Heat Rectification under Applied Voltage

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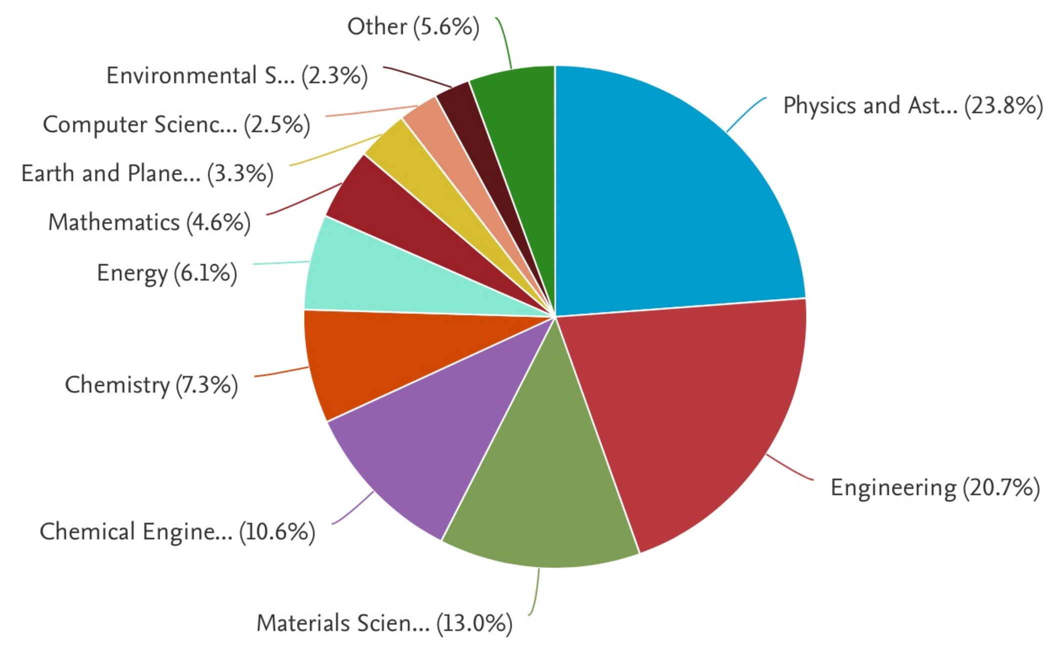
RESEARCH MOTIVATION

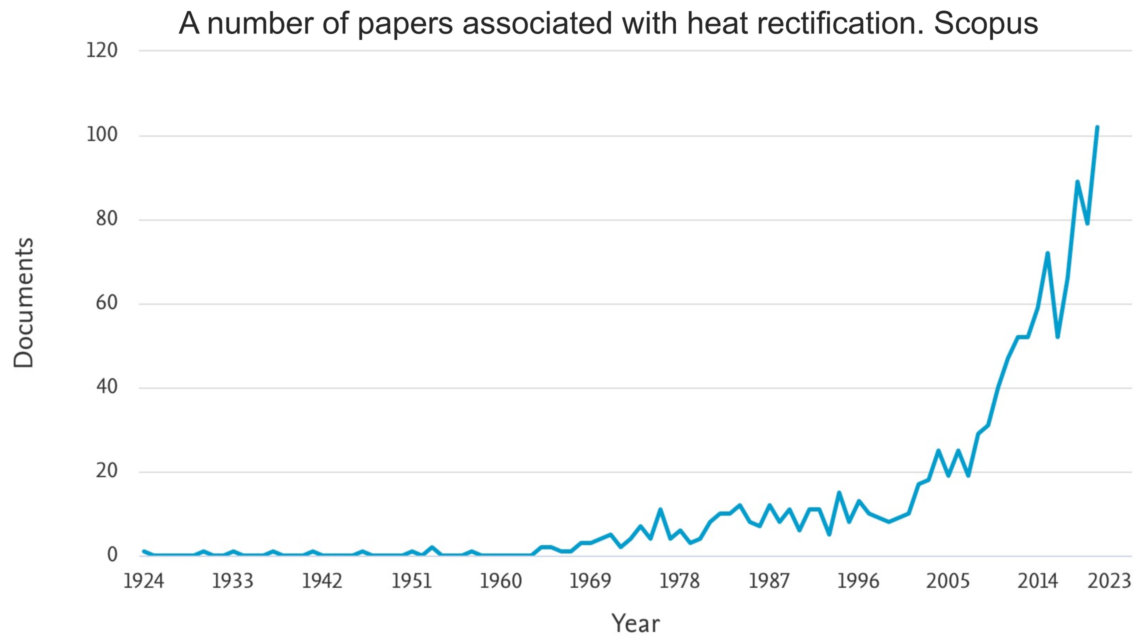
Upcoming demands

- Higher rectification coefficient
- Broader applications of thermal diodes
- Simpler device’s fabrication

