Heat hunting in a freezer

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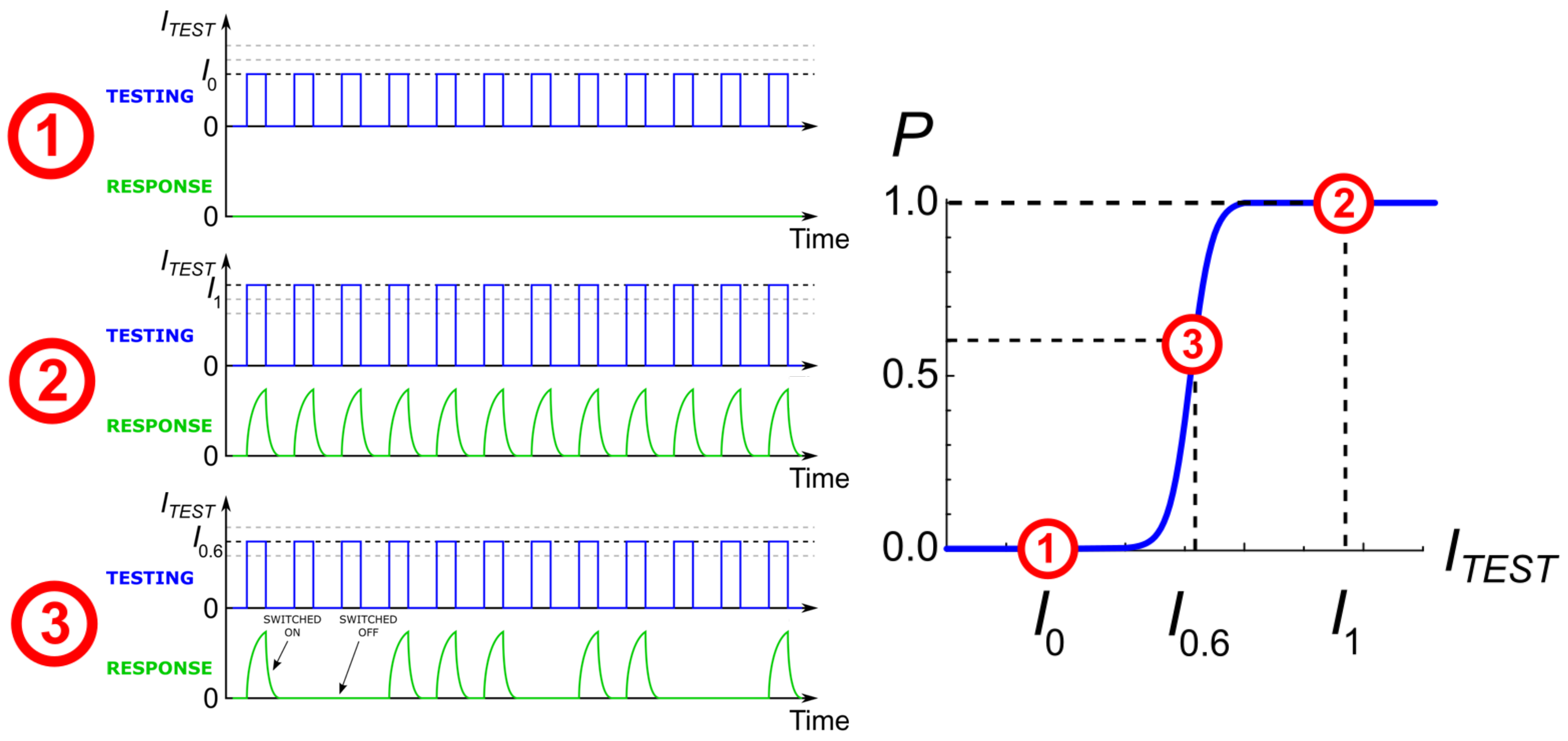
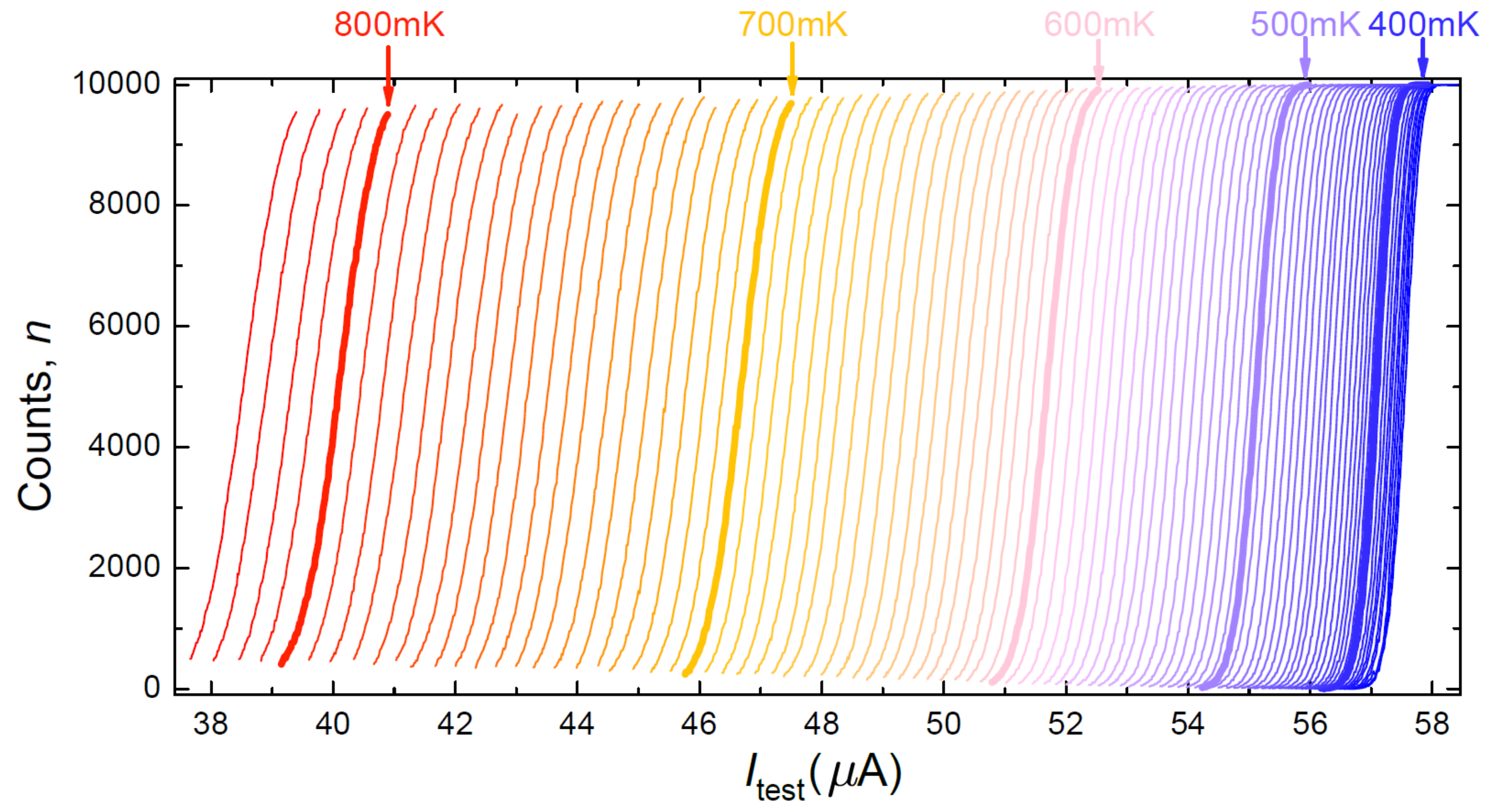
INTRODUCTION

