The fastest thermometer in the nanoworld

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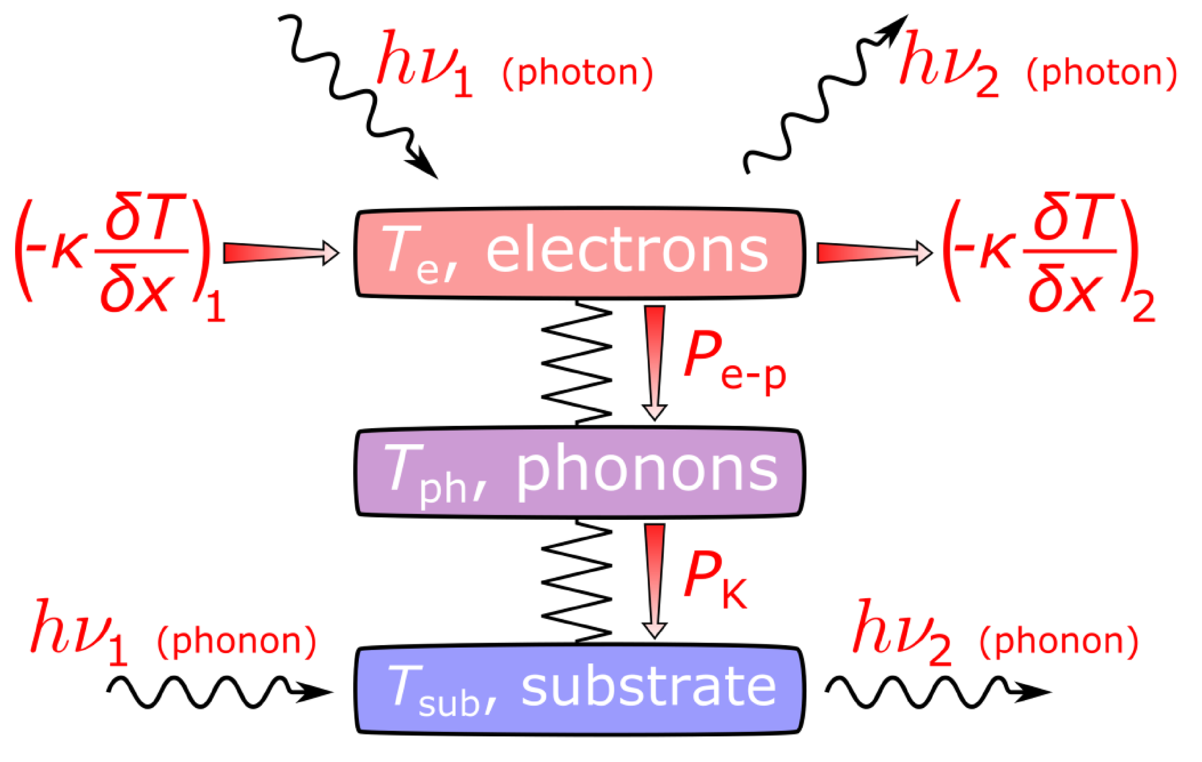
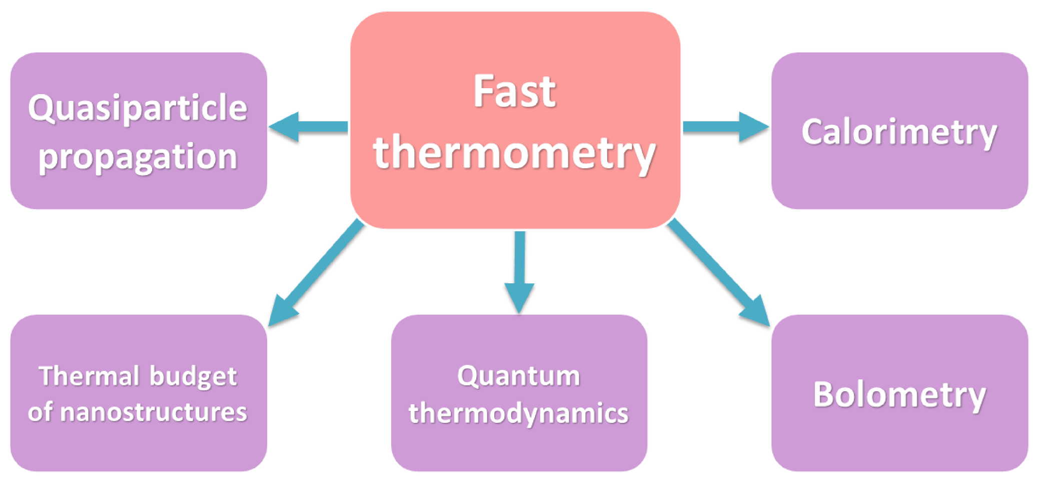
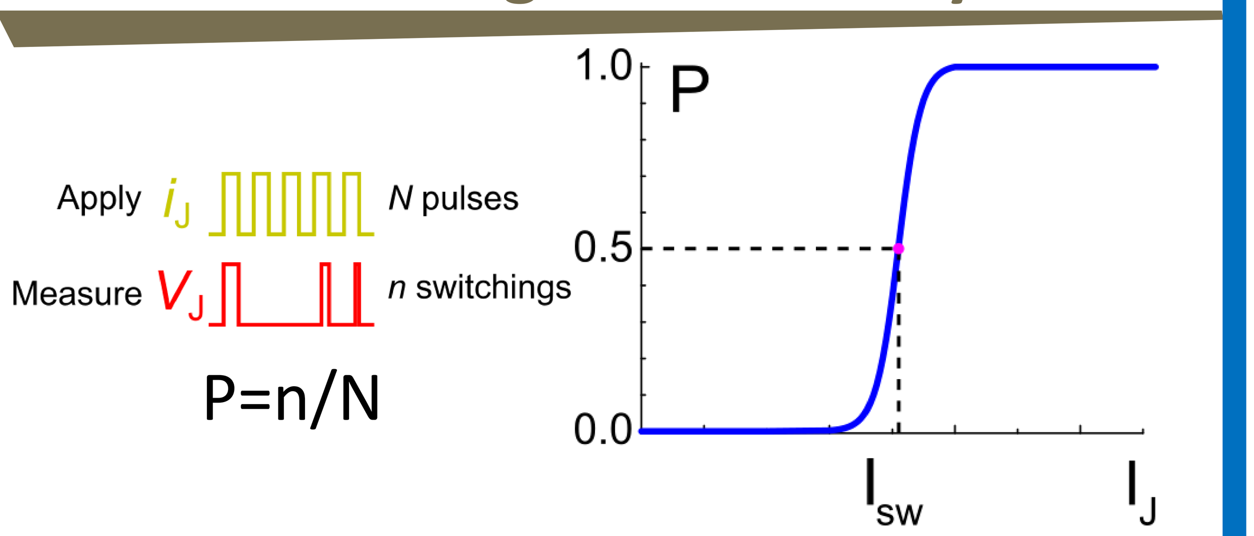
Motivation



