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Back gating of a two-dimensional hole gas in a SiGe quantum well

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A device comprising a low-resistivity, n-type, Si substrate as a back gate to a p-type (boron), remote-doped, SiGe quantum well has been fabricated and characterized. Reverse and forward voltage biasing of the gate with respect to the two-dimensional hole gas in the quantum well allows the density of holes to be varied from 8×10^{11} cm^{-2} down to a measurement-limited value of 4×10^{11} cm^{-2}. This device is used to demonstrate the evolution with decreasing carrier density of a re-entrant insulator state between the integer quantum Hall effect states with filling factors 1 and 3. © *1997 American Institute of Physics.* [S0003-6951(97)03514-6]

The introduction of back-gating techniques in semiconductor device fabrication has extended significantly the range of physical phenomena it is possible to investigate in low-dimensional electronic systems. By placing the means of varying the carrier density of a two-dimensional electron gas (2DEG) away from its conventional location on the surface of the heterostructure (either a metal gate in direct contact with the semiconductor, or with an insulating layer between the two) the latter area is left free for patterning. Some important examples of the applications of back gating are: (i) the study of electron transport through one-dimensional (1D), quantum-size constrictions, which are themselves defined using pairs of surface gates to selectively deplete areas of 2DEG, with independent control of the 1D gas density maintained via the back-gate voltage;[1] and (ii) the use of complementary front and back gates to switch on and off parallel, closely spaced 2DEGs, which is the basis of a method of making independent contact to only one of the two gases,[2] opening up many possibilities for the study of in-plane and tunnelling transport phenomena in coupled 2DEG systems.[3]

The first attempt to back gate a 2DEG involved fixing a metal plate to the bottom of a modulation-doped GaAs/$Al_xGa_{1-x}As$ heterostructure containing the 2DEG.[4] The disadvantage with this approach was that the inherently large distance between the gate and 2DEG (in this case, a substrate thickness of 0.4 mm) necessitated application of large gate-channel bias voltages ($\sim10^2-10^3$ V) to obtain significant modulation of the 2D electron density. Subsequently, devices were fabricated in which the back gate was either a low resistivity substrate[5,6] and/or a highly doped layer as the first stage of epitaxy,[5,7,8] thereby bringing the gate within 1 μm or so of the conducting channel and increasing by orders of magnitude the sensitivity of the 2DEG density to change in the gate-channel bias voltage. There are two reports in the literature of back gating of Si/SiGe heterostructures,[9,10] both of which involved evaporation of metal onto the backside of a low conductivity substrate with a high mobility Si-channel 2DEG structure on the front (in essence, the original approach to back-gating 2DEGs in III-V heterostructures[4]).

For the present study, we chose to grow a p-type modulation-doped Si/SiGe heterostructure on a low-resistivity n-type Si substrate. Holes are constrained to move in a SiGe quantum well approximately triangular in shape, which is defined by (i) the offset in the valence band at the Si/SiGe heterointerface nearest the B-doped capping layer, and (ii) the electric field established in the device due to the effects of hole transfer to the SiGe quantum well and also p-n depletion between the p-type dopant supply layer and the n-type substrate. A change of electric field in the well induced by biasing of the n-type gate (substrate) with respect to the p-type well, and thereby an adjustment to the quantum well shape together with a shift of the valence band edge in the well relative to the Fermi energy, leads to modulation of the two-dimensional hole gas (2DHG) density. For in-plane carrier-transport measurements the practical operating range of such a device, which we consider as a modified *p-i-n* diode, lies between the forward bias turn-on and reverse-bias breakdown points, provided that leakage currents in this region are negligible compared with the desired source-drain current along the quantum well. To the best of our knowledge this specific method of gating a 2D gas has been reported only once before, as introduced by Churchill *et al.*,[8] who deposited a high conductivity Be-doped GaAs layer on a GaAs substrate as the first stage of epitaxy, using this as a back gate to a 2DEG located at an $Al_xGa_{1-x}As$/GaAs heterojunction.

