Gate-controlled quantum dots and superconductivity in planar germanium

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Superconductors and semiconductors are crucial platforms in the field of quantum computing. They can be combined to hybrids, bringing together physical properties that enable the discovery of new emergent phenomena and provide novel strategies for quantum control. The involved semiconductor materials, however, suffer from disorder, hyperfine interactions or lack of planar technology. Here we realise an approach that overcomes these issues altogether and integrate gate-defined quantum dots and superconductivity into germanium heterostructures. In our system, heavy holes with mobilities exceeding 500,000 cm² (Vs)⁻¹ are confined in shallow quantum wells that are directly contacted by annealed aluminium leads. We observe proximity-induced superconductivity in the quantum well and demonstrate electric gate-control of the supercurrent. Germanium therefore has great promise for fast and coherent quantum hardware and, being compatible with standard manufacturing, could become a leading material for quantum information processing.
Solid state quantum computing is actively pursued using superconducting and semiconducting materials\(^1\)–\(^3\). The group-IV semiconductors Si and Ge come with central advantages for the realisation of spin quantum bits (qubits). Not only has their purity and technology been refined to a formidable level, they also possess an abundant isotope with zero nuclear spin\(^4\),\(^5\), enabling spin qubits to reach extremely long coherence times\(^6\)–\(^7\) and high fidelity\(^8\). These powerful properties have led to demonstrations of two-qubit logic gates\(^9\)–\(^10\) and quantum algorithms\(^11\). The exchange interaction that is central in these demonstrations is local and cannot directly be used to couple qubits at a distance. Instead, long-range coupling of spin qubits is being explored by incorporating superconductivity and in a first step strong spin–photon coupling has been achieved\(^12\)–\(^13\).

Hole quantum dots in Ge are particularly promising in this context. Ge has the highest hole mobility of all known semiconductors\(^14\), reaching values up to 1,500,000 cm\(^2\)(Vs)\(^{-1}\) in doped heterostructures\(^15\) and is expected to host strong spin–orbit coupling\(^16\),\(^17\) which facilitates electrical driving for fast qubit operations\(^18\). Furthermore, the valence band in Ge has no valley degeneracy, so, compared to electrons\(^19\), hole qubits do not have the complication of these close quantum levels\(^16\).

Experiments have shown readout of holes in Ge/Si nanowires\(^20\),\(^21\), self-assembled quantum dots\(^22\) and hut wires\(^23\), and promising spin lifetimes have been found\(^23\),\(^24\). In addition, the strong Fermi-level pinning at the valence band edge leads to ohmic behaviour for all metal–(p-type) Ge contacts\(^25\). The resulting strong coupling between metal and semiconductor enables the fabrication of hybrid devices of quantum dot and superconducting structures\(^26\),\(^27\).

Now, the crucial next step is the development of a planar platform that can bring together low disorder, potential for fast driving and avenue for scaling. Here we address this challenge and present the formation of a quantum dot in a planar Ge quantum well. Furthermore, we implement direct Al-based ohmic contacts to the quantum well created by diffusion into the top SiGe layer and the green structure represents an isolated Hall-bar-shaped top gate, which is used to control the hole density in the quantum well. Clear Shubnikov–de Haas oscillations with zero-resistivity minima and Zeeman splitting of the Landau levels at higher fields are observed in the longitudinal resistance \(ρ_{xx}\) as a function of the magnetic field \(B\) (Fig. 1c). Furthermore, we observe flat quantum Hall effect (QHE) plateaus at values \(1/ν\) for integer \(ν\) in the transverse resistance \(ρ_{xy}\) in units of \(h/ε^2\), where \(h\) is Planck’s constant and \(ε\) the elementary charge. The investigated heterostructures support a density of up

