Ballistic edge states in Bismuth nanowires revealed by SQUID interferometry

Anil Murani1, Alik Kasumov1,2, Shamashis Sengupta1, Yu A. Kasumov2, V.T. Volkov2, I.I. Khodos2, F. Brisset3, Raphaëlle Delagrange1, Alexei Chepelianskii1, Richard Debblock1, Hélène Bouchiat1 & Sophie Guéron1

The protection against backscattering provided by topology is a striking property. In two-dimensional insulators, a consequence of this topological protection is the ballistic nature of the one-dimensional helical edge states. One demonstration of ballisticity is the quantized Hall conductance. Here we provide another demonstration of ballistic transport, in the way the edge states carry a supercurrent. The system we have investigated is a micrometre-long monocrystalline bismuth nanowire with topological surfaces, that we connect to two superconducting electrodes. We have measured the relation between the Josephson current flowing through the nanowire and the superconducting phase difference at its ends, the current–phase relation. The sharp sawtooth-shaped phase-modulated current–phase relation we find demonstrates that transport occurs selectively along two ballistic edges of the nanowire. In addition, we show that a magnetic field induces 0–π transitions and φ0-junction behaviour, providing a way to manipulate the phase of the supercurrent-carrying edge states and generate spin supercurrents.
Reducing the size of a conductor usually decreases its conductivity because of the enhanced effect of disorder in low dimensions, leading to diffusive transport and to weak, or even strong localization. Notable exceptions occur when topology provides protection against disorder, such as in the quantum Hall effect or the recently discovered quantum spin-Hall effect in two-dimensional (2D) topological insulators. In the latter, crystalline symmetry combined with high spin–orbit coupling generate band inversion and one-dimensional (1D) chiral edge states with perfect spin-momentum locking, that theoretically precludes backscattering along the edges. However, since the first evidences of edge state currents, both in the normal and superconducting-proximitized states, demonstrating the robustness of ballistic conduction and spin polarization in the 1D edge states has remained a challenge. Here we provide a direct signature of ballistic 1D transport along the topological surfaces of a monocrystalline bismuth nanowire connected to superconducting electrodes. To this end, we measure the relation between the Josephson current \( I_J \), flowing through a nanostructure and the superconducting phase difference \( \phi \) at its ends, the current–phase relation (CPR). The CPR is an exquisite tool to discriminate between different transport regimes (ballistic, diffusive, tunnel).

The sharp sawtooth-shaped CPR we find demonstrates that transport of Cooper pairs occurs ballistically along two edges of the nanowire, whose positions can be deduced from experiments in different magnetic field orientations. We also show that a Zeeman field induces \( 0-\pi \) transitions and \( \phi_0 \)-junction behaviour, in agreement with recent theoretical predictions.

**Results**

### Investigated samples

Monocrystalline bismuth nanowires were grown by sputtering (Methods section), and their crystalline orientation was determined by electron backscatter diffraction. Individual nanowires with (111) top facets were then selected to exploit the predicted topological edge states of those surfaces, brought about by the Bi lattice symmetries and high (eV-range) atomic spin–orbit coupling. The wires are narrow enough (thickness and width between 30 and 200 nm) that most normal state conduction is due to surfaces and edges, with only a few per cent contribution of the bulk states, as discussed in Supplementary Note 2. Furthermore, tight-binding simulations of a Bi nanowire with a rhombic section and top and bottom (111) facets, similar to the main nanowire reported here (Fig. 1 and Methods section), predict one edge state along each (111) facet, extending the result of Murakami. These edge states coexist with 2D metallic states on the non-topological (100) surfaces but nonetheless clearly dominate the local density of states (Fig. 1c).

