# Superconductor/Ferromagnet Tunnel Junction Based Thermoelectric Bolometer and Calorimeter


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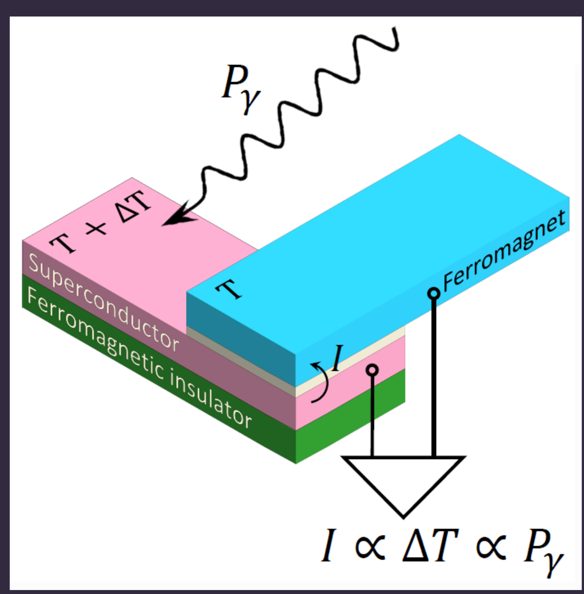
*Superconductor/Ferromagnet ThermoElectric Detector (SFTED) is a novel ultrasensitive radiation detector that is based on the giant thermoelectric effect[1]. This type of detector can be operated without the need of additional bias lines, and at the same time providing a noise performance rivaling the best TES and KID detectors, in theory. Here we report our recent numerical studies on the SFTED and the feasibility of a SQUID readout in both bolometric and calorimetric regimes, in the direction of providing a set of practical design parameters for the detector fabrication and the readout circuitry implementation.*

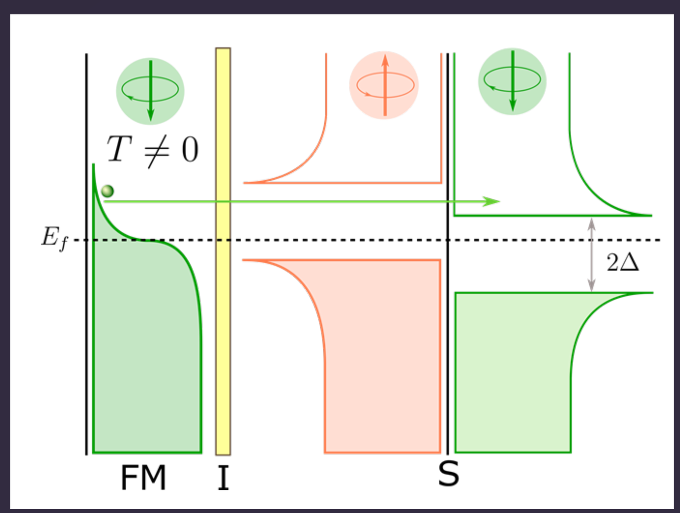

## Working Principles

Superconductor/ferromagnet thermoelectric detector (SFTED), is a novel low temperature radiation detector. Compared to other commonly used sensitive sensors, SFTED has features such as:

- Requires no bias lines and has no bias heating.
- Reduced wiring complexity for large sensor array.
- Measuring temperature difference instead of absolute temperature.
- Self-isolated by electron-phonon coupling.




*Schematic of a SFTED [2]*




*Thermoelectric effect in a FM/I/S tunnel junction.*

The working principle of SFTED is based on the newly discovery of the giant thermoelectric effect in superconducting-ferromagnet hybrids [2,3]:

$$\begin{pmatrix} I \\ \dot{Q} \end{pmatrix} = \begin{pmatrix} G & \alpha \\ \alpha & G_{th}T \end{pmatrix} \begin{pmatrix} V \\ -\Delta T/T \end{pmatrix}$$

And the figure of merit is:

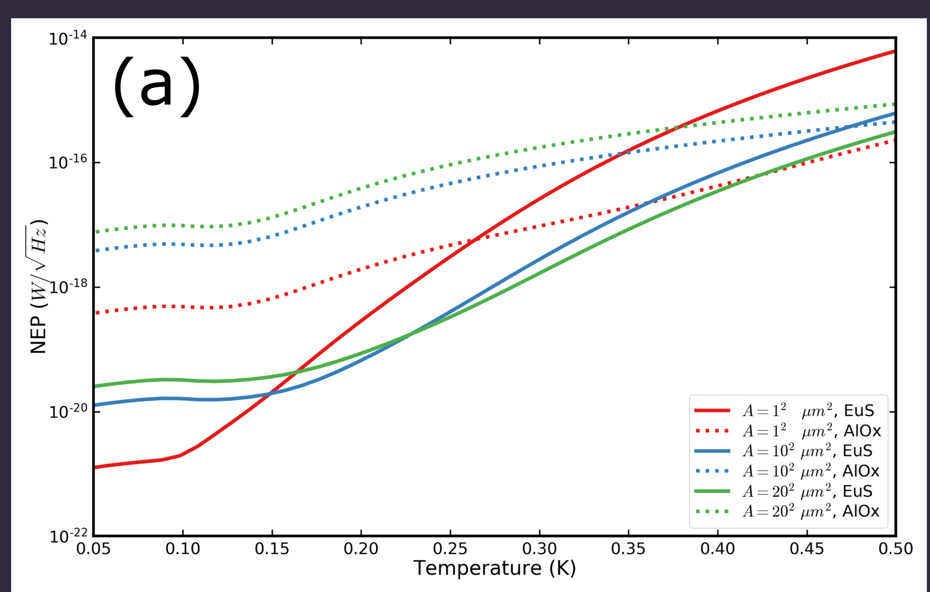
$$ZT = \frac{\alpha^2}{G_{th}^{tot} GT - \alpha^2}$$

## Bolometer

Noise equivalent power (NEP) of SFTED at zero frequency:

$$NEP_0^2 = \frac{4k_B T^2 G_{th}^{tot}}{ZT}$$

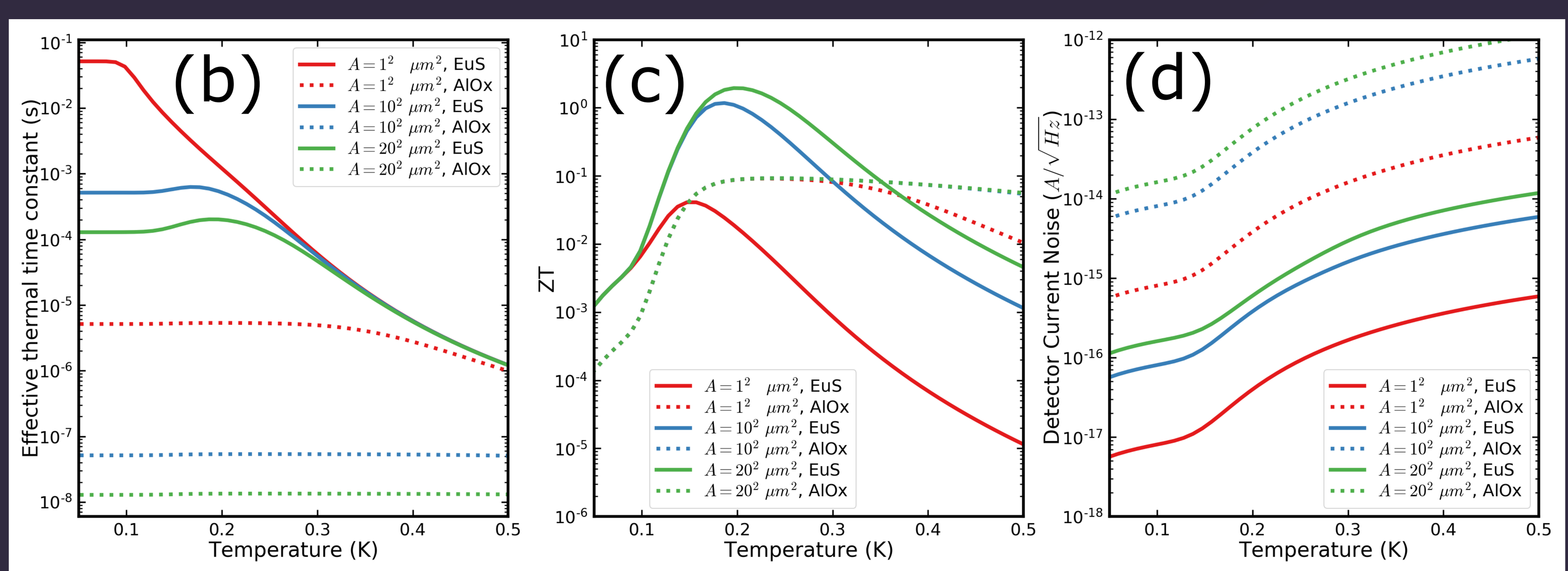
Instead of native AlOx, EuS can be used as tunnel barrier for SFTED:




- Induces spin-splitting exchange field and breaks the electron-hole symmetry.
- Filter spins between superconductor and normal metal electrode with a polarization factor exceeding 0.9 [4].

