Lightly-strained germanium quantum wells with hole mobility exceeding one million

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We demonstrate that a lightly-strained germanium channel ($\varepsilon_{//} = -0.41%$) in an undoped Ge/Si$_{0.1}$Ge$_{0.9}$ heterostructure field effect transistor supports a 2D hole gas with mobility in excess of $1 \times 10^{6}$ cm$^2$/Vs and percolation density less than $5 \times 10^{10}$ cm$^{-2}$. This low disorder 2D hole system shows tunable fractional quantum Hall effect at low density and low magnetic field. The low-disorder and small effective mass (0.068$m_e$) defines lightly-strained germanium as a basis to tune the strength of the spin-orbit coupling for fast and coherent quantum hardware.

Quantum confined holes in germanium are emerging as a compelling platform for quantum information processing because of several favorable properties.[1] The light hole effective mass ($\sim 0.05m_e$ at zero density)[2] and the absence of valley degeneracy[3, 4] give rise to large orbital splittings in quantum dots.[5] The intrinsic sizable and tunable spin-orbit coupling (SOC)[6, 7] enables all-electrical fast qubit driving.[8–11] Furthermore, the capability to host superconducting pairing correlations[12–14] is promising for the co-integration of spin-qubits with superconductors in hybrid architectures for spin–spin long-distance entanglement and quantum information transfer between different qubit types.[15–21]

Planar Ge/SiGe heterostructures are promising for scaling up to large quantum processors due to their compatibility with advanced semiconductor manufacturing.[22] The low-disorder in planar Ge quantum wells[23] enabled the demonstration of a four-qubit quantum processor based on hole spins in a two-by-two array of quantum dots.[24] These heterostructures featured a Si$_{0.2}$Ge$_{0.8}$ strain-relaxed buffer (SRB), resulting in quantum wells with compressive strain $\varepsilon_{//} = -0.63%$.[25] Alternatively, higher strained Ge ($\varepsilon_{//} = -1.18 \%$) on Si$_{0.25}$Ge$_{0.75}$ SRBs enabled singlet-triplet spin qubits.[26] Lightly-strained Ge/SiGe heterostructures are unexplored and could offer potentially larger SOC because of the reduced energy splitting between heavy-holes (HH) and light holes (LH).[27] which is $\approx 17$ meV for Ge/Si$_{0.1}$Ge$_{0.9}$ compared to $\approx 51$ meV for Ge/Si$_{0.2}$Ge$_{0.8}$, respectively.[3, 4] As such, lightly-strained Ge is interesting for exploring faster spin-qubit driving and for topological devices. In this letter we demonstrate that lightly-strained Ge quantum wells in undoped Ge/Si$_{0.1}$Ge$_{0.9}$ support a two-dimensional hole gas (2DHG) with low disorder at low density, a prerequisite for further exploration of lightly-strained Ge quantum devices.

We grow the Ge/SiGe heterostructure by reduced-pressure chemical vapor deposition on a Si(001) wafer and then we fabricate Hall-bar shaped heterostructure field effect transistors (H-FETs) with the same process as in Refs. [2, 23, 25]. Here, a 16 nm strained Ge (sGe) quantum well (QW) is positioned between two strain-relaxed layers of Si$_{0.1}$Ge$_{0.9}$, at a depth of 66 nm [schematics in Fig. 1(a)].[28] Applying a negative DC bias to the accumulation gate $V_g$ induces a 2DHG at the Ge/Si$_{0.1}$Ge$_{0.9}$ interface. The density in the 2DHG $p$ is increased above the percolation density $p_p$ by making $V_g$ more negative. We use standard four-probe low-frequency lock-in techniques for mobility-density and magnetotransport characterization at $T = 1.7$ K and 70 mK, with excitation source-drain bias of 1 mV and 100 µeV, respectively. We do not measure gate to drain current leakage over the range of applied $V_g$.

Moving on to electrical characterisation, we operate the H-FET as following. We turn on the device at $V_g \sim -0.4$ V and sweep $V_g$ to larger negative voltages ($V_g \approx -9$ V) to saturate the traps at the semiconductor/dielectric interface via charge tunneling from the quantum well, similarly to what observed in shallow Ge/Si$_{0.2}$Ge$_{0.8}$ H-FETs.[25] At these large gate voltages, the density reaches saturation ($p_{sat}$) when the Fermi level crosses the surface quantum well at the Si$_{0.1}$SiGe$_{0.9}$/dielectric interface,[30] thereby screen-
Since Ge/Si0.1Ge0.9 is characterized by such low level of disorder, we further explored the quantum transport of the 100 mm wafer and measured at T = 1.7 K. The mobility increases steeply with p due to the increasing screening of scattering from remote charged impurities.[31–33] At higher density (p ≥ 7 × 10^10 cm⁻²), short range scattering from impurities within and/or in proximity of the quantum well becomes the mobility-limiting scattering mechanism.[31] We observe a maximum mobility μmax in the range of 0.8–1.2 × 10^6 cm²/Vs for p sat in the range of 9.43–9.64 × 10^10 cm⁻² over the five investigated H-FETs. The inset in Fig. 1(c) shows a box plot of μmax across the devices, with an average value of (1.03 ± 0.15) × 10^6 cm²/Vs (black), setting a benchmark for holes in buried channel transistors. Crucially, such high mobility is measured at very low density below p = 1 × 10^11 cm⁻², a significant improvement compared to previous studies in Ge/SiGe.[23, 25]

