Hard superconducting gap in a high-mobility semiconductor

Alberto Tosato,1 Vukan Levajac,1 Ji-Yin Wang,1 Casper J. Boor,1 Francesco Borsoi,1 Marc Botifoll,2 Carla N. Borja,2 Sara Martí-Sánchez,2 Jordi Arbiol,2,3 Amir Sammak,4 Menno Veldhorst,1 and Giordano Scappucci1,*

1QuTech and Kavli Institute of Nanoscience, Delft University of Technology, PO Box 5046, 2600 GA Delft, The Netherlands
2Catalan Institute of Nanoscience and Nanotechnology (ICN2), CSIC and BIST, Campus UAB, Bellaterra, 08193 Barcelona, Catalonia, Spain
3ICREA, Passeig Lluís Companys 23, 08010 Barcelona, Catalonia, Spain
4QuTech and Netherlands Organisation for Applied Scientific Research (TNO), Stieltjesweg 1, 2628 CK Delft, The Netherlands

(Dated: June 2, 2022)

The co-integration of spin, superconducting and topological systems is emerging as an exciting avenue for exploring monolithic superconductor-semiconductor quantum circuits towards scalable quantum information processing.

The intimate coupling between superconductors and semiconductors in hybrid devices [1, 2] underlines a plethora of quantum components and exciting pursuits towards scalable quantum information technology, including topological qubits with Majorana zero modes (MZMs) [3], gate-tunable superconducting qubits (gate-memons) [4], superconductivity-mediated long-range coupling between spin qubits [5], and quantum information transfer between different types of qubits [6, 7]. Superconductor-semiconductor hybrid devices based on group III-V materials [1] have been intensively explored to construct a topological superconductor. Great progress was achieved with pristine superconductor-semiconductor interfaces with epitaxial superconducting Al [8–11]. However, as relevant as a high quality interface is a high mobility low disorder semiconductor. Thus far the current level of disorder in such hybrid devices is compromising the experimental search for MZMs [12]. In addition, spin qubits in group III-V materials suffer from the hyperfine interactions with the nuclear spin bath [13] that severely deteriorate their quantum coherence and is a challenge for integrating different types of qubits on the same platform.

Germanium quantum wells in planar heterostructures (Ge/SiGe) are emerging as an appealing alternative platform for the co-integration of spin, superconductivity or, possibly, topologically protected states [14]. Advances in Ge/SiGe epitaxy by industry compatible chemical vapor deposition [15, 16] benchmark holes in germanium as an ultra-clean material system with high mobility exceeding one million cm²/Vs [17], low percolation density, and low charge noise [18]. Furthermore, holes in germanium have inherently strong-spin orbit coupling [19] and can achieve long quantum coherence due to the suppressed hyperfine interaction [20] and the possibility of isotopic purification into a nuclear spin-free material [21]. Building on these advantages, holes in Ge have advanced superconductors spin qubits, progressing in only three years from uniform and well-controlled quantum dots [22], to single hole qubits [23] with long relaxation times [24], singlet-triplet qubits [25, 26], fast two-qubit logic [27], universal operation on a 2 × 2 qubit array [28], and simultaneous qubit driving at the fault-tolerant threshold [29].

Planar germanium heterostructures are also a compelling candidate for superconductor-semiconductor hybrids: in addition to the strong spin orbit coupling and the high-mobility—crucial for a reliable search of topological superconductivity—holes in germanium have electrically tunable g-factors [23] and can make Schottky-barrier-free contacts to superconductors by pinning of the Fermi level to the valence band [30]. Initial promising work demonstrated tunable supercurrents and high transparency superconductor-semiconductor hybrid devices by using Al to contact the quantum well either via thermal diffusion [22, 31] or by etching of the heterostructure [32, 33]. Further progress is challenged by the difficult task of contacting uniformly a buried quantum well with a superconductor, whilst maintaining the low disorder at the superconductor-semiconductor interface and in the semiconductor channel.

To overcome these limitations, we follow the microelectronics industry approach of silicidation for achiev-
Material properties of superconductor-semiconductor Ge devices. a) Schematics of the fabrication process for a superconductor-normal-superconductor quantum point contact (SNS-QPC). First, platinum is deposited on the heterostructure, then thermal annealing at 400 °C drives Pt in the heterostructure to form PtSiGe, finally two gate layers are deposited, insulated by Al2O3. b) False-color high angle annular dark field scanning transmission electron microscopy (HAADF STEM) image of a cross-section of a SNS-QPC. The PtSiGe contacts are violet, the Ti/Pd constriction gate (CG) operated in depletion mode is yellow, the Ti/Pd accumulation gate (AG), used to populate the quantum well, is green. A scanning electron microscopy top view image of this device is shown in Fig. 2. c) Atomic resolution HAADF STEM image of the Ge/PtSiGe interface along with the indexed fast Fourier transforms (FFTs) of the two regions (black squares) within the PtSiGe contacts and a schematics of the PtSiGe orthorhombic unit cell. The corresponding ternary lattice parameters $T = a_T, b_T, c_T$ that define the dimensions of the unit cell can be calculated, in a first approximation, by Vegard’s law: $T_{PtSiGe} = x T_{PtSi} + (1-x) T_{PtGe}$ where $B = a_B, b_B, c_B$ are the lattice parameters of the binary compounds PtSi and PtGe, and $x$ is the relative content of Ge with respect to Si. d) Electron energy-loss spectroscopy (EELS) composition maps showing the Pt, Ge, Si and O signals for the central area of the TEM lamella of panel b, the scale-bar indicates 50 nm.

