1.3.5 Coherent manipulation of electronic heat currents in superconducting hybrid devices

The ability to master heat currents at the nanoscale has become an essential request in many fields of nanoscience, including solid-state cooling, radiation detection and quantum information. Phase-coherent caloritronics takes advantage of long-range phase coherence in superconducting condensates to manipulate heat currents in solid-state mesoscopic circuits. The fundamental idea is to exploit suitable physical effects that depend on the superconducting phase difference φ, in order to control the electronic heat flow between two thermal reservoirs at different temperatures. Research activities at NEST led to the realization of many different nanodevices such as hybrid thermal diodes, thermal routers, a 0−π phase-controllable thermal Josephson junction (JJ). We proposed and theoretically demonstrated heat logic and memory architectures that may be operated also at GHz regimes. The aim is to realize unconventional tools for thermal management and/or thermal logic which may be beneficial for the field of quantum technologies.

The evolution of modern electronics has been boosted by the introduction of non-linear elements like interferometers, diodes and transistors. In the last 5 years, we demonstrated that superconducting hybrid structures at cryogenic temperatures represent an ideal platform to realize the thermal counterpart of these non-linear devices.

Thermal diode. In order to realize a thermal diode, i.e. a device that allows heat to flow preferentially in one direction we proposed normal metal-insulator-superconductor (NIS) junction (see Fig. 1a) [1]. It offers a sizeable asymmetry in the thermal transport due to the temperature dependence of the energy gap in the superconducting density of states.

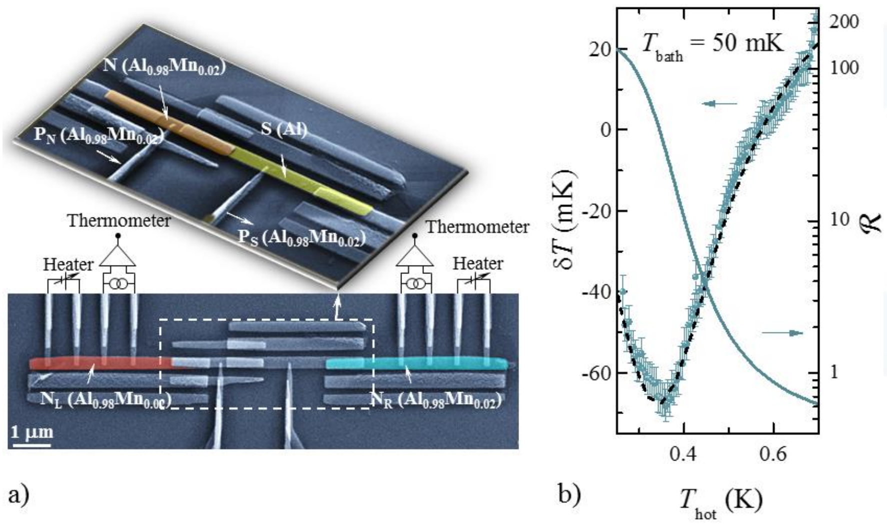

Figure 1. a) False-color scanning electron micrograph of the hybrid thermal diode. Top: NIS junction, where N stands for a normal metal (orange), I for a thin insulating layer and S for a superconductor (yellow). The probe P_N acts as a cold finger for the N electrode. Bottom: the NIS junction is inserted between two right and left N electrodes (red and blue), which act as thermal reservoirs and are connected to heaters and thermometers. b) Experimental output temperature difference δT between the forward and reverse configurations versus the bias temperature T_{hot} (left axes) measured at a bath temperature of 50 mK. Black dashed lines are the theoretical results for the device. The solid line is the thermal rectification coefficient R (right axes).

This asymmetry can be increased by connecting the N electrode to a thermalizing cold finger providing a highly efficient thermal rectification of at least one order of magnitude between the heat
current transmitted in the forward (J_{fw}) and reversal (J_{rev}) direction leading to R = $J_{fw}/J_{rev} \gg 1$ or $\ll 1$. Notably in previous experiments, a maximum R ≈ 1.4 was reported in phononic devices but our structure showed a maximum difference of more than 60 mK between the output temperatures in the forward and reverse configurations, corresponding to a heat rectification factor R ≈ 140 @50 mK (see Fig. 1b).

