The detection of individual quanta of light is important for quantum communication, fluorescence lifetime imaging, remote sensing and more. Due to their high detection efficiency, exceptional signal-to-noise ratio and fast recovery times, superconducting-nanowire single-photon detectors (SNSPDs) have become a critical component in these applications. However, the operation of conventional SNSPDs requires costly cryocoolers. Here we report the fabrication of two types of high-temperature superconducting nanowires. We observe linear scaling of the photon count rate on the radiation power at the telecommunications wavelength of 1.5 μm and thereby reveal single-photon operation. SNSPDs made from thin flakes of Bi₂Sr₂CaCu₂O₈₊ₓ exhibit a single-photon response up to 25 K, and for SNSPDs from La₁.₅₅Sr₀.₄₅CuO₄/La₂CuO₄ bilayer films, this response is observed up to 8 K. While the underlying detection mechanism is not fully understood yet, our work expands the family of materials for SNSPD technology beyond the liquid helium temperature limit and suggests that even higher operation temperatures may be reached using other high-temperature superconductors.
The SNW region is chosen to reduce the total resistance of the gold electrodes. Scale bar, 3 μm. Inset: example SEM image of a BSCCO SNW produced by He+ beam exposure (similar but not identical to that from the photograph: to avoid degradation, we refrained from characterizing the photodetector using SEM imaging). Scale bar, 2 μm. Schematic of the LSCO–LCO single-photon detector: a high-\( T_c \) two-dimensional superconductor (SC) is formed at the interface between the 5-UC-thick layer of the LCO insulator and the 5-UC-thick layer of the LSCO metal on strontium lanthanum aluminate (LSAO) substrate. The contact leads are 50-nm-thick titanium–gold. An SEM image of a typical LSCO–LCO SNW device. Scale bar, 2 μm.

Fig. 1 | High-\( T_c \) superconducting nanowires. a, Schematic of the BSCCO single-photon detector: a relatively thin flake of BSCCO is covered by a much thicker flake of hBN and transferred onto ultra-flat gold contacts. The SNW region is defined by a He+ beam exposure. b, Optical photograph of the BSCCO device. The green line demarcates the photodetector area. The contact geometry was chosen to reduce the total resistance of the gold electrodes. Scale bar, 3 μm. Inset: example SEM image of a BSCCO SNW produced by He+ beam exposure (similar but not identical to that from the photograph: to avoid degradation, we refrained from characterizing the photodetector using SEM imaging). Scale bar, 2 μm. c, Schematic of the LSCO–LCO single-photon detector: a high-\( T_c \) two-dimensional superconductor (SC) is formed at the interface between the 5-UC-thick layer of the LCO insulator and the 5-UC-thick layer of the LSCO metal on strontium lanthanum aluminate (LSAO) substrate. The contact leads are 50-nm-thick titanium–gold. d, An SEM image of a typical LSCO–LCO SNW device. Scale bar, 2 μm.

Fig. 2 | Transport properties of cuprate SNWs. a, b, Examples of the \( R(T) \) dependencies for BSCCO (a) and LSCO–LCO (b) flake, film and SNWs. c, \( I-V \) curve for BSCCO SNWs measured at \( T = 3.7 \) K in the four-terminal configuration. d, Typical \( I-V \) curves of LSCO–LCO SNWs measured in the two-terminal configuration at \( T = 3.7 \) K before and after He+ ion exposure.
of magnitude, among the smallest of any SNW so far reported. Finally, LSCO–LCO bilayers are stable in air for years, and resilient to degradation during standard lithography, etching and contact deposition processes. In this work, we used heterostructures comprised of a 5-unit-cell (UC)-thick layer of LCO grown on top of a 5-UC-thick layer of LSCO (Fig. 1c). We used the electron-beam lithography to define an SNW meander structure typical for SNSPDs, 60 μm in length and 100 nm in width, with a filling factor 0.28 (Fig. 1d). For the fabrication details, see Methods and Supplementary Information, section 2.

