Unconventional superconductivity and, in particular, triplet superconductivity have been front and center of topological materials and quantum technology research. Here, we report our observation of triplet pairing in nonmagnetic CoSi$_2$/TiSi$_2$ heterostructures on silicon. CoSi$_2$ undergoes a sharp superconducting transition at a critical temperature $T_c \approx 1.5$ K, while TiSi$_2$ is a normal metal. We investigate conductance spectra of both two-terminal CoSi$_2$/TiSi$_2$ contact junctions and three-terminal T-shaped CoSi$_2$/TiSi$_2$ superconducting proximity structures. Below $T_c$, we observe (i) a narrow zero-bias conductance peak on top of a broad hump, accompanied by two symmetric side dips in the contact junctions, (ii) a narrow zero-bias conductance peak in T-shaped structures, and (iii) hysteresis in the junction magnetoresistance. These three independent and complementary observations point to chiral p-wave pairing in CoSi$_2$/TiSi$_2$ heterostructures. The excellent fabrication compatibility of CoSi$_2$ and TiSi$_2$ with present-day silicon-based integrated-circuit technology suggests their potential use in scalable quantum-computing devices.

INTRODUCTION

Ever since the discovery that superfluid $^3$He realizes chiral p-wave pairing (1, 2), condensed matter and materials scientists have been on the search for electronic systems that show triplet superconductivity (3–8). This interest further intensified when it became clear that vortex cores of topological superconductors may offer a route toward the realization of non-Abelian statistics and fault-tolerant quantum computing (4, 7, 9, 10). Although several superconductors appear to be triplet superconductors, only a rather limited number is suspected to realize chiral p-wave pairing (3, 5, 11). Superconductivity induced in the doped topological insulators (e.g., Cu$_x$Bi$_2$Se$_3$ and Sn$_{1-x}$In$_x$Te (12, 13), topological semimetals (e.g., Cd$_3$As$_2$) (14), and semiconductors with strong Rashba spin-orbit coupling was recently discussed in this context (15, 16).

Identifying chiral p-wave superconductors is challenging (5, 11, 17). In superconductor/normal metal (S/N) junctions, the pairing potential can be probed by superconducting tunneling spectroscopy, which is essentially phase sensitive (18–23). This leads to the insight that spin-triplet pairing results in an odd-frequency proximity effect (24). In T-shaped proximity structures, this extraordinary proximity effect leads to a zero-bias conductance peak (ZBCP) for spin-singlet superconductors (25), while spin-singlet superconductors result in conductance dips and the absence of an odd-frequency pairing amplitude. This kind of conductance dip was indeed observed in T-shaped aluminum-copper proximity structures despite the technical challenges to fabricate these T-shaped junctions (26).

Here, we report successful fabrication of and systematic measurements on these two types of heterostructures using CoSi$_2$ as S and TiSi$_2$ as N components (see Materials and Methods and section S1). The conductance spectroscopies based on these two types of devices provide independent and complementary evidence for the unexpected observation of a dominant triplet pairing amplitude in CoSi$_2$/TiSi$_2$ heterostructures. In the superconducting state of CoSi$_2$, i.e., for $T < T_c \approx 1.5$ K, we observe a two-step ZBCP consisting of a broad hump and a sharp peak in the S/N contact junctions, as well as a sharp ZBCP in the T-shaped S/N proximity structures. In our design, the sizes of all involved devices are such that they give rise to substantial Thouless energies, which determine the full width at half maximum (FWHM) of the proximity-induced ZBCPs (25).

Paramagnetic CoSi$_2$ is a type II superconductor (27, 28) with a fairly small Ginzburg-Landau parameter $\kappa = \lambda/\xi \approx 0.82 > 1/\sqrt{2}$ and a correspondingly large $B_{c1}/B_{c2}$ (section S2), where $\lambda$ is the penetration depth, $\xi$ is the coherence length, and $B_{c1}$ and $B_{c2}$ are the lower and upper critical magnetic fields, respectively. We find an unexpectedly large spin-orbit coupling in CoSi$_2$ films. This is inferred from the weak-antilocalization effect in CoSi$_2$ films (section S3) (29). As the characteristic energy scale of the spin-orbit coupling is much larger than the superconducting gap, ramifications for the superconducting pairing state are expected. TiSi$_2$ is a non-magnetic metal. Three-dimensional TiSi$_2$ wires show no superconducting signal down to 50 mK (section S3). A highly transparent, clean CoSi$_2$/TiSi$_2$ interface embedded in a Si(100) substrate plays a key role in our study (section S1). Because of their epitaxial growth characteristics, our CoSi$_2$ films (105 nm thick in all cases) have a long lateral electron mean free path ($l_e \approx 300$ nm) and ultralow 1/f noise (30). We note that the 1/f noise magnitudes of epitaxial CoSi$_2$/Si(100) films are about two to three orders of magnitude lower than those in polycrystalline (single-crystalline) aluminum films (30), which are commonly used as a basis for superconducting qubits and quantum computing. Moreover, high-resolution transmission electron microscopy (TEM) studies have indicated that the as-grown
epitaxial CoSi₂/Si(100) heterostructure is extremely clean, without any detectable traces of residual (magnetic) Co or (nonmagnetic) CoSi and Co₂Si after thermal annealing (30). The absence of magnetic impurities is confirmed by the superconducting quantum interference device magnetization measurements (section S4) and further supported by our measured $T_c = 1.5$ K (section S3), which is among the highest $T_c$ value ever reported for CoSi₂ (31).