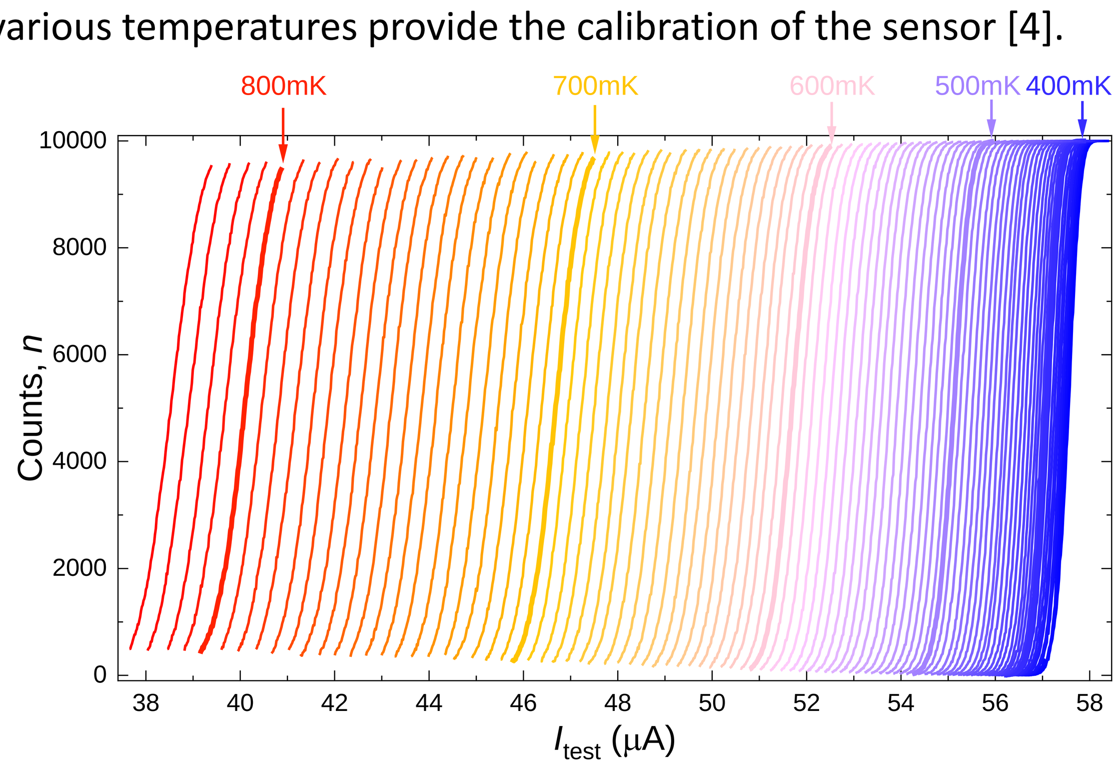
There are many thermal processes that are responsible for the energy transfer in the nanoscale e.g. hot electron diffusion, electron-phonon coupling, phonon propagation and absorption/emission of photons. Each of them sets its own timescale of reaching equilibrium in small, conducting structures at low temperature. It is vital to know the dynamics of these fast processes to be able to construct a novel-concept nanodevices. We develop an idea of time-resolved thermometry, which uses a superconducting junction in a form of a Dayem nanobridge as a temperature sensitive element.