### Ballistic CPR

To measure the CPR of the superconductor/bismuth nanowire/superconductor (S/Bi/S) junction, we inserted a single-Bi nanowire with (111) surfaces into an asymmetric SQUID set-up. The set-up consists of a high-critical-current Josephson junction, made of a W superconducting nanoconstriction, in parallel with a 1-μm-long S/Bi/S junction characterized beforehand (Figs 1 and 3). In this configuration the modulation of the SQUID’s critical current by the magnetic flux yields the CPR of the junction with the smallest critical current. It is well known that the CPR of the superconductor/insulator/superconductor (SIS) Josephson junction is sinusoidal \( I_J(\phi) = I_c \sin \phi \). The CPR of a ballistic superconductor/norma metal/superconductor junction, on the other hand, is a characteristic sawtooth in a long junction (for which \( L > h \nu_F/\Delta \)), or segments of a sine in a short junction (Fig. 2c) \( L \) is the length of the normal metal, \( \nu_F \) the Fermi velocity and \( \Delta \) the superconducting gap). Any disorder smooths the CPRs, as illustrated in Fig. 2c for a junction in the diffusive regime, (that is, with a mean free path shorter than the length \( L \). While the CPR of atomic point contacts, nanowire-based quantum dots and graphene have previously been measured in this way, the CPR of micrometre-long, quasi-ballistic channels has, to our knowledge, not been accessed.

The switching current of the asymmetric Bi-SQUID (Fig. 2a) clearly displays sawtooth-shaped oscillations of amplitude 400 nA, superimposed on the 80 μA critical current of the nanoconstriction. The oscillation period of 9.5 G corresponds to a flux quantum \( \Phi_0 = h/2e \) through the SQUID loop area of 2 μm². Those oscillations demonstrate the sawtooth CPR characteristic of
of a long, perfectly connected ballistic channel. This is a key result of our paper. Eleven harmonics are visible in the Fourier transform of the signal at 100 mK. Figure 2b displays how the $1/n^2$ amplitude of the $n$th harmonic, $I_n$, expected for a perfect sawtooth, is exponentially damped by a small factor: $I_n = I_0/n \exp(-an)$, with $a = 0.19$ at 100 mK and 0.25 at 1.2 K. Since the $n$th harmonics can be interpreted as the contribution to the supercurrent of the $n$th order Andreev reflection, the damping can be understood as due to an imperfect transmission encountered $n$ times, as well as due to temperature $T$ (refs 11–13), yielding the phenomenological expression $I_n = I_0/(nT)^8 \exp(-n/m^2T^4)$, where $m$ is the modulus of the total transmission in the normal state. Other effects, such as high frequency noise, may also contribute to this decay. The damping coefficient at 100 mK yields a quasi perfect transmission $t \geq 0.9$, and we deduce the Thouless energy $E_{Th} = 4$ K from the damping coefficient at 1.2 K.

**Signatures of a second supercurrent-carrying path.** Predicted by our tight-binding modelling of the wire (Fig. 1c), a second path can be identified upon closer inspection of the CPR: a wiggle with a smaller period is superimposed to the main sawtooth signal. The full critical current modulation is reproduced by adding to the main sawtooth the contribution of a second sawtooth with a four times smaller amplitude and a 10% smaller period than the

