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2D materials

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Superconducting single-photon detectors get hot

Jin Chang & Iman Esmaeil Zadeh

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High-T_c superconducting nanowire detectors can detect single photons of telecom wavelengths at a temperature of 25 K and may enable applications in quantum sensing and quantum information processing.

From the foundation of modern physics to the recent wave of quantum technologies, single photons and the techniques to detect them have played a decisive role in many scientific breakthroughs. Only last year, the Nobel prize in Physics was awarded for the demonstration of entanglement, which relied critically on single-photon detection. Among established single-photon detector technologies, superconducting nanowire single-photon detectors (SNSPDs) are distinct for their combination of near unity efficiency, their remarkable high time resolution – down to a few picoseconds – as well as their extended wavelength range of single-photon detection (from X-ray to mid-infrared)[1]. SNSPDs have already become the detector of choice in fields such as quantum photonic computation and quantum communication. However, due to their low operation condition (below liquid helium temperature, 4.2 K), their widespread utilization in other scientific domains, such as biology and astronomy, has yet to be established. Charaev et al.[2] and Merino et al.[3] now independently demonstrate single-photon detection with SNSPDs based on high-T_c superconductors, operating at temperatures above the liquid helium temperature limit.

In past years, research on SNSPDs has seen remarkable progress along two paths; a) performance optimization has transformed SNSPDs into suitable instruments for a diverse set of applications ranging from quantum communication to neuroimaging and space exploration; b) several experiments have enhanced our understanding of the physical mechanisms behind the single-photon detection[4]. As for the latter, despite significant progress in the field, the exact detection mechanism still remains elusive. Importantly, while SNSPDs have excelled in many performance metrics, pushing their limits even further, e.g., improving the sensitivity to low energy photons, or increasing the operating temperature, may require deeper insights into the detection mechanism. Elevating the working temperature of SNSPDs has been a major research endeavour for more than a decade. Remarkable efforts have gone into implementing SNSPDs on high-T_c superconducting platforms[5], but with little success. Higher operation temperature SNSPDs are of prime interest because cryocoolers with base temperatures above 20 K are much simpler than those that are currently operating state-of-the-art SNSPDs. Their compact and inexpensive nature can significantly enhance the latitude of SNSPDs applications. Additionally, thanks to the exponential dependence of cooling capacity on the base temperature, higher-temperature SNSPDs may allow for scaling up sensor arrays and their corresponding readout electronics, potentially leading to a fast and efficient SNSPD-based camera technology.

The two independent groups have now demonstrated single telecom photon detection (wavelength 1550 nm) with SNSPDs, made from $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) flakes, at temperatures as high as 20 K (ref. [3]) and 25 K (ref. [2]). To achieve the best performance, the researchers overcome the immense challenges in processing high-T_c superconducting flakes, prone to degradation in the ambient environment, by utilizing helium ions for pattering BSCCO without damaging the encapsulating hBN protection layers. The researchers in both works draw a path with helium ions on the hBN-encapsulated BSCCO flake as shown in Fig. 1. This leaves the exposed section non-superconducting and hence false patterns of the active nanowire structure. Both reports show single-photon sensitivity at 1550 nm. Merino et al.[3] produced a micro-bridge on BSCCO. Instead, Charaev et al.[2] fabricated a nanowire

