Switching thermometry

for dynamical investigations of thermal processes at nanoscale

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Achievement: the creation of the pioneering time-resolved low-temperature thermometry and its application for the experimental investigation of the dynamical thermal processes at the nanoscale

Research profile (key-words):

Scientific: low T_c superconductivity, weak links, Josephson Junctions (JJs), SQUIDs, experimental thermodynamics at miliKelvin temperatures, electron thermometry at miliKelvin temperatures, calorimetry of thin metallic films and nanoobjects, microwave bolometers, superconducting vortices

Technical: nanotechnology (e-beam lithography, e-beam evaporation, ion beam sputtering), miliKelvin techniques, low noise electrical measurements, pulse probing of weak links and nanowires, pulsed magnetic fields, microwave probing

The habilitation procedure based on a set of research publications on a common subject (legal basis: Dz.U.2018 poz.1668, dated 20/07/2018, art.219, §1 p.2):

H1. M. Foltyn, **M. Zgirski***,
Phys. Rev. Applied **4**, 024002 (2015)

H2. M. Zgirski*, M. Foltyn, A. Savin, K. Norowski, M. Meschke, J. Pekola,
Phys. Rev. Applied **10**, 044068 (2018)

H3. M. Zgirski*, M. Foltyn, A. Savin, K. Norowski,
Phys. Rev. Applied **11**, 054070 (2019)

H4. M. Zgirski*, M. Foltyn, A. Savin, A. Naumov, K. Norowski,
Phys. Rev. Applied **14**, 044024 (2020)

H5. M. Zgirski*, M. Foltyn, A. Savin, K. Norowski,
Phys. Rev. B **104**, 014506 (2021)

Content

<u>Attachments:</u>

1. **Five publications comprising the basis for the habilitation**
2. **Statements of coauthors considering their role in the indicated publications**

1. Description of the achievement

1.1. Abstract

I proposed and demonstrated experimentally a new type of nanothermometry, which I dubbed the switching thermometry, for testing electron temperature of nanostructures in thermal transients with unprecedented resolution approaching a single nanosecond. In my pioneering studies, I used a superconducting Josephson junction tested with short (≥1 ns) current pulses to measure the current threshold for which the transition from the superconducting to the normal state occurs [H1]. The junction biased with the current pulse is in a metastable state (like for a decaying atom this state is characterized with a finite lifetime) and may spontaneously switch from the superconducting to a non-zero voltage state. The switching probability depends on the current amplitude and, importantly in the current context, on temperature, providing the feature necessary for a temperature sensor. The switching process, once initiated by a thermal or quantum fluctuation, exhibits a very fast intrinsic dynamics falling into picoseconds range making it perfectly suited for sensing rapidly changing physical parameters. The switching measurements of Josephson junctions has been known for years but I am the first one to use them for electron thermometry. My method provides the fastest-to-date monitoring of rapidly changing electron temperature in a solid state. I successfully implemented the idea by measuring the temperature relaxation in a superconducting aluminum nanowire [H2,H3].

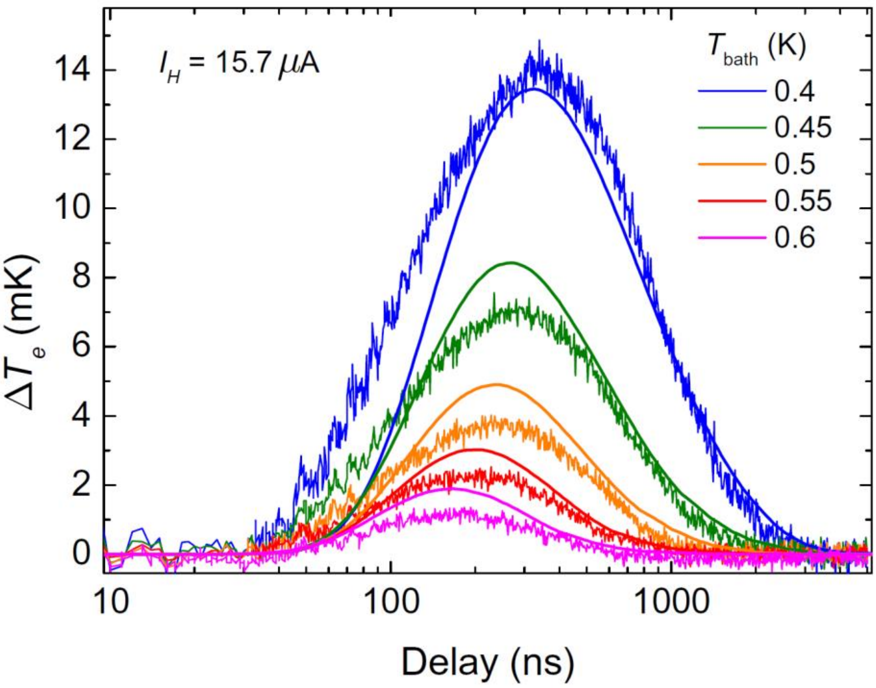

Fig.1. ***The temperature dynamics of the superconducting nanobridge*** *after creating nonequilibrium quasiparticles in copper island placed 60 µm away with a 10 ns-long heating pulse. The hot electron signal peaks up ~300 ns after application of the heating pulse which well agrees with expected diffusion time across 60 µm long nanowire. One can observe the delay of ~40 ns between the heating pulse and the onset of the signal. This delay shows that switching current of the bridge depends on the local distribution (local temperature) of quasiparticles. This measurement is an example of the excellent temporal and temperature resolution of my method. I consider this result to be my biggest scientific achievement obtained during my independent scientific career. For details see ref. H4.*

I also monitored heat pulse carried by a flux of nonequilibrium quasiparticles when it was passing by the temperature detector (**Fig.1**). This demonstration accesses the quasiparticle dynamics in superconducting nanostructure in the real-time domain, providing for the first time the direct picture of the quasiparticle diffusion in a superconductor [H4].

The developed thermometry allowed me to get a deep insight into the dynamics of overheated electrons and phonons in a superconducting nanostructure as exemplified in the thermal feedback mechanism observed for correlated switching measurements, when the switching probability depends on the thermal history of the junction [H5].

The ease of integration, true nanometer size and simplicity make my thermometer a good candidate for exploring thermodynamics of low temperature quantum circuits [6]. It can be also employed in the emerging field of the phase coherent caloritronics [7] – a discipline involving generation and manipulation of heat currents to demonstrate novel-concept devices. The presented, already performed experiments show that switching thermometry is a powerful tool for obtaining new insight into thermal physics at nanoscale at so far unavailable time scales.

1.2. Motivation, novelty, state-of-the-art and importance

Thermometry is a key in studies of thermodynamics - discipline investigating heat flows arising from the difference in temperature between two bodies. Investigation of thermal properties in nanoscale is much less common than corresponding electrical and magnetic studies. Partially it is because of the lack of fast thermometers that would be able to trace thermal transients appearing when electrical circuit is driven out of equilibrium due to, say, rapidly changing current responsible for Joule heating or photons absorbed in the bolometer. Yet, a proper understanding of thermal processes is essential for failure-free functioning of quantum circuits, involving design of nanoscale calorimeters, bolometers and quantum computers based on qubits. To give motivation to the presented studies I quote below the two statements:

"Thermometry is a key in studies of thermodynamics. In small systems (…) temporal statistical variations become increasingly important and it would be of great benefit to determine the effective temperature over time scales shorter than the relevant thermal relaxation time of the measured system. Despite the apparent lack of fast thermometers in mesoscopic structures, interesting experiments in thermal physics have been performed (…). Fast thermometry and calorimetry would tremendously expand the variety of phenomena to be explored , providing direct access to the temporal evolution of effective temperatures under nonequilibrium condition, the energy-relaxation rates, and the fundamental fluctuations of the effective temperature in small systems."

S.Gasparinetti, K.L. Viisanen, O.-P. Saira, T. Faivre, M. Arzeo, M. Meschke, and J.P. Pekola
Fast Electron Thermometry for Ultrasensitive Calorimetric Detection
Phys. Rev. Appl. 3, 014007 (2015)

"Thermodynamic studies of mesoscopic devices have lagged far behind the corresponding electrical and magnetic investigations. This dearth can be attributed to a lack of fast, robust thermometers that can be easily integrated with nanoscale structures. Electronic thermometers that function at very low temperatures and have fast response times will enable future probes of thermal

physics at smallest time scales and shorter time spans than have previously been explored, and are also a key technology for far infrared bolometry."

D.R. Schmidt, C.S. Yung, and A.N. Cleland
Nanoscale radio-frequency thermometry, Appl. Phys. Lett. 83, 1002 (2003)

Measurements over time scales shorter than thermal relaxation times are critical for developing a complete understanding of the thermodynamics of mesoscopic systems. However, a vast number of experimental researchers dealing with heat transfer have relied on static methods by analyzing systems in a steady state [8-13]. One of the limiting factors is stray cabling capacitance which limits the measurement bandwidth of many mesoscopic devices tested at cryogenic temperatures to the audio range. To circumvent the bandwidth-reducing effects of this capacitance some researchers embed temperature sensing nanoelements in an RF or a microwave resonant circuits [14-17]. Such approach has pushed the speed of thermometers into a few 10 MHz range. While in principle the method seems to be adequate for single-shot measurement of a microwave photon impinging on an optimized absorber, it cannot compete in terms of speed with a Josephson junction (JJ) which is able to respond up to THz frequencies [18].

In the quest to measure temperature even faster I utilized the ability of current-carrying superconducting weak link to instantaneously switch from the superconducting to the normal metal state [H1]. This switching depends on the temperature, thus providing a feature required for a temperature sensor [H2]. The ease of integration, true nanometer size and simplicity make my thermometer a good candidate for exploring thermodynamics of low temperature quantum circuits. This involves various heat relaxation channels: electron-phonon coupling [H2,H3,H4], hot electron diffusion [H4], emission and absorption of photons (to be presented in the future). In addition one can study relaxation of energy on the nanostructure-substrate interface and the propagation of phonons in the substrate (currently studied in my research group). These fundamental processes governing the thermal dynamics at nanoscale are depicted in **Fig.2.**

The introduced method can prove to be very attractive in the determination of vanishingly small heat capacities and studying heat exchange mechanisms involving real-time visualization of hot electron diffusion in nanostructures [H4] and calorimetric counting of microwave photons. It is worth mentioning that while cryogenic optical photon detectors have been known already for at least 30 years [19] and find commercial applications, detection of single microwaves photons of much smaller energy remains a challenge [20-23]. The developed thermometry will find application in rising discipline of experimental quantum thermodynamics [6, 24] for its ease of integration with superconducting qubits operating on microwave frequencies. My studies may also offer new ways for advancement of the emerging field of phase-coherent caloritronics, that involves generation and manipulation of heat currents to demonstrate novel-concept devices [7].

One should also not forget that many quantum phenomena can be mimicked by thermal effects. It is mandatory to keep the thermal budget of the studied nanostructures under control and understand its influence on the final interpretation.

More generally, my thermometry allows to study the dynamics of quasiparticles in metallic nanostructures [H4]. Such quasiparticles may have a detrimental effect on the performance of single-electron boxes, proposed as building blocks for modern current standard, for they give rise to leakage currents and resulting counting errors. Similarly, microcoolers and superconducting qubits suffer from the quasiparticle poisoning. On the other hand, the creation of non-equilibrium quasiparticles by absorption of photons of the incident radiation is indispensable for proper operation of bolometers with their intrinsic bandwidth set by the quasiparticles' lifetime.

