# Ultra-thin $YBa_2Cu_3O_{7-x}$ films: towards high-$T_c$ superconducting single-photon detector

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Single-photon detectors are used in an expanding range of topics, such as metrology, quantum information processing, medical physics, sensing, photonics, biotechnology, information security and other applications, where the sensitivity to the lowest light levels is required or where the quantum nature of light is the key factor [1].

Invented in 2001 a superconducting nanowire single-photon detector (SNSPD) due to the excellent detector characteristics and integration flexibility offers outstanding possibilities for the development of high performing systems, where the 100% detection efficiency and high detection speed are required [2]. Operating at T = 4.2K the SNSPD is superior in terms of the long wavelength sensitivity, signal-to-noise ratio and the detection efficiency compared to the room-temperature single-photon detectors, such as avalanche photodiodes [3] or photomultipliers. The SNSPD is an order of magnitude faster than other superconducting single-photon detectors, such as superconducting tunnel junctions [4], transition edge sensors [5] or kinetic inductance detectors [6], which require sub-Kelvin cooling. At the present time, SNSPDs are used not only as a discrete component, but as a part of complex nanophotonic integrated circuits.

Despite impressive progress in SNSPD development, the main obstacle for the widespread use of SNSPDs is the low operating temperature required for low-temperature superconductors, such as NbN, NbTiN or WSi, which are used for SNSPD fabrication. A further increase in the operating temperature of SNSPDs is, in principle, possible with ultra-thin (few unit cell thick) films from high-temperature (high-$T_c$) superconductors. The ultra-thin high-$T_c$ superconductors together with “invisible” cooling by compact cryogen-free and maintenance-free coolers could bring the SNSPDs and SNSPD based devices from labs into industry scale, where they could be used in emerging application like the quantum key distribution or the free-space optical communication between satellites.

Recently we have fabricated ultra-thin (down to 1 unit cell thick superconducting layer) $YBa_2Cu_3O_{7-x}$ films with flat (± 1 unit cell) surface and very high critical current density up to 14 MA/cm$^2$ at T = 78 K and 125 MA/cm$^2$ at T = 8 K [7,8]. The first sub-100 nm wide nanobridges fabricated from ultra-thin $YBa_2Cu_3O_{7-x}$ films by the FIB etching demonstrated a sharp superconducting-to-normal transition and small hysteresis, which are required for the single-photon detection, starting from 15 K [8]. At these temperatures the penetration of a single vortex into the bridge is enough to trigger the superconducting-to-normal transition. The dependence of the critical current density on the dimension of the bridge was consistent with the edge barrier model [8]. An advanced nanopatterning technology is required for the further reduction of the bridge width and sharper edges. These measures could increase the height of the edge barrier and shift the temperature range of the zero-voltage superconducting-to-normal transition to higher temperatures, which can be reached with compact cryogen-free coolers. Two designs of high-$T_c$ SNSPD based on $YBa_2Cu_3O_{7-x}$ films with vertical and tilted c-axis are proposed. The SNSPD based on $YBa_2Cu_3O_{7-x}$ film with tilted c-axis could have better sensitivity at longer wavelengths due to an anisotropic hot spot expansion. We think that such ultra-thin $YBa_2Cu_3O_{7-x}$ films could be very promising for high-$T_c$ SNSPD fabrication.

An extensive experience of cooling $YBa_2Cu_3O_{7-x}$ devices with Stirling cryocoolers obtained by authors in the project HRJRG-207 “Liquid identification by Hilbert Spectroscopy for security screening”, supported by program “Helmholtz Russia Joint Research Group”, will be used to integrate high-$T_c$ SNSPD with compact cryogen-free coolers.

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