RESULTS
Characterization of device structure and conductance for CoSi₂/TiSi₂ S/N junctions
We first discuss the differential conductance spectra $dI(V, T)/dV$ (where $V$ is the bias voltage and $I$ is the current) of highly transparent CoSi₂/TiSi₂ S/N contact junctions like the one depicted in the optical micrograph in Fig. 1A. Figure 1B shows cross-sectional TEM images of the junction cut by a focused ion beam along the dashed line indicated in Fig. 1A. In the right panel, an enlarged version of the interface region indicated by a red arrow in the left panel, is presented. It reveals a well-defined atomic arrangement at the interface. The corresponding diffraction patterns of CoSi₂ and TiSi₂ are also shown. As the lattice mismatch between TiSi₂ and Si(100) is large (32), the crystalline structures of TiSi₂ grains are usually tilted with respect to Si(100) and to each other. This may be the reason why the quality of the TEM image and the diffraction pattern for TiSi₂ is not as good as that for CoSi₂. Figure 1C schematically depicts the junction structure and our $dI/dV$ measurement configuration. Below $T_c$, the total resistance is given by $R(T) = R_1(T) + R_{N2}$, where $R_1$ denotes the junction resistance of the S/N interface and $R_{N2}$ the residual resistance of the TiSi₂ counter electrode, which can be independently determined (section S3) and subtracted from $R(T)$.

The S/N interface of our junctions is right-angle shaped; see Fig. 1C. The top interface, indicated by a dashed blue line, is opaque because of the fabrication process. The clean vertical interface immersed in and protected by the Si(100) substrate, indicated by a red line, dominates the measured Andreev tunneling spectra (section S5). Figure 1D shows the zero-bias junction conductance $G(V = 0, T = 1/R_1(T)$ for a typical device, referred to as J1, below 2 K. In $B = 0$ T (blue curve), an increase of $G_0(0, T)$ with decreasing $T$ for $T < 1.48$ K is evident. A second conductance increase setting in at ~0.65 K is also clearly discernable. The excess tunneling conductance (blue curve) is fully suppressed in $B = 0.12$ T (red curve). In between the curves of 0 and 0.12 T, there are eight curves measured in increasing $B$ of 10-mT increment between consecutive curves from 10 to 80 mT. We find that the second conductance increase is just fully suppressed in $B = 60$ mT (indicated by an arrow). The small conductance decrease forming a dip at 1.48 K (for $B = 0$ T) is caused by the contribution from the dirty top interface. After removing part of the protruding TiSi₂–Si(100) section on top of CoSi₂ with chemical etching, we found that the junction $G_0(0, T)$ is downshifted, but its characteristic features remain essentially unchanged (section S6). Therefore, the small drop at 1.48 K does not affect the superconducting $dI/dV$ characteristics and will be ignored below. The inset shows the resistivities of the CoSi₂ and TiSi₂ films below 2 K.