Material properties

Our approach to superconductor-semiconductor hybrid devices in germanium is illustrated in Fig. 1a. We use an undoped and compressively-strained Ge quantum well, grown by chemical vapor deposition on a Si(001) wafer [15] and separated from the surface by a SiGe barrier (Methods). This heterostructure supports a two-dimensional hole gas (2DHG) with high mobility ($6 \times 10^5$ cm$^2$/Vs) and long mean free path ($7.3\mu$m) (Supplementary Fig. S1) and hosts high-performance spin-qubits [27].

As shown by the schematics in Fig. 1a, we obtain PtSiGe contacts to the quantum well by room-temperature evaporation of a Pt supply layer, metal lift-off, and rapid thermal process at 400 °C (Methods). This low-temperature process preserves the structural integrity of the quantum well grown at 500 °C, whilst activating the solid phase reaction driving Pt into the heterostructure and Ge and Si into the Pt (Supplementary Fig. S3). As a result, low-resistivity germanosilicide phases are formed [38] and under these process conditions the obtained PtSiGe films are superconducting with a $T_c \approx 0.5$ K and an in-plane critical field of $B_{c2} \approx 400$ mT (Supplementary Fig. S2). Finally, we use patterned electrostatic gates, insulated by dielectric films in between, to accumulate charge carriers in the quantum well and to shape the electrostatic confinement potential of the hybrid superconductor-semiconductor devices (Methods).

The morphological, structural, and chemical prop-
Highly-transparent Josephson junctions. a) False-color scanning electron microscope image of the SNS device. The PtSiGe contacts are violet, the constriction gates (CG) are yellow and the accumulation gate (AG) is green. The channel length between the two superconducting leads is 70 nm and the channel width between the constriction gates is of 40 nm. The two constriction gates are separate by design but always shorted together during measurements. b) Color map of the voltage drop across the junction $V$ vs source-drain current $I_{SD}$ and constriction-gate voltage $V_{CG}$ along with normal-state conductance ($G_N$) trace vs $V_{CG}$. $G_N$ is calculated as the conductance average where the voltage drop across the device is in the range $[500, 650]$ mV or $[-650, 500]$ mV, that is much higher than the estimated superconducting gap. c) Color map of $G$ in units of $2e^2/h$ vs the source-drain voltage $V_{SD}$ and $V_{CG}$. Bottom panel shows line-cuts of conductance at $V_{CG} = [-1.25, -1.4, -1.49]$ V, red lines are the fit with the coherent scattering model from which transparency $\tau$ is extracted. Right inset shows the evolution of the transparency, as extracted from the fitting of conductance curves to the coherent scattering model (Methods), with the constriction gate $V_{CG}$. d) Color map of $G$ vs $T$ and $V_{SD}$ (top panel), and vs $B_\parallel$ and $V_{SD}$ (bottom panel), where $B_\parallel$ is the in-plane magnetic field in the direction of transport and $T$ the temperature. The colorscale in panel (d) has been saturated to better infer the low conductance limit. The source-drain bias is applied between the PtSiGe contacts, and the voltage drop across the junction is measured with a standard 4-terminal setup.

The analysis of EELS elemental concentration profiles across the Ge QW$\rightarrow$PtSiGe heterointerface (Supplementary Fig. S4) reveals that the threefold PtSiGe stoichiometry is Ge-rich, with relative composition in the range between $\text{Pt}_{0.1}\text{Si}_{0.2}\text{Ge}_{0.7}$ and $\text{Pt}_{0.1}\text{Si}_{0.05}\text{Ge}_{0.85}$ depending locally on the analysed grain. The EELS compositional maps in Fig. 1d show the elemental distribution of Ge, Si, Pt, Al, and O, at the key regions of the device. We observe Pt well confined to the two contacts areas, which also appear Ge-rich. Crucially, O is detected only in the $\text{Al}_2\text{O}_3$ dielectric layer below the gates, pointing to a high-purity quantum well and a pristine superconductor-semiconductor interface.