Propagation and relaxation of nonequilibrium quasiparticles in superconductors are of key importance for functioning of numerous nanoscale devices, enabling operation of some of them, and limiting the performance of the others. The quasiparticles heated above lattice temperature may relax locally via phonon or photon emission channels, or diffuse over appreciable distances in a nanostructure altering the functionality of their remote components. Tracing quasiparticles experimentally in real-time domain has remained the challenging task owing to their rapid dynamics. With electronic nanothermometry, based on probing of the temperature-dependent switching current of a superconducting nanobridge, we monitor heat pulse carried by a flux of nonequilibrium quasiparticles as it passes by our detector with a noise-equivalent temperature of 10 mK/$N^{0.5}$, where N is the number of pulses probing the bridge (typically N = 10 000), and temporal resolution of a single nanosecond. The measurement provides the picture of quasiparticle diffusion in a superconducting aluminum strip and direct determination of the diffusion constant D equal to 100 cm^2/s with no energy dependence visible.

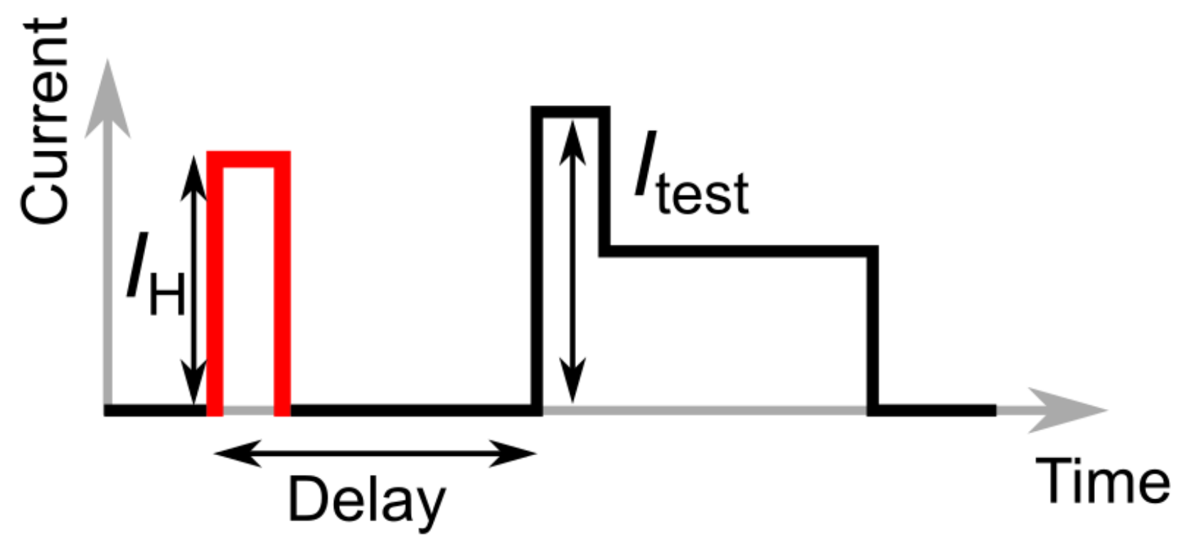
JOSEPHSON JUNCTION AS A TEMPERATURE-SENSITIVE SWITCH



Josephson junctions (JJs) are sometimes referred to as switches for their ability to carry supercurrent (case 1) only to a certain level and, above this level, they switch to a finite voltage state (case 2). A rectangular current pulse is applied to the junction and the response of the junction is measured: it switches or remains in the superconducting state (case 3). Sending a pulse train allows to determine the switching probability P corresponding to a given pulse amplitude [1]. Repeating the same experiment for different current amplitudes gives what is called S curve: current amplitude dependence of the switching probability $P(I_{TEST})$.