After fabrication, we characterized the transport properties of our high-Τ SNWs. Figure 2a,b shows the typical temperature dependence of the resistance, R(T), of SNWs fabricated out of BSCCO and LSCO–LCO, revealing their respective critical temperatures of 69.8 K and 34.4 K as determined from the maximum of dR/dT(T). The obtained values are somewhat lower than those obtained for the parent BSCCO flake and LSCO–LCO bilayer film, that is, 79.8 K and 35.5 K, respectively (Fig. 2a,b, black traces). This indicates a mild degradation of the materials’ superconducting properties during the fabrication. BSCCO underwent a more substantial change in Τc, probably because of its much stronger sensitivity to the environment.

An important characteristic of most SNWs, enabling the generation of a voltage pulse upon single-photon absorption, is the metastable state that emerges under current biasing. This metastable state appears due to the competition between the current-induced Joule self-heating of the SNW in the normal state and electron cooling processes, and manifests itself as a pronounced hysteresis on the I–V characteristics. Figure 2c shows a typical I–V curve measured in our BSCCO device below Τc when the SNW is current-biased. A clear hysteresis with h = 516 μA is observed. The origin of the I–V hysteresis with hysteresis-free and thus these SNWs were not suitable for a single-photon detector per se (Fig. 2d). To circumvent this problem, we exposed the device to a relatively small dose of He+ ions (1016 cm−2) (Supplementary Information, section 3). Such exposure had only a mild effect on Ic, Τc and the normal state Rn; however, it led to the desired I–V hysteresis with Ic = 86.7 μA and Iph = 36.3 μA (Fig. 2d and Supplementary Information, section 4). The origin of I–V hysteresis in the exposed LSCO–LCO bilayer SNWs is yet to be understood; we tentatively attribute it to the modification of the electron cooling rate caused by the introduced defects.

**Photoresponse measurements**

To perform the photoresponse measurements, we mounted our cuprate SNWs in a variable-temperature cryostat equipped with radiofrequency coax cables and an optical fibre. The latter was held approximately 1 cm away from the device so that a defocused continuous-wave laser beam covered the entire device area. The cooling power of our cryogenic set-up significantly exceeds the power of incident laser radiation, ensuring the thermal stability of our samples upon illumination. The simplified circuit diagrams, used for the photoresponse measurements, are shown in Fig. 3a,b. The LSCO–LCO device was measured in a conventional SPD configuration in which the SNW was biased through a d.c. input of the bias tee using an isolated voltage source connected in series with a resistor, Rsh. The a.c. output was connected to a low-noise amplifier, the output of which was fed to an oscilloscope or a photon counter (Fig. 3a). To mitigate latching effects in this superconducting photodetector, the SNW was connected in series with an on-chip kinetic inductor, Lsh, as well as made out of the superconducting LSCO–LCO bilayer. The BSCCO measurement configuration was somewhat similar, but in this case, we used a more conventional low-frequency reset loop formed by an inductor, Lsh, and a resistor, Rsh, connected in series with each other (Fig. 3b).
Figure 3c shows an example of the photovoltage generation, $V_{ph}$, measured across the current-biased LSCO–LCO SNWs when the device was exposed to laser beam radiation of wavelength $\lambda = 1.5 \, \mu m$. The $V_{ph}(t)$ traces of this SNW shared common features with the photoresponse of conventional SNSPDs. After photon absorption, $V_{ph}(t)$ spikes and quickly reaches its maximum value. This is followed by a much slower decay with the characteristic time $\tau$, often referred to as dead or recovery time, which depends on the total kinetic inductance, $L_s$, of the superconducting circuit\(^4\). The measured value, $\tau = 7 \, ns$ (determined as the time when the signal dropped to 30% of its maximum value) is in agreement with our measurements of the kinetic inductance in the LSCO–LCO bilayer films (Supplementary Information, section 5). The $V_{ph}$ spikes in the LSCO–LCO SNW device were observed below and above the liquid helium temperature and could be detected up to $T = 8 \, K$. At higher $T$, LSCO–LCO SNWs did not exhibit an $I$–$V$ hysteresis, and thus no voltage pulses were observed upon illuminating the SNW with low-intensity laser light (Supplementary Information, section 4).

