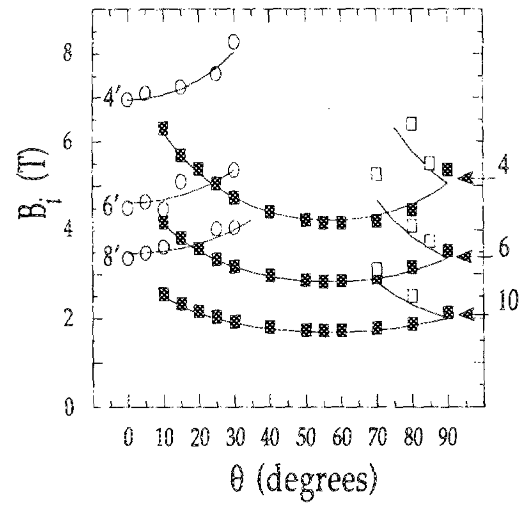

FIG. 3. Positions of the Shubnikov–de Haas minima B_i as a function of the magnetic field angle θ. Filled squares are the $i=4$, 6, 10 minima of the 2DEG at the active sidewall; open squares are the $i=4$, 6, 10 minima of the 2DEG at the opposite sidewall; circles are the $i=4$, 6, 8 minima of the 2DEG at the bottom (see Fig. 1 for the measurement geometry). The lines are fits from Eq. (1) with sheet densities $n_s = 4.1\times10^{11}$ cm^{-2} (sidewall) and 6.7×10^{11} cm^{-2} (bottom), and $\theta_0 = 57°$.

$$B_i = \begin{cases} (hn_s/ie)/\cos(\theta \pm \theta_0) & \text{(sidewall)} \\ (hn_s/ie)/\cos\theta & \text{(bottom)}, \end{cases} \tag{1}$$

where i is the filling factor, n_s is the 2DEG sheet density, and θ_0 is the angle the sidewalls make with the horizontal. Curves calculated from Eq. (1) give very good agreement with the experimental data for $n_s = 6.7\times10^{11}$ cm^{-2} (bottom), $n_s = 4.1\times10^{11}$ cm^{-2} (sidewall) and $\theta_0 = 57°$. We note that once the two sheet densities and the angle θ_0 are selected, there are no adjustable parameters in (1) and that θ_0 agrees with the observed angle between the sidewalls and the bottom corresponding to the [111] planes (see Fig. 1). Also, the two 2DEG densities obtained from (1) fall in the range of typical 2DEG densities obtained by our LPE regrowth procedure.[10]

In conclusion, *in situ* meltback in LPE has been employed to produce a patterned GaAs substrate and subsequent regrowth of *n*-AlGaAs to create a 2DEG in the meltback-created V-groove channels. Our low-temperature magnetotransport measurements in a tilted field demonstrate unambiguously that 2DEG exists both on the sidewalls of the channels and on the flat bottoms. This is in contrast to the previous LPE regrowth on a patterned substrate exposed to air,[5] where 2DEG was only observed on the sidewalls. Since *in situ* meltback leaves the regrowth surface free of oxides that result from chemical processing or exposure to air, this technique can produce improved patterned interfaces and hence better quality 2DEG. Furthermore, since *in situ* meltback is an easily implemented procedure in LPE, the meltback and regrowth technique is quite promising in the fabrication of devices involving nonplanar 2DEG and also quantum confinement devices based on high quality planar MBE substrates.

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