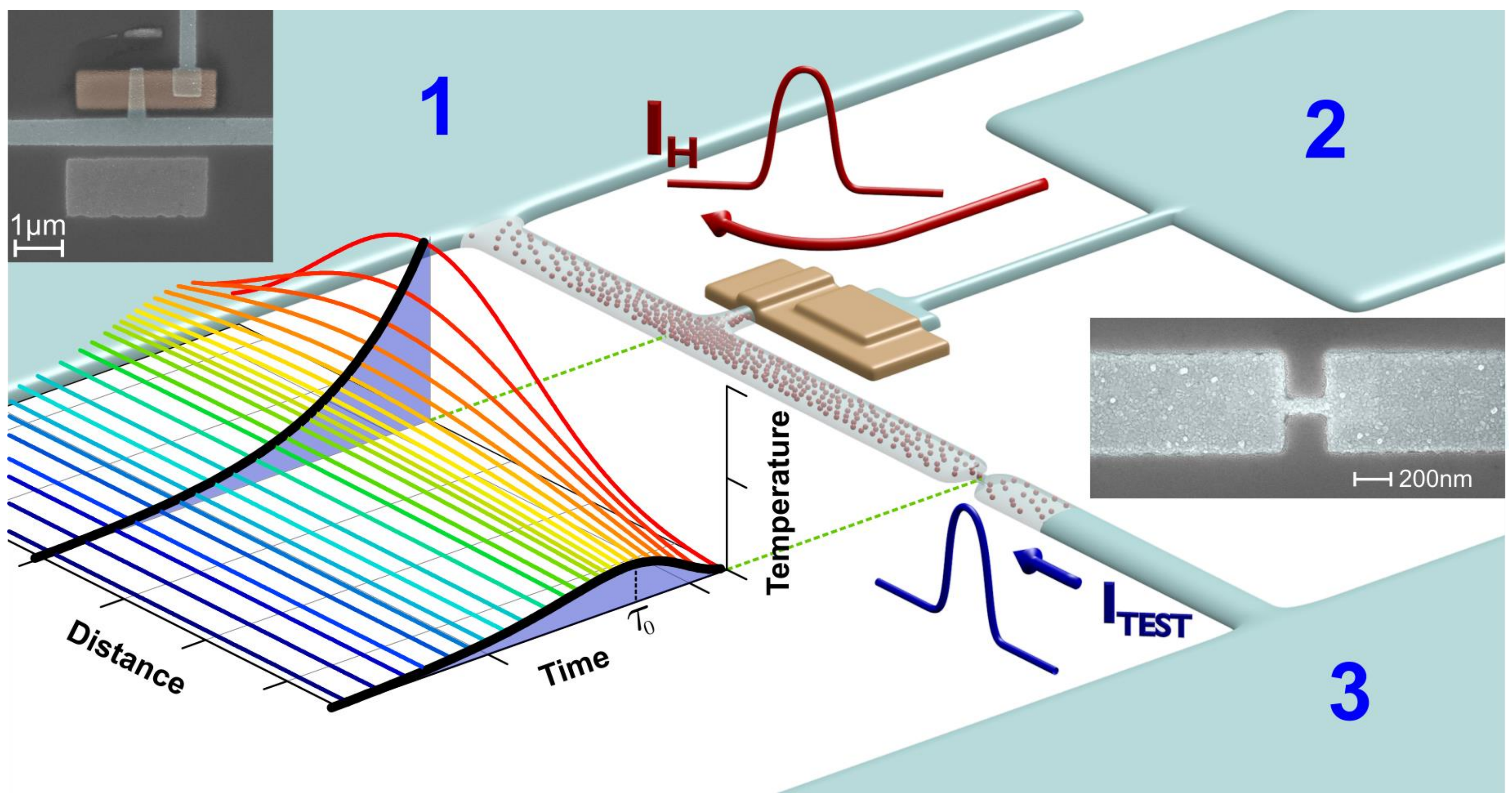
The switching process is both current and temperature dependent. The collection of S curves measured for wide range of temperatures serves as the calibration curve.



Typical measurement consists of application of the heating pulse (red rectangle), which brings the system to non-equilibrium state, followed by the testing pulse (black), which allows to read the state of the sensor[2,3]. We repeat this sequence N times to measure switching probability corresponding to the given delay between the two pulses.