---

**Figure 2 | Sawtooth-shaped CPR of the S/Bi/S junction.** (a) Critical current of the asymmetric SQUID, at 130 mK (blue) and 1 K (red), revealing the bismuth junction’s CPR and combination of two sawtooth-shaped currents $\sum (-1)^j/n \exp(-0.19n) + 0.35 \sin(1.2n) \exp(-0.85n)$ (black). Here $\phi = 2\pi B_{Si}/\Phi_0$, with $\Phi_0 = h/2e$ and $S_{in}$ is the area delimited by the SQUID loop and the inner edge of the wire. (b) Sketch of the asymmetric SQUID made of the tungsten nanoconstriction in parallel with the Bi nanowire, with its two edge states running along the top outer edge and inner bottom edge. (c) Fourier transform of the measured curves at 130 mK and 1 K. We have included the $1/n$ dependence expected for the harmonics of the pure sawtooth (dashed blue line) as well as the phenomenological fits to the decay of these harmonics. We also show the $1/n^2$ dependence of a diffusive junction (dashed black line). (d) Satellite peak on the CPR’s Fourier transform due to the second conduction path at the outer edge of the wire (delimiting an area $S_{out}$), next to the main peak (corresponding to the area $S_{in}$). (e) Theoretical zero-temperature CPRs of superconductor/normal metal/superconductor junctions from tight-binding simulations on a square lattice in different regimes: green, short junction with one N site, the CPR is close to the ideal relation $I_n = 2\pi \Delta/h \sin(\phi/2) \sin(\pi\phi)$; blue, sawtooth CPR of a long single-channel ballistic junction, calculated for length $L = 1.2 \times d_c$. Black: CPR of a multichannel diffusive wire $\sum (-1)^j/(2n+1)(2n-1) \sin(\phi)$, with normal state resistance $h/2e^2$. All curves are normalized to the maximum value of the CPR. (f) Sketch of the reference asymmetric SQUID, made of a similar tungsten constriction in parallel with a superconducting aluminium/oxide/aluminium SIS tunnel junction. (g) Critical current of the reference asymmetric SQUID, yielding, as expected, a sinusoidal CPR (dashed line is a sinusoidal fit to the data). The small effect of the circuit inductance has been corrected for. This correction is negligible for the Bi-SQUID because of its smaller dimensions.
Number of channels and Josephson current amplitude. The amplitude of the measured supercurrent as well as its resilience up to high magnetic fields ($B_{\text{max}} = 0.5$ T) (Fig. 3, Supplementary Fig. 6 and ref. 25) are consistent with a small number of channels, each of them confined to an extremely narrow region in space (within $<4$ nm = $\Phi_0/B_{\text{max}}L$). The maximum supercurrent through one ballistic channel is $I_1 = \frac{\pi}{2} A/\Phi_0 = e A/2\hbar \approx 250$ nA for a short junction (that is, much shorter than $\xi = \hbar v_F/\Lambda \approx 600$ nm). It is smaller for a long junction$^{13}$, of the order of $ev_F/L \approx 100 \pm 30$ nA for $L = 1$ µm and $v_F = 6 \pm 2 \times 10^5$ m s$^{-1}$. This value of $v_F$, deduced from the Fourier spectrum of the CPR at 1 K, is in qualitative agreement with the values deduced from the dispersion relation of 1D edge states of (111) Bi triangular surfaces, measured by photoemission in ref. 27. The critical current of the nanowire, given by the modulated current amplitude of $400$ nA (Fig. 2a), thus implies that at most six perfectly transmitted channels carry the supercurrent. A reasonable assumption is that one path contains three to four quasi perfect channels, each with the same sawtoothing-shaped CPR, and all situated at the inner edge of the wire, on the bottom (111) facet. They could be associated to the orbitals $p_x,p_y,p_z$ of Bi, as suggested by Murakami$^{15}$, or could also run along the edges of few parallel terraces at the facet edge. The smaller contribution of the second path is attributed to one or two other channels of smaller transmission, at the outer edge of the top (111) facet (see sketch in Fig. 2b).

