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Enhancing cryogenic thermal diode performance via temperature-dependent contact resistance

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Thermal diodes: rectifiers of heat

FORWARD – HEAT TRANSFER

REVERSE – THERMAL INSULATION

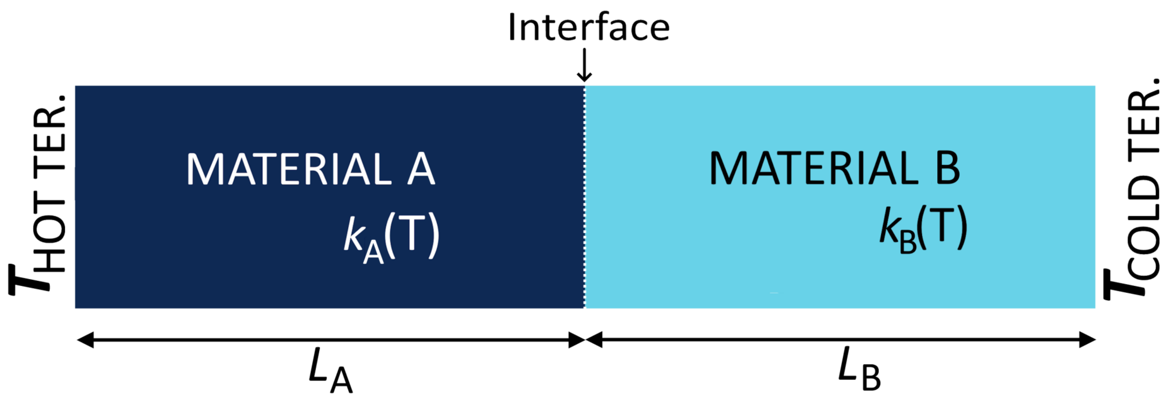
Thermal bias: $\Delta T = T_{\text{HOT TER.}} - T_{\text{COLD TER.}}$

Rectification factor (RF): ratio of forward and reverse heat fluxes

$$\text{RF} = \frac{\dot{q}_{\text{for}} - \dot{q}_{\text{rev}}}{\dot{q}_{\text{rev}}}$$

Macroscopic solid-state thermal diodes (MSTDs)

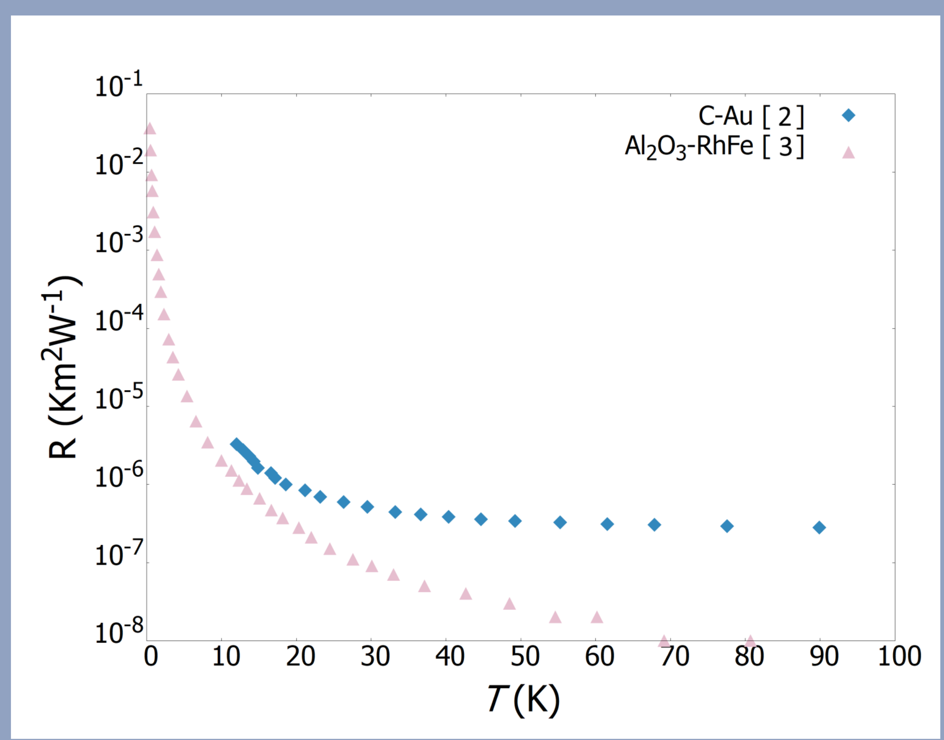
MSTDs are composed of two material segments exhibiting distinct temperature dependencies of thermal conductivity, $k_A(T)$ and $k_B(T)$.