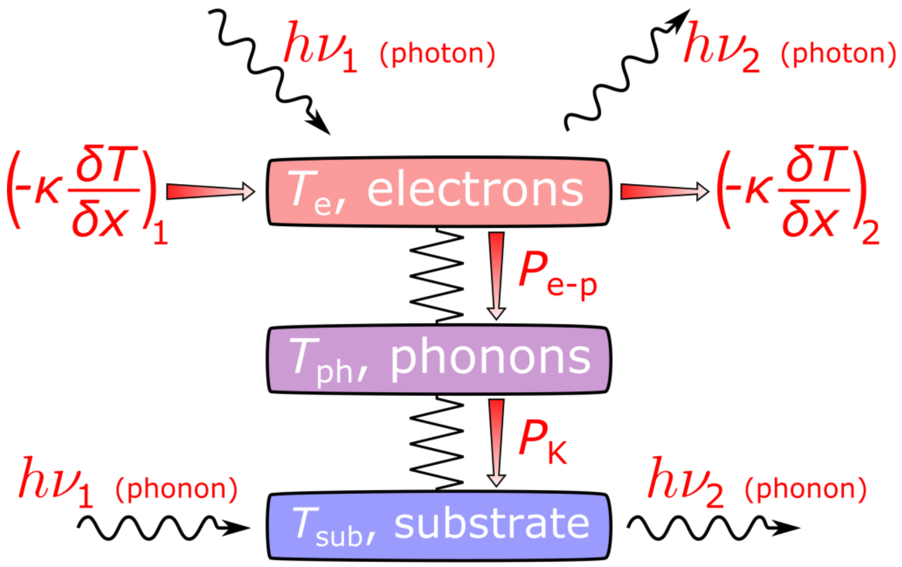

Fig.2. Schematic representation of energy relaxation channels in a nanostructure. *Electrons at low temperatures are thermally decoupled from the lattice. It results in a need to define two temperatures: one for electrons –* T_e *and one for phonons –* T_{ph}*.* $P_{e\text{-}p}$ *denotes the power transferred from electrons to phonons.* P_K *is the power exchanged between the phonons in the nanostructure and the phonons in the substrate.* κ *is the electron thermal conductivity. Electrons may also absorb photons (e.g. in bolometers) and emit them in a radiative relaxation channel (black body radiation). The phonons in the insulating substrate (e.g. in Si or* Al_xO_y*) redistribute the energy between metallic nanostructures, which do not need to be connected galvanically.*

1.3. New thermometer: concept and methodology

A working horse of my work is a superconducting Josephson junction (JJ, superconducting weak link) in a form of an aluminum nanobridge referred to in literature as Dayem nanobridge (***Fig.3a***). Other types of JJ involve very thin oxide layer sandwiched between two superconducting electrodes (***Fig.3b***), or superconductor-normal-metal-superconductor (SNS) proximity junction. Such a *JJ* is sometimes called a switch for its ability to carry supercurrent only to a certain level and, above this level, it switches to a finite voltage state (***Fig.4***).

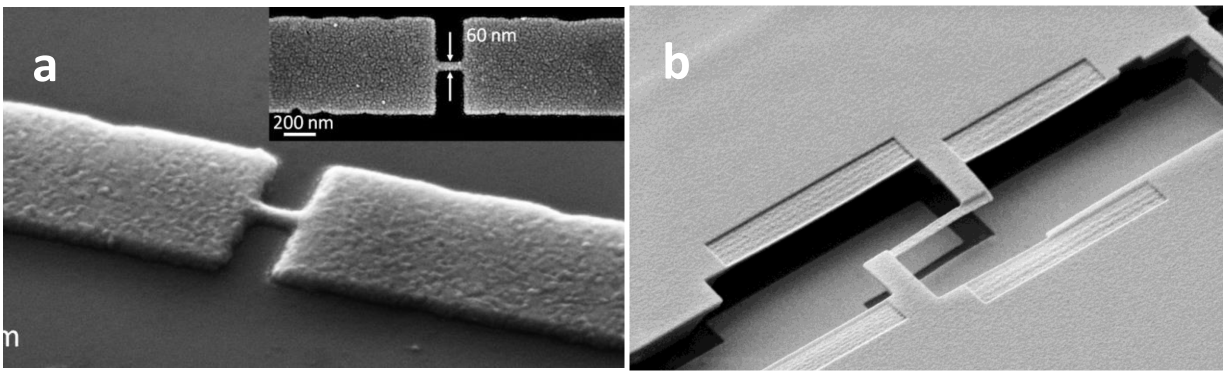

Fig.3. SEM photos of the nanostructures *routinely obtained in my lab:* ***(a)*** *Aluminum nanobridge* ***(b)*** *E-beam defined PMMA/MMA mask for Al/AlxOy/Al tunnel junction (images taken at an angle).*

The methodology of the switching current measurement is known [H1,25,26]: it consists of sending a rectangular pulse of current of given amplitude and duration and measuring if the *JJ* switched or not. Sending a train of such pulses (of the defined amplitude) allows to experimentally determine the estimator of the switching probability *P*. Repeating the same experiment for different current amplitudes gives what is called an S *curve:* the current amplitude dependence of the switching probability (**Fig.4**). A more detailed study of the switching process involves thermal escape analysis of *JJ* out of its metastable state (according to Arrhenius law) [27,28]. The switching experiments on JJ have shed some light on the nature of Andreev bound states in the superconducting point contacts [25,26] and allowed for magnetization measurements with nanoSQUIDs [29]. They have been statistically studied proving to be useful for generating random numbers [H1] and recently I used the probing of JJ with pulses for fast temperature measurements creating a new paradigm in nanoscale low temperature thermometry [H2-H5], which I call the switching thermometry. Below I briefly describe the main principle of the method. For detailed description please look into the references H1-H5.

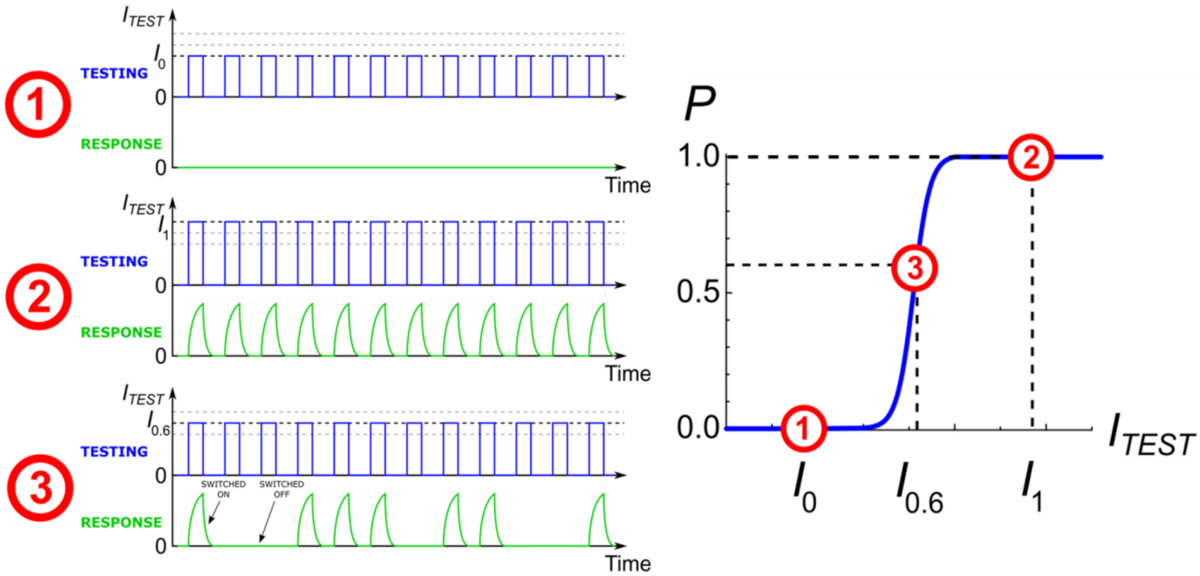

Fig.4. Principle of collecting the S curve. *In response to a single testing current pulse JJ may remain in a superconducting state or switch to a finite voltage state. The switching event is observed as a pulse of voltage. When JJ is tested with current pulses of low amplitude no switching is observed (scenario no. 1). When JJ is tested with current pulses of high amplitude switching events are observed for all testing pulses (scenario no.2). For intermediate testing amplitudes there is a region where switching exhibits stochastic character which can be quantified by measuring the switching probability defined as the ratio of the number of switching events n to the total number of trials N (scenario no.3). The switching probability dependence on the testing current is often referred to for its typical shape as an S curve. Typically, I send N = 10000 testing pulses with duration ranging from 1 ns to 1 μs and a typical period of 100 μs which corresponds to 1 s acquisition time for a single point in the S curve.*

The experimental setup used in the switching measurements is presented in **Fig.5**. It is worth to highlight *a probe and hold* feature of the JJ: it reaches THz response bandwidth, but, due to hysteresis (retrapping current at which JJ returns to the superconducting state is much lower than the switching current), it may be read-out with low frequency wiring and electronics. The key observation in the current context is the dependency of the switching current threshold on temperature. The JJ thermometer is calibrated by measuring its switching current corresponding to $P = 0.5$ against the bath temperature T_{bath}, with T_{bath} set at points in the range of interest - it is "Temperature from switching current" method (**Fig.6**). Alternatively, one can use the switching probability dependence on temperature directly – it is "Temperature from probability" method (**Fig.6**). The full experimentally recorded variation of the switching probability with testing current and temperature is presented in **Fig.7.**

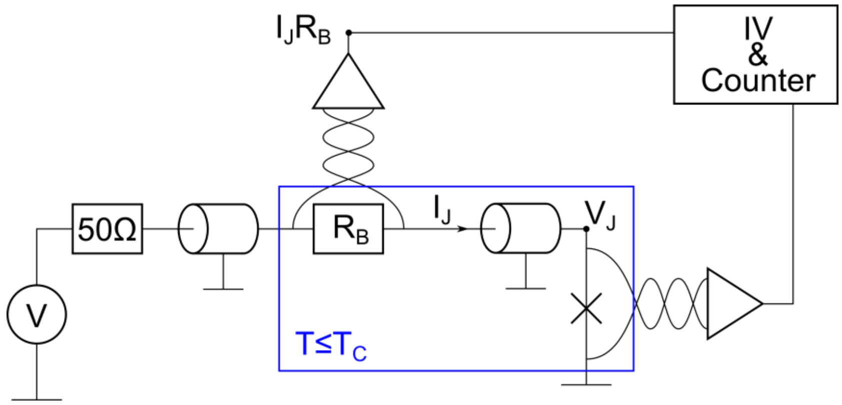

Fig.5. **A simplified electrical circuit** *used in my laboratory to probe a junction with current pulses. It allows also to measure current-voltage (IV) characteristics of the junction (X in the figure). A counter (oscilloscope) records number of switching events observed as a voltage pulses V_J developing on the junction. R_B is a bias resistor for monitoring the current sent to the junction I_J. V stands for Arbitrary Waveform Generator (AWG) with 50 Ω output.*

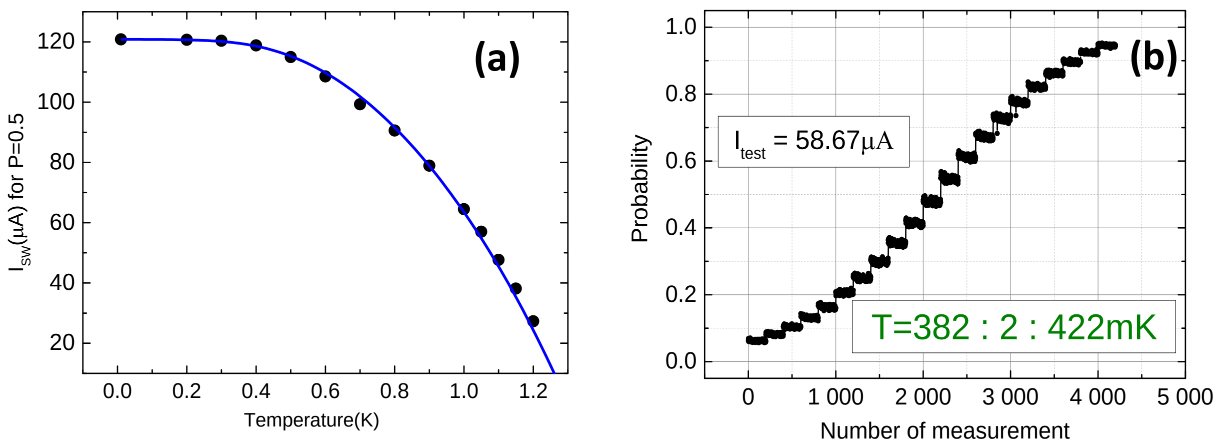

Fig.6. Calibration curves. (a) *Temperature dependence of the switching current (P=0.5) for the aluminum nanobridge. Published [H2].* ***(b)*** *Measurement of the switching probability P for temperatures indicated in the graph. Each plateau corresponds to a fixed value of temperature stabilized with PID controller of Triton 400 dilution refrigerator. The increment in temperature is only 2 mK. The broadening of each plateau results from the statistical uncertainty of the measurement (for details refer to p.1.4e). The data reveals excellent temperature stability of the experimental setup.*