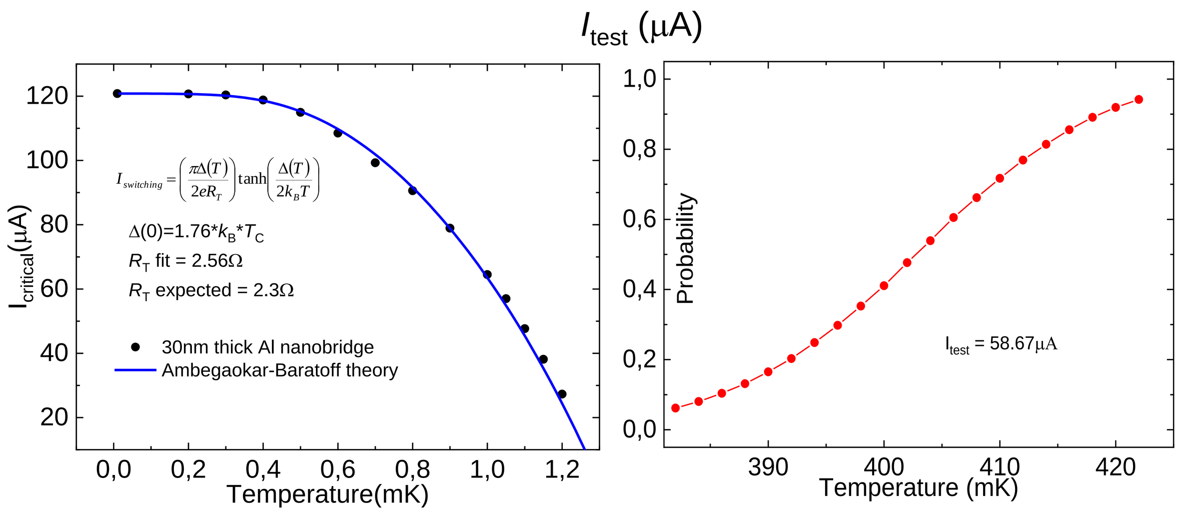


Switching thermometry



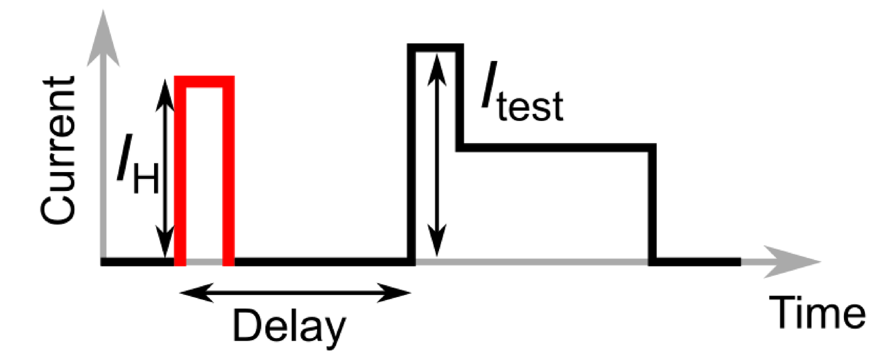
Upon the application of a current pulse our superconducting sensor can switch to the normal state or remain in the superconducting state. The switching process is stochastic with the probability P, which is dependent both on the testing current amplitude I_J and temperature. The current dependence of the switching probability is called an S-Curve. The S-Curves measured at various temperatures provide the calibration of the sensor [4].