Conductance spectra of S/N junctions
Figure 2A shows the $dI/dV$ curves for device J1 between 0.370 and 1.78 K in $B = 0$. At 0.370 K, the $dI/dV$ curve displays energy gap signatures (i.e., two symmetric side dips) (20, 21) at bias voltages $V_g \approx \pm 0.225$ mV and a broad conductance hump spreading across an $eV$ range equivalent to the energy gap, where $e$ is the electronic charge. This broad hump arises from midgap Andreev resonant states (23). It gradually diminishes as $T$ is increased to $T_c$. As shown in Fig. 2C (section S7), the extracted $T$ dependence of the gap amplitude $\Delta(T) = |eV_g(T)|$ deviates from the weak-coupling Bardeen-Cooper-Schrieffer (BCS) expressions for $T_c = 1.48$ K (Fig. 1D) and $2\Delta_0/k_B T_c = 3.528$, where $\Delta_0$ is the energy gap at zero temperature (33, 34). Alternatively, a satisfactory fit with $T_c = 1.385$ K and $2\Delta_0/k_B T_c = 3.837$ can be obtained by ignoring the two highest temperature data points, which are subject to large experimental uncertainties. This slightly reduced $T_c$ value may be due to, e.g., inhomogeneities and/or tiny heating at the S/N contact or may arise from multiband effects in combination with interface-related changes of the $d$-electron bands. We note in passing that the $dI/dV$ spectra for the $d$-wave superconductor $YBa_2Cu_3O_7-x$ have a sharp peak at zero bias, instead of a broad hump, due to the flat dispersion of its Andreev bound states (22, 23). Figure 2A also shows that the $dI/dV$ spectra feature a second, narrow ZBCP that is visible for $T \leq 0.65$ K. This ZBCP is responsible for the increase of $G_0(V = 0, T \leq 0.65$ K) in $B = 0$ T shown in Fig. 1D. We will comment on its origin below.

Figure 2B shows the $dI/dV$ curves of device J1 for several $B$-field values at $T = 0.366$ K. It demonstrates that the two-step ZBCP is
progressively suppressed as $B$ is increased, with the narrow peak first vanishing at $B^* \approx 60$ mT. The two-step ZBCP cannot be due to thermal effects as the accompanying spikes at high bias $V > V_g$ (Fig. 2, A and B) signal a current density equal to the local critical current density of CoSi$_2$. Figure 2 (D to F) shows the normalized $(dI/dV)_n$ curves for three different junctions (devices J1, J2, and J3) at $T = 0.37$ K and in $B = 0$, where $(dI/dV)_n$ denotes the differential conductance normalized to its corresponding normal-state value. Pronounced two-step conductance peaks are seen in every junction, although the details of the line shapes vary from junction to junction.

These line shapes neither fit expectations based on pure s- nor d-wave pairing potentials (section S8) (19). We thus have analyzed the spectra by applying a chiral p-wave gap function (20, 21), assuming that the CoSi$_2$/TiSi$_2$ interface lies in the $y$-$z$ plane. Notably, the differences in line shape can be (almost completely) ascribed to the varying magnitudes of the dimensionless potential barrier height $Z$, which cannot be fully controlled experimentally. This phenomenological parameter may, e.g., be affected by the tilted orientations of TiSi$_2$ grains with respect to Si(100), thus accounting at least partly for the different $Z$ values inferred for different junctions. The broad hump is essentially flat in Fig. 2F, implying $Z \ll 1$ in this

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**Fig. 2. Conductance spectra of CoSi$_2$/TiSi$_2$ contact junctions.** (A) $dI/dV$ curves for device J1 at several $T$ values, as indicated, and in $B = 0$. The dashed curves indicate the superconducting gap $2\Delta$. (B) $dI/dV$ curves for the same device in several $B$ values, as indicated, and at $T = 0.366$ K. In (A) and (B), the $dI/dV$ curves are vertically offset for clarity. The spikes outside the superconducting gap occur when the applied bias current matches the superconducting critical current of the device. (C) Superconducting gap magnitude $2\Delta(T)$ versus temperature for device J1 taken from two runs: the first run on a $^3$He cryostat and the second run on a dilution refrigerator. BCS expressions are plotted for two $T_c$ values with corresponding $2\Delta_0/k_BT_c$ ratios, as indicated. The side dips at $T/T_c \leq 0.75$ are well developed, and the error bars are compatible with the symbol size. (D to F) Normalized $(dI/dV)_n$ curves for three devices at $T = 0.37$ K and in $B = 0$. These contact junctions were fabricated under nominally similar conditions. The junction resistances are $R_J(0.37$ K) = 0.61 $\Omega$ (D), 0.92 $\Omega$ (E), and 0.16 $\Omega$ (F). The red solid curves in (D) to (F) are theoretical predictions for a chiral p-wave pairing superconductor with fitted barrier parameter $Z = 0.67$ (D), 0.81 (E), and 0.10 (F) (see the main text and section S8).
particular junction. The red solid curves in Fig. 2 (D to F) are fits to the data based on a chiral $p$-wave gap function (20, 21) with the fitted values $Z = 0.67$ (Fig. 2D), 0.81 (Fig. 2E), and 0.10 (Fig. 2F) (section S8). Because the $S/N$ junctions are made of diffusive (TiSi$_2$) thin films, which have higher-than-average effective interface transparencies, correspondingly smaller $Z$ values are expected, in line with the fitted values (35).

