Existence of an independent phonon bath in a quantum device

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Electron thermometry and cooling in N-I-S junctions
The energy gap induces an energy-selective tunnel charge current:

\[ I_T = \frac{1}{eR_n} \int_{-\infty}^{+\infty} n_S(E) \left[ f_S(E - eV) - f_N(E) \right] dE \]

At a fixed bias current: sensitive electron thermometer.
Heat current (symmetric in bias):

\[ P_{\text{cool}}(V) = \frac{1}{e^2 R_n} \int_{-\infty}^{+\infty} (E - eV)n_S(E)[f_N(E - eV) - f_S(E)]dE \]

At \( eV < \Delta \): electronic cooling in N.
S-I-N-I-S coolers

Two cooling junctions in series: double cooling power

Electronic cooling from 300 mK down to 100 mK.

Electronic temperature directly measured.


FIG. 1. Scanning electron micrograph of a typical cooler sample in (a), and cooling data in (b), where voltage $V_P$ across the probe junctions in a constant current bias (28 pA) is shown against voltage $V_C$ across the two injection junctions. Cryostat temperature, corresponding to the electron temperature on the N island at $V_C = 0$ is indicated on the right vertical axis. Below 100 mK this correspondence is uncertain, because of the lack of calibration and several competing effects to be discussed in the text.
Basics of electronic refrigeration

Superconductor $T_{\text{bath}}$  
Out-of-eq. q.p. at $E > \Delta$

$I_T V$  
$I_T V + P_{\text{cool}}$

$I_A V$

$P_{\text{cool}}$

Normal metal $T_e$

Photons

Phonons

$T_{\text{ph}} < T_{\text{bath}}$?

Limitations of electronic refrigeration

Our objective:
Understand the coupling between the cooled e- and the phonon bath
Role of phonons?

Thermal model including phonons decoupling from the bath.

Cooling junctions, $R_t$ about 1 kΩ.

Quasi-particle trap

Phonon cooling vs electron cooling
Electron and phonon baths

Electron-phonon coupling

\[ P_{e-ph} = \sum U \left( T_e^n - T_{ph}^n \right) \]

n = 5 in a bulk clean metal


Phonon interface coupling: Kapitza resistance

\[ P_K = K A \left( T_{ph}^4 - T_{substrate}^4 \right) \]

At low T, phonon wave-length becomes comparable to structure size:

\[ \lambda_{ph} = \frac{hc}{4k_B T} \approx 60 \text{ nm in Cu at 1K} \]
Electronic refrigeration of bulk material

Cooler on a thin membrane: cooler electrons & phonons, substrate phonons at the same temperature

Electron-phonon coupling = thermal bottleneck

Heating a mesoscopic wire, while reading its electronic temperature.

\[ \frac{d\log P}{d\log T} = 5 \text{ means } T^5 \text{ law of e-ph coupling.} \]

Phonons from the substrate?

Heating experiment on different substrates.

Little sensitivity to substrate: independent phonon population in N?

A phonon thermometry experiment
A two-stage sample

A usual electronic cooler:
two junctions for cooling, two junctions for electron thermometry.
A two-stage sample

A usual electronic cooler
+
A similar device on top of the first:
can be used for electron thermometry while cooling/heating.

Inter-stage coupling through phonons only: phonon behavior accessible.
A phonon thermometer

\[ T_{e,t} - \dot{Q}_{e-ph} - T_{ph,t} = K_{t-s} \]

\[ T_{e,b} - \dot{Q}_{e-ph} - T_{ph,b} = K_{b-t} \]

\[ T_{bath} \]
Cooling and heating of the bottom stage

Differential conductance of cooler

EI. thermometry in same island
Cooling and heating of the bottom stage

Differential conductance of cooler

\[ \frac{dI}{dV}(S) = \int_{-\infty}^{+\infty} n_S(E)[f_S(E - eV) - f_N(E)]dE \]

El. thermometry in same island

Consistency check: fit using measured electron temperature + BCS DOS
Bottom cooler biased from cooling to heating regime: bottom and top electron temperature measured.
Thermal analysis

Power calculated using:

\[ P_{\text{cool}}(V) = \frac{1}{e^2 R_n} \int_{-\infty}^{+\infty} (E - eV) n_S(E) \left[ f_N(E - eV) - f_S(E) \right] dE \]

Plot as a function of absolute value of power.

Raw data show multiple-valued temperature.
Taking into account qp back-flow

Superconductor $T_{bath}$

Out-of-eq. q.p. at $E > \Delta$

$I_T V$ $I_T V + P_{cool}$

$P_{cool}$

$\alpha \cdot I_T V$

Normal metal $T_e$
Thermal analysis

Power calculated using:

\[ P_{\text{cool}}(V) = \frac{1}{e^2 R_n} \int_{-\infty}^{+\infty} (E-eV)n_S(E)[f_N(E-eV)-f_S(E)] \]

Plot as a function of **absolute value** of power.

Taking into account energy back-flow, one recovers a single curve.

\[ P = P_{\text{cool}} - \alpha |V| \]

\[ \alpha = 0.087 \]
Thermal model

Assuming two independent phonon baths

\[ T_{e,t} \quad Q_{e-ph}^t \quad T_{ph,t} \]
\[ T_{e,b} \quad Q_{e-ph}^b \quad T_{ph,b} \]

Data fit using usual e-ph and Kapitza coupling laws.

\[ K_{x-y} = KA \left( T_x^4 - T_y^4 \right) \]
\[ Q_{e-ph} = \sum U \left( T_e^5 - T_{ph}^5 \right) \]
Thermal analysis

+ symmetric exp.
Fit using usual e-ph and Kapitza coupling laws.

\[ \Sigma = 2 \text{nW.}\mu\text{m}^{-3}.\text{K}^{-5} \]
\[ A_{b-s}K_{b-s} = 2.4 \times 10^{-10} \text{pW.K}^{-4} \]
\[ A_{b-t}K_{b-t} = 9.6 \times 10^{-11} \text{pW.K}^{-4} \]
\[ A_{t-s}K_{t-s} = 1.1 \times 10^{-9} \text{pW.K}^{-4} \]

Values fit expectation except for top-substrate coupling.
Thermal analysis

Alternative models:
• $n = 4$ or $6$ in e-ph coupling
• Only one phonon bath give lower quality fit.

Need to assume independent phonon bath in the device.
Conclusion

Existence of an independent phonon bath demonstrated

Basic thermal model works

Phonon bath to be taken into account, at least in specific geometries


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