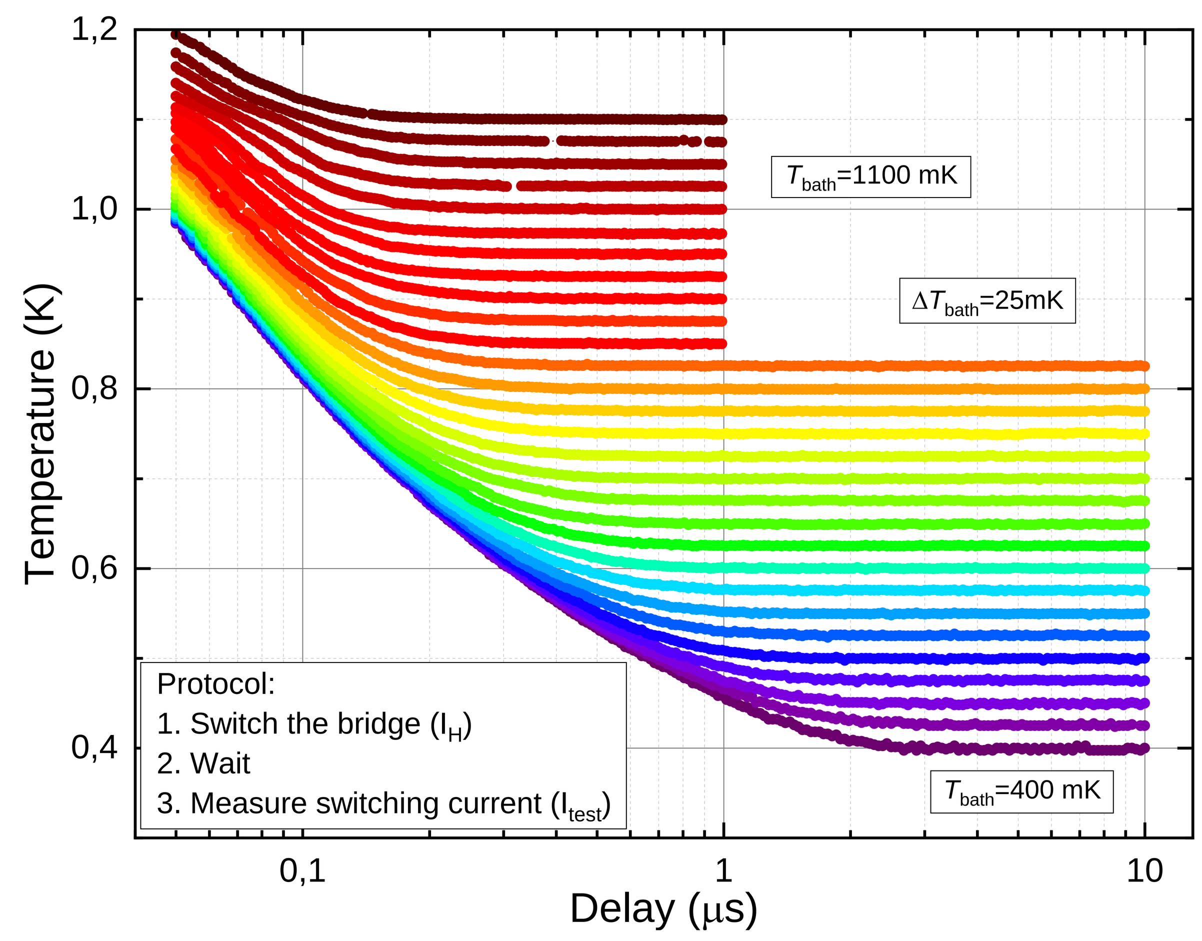


From a set of S-curves we can obtain the calibration curve: temperature dependence of the switching current [2]. Alternatively, we can keep the current pulse amplitude constant and directly measure the switching probability at fixed temperature steps.