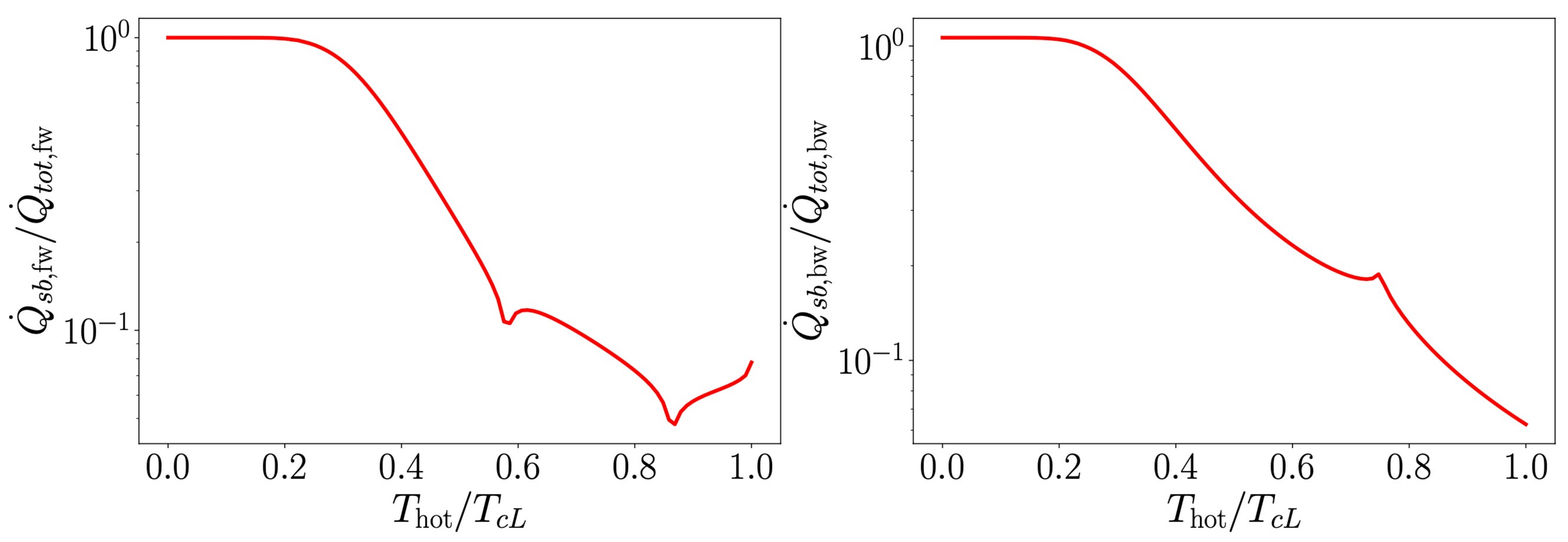


A distribution of publication related to heat rectification. Scopus

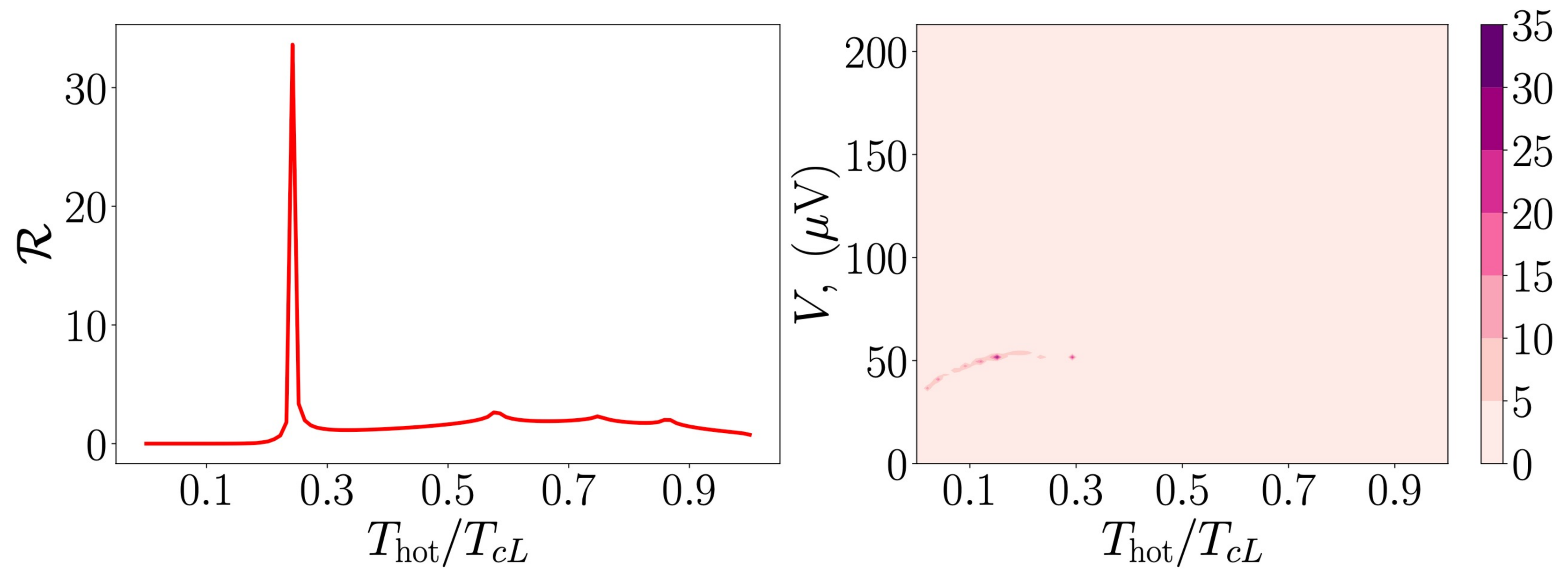
A number of papers associated with heat rectification. Scopus