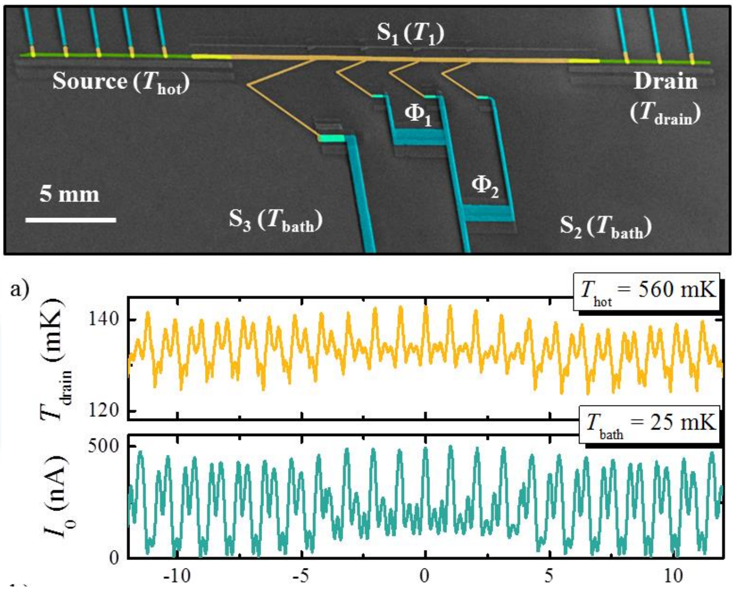

Figure 2. a) False-color scanning electron micrograph of the double-loop Josephson heat modulator. Source and drain N electrodes, depicted in green, are connected to the superconducting island S_1 (represented in orange) and to a set of heaters or thermometers (dark cyan). S_1 is tunnel-coupled to the superconducting lead S_2 (dark cyan) by means of three parallel JJs forming the double-loop SQUID and to a superconducting probe S_3 (dark cyan). b) Top: output drain temperature T_{drain} versus magnetic flux Φ_1 for a bias temperature T_{hot} = 560 mK. Bottom: magnetic flux modulation of the SQUID critical current I_0. Both curves were measured at a bath temperature of 25 mK.

Phase controlled Josephson modulator. On the other hand, it has been shown that the heat current flowing through a temperature-biased Josephson junction (JJ) has a coherent component that depends on the phase difference of the macroscopic condensates in the superconductors. This component can be manipulated at will by using a double-loop superconducting quantum interference device (SQUID) with three JJs in parallel (see Fig. 2a) [2]. Such heat modulator proved to be robust against unavoidable structure asymmetries showing exotic interference patterns of the output temperature, with large oscillation amplitude (reaching a maximum of 40 mK) and enhanced sensitivities to variations of the magnetic flux threading the loops (up to 200 mK per flux quantum). Foremost, the interferometer demonstrated the perfect correspondence between charge and heat currents (see Fig. 2b), breaking ground for advanced caloritronic nanodevices such as thermal splitters, heat pumps and time-dependent electronic engines.

Coherent caloritronics. The last experimental achievement [3] in coherent caloritronics brought us to the realization of a 0-π phase-controllable thermal JJ [4]. The latter is embedded in a superconducting quantum interference device (SQUID) containing three JJs (Fig. 3a), one of which (j) supports a lower Josephson critical current than the others (a and b).