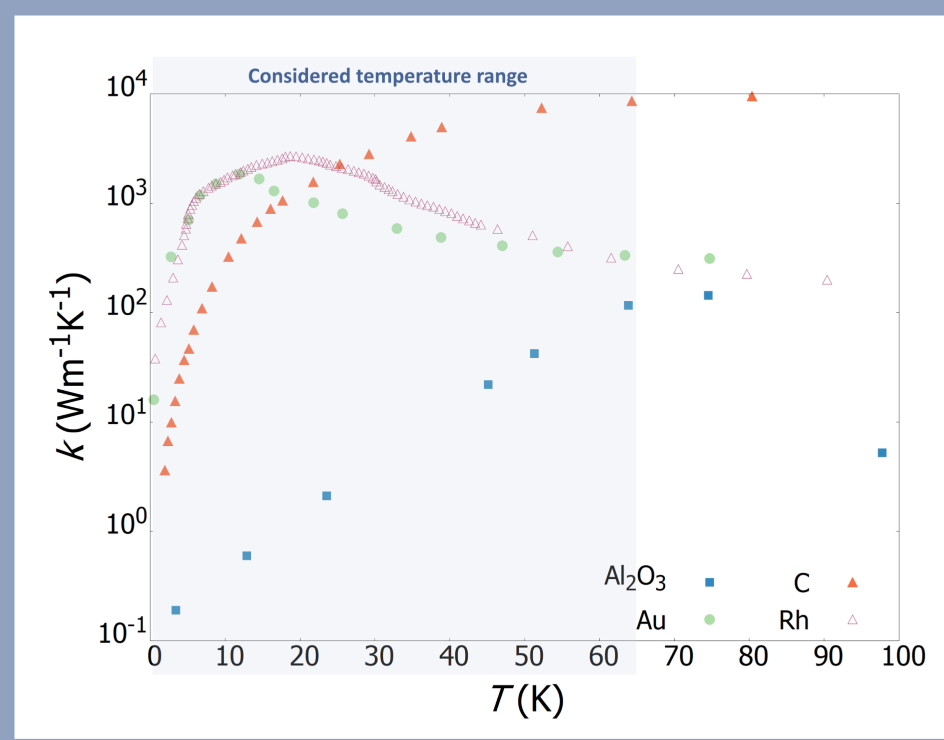
RFs are still too low for practical applications. Our analysis explores a new approach to enhance MSTD performance: leveraging the **temperature dependence of thermal contact resistance** (TCR) at the interface between materials.

At cryogenic temperatures, **TCR increases exponentially with decreasing temperature** due to a transition from diffusive to ballistic heat transport [1]. This effect, combined with suitable material thermal conductivities, can further enhance asymmetric heat flow across the interface.

We investigate this numerically using Fourier's law and the finite volume method.



The temperature dependence of the materials' thermal conductivities and the TCR are incorporated into the model. Examples of temperature-dependent TCR values at low temperatures as well as thermal conductivities are taken from the literature [2,3]. The material pairs considered are: rhodium-iron alloy (RhFe) - sapphire (Al_2O_3), and diamond (C) - gold (Au).