Beyond μmax, pFP is a key metric for characterizing the disorder potential landscape at low density, the regime relevant for quantum dot qubits. Figure 1(d) shows the conductivity σxx (circles) as a function of density p for all the investigated devices and their fit to percolation theory (lines) σ ∼ (p − pFP)¹.31, where the exponent 1.31 is fixed for 2D systems.[34] pFP ranges from 3.5 to 4.8 × 10^10 cm⁻². Figure 1(d) inset shows a box plot of the percolation density pFP across the devices with an average value of pFP = (4.2 ± 0.6) × 10^10 cm⁻² (black). We take these values as an upper bound for pFP, since we observed smaller values of pFP [(1.76 ± 0.04) × 10^10 cm⁻² at T = 70 mK if the range of applied gate voltage is restricted to small voltages above the turn-on threshold.

Since Ge/Si0.1Ge0.9 is characterized by such low level of disorder, we further explored the quantum transport properties of these devices.
properties of the 2DHG at 70 mK. Figure 2(a) shows the longitudinal resistivity $\rho_{xx}$ (black) and transverse Hall resistivity $\rho_{xy}$ (red) as a function of perpendicular magnetic field $B$ up to 0.75 T and at a Hall density of $7.2 \times 10^{10}$ cm$^{-2}$ and $\mu = 8.1 \times 10^5$ cm$^2$/Vs. We observe clear Shubnikov–de Haas (SdH) resistivity oscillations above 80 mT. The onset for resolving the spin-degeneracy by Zeeman splitting is 0.17 T and $\rho_{xx}$ minima reach zero already at 0.5 T. We do not observe beatings in the SdH oscillations associated with increased Rashba spin-splitting. We speculate that such beatings are more likely to be visible at higher densities, that require the quantum well to be closer to the dielectric interface.[2]

Fig. 3(b) shows the SdH oscillations at higher magnetic fields: strong minima are developed for filling factors $\nu$ with integer and fractional values. Clear plateaus are visible in $\rho_{xy}$ for $\nu = 2/3$ and 1/3, where correspondingly $\rho_{xx}$ vanishes. Such high quality fractional quantum Hall effect (FQHE) has previously only been reported holes in modulation-doped systems at higher carrier density and, hence, at larger magnetic fields.[35–37] Here, in undoped heterostructure, we use the top-gate to follow the evolution of FQHE states down to low density, providing avenues for studying the underlying physics.

The color map in Fig. 3(a), measured at $T = 70$ mK, shows $\rho_{xx}$ (normalized to the value $\rho_{xx,0}$ at zero magnetic field) as a function of magnetic field $B$ and Hall density $p$ in the range of $4.1 - 7.1 \times 10^{10}$ cm$^{-2}$. Yellow and blue regions in the color map correspond to peaks and dips in the normalized $\rho_{xx}$, highlighting the density-dependent evolution of integer and fractional filling factors. All filling factors fan out towards higher magnetic field and density, and fractional filling factors are well resolved across the full investigated range of density and magnetic field. Three line cuts from the color map are shown in Fig. 3(b–d), at decreasing density $p = 7.1$ (blue), 5.9 (green), and $4.2 \times 10^{10}$ cm$^{-2}$ (red), respectively. We observe that the minima associated with fractional $\nu$ become shallower as the density is decreased, possibly because of increased level broadening by unscreened disorder and because of weaker Coulomb interactions and correlation effects,[36, 37] We also observe the distance between the onset of Shubnikov-de Haas oscillations ($B_L$) and Zeeman splitting ($B_Z$) reducing from Fig. 3(b) to Fig. 3(c). In Fig. 3(d), $B_L$ and $B_Z$ have crossed, meaning that at $p = 4.2 \times 10^{10}$ cm$^{-2}$ the Zeeman gap is larger than the cyclotron gap and therefore the spin susceptibility $(g^* m^*)/m_e \geq 1$,[38] where $m^*$ is the effective mass and $g^*$ the effective g-factor out of plane. Indeed, from thermal activation measurement (Supplementary Material) we estimate $m^* = (0.068 \pm 0.001)m_e$ and $g^* = 13.95 \pm 0.18$ at a density of $5.8 \times 10^{10}$ cm$^{-2}$, corresponding to a spin susceptibility of $\approx 1$. We note that similar values of $m^*$ and $g^*$ were reported in Ge/Si$_2$Ge$_{0.8}$[2, 5] albeit at much higher density, pointing to higher HH-LH intermixing in the lightly strained quantum wells at lower density, as expected from theory.[3]

In conclusion, we demonstrated a lightly-strained Ge/SiGe heterostructure supporting a 2DHG with mobility in excess of one million and low percolation density.