The consistently high quality of these fits are indicative of a dominating $p$-wave pairing amplitude in CoSi$_2$/TiSi$_2$ interfaces. These fits, which are based on the clean limit of TiSi$_2$, very well capture the overall line shape of the $dI/dV$ spectra but fail to reproduce the sharp, second ZBCP [this second ZBCP will be attributed to the proximity effect in diffusive chiral $p$-wave $S/N$ junctions (36); see below]. We note that the $T$, $V$, and $B$ dependences shown in Figs. 1D and 2 (A and B) rule out magnetic Kondo impurities as a possible origin of this ZBCP. Another possible source of the central ZBCP could be reflectionless tunneling due to the presence of disorder in TiSi$_2$. We can also rule out this phase-coherent Andreev scattering (37) as the underlying reason of the ZBCP because of its $V$ and $B$ dependences. The threshold magnetic field of the ZBCP is much larger than that expected for phase-coherent Andreev reflection, which can be estimated via $h = E_F \phi_L / (e \Delta_0 N)$, where $h$ denotes the Planck constant, $E_F$ the phase-coherent length of TiSi$_2$ ($\approx 1 \mu$m at 0.37 K; section S3), and $N$ the thickness of TiSi$_2$ ($\approx 125$ nm; see Materials and Methods). This results in an expected $h/\Delta_0$ for reflectionless tunneling of the order of a few milliTesla.

The diffusion constant of TiSi$_2$ is estimated as $D_{DN} \approx 65$ cm$^2$/s, while the FWHM ($=0.04$ meV) of the narrow ZBCP is of the same order of magnitude as that observed in the $T$-shaped proximity structures discussed below (cf. Fig. 3C, section S10, and Table 1). This FWHM reflects the Thouless energy of the diffusive normal metal (DN) $E_T = hD_{DN}/L_{DN}^2$, where $L_{DN}$ is the characteristic length of a diffusive segment of TiSi$_2$ bound by grain boundaries (cf. Fig. 1C and section S1). Thus, a $L_{DN}$ can be estimated from $E_T$ and $D_{DN}$, whose value $\approx 330$ nm is in line with the $L_{DN}$ evaluated from scanning electron microscopy (SEM) and TEM images (section S1). This points to the narrow ZBCP as being intrinsic to diffusive CoSi$_2$/TiSi$_2$ junctions. This is further corroborated by the magnitude of the threshold magnetic field (cf. the threshold $B$ field in the $T$-shaped proximity structures discussed below). Because $E_T \ll \Delta$, such a narrow ZBCP has been predicted to occur in diffusive chiral $p$-wave $S/N$ junctions (36).

In terms of the point contact spectroscopy, our planar $S/N$ junctions are predominantly in the diffusive regime (section S9) (38–40), i.e., $l_c \ll \sqrt{4A} < L_{DN}$, where $l_c \approx 8$ nm in TiSi$_2$ (section S3) and $\sqrt{4A}$ is the lateral contact size of the “active” junction (Table 2). Contributions to the $I$-$V$ characteristics from Joule heating, backflow currents, and other nonequilibrium effects are small (section S9).

Conductance spectra of $T$-shaped proximity structures

As an independent and complementary analysis to further substantiate this finding, we analyze conductance spectra of highly transparent CoSi$_2$/TiSi$_2$ proximity structures (25). Figure 3A shows a schematic diagram of such a $T$-shaped proximity structure. It was shown by Asano et al. (25) that the Cooper pairs from a spin-triplet $S$ penetrating into $N$ will be transferred into odd-frequency spin-triplet, even-parity $s$-wave pairs, which lead to an enhanced quasiparticle local density of states (LDOS) at the Fermi energy $E_F$ of $N$ (25, 41). In contrast, for any spin-singlet $S$, a zero-bias dip in $(dI/dV)_n$ is expected because of the reduction of LDOS at $E_F$ in $N$ (25, 41). This is illustrated in Fig. 3A and explains the suppression of the LDOS at $E_F$ for such a proximity structure of superconducting aluminum mentioned above (26, 42). The inset of Fig. 3B shows a SEM image (false-colored for clarity) of our $T$-shaped proximity structure, referred to as device A1. The measured $(dI/dV)_n$ curve of device A1 exhibits a characteristic ZBCP as shown in Fig. 3C, which confirms the existence of a spin-triplet pairing amplitude in $S$ (25, 41).