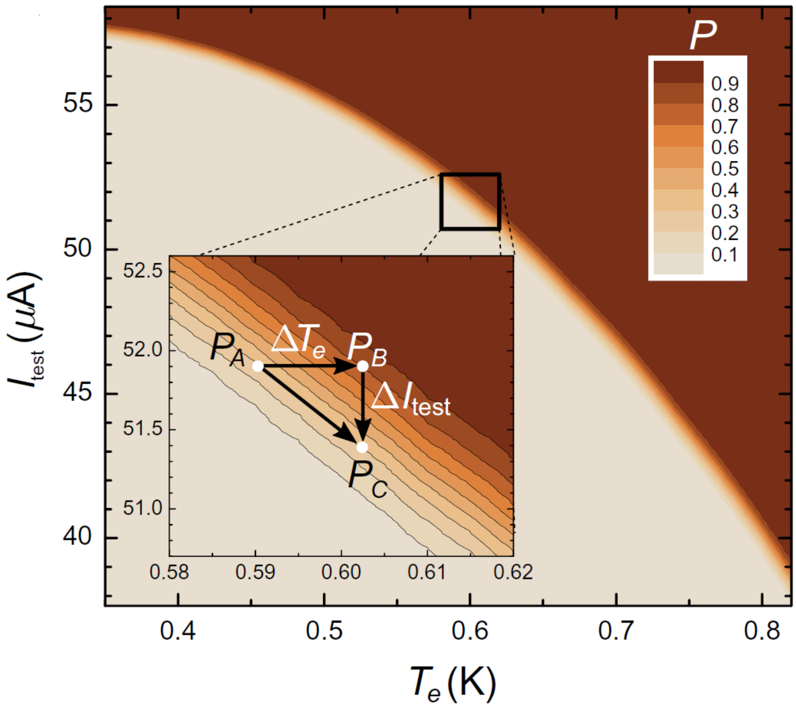

Fig.7. Switching probability map P(I_{test}, T_e). *Experimental dependence of the switching probability P on the testing current I_{test} and electron temperature T_e. Inset: close up of the dependence with indicated probabilities P_A, P_B, and P_C = P_A. An increase in temperature ΔT_e corresponds to increase in the switching probability from P_A to P_B – it is the basis for the "Temperature from probability" method. Alternatively, keeping the same switching probability P_C=P_A after the same temperature increase requires a reduction of the testing current by ΔI_{test} – it is the basis for the "Temperature from switching current" method. Published [H4].*

To bring in the temporal resolution of the thermometer, I make use of *a pump and probe* idea. A nanostructure in thermal contact with the JJ is heated with *a pump pulse* and then, say a few tens of nanosecond later, the JJ is tested with *a probe pulse* (**Fig.8**). The delay between pulses can be controlled with accuracy of a single nanosecond and in combination with very short (≳ 1 ns) duration of the testing part of the probing pulse provides the unprecedented temporal resolution. The switching current (corresponding to $P = P_0$) or switching probability (for I_{test}=I_{test0}) measured at a given delay is uniquely related to the junction temperature. It allows to reconstruct the temperature profile in time domain with the aim of the corresponding calibration curves.

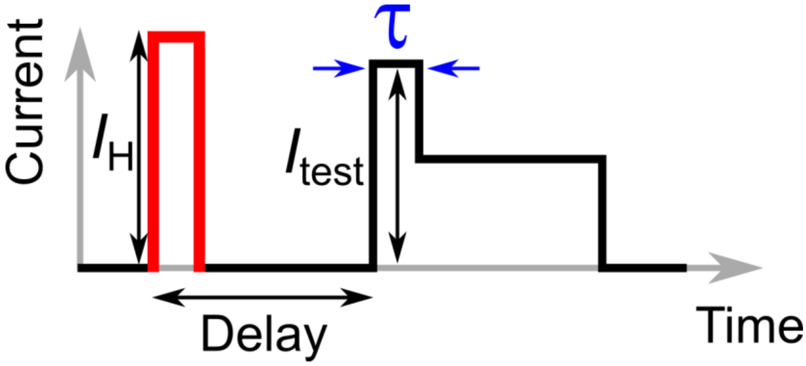

Fig.8. The principle of the pump and probe experiment. *By applying the current pulse we heat a nanostructure and create an excessive population of quasiparticles. The probe sequence, delayed with respect to the pumping pulse, measures the dynamic temperature of the nanobridge: the higher amplitude of the probing pulse (so called testing pulse) is intended to test the temperature of the junction and the lower, much longer part (so called sustaining part) allows for discriminating the state of the junction with room temperature electronics. The temporal resolution of the method is set by the duration of the testing pulse τ, falling into a single nanosecond range.*

1.4. Overview of scientific results

In this paragraph I briefly describe some important results presented in my publications, which comprise the basis for the current habilitation application (H1-H5). It is an overview intended to give only a flavor of my investigations. The more inquisitive reader is encouraged to study the corresponding papers and supplementary materials assisting them. All presented data were obtained in my laboratory built by me from scratch (see p.8).

a) The verification of probabilistic behavior in switching of a superconducting nanobridge. The generation of random numbers [H1]

In ref.[H1] I verified the stochastic nature of switching from superconducting to normal state for a superconducting aluminum nanobridge. The work is prerequisite for using the Josephson junction as a tool for probabilistic determination of physical parameters such as temperature, magnetic flux, and current.

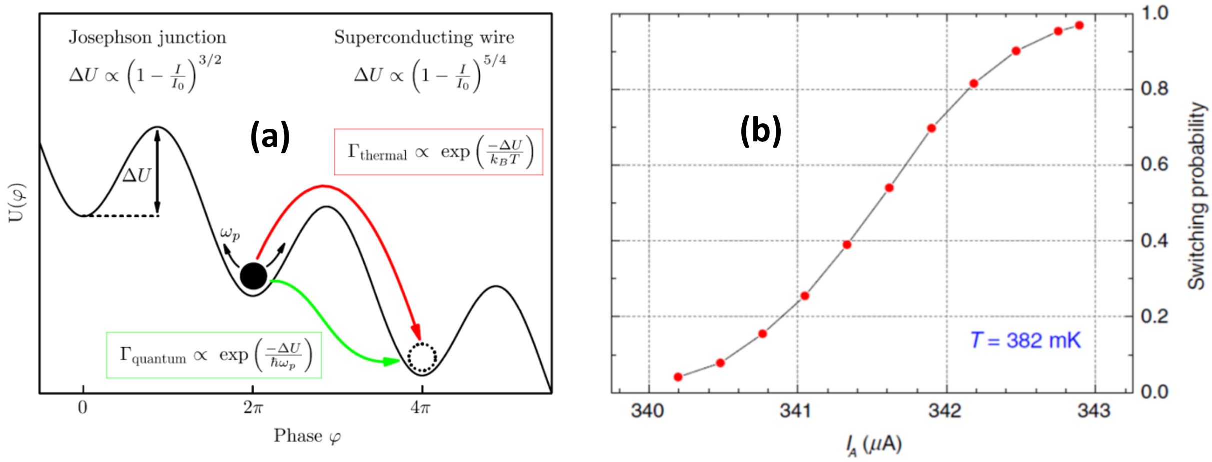

***Fig.9. (a) Brownian particle undergoing random oscillations in tilted washboard potential** can jump over or tunnel through a barrier (switching), or may stay trapped in the well (no switching). Γ's denote rates for both processes. **(b)** Experimentally obtained S curve. Each point is the estimator for the switching probability at given current amplitude I_A, measured with a train of N = 10000 pulses. The line is a guide for the eye. Published [H1].*

*"A supercurrent-carrying state of a JJ or a superconducting nanowire is conveniently described with tilted washboard potential arising from the resistively and capacitively shunted junction model (RCSJ) […](**Fig.9**). In the model, the state of the superconducting wave function is mapped into a position of a particle moving in the one-dimensional potential. The particle exhibits Brownian fluctuations due to interaction with the constant temperature bath […]. The fluctuations correspond to random changes in the superconducting phase across the JJ around a mean value, meaning, by virtue of dc Josephson effect, average dc supercurrent flowing in the JJ. The height of the potential barrier separating two local minima is controlled by biasing current. For supercurrents much below the critical current, the height of a potential barrier is much larger than accessible thermal energy k_BT and the particle cannot escape through the barrier. However, increasing the biasing current, one can reduce the barrier height to an extent that thermal or quantum fluctuations are sufficient to drive the particle over the barrier […]. If such a so-called phase slip happens […], the*

particle acquires sufficient inertia to jump over lower barriers (this is true for an underdamped junction). The superconducting wave function accumulates the phase and this, by virtue of the ac Josephson effect, creates voltage across the JJ, giving an experimentalist a means to test the escape. We call such an event switching. In the case of superconducting wires and Dayem nanobridges, the voltage appears due to phase slip followed by overheating and transition to the normal state […]. For current pulse of length T, the probability for the particle to escape is P = 1 – exp(−ΓT), where Γ is the corresponding thermal or quantum escape rate [H1, my own text]."

The probed junction behaves like a coin with the electric current-tunable probability. After probing with the current pulse, JJ can be found in two easily distinguishable states: normal (the head, with probability *P*) or superconducting (the tail, with probability 1 − *P*), with no arbitrary criterion separating the two. This fact allowed us to demonstrate operation of the random number generator (RNG). It is, to the best of our knowledge, the smallest solid-state-based RNG (a decaying atom is smaller but it can generate only 1 bit while our generator can work perpetually). It is also very simple—a piece of a nanowire interrupting a thicker wire. The RNG passed tests for randomness [H1] and was patented (see p.3.3.2).

b) Measurement of rapidly changing electron temperature in a superconducting nanowire [H2]

In the pioneering experiment I employed the switching thermometry to measure rapidly changing electron temperature in a long superconducting nanowire with nanosecond resolution (**Fig.4**, [H2]).

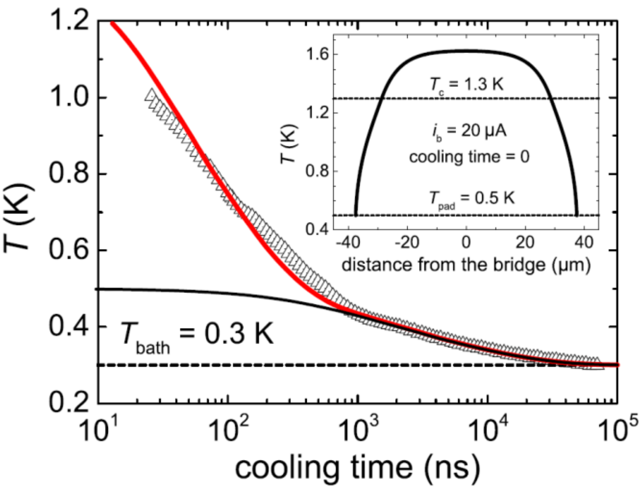

***Fig.10. Relaxation of the electron temperature** in 75 μm long superconducting nanowire (black triangles) and thermal model (red curve, see p.1.5) taking into account 2 relaxation channels: electronic heat diffusion and electron-phonon scattering. Inset shows calculated steady-state temperature profile, which is the initial condition for the considered relaxation. Published [H2].*

The measurement and modelling point to the important role of hot electron diffusion below ~ 600 mK. At higher temperatures the dominating energy relaxation channel for hot electrons is emission of phonons. I stress that this experimental demonstration explores directly the temporal dynamics of electron energy relaxation at previously inaccessible times i.e. below 1 μs, "magnifying" the time scale of the experiment by 2 orders of magnitude as compared to the other reported techniques.

c) Measurement of two thermal relaxation times in samples driven to strong non-equilibrium [H3,H5].

The switching thermometry proved also to be a useful tool for studying much longer relaxation times attributed to overheating of local phonons. It was found that thermalization of a strongly overheated nanostructure is much longer, in excess of 1 ms. Importantly, the measurement also revealed the time scale of the electron energy relaxation due to coupling with phonons, around 1 μs. Both relaxations are well visible in the experimental data presented in **Fig.11**.