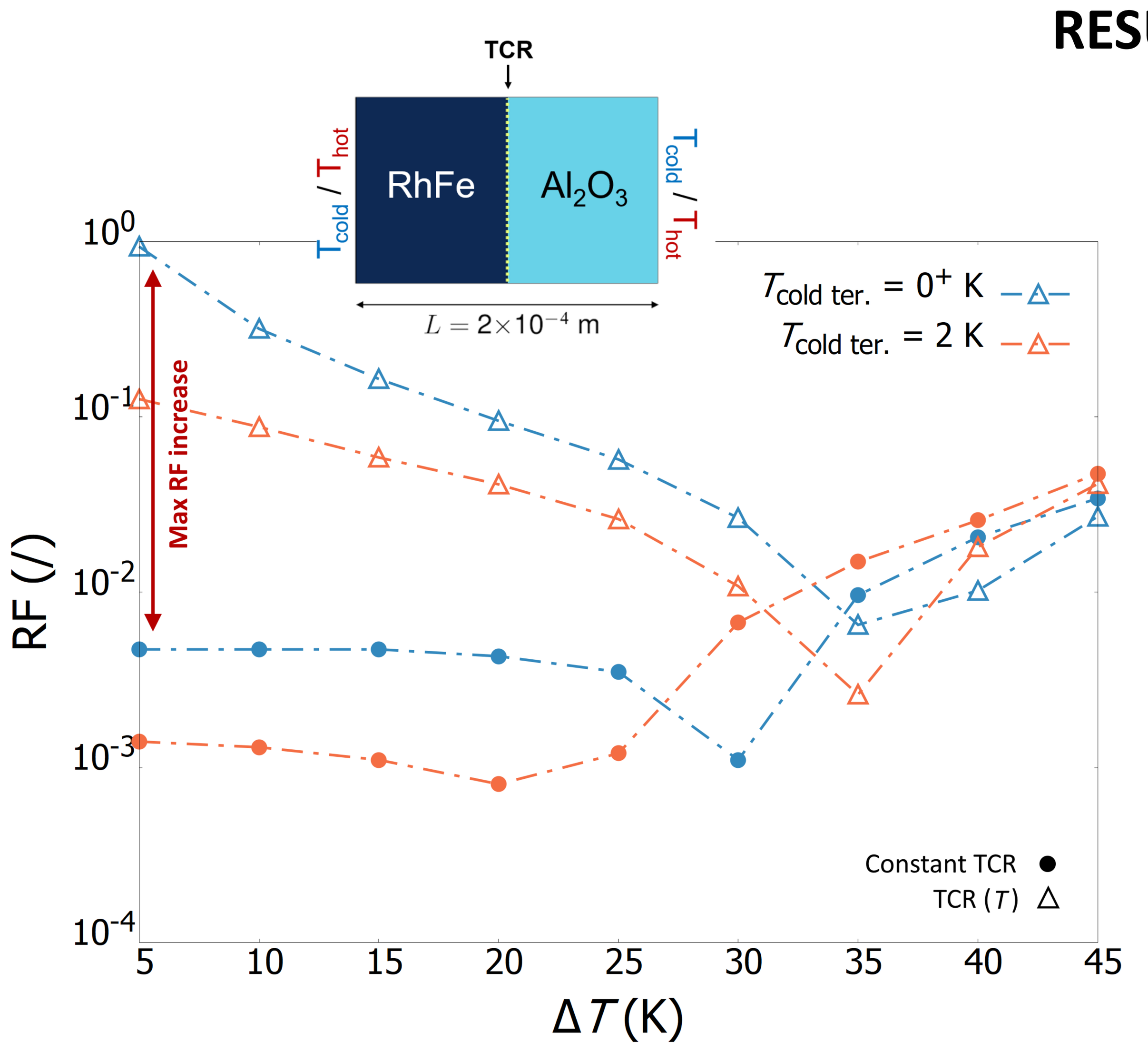


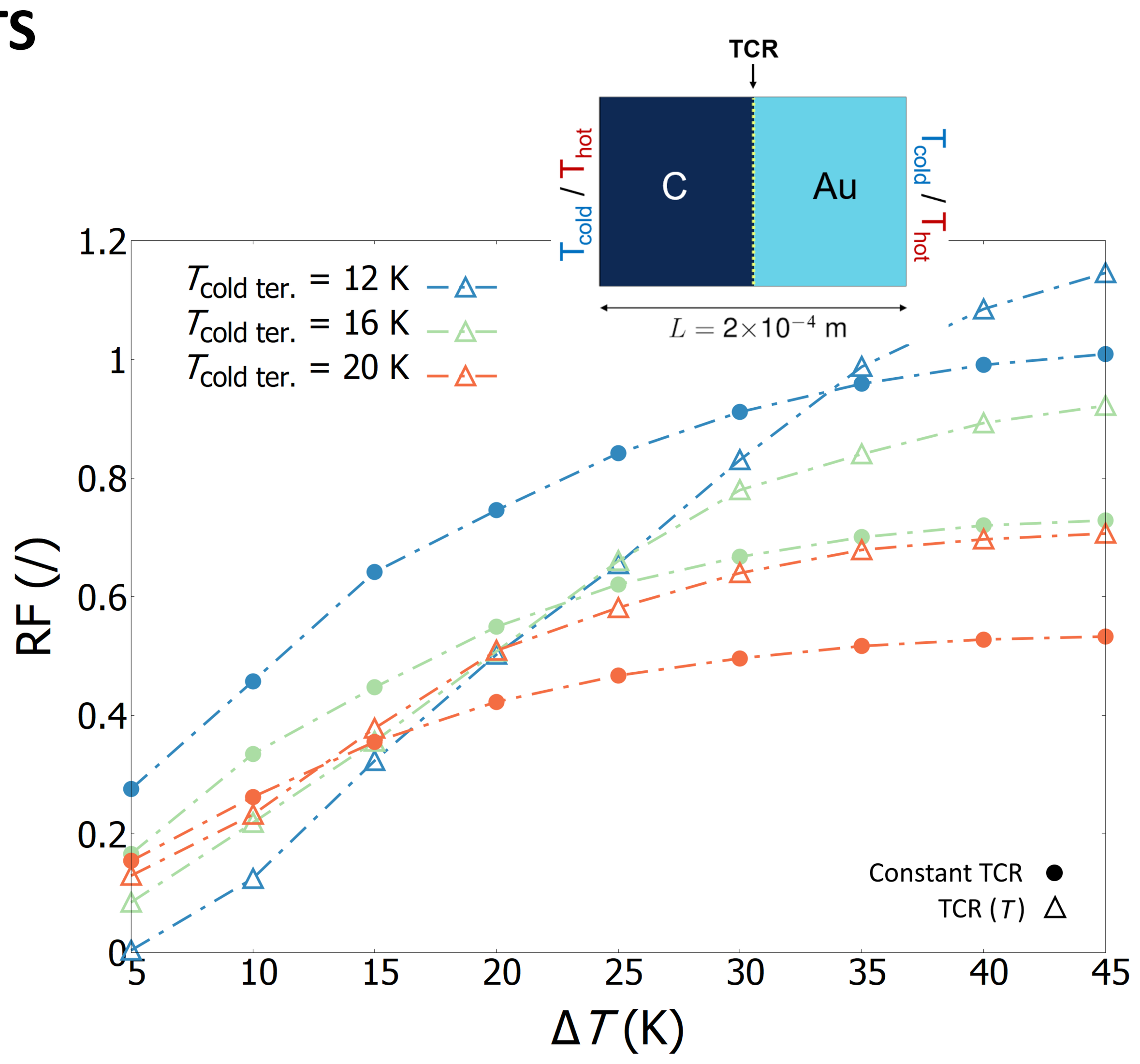
RESULTS

The calculated RF values are compared with the case where the TCR is not temperature-dependent and has a constant value equal to the value above 100 K. This comparison isolates the temperature dependence of the TCR to assess its influence relative to the TCR itself.