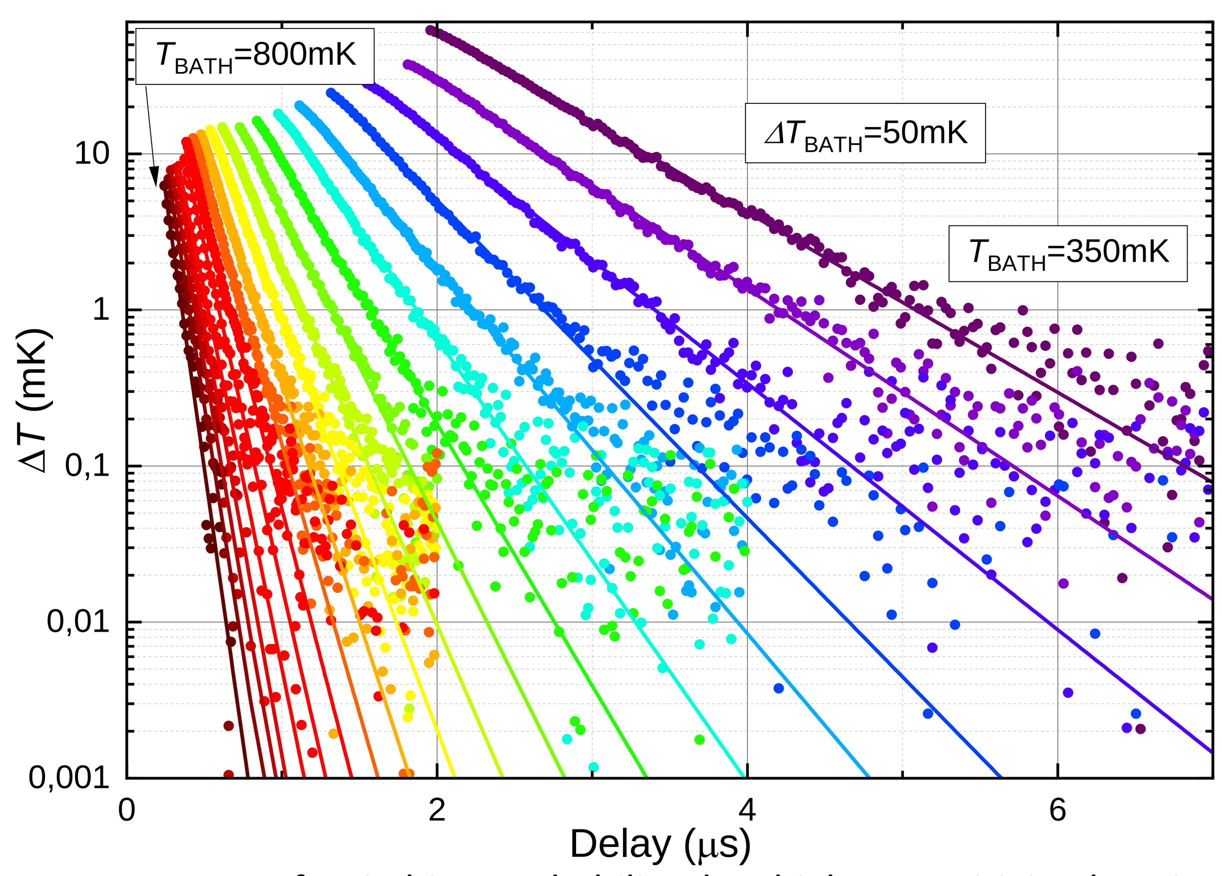
Relaxation measurement



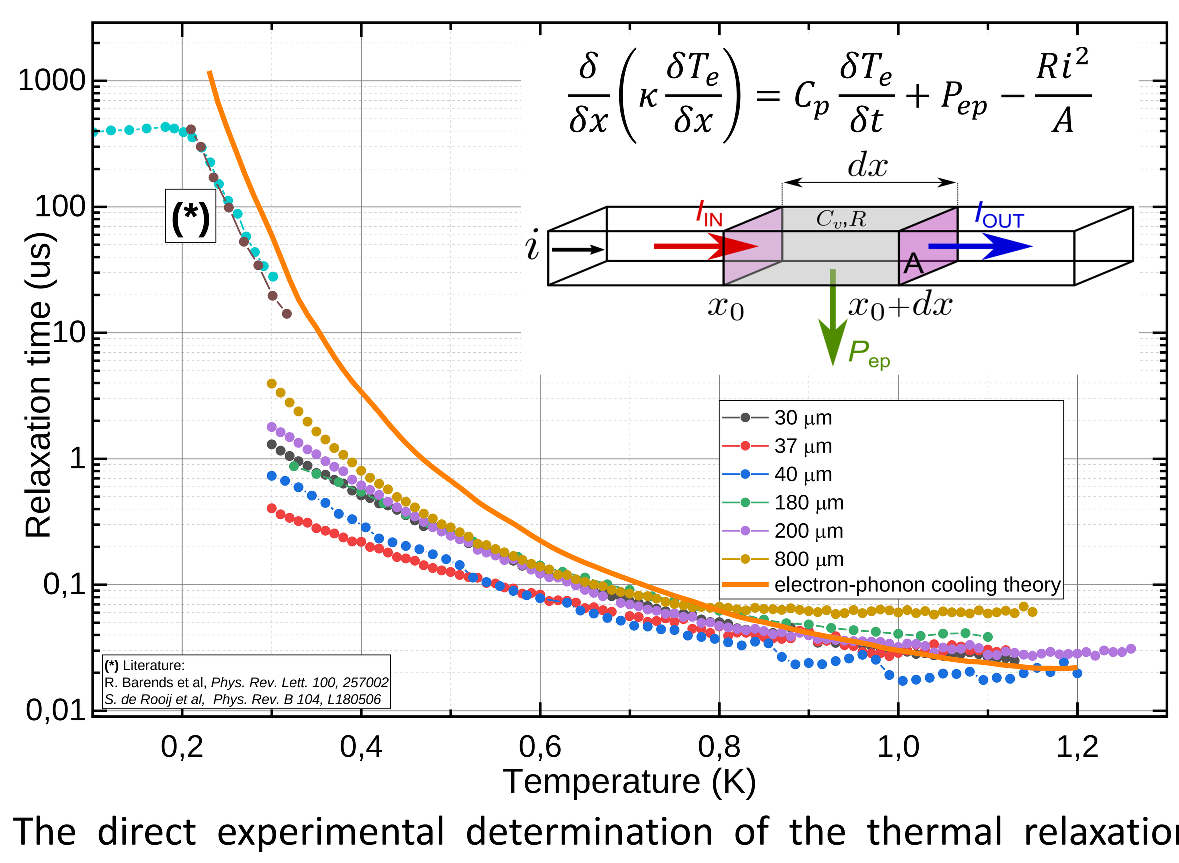
Typical measurement consists of the application of the heating pulse (red rectangle), which brings the system to non-equilibrium state, followed by the testing pulse (black), which allows to read the state of the sensor. We repeat this sequence N times to measure switching probability corresponding to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



Measurements of switching currents at various delays allow to reconstruct the variation of the absolute temperature in a wide range with nanosecond resolution. It is useful for monitoring highly nonlinear thermal processes.