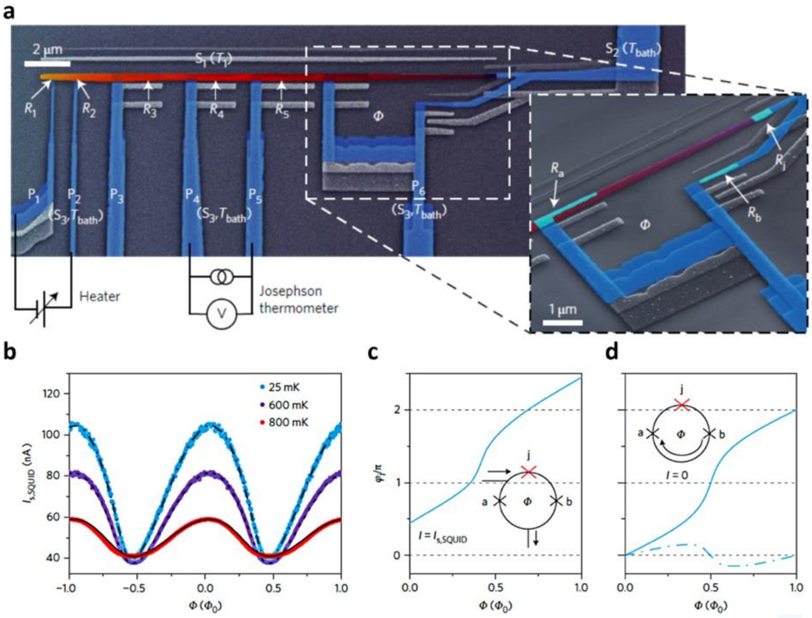

Figure 3. a) Pseudo-color scanning electron micrograph of the 0-π Josephson junction. The S_1 electrode, depicted in a yellow–red gradient, is coupled to five superconducting probes P_i (i =1,2,..,5) and to the lower branch of the SQUID P_6 (S_3, represented in blue). On the right side, S_1 is connected to the superconductor S_2 (also in blue). P_1 and P_2 are used as Joule heaters, whereas P_3, P_4, and P_5 are used to measure the electrical properties of the interferometer and to probe the electronic temperature of S_1. Inset: enlarged image of the SQUID, composed of three JJs.(b) SQUID total switching current $I_{s,SQUID}$ versus magnetic flux φ piercing the loop of the interferometer for selected values of the bath temperature T_{bath}. The filled circles are experimental values, and the black lines are the theoretical fits. (c) Calculated behavior of φ_j versus φ for the supercurrent $I=I_{s,SQUID}$ flowing through the interferometer at T_{bath}=25mK.(d) Calculated φj versus φ for I=0 and for the same parameters used in b. Dash-dotted line represents the calculated φ_a for the same parameters.

This configuration enables the phase-biasing of (j). When the magnetic flux threading the SQUID ring is varied from 0 to $\Phi_0/2$, φ_j ranges from 0 to π, namely, a result achieved for the first time in a coherent caloritronic device. As a consequence, unprecedented temperature-modulation amplitudes (~100mK at T_{bath}=25mK, see Fig. 3b), high magnetic sensitivities, and a remarkably high operational temperature up to 800mK are obtained.

Phase tunable thermal amplifiers. The advent of heat transistors and thermal memories could pave the way to a new field called thermal logic, where information is transferred, processed, and stored in the form of thermal energy.
We theoretically demonstrated the first fully-thermal caloritronic device based on an efficient thermoelectric hybrid junction coupled to a proximity heat valve: a very efficient temperature amplifier (Fig. 4a) [5]. When the input temperature T_{in}>T_{bath}, a thermoelectric current flows through a closed circuit including a superconducting coil, whose flux controls the thermal current across the heat valve. While maximum and minimum values of the output temperature T_{out}

depend on T_{bath} and T_{supply}, the value of T_{in} corresponding to the maximum T_{out} decreases as the inductive coupling is raised (see Fig. 4b). This device can provide T_{out} values in the same range as T_{in}, thus representing a crucial element for the realization of thermal logic gates.

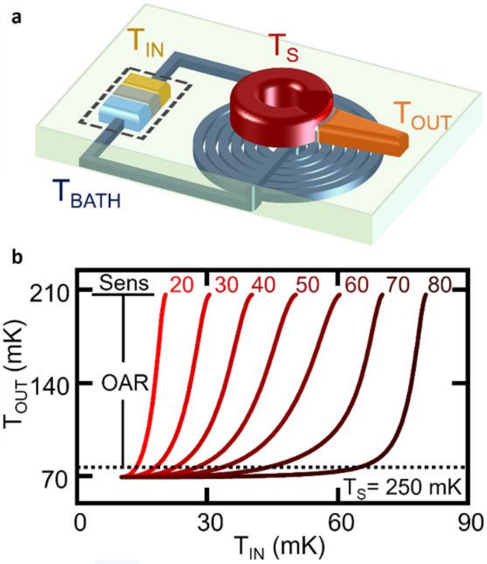

Figure 4. (a) Schematic representation of the temperature amplifier: the thermoelectric element highlighted with the dashed rectangle is constituted of a metal (yellow), a ferromagnetic insulator (gray) and a superconductor (turquoise). The turquoise depicts the superconducting coil. The SQUIPT (red) is composed of a superconducting ring interspersed by a normal metal wire and a tunnel-coupled metal probe (orange) through a thin insulator (dark gray). (b) Output temperature T_{OUT} as a function of T_{IN} calculated for T_{S}=250mK and for different values of Sens. The black dotted line represents the minimum value of active output T_{OUTMIN}. The output active range (OAR) is shown.

Thermal logic, routers and memories We envisioned novel unconventional thermal gates and logic [6] and realized thermal routers [7]. We also theoretically discussed other fundamental block required for a thermal logic: a superconducting thermal memory that exploits the thermal hysteresis in a flux-controlled, temperature-biased SQUID with a non-negligible inductance of the superconducting ring [8]. This system reveals a temperature bistability, which can be used to define two distinct logic states [9].

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