Highly transparent Josephson junction

We perform low-frequency four-terminal current and voltage bias measurements (Methods) on the SNS-QPC device shown in Fig. 2a to infer the properties of the superconductor-semiconductor interface. Accumulation (AC, in green) and constriction (CG, in yellow) gates control transport within the 70 nm long channel between...
Figure 3. **Hard induced superconducting gap.** a) False-color SEM image of the superconductor-normal quantum point contact device (SN-QPC). The PtSiGe contact is violet, the constriction gate (CG) are yellow and the accumulation gate (AG) is green. The two constriction gates are separate by design but always shorted together during measurements. b) Color map of conductance $G$ vs the source-drain voltage $V_{SD}$ and constriction gate $V_{CG}$, along with linecuts in log-scale of $G$ at the constriction gate voltages $V_{CG} = [-733, -710, -695]$ mV marked by the colored segment in the color-plot. c) Color map of $G$ in units of $2e^2/h$ vs the in-plane magnetic field $B_\parallel$ perpendicular to the transport direction and constriction gate $V_{CG}$, along with linecuts in log-scale of $G$ at the field strength $B_\parallel = [0.01, 0.1, 0.2, 0.3]$ T marked by the colored segment in the color-plot. d) Conductance traces normalised to the above-gap conductance ($G/G_N$) vs $V_{SD}$ in tunneling regime for 6 different SN-QPC devices $D_1$-$D_6$ processed in the same fabrication run, device $D_1$ is the one reported in Fig3 a-c, in the remaining devices the constriction gates separation varies (specifications of these devices are provided in Supplementary Fig. S8).

The measured $I_{sw}R_N$ product is $\sim 0.5$ the theoretical $I_cR_N$ product calculated for a ballistic short junction using the Ambegaokar–Baratoff formula $\pi\Delta^*/2e = 110 \mu$V with $I_c$ being the critical current, $\Delta^*$ the induced superconducting gap and $e$ the electron charge [41]. This discrepancy has been observed in previous works [11, 31] and is consistent with a premature switching due to thermal activation [42].

By operating the device in voltage-bias configuration and stepping the constriction gates, we observe in the conductance color plot the typical signature of multiple Andreev reflections (MARs) (Fig. 2c). When the applied voltage bias corresponds to an integer fraction of $2\Delta^*$, with $\Delta^*$ being the induced superconducting gap, we observe differential conductance $dI/dV$ peaks (dips) in the tunneling (open) regime [43, 44]. We measure MARs up to the 5th order, suggesting that the coherence length $\xi_N$ in the Ge QW is a few times larger than the junction length $L$, and setting a lower bound to the phase coherence length in the QW $l_\psi > 5L = 350$ nm. These observations are consistent with the findings of ref. [33] where a similar Ge/SiGe heterostructure is used. Fitting the differential conductance with the coherent scattering...
model described in ref. [45] (and used in refs. [11, 44, 46]) reveals single channel transport with gate tunable transparency up to 96%. Such a high transparency confirms the high quality interface between the PtSiGe and the Ge QW. From the MARs fit we also obtain an estimate of the induced superconducting gap $\Delta^* = 70.6 \pm 0.9 \mu$eV.

Further, we characterise the evolution of the induced superconducting gap with temperature and magnetic field. After setting the device in tunneling regime, where sharp coherence peaks are expected at $|V_{SD}| = 2\Delta^*$ (Fig. 2d), we observe the induced superconducting gap closing with increasing temperature and magnetic field. By fitting the temperature dependence of the coherence peaks with the empirical formula from ref. [47] we obtain a critical temperature of 0.5 K. The peak close to zero bias emerging at $T > 0.2$ K can be explained in terms of thermally-activated quasi-particle current [46]. The in-plane magnetic field in the transport direction quenches the superconductivity at $B_{\parallel} = 0.37$ T. The same critical field is found for the in-plane direction perpendicular to the transport direction while for the out of plane direction $B_{\perp} = 0.1$ T (Supplementary Fig. S6). This in-plane vs out-of-plane anisotropy is expected given the thin-film nature of the PtSiGe superconductor [42].

**Hard induced superconducting gap**

To gain insights into the quality of the Ge/PtSiGe junction we characterise transport through the superconductor-normal quantum point contact (SN-QPC) device shown in Fig. 3a. On the left side of the QPC there is a PtSiGe superconducting lead and on the right side a normal lead consisting of a 2DHG accumulated in the Ge QW. With the accumulation gate (AG) set at large negative voltages to populate the QW we apply a more positive voltage to the constriction gates (CG), creating a tunable barrier between the superconducting and the normal region. In Fig. 3b we progressively decrease the barrier height (decreasing $V_{CG}$) going from the tunneling regime, where conductance is strongly suppressed, to a more open regime where conductance approaches the single conduction channel conductance $G_0$. Line-cuts of the conductance colormap are presented in the bottom panel of Fig. 3c. In the tunneling regime, we observe a hard induced superconducting gap, characterised by a two orders of magnitude suppression of the in-gap conductance to the normal-state conductance, and the arising of coherence peaks at $|V_{SD}| \approx \Delta^* = 70 \mu$eV. Fig. 3b also shows that the induced superconducting gap varies with the constriction gate voltage. A possible explanation is that, upon increasing the density in the semiconductor nearby the junction, the coupling to the parent superconductor might vary, as also observed in other hybrid nanostructures [48].