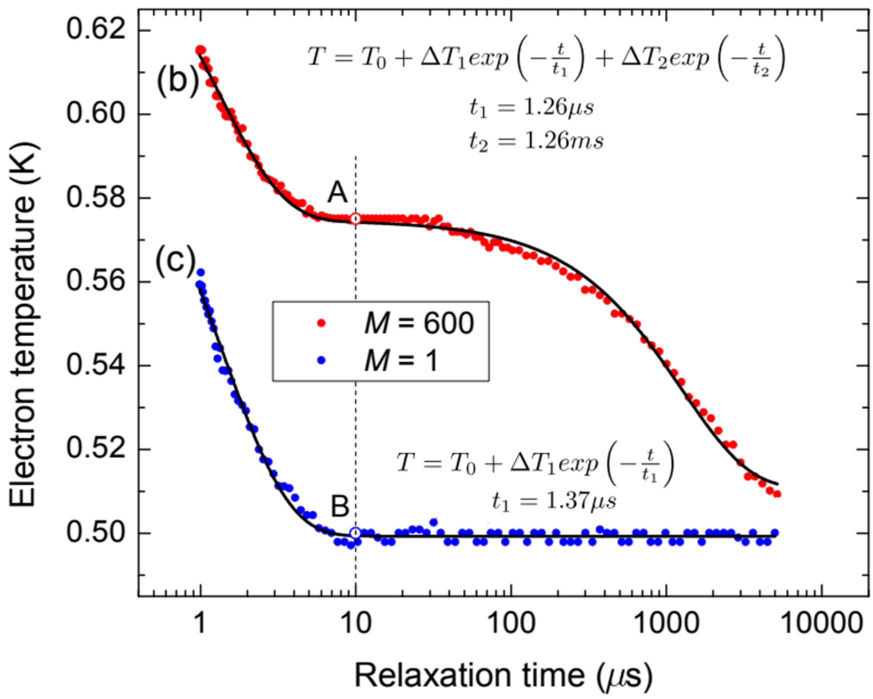

Fig.11. Two relaxation times. (b) *Relaxation of the nanobridge after M = 600 forced switchings. Two relaxation mechanisms are visible: the fast process is the same as in (c) and the slow one is approximately 1 000 times longer and is attributed to relaxation of the local phonon temperature (substrate) toward the bath temperature. The line is a fit to the sum of two exponential functions.* ***(c)*** *Relaxation of the excess hot-electron energy toward equilibrium with local phonons after a single forced switching (M = 1): the local phonons are at bath temperature. The line is a fit to the single exponential function. Published [H3].*

d) Direct measurement of quasiparticle diffusion in superconducting aluminum [H4]

Nanostructure consists of the heater and remote superconducting bridge measuring temperature which is placed 60 μm away from the heater (**Fig.12**). Application of a short heating pulse (~10 ns) on the heater creates quasiparticles (hot electrons) spreading around in the nanostructure. My thermometer is able to see the onset of hot electrons arrival ~30 ns after application of the heating pulse, maximum of the hot electrons signal and "slow" relaxation tail.

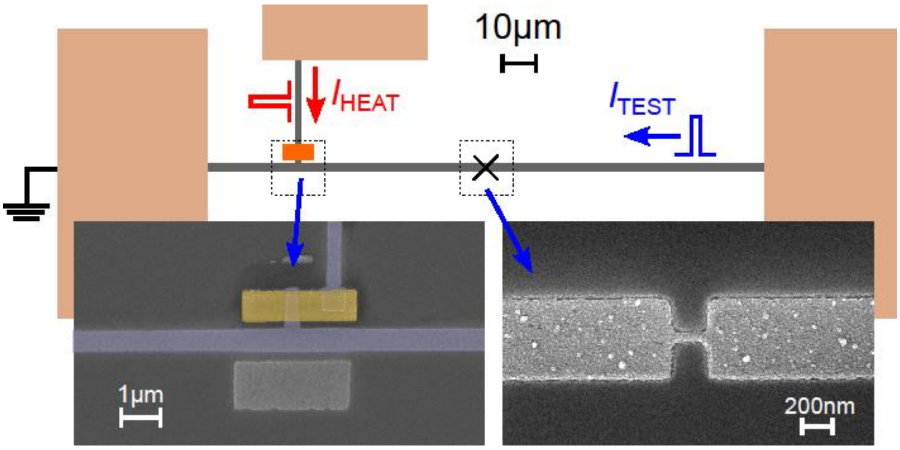

Fig.12. Layout of the sample *for studying the dynamics of hot electron diffusion at miliKelvin temperatures. It consists of resistive copper island (SEM photo to the left) and a remote temperature sensor (aluminum nanobridge). A short heating pulse I_{HEAT} creates hot electrons which start diffusing towards thermometer along superconducting nanowire. The test pulse I_{TEST} is launched with time delay and probes temperature of the bridge (**Fig.13**).*

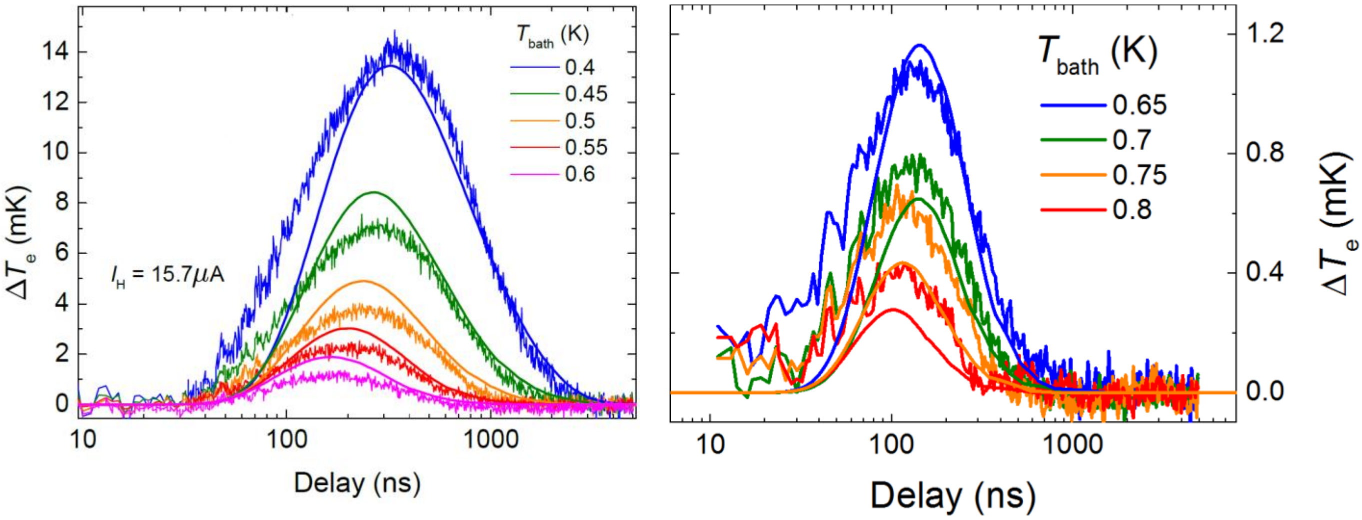

Fig.13. ***Hot electron diffusion.*** *Temperature dynamics of the superconducting nanobridge after creating nonequilibrium QPs in the copper heater placed 60 µm away with a short heating pulse. Noteworthy, the hot-electron signal for T = 800 mK shows only 400 µK peak with accuracy better than 100 µK. The "noisy" profiles are experimental data for which the temperature is extracted with the "temperature from probability" method. The suppression of hot electron signal at higher temperatures stems from the enhanced electron-phonon coupling and the larger electron heat capacity. Solid lines are calculated numerically for the 1D heat-flow model discussed in p.1.5. Published [H4].*

"We demonstrate the real-time measurement of the nonequilibrium QP diffusion D in the superconducting aluminum nanowire. Such an investigation is possible because our fast thermometry delivers resolution at single nanosecond level (t_{res} ~ 1 ns) accessing the regime where $t_{res} << L^2/D$ with L being the spatial extent of the experiment (i.e., distance between QP source and detector). Our data are in agreement both with the simple model of the free-particle diffusion (allowing for direct determination of the diffusion constant), and a more involved thermal model taking into consideration the electron-electron and electron-phonon scatterings with the first mechanism being accounted for by the electron heat capacity term and the second one by electron-phonon coupling in the heat-flow equation [H4, my own text]."

e) The JJ as an electric coin and the definition of the clean switching experiment [H3]. Uncertainty of the switching thermometry [H4].

Switching measurement is analogous to a familiar "head or tail" experiment, in which we toss a coin. In response to each measuring pulse junction may switch to the normal state – then we get a head, or it may remain in the superconducting state – we get a tail. Hence, I tend to think about Josephson junction probed with current pulses as it was an electrical coin. However, unlike for a fair coin, the probability for obtaining the head in a single switching measurement can be tuned with the amplitude of the probing pulse. If we toss the electrical coin $N = 10000$ times we should obtain a certain number of heads n_s, say 4807. When we repeat the same experiment second time, the measured number of heads will be almost for sure different. Repeating the same experiment again and again we will be able to build histogram of the n_s. The histogram should be described with binomial distribution characterized by the mean number $n_{s0}=NP_0$, where P_0 is the switching probability in a single pulse, and the standard deviation $\Delta n_s = \sqrt{P_0(1-P_0)N}$. It is what we get in a carefully performed experiment (**Fig.14a**). The compliance of the number of measured switching events n_s with the expected statistical broadening comprises an important criterion of a clean switching measurement. The standard deviation of the binomial distribution can be perceived as a statistical noise setting the intrinsic uncertainty of the measurement when it comes to an accurate temperature determination. The temperature responsivity of the junction $\Delta P/\Delta T_e$ together with statistical broadening sets the smallest resolvable temperature difference in experiment $\Delta T_{e,un} = (\Delta P/\ \Delta T_e)^{-1}\Delta P_{un}$ with $\Delta P_{un}=\Delta n_s/N$ (**Fig.14b**). This figure of merit is confirmed experimentally for temperature rise ΔT_e due to diffusing quasiparticles presented in **Fig.13**, where it yields an impressive number of 100 μK at 800 mK. The issues related to the noise-equivalent-temperature (NET) in the switching thermometry are rigorously and deeply described in the manuscript [H4].

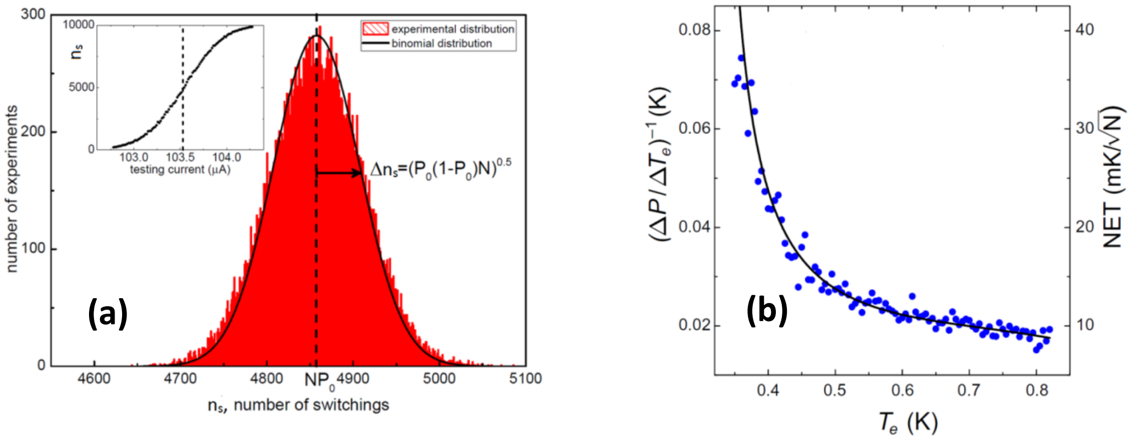

Fig.14. (a) The "flipping coin" experiment *for the independent switching events at $T = 300$ mK. The histogram represents the number of experiments resulting in the given number of switching events n_s for the constant testing current, indicated with a dashed line in the inset. The single experiment consists of sending $N = 10000$ pulses and measuring the number of switching events n_s. The experiment is repeated 35372 times to build the presented histogram. The imposed black solid line is the expected binomial distribution. Δn_s is the statistical broadening of the measurement.* ***(b)*** *Inverse temperature responsivity $(\Delta P/\ \Delta T_e)^{-1}$, serving as the calibration curve in the "Temperature from probability" method and the corresponding noise-equivalent temperature (NET). NET = 10 mK/$N^{0.5}$ yields for $N = 10000$ uncertainty in the electron temperature determination $\Delta T_{e,un} = 100$ μK. Published [H2,H3,H4].*

f) Investigation of the correlated switching: discovery of the stochastic thermal feedback in an artificially created random thermal process [H5]