**Results**

**Ge/SiGe heterostructure.** Si and Ge are completely miscible and the lattice constant of their alloy, SiGe, varies continuously between its constituents. This is exploited by using strain-relaxed compositionally graded SiGe layers as virtual substrates to define Ge/SiGe heterostructures as shown schematically in Fig. 1a. We use a high-throughput reduced-pressure chemical vapour deposition (RP-CVD) reactor to grow the complete heterostructure in one deposition cycle on a 100 nm Si(001) substrate. The Ge quantum well is deposited pseudomorphically on a strain-relaxed \(Si_{0.2}Ge_{0.8}/Ge/Si\) virtual substrate obtained by reverse grading\(^28\) (see Methods). The resulting in-plane compressive strain in the quantum well splits the valence band states, which further increases the hole mobility\(^29\). The quantum well layer is separated from the surface by a \(Si_{0.2}Ge_{0.8}\) spacer and a Si cap.

Because of the type-I band alignment in Ge-rich Ge/SiGe heterostructures, the valence band maximum is energetically higher in Ge than in SiGe, such that holes accumulate in the Ge quantum well\(^30\). Heavy and light hole (HH and LH, respectively) electronic states and the related band profiles have been calculated by solving the Schrödinger–Poisson equation for low temperatures as a function of vertical electric field. In our simulations, both a multi-valley effective mass approach\(^31\) and an atomistic tight-binding model\(^32\) have been used, obtaining consistent data. The calculated valence band edge profile is shown in Fig. 1b, where the wave function of the fundamental state HH\(_0\), which has HH symmetry and is well confined in the Ge layer, is also sketched. The strain-induced splitting of the HH and LH band edges in the Ge region increases the energy of the fundamental LH state LH\(_0\) (not shown), which is found at about 46 meV above HH\(_0\). Furthermore, we estimate a separation of 14 meV for the first excited HH level HH\(_1\) (not shown). Notice that these energy splittings are significantly larger than those resulting from the valley interaction in Si/SiO\(_2\) and Si/SiGe devices, and thus excellent conditions for the operation of spin qubits are expected in this material.

The hole mobility is measured in magnetotransport experiments at 50 mK using a heterostructure field effect transistor as shown in the inset of Fig. 1c. Here the yellow boxes indicate metallic ohmic contacts to the quantum well created by diffusion into the top SiGe layer and the green structure represents an isolated Hall-bar-shaped top gate, which is used to control the hole density in the quantum well. Clear Shubnikov–de Haas oscillations with zero-resistivity minima and Zeeman splitting of the Landau levels at higher fields are observed in the longitudinal resistance \(ρ_{xx}\) as a function of the magnetic field \(B\) (Fig. 1c). Furthermore, we observe flat quantum Hall effect (QHE) plateaus at values \(1/ν\) for integer \(ν\) in the transverse resistance \(ρ_{xy}\) in units of \(h/ε^2\), where \(h\) is Planck’s constant and \(ε\) the elementary charge. The investigated heterostructures support a density of up
to $6 \times 10^{11}$ cm$^{-2}$ and have a maximum mobility of more than 500,000 cm$^2$ (Vs)$^{-1}$, corresponding to a mean free path of $L_m = 6.4 \mu$m and providing new benchmarks for holes in undoped structures. Figure 1d shows the Hall conductivity $\sigma_{xy}$ in units of $e^2/h$ as a function of the hole density $p$, controlled by the top gate potential. Again, zero-resistivity minima in $\rho_{xx}$ and clear linear quantisation steps in $\sigma_{xy}$ are observed. This demonstrates the control of the hole density over a large range using the top gate, which is a central prerequisite for the formation of electrostatically defined quantum dots.

Quantum dot. A scanning electron microscope (SEM) image of the quantum dot nanostructure is shown in Fig. 2a. Here the ohmic Al contacts are coloured in yellow and the isolated Ti/Pd gates are shown in green. In a first step, the Al contacts to the Ge quantum well are defined by electron beam lithography, local etching of the Si capping layer and thermal evaporation of Al. Subsequently, an Al$_2$O$_3$ gate dielectric is grown by atomic layer deposition at 300 °C, which also serves as an annealing step to enable the diffusion of Al into the SiGe spacer. In the Ti/Pd gate layer, we design a circular top gate between the two Al leads under which a single quantum dot will be formed. In addition, a central plunger gate $P$ is included to control the dot occupation, as well as barrier gates (BS and BD) and additional finger gates (FS and FD) in the corners of the device. These allow for additional control of the dot size and the tunnelling rates between the quantum dot and the source and drain leads.