Measurement of switching probability has higher sensitivity, but it is appropriate only in linear regime when small departures from thermal equilibrium are traced.

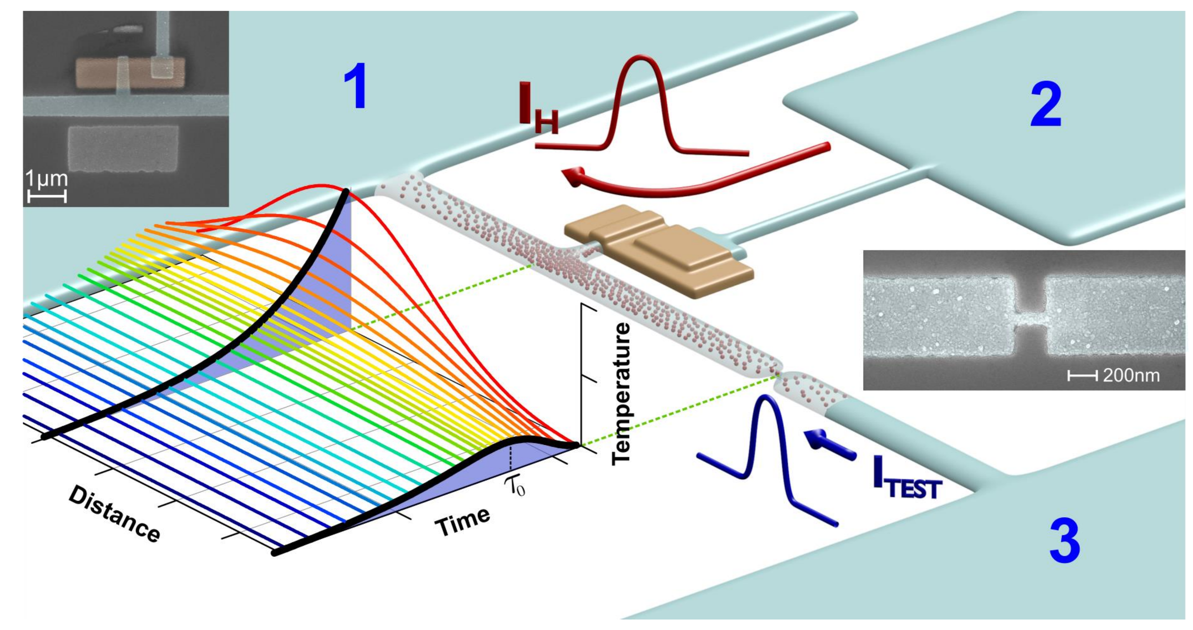


The direct experimental determination of the thermal relaxation times, as compared to simple analytical model and experiments of other groups. We observe the effect of the geometry (wire length) on the relaxation, which affects the diffusion of quasiparticles.