*"For pulses with low repetition rate each pulse transits the superconducting bridge to normal state with probability P independent of the outcomes in the preceding pulses. We show that with reduction of the time interval between pulses long range correlation between pulses occurs: stochastic switching in a single pulse rises temperature of the bridge and affects outcome of the probing for next pulses. As a result, an artificial intricate stochastic process with adjustable strength of correlation is produced (**Fig.15**) [H5, my own text]".*

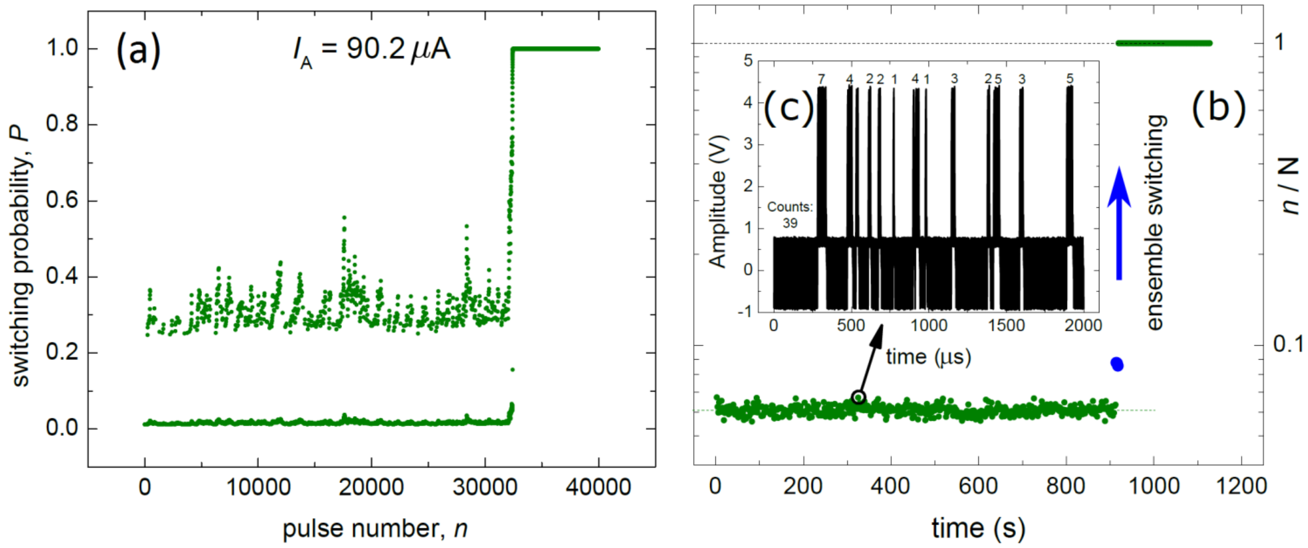

***Fig.15. Metastable state close to transition point. (a)** Numerically calculated trace of the switching probability P(n). The evolution proceeds along two branches with P jumping between them dependently on the history of the system: if there is a switching event for the (n-1)th pulse, the probability for the nth pulse adds a point to the upper branch of the trace; otherwise the evolution progresses through the lower branch. Stochastic trajectory reveals moment when the system transits to state P = 1. This phenomenon was nicknamed "ensemble switching". **(b)** Experimental demonstration of the ensemble switching and **(c)** preceding it, bunching of switching events corresponding to enhanced switching probability of the upper branch of P(n) from the panel (a). Published [H5].*

The exact explanation of the presented stochastic process involves a numerical recursive model incorporating the stochastic heating and deterministic cooling with both ingredients determined with the switching thermometry. *"The model involves overheating of electrons, giving rise to nearest-neighbor correlation in the switching measurements, and overheating of phonons, accounting for long-range correlations between pulses. The engineered stochastic trajectories, like the one presented in the **Fig. 15c**, can be viewed as an artificial phase transition, and provide an interesting experimental framework for studying correlated systems and lifetimes of metastable states. The process resembles the familiar transition from superconducting to normal state in the current-bias nanowire, proceeding through phase slip avalanche. The introduced switching protocol, using continuous pulse trains, can be used as a basis for a hysteretic detectors of magnetic flux, current and* *temperature when a vanishingly small, but permanent changes of these parameters are traced [H5, my own text]".*

g) Static and dynamic temperature

One may wonder if the electron temperature T_e is a properly defined concept during the rapid thermal transient considered in my experiments. Can we define the electron population with the Fermi-Dirac distribution which would be uniquely described by the parameter T_e during such transients? Such apprehension makes some physicists use term of *effective* or *dynamic* temperature for studying rapid thermal transients to distinguish it from the thermodynamic temperature. For nonequilibrium states it is also common approach to consider number and energies of quasiparticles explicitly ("microscopic approach"). Such treatment is computationally much more complicated and must involve many simplifications or assumptions. In equilibrium it may be fortunately replaced by thermodynamical approach, since the temperature describes then the number and energies of quasiparticles. In fact, the question is equivalent to asking what is the rate of electron-electron interaction G_{ee} in a superconducting material. If it is much larger than the rate of electron-phonon relaxation G_{ep}, the temperature is properly defined. Electrons have enough time to "agree" the occupation of states themselves before they have chance to emit phonons. In the opposite limit, $G_{ee} << G_{ep}$, and electrons can be found in non-equilibrium occupation of states. It is a deep fundamental issue which has been speculated on the theoretical grounds so far. The switching thermometry puts some experimental light on this problem and seems to confirm that electrons after initial disturbance converge very quickly to the equilibrium Fermi-Dirac distribution. As far as I understand electron-electron interaction (e-e) is the fastest in the studied nanostructures and it makes the electron distribution approach the equilibrium with a well-defined thermodynamic temperature very quickly. Such interpretation is supported by the work H4, where it is shown that the dynamic temperature (as measured during temporal transients) is the same as the static temperature (measured in equilibrium). It is evidenced by exactly the same shape of S curves measured in static and dynamic conditions (**Fig.16**). This result suggests that in the steady state Joule-heated electrons converge very quickly to Fermi-Dirac distribution, as expected for temperatures above T_c=1.3 K in the normal state (although the bath (phonon) temperature is, say, T_0=0.4 K). When the heating current is switched off, electrons start to lose energy cooling down towards bath temperature. It can be thought of as a quasi-static relaxation of the Fermi-Dirac distribution: electrons give up energy to phonons and the temperature defining the Fermi-Dirac distribution becomes lower as time progresses. Thus, electron temperature is a properly defined concept in the discussed experiments.

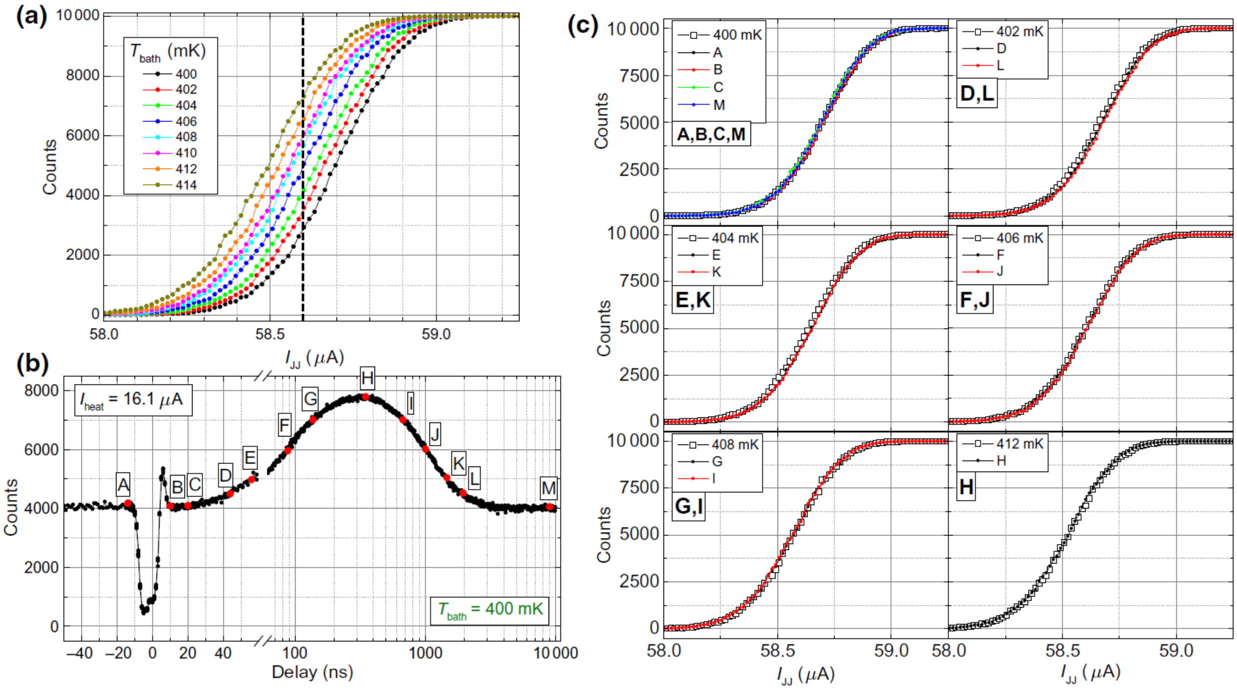

Fig.16. Comparison of the S curves collected in the static and dynamic measurements. (a) *Set of the static S curves collected at the fixed bath temperatures (in the equilibrium state).* ***(b)*** *Temporal trace of the switching probability after exciting electrons with a short (duration <10 ns) heating pulse at Delay = 0* ***(c)*** *The dynamic S curves (solid circles) collected for various delays corresponding to points A, B,. . ., M in (b) as compared to the static S curves measured at fixed bath temperatures (open squares). If to assume that S curve is a unique fingerprint of quasiparticle occupation, remarkable coincidence of the dynamic and static S curves, implicates well-defined thermodynamic temperature of electron gas overheated with respect to the lattice during thermal transient. Published [H4].*

1.5. Heat balance equation

Throughout my work I analyzed the thermal dynamics of electron gas in a nanostructure using one dimensional heat balance equation (**Fig.17**):

$$I_{IN} + Ri^2 = P_{ep} + I_{OUT} + C_v \frac{dT}{dt}$$

The equation states that the change in the internal energy of electron gas $C_v dT$ arises from the difference in energy of the ingoing and outgoing fluxes of hot electrons I_{IN}-I_{OUT}, power released to phonons P_{ep} and, if electric current is present, Joule heating Ri^2.

The equation can be converted into the partial differential equation:

$$\frac{\delta}{\delta x}\left(\kappa(T_e)\frac{\partial T_e}{\partial x}\right) = C_v(T_e)\frac{\partial T_e}{\partial t} + P_{ep}(T_e) - \frac{r \cdot i^2}{A},$$

where κ is the electron thermal conductivity, C_v is the electron heat capacity, P_{ep} is power transferred from electrons to phonons and r is the unit volume resistance. For more information on these parameters see Supplementary Materials of ref. H2 and ref. H4.

I developed a versatile solver for this equation with the *Matlab PDE toolbox*, subsidized by numerical calculation of $\kappa(T_e)$ and $P_{ep}(T_e)$ in the *Wolfram Mathematica*.

The discussed heat balance equation was used in the analysis of experiments presented in sections 1.4b and 1.4d.

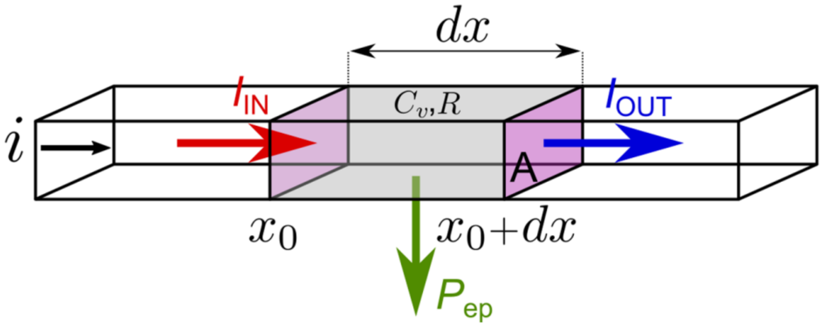

Fig.17. The graphical representation of energy conservation *in a small volume Adx.*

1.6. Summary

I have presented a novel type of nanoscale low temperature electron thermometry dubbed the switching thermometry, that was developed by me over recent years in Poland. I employed the new method for a few cutting-edge experiments in the field of experimental low temperature thermodynamics, providing a proof-of-the-concept of my idea. The experiments are described in 5 Physical Review papers, which constitute the basis for habilitation procedure. My approach offers the unique probing capabilities outperforming any other system in the world in experiments where fast temperature monitoring is a key to understand thermal processes at nanoscale**.** Curiously enough, the method is based on the measuring an abstract probability from which the electron temperature can be uniquely deduced. The presented research is scientifically and technologically sound, original and concrete. It has been appreciated by positive reviewers' evaluations of my publications and successful grant applications. As a leader of projects funded by FNP and NCN I was able to raise the budget of ~7 MPLN to support my already finished and still ongoing experiments.

