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# Tuning the electron transport properties of a one-dimensional constriction using hydrostatic pressure

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Hydrostatic pressure and illumination have been used to investigate electron transport through a clean one-dimensional constriction in a deep two-dimensional electron gas (2DEG) formed at a GaAs/$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ interface. Up to 20 quantized conductance steps were observed at integer multiples of $2e^2/h$, as well as a clear additional step (the "0.7 structure") at approximately $0.7\times 2e^2/h$. Using both pressure and illumination the electron density in the 2DEG was reduced from $2.14\times 10^{15}\ \mathrm{m}^{-2}$ to $0.6\times 10^{15}\ \mathrm{m}^{-2}$, and a shift in the conductance of the "0.7 structure" towards the spin-split value of $e^2/h$ was observed. The density measurements are compared to calculations of the 2D electron density as a function of pressure, obtained by solving the Schrödinger-Poisson equation for the heterostructure. There is also a reversal of the persistent photoconductivity effect at high pressures that cannot be accounted for.

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## I. INTRODUCTION

Hydrostatic pressure is a useful experimental tool to directly change the band structure (and hence the effective mass and g factor[1]) of a single semiconductor sample. Due to limitations in sample space and the amount of wires that can be used within a pressure cell,[2] hydrostatic pressure is not generally used for low-dimensional transport measurements, especially if gated samples are involved. Despite these technical difficulties, transport measurements under hydrostatic pressure have been performed on two-dimensional electron gases (2DEGs) in the fractional quantum Hall regime[3]and field-effect transistors;[4] to our knowledge no pressure measurements have been performed on gated 2DEGs to investigate mesoscopic transport.

Electrostatic confinement of electrons in a 2DEG into a 1D constriction by applying a voltage to a surface split gate leads to a depletion of electrons and ballistic transport through the constriction gives rise to steps in the conductance as a function of the applied gate voltage, with quantized plateaus occurring[5,6] at integer multiples of $2e^2/h$, where $e$ is the electron charge and $h$ is Planck's constant. By applying a strong parallel magnetic field, the spin degeneracy is lifted and conductance plateaus at integer multiples of $e^2/h$ are measured.[5] In addition to these theoretically well understood $2e^2/h$ steps, a structure close to $0.7\times(2e^2/h)$ has been observed,[7] not only in split-gate devices, but also in etched[8] and induced[9,10] 1D electron gases. A theoretical description of the "0.7 structure" is not well established, though there is evidence for a zero-field spin polarization accompanied by an increase of the electron g factor as the 1D subbands are depopulated.[7] An investigation[11] into the effect of carrier density, tuned by an additional surface gate, showed a movement of the "0.7 structure" towards the spin-split value of $e^2/h$ with decreasing carrier density. Here we use both pressure and illumination to tune the carrier concentration within a single sample, without using an additional surface gate.

## II. EXPERIMENTAL SETUP

The heterostructure used in these measurements was grown by molecular-beam epitaxy and features a deep (277 nm) 2DEG, which results in high mobility samples ($\mu_e = 450\ \mathrm{m}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$ at ambient pressure and after illumination).[12] Photolithography and electron-beam lithography were used to pattern the Hall bar and the surface gates, forming split gates with a constriction length and width of 750 nm. Large bond pads (750 $\mu$m in diameter) allowed insulated 50 $\mu$m diameter copper leads to be glued onto the bond pads with conducting silver paint. Scanning electron microscope images of one of the devices are shown in the insets of Fig. 1.

A commercial nonmagnetic BeCu liquid pressure cell[13] equipped with 12 wire leadthroughs, together with an InSb crystal as a calibrated four-terminal resistance pressure gauge, was used to give pressures up to $1\times 10^9$ Pa at 300 K ($0.8\times 10^9$ Pa for $T\approx 4$ K).[14] A 1:1 mixture of petroleum spirit and oil was used as the pressure transmitting medium, which is known[3] to be hydrostatic over the operating pressure range, even at low temperatures. Pressurization of the cell took place at room temperature with the cell dismounted from the cryostat. The samples were illuminated by a red light-emitting diode, which was placed directly above the sample within the pressure cell.