A cross-sectional view of the device fabricated in this work is shown in Fig. 1(a). The following layers were deposited by solid-source molecular beam epitaxy (MBE) on a 100-mm-diam, n-type (100) Si substrate of resistivity <0.01 Ω cm: first of all, 430 nm of Si; next, 40 nm of $Si_{0.8}Ge_{0.2}$; then a 10 nm spacer layer of Si; and finally, a Si:B doping layer of thickness 50 nm, with an acceptor concentration $N_A=2\times10^{18}$ cm^{-3}.

The first step in device fabrication was to make electrical

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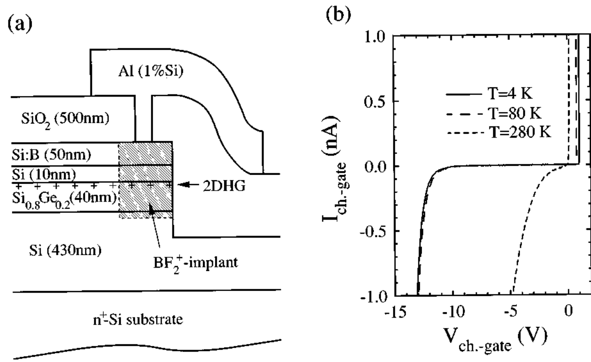

FIG. 1. (a) Cross section of part of a Hall bar device. (b) Current–voltage characteristics for the channel (2DHG)-gate(substrate) p-i-n diode at various temperatures.

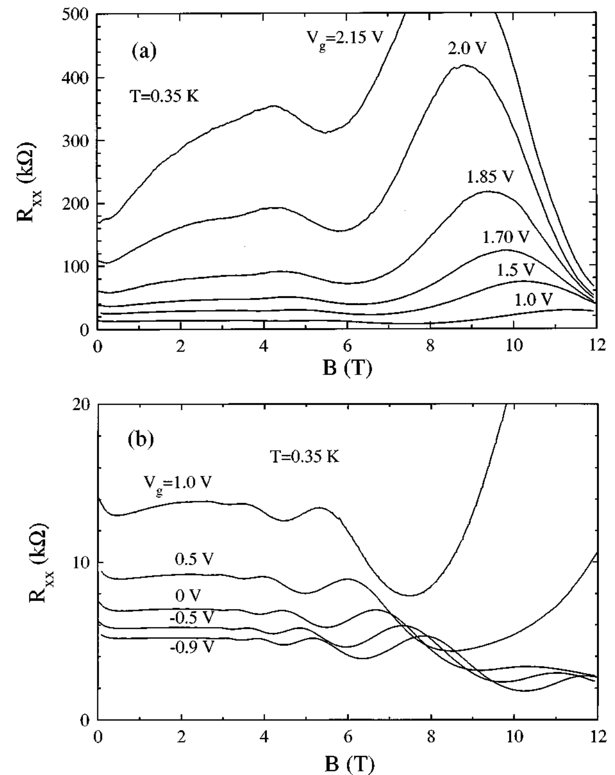

FIG. 2. Magnetoresistance oscillations in R_{xx} as a function of gate voltage: (a) $V_g=1.0\rightarrow 2.15$ V; (b) $V_g=-0.9\rightarrow +1.0$ V.

