Development of Cryogenic Thermal Detectors for Sub-GeV Dark Matter

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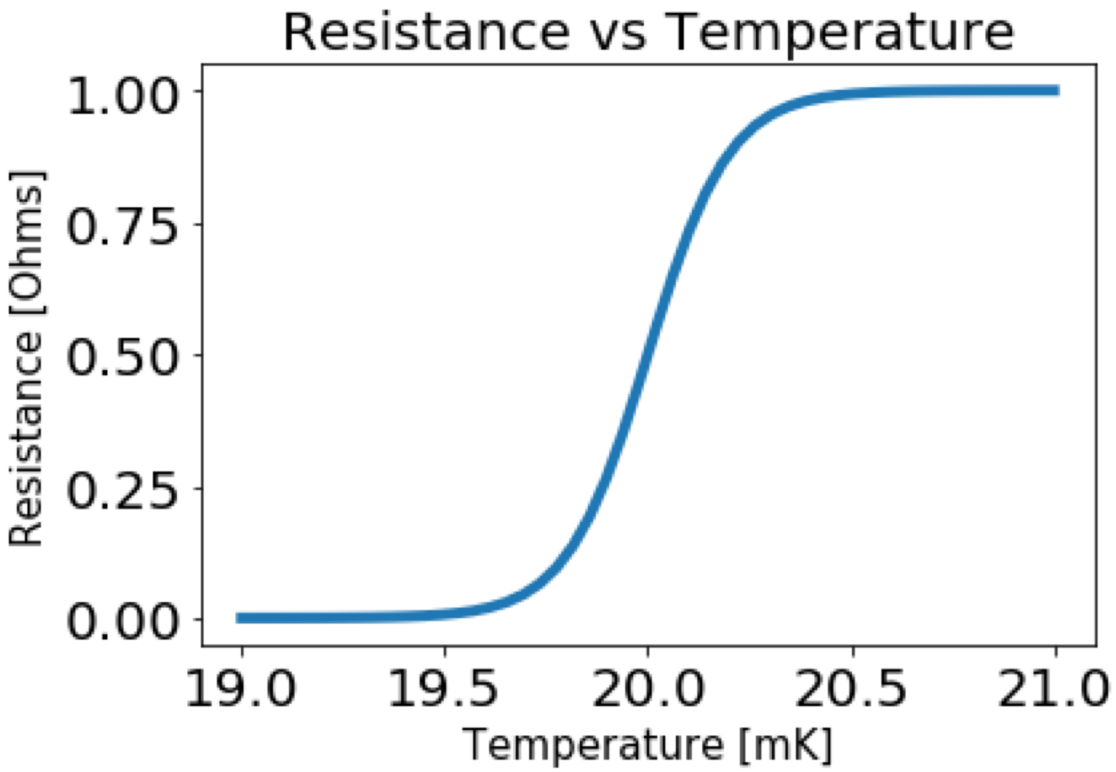
Motivation

- Low mass dark matter ($M_{DM} < 1$ GeV) is an interesting problem to solve
- Could be detected via collision with Silicon nuclei with detector threshold of around 10 eV
- Will describe the design/fabrication efforts of such a cryogenic detector

Transition Edge Sensor (TES) Basics

- Use the sharp temperature-resistance transition of a superconductor to convert thermal to electrical signals



Using the TES

- How can we reach 10 eV threshold with this method?
  - Low heat capacity
  - Lowers exposure mass