At $T = 0.37$ K, the FWHM of the ZBCP is $\approx 0.03$ meV; see also Fig. 3D. This is consistent with the independently determined Thouless energy $E_T$ ($=0.05$ meV; section S10 and Table 1) of the penetrated Cooper pairs undergoing diffusive motion in TiSi$_2$. Figure 3D demonstrates that the ZBCP (at 0.37 K) of the same device is gradually suppressed by an increasing $B$ field and completely vanishes at $B = 30$ mT, a value that is smaller than the critical magnetic field of CoSi$_2$ ($B_{c2} \approx 100$ mT; cf. section S2). The inset of Fig. 3D shows the variation of the ZBCP with $B$ at $T = 0.37$ K. The dashed blue line is a linear fit to the background conductance. The two red curves are exponential fits to the ZBCP in $B$ and $+B$ regimes, respectively. We see that the ZBCP is fully suppressed around 30 mT. The value of $B^*$ is comparable to the threshold value at which the sharp ZBCP observed in CoSi$_2$/TiSi$_2$ $S/N$ junction vanishes (cf. Fig. 2B) and thus points to a common origin.

The inset of Fig. 3E shows a false-color SEM image of a further $T$-shaped device, referred to as A4, which is composed of a more resistive form of TiSi$_2$ than device A1 (section S10 and Table 1). The main panel shows the pronounced ZBCPs occurring below $T \approx 1.35$ K. In Fig. 3F, the ZBCP is suppressed by an increasing $B$ field and vanishes at $B^* \approx 100$ mT at $T = 0.37$ K. The enhanced ZBCP occurring in the more resistive DN well fits the theoretical expectation of a triplet superconductivity–induced proximity effect (25). This, the conductance spectra of $T$-shaped CoSi$_2$/TiSi$_2$ structures indicate the presence of triplet superconductivity. To the extent that conductance spectroscopy can distinguish between helical and chiral triplet superconductivity, these spectra are compatible with chiral $p$-wave superconductivity.

Hysteretic magnetoresistance of $S/N$ junctions

The presence of chiral $p$-wave superconductivity in CoSi$_2$/TiSi$_2$ heterojunctions implies the existence of supercurrents associated with chiral domains. To test for their existence, we turn to a careful analysis of the magnetoresistance of the $S/N$ junctions (23, 43). Intriguingly, the magnetoresistance displays a peculiar hysteretic behavior. Figure 4A shows the zero-bias magnetoresistance curves for device J4 measured in sweeping in-plane $B$ fields and at three different $T$ values. The arrows and numbers indicate the $B$ sweeping sequence. At 1.74 K, no magnetoresistance is detected. Once $T$ decreases below $T_c$, a hysteresis appears. The size of the hysteresis, indicated by $\Delta B/2$, is $\approx 5.5$ mT. A hysteresis of $\Delta B/2 \approx 20$ mT is found in device J5 at 0.37 K, as can be read off from Fig. 4B. Figure 4C shows the magnetoresistance curves for device J2. Note that in these three junctions, the magnetoresistance minimum occurs before $B$ passes through zero. This “advanced” feature is reminiscent of the anomalous magnetic response reported for Bi/Ni bilayer superconductors (44) and Sr$_2$RuO$_4$ (45) and theoretically interpreted by Bouhon andSigrist (46). It is, however, incompatible with the hysteresis expected for magnetic flux pinning in a conventional superconductor.
Fig. 3. T-shaped CoSi₂/TiSi₂ superconducting proximity structure and conductance spectra. (A) Schematic of a T-shaped S/N proximity structure, with I-V characteristic measurement configuration. The sketch also depicts the predicted ZBCP (dip) for a spin-triplet (spin-singlet) S. (B) Inset: A false-colored scanning electron microscopy (SEM) image of the T-shaped device A1. Scale bar, 1 μm. The main panel shows the zero-bias dI(0, T)/dV curve in B = 0 and 50 mT. The proximity effect sets in at Tₜₒₜₜₑₜ ≈ 1.4 K. (C) Normalized conductance spectra (dI/dV)ₙ of device A1 at several T values show a ZBCP at T < Tₜₒₜₜₑₜ. (D) At 0.37 K, the ZBCP is gradually suppressed with increasing B and completely vanishes at B = 30 mT. Inset: Variation of the ZBCP with B at 0.37 K. The dashed blue line is a linear fit to the background conductance. The two red curves are exponential fits to the ZBCP in −B and +B regimes, respectively. (E) Normalized conductance spectra (dI/dV)ₙ of T-shaped device A4 at different T values. The renormalized bias voltage Vᵣᵣᵣᵣᵣᵣ of the independent axis is defined as the voltage drop over the TiSi₂ grain, which is responsible for the proximity effect (section S10). Inset: A false-colored SEM image of device A4. (F) At T = 0.37 K, the ZBCP of device A4 is gradually suppressed with increasing B and vanishes completely at B = 100 mT.