Phase shifts of the CPR induced by an in-plane magnetic field. The purely 1D nature of the edge Andreev bound states that carry the supercurrent across the nanowire implies that they are insensitive to orbital dephasing and offers the possibility to explore the effect of a Zeeman field on the phase of the Josephson current. A Zeeman field can induce a crossing of the Andreev levels, turning an energy maximum into a minimum$^{28}$: this phase shift of its $0\rightarrow \pi$ transitions are expected when dephasing by the magnetic field equals dephasing by the propagation time through the wire, that is, when the Zeeman energy equals the Thouless energy, $g_{\text{eff}} hB = \hbar < v_F > /L$. Such $0\rightarrow \pi$ transitions are visible in Fig. 4a,b,e, as phase jumps in the CPR plotted as a function of a magnetic field in the (111) plane, either perpendicular or parallel to the wire axis. The characteristic field $B_{\perp,\parallel} \approx 600$ G, $B_{\perp,\parallel} \approx 400$ G between two successive $0\rightarrow \pi$ transitions yields an effective $g$ factor $g_{\text{eff}} \approx 30\rightarrow 100$, consistent with the high $g$ factors of some bands in Bi (ref. 29) as well as recently found for the surface states with ARPES experiments$^{30}$ in high magnetic field. We note that penetration of vortices in the superconducting electrodes would also lead to phase jumps. This is, however, unlikely as no sign of hysteresis was found in our data. This realization of a $0\rightarrow \pi$ transition induced by the Zeeman field is possible because the junction is long, contains few channels and the $g_{\text{eff}}$ are high.
enough that the transition occurs at a magnetic field below the superconducting electrodes’ (relatively high) critical field. The usual conversion of phase difference into a charge (super-)current can be supplemented by a conversion into a spin current in the presence of strong spin–orbit interaction. Consequently, a magnetic field can shift the CPR by a phase \( \phi \). This effect is related to the spin-splitting of Andreev states induced by spin–orbit interactions, that generates spin-dependent velocities, in addition to being ballistic rather than diffusive, topological edge states. We are now working on microwave experiments on these same wires that, by exploring the nature of the level crossing at \( \phi = \pi \), should be more definite on this issue.

Discussion

The CPR of a Bi-nanowire-based Josephson junction demonstrates that conduction occurs along ballistic channels confined at two edges of the wire’s (111) facets. Whereas narrow edge states were predicted for a bilayer of (111) Bi (ref. 15), it was not obvious that such states should exist in thicker samples, until 1D edge states were detected by scanning tunnelling microscopy recently, in two layer-deep pits at the (111) surface of bulk Bi crystals. Our work shows that in the superconducting proximity regime, the contribution of the nanowire’s two ballistic edge states outweighs that of the more numerous diffusive channels on the wire’s non-topological surfaces. That is because the contribution to the supercurrent is proportional to the conductance times the mean free path, whereas the mean free path of the surface and bulk states, whose contribution dominates the transport in the normal state, does not exceed 200 nm (Supplementary Note 1). This result in itself points towards a topological protection for these edge states. We are now working on microwave experiments on these same wires that, by exploring the nature of the level crossing at \( \phi = \pi \), should be more definite on this issue.

Methods

Sample fabrication and measurement. Bismuth nanowires were grown by RF-sputtering a Bi target of 99.999% purity onto Si substrates at 473 K and in an argon pressure of 10 mBar. A Bi film of 400 nm deposited at a rate of 0.7 nm s\(^{-1}\) in these conditions exhibits sparse arrays of nanowires, typically 100 \( \mu \)m long and distant by 10 \( \mu \)m from one another. High resolution transmission electron microscope observations indicated high quality single crystals, of rhombohedral or hexagonal sections as well as clear facets, with typical width of 50–300 nm. The nanowires were then dry deposited on an oxidized silicon substrate. After optical
selection, their crystalline orientation was determined using electron backscatter diffraction. An example is shown in Supplementary Fig. 2. This characterization was performed at the majority of the nanowires to avoid electron beam-induced damage of the Bi wire. We also checked on similar nanowires that their crystalline orientation was constant as we changed the position of the beam spot, as is expected for single crystals. At this stage, we selected nanowires whose top surface was determined to be oriented perpendicular to the trigonal [111] axis. Electrical connections were then made using gallium focused ion beam (FIB)-deposited superconducting tungsten wires. For all the measured nanowires, the lengths between the W lines were chosen to be greater than 1 μm to avoid possible superconducting contamination. Previous studies using the same set-up showed that this could be an issue for wires whose length is below 200 nm. For the same reasons, we minimized the total exposure time of the nanowires under the FIB to a single scan at high scanning rate and low magnification. We connected nine segments with different lengths, from a total of three such nanowires. Their resistances and lengths are summarized in the Supplementary Table 1, and show low contact resistance on average. The samples were then cooled to 100 mK and their critical current versus magnetic field was measured using a lock-in detection technique.