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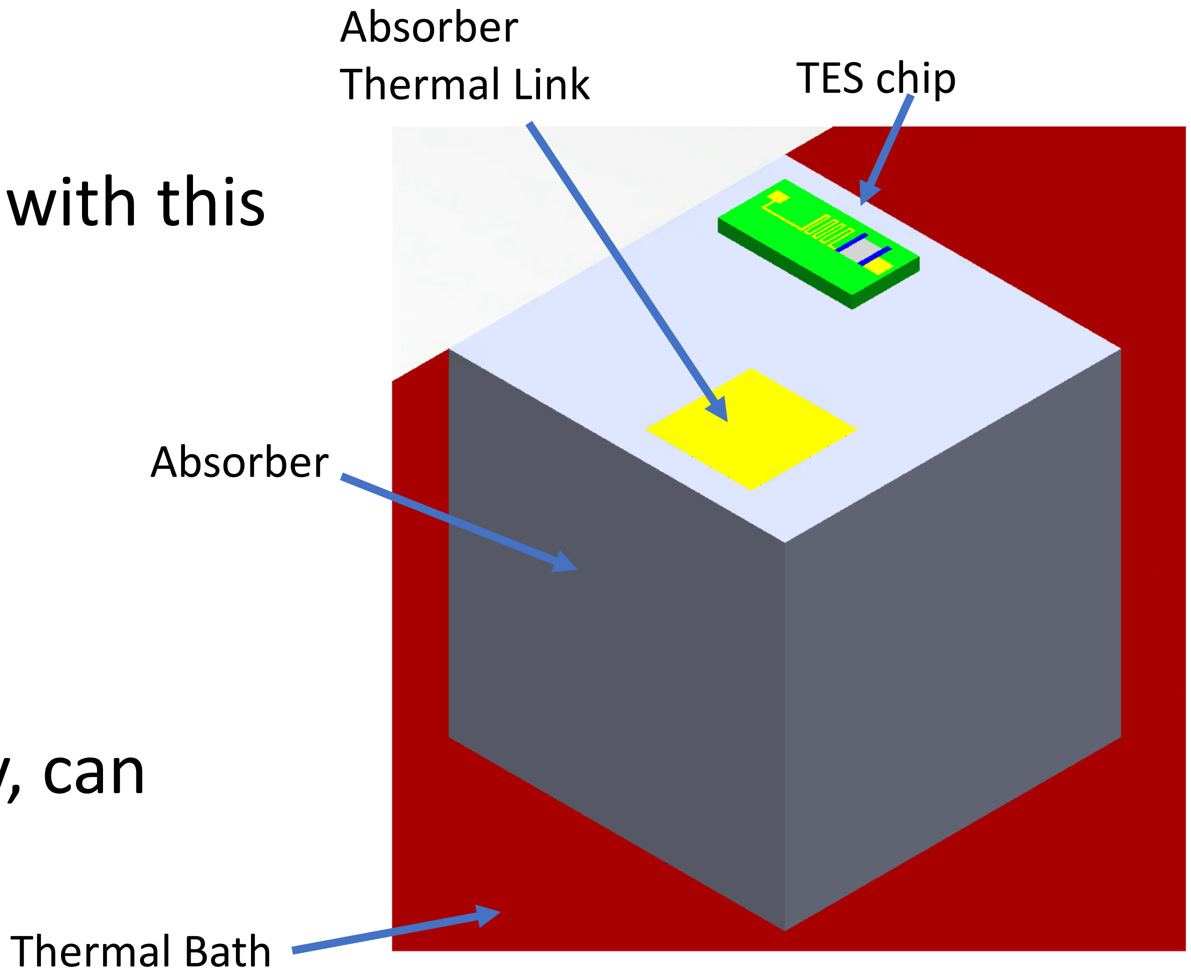