With EuS barriers, SFTED can have ZT larger than unity (figure (c)), and have NEP in <100 zW/rtHz range with effective thermal time constant <100 ms at around 0.15 K in theory (figure (b)) for microwave and far-infrared applications.

However, tunneling resistances of EuS barrier are usually vary large (10 k to 10 Mohm), and a current sensing scheme based on SQUID can be very hard to achieve due to the low detector current noise (see figure (d)). Voltage readout will be preferred.




*(a): Zero frequency detector NEP calculations. (b): Effective thermal time constant of detector. (c): Figure of merit of detector. (d): Junction current noise. In these calculation, superconductor was assumed to be Al with 2 μm^3 volume.*

## Calorimeter

After optimal filtering, the energy resolution of SFTED with readout amplifier is:

$$\Delta E_{tot} = NEP_{0,tot}\sqrt{\tau_{tot}^{eff}}$$

where:

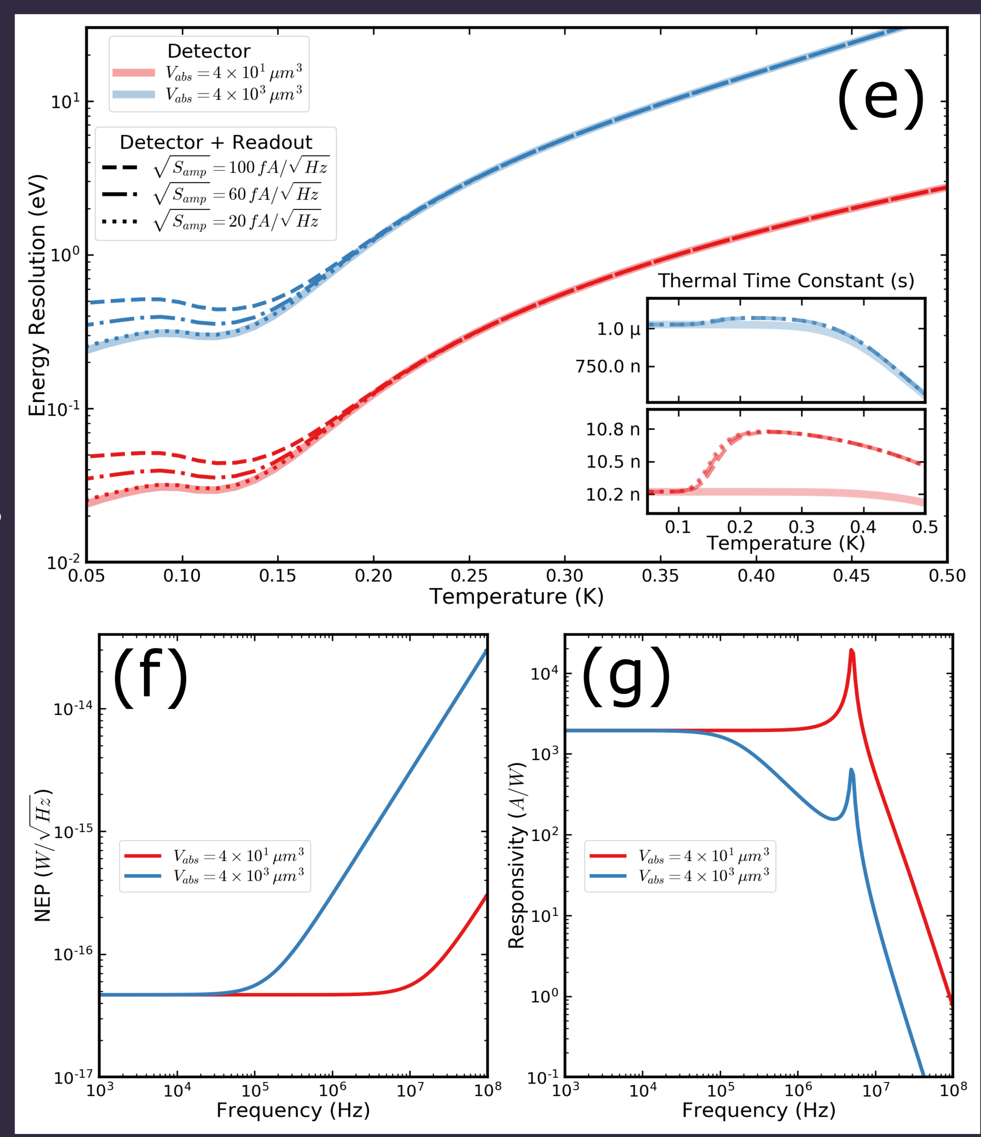
$$NEP_{0,tot}^2 = NEP_{0,TED}^2 + NEP_{0,amp}^2$$