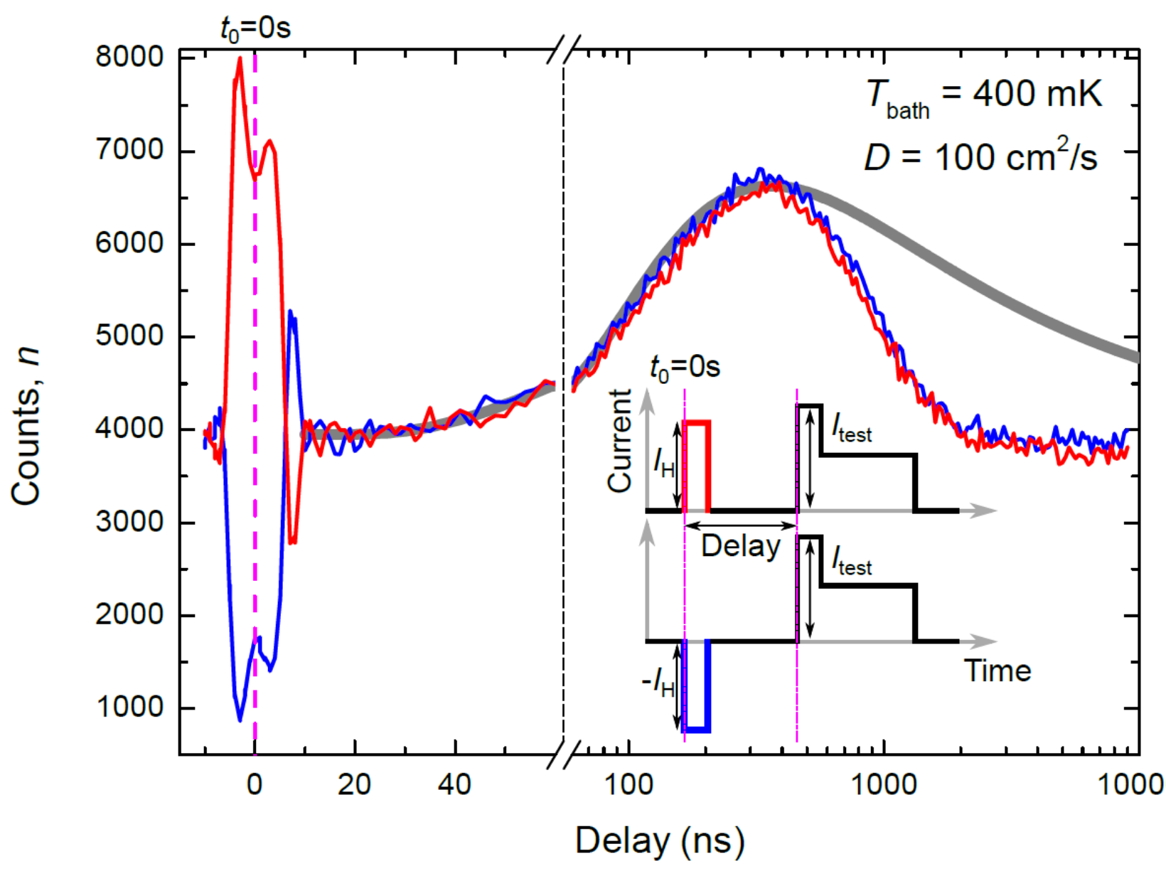
References:
[1] M. Foltyn, M. Zgirski, *Phys. Rev. Applied* **4**, 024002 (2015)
[2] M. Zgirski, M. Foltyn, A. Savin, K. Norowski, M. Meschke, J. Pekola, *Phys. Rev. Applied* **10**, 044068 (2018)
[3] M. Zgirski, M. Foltyn, A. Savin, K. Norowski, *Phys. Rev. Applied* **11**, 054070 (2019)
[4] M. Zgirski, M. Foltyn, A. Savin, A. Naumov, K. Norowski, *Phys. Rev. Applied* **14**, 044024 (2020)