The evolution of the gap as a function of in-plane magnetic field ($B_{\parallel}$) shown in Fig. 3c confirms that the gap remains hard for finite magnetic fields up to 0.25 T, ultimately vanishing at $B_{\parallel} \approx 0.37$ T. The magnetic field evolution of the gap in all three directions matches the behaviour observed in the SNS-QPC (Supplementary Fig. S7).

Finally, Fig. 3d reports the conductance traces in tunneling regime for all the six measured devices (an overview of the geometries of these devices and the respective measurements are available in the Supplementary Fig. S8, the conductance maps for all these devices are shown in Supplementary Fig. S9). Crucially, we always observe suppression of conductance equal or larger than two orders of magnitude, consistent with a hard induced superconducting gap free of subgap states [8, 11]. This finding is the signature of a robust process that yields a reproducible high-quality superconductor-semiconductor interface, overcoming a long-standing challenge for hybrid superconductor-semiconductor quantum devices in germanium.

**Superconducting quantum interference devices**

We use the superconducting quantum interference device (SQUID) in Fig. 4a to demonstrate phase control across a Josephson junction, an important ingredient for achieving topological states at low magnetic field [49–51]. The device is composed of two Josephson field-effect transistors (JoFETs) with a width of 2 $\mu$m and 1 $\mu$m for JoFET$_1$ and JoFET$_2$ respectively, and equal length of 70 nm. The critical current of the junctions $I_{c1}$ and $I_{c2}$ can be tuned independently by applying the accumulation gate voltages $V_{AG1}$ and $V_{AG2}$ to the corresponding gates. We investigate the SQUID oscillations by measuring the switching current of the SQUID as a function of the out-of-plane-magnetic field penetrating the SQUID loop. Namely, we set $V_{AG1}$ and $V_{AG2}$, such that both arms support supercurrent and $I_{c1} \gg I_{c2}$. This condition provides that the first junction is used as a reference junction and that the phase drop on it is flux independent, while the phase drop over the second junction is therefore modulated by the external flux through the loop, allowing for measuring the current-phase-relation (CPR) of the second junction. This is demonstrated in Fig. 4b where the shown SQUID oscillations are well fitted by the relation: $I_{c \text{SQUID}} = I_{c1}(B_{\perp}A_1) + I_{c2}(B_{\perp}A_2)\sin(\pi B_{\perp}A_{\text{SQUID}} - Lc_{e1}(B_{\perp}A_1)/\Phi_0)$ where $I_{c1,2}(BA_{1,2})$ are the Fraunhofer dependencies of the critical current obtained from fitting the Fraunhofer pattern of each junction (Supplementary Fig. S10), $A_{1,2}$ are the junction areas, $B_{\perp}$ is the out-of-plane magnetic field and $\Phi_0$ the flux quantum. From the fitting in Fig. 4b (red dashed-line) we extract the
Figure 4. **Phase control of a Josephson junction in a SQUID.** (a) False-color SEM image of the two JoFET SQUID device. The JoFETs have a channel length of 70 nm and a channel width of 1 µm and 2 µm respectively and can be independently controlled by gates AG1 and AG2. The geometric loop area of the SQUID is of 10 µm². (b) Color-plot of voltage drop (V) across the SQUID vs current (I) and out-of-plane magnetic field (B⊥). Arrows represent the direction of the current (I) sweep. With the gate voltages set at VAG1 = −3.5 V and VAG2 = −1.65 V the superconducting phase drops mainly over the second junction. Upon sweeping the out-of-plane magnetic field B⊥, we observe oscillations of the switching current. Red and blue dashed lines are the fit of the evolution of the critical current with magnetic field. The magnetic field is applied in the out of plane direction as depicted in panel (a).

**Effective SQUID loop area** \( A_{\text{SQUID}} = 17.8 \, \mu \text{m}^2 \) and the self-inductance \( L = 1.65 \, \mu \text{H} \). In order to confirm for the self-inductance effects, we also fit SQUID oscillations for the opposite direction of the current bias (blue dashed-line) and we get similar values for the effective loop area and self-inductance. We ascribe the discrepancy between the extracted SQUID loop area and the geometric area (10 µm) to the flux focusing effects.