A conceptual drawing of the device cross-section is shown in Fig. 2b, where the diffused Al leads that contact the Ge quantum well are indicated by the stripe-patterned regions. Because of the ohmic nature of the contact, the transport through the quantum dot can be measured without the need for additional reservoir gates and dopant implantation. As a result, no annealing step at temperatures higher than the quantum well deposition temperature (500 °C) is needed during the fabrication, avoiding harmful Ge/Si intermixing at the interface.

When measuring the source drain conductance $dI/dV$ as a function of the top gate voltage, conductance peaks are expected when the dot potential aligns between the source and drain potentials, which are the so-called Coulomb oscillations. This is shown in Fig. 2c, where $dI/dV$ was measured as a function of the top gate voltage $V_{TG}$. The expected oscillations are observed, which is a clear sign of the formation of a quantum dot. The spacing between the peaks is quite regular, indicating that the quantum dot is operated in the many-hole regime. From the period of the conductance peaks, we can extract a top gate capacitance of $\sim 56$ aF, which is in very good agreement with the expected capacitance of $52$ aF of a parallel plate capacitor using the lithographic dimensions of the top gate. When the top gate voltage is increased and the quantum dot is depleted, the amplitude of the observed peaks is reduced and eventually vanishes, as the tunnelling rates to source and drain reservoirs drop as an effect of the reduced size of the dot. As shown in the supplementary material, we are able to circumvent this effect using an additional accumulation gate in a different device, which allows us to reach the few-hole regime (Supplementary Fig. 1). When TG is tuned to the quantum dot regime, similar oscillations are observed as a function of the plunger gate voltage $V_p$. Here a larger spacing of the Coulomb peaks is observed, corresponding to a gate capacitance of $\sim 6.4$ aF, in agreement with the expected weaker coupling of $P$ to the quantum dot. Note that because of the structure of the source and drain leads no additional tuning of the device is necessary. Equivalent to a classical transistor, the quantum dot can be defined using a single gate (TG), which bodes well for the scaling up of qubits in this system.

As shown in Fig. 2d, e, the dot occupancy can also be controlled using the barrier gates BS and BD. The observed conductance lines are diagonal and very equivalent for each of the two barriers and the plunger, indicating that the coupling to the quantum dot is nearly identical. This confirms that the quantum dot is formed in a central position under TG and that, as an effect of low disorder in the heterostructure, a very high level of control is achieved. Furthermore, by implementing a second layer of Ti/
Pd gates we can also independently control the tunnelling rate between the quantum dot and the reservoir (Supplementary Fig. 2).

To further characterise the quantum dot, we measure $\frac{dI}{dV}$ as a function of $V_p$ and the DC bias voltage $V_{SD}$. As shown in Fig. 3a, Coulomb diamonds are observed\(^{33}\). From the height and width of these diamonds, the charging energy $E_C$ and the lever arm of the corresponding gate $a$ can be extracted. In the regime shown here ($V_{BS} = V_{BD} = 550$ mV and $V_{FD} = 600$ mV), we find $a_p = 0.037(3)$ and $E_C = 1.3(1)$ meV.

Similar diamonds are observed as a function of $V_{TG}$ (Fig. 3b). Here the lever arm is found to be significantly larger ($a_{TG} = 0.41(3)$), as is expected because the dot is formed directly under TG. A substructure is clearly visible in the conducting areas. These additional lines could correspond to either charge transport via excited states of the dot or to a modulation of the density of states subject to this splitting, which we extract by fitting the observed conductance for $V_{SD} = -0.26$ mV using Gaussian profiles and multiplying the splitting in voltage with the measured lever arm $a_p$ (Fig. 3e).