It is my hope to establish a new research field in Poland. I am not merely continuing the investigations within one of the well-established experimental directions in Poland, but trying to bring very fresh ideas and concepts making use of a new technological potential that has appeared in Poland recently with the purchase of expensive and advanced equipment i.e. facilities for fabricating the functional nanostructures and the low temperature apparatus.

1.7. References

H1. M. Foltyn, **M.Zgirski***, *Gambling with Superconducting Fluctuations* , **Phys. Rev. Applied** 4, 024002 (**2015**)

H2. **M. Zgirski***, M. Foltyn, A. Savin, K. Norowski, M. Meschke, J.Pekola, *Nanosecond thermometry with Josephson junctions*, **Phys. Rev. Appl.** 10, 044068 (**2018**)

H3. **M. Zgirski***, M. Foltyn, A. Savin, K. Norowski, *Flipping coin experiment to study switching in Josephson junctions and superconducting wires*, **Phys. Rev. Appl.** 11, 054070 (**2019**)

H4. **M. Zgirski***, M. Foltyn, A. Savin, A. Naumov, K. Norowski, *Heat Hunting in a Freezer: Direct Measurement of Quasiparticle Diffusion in Superconducting Nanowire*, **Phys. Rev. Applied** 14, 044024 (**2020**)

H5. **M. Zgirski*,** M. Foltyn, A. Savin, and K. Norowski, *Stochastic thermal feedback in switching measurements of superconducting nanobridge caused by overheated electrons and phonons*, Phys. Rev. B, accepted 15/06/2021

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17. O.-P. Saira, **M. Zgirski**, K.L. Viisanen, D.S. Golubev, and J.P. Pekola, *Dispersive thermometry with a Josephson junction coupled to a resonator*, Phys. Rev. Appl. 6, 024005 (2016)
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K.Ch. Fong, *Graphene-Based Josephson junction Single-Photon Detector*, Phys. Rev. Applied 8, 024022 (2017)

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26. **M. Zgirski**, L. Bretheau, Q. Le Masne, H. Pothier, D. Esteve, C. Urbina, *Evidence for long-lived quasiparticles trapped in superconducting point contacts*, Phys. Rev. Lett.106, 257003 (2011)
27. M. Devoret, D. Esteve, C. Urbina, J. Martinis, A. Cleland, J. Clark, *Macroscopic Quantum Mechanics of the Current Biased Josephson Junction*, "Exploring the quantum/classical frontier" edited by J. Friedman, S. Han, Nova Science Publishers (2003)
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29. W. Wernsdorfer, *From micro- to nano-SQUIDs: applications to nanomagnetism,* Superconductor Sci. Techn. 22 (2009) 064013

2. Scientific experience

Since 12/2010: Researcher, Institute of Physics, Polish Academy of Sciences, Laboratory of Cryogenic and Spintronic Research SL2.2, Warsaw, Poland.

10/2021 – 12/2021 visit to the Low Temperature Laboratory, Aalto University, Finland, supported by European Microkelvin Platform (https://emplatform.eu/).
Implementation of my own project:
Quasiparticle diffusion and thermal relaxation in Meissner and vortex states

07/2014 - 12/2014: Internship, PICO Group headed by Academy Professor Jukka Pekola, Low Temperature Laboratory, Aalto University, Finland.
http://ltl.tkk.fi/PICO/wordpress/
Development of the fast thermometer based on the proximity Josephson junction embedded in the microwave coplanar superconducting resonator and probed with microwaves.

10/2008 – 09/2010: PostDoc, Quantronics Group , CEA Saclay, France,
http://iramis.cea.fr/spec/Pres/Quantro/static/index.html
Spectroscopy of Andreev bound states in superconducting atomic contacts.

01/2004 – 09/2008: PhD studies, Nanoscience Center, University of Jyväskylä, Finland. **Thesis title: Experimental study of fluctuations in ultra-narrow superconducting nanowires** , available at https://jyx.jyu.fi/handle/123456789/18917?locale-attribute=en, for list of publications see page XV of the thesis

10/2001 – 06/2002: Student, Socrates-Erasmus scholarship,
Department of Physics, University of Jyväskylä, Finland

09/2003: Master of Science (with distinction), Warsaw University of Technology, Faculty of Physics, Solid State Ionics, Physics, Best Master Thesis Award at WUT in 2003, founded by FIAT company.

1998 - 2003: Student, Warsaw University of Technology, Faculty of Physics, Poland
Specialization: Solid State Physics
Obtained scholarship for excellence twice (2001/2002 and 2002/2003)

3. The works published after obtaining PhD

3.1. Publications comprising the basis for habilitation

Publications, for which I was a leader and a main investigator. I am corresponding author for all of them (*). They all appeared in the course of realization of my own research grants (Homing Plus, FNP and First Team, FNP). They were all fully written by me. I was also preparing the response to reviewer criticism in all cases. They serve as a proof of my scientific maturity. All measurements (except for H1) were carried out in my laboratories placed at IP PAS. H1 was also measured at IP PAS but not in my refrigerator. The laboratories were built by me from scratch involving hardware installation and writing the software for data acquisition – see also section 8.

H1. M. Foltyn, **M. Zgirski***,
Gambling with Superconducting Fluctuations, **Phys. Rev. Applied 4**, 024002 (2015)

H2. M. Zgirski*, M. Foltyn, A. Savin, K. Norowski, M. Meschke, J. Pekola,
Nanosecond Thermometry with Josephson Junctions, **Phys. Rev. Applied 10**, 044068 (2018)

H3. M. Zgirski*, M. Foltyn, A. Savin, K. Norowski,
Flipping-Coin Experiment to Study Switching in Josephson Junctions and Superconducting Wires,
Phys. Rev. Applied 11, 054070 (2019)

H4. M. Zgirski*, M. Foltyn, A. Savin, A. Naumov, K. Norowski,
Heat Hunting in a Freezer: Direct Measurement of Quasiparticle Diffusion in Superconducting Nanowire, **Phys. Rev. Applied 14**, 044024 (2020)

H5. M. Zgirski*, M. Foltyn, A. Savin, K. Norowski,
Stochastic thermal feedback in switching measurements of superconducting nanobridge caused by overheated electrons and phonons, **Phys. Rev. B 104**, 014506 (2021)

3.2. Other publications

a) Publication, for which I was a leader and a main investigator. I am corresponding author (*****). It was fully written by me. It appeared as a result of the realization of my own research grant (Homing Plus). It is not thematically related to my habilitation.

1. Ł. Pawliszak, M. Tekielak, **M. Zgirski***, *Miniature coils for producing pulsed inplane magnetic fields for nanospintronics*, Rev. Sci. Instrum. **86**, 034711 (2015)

b) Publication, which appeared as a main result of my 2-years long PostDoc in Quantronics group (2008-2010). It is work thematically related to my habilitation and comprises part of the necessary background for my current scientific investigations. I was the main investigator, but not a leader. I prepared sample, performed measurements, took part in analysis and interpretation of results but I did not write the paper.

1. **M. Zgirski**, L. Bretheau, Q. Le Masne, H. Pothier, D. Esteve, C. Urbina,
Evidence for Long-Lived Quasiparticles Trapped in Superconducting Point Contacts,
Phys. Rev. Lett. **106**, 257003 (2011)

c) Publication , which appeared as a result of my half an year internship in PICO group (07-12/2014). I was one of the two experimental investigators. I provided a strong support in design, fabrication, measurement and analysis of on-chip microwave circuits. I did not write the paper.

1. O.-P. Saira, **M. Zgirski**, K. L. Viisanen, D. S. Golubev, and J. P. Pekola,
   Dispersive Thermometry with a Josephson Junction Coupled to a Resonator,
   Phys. Rev. Applied **6**, 024005 (2016)

d) Publications, in which I delivered a technical support/expertise:

1. B. J. O'Dowd, T. Wojtowicz, S. Rouvimov, X. Liu, R. Pimpinella, V. Kolkovsky, T. Wojciechowski, **M. Zgirski**, M. Dobrowolska, I. V. Shvets, J. Furdyna,
   Effect of catalyst diameter on vapour-liquid-solid growth of GaAs nanowires,
   J. Appl. Phys. **116**, 063509 (2014)
2. D. Sztenkiel, M. Foltyn, G. P. Mazur, R. Adhikari, K. Kosiel, K. Gas, **M. Zgirski**, R. Kruszka, R. Jakiela, Tian Li, A. Piotrowska, A. Bonanni, M. Sawicki, T. Dietl,
   Stretching magnetism with an electric field in a nitride semiconductor,
   Nat. Commun. **7**, 13232 (2016)
3. G. P. Mazur, K. Dybko, A. Szczerbakow, J. Z. Domagala, A. Kazakov, **M. Zgirski**, E. Lusakowska, S. Kret, J. Korczak, T. Story, M. Sawicki, T. Dietl,
   Experimental search for the origin of low-energy modes in topological materials,
   Phys. Rev. B **100**, 041408(R) (2019)

3.3. Patents granted (with my > 50% participation):

1. **M. Zgirski**, Ł. Pawliszak, *Microscope stage for magnetic measurements*,
   Polish patent no. 226304
2. **M. Zgirski**, M. Foltyn, *Method for generating random numbers and the system for generating random numbers*, Polish patent no. 227546
3. **M. Zgirski**, M. Foltyn, *Method for measuring temperature of nonequilibrium thermal processes and the circuit for the application of this method*, Polish patent no. 231182

4. Grants awarded

a) where I am/was a leader:

1. SONATA BIS-9, National Center for Science, *Thermodynamics of nanostructures at low temperatures*, start: 01/04/2020, nominal duration: 5 years, budget: **3 341 000 PLN**
2. First Team (0036) – extension of the basic grant awarded in the contest, Foundation for Polish Science, *Stochastic thermometry with Josephson Junction down to nanosecond resolution*, duration: 01/04/2020 - 30/06/2022, budget: **1 200 000 PLN**
3. First Team (0036), Foundation for Polish Science, *Stochastic thermometry with Josephson Junction down to nanosecond resolution*, duration: 01/09/2016 - 31/03/2020, budget: **2 000 000 PLN**
4. Homing Plus (066), Foundation for Polish Science, *Properties of magnetic nanostructures studied with superconducting devices*, duration: 01/09/2011 – 30/11/2013, budget: **328 000 PLN**

b) where I played one of key roles:

1. FP7-REGPOT-2012-2013-1 (316014), EU & Polish Ministry of Science and Higher Education, European Action towards Leading Centre for Innovative Materials – I was in a small group of scientists that initiated the application and defined the successful strategy, and took part in writing the proposal; Work Package 4 Vice-Leader (purchase of Triton and Heliox refrigerators), responsible for twinning with 2 foreign partners, duration: 01/10/2013 – 30/11/2016, budget: **5 000 000 EUR**,

5. Teaching activities

5.1. Lectures

1. Set of 5 x 2h lectures on *Macroscopic manifestation of quantum mechanics* delivered within Modern Problems in Physics for 5th year students of Faculty of Physics at Warsaw University of Technology (in 2011 and in 2012), http://info.ifpan.edu.pl/~zgirski/zgirski_teach.html

5.2. PhD student supervision

1. Konrad Norowski (started 01/01/2018), employed in my FNP project.

5.3. Supervised Master Theses (performed within my own research projects)

1. Anna Jodko, *Zastosowanie metody impulsowej do pomiarów magnetycznych przy użyciu czujników SQUID*, Warsaw 2012
2. Łukasz Pawliszak, *Kontrola ruchu domen magnetycznych w nanodrutach permalojowych wytwarzanych metodą litografii elektronowej*, Warsaw 2014
3. Konrad Norowski, *Wytworzenie i charakteryzacja złącz Josephsona do zastosowań w magnetometrii i termometrii*, Warsaw 2017
4. Paulina Grządczkowska, *Wyznaczanie czasu relaksacji termicznej nanostruktur nadprzewodzących*, Warsaw 2020

