# Quantum tunneling phenomena in ultra-thin superconducting wires

M.Zgirski, K.-P.Riikonen, T. Holmqvist, M. Savolainen, V. Touboltsev and K. Arutyunov

*University of Jyväskylä, Nanoscience Centre, Department of Physics, PB 35, 40014, Jyväskylä, Finland*

A superconducting wire can be considered as quasi-one dimensional (1D) if its characteristic transverse dimension $\sqrt{\sigma}$ ($\sigma$ being the cross section) is smaller than the coherence length $\xi(T)$. The shape of the bottom part of the resistive transition $R(T)$ of a 1D superconducting strip is described by the model of phase slips activation. If the wire is infinitely long, then there is always a finite probability that a 'small' part of the sample is instantly driven normal: locally the modulus of the order parameter $|\Delta|$ goes to zero and its phase $\varphi$ 'slips' by $2\pi$.

Free energy of a current-carrying 1D superconductor is described by so called 'tilted washboard' potential (Fig.1). The black circle denotes a thermodynamically metastable state of a macroscopically coherent superconductor. The system can relax to a state of lower energy. There are two possible ways for a superconductor to decrease its energy. First, due to thermal excitation it can 'jump' over the energy barrier $\Delta F$ to a new potential minimum [1]: solid arrow in Fig. 1. Second, the system can tunnel through the energy barrier [2]: dotted arrow in Fig. 1. In the limit of infinitely small supercurrent the height of the barrier $\Delta F$ is the energy difference between normal and superconducting states of a system of the smallest possible size $\Omega = \xi \cdot \sigma$: $\Delta F = B_c^2 \cdot \Omega$, $B_c$ being the critical magnetic field. Corresponding decrease of energy is accompanied by the change in phase by $2\pi$ (Fig. 1). It can be shown [1], that in case of thermally activated phase slips the effective resistance $R(T) \sim \exp(-\Delta F / k_B T)$. For a not too long wire $L \geq \xi(T)$ (only single phase slip event can happen at a time) with normal state resistance $R_N$ the quantum tunneling contribution is [2]: $R(T) / R_N = (\xi / L) \cdot (\tau_0 \cdot \Gamma_{QPS})$, where $\tau_0 \sim h / \Delta$ is the duration of a phase slippage, and $\Gamma_{QPS} = B \exp(-S_{QPS})$ is the rate of quantum phase slip events, where $B \approx (S_{QPS} / \tau_0) \cdot (L / \xi)$, $S_{QPS} = A \cdot (R_Q / R_N) \cdot (L / \xi)$, $A \sim 1$, $R_Q = h / 4e^2 = 6.47\ k\Omega$.

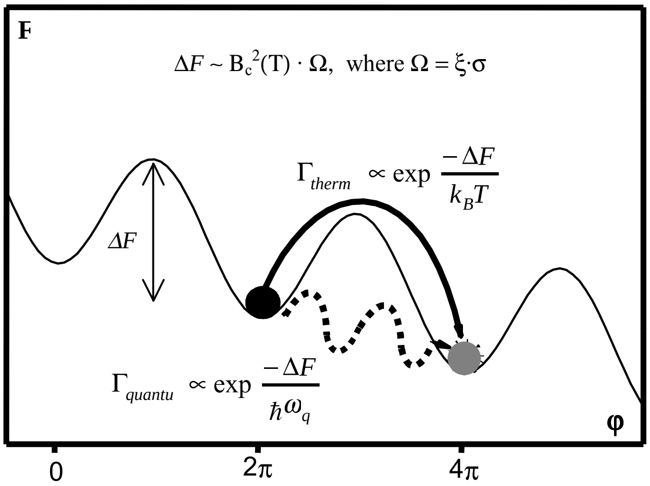

Fig. 1. Dependence of the free energy F vs. superconducting phase φ of a 1D current-carrying superconductor. The system (represented by a circle) can change its quantum state in two ways: by thermally activated phase slips (solid arrow), or by quantum tunneling (dotted arrow). Γ stands for the rates of the corresponding processes.

Several experimental attempts have been made to detect the QPS mechanism in narrow superconducting channels: ultra-thin In and Pb-In wires [3] and Mo-Ge film evaporated on top of a carbon nanotube [4]. The results are very intriguing, but the matter is far from being settled. The motivation of this work was to study the manifestation of the QPS mechanism in the *same* superconducting wire as a function of its cross section.

We have developed a method of progressive reduction of transverse dimensions of e-beam lift-off fabricated nanostructures by ion-beam sputtering [5]. The method enables galvanomagnetic measurements of the same sample in between the sessions of etching. Sputtering can be considered as an erosion of the surface due to bombardment of primary ions. The method is very promising, for it lets us directly follow changes in superconductive transition in a 1D superconductor along with successive reduction of its cross section. AFM control revealed that sputtering makes the sample surface smoother and more homogenous, eliminating inevitable imperfections while original lift-off process. For not too narrow Al wires the shape of R(T) transition can be perfectly fitted by the thermal activation model [1]. While for the wires that after few sputtering sessions have reached the effective diameter $\sqrt{\sigma} < 35$ nm a low temperature 'foot' develops, which can be associated with the QPS phenomena (Fig. 2).

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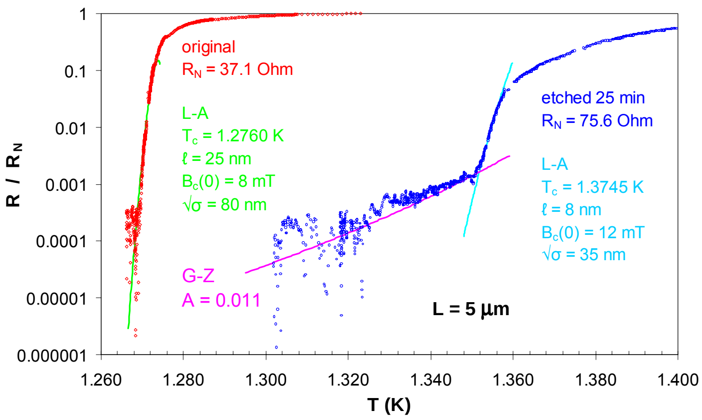

Fig. 2. Resistive transition R(T) of a 5 µm long *same* Al wire before sputtering (left curve) and after (right). High-temperature part of the transition can be described by the thermal PS activation mechanism (solid lines), while for the thinner wire the bottom 'foot' can be fitted by the QPS model.

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