Table 1. Device parameters of T-shaped CoSi₂/TiSi₂ superconducting proximity structures. Rᵣ (µΩ) is the residual resistance (resistivity) of TiSi₂ wire. L₁ and L₂ are defined in Fig. 3A in the main text. ∆(dI/dV)ₙ ≡ (dI/dV)ₙ − 1 is the increase in normalized conductance at 0.37 K. FWHM is the full width at half maximum of the ZBCP. The Thouless energy is given by Eₜₒₜₑₜ = ℏDₙₙₙₙ/L₁², where Dₙₙₙₙ is the diffusion constant of TiSi₂. Tₜₒₜₑₜ is the onset temperature of the proximity effect. A₄ₜₐₐₐₐₐₐ lists the renormalized parameters for the A₄ device, as described in section S10.

| Device | Rᵣ(2 K) (Ω) | ρᵥ(2 K) (µΩ cm) | L₁ (μm) | L₂ (μm) | ∆(dI/dV)ₙ | FWHM (meV) | Eₜₒₜₑₜ (meV) | Dₙₙₙₙ (cm²/s) | Tₜₒₜₑₜ (K) |
|--------|-------------|-----------------|---------|---------|-------------|-------------|-------------|--------------|-------------|
| A1     | 0.59        | 4.9             | 0.24    | 0.5     | 0.25%       | 0.032       | 0.053       | 46           | 1.44        |
| A2     | 0.77        | 3.5             | 0.34    | 0.07    | 0.16%       | 0.054       | 0.037       | 65           | 1.49        |
| A3     | 1.61        | 5.4             | 0.42    | 0.37    | 0.11%       | 0.042       | 0.016       | 42           | 1.48        |
| A4     | 29.61       | 126             | 0.45    | 0.18    | 0.75%       | 0.35        | 0.0016      | 4.9          | 1.46        |
| A₄ₜₐₐₐₐₐₐ | 2.61      | 22.1            | 0.27    | 0.18    | 9.2%        | 0.024       | 0.014       | 15           | 1.46        |
Table 2. Device parameters of CoSi$_2$/TiSi$_2$ (S/N) contact junctions. $R_j$ is the junction resistance of the S/N interface. $(dI/dV)_n$ lists the magnitude of the normalized two-step zero-bias conductance. The magnitude of the broad hump is also listed (cf. Fig. 2 in the main text). $\Delta$ is the superconducting gap amplitude. $Z$ is the dimensionless potential barrier height extracted from least-squares fits of the measured conductance spectra as described in section S8. $\Delta B$ is the size of hysteresis in junction magnetoresistance defined in Fig. 4 in the main text. All values are measured at 0.37 K.

| Device | $R_j$ (Ω) | $(dI/dV)_n$ | $(dI/dV)_n$ (broad hump) | $\Delta$(meV) | $Z$ | Active junction area ($\mu$m$^2$) | $\Delta B$ (mT) |
|-------|-----------|-------------|--------------------------|--------------|----|-------------------------------|--------------|
| J1    | 0.61      | 2.16        | 1.66                     | 0.225        | 0.67 | 0.58                          | 0            |
| J2    | 0.92      | 1.55        | 1.39                     | 0.24         | 0.81 | 0.22                          | ~17          |
| J3    | 0.16      | 2.36        | 1.36                     | 0.12         | 0.1  | 1.6                           | 0            |
| J4    | 0.45      | 1.99        | 1.59                     | 0.14         | 0.84 | 0.10                          | ~11          |
| J5    | 1.15      | 1.34        | 1.31                     | 0.22         | 0.83 | 0.05                          | ~40          |

Microscopically, in a chiral superconductor, internal magnetic fields will be induced by spontaneous supercurrents that flow along the domain surfaces (47, 48). In a sample containing several chiral domains, these magnetic fields will not fully average out and hysteresis can appear. Neighboring domains may have opposite chiralities ($p_x \pm ip_y$) and corresponding orbital angular momentum of a Cooper pair described by $L_z = \pm \hbar$. As a characteristic average size of these chiral domains, we take the mean grain size, which, in our CoSi$_2$/Si(100) films, have an average lateral size of ~300 nm (30). Thus, for our junctions with typical areas ~$(0.05 – 1)$ μm$^2$ (Table 2), the Andreev tunneling currents will flow through only a limited number (~10) of domains. Consequently, a net local field persists, causing a hysteretic magnetoresistance. In contrast, devices J1 and J3 have comparatively large S/N interface areas, allowing for an averaging out of different chiralities. As a result, a considerably diminished hysteresis in the junction magnetoresistance is expected in larger junctions. This is indeed what we find in Fig. 4 (D and E). This should be compared with a vortex pinning–driven hysteresis, where all vortices should have the same helicity in a nonzero magnetic field so that no averaging out occurs. As mentioned above, $\chi$ is only slightly above $1/\sqrt{2}$, which implies not only a $B_{c1}$ close to $B_{c2}$ but also that the flux lines in the vortex phase only weakly interact. Thus, no strong hysteresis is expected from vortex pinning (49).