After this first characterization step, the CPR was measured on one segment (s1JU segment of Supplementary Table 1) using the asymmetric SQUID technique with a reference junction made of a W constriction. To this end, a FIB-deposited W wire was added between the two tungsten electrodes, in parallel to the Bi nanowire (Fig. 1), and was subsequently etched with the Ga+ beam while measuring the total resistance between the contacts, until the total resistance reached 190Ω, corresponding to a constriction resistance of 300Ω. The critical current of the SQUID was deduced from the average of 100 to 400 measurements of the switching current, using a counter synchronized to a current ramp at 180 Hz, and triggered by the jump in the sample resistance. In those measurements, the sample resistance was measured at 100 kHz with a lock-in detector operating with a time constant of 1 ms.

**Data availability.** All data presented in the main paper and supplement are available from the authors upon request.

**References**

1. Kane, C. L. & Mele, E. J. Quantum spin Hall effect in graphene. *Phys. Rev. Lett.* 95, 226801 (2005).
2. Bernevig, B. A. & Zhang, S. C. Quantum spin Hall effect. *Phys. Rev. Lett.* 96, 010402 (2006).
3. Van Wees, B. J. et al. Observation of zero-dimensional states in a one-dimensional electron interferometer. *Phys. Rev. Lett.* 62, 2523–2526 (1989).
4. König, M. et al. Quantum spin Hall insulator state in HgTe quantum wells. *Science* 318, 768–771 (2007).
5. Scaffidi, V. S. et al. Bi-induced superconductivity in a two-dimensional topological insulator. *Nat. Nanotechnol.* 10, 593–597 (2015).
6. Hart, S. et al. Induced superconductivity in the quantum spin Hall edge. *Nat. Phys.* 10, 638–643 (2014).
7. Du, L., Knez, I., Sullivan, G. & Du, R. Robust helical edge transport in gated InAs–GaSb bilayers. *Phys. Rev. Lett.* 114, 096802 (2015).
8. Golubov, A. I., Suprunyanov, M. Y. & Il’ichev, E. The current-phase relation in Josephson junctions. *Rev. Mod. Phys.* 76, 411–469 (2004).
9. Kulik, I. O. Macroscopic quantization and the proximity effect in SNS junctions. *Sov. Phys. JETP* 30, 944 (1970).
Acknowledgements

We acknowledge fruitful discussions with M. Aprili, S. Bayliss, C. Beenakker, S. Bergeret, D. Carpentier, J. Jobo, M. Houzet, F. Konschelle, J. Meyer, J. Enrique Ortega, P. Simon, T. Wakamura, A. Yazdani and financial support from CNRS, ANR MASH (ANR-12-IS04-0016), ANR DYMESIS (ANR-2011-IS04-001-01), ANR DIRACFORMAG (ANR-14-CE32-0003) and ANR JETS (ANR-16-CE30-0029-01). Yu.A.K. acknowledges financial support by RFBR and Moscow region grant 14-48-03664.

Author contributions

A.M., R.Del., R.Deb., H.B. and S.G. conceived the experiment and performed the measurements. A.K., Yu.A.K., V.T.V. and I.I.K. grew the Bi nanowires and characterized the nanowires with transmission electron microscope, A.M., A.K., S.S. and S.G. fabricated the circuits using FIB, F.B. and A.M. characterized the crystalline orientation of the nanowires. A.M., H.B. and S.G. wrote the manuscript with input from all authors. A.C., A.M. and H.B. conducted the numerical simulations.

Additional information

Supplementary Information accompanies this paper at http://www.nature.com/naturecommunications

Competing interests: The authors declare no competing financial interests.

Reprints and permission information is available online at http://npg.nature.com/reprintsandpermissions/

How to cite this article: Murani, A. et al. Ballistic edge states in Bismuth nanowires revealed by SQUID interferometry. Nat. Commun. 8, 15941 doi: 10.1038/ncomms15941 (2017).

Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/