## III. RESULTS

Figure 1 shows the conductance characteristics of the device at ambient pressure, with up to 20 conductance steps clearly visible at 300 mK. The application of pressure not only changes the band structure and therefore decreases the absolute value of the electron g factor in the bulk GaAs,[15] it

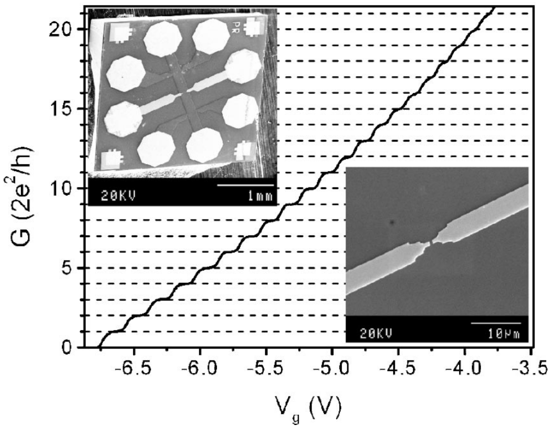

FIG. 1. Conductance quantization of the high mobility sample, measured at ambient pressure and 300 mK. A series resistance due to the connecting 2DEG regions was subtracted. Insets: scanning electron microscope (SEM) image of the sample at two different magnifications.

also reduces the electron carrier density in the 2DEG (see Sec. IV), which leads to an increase of the absolute value of the electron g factor in the 2DEG due to changes in the electron-electron interactions.[16] To distinguish between density and band-structure effects, illumination was used as an alternative way of varying the electron density in the 2DEG, without influencing the electron g factor in the bulk GaAs. The same technique was used previously[3] to vary the g factor, keeping the electron density in the 2DEG constant at different pressures. At ambient pressures the electron density increases with illumination until a saturation point is reached, whereas at high pressures the reduced electron density (due to pressure) decreases further with illumination as is shown in Fig. 2. This behavior below 60 K is opposite to that previously observed;[3] at temperatures higher than 60 K illumination leads to an increase in carrier density, even at high pressures. We therefore chose to cool our sample to 60 K under continuous illumination, and so we were able to increase the carrier density at base temperature (1.3 K) compared with unilluminated cooldowns.

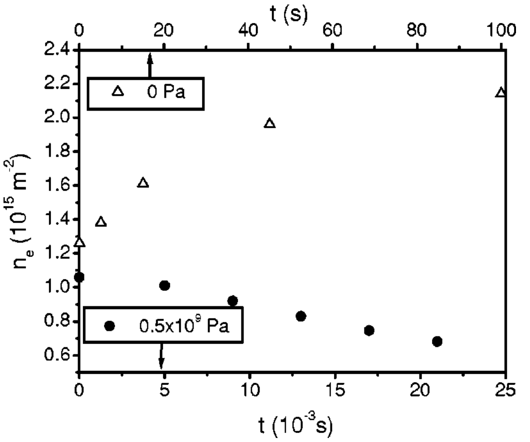

FIG. 2. The carrier density (obtained from Shubnikov–de Haas measurements) as a function of pulsed illumination time at ambient pressure (open triangles, upper scale) and $0.5\times10^9$ Pa (filled circles, lower scale).