„HOT" EXPERIMENT

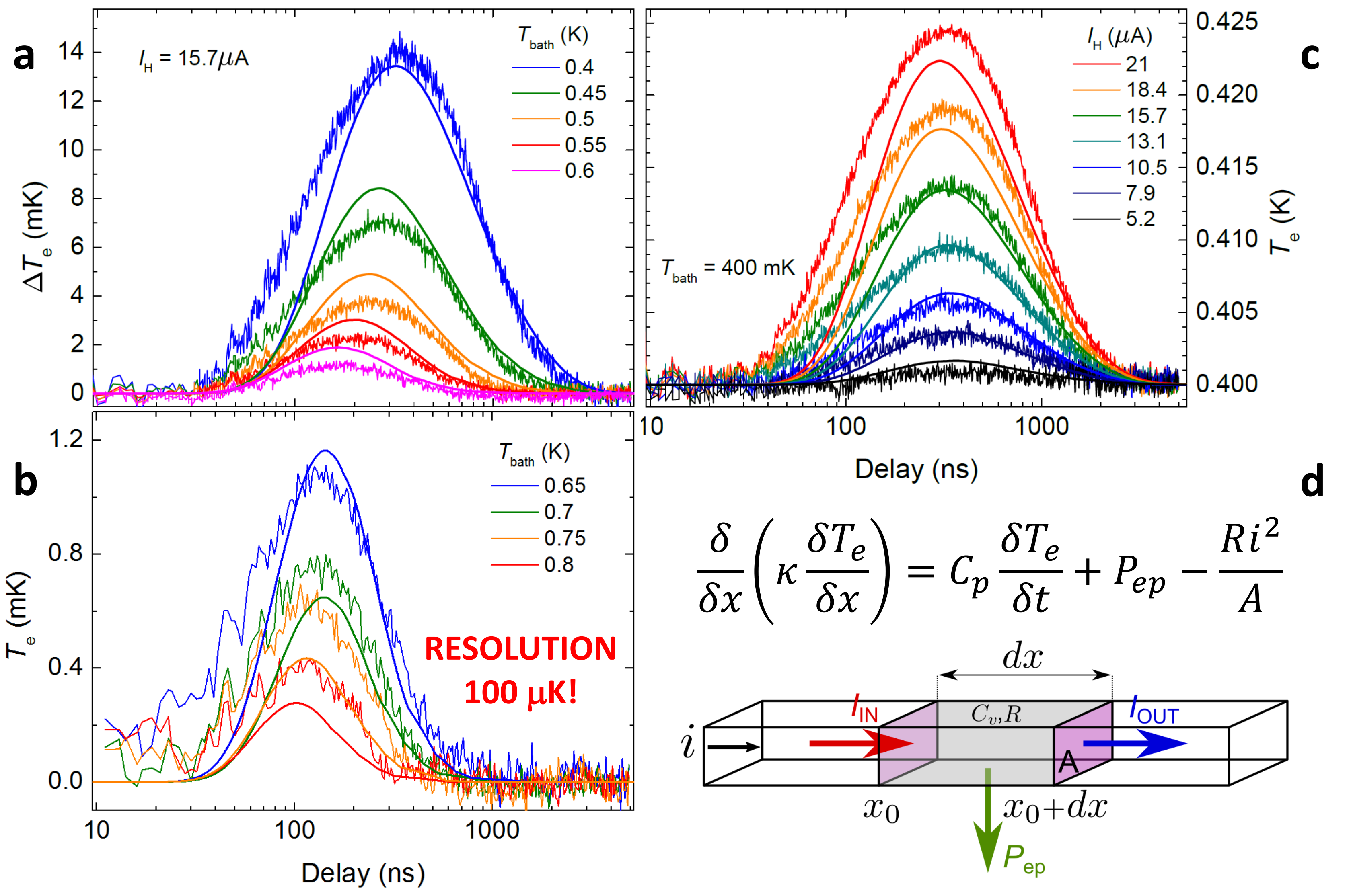


Real-time observation of hot electron diffusion. Hot electrons are created in the copper heater by applying short current pulse I_H. They start diffusing towards the bridge (thermometer). Qualitatively, their population at the bridge location is derived from the time-evolving Gaussian profile. For granular wire with l_{MEAN}=30nm and V_f=2*10^{6}m/s, the diffusion constant, governing the spreading of electrons in a one particular direction (i.e. along the length of the wire) is equal to D=1/3*V_f*l_{MEAN}=0.02m^2/sec. If we place a thermometer X_T=60µm away from the heater, the Einstein-Smoluchowski law predicts that hot electrons arrive to the thermometer after time τ_0=180ns. The simple picture of the diffusion process corresponds to the evolution of the Gaussian profile with variance equal to $D*\tau$.

QUASIPARTICLE DIFFUSION MEASUREMENT



Switching probability as a function of delay between heating (red or blue, I_H applied between ports 1 and 2) and testing pulse (black, I_{TEST} applied between ports 1 and 3). The hot-electron signal peaks up approximately 300 ns after application of nominally 10-ns-long heating pulse, which qualitatively agrees with diffusion time across 60-µm-long nanowire (thick grey line – Gaussian model) [4].



$$\frac{\delta}{\delta x}\left(\kappa\frac{\delta T_e}{\delta x}\right) = C_p\frac{\delta T_e}{\delta t} + P_{ep} - \frac{Ri^2}{A}$$

Temperature dynamics of the superconducting nanobridge after creating nonequilibrium QPs in the copper heater placed 60-µm away with a short heating pulse. Electron temperature T_e measured for the same heating pulse at various bath temperatures: 0.4–0.6 K and 0.65–0.8 K is presented in (a) and (b), respectively. Noteworthy, the hot-electron signal for T_0 = 800 mK shows only 400−µK peak with accuracy better than 100 µK. Figure (c) shows hot-electron signal measured at constant temperature for various heating pulses. Solid lines are calculated numerically for the 1D heat-flow model (d). The onset of the quasiparticles is well described by the free-particle diffusion model, which nevertheless fails to explain the observed signal at longer delays. To understand the overall shape of the experimental diffusion profile we elaborate a more detailed thermal model describing evolution of temperature in the wire (equation in d). The model incorporates the Joule heating, electron-phonon coupling P_{ep} , thermal conductivity κ and heat capacity C_p.

European Funds
Smart Growth

FNP Foundation for Polish Science

European Union
European Regional Development Fund