**Scalable junctions**

As a first step towards monolithic superconductor-semiconductor quantum circuits in two dimensions, we fabricate and study transport in a macroscopic hybrid device comprising a large array of 510 PtSiGe islands (Fig. 5a) and a global top gate. Each pair of neighbouring islands forms a Josephson junction whose transparency can be tuned by the global accumulation gate. The top panel of Fig. 5b shows a current bias measurement of the junctions array resistance. As the accumulation gate becomes more negative, all the junctions are proximitized and a supercurrent flows through the device. Remarkably, as the source-drain current approaches the junctions critical current the whole array simultaneously switches from superconducting to resistive regime, as shown from the sharp resistance step (Fig. 5b top).

With this device we also study the evolution of the switching current in a small perpendicular magnetic field. In the bottom panel of Fig. 5b we observe Fraunhofer-like interference, along with the fingerprint of flux commensurability effects associated with the periodicity of the array. At integer numbers of flux quantum per unit area of the periodic array \( f = B_⊥/B_0 \), where \( B_0 = \Phi_0/A \) with \( A \) the junction area and \( \Phi_0 \) the flux quanta, we observe switching current peaks at \( \pm 1f, 2f, 3f, 4f \) and \( 5f \), denoted by a black arrow in the plot. We also notice this effect at fractional values of \( f \), most notably at \( f/2 \) (red arrow). Flux commensurability effects, due to the pinning and interference of vorticies in Josephson junctions, have been previously reported [52, 53].

The observation of simultaneous switching of supercurrent and of the Fraunhofer pattern with flux commensurability effects, suggests that all islands effective areas are similar and that the supercurrent through the various junctions is comparable, meaning that all junctions respond synchronously to the applied gate voltage. This is further supported by the observation of sharp switching of super-current and the Fraunhofer pattern of a 1D array of superconducting islands presented in Supplementary Fig. S11.

Finally we present in Fig. 5 the sheet resistance as a function of temperature for different gate voltages. As the gate voltage becomes more negative the coupling between neighbouring superconducting islands increases and the system exhibits regimes of superconducting, metallic and insulating behaviour [53]. At small gates the resistance increases with decreasing temperature (yellow curves) indicating the insulating state, while at high gates the resistance exhibits a step like behaviour to zero resistance (purple curves) owing to the global superconducting state. At intermediate gate voltages \((-1.95 \, \text{V} \leq V_G \leq -1.93 \, \text{V}, \text{orange curves})\) the resistance saturates with decreasing temperature, suggesting the presence of the long-debated anomalous metal state [53, 54].

In conclusion, we contacted a germanium quantum well with a superconducting germanosilicide, resulting in excellent superconducting properties imparted to the high-mobility 2DHG. While we focused on the poly-crystalline superconducting PtSiGe compound, we anticipate that other ternary germanosilicides may be explored to further improve the superconducting gap, starting from the deposition and thermal anneal of other metals. The strong suppression of in-gap states and the hard gap observed consistently in our measurements indicate a robust and reproducible process. The absence of in-gap states within the superconducting gap is pivotal for the emergence of topological states in semiconductor-superconductor devices, and is key for superconductivity-
mediated long-range spin-qubit coupling, for quantum information transfer between different types of qubits and for high-coherence gateon devices. Furthermore, we demonstrate phase control across a Josephson junction, a key ingredient for accessing topological states with relaxed magnetic field and spin-orbit constrains. The observation of a superconducting to insulating transition in a gate-tunable superconducting array of Josephson junctions, with synchronous response of the junctions to the gate voltage and the magnetic field, underlines the uniformity of the superconducting islands and provides avenues for scaling this hybrid technology in 2D. All-together, these findings represent a major step in the germanium quantum information route, aiming to co-integrate spin, superconducting, and topological systems for scalable quantum technology on a silicon wafer.

Figure 5. Superconducting to insulator transition in a gated 2D superconductor-semiconductor array. a) 3D and top view schematics of an array of $51 \times 10$ PtSiGe islands. The inset shows an atomic force microscopy image of the PtSiGe islands of the array. The separation between neighbouring islands is of 70 nm. b) Top panel shows a color map of sheet resistance ($R_S$) vs accumulation gate voltage $V_G$ and source-drain current $I_{SD}$. Bottom panels shows a color map of sheet resistance vs out of plane magnetic field $B$ and source-drain current $I_{SD}$. The measurement is taken at gate voltage $V_G = -1.99$ V. Black arrows denote the magnetic field corresponding to one flux quantum $\Phi_0$ per unit cell of the array. Red arrows correspond to one-half flux per unit cell. c) Sheet resistance as a function of temperature for different gate voltages. Yellow curves correspond to small negative gates, and purple curves to large negative gates.