contact to the buried 2DHG. Implantation of BF_2^+ ions (75 keV energy, dosage of 1×10^{15} cm^{-2}) was chosen in preference to metal deposition plus an alloying anneal, in order to avoid the possibility of the contact spiking through to the substrate and thereby shorting the 2DHG to the gate. The implanted regions were recrystallized by an anneal in flowing N_2 at 750 °C for 30 min, a procedure which was known not to relax the strained $Si_{0.8}Ge_{0.2}$ layer.[11] Hall bar shaped mesa areas of 2DHG were then defined using reactive-ion etching with CF_4, to a depth of 300 nm. The mask design ensured partial self-alignment of the implant with the mesa boundary, thereby preventing the occurrence of (unwanted) Corbino effects in the magneto-resistance under quantum Hall effect conditions, these being associated with complete loops of 2DHG around contacts. Finally, a passivating layer of SiO_2, 500 nm thick, was deposited on the wafer, windows opened in the oxide above the implants using hydrofluoric acid and Al:Si(1%) evaporated onto the wafer and patterned into contact pads and tracks by etching with orthophosphoric acid.

Current–voltage ($I-V$) characteristics for the gate-channel (p-i-n) diode are shown in Fig. 1(b). At a temperature $T=4$ K, the abrupt turn-on voltage of 1.0 V in forward-bias and reverse breakdown threshold around 10 V, with a leakage current of less than 10 pA in the intermediate region, constitute very favorable conditions for in-plane transport experiments on the 2DHG. These were carried out using an ac lock-in method at a frequency of 7 Hz, with currents of 2 nA or less, in order to avoid electron heating effects at the lowest lattice temperatures. Two Hall bars were used, of dimensions 15 μm × 170 μm and 30 μm × 280 μm, with corresponding distances between voltage probes used for R_{xx} measurement of 85 and 90 μm. No discrepancy was seen between results from the two different geometry devices.

Magnetotransport measurements of R_{xx} and R_{xy} were made in the range $B=0-12$ T at $T=0.35$ K. The dependence of R_{xx} on B for various gate voltages (V_g) is shown in Fig. 2, with the shifts in positions of Shubnikov-de Haas oscillation minima reflecting the dependence of sheet density (n_s) on V_g. Values of n_s were determined from the data for forward- and small reverse-bias voltages in the usual way, by relating positions of the various R_{xx} oscillation minima to filling factors (ν) using the defining relationship $\nu=n_s/(eB/h)$, where e is the electron charge and h is Planck's constant. For $V_g\geqslant 1.5$ V, n_s could only be estimated from the value of B field at the single, observable R_{xx} minimum (at $\nu=3$). It was not possible to use the low B-field Hall voltage (V_{xy}) to determine a value of n_s since the low current used to avoid sample heating meant that V_{xy} was not well resolved in our experiment. In any case, the Hall resistance R_{xy} at small B fields is sensitive to quantum corrections due to disorder (i.e., enhanced interaction effects[12]), which must be extracted in order to obtain a meaningful estimation of n_s, while the analysis of high B-field R_{xx} oscillations has no such complications. A plot of the dependence of n_s on V_g in Fig. 3 shows an approximately linear relationship, which is expected since the thickness of doped substrate depleted as V_g is swept is a very small fraction of the gate-channel sepa-

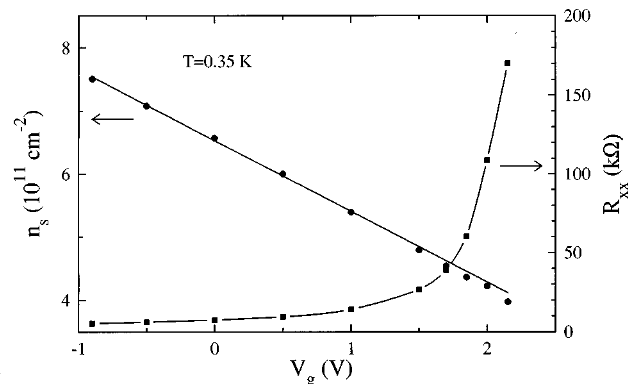

FIG. 3. Dependence of n_s and $R_{xx}(B=0$ T) on gate voltage (data extracted from Fig. 2), plus a fit to the n_s-V_g data (the line through the R_{xx} data points is for guidance only).