As compared to LSCO–LCO, the $V_{ph}$ pulses in biased BSCCO SNWs were observed up to much higher $T = 25 \, K$ (Fig. 3d), above which the $I$–$V$ hysteresis disappeared (Supplementary Information, section 4). The spikes were characterized by a much faster recovery time $\tau = 0.8 \, ns$. We attribute this short $\tau$ to a smaller total kinetic inductance of the BSCCO photodetector (Supplementary Information, section 5). We have also tested the dependence of $V_{ph}$ on the photon energy and found that the LSCO–LCO and BSCCO SNWs yielded spikes at both $\lambda = 1.5 \, \mu m$ and $\lambda = 780 \, nm$ (Fig. 3e,f). Finally, we note that above the critical current our devices latch, and therefore do not feature voltage pulses on an oscilloscope and corresponding counts on a photon counter.

### Single-photon sensitivity of the cuprate photodetectors

To get further insight into the performance of our cuprate photodetectors, we recorded the photon count rate, PCR (the number of $V_{ph}$ pulses per unit time), as a function of the bias current, $I_{bias}$. Figure 4a shows the PCR normalized to its maximum value, measured in our BSCCO device in the dark and upon exposing it to the $\lambda = 1.5 \, \mu m$ laser light. In the dark, spontaneous voltage pulses emerge close to the critical current, a typical behaviour of SNSPDs. The absolute value of these dark counts did not exceed $10^3$ s$^{-1}$, comparable to the values in conventional NbN SNSPDs. Upon illumination, the counts appeared at much lower onset current $I_{bias} = 0.62I_c$, whereas the PCR showed some tendency to saturation upon approaching $I_c$. This saturation indicates high internal detector efficiency\(^5\). With increasing $T$ to 25 K, the onset current decreased together with $I_c$, as expected for conventional SNSPDs (Fig. 4c). Furthermore, we found that the PCR for a given $I_{bias}$ was almost independent of $\lambda$ and featured similar PCR($I_{bias}$) functional dependencies for $\lambda = 780 \, nm$ and $\lambda = 1.5 \, \mu m$ (Supplementary Information, section 5).
6). We observed zero PCR on devices made out of non-optimally doped BSCCO flakes; the latter exhibited only signatures of the bolometric photoresponse (Supplementary Information, section 6).

The PCR–I_bias characteristics obtained for the LSCO–LCO photodetector at λ = 1.5 μm were rather similar to those for BSCCO yet the counts emerged at much smaller I_bias due to a smaller critical current in this SNW (Fig. 4b,d). The onset current was about 0.75 μA for both T = 3.7 and 8 K. Notably, upon decreasing λ to 780 nm, the functional form of the PCR(I_bias) scaling changed drastically and featured a rather unusual dependence (Fig. 4d). First, the counts appeared at much lower I_bias = 20 μA. Then, the PCR exhibits a tendency to saturation on increasing I_bias to ~52 μA. Finally, above this value, the PCR started to ascend again, suggesting two distinct operation modes of the LSCO–LCO photodetector.

While the data support the hypothesis of single-photon detection in these two materials, a number of features of the data are different from the observations in SNSPDs in conventional superconductors. Specifically: (1) we observed unusual λ–I characteristics in hysteretic LSCO–LCO SNWs (Fig. 2d); (2) we observed at one temperature (16 K) a < 1 slope in the PCR(A) curve for BSSCO at high A; and (3) we observed unusual structure in the PCR(A) curves for the LSCO–LCO SNSPD. Given the early stage of development of materials processing used in this work, such anomalies are not unexpected. While our high-T, films are homogeneous, we expect non-uniformity in the patterning and processing, so different regions of the SNWs could be participating in the detection process at different T, λ and I_bias.