A linear trend is observed as a function of the applied magnetic field as shown in Fig. 3f, g. Note that small splittings $\Delta E_B < 20$ $\mu$eV could not be resolved because of the finite width of the conductance peaks. We find the effective $g$-factors $g_{GS} = 0.29(2)$ and $g_{ES} = 0.27(5)$ for the ground state and excited state, respectively, from the linear fits in Fig. 3h. For the excited state, our data point to either a non-linearity at lower fields or a significant zero-field spin splitting $\Delta E_{Z,0} \sim 11$ $\mu$eV. The $g$-factor of the pure HH state is expected to vanish completely for an in-plane field. However, the additional confinement of the holes in the $x,y$-plane leads to a significant admixture of LH states and a non-zero in-plane Zeeman splitting\(^{32}\).

The observed spin splitting of the first line parallel to the diamond edge ground state identifies it as belonging to the first excited state rather than being connected to the reservoir. The measured energy splitting with respect to the ground state $\Delta E = 100$ $\mu$eV remains unchanged as a function of magnetic field strength. It can be compared to the expected level splitting for a two-dimensional (2D) quantum dot with area $A$ and effective hole mass $m^*$, which is given by $\Delta E = \hbar^2 / m^* A$. From the temperature dependence of the Shubnikov–de Haas oscillations

\[ \frac{dI}{dV}(10^{-2}e^2/h^{-1}) \]

**Fig. 3** Bias spectroscopy and $g$-factor measurements. a, b Colour plots of bias spectroscopy as a function of $V_p$ (a) and $\Delta V_{TG} = V_{TG} - 2084$ mV (b), showing Coulomb diamonds with $E_C = 1.3(1)$ meV. c Schematic drawing of the Zeeman splitting $\Delta E_Z = g_B \mu_B B$ of the quantum dot levels, illustrating the hole transport via the Zeeman-split energy levels. d Bias spectroscopy showing the line splitting in a 2.9 T in-plane field. Dashed line indicates the cut plotted in e. e Differential conductance as a function of $\Delta V_p$ for $B = 3$ T, at $V_{SD} = -0.26$ mV. Solid line corresponds to a fit to the data using the sum of five Gaussian profiles. f, g Differential conductance for both the ground (f) and the excited state (g) as a function of $B$ and $\Delta V_p$, with $\Delta V_p = V_p - V_{peak}$ and $V_{peak}$ being the average voltage of the two transition peaks corresponding to either the ground or the excited state (for raw data, see Supplementary Fig. 3). Dotted lines represent linear fits to the peak positions (same as in g). h Energy splittings for the ground and excited state as a function of $B$. Solid lines are linear fits to the data yielding the corresponding $g$-factors.
measured for the Hall bar structures, we find \( m^* = 0.08 \, m_e \), with the electron mass \( m_e \), and with our device geometry (\( A = 0.019 \, \mu \text{m}^2 \)) we obtain \( \Delta E \approx 150 \, \mu \text{eV} \), in good agreement with the measured value.

The creation of ohmic leads by the diffusion of Al in the direct vicinity of the quantum dot could be suspected of creating additional charge traps that have a negative influence on the coherence of a potential qubit. To quantify this effect, we measure the charge noise acting on our quantum dot by recording the transport current \( I_{\text{dot}} \) in a sensitive region, i.e. on the slope of a Coulomb peak. A 100-s-long time trace of \( I_{\text{dot}} \) is acquired at a sampling rate of 30.5 kHz and is decomposed into 15 traces of equal lengths. The discrete Fourier spectra obtained from these traces are averaged, yielding the noise spectral density \( S_f \) presented in Fig. 4 in comparison to the corresponding spectrum measured in a low sensitivity region (Coulomb blockade). The difference between the two traces confirms that the measured low-frequency noise spectrum is indeed dominated by charge noise acting on the quantum dot. The noise spectrum follows a typical \( 1/f \) trend for low frequencies\(^{36,37} \) (solid line in Fig. 4). We find the equivalent detuning noise at 1 Hz to be \( 1.4 \, \mu \text{eV}/\sqrt{\text{Hz}} \). This compares well to noise figures at 1 Hz in other materials, such as 7.5, 0.5, or 2.0 \( \mu \text{eV}/\sqrt{\text{Hz}} \) in GaAs\(^{36} \), Si/SiO\(_2\)\(^{38} \) and Si/ SiGe\(^{37} \), respectively, showing the suitability of our approach for the creation of low-noise qubits.