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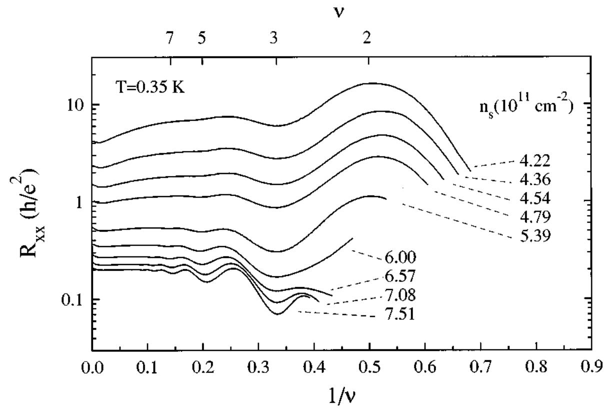

FIG. 4. Magnetoresistance data (units of $h/e^2=26$ kΩ) against reciprocal filling factor $1/\nu$.

ration ($\leqslant 1\%$), such that the capacitance of this p^+-i-n^+ diode is effectively independent of V_g. In contrast with this, the variation of R_{xx} with V_g at $B=0$ T is highly non-linear (Fig. 3): for $V_g \leqslant 1.5$ V (corresponding to $n_s \geqslant 5\times 10^{11}$ cm^{-2} and $R_{xx} \leqslant 25$ kΩ) R_{xx} changes very slightly with n_s, but for higher V_g there is a rapid increase in R_{xx} with decreasing n_s. This transition, which is from weak to strong localisation of holes, occurs when n_s (proportional to the Fermi energy of the 2DHG) falls below some threshold value corresponding to $R_{xx}\sim h/e^2$ (=26 kΩ), and is familiar in other 2D systems.[13]

The dependence of n_s on V_g has been modelled by solving self-consistently a set of expressions based on the solutions of Poisson's and Schrödinger's equations applied to this heterostructure. The fit to the $n_s - V_g$ data in Fig. 3 is obtained firstly by choosing either a 23% Ge composition in the alloy (instead of the intended value of 20%) or adjusting the Si spacer thickness between the dopant supply layer and SiGe from the 10 nm intended to 8 nm (both of these discrepancies are almost within the uncertainty expected for the growth). Second, however, it is necessary to set the thickness of Si between the SiGe layer and substrate to 525 ± 30 nm, which disagrees with the value of 430 nm expected from the growth. Secondary ion mass spectrometry yielded a value for this thickness of 485 ± 20 nm, which is in good agreement with our electrical analysis of the device operation.

We note that, although our measurements of n_s are limited at higher reverse-bias voltages by very large sample resistances (a low carrier mobility, leading to loss of Shubnikov-de Haas oscillations in R_{xx}), an extrapolation of the $n_s - V_g$ data in Fig. 3 to $n_s=0$ together with the apparent reverse-bias breakdown voltage of 10 V [Fig. 1(b)] indicate that it should be possible to fully deplete the channel of holes without breakdown occurring. This means that the technique of p-i-n biasing in a Si/SiGe heterostructure may be used as a current switch, for example, such that the design and fabrication of more complex devices, similar to those mentioned at the beginning of this letter, may be undertaken.

Using the values of n_s determined previously, the $R_{xx}-B$ data have been re-plotted as $R_{xx}-\nu$ in Fig. 4, which illustrates the appearance of a peak in R_{xx} around $\nu=2$ for $n_s \leqslant 6\times 10^{11}$ cm^{-2} and the gradual increase of its magnitude with decreasing n_s. This feature, caused by the formation of a re-entrant insulator state, has been observed previously in un-gated Si/SiGe p-channel devices,[14–16] and its origin explained on the basis of long range potential fluctuation in a sample.[17] Experiments at higher magnetic fields are in progress, so that filling factor $\nu=1$ can be reached at all the values of n_s accessible in the device (see Fig. 4), such that evolution of the insulating state around $\nu=2$ can be investigated in detail.

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