5.4. Supervised Bachelor Thesis (performed within my own research project)

1. Aleksandra Szymańska, *Pomiary impulsowe nanostruktur nadprzewodzących*, Warsaw 2020

5.5. PostDoc supervision

1. Andrii Naumov, employed in my FNP project from 01/04/2018 to 31/07/2020

6. Reviewing activity

Journal and number of reviews prepared by me:

Physical Review Letters - 5
Physical Review X Quantum - 2
Physical Review B - 17
Physical Review Applied - 4
Physical Review Materials - 2

Physical Review A - 1
Physical Review Research - 3
Journal of Applied Physics - 1

7. Conference and seminars after obtaining PhD

7.1. Invited presentations (oral, if not stated otherwise):

1. *Josephson effect in weak superconducting links (Observation of single Cooper pairs)*,
Faculty of Physics, University of Białystok, December 2011

2. *Quasiparticle trapping in Andreev Bound States*,
Non-equilibrium and coherent phenomena at nanoscale, Chernogolovka, Russia, June 2012

3. *SQUIDs in physics*, PTB Berlin, Germany, November 2013

4. *Josephson Junction as a thermometer*,
PICO group/Lounasmaa Low Temperature Laboratory, Aalto University, Finland, July 2014

5. *Sensitivity of NIS thermometer (linear microwave probing)*, PICO group/Lounasmaa Low Temperature Laboratory, Aalto University, Finland, October 2014

6. *Heat conduction in a superconducting wire*, PICO group/Lounasmaa Low Temperature Laboratory, Aalto University, Finland, November 2014

7. *Stochastic thermometry with Josephson junction down to nanosecond resolution*, PICO group /Lounasmaa Low Temperature Laboratory, Aalto University, Finland, September 2016

8. *Pomysł na Spin-off*, Center for Technology Transfer of the Institute of Physics PAS Workshop in the series „INNOVATION DAY: innowatorzy vs. Biznes", Jachranka, Poland, October 2017

9. *Nanosecond thermometry with Josephson junction*, International Workshop – Probing Coherent Superconducting Hybrids at the Nanoscale, Eilat, Israel, February 2019

10. *How to measure temperature by flipping a coin?*,
Vortex 2019, Antwerp, Belgium, May 2019, invited "super" poster

11. *Switching thermometry: How to measure temperature by flipping a coin?*,
BTNT 2019, Bhubaneswar, India, December 2019

12*. Thermodynamics of nanostructures at low temperatures. How to measure temperature by flipping a coin?*, Faculty of Physics, Adam Mickiewicz University of Poznań, November 2020 (online)

13. *Switching thermometry for dynamical investigations of thermal processes at nanoscale*,
LCN workshop, Laboratory of Superconducting Nanoelectronics, Nizhny Novgorod State Technical University and Center for Quantum Technologies, 01/10/2021 (online)

14. *Switching thermometry for dynamical investigations of thermal processes at nanoscale,*
Aalto Quantum Physics Seminars, Aalto University, Finland, 07/12/2021 (on-site, transmitted)

7.2. Other presentations (talks):

15. *Wytwarzanie bramki typu T tranzystora HEMT metodą litografii elektronowej*,
Krajowa Konferencja Elektroniki, Darłówko, Poland, June 2012

16. *Dispersive thermometry with a Josephson junction coupled to a resonator*,
Reporting session of the Institute of Physics PAS, February 2017

17. *How to measure temperature by flipping a coin?*,
Reporting session of the Institute of Physics PAS, February 2019

18. *Nanosecond thermometry with Josephson junction*, EUCAS 2019 - 14th European Conference on Applied Superconductivity, Glasgow, UK, September 2019

19. *Heat hunting in a freezer: direct measurement of quasiparticle diffusion*,
Reporting session of the Institute of Physics PAS, February 2021

20. *Heat hunting in a freezer: direct measurement of quasiparticle diffusion in a superconducting nanowire*,
Vortex 2021 - the 18th International Workshop on Vortex Matter in Superconductors (online)

21. *Heat hunting in a frezer: Direct measurement of quasiparticle diffusion in a superconducting nanowire*,
EUCAS-2021 - the 15th European Conference on Applied Superconductivity, Moskwa, Rosja (online)

22. *Stochastic thermal feedback in switching measurements of a superconducting nanobridge caused by overheated electrons and phonons*,
Reporting session of the Institute of Physics PAS, February 2022

8. Creating a new experimental infrastructure at IF PAN

My accomplishments:

a) Securing funding (see section 5, EAGLE project), organization and technical supervision of the purchase (writing a tender, consultations with laboratories in France, Finland and Poland – on-site inspections), installation and tests of the Triton 400 dilution refrigerator (**Fig.18**), and the He^3 sorption Heliox refrigerator (**Fig.19**). http://www.eagle-regpot.eu/EAgLE-Equipment_Triton400.html

b) Building from scratch two laboratories (hardware, room, equipment, sample holders, extended wiring, installation of home-built and commercially available EM filters) for Triton 400 and Heliox (2013-2021).

c) Constructing the compact, easy-to-use gas handling system and designing the ergonomic He^4 dewar for Heliox.

Fig.18. Triton 400 laboratory. *Cryogen-free dilution refrigerator. Sample is cooled to the base temperature of 10mK in 12 hours with bottom loading mechanism. Equipped with 6-1-1T vector magnet.* ---→

Fig.19. Heliox laboratory. *Base temperature is 230 mK. The cool-down time from room temperature is only 45 minutes. The holding time for a single experiment with initially full dewar (100l of LHe^4) is 12 days.*

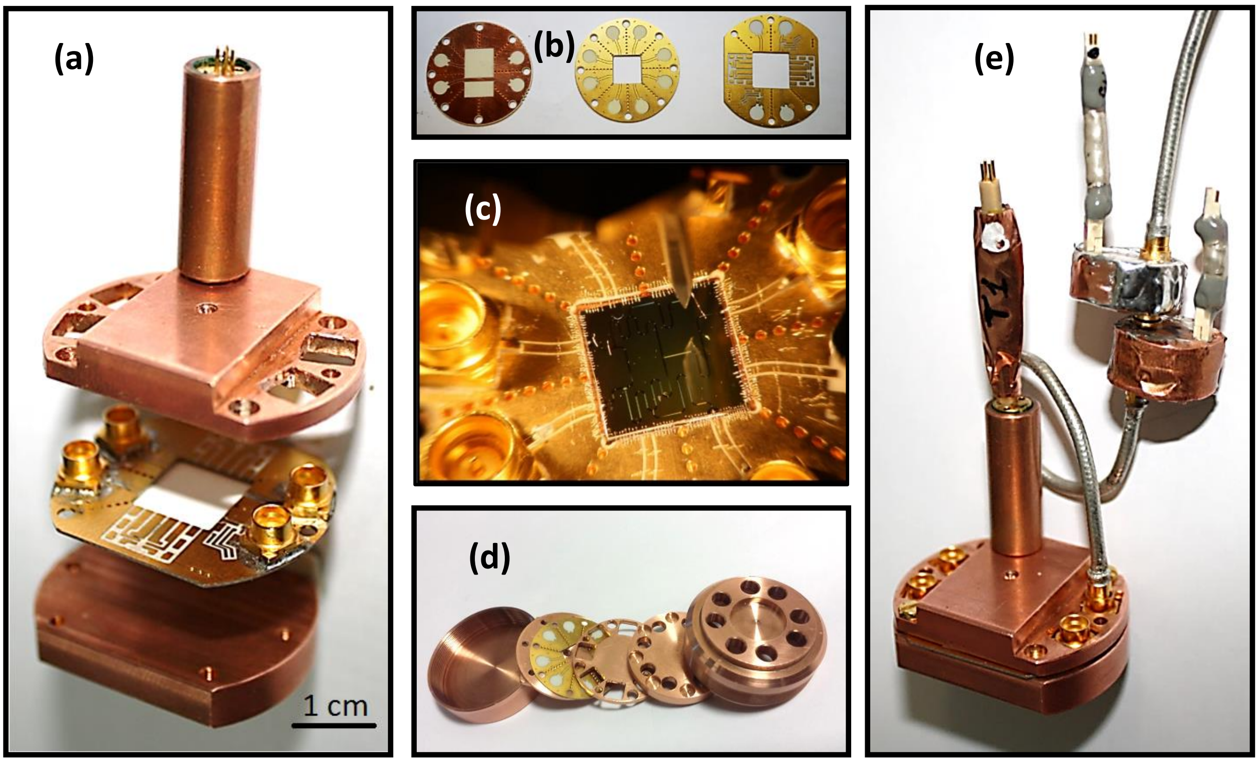

Fig.20. *The essential* ***home-made hardware*** *compatible with the Triton 400 dilution refrigerator and Heliox He3 sorption refrigerator.* ***(a)*** *Exploded view of the shielded microwave-compatible sample holder designed by me and fabricated in the IF PAN workshop by Stanisław Jasiński. The column at the top contains RuO_x thermometer for 4-probe measurements of the temperature.* ***(b)*** *Microwave compatible PCBs developed in my group either by me (two in the left) or under my supervision (by my PhD student Konrad Norowski).* ***(c)*** *The PCB with the installed sample.* ***(d)*** *Disassembled microwave-compatible home-made sample holder. It was designed and fabricated within a joint collaboration of me and PICO group of Aalto University (twinning partner in the Eagle Project).* ***(e)*** *The assembled view of the sample holder with two cylindrical boxes – one for sensing the voltage, another for sensing the current, each connected to a visible low pass EM filter. Thermometer input/output terminated with another filter. Boxes and filters designed by me and manufactured under my supervision by my PhD student Konrad Norowski and my PostDoc Andrii Naumov.*

d) Organization of a tender for the PREVAC electron-beam evaporator equipped with ion gun. Serving as a consultant (2013-2016) in the frame of the IP PAS – PREVAC development cooperation allowed to reduce the price of the device significantly. In the next years subsequent gain in functionality and ergonomics by hardware extension and modification of the evaporator.

e) Creation of the system for the switching measurements of Josephson junctions - hardware (**Figs.20,22**) and software in LabView **Fig.23** using the fast pulse method. Pioneering use of the Josephson junction as a thermometer with nanosecond resolution (2014-2020). Purchase of two LeCroy oscilloscopes (12 bits, 600 MHz and 12 bits, 4 GHz), 3 arbitrary waveform generators (2 x 80 MHz and 120 MHz) and 6 amplifiers (NF-75, DL-1201).

f) Organization of a tender for a Vector Network Analyzer (VNA) and microwave source. Purchase of microwave components (cryogenic amplifiers, attenuators, RF cables, circulators, room temperature amplifiers). Creation of bases, from scratch, for ferromagnetic resonance measurements of thin magnetic layers coupled with a coplanar transmission line. Construction of a microwave holder and writing a software in LabView (2014-2015).