**Josephson field effect transistor (JoFET).** The direct ohmic contact of the Al leads to the Ge quantum well can proximity-induce superconductivity in the semiconductor system. To demonstrate this effect, we fabricate a JoFET device with two thicker (\( d = 30 \, \text{nm} \)) and broader (\( w = 1 \, \mu \text{m} \)) aluminium leads. These are positioned with a separation of 100 nm and are overlaid with a single top gate; a SEM image of the device is shown together with a schematic drawing of the layer structure in Fig. 5a, b. When the source-drain voltage is measured as a function of the sourced current \( I_{\text{SD}} \) at negative top gate potential, a zero-resistance plateau is observed as a clear sign of a supercurrent. This is shown in Fig. 5c, where the blue and orange traces represent measurements in different sweep directions, respectively. Sweeping towards higher absolute values of \( I_{\text{SD}} \), the critical current \( I_c \) is reached at \( \sim 12 \, \text{nA} \). Beyond these values, linear (ohmic) behaviour is observed. A hysteresis can be observed when sweeping back, which can be expected for proximity induced SNS-junctions and is usually caused by self-heating of the junction when it exits the superconducting state\(^{38} \). To demonstrate that this supercurrent is induced in the quantum well, we measure the observed bias current dependence of the source-drain resistance \( dV/dI \) as a function of the top gate potential \( V_{\text{TG}} \), shown in Fig. 5d. The critical current, which defines the borders of the zero resistance range observed as a black region in the colour plot, is reduced towards increasing \( V_{\text{TG}} \). This is an effect of the decrease in the carrier density and the resulting increase of the normal state resistance. For voltages above \( V_{\text{TG}} = -1.27 \, \text{V} \), \( I_c \) cannot be resolved at the limited instrumental resolution in our measurements. For decreasing gate potential, we find that the increase in \( I_c \) is more significant than the reduction in the normal resistance \( R_n \). The characteristic voltage \( I_c R_n \) hence increases and reaches values higher than \( \sim 10 \, \mu \text{V} \). Additionally, a modulation of the critical current can be observed as a function of magnetic field, which is a clear hallmark of the Josephson effect (Supplementary Fig. 4). These proof-of-principle experiments should be followed by a detailed characterisation of the proximity-induced superconductivity in this
platform. Interesting future paths of research include the study of ballistic transport and the investigation and optimisation of the sharpness of the Al–Ge interface, which could significantly increase the $I_R$ product.

**Discussion**

In conclusion, we have shown the operation of a hole quantum dot in a planar, undoped and buried Ge quantum well with a record hole mobility. The Al ohmic leads to the quantum dot significantly simplify the fabrication and tuning processes without an increase of the measured charge noise in comparison to other systems. The strong capacitive coupling between the superconductor and the quantum dot makes this system ideal for reaching strong spin–photon coupling, while the strong spin–orbit coupling present in HHs could be exploited for fast electrical qubit driving. Furthermore, the demonstration of gate-tunable superconductivity opens up new research directions, including Majorana modes and gatemones.

Hole quantum dots in planar Ge constitute thereby a versatile platform that can leverage semiconductor manufacturing to advance and broaden the field of quantum computing.