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* g.scappucci@tudelft.nl

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METHODS

Ge/SiGe heterostructure growth. The Ge/SiGe heterostructure of this study is grown on a 100-nm n-type Si(001) substrate using an Epsilon 2000 (ASMI) reduced pressure chemical vapor deposition reactor. The layer sequence comprises a Si$_{0.2}$Ge$_{0.8}$ virtual substrate obtained by reverse grading, a 16 nm thick Ge quantum well, a 22 nm-thick Si$_{0.2}$Ge$_{0.8}$ barrier, and a thin sacrificial Si cap [15].

Device fabrication. The fabrication of the devices presented in this paper entails the following steps. Wet etching of the sacrificial Si-cap in buffer oxide etch for 10 s. Deposition of the Pt contacts via e-gun evaporation of 15 nm of Pt at pressure of 3 × 10$^{-6}$ mbar at the rate of 0.5 Å/s. Rapid thermal anneal of Pt contacts at 400 °C for 15 minutes in a Halogen lamps heated chamber in Argon atmosphere. Atomic layer deposition of 10 nm of Al$_2$O$_3$ at 300 °C. Deposition of the first gate layer via e-gun evaporation of 3 nm of Ti and 17 nm of Pd. For the devices with a second gate layer the last two steps are repeated, 27 nm of Pd are deposited for the second gate layer to guarantee film continuity where overlapping with first gate layer.

Transport measurements. Electrical transport measurements of the SNS-QPC, SN-QPC, SQUID devices are carried out in a dry dilution refrigerators at a base temperature of 15 mK, corresponding to an electron temperature of ≈25 mK measured with a metallic N–S tunnel junction thermometer. This refrigerator is equipped with a 3-axis vector magnet. Measurements of the junctions array are carried out in a wet dilution refrigerator with base temperature of 50 mK and z-axis magnet.

Measurements are performed using a standard 4-terminals low-frequency lock-in technique at the frequency of 17 Hz. Voltage bias measurements are performed with an excitation voltage $V_{AC} < 4\mu$V. By measuring in a four-terminal setup, additional data processing to subtract series resistances of various circuit components is avoided.

Simulations and fitting of MARs. The experimentally measured conductance $G_{exp}(V)$ of an SNS junction is assumed to be superposition of N single-mode contributions [44]:

$$G_{theory}(V) \sum_{i=1}^{M} N_i G^{(\tau_i, \Delta)}(V)$$

where $G^{(\tau_i, \Delta)}$ is the simulated conductance for the $N_i$ modes with transparency $\tau_i$. We allow for $M$ different transparencies, but all $N_i$ modes have the same superconducting gap $\Delta$. The simulations of conductance were implemented in Python using a modified version of the code presented in ref. [55].

The theoretically computed conductance $G_{theory}(V)$ is fitted to $G_{exp}(V)$ using a nonlinear least-squares procedure: $\chi = \int [G_{exp}(V) - G_{theory}(V)]^2 dV$ is minimised for the fitting parameters $\Delta$, $N_i$, $\tau_i$ with $i \in 1,...,M$. The fitting is performed for increasing $M$, provided that all $N_i$ and $\tau_i$ are nonzero.

ACKNOWLEDGEMENTS

We thank L. Kouwenhoven for fruitful discussions. A. T. and G. S. acknowledges support through a projectrunite associated with the Netherlands Organization of Scientific Research (NWO). M. V. acknowledges support through an ERC Starting Grant.

ICN2 acknowledges funding from Generalitat de Catalunya 2017 SGR 327. ICN2 is supported by the Severo Ochoa program from Spanish MINECO (Grant No. SEV-2017-0706) and is funded by the CERCA Programme / Generalitat de Catalunya and ERDF funds from EU. Part of the present work has been performed in the framework of Universitat Autonoma de Barcelona Materials Science PhD program. Authors acknowledge the use of instrumentation as well as the technical advice provided by the National Facility ELECM ICTS, node "Laboratorio de Microscopias Avanzadas" at University of Zaragoza. M.B. acknowledges support from SUR Generalitat de Catalunya and the EU Social Fund; project ref. 2020 FI 00103. We acknowledge support from CSIC Research Platform on Quantum Technologies PTI-001.

AUTHOR CONTRIBUTIONS

A.S. grew the Ge/SiGe heterostructures. A.T. fabricated the devices. C. N. B., M. B., S. M., J. A. performed transmission electron microscopy characterisation. A. T. with C. B. measured Josephson junction devices, SNS-QPCs and 2D arrays in wet dilution refrigerators, analysed the data and performed numerical simulation of the
MARs processes. V. L. and A.T. measured SNS-QPC, SN-QPC devices and SQUIDs in dry dilution refrigerators and analyzed the data with the supervision of J. W.. A.T. wrote the manuscript with input from all authors. G.S. conceived and supervised the project.

ADDITIONAL INFORMATION

COMPETING INTERESTS

The authors declare no competing interests.