Figure 3. (a) Normalized longitudinal resistivity $\rho_{xx}/\rho_{xx,0}$ as a function of magnetic field $B$ and Hall density $p$ at $T = 70$ mK. Labels of integer and fractional $\nu$ assigned from the quantum Hall effect are reported. Amplitude color scale: 0 to 60. Dashed lines correspond to the line cuts $\rho_{xx}$ vs. $B$ at different densities are reported for (b) $p = 7.1$, (c) 5.9, and (d) $4.2 \times 10^{10}$ cm$^{-2}$. Labels of Landau levels ($B_L$) and Zeeman splitting ($B_Z$) onset are reported.
Such low disorder enables measurement of FQHE at tunable low density and low magnetic fields. To mitigate the effect of traps at the interface and to suppress tunneling from the quantum well to the surface, we speculate that lightly-strained Ge channels could be positioned deeper compared to more strained channels[23, 30] because of the smaller band offset ($\approx 66$ meV Ge/\(\text{Si}_{0.2}\text{Ge}_{0.9}\) vs. $\approx 130$ meV in Ge/\(\text{Si}_{0.2}\text{Ge}_{0.8}\)). Further measurements in quantum dots, where confinement increases the HH-LH mixing, will help to elucidate the effect of reduced strain on the spin-orbit coupling in the system. The demonstration that holes can be defined in QWs with varying strain provides avenues to explore the opportunities in the germanium quantum information route.

**SUPPLEMENTAL MATERIAL**

Supplemental material is provided with measurements of the effective $g$-factor and effective mass.

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**DATA AVAILABILITY**

Data sets supporting the findings of this study are available at doi.org/10.4121/17306906.v1.

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Supplemental material: Lightly-strained germanium quantum wells with hole mobility exceeding one million

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Figure 1. Temperature dependent longitudinal resistivity $\rho_{xx}$ as a function of filling factor $\nu$ in the temperature range from $T = 68$ mK (blue) to 1.2 K (orange).

We extrapolate the effective $g^\ast$ factor and the effective mass $m^\ast$ from the temperature-dependent decay of the longitudinal resistivity $\rho_{xx}$ at different filling factors $\nu = \frac{\hbar v}{eB\nu}$, where $\hbar$ is the Planck constant, $e$ is the electron charge, and $B_{\nu}$ is the magnetic field at integer values of $\nu$. Figure 1 shows the Shubnikov-de Haas oscillations as a function of $\nu$ measured at a density of $p = 5.8 \times 10^{10}$ cm$^{-2}$ in the temperature range from $T = 68$ mK to 1.2 K. Filling factors $\nu = 2$ is resolved at a magnetic field $B \sim 1.2$ T, and both even and odd filling factors are resolved up to $\nu = 26$ and 15 at lower field at the coldest temperature, respectively.

The activation energy gap $\Delta_{\nu}$ of each filling factor can be obtained from the thermally activated dependence of the SdH oscillation minimum for a given filling factor, as reported in the Arrhenius plot of the $ln(\rho_{xx,\nu})$ vs. $1/T$ (black circles, inset Fig. 2). Following the Boltzmann statistics, the longitudinal magnetoresistance of a specific minima can be described via the relation

$$ln(\rho_{xx,\nu}) \propto -\Delta_{\nu}/(2k_B T)$$

where $k_B$ is the Boltzmann constant. The activation energy of the filling factors $\Delta_{\nu}$ can be extrapolated from the slope of a linear fit (red).

Since the even and odd filling factors corresponds to the cyclotron frequency and the Zeeman splitting, respectively, and a linear relation links activation energy $\Delta_{\nu}$ and the magnetic field $B_{\nu}$ at which each $\nu$ occur, the effective mass $m^\ast$ and the effective $g^\ast$ can be

extrapolated from a linear fit of the $\Delta_{\nu}(B_{\nu})$ dependence.

Figure 2 shows the extrapolated activation energy $\Delta_{\nu}$ as a function of magnetic field $B$ for all the investigated even and odd filling factors (red and green, respectively). The effective $g^\ast$ can be extrapolated from the slope of a linear fit $\Delta_{\nu,odd} = g^\ast \mu_B B$ (green line), where $\mu_B$ is the Bohr magnetron. Once the $g^\ast$ is know, then the effective mass $m^\ast$ can be obtained from the slope of the linear fit $\Delta_{\nu,even} = \hbar e B/m^\ast - g^\ast \mu_B B$ (red line).

For a density of $p = 5.8 \times 10^{10}$ cm$^{-2}$, we found an effective $g^\ast$ factor of $13.95 \pm 0.18$ and an effective mass $m^\ast$ of $0.068 \pm 0.001$.

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