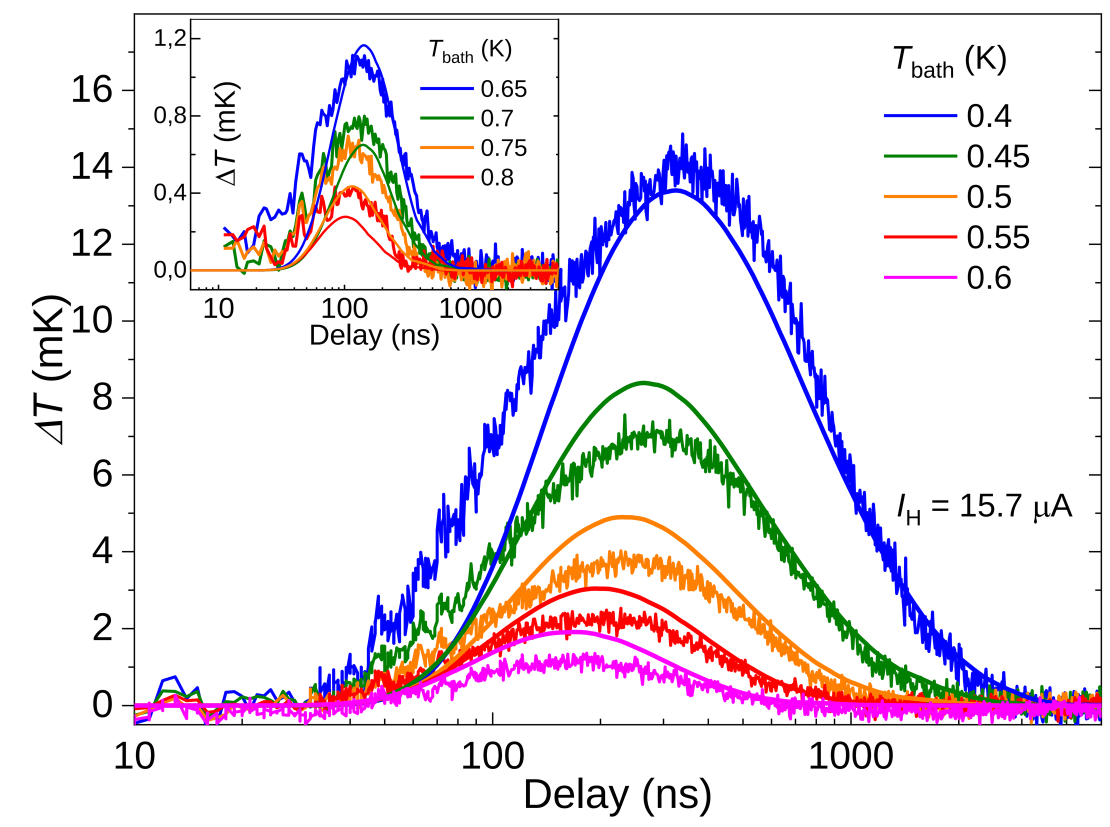
References

[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)
[5] M. Zgirski, M. Foltyn, A. Savin, K. Norowski, **Phys. Rev. B 104**, 014506 (2021)

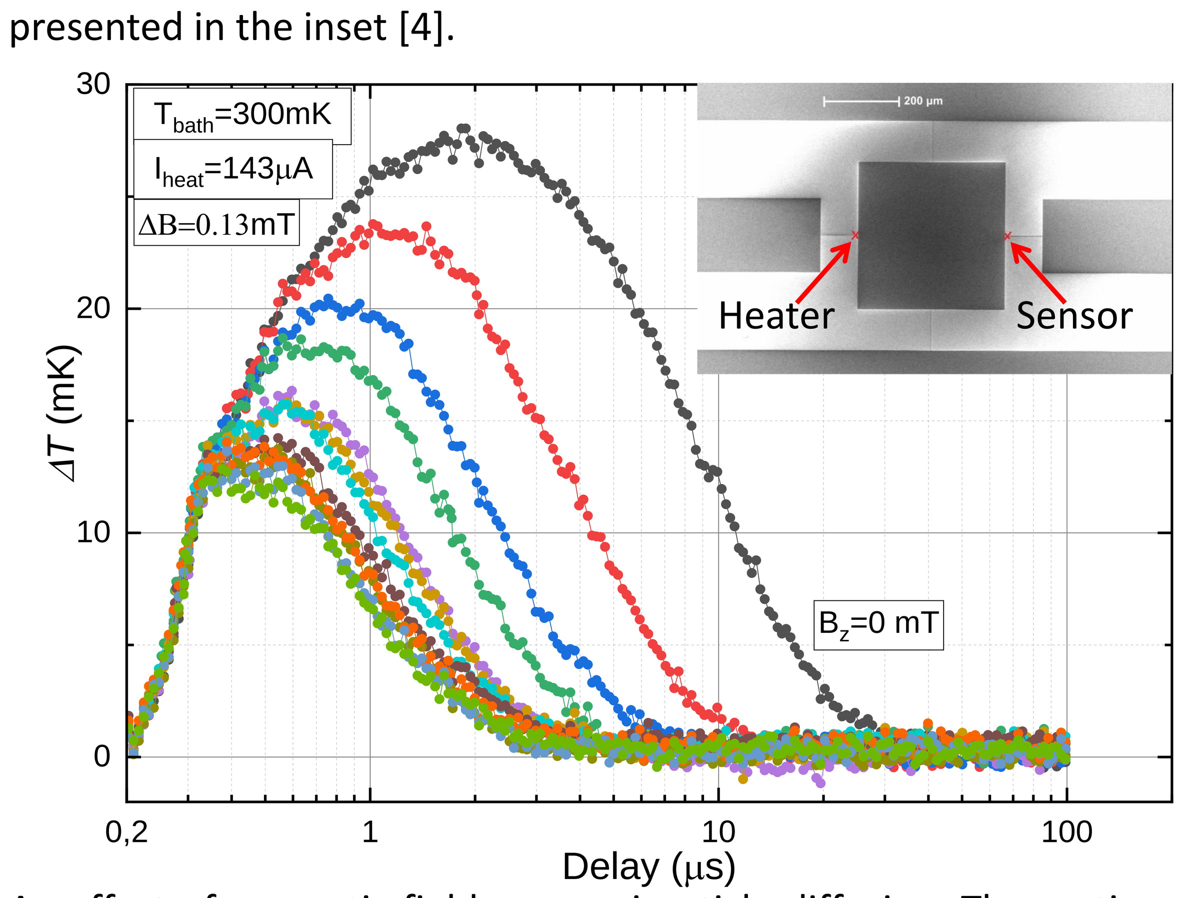
Quasiparticle transport



Hot electron diffusion in Al nanowire [4]. The heater and the thermometer are spatially isolated (60 μm apart). We see a burst of quasiparticles injected into the wire, as they pass by the detector. The study provides a direct determination of the diffusion constant.