DATA AVAILABILITY

All data included in this work are openly available at 4TU research data repository https://doi.org/10.4121/19940174.
Supplementary Information: Hard superconducting gap in a high-mobility semiconductor

Alberto Tosato,1 Vukan Levajac,1 Ji-Yin Wang,1 Casper J. Boor,1 Francesco Borsoi,1 Marc Botifoll,2 Carla N. Borja,2 Sara Martí-Sánchez,2 Jordi Arbiol,2,3 Amir Sammak,4 Menno Veldhorst,1 and Giordano Scappucci1,*

1QuTech and Kavli Institute of Nanoscience, Delft University of Technology, PO Box 5046, 2600 GA Delft, The Netherlands

2Catalan Institute of Nanoscience and Nanotechnology (ICN2), CSIC and BIST, Campus UAB, Bellaterra, 08193 Barcelona, Catalonia, Spain

3ICREA, Passeig Lluís Companys 23, 08010 Barcelona, Catalonia, Spain

4QuTech and Netherlands Organisation for Applied Scientific Research (TNO), Stieltjesweg 1, 2628 CK Delft, The Netherlands

(Dated: June 2, 2022)
TWO-DIMENSIONAL HOLE GAS PROPERTIES

Figure S1. **2DHG transport properties.** Mobility $\mu$ vs 2D-carrier density $\rho_{2D}$ (left panel) and mobility $\mu$ vs accumulation gate $V_G$ for a Hall-bar shaped heterostructure field-effect transistor fabricated on the same 22 nm deep Ge/SiGe heterostructure used for all devices in this work. The maximum mobility of $615 \times 10^3 \text{ cm}^2/\text{Vs}$ is reached at the density of $5.5 \times 10^{11} \text{ cm}^{-2}$. The density vs gate curve deviates from the expected linear behaviour due to tunneling of charges from the quantum well to the trap states at the oxide interface, partly screening the electric field in the quantum well. The density and mobility reach saturation when the states at the triangular well in the SiGe barrier at the oxide interface start to populate and thus screen the electric field in the QW.
Figure S2. **PtSiGe film characterization.** a) Critical perpendicular magnetic field $B_{c\perp}$ and critical temperature $T_c$ of a PtSiGe film deposited and annealed in a 22 nm deep Ge/SiGe QW for different process conditions. The colours of the markers indicate the thickness of the deposited platinum layer (that covers the whole surface of a 3 × 3 mm Ge/SiGe heterostructure) and the anneal temperature. The filled (open) markers correspond to an anneal time of 15 (30) minutes. The marker’s shape signifies the used atomic layer deposition (ALD) of Al$_2$O$_3$ process: no ALD (circles), ALD with 60 min pre-heating at 300 °C (squares), or ALD with 15 min pre-heating (triangles). In both ALD processes, 10 nm of Al$_2$O$_3$ was deposited. b, c) Analysis of the critical temperature and fields of a 3 µm wide PtSiGe strip (15 nm Pt has been annealed for 15 minutes at 400 °C). Resistance $R$ versus perpendicular magnetic field ($B_{\perp}$) and parallel magnetic field ($B_{||}$) for various temperatures $T$. These measurements were performed in a 4-probe configuration with standard low frequency lock-in technique in a wet dilution refrigerator with electron temperature of 100 mK.
Figure S3. **Structural details of the PtSiGe poly-cristalline phase.** High-angle annular dark field scanning transmission electron microscopy (HAADF STEM) and crystallographic information of the SNS-QPC device. The yellow and blue insets show atomic-resolution images of both the left and right contacts highlighting the sharp interfaces between the QW and the PtSiGe film. The atomic-resolution micrograph in the center (green) displays the high quality of the Ge QW interfaces with diamond-structure (FD3-MS, space group number 227). The local contrast variations observed here are attributed to uneven thickness distribution of the lamella due to the focused ion beam (FIB) sample preparation. The fast Fourier transform (FFT) on the top right (green) indicates that the (002) planes in the QW grow epitaxially following the [001] axis. In addition, no dislocations were identified. The insets on the bottom left and right show the power spectra that identify the orthorhombic phase (PBNM, space group number 62) of the PtSiGe film.
Figure S4. **PtSiGe stoichiometry.** Electron energy-loss spectroscopy (EELS) quantitative compositional map of the region indicated from the white arrow in the HAADF STEM image (a) of the Ge/PtSiGe interface of the SNS-QPC. The threefold PtSiGe stoichiometry is Ge-rich, with relative composition in the range between $\text{Pt}_{0.1}\text{Ge}_{0.7}\text{Si}_{0.2}$ and $\text{Pt}_{0.1}\text{Ge}_{0.85}\text{Si}_{0.05}$ depending locally on the analysed grain.
SNS-QPC MEASUREMENTS

Figure S5. **Supercurrent discretization.** a) Voltage drop $V$ across an SNS-QPC device as a function of the source drain current $I_{SD}$ and constriction gate voltage $V_{CG}$. Discrete plateaus in the switching current can be observed, indicating a discrete number of modes in the QPC. b) Normal-state differential conductance $G$ versus $V_{CG}$ taken at out-of-plane magnetic field $B_{\perp} = 0.6 \, T$, showing plateaus at quantized value of conductance. The plateaus in the two plots are slightly shifted with respect to each other due to the hysteretic behaviour of the device.

