Towards high-T_c superconducting qubit with THz plasma frequency

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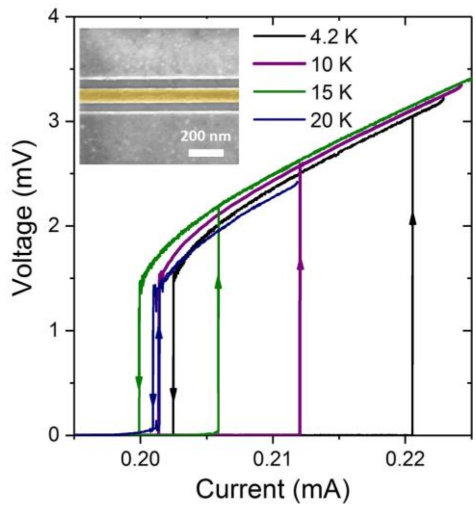

Figure 1 Current-voltage characteristics of the phase-slip YBCO nanowire in the 4.2 – 20 K temperature range. Inset shows a top-view micrograph of the nanowire shaped by two cuts. Nanowire is highlighted in orange.

Nowadays, superconducting quantum circuits are mainly based on the tunnel junctions fabricated from low-temperature (low-T_c) superconductors [1]. The superconducting tunnel junctions can be considered as LC oscillators in which the Josephson effect provides the nonlinearity required for selective access to quantum levels. Quantum processors consisting of hundreds of qubits have already been demonstrated. However, the quality factor of low-temperature superconducting qubits is limited to a few million and a little progress has been made in recent years. It is therefore important to explore new platforms for the superconducting qubits where higher quality factors can be achieved.

Despite having large energy gaps, the cuprate high-temperature (high-T_c) superconductors were out of the quantum scene because of the d-wave symmetry of the order parameter where the energy gap vanishes in nodal directions [2]. However, there are numerous evidences that the d-wave symmetry of the order parameter can be broken in nanoscale devices made of cuprate superconductors. We systematically studied the order parameter symmetry in the ultra-thin $YBa_2Cu_3O_{7-x}$ (YBCO) films using Andreev reflection spectroscopy and found that it is possible to achieve a fully-gaped state with an exponentially low number of quasiparticles at low temperatures [3]. The nanoscale YBCO film can be considered as a quantum-engineered superconductor where the superconducting gap is controlled by quantum size effects. These fully-gapped films can be used for the quantum applications including quantum computing. To prove this idea, we fabricated the ultra-thin YBCO nanowires which demonstrated an abrupt switching from the superconducting to normal state due to the phase slippage and a current hysteresis as shown in Figure 1 [4]. The behaviour of the phase-slip YBCO is very similar to that of the underdamped Josephson junction. The plasma frequency of the phase-slip YBCO nanowires is in the THz frequency range resulting in the crossover between the thermal-activated and quantum regimes at 12-13 K [5]. The switching current distribution of the nanowires shows the distinct peaks which is a manifestation of the quantized energy levels. We found that the life time of the excited state in YBCO nanowires probed with incoherent broadband THz radiation from the thermal radiation source exceeds 20 msec at a temperature of 5.4 K providing the quality factor of order of 10^{10} which is 3-4 orders of magnitude higher than that in the low-T_c Josephson junctions. The absorption of a single optical photon results in the switching of the nanowire from the excited to the ground energy level which is an independent evidence of low number of unpaired quasiparticles in the nanoscale YBCO devices.

Our findings show that nanoscale high-T_c superconducting films and devices made from these films are promising platforms for quantum applications that in the future might outperform the conventional superconducting qubits and superconducting single-photon detectors fabricated from low-T_c superconductors.

[1] M. H. Devoret & R. J. Schoelkopf, "Superconducting Circuits for Quantum Information: An Outlook", *Science*, vol. 339, pp. 1169-1174, 2013.
[2] C.C. Tsuei & J.R. Kirtley, "Pairing symmetry in cuprate superconductors", *Rev. Mod. Phys.*, *vol.* 72, pp. 969-1016, 2000.
[3] M. Lyatti, I. Gundareva, T. Röper, Z. Popovic, D. Grützmacher, T. Schäpers, "Quantum size effects in ultra-thin $YBa_2Cu_3O_{7-x}$ films", arXiv:2304.03591, 2023.
[4] M. Lyatti, M. A. Wolff, A. Savenko, M. Kruth, S. Ferrari, U. Poppe, W. Pernice, R. E. Dunin-Borkowski, and C. Schuck, "Experimental evidence for hotspot and phase-slip mechanisms of voltage switching in ultra-thin $YBa_2Cu_3O_{7-x}$ nanowires", *Phys. Rev. B*, vol. 98, 054505, 2018.
[5] M. Lyatti, M. A. Wolff, I. Gundareva, M. Kruth, S. Ferrari, R. E. Dunin-Borkowski, C. Schuck, "Energy-level quantization and single-photon control of phase slips in $YBa_2Cu_3O_{7-x}$ nanowires. *Nat Commun.*, vol. 11, 763, 2020.

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