Specifically, as the lower critical field in our films can be estimated to have a lower bound of 62 mT (section S2), no vortex contribution is expected at the field strengths where the hysteresis minimum occurs. For large positive (negative) fields, the magnetoresistance slope has to be positive (negative) as the normal-state behavior is approached, while the field derivative near zero field in a down-sweep ($|B| \rightarrow 0$, so that one chirality dominates) is negative for positive chirality and vice versa (23, 43). Thus, in a down-sweep before reaching $B = 0$, a minimum in the magnetoresistance has to occur. This unique hysteretic behavior thus provides yet another indication for chiral superconductivity in CoSi$_2$/TiSi$_2$ heterojunctions (44, 45). The winding number of the vortex in the domain of a chiral $p$-wave state is either 0 or $\pm 2$, depending on the $B$ field direction and the chirality (5, 45), and may lead to step-like changes in magnetoresistance. At present, we are unable to resolve these tiny changes in the magnetic response. This may be related to the comparatively large, lower critical field $B_{c1}$ of CoSi$_2$.

Last, the shape of the magnetoresistance curve beyond the hysteresis in a given junction is determined by the combined responses of the broad hump and the sharp central peak of the conductance.

Fig. 4. Hysteretic zero-bias magnetoresistance in CoSi$_2$/TiSi$_2$ contact junctions. Zero-bias magnetoresistance curves of devices J4 (A), J5 (B), and J2 (C) at several $T$ values, as indicated. In (C), left (right) inset shows a zoom-in for the magnetoresistance at 1.43 and 1.78 K (0.37 and 0.90 K). The arrows and numbers indicate the sweeping sequence of the magnetic field. $\Delta B$ denotes the size of the hysteresis. (D) Magnetoresistance curves of device J1 at different temperatures. (E) Magnetoresistance curves of devices J1 (top) and J3 (bottom) at 0.50 and 0.37 K at an enlarged scale. Note that these two devices have comparatively large S/N interface areas among the tunnel junctions studied in this work (Table 2). No hysteresis in the magnetoresistance is observed to within experimental uncertainties in these two devices.
rising annealing temperature, under this Si-rich condition and with es feature an unexpectedly large spin-orbit coupling with a characteristic energy scale (∆_s ≈ 6 meV; section S3) corresponding to ~30Δ, where 2Δ is the superconducting gap. It is known that time-reversal invariant odd-parity pairing arises naturally in such a situation (13). While it is difficult to distinguish helical from chiral p-wave superconductivity via Andreev spectroscopy, the unusual features of the magnetotransport point to the presence of chiral Cooper pairing. In this context, we recall that the observed possible deviation from the BCS gap equation mentioned above might result from the different 3d electron bands and their expected bandwidth narrowing in the vicinity of the interface. On the other hand, future thermodynamic and zero-field muon spin relaxation and optical Kerr measurements will be useful in discriminating whether the triplet superconductivity is a bulk property of CoSi2. As the CoSi interfaces have a comparatively high quality (30), our findings should also prove helpful in relation to addressing other systems with possible chiral p-wave pairing like Sr2 RuO4 (11, 45). In particular, given that the fabrication processes and scalability of epitaxial CoSi2/Si heterostructures are fully compatible with state-of-the-art silicon-based integrated-circuit technology (32), we expect that our observation can provide a viable route for realizing novel p-wave–based devices in silicide-based material systems.

DISCUSSION
Taking the magnetoresistance hysteresis together with the results for the S/N junctions and the T-shaped proximity structures, our observations indicate that CoSi2/TiSi2 heterostructures feature a dominant triplet pairing amplitude whose order parameter appears to be compatible with chiral p-wave pairing. Our proximity structure results also establish the presence of even-parity odd-frequency, spin-triplet pairs in TiSi2 (24, 25). Odd-frequency pairing has recently received renewed interest, and CoSi2/TiSi2 heterostructures offer a promising route to systematically explore its properties via, e.g., single-particle spectroscopy (6, 8). We find that CoSi2 interfaces feature an unexpectedly large spin-orbit coupling with a characteristic energy scale (∆_s ≈ 6 meV; section S3) corresponding to ~30Δ, where 2Δ is the superconducting gap. It is known that time-reversal invariant odd-parity pairing arises naturally in such a situation (13). We had patterned the EBL area so that the TiSi2 counter electrode was in contact and overlapped the CoSi2/Si(100) heterostructure (see fig. S1). This protruding TiSi2 section of a few micrometers long was an indispensable design. It served as a passivating layer to protect the active CoSi2/TiSi2 interface from oxidation and contamination during the second-step annealing process. On the other hand, because the top surface of the CoSi2/Si(100) heterostructure was exposed to air and was dirty, this passivated CoSi2/TiSi2 interface (indicated by a horizontal dashed blue line in fig. S1D) contributed only a negligible Andreev tunneling current at T < Tc. Our control dI/dV measurements indicated that the junction resistances of the top passivated CoSi2/TiSi2 interfaces were two to three orders of magnitude larger than those of the active CoSi2/TiSi2 junctions (section S5).