is the sum of zero frequency NEPs of detector (SFTED) and amplifiers. And:

$$\tau_{tot}^{eff} = \tau_{th}\sqrt{1+ZT_{tot}}$$

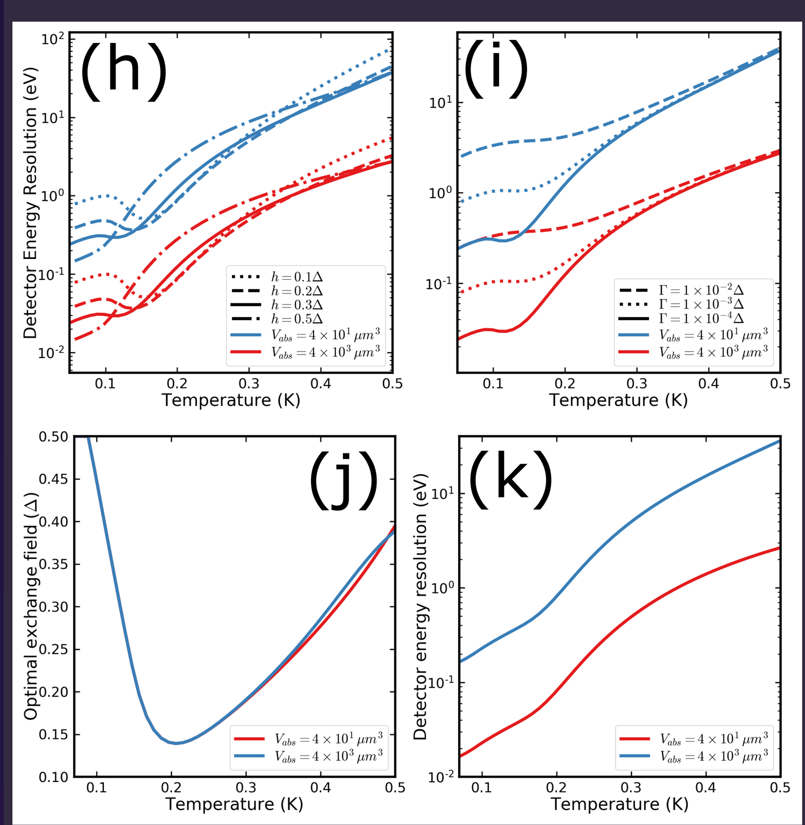
$$ZT_{tot}^{-1} = ZT^{-1} + \frac{S_{amp}G_{th}^{tot}}{4k_B\alpha^2}$$

is the total effective thermal time constant.




Compared with SFTED bolometer, although detectors with AlOx tunnel barrier have much higher intrinsic zero frequency NEP, their thermal time constants are significantly faster than those with EuS barriers due to high specific transparency. This leads to better total energy resolution after optimal filtering.

We can see from figure (e) that a SQUID readout 20 fA/rtHz current noise had already matched well with SFTED (dotted and solid lines), and the total energy resolution begins to be determined by detector. A SQUID with superconducting flux transformer can practically achieve noise level of <60 fA/rtHz with optimized design [5], and SFTED will not be limited by readout noise at operation temperature higher than 150 mK with such SQUID system, and provides a sub-eV overall energy resolution with absorber volume of 4x10^3 um^3.




At low temperatures, energy resolution of SFTED is very sensitive to exchange field (figure (h)) and broadening parameter (figure (i)). At temperature <100 mK, energy resolution is limited by sub-gap current leakage of the tunnel junction. To further improve resolution, multistage shieldings are required [6]. Different exchange fields will change the temperature dependency of energy resolution, and an optimal value can be found for a given detector operation temperature (see figure (j) and (k)).

*(e) Detector and overall energy resolution. (f) Detector NEP. (g) Detector (with a 2 uH flux transformer) responsivity. (h) Detector energy resolution with different exchange fields. (I) Detector energy resolution with different broadening parameter. (j) Optimal exchange field. (k) Detector energy resolution with optimal exchange fields. In these calculations, superconductor was assumed to be Al with 10^4 μm^2 junction area.*

## References:


[1] A. Ozaeta, et al, Phys. Rev. Lett. 112, 057001 (2014).
[2] T. T. Heikkila, et al, Phys. Rev. Appl. 10, 034053 (2018)
[3] Kolenda, et al, Phys. Rev. Lett. 116, 097001 (2016).
[4] J.S. Moodera, et al, J. Phys. Condens. Matter 19, 165202, (2007).
[5] D. Drung, et al, IEEE Trans. Appl. Supercond. 17, 699 (2007)
[6] O.P. Saira, et al, Phys. Rev. B - Condens. Matter Mater. Phys. 85, 012504, (2012).



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