Figure S6. **SNS-QPC, evolution of the superconducting gap with magnetic field.** Color map of conductance $G$ in units of $2e^2/h$ vs source-drain bias $V_{SD}$ and magnetic field $B$ for the SNS-QPC. From left to right the magnetic field direction is: in-plane parallel to transport ($B_{\parallel\parallel}$), in-plane perpendicular to transport ($B_{\parallel\perp}$), out of plane ($B_{\perp}$). The device is tuned in the tunneling regime to show the evolution of the induced superconducting gap with the strength of the magnetic field.
Figure S7. **SN-QPC, evolution of the induced superconducting gap with magnetic field.** Color map of conductance $G$ in units of $2e^2/h$ vs source-drain bias $V_{SD}$ and magnetic field $B$ for the SN-QPC. From left to right the magnetic field direction is: in-plane parallel to transport ($B_{\parallel\parallel}$), in-plane perpendicular to transport ($B_{\parallel\perp}$), out of plane ($B_{\perp}$). The device is tuned in the tunneling regime to show the evolution of the induced superconducting gap with the strength of the magnetic field.

![Color map of conductance](image_a)

| Device | Constriction width (nm) |
|--------|-------------------------|
| 1      | 25                      |
| 2      | 25                      |
| 3      | 50                      |
| 4      | 50                      |
| 5      | 50                      |
| 6      | 75                      |

Figure S8. **SN-QPCs devices specifications.** False-color SEM image of a superconductor-normal quantum point contact device (SN-QPC). The PtSiGe contact is violet, the constriction gates (CG) are yellow and the accumulation gate (AG) is green. The constriction width ($w$) between the two CGs is varied across the 6 measured devices and is reported in the table. The 6 devices were fabricated in the same fabrication run.
Figure S9. **Conductance maps of 6 SN-QPC devices.** Color map of $G$ in units of $2e^2/h$ vs. the source-drain voltage $V_{SD}$ and constriction gate $V_{CG}$, for the 6 NS-QPC devices presented in the main text. The red segment indicates the $V_{CG}$ voltage of the linecuts presented in Fig. 3d main text. Variation on the $V_{CG}$ operational window can be ascribed both to the different constriction gate size and to the accumulation gate voltage used for the specific measurement. The different evolution of $G$ as a function of $V_{CG}$ can also be related to the different accumulation gate voltages.

SQUID MEASUREMENTS

Figure S10. **JoFETs Fraunhofer pattern for the SQUID device.** Fraunhofer pattern of the small junction (JoFET₂, left panel) and large junction (JoFET₁, right panel) of the SQUID device. White dashed line represents the fitting of the switching current to the theoretical Fraunhofer formula.
We measured the Fraunhofer pattern for each junction of the SQUID device independently by measuring the dependence of its critical current on the out-of-plane magnetic field while the gate voltage of the measured junction is set to $-3.5\,\text{V}$ and the other junction is pinched-off. By fitting the obtained dependencies $I_{c1,2}(\Phi_{1,2})$ as $I_{c1,2}(BA_{1,2}) = I_{c01,2} \sin(\pi BA_{1,2}/\Phi_0)/(\pi BA_{1,2}/\Phi_0)$, where $B$ is the out-of-plane magnetic field and $\Phi_0$ is superconducting flux quantum, we obtain from the fits the areas of the two junctions to be $A_1 = 1\,\text{um}^2$ and $A_2 = 0.48\,\text{um}^2$. Note that the ratio $A_1/A_2 \sim 2$, as designed and shown in Fig. 4a, while the values for both areas are smaller than the geometrical areas in the design due to the flux focusing effects.

**1D ARRAY**

![1D Array Diagram](image)

Figure S11. 1D PtSiGe superconducting array. a) Top view schematics of an array of $51 \times 1$ PtSiGe islands on a Ge/SiGe heterostructure. The separation between the PtSiGe islands is of 70 nm. b) Color map of the sheet resistance ($R_S$) vs accumulation gate voltage $V_G$ and source-drain current $I_{SD}$. Increasing the negative voltage of the accumulation gate the array becomes superconducting ($R_S$ goes to zero) when the source-drain current is below the switching current. c) Color map of the sheet resistance vs out-of-plane magnetic field $B$ and source-drain current $I_{SD}$. The switching current shows the typical Fraunhofer pattern expected for a single Josephson junction. Compared to the 2D PtSiGe array this device does not present any signature of commensurability effects in the switching current, as expected for a linear array.