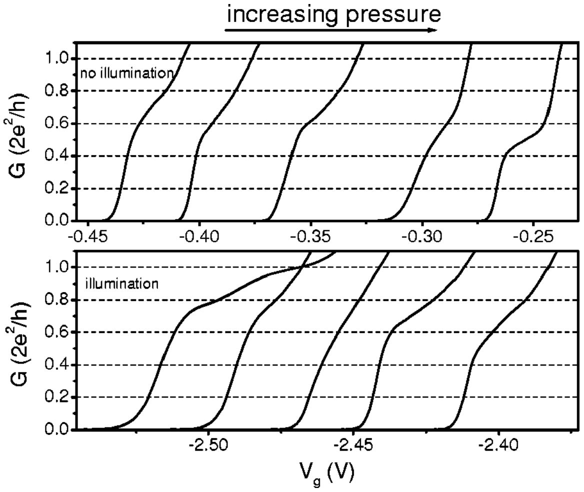

FIG. 3. The "0.7 structure" as a function of applied pressure (0, 0.2, 0.3, 0.6, and $0.8\times10^9$ Pa from left to right) measured at 1.3 K. The data in the upper graph were obtained after cooling the sample in the dark, while the traces in the lower graph were measured after cooling under illumination with an light emitting diode. All traces except for those at ambient pressure are offset for clarity.

Figure 3 shows the "0.7 structure" at five different pressures after cooling in the dark (top plot) and after cooling with illumination (bottom plot) as described above. A series resistance due to the 2DEG regions and the probe wires was subtracted from the raw data. This series resistance varied from 351 Ω to 7311 Ω and was measured as the total resistance along the Hall bar without any applied gate voltages. The calculated effective g factor in the bulk material, assuming a linear decrease[15] of 5.9% per $0.1\times10^9$ Pa, varies from $-0.44$ to $-0.23$ in the traces from left to right. Except for the data obtained at the highest carrier density, no integer conductance steps were observed at the relatively high temperature of 1.3 K. In both sets of data a clear decrease of the conductance value of the "0.7 structure" with increasing pressure is observed.

Figure 4 shows the two sets of data combined, and replotted in order of decreasing electron density; an almost monotonic decrease of the conductance value of the "0.7 structure" is observed with decreasing carrier density. Due to the reordering of the data in Fig. 4, the pressure varies in an unordered sequence (0, 200, 300, 600, 0, 200, 800, 300, 600, and 800 MPa of applied pressure from left to right), and therefore the drop of the conductance value can be attributed to the changes in electron density rather than to changes in pressure (and hence band structure).

This shift of the conductance value with decreasing electron density is in agreement with previous measurements,[11] where the overall electron density of the 2DEG was decreased using a back gate. Similar behavior with pressure was observed in a lower mobility sample ($\mu_e = 260\ \mathrm{m}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$).

## IV. DISCUSSION

The reduction of the 2D electron density with pressure can be explained by taking account of the different shifts[17] of

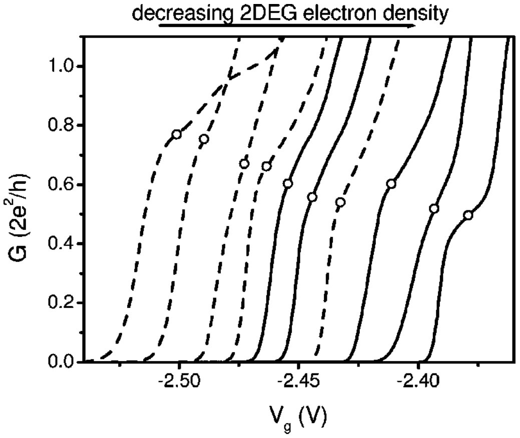

FIG. 4. Reordering of the traces in Fig. 3 as a function of measured carrier density, decreasing from left ($n_e = 2.14\times10^{15}$ m$^{-2}$) to right ($n_e = 0.6\times10^{15}$ m$^{-2}$). Except for the left-hand trace, all have been offset for clarity. The ''0.7 structure'' is indicated by an open circle in each trace, the position of which was determined by a local minimum in the first derivative.