Junction structure characterizations
Several junctions were processed by using the focused ion beam technique (TESCAN GAIA3) to make specimens for the CoSi2/TiSi2 interface structure studies. The structure characterizations were carried out on a field emission transmission electron microscope (JEOL JEM-F200).

MATERIALS AND METHODS
Junction fabrication
We used two-step thermal-evaporation deposition and thermal annealing to fabricate CoSi2/TiSi2 junctions (see section S1 for schematic fabrication procedures). In the first step, a 30-nm-thick Co film was deposited on an electron beam lithographically (EBL) defined micrometer-wide area of an undoped Si(100) substrate. The deposited Co film on the Si(100) substrate was annealed at 700°C for 1 hour and then at 800°C for 1 hour to form a 105-nm-thick CoSi2 film (32). Because CoSi2 is the final high-temperature phase along the phase formation sequence (Co2Si → CoSi → CoSi2) with rising annealing temperature, under this Si-rich condition and with a long period of annealing time, all Co atoms were transformed into a single-phased, paramagnetic CoSi2 (50). In this step, Co atoms were the major moving species, namely, they diffused downward into the Si(100) substrate to form an epitaxial CoSi2/Si(100) heterostructure (32). After formation of the compound CoSi2, Co atoms are connected to Si atoms in an eightfold coordinated structure through strong covalent bonding, and therefore, Co atoms lose their diffusivity (32, 50). The CoSi2/Si(100) heterostructure had high thermal stability up to 900°C and a melting point of 1326°C (32).

After annealing, the Si(100) substrate with CoSi2/Si(100) heterostructure was exposed to air for the second step of the EBL process. A 50-nm-thick Ti film was deposited on the patterned area close to the CoSi2/Si(100) heterostructure. The deposited Ti was annealed at a temperature between 720° and 800°C to form a 125-nm-thick TiSi2 film. Different annealing temperatures resulted in different device properties and thus tuned the device parameters. During this annealing process, Si atoms were the major moving species (32), i.e., the Ti atoms had negligible interdiffusion with the compound CoSi2. This fabrication method led to the formation of a high-quality active CoSi2/TiSi2 junction (indicated by a vertical red line in Fig. 1C and fig. S1D), which was immersed in the Si(100) substrate and protected by a “passivated” TiSi2−x thin layer (see Fig. 1, B and C).

Energy-dispersive x-ray spectroscopy and cross-sectional TEM studies indicated that x varied from x ≈ 0 near the bottom surface to x ~ 0.55 near the top surface of the TiSi2−x thin layer. This composition variation likely stems from the existence of a position-dependent diffusion barrier for the main moving species (Si) during the titanium-silicidation process (32).

Electrical measurements
Ti/Au (15/65 nm) bonding pads were deposited on the CoSi2/TiSi2 (S/N) contact junction and T-shaped proximity structure devices via electron gun evaporation through a mechanical mask. Thin Au wires were attached to the bonding pads by a wire bonder. Devices were mounted on the sample holder of an Oxford Heliox ³He cryostat equipped with a 2-T superconducting magnet or in a BlueFors LD-400 dilution refrigerator equipped with a 9-T superconducting magnet. The dI/dV and magnetoresistance curves were measured using the four-probe method. The applied current I was composed of a dc component (I_{dc}) and an ac component (I_{ac}). The two components were added by a homemade bias circuit. The I_{dc}...
was generated by a Keithley Model 6221 dc current source, while the \( I_{\text{dc}} \) was generated by a Linear Research Model LR700 ac resistance bridge operating at 16 Hz. The dc voltage drop across the device was measured by a Keithley Model 2182 nanovoltmeter. The differential resistances (conductances) were registered by the LR700 ac resistance bridge.

**SUPPLEMENTAL MATERIALS**

Supplemental material for this article is available at http://advances.sciencemag.org/cgi/content/full/7/29/eaab6569/DC1

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