**Methods**

**Heterostructure growth.** The Ge/SiGe heterostructures were grown in one deposition cycle in an Epsilon 2000 (ASML) RF-CVD reactor on a 100 mm n-type Si(001) substrate (resistivity 5 Ω cm). The growth starts with a 1-μm-thick layer of Ge, using a dual-stage process with initial low-temperature (400 °C) growth of a Ge seed layer followed by a higher-temperature (625 °C) overgrowth of a thick relaxed Ge buffer layer. A cycle anneal at 800 °C is performed to promote full relaxation of the Ge. Subsequently, a 700 nm reverse-graded Si$_1$Ge$_{0.7}$ layer grows at 800 °C with $x$ changing linearly from 1 to 0.8. A relaxed 300 nm buffer Si$_{0.7}$Ge$_0.3$ is then grown in two steps at an initial high temperature of 800 °C followed by a low-temperature growth at 500 °C. The growth continues with a 18 nm-thick strained Ge quantum well, a 22 nm-thick Si$_{0.7}$Ge$_0.3$ barrier and a 1 nm-thick Si cap. The final layers are all deposited at a temperature of 500 °C.

**Device fabrication.** The photolithography process for fabricating the Hall bar field effect transistors includes the following steps: mesa etching, deposition of 60-nm-thick Pt layer ohmic contacts, and atomic layer deposition (ALD) at 300 °C of a 30-nm-thick Al$_2$O$_3$ dielectric to isolate a Ti/Al gate top layer (thicknesses 10/150 nm). For the quantum dot, the contact and gate structures are created by electron beam lithography, electron beam evaporation of Al and Ti/Pd and lift-off. Following the Al contact layer (20 nm), ALD is used to grow 17 nm of Al$_2$O$_3$ at 300 °C as a gate dielectric, followed by the Ti/Pd (5/35 nm) gate structures. For the JoFET device, the same process is done with layer thicknesses 30 nm (Al), 25 nm (Al$_2$O$_3$) and 5/35 nm (Ti/Pd).

**Measurement system.** Magnetotransport data has been obtained in a He dilution refrigerator with a base temperature of 50 mK, equipped with a 9 T magnet. The carrier density $n = (\rho/h) e^{-1}$ in the quantum well is derived from the measured Hall resistivity for fields B < 0.3 T, where no QHE steps are observed. This density can also be derived from the Fourier transform of the longitudinal resistance data as a function of 1/B. From the observed peak width of 1.5 T, we estimate an upper bound for the zero-field spin splitting in our two-dimensional hole gas of 1.5 meV.

All quantum dot and JoFET measurements were performed in a He dilution refrigerator with a base temperature of <10 mK, equipped with a 3 T magnet. All quantum dot measurements of $dI/dV$ are performed using lock-in amplification with typical modulation amplitude and frequency of $\delta V_{mod} = 10–100 \mu V$ and $f_{mod} = 73.5$ Hz, respectively, and a small offset in bias voltage due to the measurement electronics is subtracted. The JoFET device was measured in a four-point configuration, sourcing a current and measuring the potential across the superconducting junctions. The plotted voltage is corrected by a small offset of the measurement electronics. The differential resistance is measured using lock-in amplification with typical a modulation amplitude of $\delta V_{mod} = 0.3$ nA.

**Data availability.** All data underlying this study are available from the 4TU ResearchData repository at https://doi.org/10.4121/uuid:8a6ac90c9-1fd442f-5b21-8be6676e1ea.

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Author contributions
N.W.H. fabricated the quantum dot devices, M.K. fabricated the JoFET devices and N.W.H. and D.P.F. performed the experiments, supported by M.L.V.T. and R.L. A.S. prepared the heterostructures, D.S. fabricated the Hall bar transistors measured at low temperature by D.S., L.Y. and G.S. G.S. supervised the material development. N.W.H., D.P.F., G.S. and M.V. analysed the data; M.Vi. and G.C. carried out additional analysis. N.W.H. and D.P.F. wrote the manuscript with input from all authors. M.V. conceived and supervised the project.

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