Next, in Supplementary Information, section 7, we provide estimates for the BSCCO detector efficiency, DE. To this end, we used experimentally determined absorption of thin BSCCO flakes deposited onto SiO2 substrate. We found that at 25 K, at which PCR is ~10^{-3} s^{-1} for the 10 dB attenuation, the DE is of the order of 1.5%. Note, these estimates and their approximations cannot be used because they take into account the absorption and the transmission of the SiO2 substrate. In the cases of the LSCO–LCO SNSPD, the detection process at different T, λ and I_bias.

Conclusions

In this work, we demonstrated single-photon detection in high-Tc cuprate SNWs at temperatures up to 25 K. Our results refute the long-standing opinion that large-gap superconductors have lower sensitivity to low-energy photons. Additionally, it is surprising that these materials, which are very different from past examples, also exhibit single-photon detection, suggesting that the detection mechanism may need to be reconsidered. Finally, our work opens prospects of further developments in the high-Tc quantum sensors and their integration into on-chip phononic quantum information circuits.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41565-023-01325-2.

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Methods

Fabrication of BSCCO photodetectors
To fabricate SNWs out of BSCCO we mechanically exfoliated bulk crystals and deposited cleaved flakes onto polydimethylsiloxane (PDMS) polymer stamps attached to the glass slide. To avoid the degradation of the flakes, the exfoliation was done in the inert atmosphere of the argon-filled glovebox. The flakes were then transferred onto prepatterned Si/SiO₂ substrates with ultra-flat titanium/gold contacts and covered by relatively thick (~50 nm) slabs of hBN.

The fabrication of ultra-flat contacts comprised several steps and relied on a lift-off-free procedure. First, thin layers of titanium (3 nm) and gold (25 nm) were evaporated onto the Si/SiO₂ wafer. Next, negative e-beam lithography was used to define a mask for selective removal of the metal outside the designated contact areas. This removal was done by a combination of argon and oxygen etching. Resist residues were further removed by immersing the substrates into N-methyl-pyrrolidone (NMP) solution and subsequent aggressive stripping using extensive oxygen plasma cleaning. We intentionally increased the typical dwell time of the plasma cleaning to reduce the thickness of the gold layer to 20 nm.

To define superconducting SNWs out of prepared partially encapsulated BSCCO devices by He+ ion beam, we first ran the simulation of the ion collision damage using SRIM software (Supplementary Information, section 1). This allowed us to estimate the characteristic doses needed to introduce a significant number of defects into the BSCCO crystal lattice and suppress superconductivity. Next, starting from the obtained values, we performed dose tests using a Zeiss Orion microscope equipped with a Raith pattern generator. The irradiation was realized through sweeping of the beam across the SNW area. The exposed area is a rectangle with approximate dimensions of 5 × 3 μm² (to cover the whole meander area). The beam spot is ~2 nm. The dose varied in the range from 10¹⁵ to 10²⁰ ions per cm² (Supplementary Information, section 1). This allowed us to estimate the characteristic doses needed to introduce a significant number of defects into the BSCCO crystal lattice and suppress superconductivity.

Data availability
The data reported in Figs. 2–4 can be found on Zenodo (https://doi.org/10.5281/zenodo.7501827). The other data that support the findings of this study are available from the corresponding authors upon reasonable request.

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Author contributions
D.A.B. and I.C. conceived and designed the project. I.C. and D.A.B. performed transport measurements. I.C. performed the photoresponse measurements. D.A.B., I.C. and I.Y.P. fabricated the devices. B.A.B., M.C. and I.C. designed the readout circuit. O.M. simulated the readout circuit. I.C. and D.A.B. analysed the experimental data with help from I.B., P.J.-H. and K.K.B. I.D. provided BSCCO crystals. X.H., A.T.B. and I.B. synthesized and characterized the LSCO–LCO bilayer films. T.T. and K.W. provided high-quality hBN crystals. I.C. and D.A.B. wrote the manuscript with input from all coauthors. P.J.-H., I.B. and K.K.B. supervised the project. All authors contributed to discussions.

Competing interests
The authors declare no competing interests.

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