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Nonequilibrium state in quasi-one-dimensional superconducting channels (Mini-review)

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Superconducting properties of metallic micro- and nanowires can be entirely different from those of bulk superconductors. Of particular interest is the nonequilibrium current-induced state of a quasi-one-dimensional superconducting channel. The most interesting phenomenon here is the stepped $I-V$ characteristic, explained by a process known as phase slip center activation. If the origin of such step-like $I-V$ dependencies is at least qualitatively well understood, a commonly accepted explanation for the step-like $R(T)$ characteristics is still missing. We review theoretical and experimental activities in the field and demonstrate dramatic progress in understanding of the phenomenon of quasi-one-dimensional superconductivity.

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Zero resistance is considered as one of the essential attributes of superconductivity: if, at a temperature T below the superconducting transition point T_c, the measured current I does not exceed the critical value I_c, then the voltage drop $V = 0$. It has been discovered that in macroscopic samples, the destruction of the superconducting state by a current $I \geq I_c$ occurs due to an abrupt transition to the normal state. The process is described by a model of avalanche-like propagation of a "hot" domain of the normal phase, originating at the sample surface in a thin current-carrying layer of the order of the magnetic field penetration depth $\lambda_L(T)$. The aforementioned model of superconductivity current destruction is not valid for quasi-one-dimensional (1D) systems with a characteristic diameter $d_{\text{eff}} \approx \sqrt{\sigma} \leq \min\{\lambda_L(T), \xi(T)\}$, where σ is the cross-sectional area of the wire and $\xi(T)$ is the temperature dependent superconducting coherence length. If the case, there is only one channel for supercurrent to flow, and, accordingly, the superconducting and normal phases cannot coexist "across" the sample. To describe the phenomenon of a dissipative state of a 1D superconductor the concept of a phase slip (PS), being a topological singularity of the order parameter, has been introduced [1].

The PS term is often referred to two different processes: stochastic and deterministic. At sufficiently small bias currents $I \ll I_c$ experimentally observed broadened $R(T)$ dependencies of a 1D superconductor are due to stochastic PS events mediated by thermal or quantum fluctuations of the order parameter [2]. Contrary to stochastic fluctuation-driven PS events, the current-induced nonequilibrium state of a 1D superconductor (Fig. 1, left panel) originates from deterministic process: formation of, so-called phase slip centers (PSC), which are localized in space and their activation is strictly periodic in time.

The regular step-like pattern (Fig. 1, left panel) suggests that the entire $I-V$ characteristic is determined by a series of identical physical processes: PSC activation. The non-zero excess current, $I(V = 0) > 0$ (Fig. 1, left panel), excludes a trivial explanation based on formation of normal domain(s) across the sample and mandatory requires consideration of superconducting phase impact: the finite supercurrent. Experiments with quasi single crystalline superconducting filaments with length $L \gg \xi(T)$ revealed the long-range interaction of PSCs [4]. The effect can be associated with propagation of electromagnetic waves generated by repeating PS events [5].

The step-like $I-V$ dependencies, similar to Fig. 1, left panel, have received much attention and have been observed in various quasi-1D superconducting systems [6]. The origin of the effect is, at least qualitatively, understood. Though, to our best knowledge, a comprehensive microscopic model has not been developed yet.

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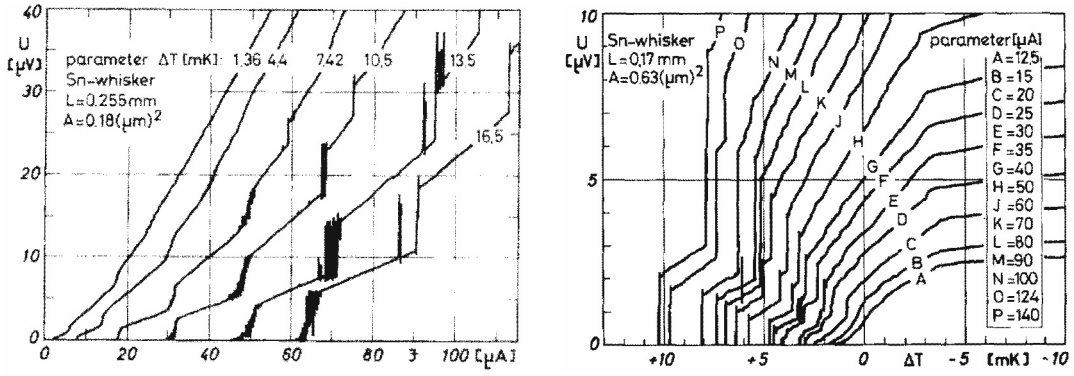

Fig. 1. Left panel: $V-I$ characteristics of a tin whisker with length L and cross section A at various temperatures below the critical. Right panel: temperature dependencies of the voltage drop across the same sample at various fixed bias currents, indicated close to the curves. Adapted from J. D. Meyer et al. [3] https://doi.org/10.1016/0375-9601(72)90802-X. By courtesy of Elsevier

Contrary to $I-V$ characteristics, the physics leading to step-like $R(T)$ dependencies (Fig. 1, right panel) is not clear. The quantized resistive $R(T)$ steps, observed in short superconducting samples with length $L \sim \xi(T)$ [7], are still missing any commonly accepted explanation.

In conclusion, one can state that physics of quasi-one-dimensional superconductors reveals many intriguing issues. Eventually further experimental and theoretical studies are required to clear certain "white spots" in the field.

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Conflict of interest. The authors of this work declare that they have no conflicts of interest.

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