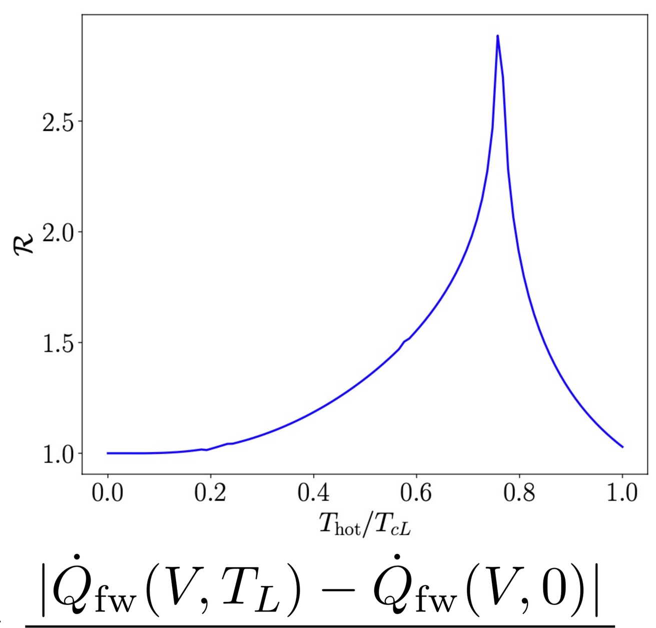
Results



A portion of the subtracted heat from the total heat flux. The results are depicted in the logarithmic scale for better visualization.



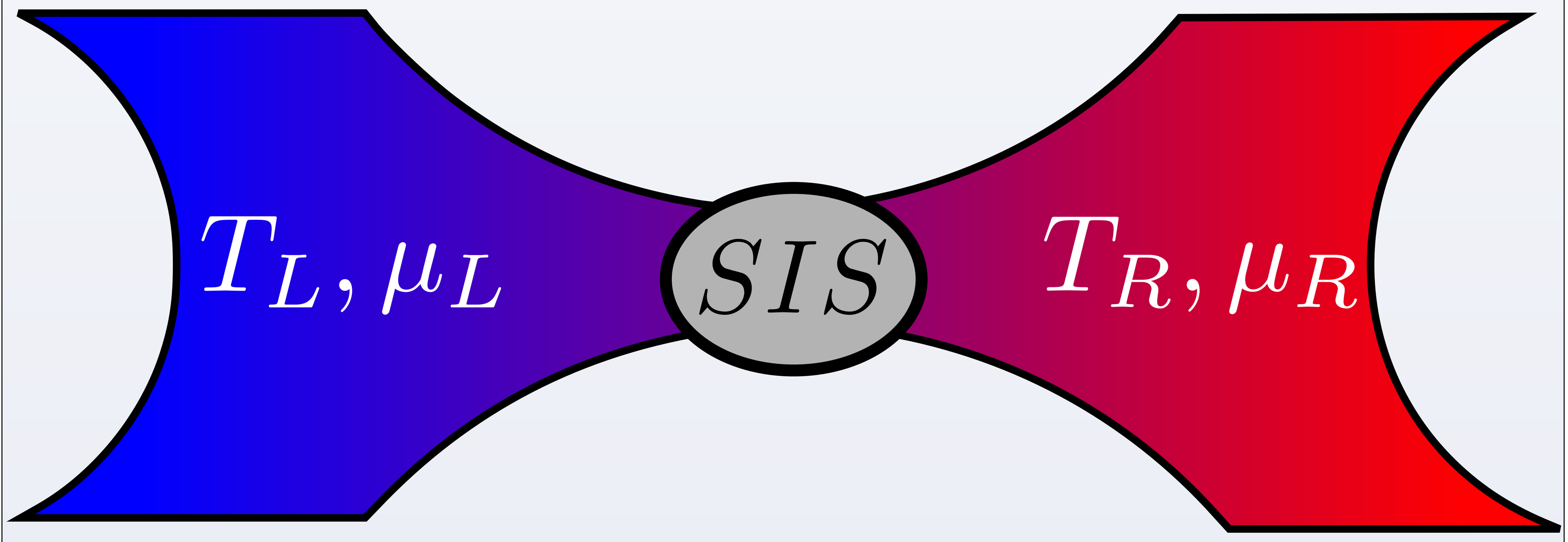
An average over time rectification coefficient as a function of temperature (left) and voltage and temperature (right). The maximum of the rectification coefficient corresponds to the frequency $\omega = 0.46$ GHz. We plotted all the curves for $T_R = 0.01T_{cL}$ and gaps’ ratio $\Delta_R(T_R = 0)/\Delta_L(T_L = 0) = 0.75$.