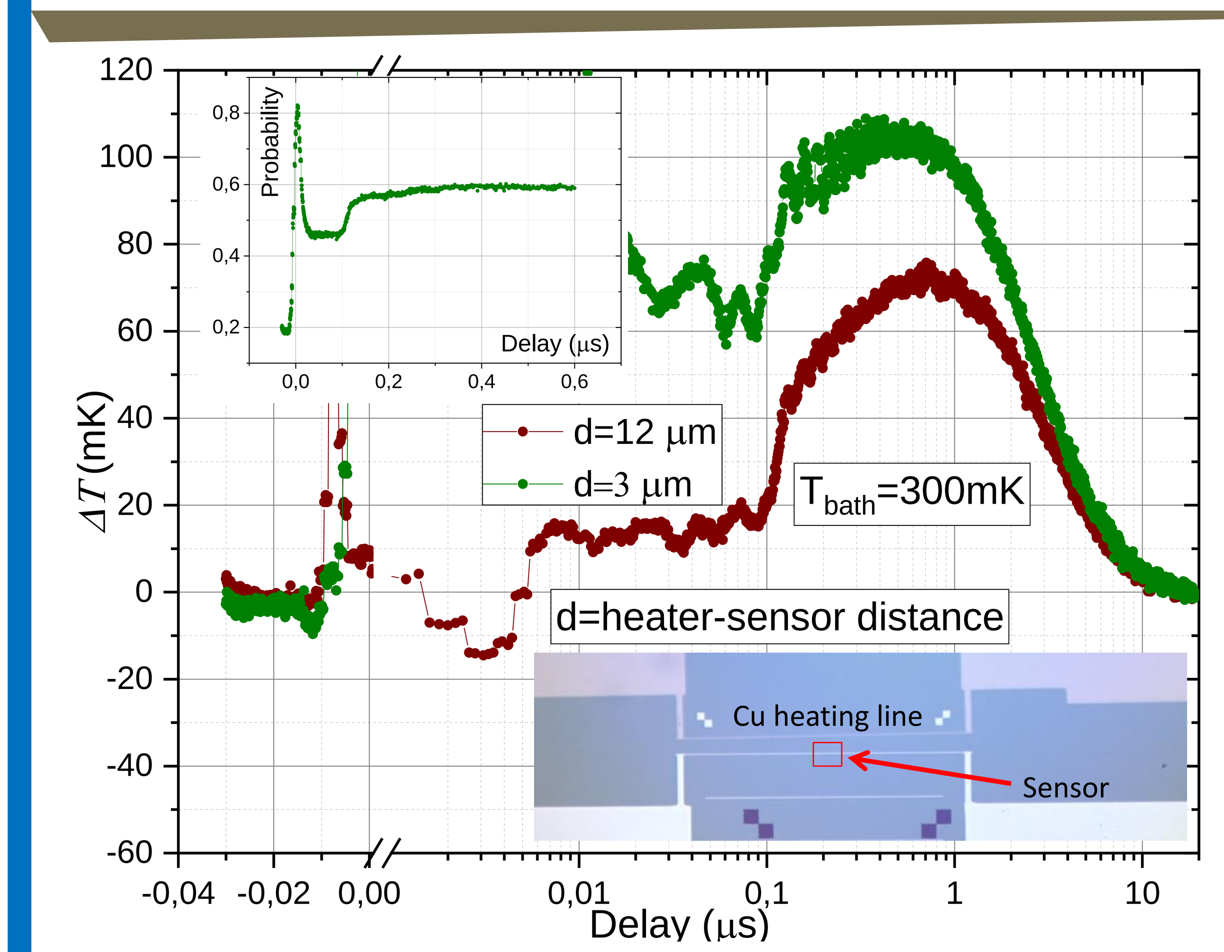


Diffusion profiles at various temperatures. At higher temperatures strong electron-phonon coupling annihilates hot electrons before they reach the detector. Note the excellent temperature resolution presented in the inset [4].



An effect of magnetic field on quasiparticle diffusion. The vortices, that are present in a big central pad, trap quasiparticles. It leads to the weakening of the diffusion signal.

Phonon propagation



A galvanic isolation of the heater and the thermometer allows for the measurement of energy exchange between two nanostructures via phonons propagating in a non-conducting substrate. We would like to know if we deal with diffusive or ballistic phonons.

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