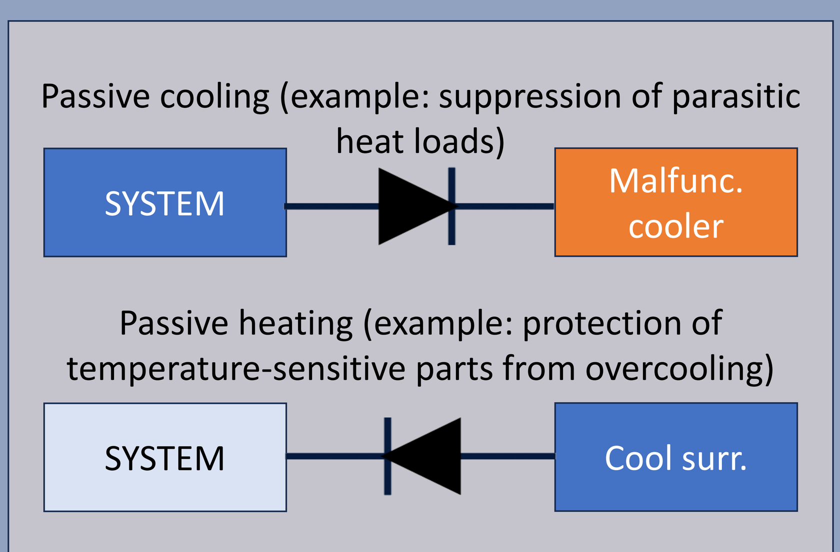
Results show RF enhancement from a negligible value to unity when MSTD (RhFe-Al_2O_3) operates between just above zero and 5 K, where the TCR function is the steepest.

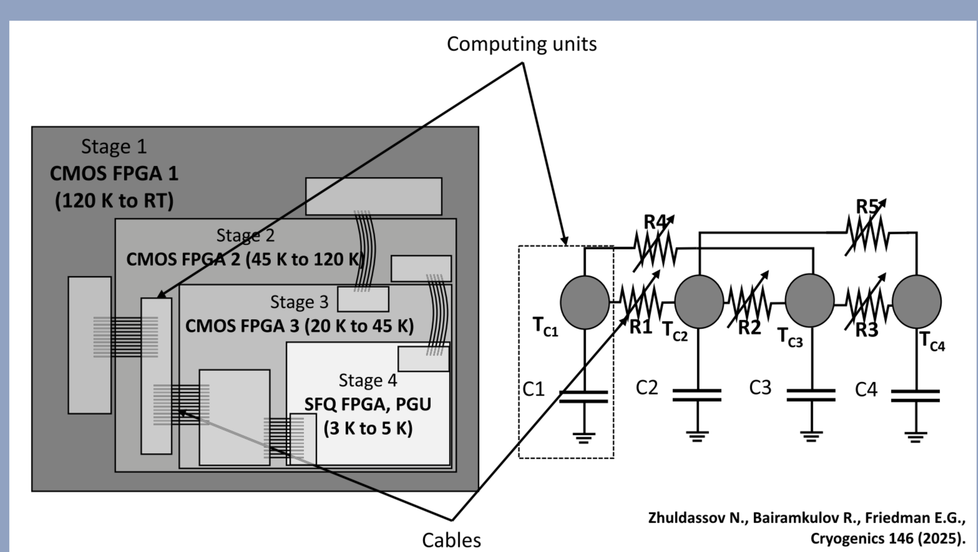
Limited improvement is possible at higher temperatures and larger thermal biases. For example, when MSTD (C-Au) operates between approximately 15 and 60 K.





POSSIBLE APPLICATIONS





Key Takeaways:

- The temperature dependence of the TCR can facilitate rectification.
- The largest RF increase occurs at temperatures where the TCR exhibits the strongest temperature dependence.
- Each case must be evaluated individually due to non-analytic thermal conductivity functions.
- Such MSTDs may be beneficial for cryogenic thermal management.

References

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2. Stoner R.J., Maris H.J., *Phys. Rev. B* 48 (1993) 16373–16387.
3. Swartz E.T., Pohl R.O., *Appl. Phys. Lett.* 51 (1987) 2200–2202.