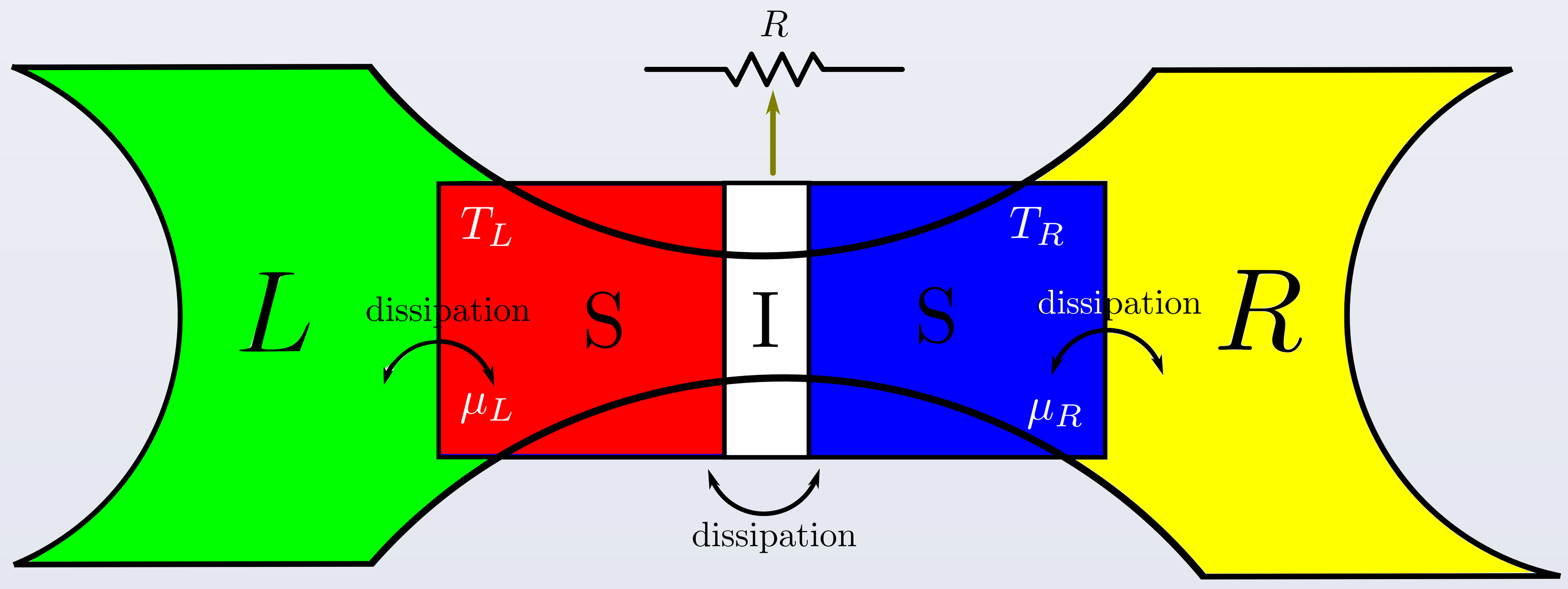
An average over the phase rectification coefficient as a function of temperature. We plotted all the curves for $T_R = 0.01T_{cL}$ and gaps’ ratio $\Delta_R(T_R = 0)/\Delta_L(T_L = 0) = 0.75$.