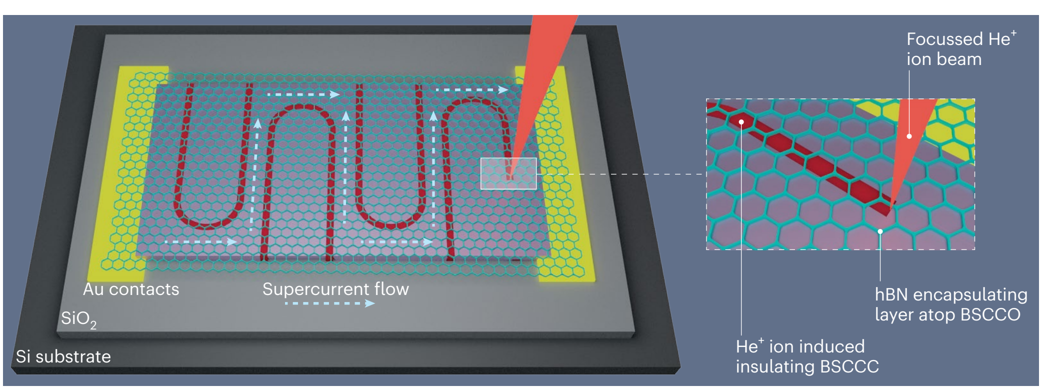

Fig. 1 | Illustration of the Bi2Sr2CaCu2O8+δ (BSCCO) nanowire fabrication process from[2]. The transferred BSCCO flake (pale purple) was first encapsulated by a few hBN layers (cyan) on top to prevent degradation. Then a focused helium ion beam (light red) was used to expose the area between the nanowires (dark red) to change them from superconducting to insulating. As a result, the current is forced to flow through the unexposed nanowires.

meander-like device, demonstrating a more prominent saturation of the internal efficiency. Additionally, they show $La_{1.55}Sr_{0.45}CuO_4/La_2CuO_4$ (LSCO–LCO) heterostructure, grown by atomic layer-by-layer molecular beam epitaxy, and demonstrate high-T_c interface superconductivity and single-photon sensitivity at 8 K (ref. [2]). LSCO–LCO is stable in air, and therefore, conventional lithography and Ar^+ milling can be used to pattern the nanowire structure. The scalable deposition method, as well as compatibility with conventional nanofabrication, promises an easier route to commercialization.

These two reports show how future SNSPDs may operate at much higher temperatures, thereby removing a major obstacle keeping SNSPDs from being utilized within a wider range of disciplines. They may also help a better understanding of the underlying detection mechanism in both conventional and high-T_c superconductors. The latter hope is two-fold: firstly, thanks to the pristine crystal structure of 2D materials, these platforms can assist scientists in experimentally verifying their detection models without the practical complexity of conventional polycrystalline (e.g., NbN or NbTiN) films; and second, the interaction of light with BSCCO, being a d-wave superconductor, is an interesting topic on its own. The understanding gained for this material can directly apply to a larger family of high-T_c superconductors.

Commercially, SNSPDs have been very successful[1,6]. Yet, for the practical use of 2D SNSPDs, several questions remain: What is the typical time resolution (time jitter) and efficiency recovery time of these detectors? Can these detectors provide single-photon detection at temperatures even higher than 25 K, at least for more energetic photons? A crucial step for the future commercialization of the reported technology is the integration of these detectors in optical cavities to enhance light absorption and hence their system detection efficiency.

Following these pioneering works, technical improvements of high-T_c nanowire detectors can be expected in the near future. The integration of such detectors with optical cavities can increase the system detection efficiency (SDE). High SDE, together with 25 K operation temperature, would enable new quantum optics applications for which conventional SNSPD systems are not suitable. Combining the high-T_c superconductor flakes with other 2D functional materials or on-chip optics components, such as quantum emitters or waveguides, would further benefit integrated photonics experiments and applications. Furthermore, the optimization of the material and its processing – such as large-area flake transfer – may further improve the SNSPD metrics.

As for the more fundamental physics aspect, the photon detection mechanism of BSCCO and LSCO–LCO devices remains unclear to date. A detailed characterization of the single-photon detection including timing performance tests (timing jitter, high count-rate test) may help the mechanistic understanding. Thus, we expect the reported discoveries to trigger new lines of research into the interaction of light with high-T_c superconductors, which offer a testbed for verifying single-photon detection models.

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Competing interests

I.E.Z. is a research scientist at Single Quantum B.V., Delft, the Netherlands. J.C. declares no competing interests.