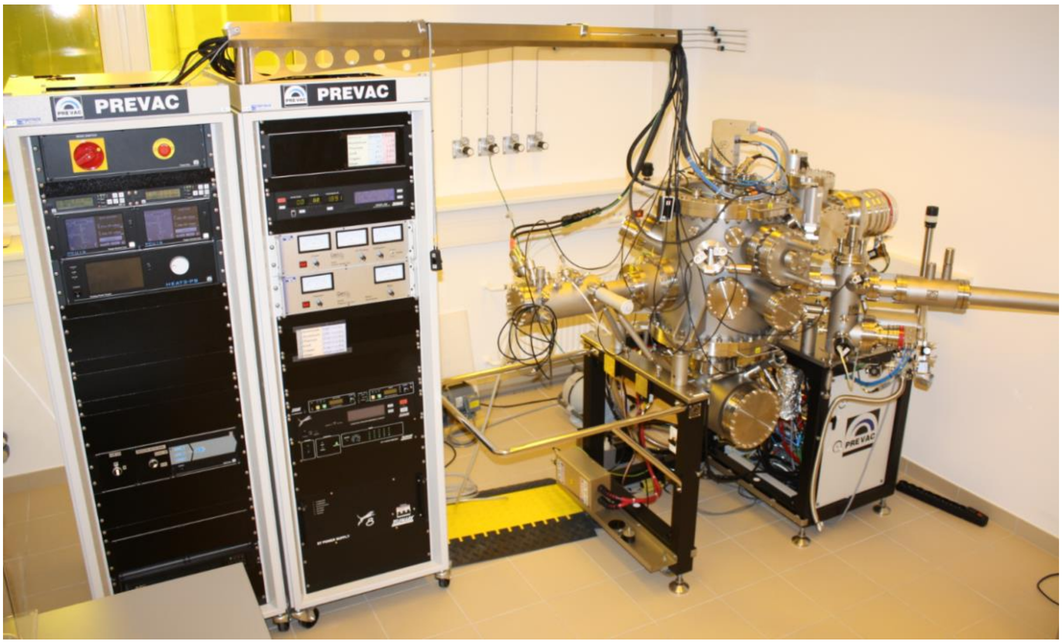

Fig.21. Electron-beam evaporator with ion gun. *Base vacuum 2*10^{-9} mBar (without annealing). The system is compatible with multi-angle e-beam lithography.*

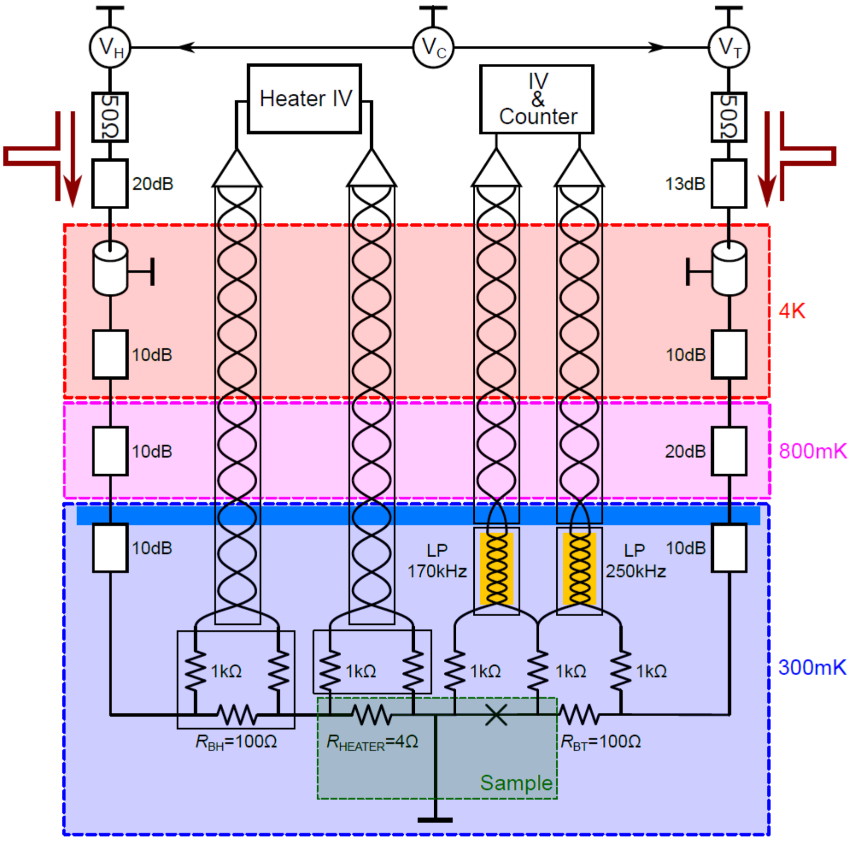

Fig.22. *The essential* ***wiring of the Triton 400 dilution refrigerator for switching measurements*** *of Josephson junctions used in publication H4. There are two microwave lines with attenuators placed at different temperatures visible in the diagram. They are used for sending fast pulses. The signal from the sample is monitored with four twisted pairs (wiggling lines). Two such pairs are additionally terminated with home-made low pass filters (LP). Two slave pulse sources V_T and V_H are triggered by master generator V_C synchronously. The switching events are monitored on the counter (oscilloscope). The diagram was published in Supplementary Material of publication H4.*

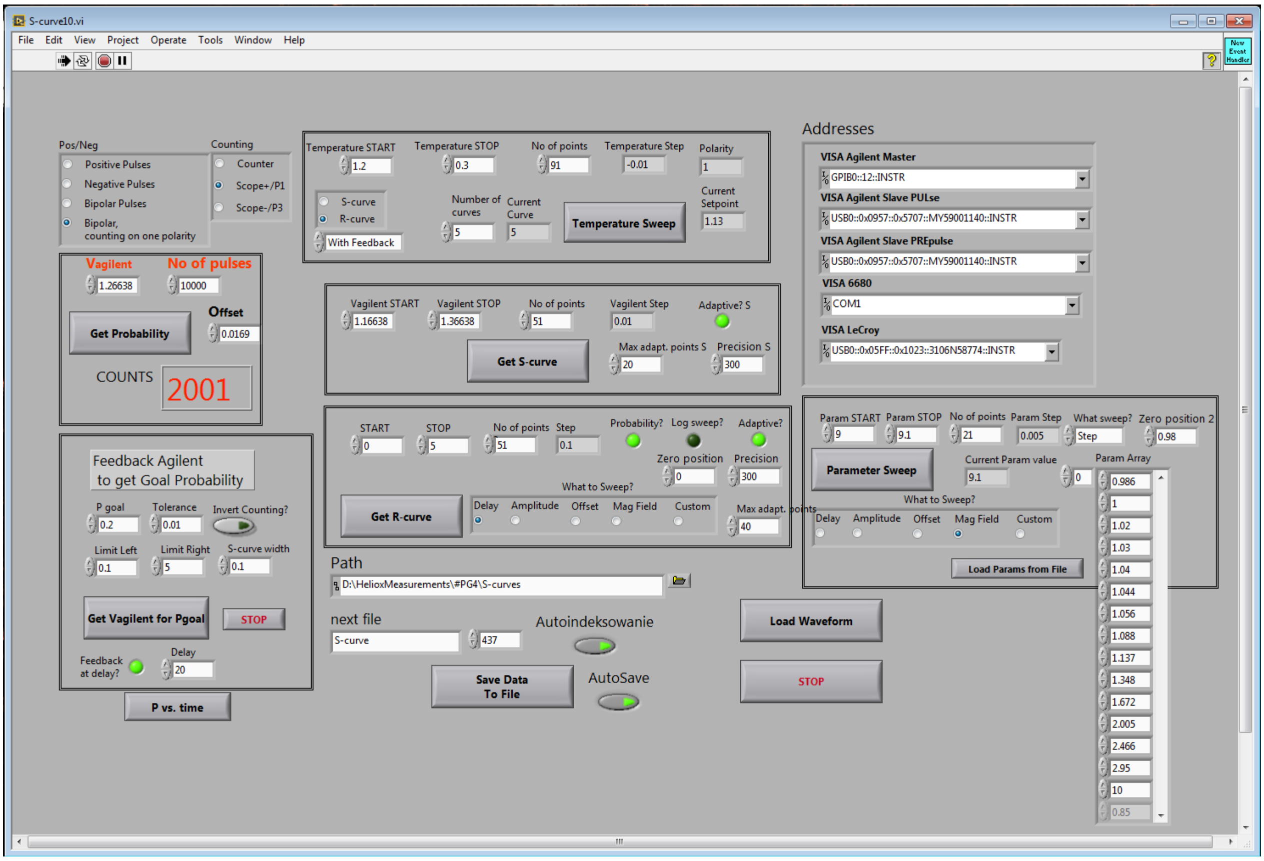

*Fig.23. Front Panel of the **LabView acquisition program for performing switching measurements** on Josephson junctions developed over recent years by me. All data presented in publications **H1-H5** were acquired with that software being extended in time.*

g) Creating an experimental setup for measuring the domain walls movement (hardware and software written in LabView) (2012-2015) – see section 3.2.a) (publication) and 3.3.1 (patent).

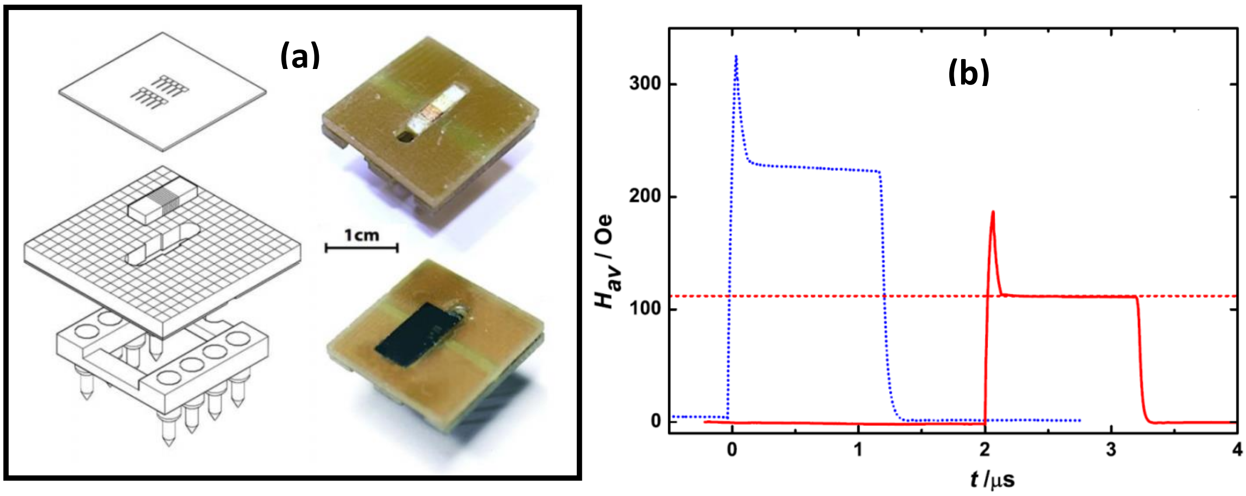

***Fig.24. Miniature coil for delivering fast magnetic field pulses** with rising times at the level of a few dozens of nanoseconds. **(a)** Exploded view of the coil assembly and its actual realization showing sample stage with and without a silicon chip. The coil is wound on a piece of a stick and it is visible in the middle of the bare stage. **(b)** Traces of magnetic field generated at the surface of silicon chip – one with a ferrite core (left, dotted line), the other with a Teflon core (right, solid line). Published [see section 3.2.a)] and patented (see 3.3.1).*

h) The purchase consultations for the apparatus installed in the Institute: Reactive Ion Etching Oxford PlasmaPro 100 Cobra, Atomic Layer Deposition FlexAl, Optical lithography MBJ4, Wire Bonder HB10 TPT (2014).

9. Popularization

1. Workshop for Young Scientist (01.2012) – Institute of Physics, PAS
2. Participant of 17. Piknik Naukowy Polskiego Radia i Centrum Nauki Kopernik ŻYCIE, National Stadium, 15/06/2013
3. Seminar for students of the Faculty on Physics of Warsaw University in the frame of cycle "Opowieści Nanotreści", *Stochastic thermometry with Josephson junction down to nanosecond resolution*, 21/11/2016

10. Prizes

2015: Supervised Master thesis won the XII edition (2015) of ABB contest for the Best Master and PhD thesis (one contest for both kind of theses), 30 000 PLN, Poland.

2016: IP PAS Director's award for the best publication in 2016 (see 3.2.d2)

11. Other activity

1. A member of the Scientific Council of the Institute elected for the 2019-2022 term.

2. A member of the IP PAS recruitment committee led by Piotr Deuar for Warsaw PhD School in Natural and BioMedical Sciences (from June 2020).

Attachments:

1. **Set of publications comprising the basis for habilitation (involves the published supplementary information):**

H1. M. Foltyn, **M. Zgirski***, *Gambling with Superconducting Fluctuations*, Phys. Rev. Applied **4**, 024002 (2015)

H2. M. Zgirski*, M. Foltyn, A. Savin, K. Norowski, M. Meschke, J. Pekola, *Nanosecond Thermometry with Josephson Junctions*, Phys. Rev. Applied **10**, 044068 (2018)

H3. M. Zgirski*, M. Foltyn, A. Savin, K. Norowski, *Flipping-Coin Experiment to Study Switching in Josephson Junctions and Superconducting Wires*, Phys. Rev. Applied **11**, 054070 (2019)

H4. M. Zgirski*, M. Foltyn, A. Savin, A. Naumov, K. Norowski, *Heat Hunting in a Freezer: Direct Measurement of Quasiparticle Diffusion in Superconducting Nanowire*, Phys. Rev. Applied **14**, 044024 (2020)

H5. M. Zgirski*, M. Foltyn, A. Savin, K. Norowski, *Stochastic thermal feedback in switching measurements of superconducting nanobridge caused by overheated electrons and phonons*, Phys. Rev. B **104**, 014506 (2021)

2. **Statements of coauthors considering their role in the indicated publications.**