$$\mathcal{R} = \frac{|\dot{Q}_{\mathrm{fw}}(V, T_L) - \dot{Q}_{\mathrm{fw}}(V, 0)|}{|\dot{Q}_{\mathrm{bw}}(V, T_R) - \dot{Q}_{\mathrm{bw}}(V, 0)|} \qquad \Delta(T_{L(R)}) = 1.764 k_B T_{cL(R)} \tanh\left(\sqrt{\frac{T_{L(R)}}{T_{cL(R)}} - 1}\right)$$

Schematic Model of the Setup



Detailed Model of the Heat Rectifier



Energy conversion in an SIS junction: $\dot{Q}_{\mathrm{fw}} + \dot{Q}_{\mathrm{bw}} + I_{\mathrm{fw}}V = 0$

AC Josephson equation: $\dfrac{d\varphi}{dt} = \dfrac{2eV}{\hbar}$

Josephson currents:

$$I_{\mathrm{fw(bw)}} = I_{\mathrm{qp,fw(bw)}} + I_{j,\mathrm{fw(bw)}} \sin\varphi + I_{\mathrm{int,fw(bw)}} \cos\varphi,$$

$$\dot{Q}_{\mathrm{fw(bw)}} = \dot{Q}_{\mathrm{qp,fw(bw)}} + \dot{Q}_{j,\mathrm{fw(bw)}} \sin\varphi + \dot{Q}_{\mathrm{int,fw(bw)}} \cos\varphi.$$

Kirchhoff's current law: $[C\partial_t^2 + \dfrac{1}{R}\partial_t + 1]\varphi + \dfrac{2\pi I_c}{\Phi_0}\sin(\varphi) = -\dfrac{I_{\mathrm{fw}}}{\Phi_0}$,

where $I_{\mathrm{fw}} = -I_{\mathrm{bw}}$, $I_c = I_j(V = 0)$, $\Phi_0 = \hbar/(2e)$.

CONCLUSIONS

1. The voltage bias allows drastically increase in the rectification coefficient.
2. The amount of the suppressed Peltier heat is small near the peak.
3. An SIS junction might serve as a simple and effective tool for circuit engineering.
4. The interplay between voltage, a superconducting gaps ratio, and temperatures of superconductors in the SIS junction shows a huge number of opportunities to optimize heat rectification.
5. Time-dependent voltage might give an increase in the rectification coefficient.

APPENDIX

$$\begin{pmatrix} I_{\mathrm{qp,k}} \\ Q_{\mathrm{qp,k}} \end{pmatrix} = \frac{G_T}{e^2}\int_{-\infty}^{\infty} \begin{pmatrix} -e \\ E_k \end{pmatrix} dE\; N_k(E_k)N_m(E_m)[f_k(E_k) - f_m(E_m)],$$

$$\begin{pmatrix} I_{j,\mathrm{k}} \\ Q_{j,\mathrm{k}} \end{pmatrix} = \frac{G_T}{e^2}\int_{-\infty}^{\infty} \begin{pmatrix} -e \\ E_k \end{pmatrix} E_k dE \Big\{ \mathrm{Im}[F_k(-iE_m)]\mathrm{Re}[F_m(iE_k)]\tanh\Big(\frac{E_m}{2k_BT_k}\Big) + \mathrm{Im}[F_m(iE_k)]\mathrm{Re}[F_k(-iE_m)]\tanh\Big(\frac{E_k}{2k_BT_m}\Big)\Big\}$$

$$\begin{pmatrix} I_{\mathrm{int,k}} \\ Q_{\mathrm{int,k}} \end{pmatrix} = \frac{G_T}{e^2}\int_{-\infty}^{\infty} \begin{pmatrix} -e \\ E_k \end{pmatrix} dE\; \mathrm{Im}[F_k(-iE_m)]\mathrm{Im}[F_m(iE_k)][f_k(E_k) - f_m(E_m)], \quad k = \mathrm{fw,bw},\; m = \mathrm{bw,fw},\; E_{k,m} = E - \mu_{k,m}.$$

$$N_k(E) = \left|\mathrm{Re}\left[\frac{E + j\Gamma_k}{\sqrt{(E + j\Gamma_k)^2 - \Delta_k^2}}\right]\right|, \; F_k(E) = \frac{j\Delta_k}{\sqrt{\Delta_k^2 - (E + j\Gamma_k)^2}}.$$

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