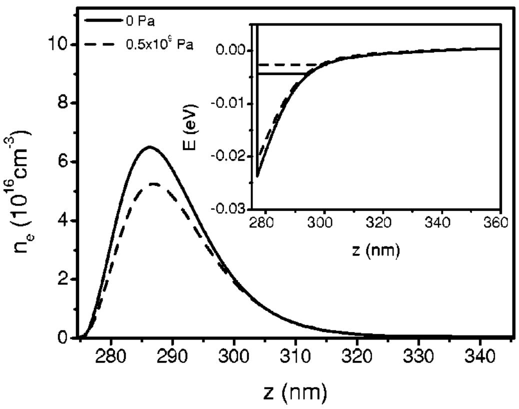

FIG. 5. Main figure: Calculated electron density $n_e$ at $p=0$ and $0.5\times10^9$ Pa. Inset: The calculated conduction-band profile with the Fermi energy fixed at zero. The two horizontal lines indicate the bottom of the 2D subband at the two pressures.

the conduction-band minima in Al$_x$Ga$_{1-x}$As. The energy of the Γ-point minimum increases with respect to the *X* and *L* minima.[18] For $x>0.22$ the Si donor states, which can form so-called *DX* centers, will energetically follow either the *X* or the *L*-point minima,[19] while the electron states in the 2DEG will be created at the Γ-point minimum. Therefore the Fermi energy is lowered with respect to the conduction-band Γ-point minimum, and hence the carrier density reduces with increasing pressure. We modeled this behavior by self-consistently solving the Schrödinger and Poisson equations for our heterostructures, taking into account changes in the band gap and the effective electron and hole masses due to pressure.[20] Results of these calculations are shown in Fig. 5, where a comparison between calculated and measured values of the carrier density at ambient pressure ($n_{calc}=1.17\times10^{15}$ m$^{-2}$, $n_{meas}=1.26\times10^{15}$ m$^{-2}$) and $p=0.5\times10^9$ Pa ($n_{calc}=0.99\times10^{15}$ m$^{-2}$, $n_{meas}=1.06\times10^{15}$ m$^{-2}$) show good qualitative agreement.

It is believed[7] that electron-electron interactions are the cause of the structure at $0.7\times(2e^2/h)$, with one proposed mechanism being a spin polarization at zero field due to an enhancement of the exchange energy in the purely one-dimensional limit.[21] In 2D an enhancement of the exchange energy with respect to the Hartree term of the Coulomb interaction has been observed[22] in optical measurements of a 2DEG under hydrostatic pressure. At electron densities below $0.3\times10^{15}$ m$^{-2}$ an enhancement of the exchange energy accompanied by a collapse of the Hartree energy was measured; at the lowest 2D electron densities ($0.6\times10^{15}$ m$^{-2}$) we could obtain in our experiment the two energies would be comparable.[22] The electron density below the split gate is lower than in the 2DEG, and so it is possible that the exchange energy could be significantly enhanced with the Hartree term being completely collapsed inside the constriction. Theoretically such an enhancement could lead to a spin polarization.[21] Although a spin polarization is expected to result in an additional plateau at $e^2/h$, recent theoretical work[23] shows that a spin polarization could also lead to a structure at $0.7\times2e^2/h$. Within this theory an increase of the spin gap between the up and down states should result in a shift of the ''0.7 structure'' towards $e^2/h$. Such an increase in the energy gap would be expected to happen with decreasing electron density, because of the further enhancement of the exchange energy.

In Figs. 3 and 4 the strength of the ''0.7 structure'' does not depend on either the pressure or the electron density directly, but appears to change in a more random fashion. This is probably due to changes in the landscape of the electrostatic potential around the potential[24] because of repeated thermal cycling of the sample between measurements. Any trend in the strength of the ''0.7 structure'' as it evolves into the spin-split plateau at $e^2/h$ (including a predicted strengthening[23]) could not be observed in our data. These changes in the constriction potential could also be the reason for the deviation from the monotonic decrease of the position of the ''0.7 structure'' in trace eight from the left in Fig. 4.

In summary, measurements of 1D electron transport under hydrostatic pressure show a shift of the conductance value of the ''0.7 structure'' to lower values, which could be attributed to an increase of the energy gap between the two spin states with decreasing electron density. We are able to model the observed decrease in the 2D electron density due to pressure by using a self-consistent Schrödinger-Poisson equation calculation, and we experimentally detect an inversion of the persistent photoconductivity effect at high pressures that was not seen in previous pressure studies.[3]

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