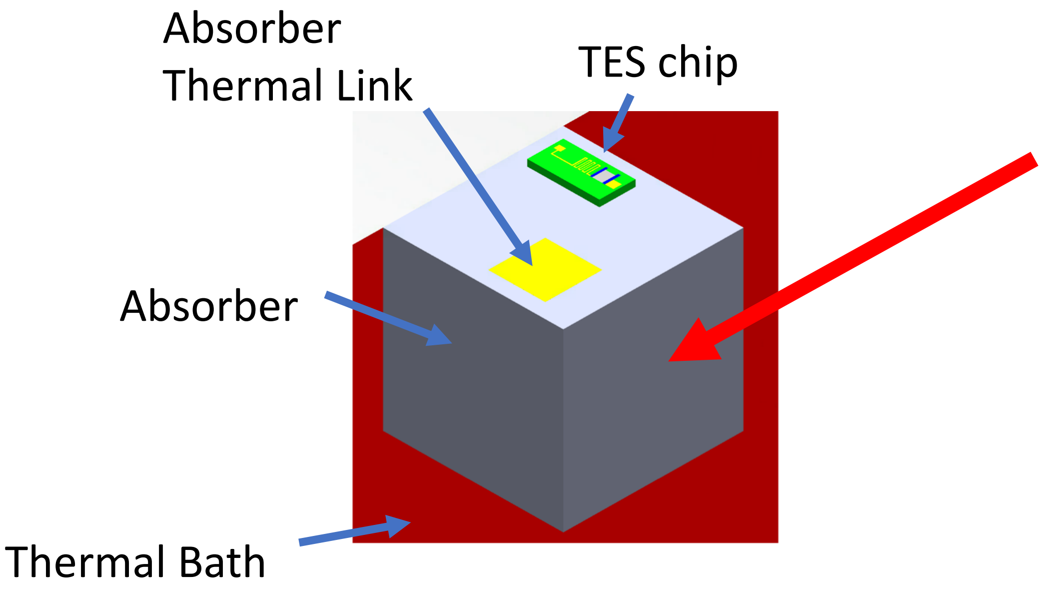
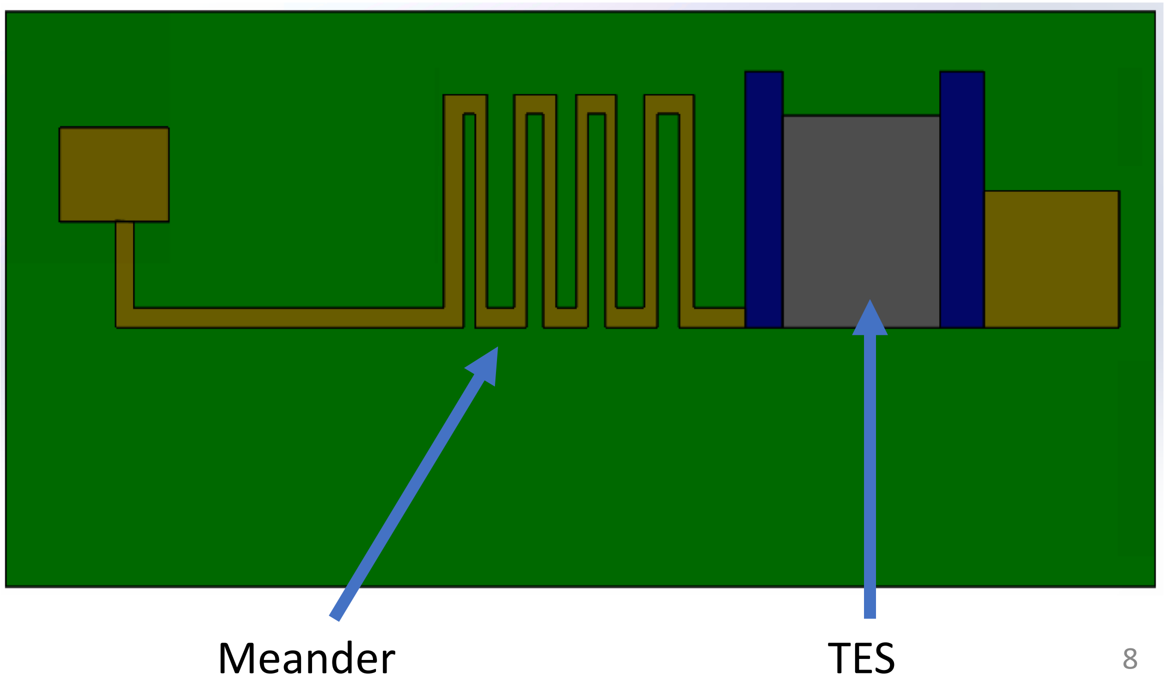


Thermal Circuit

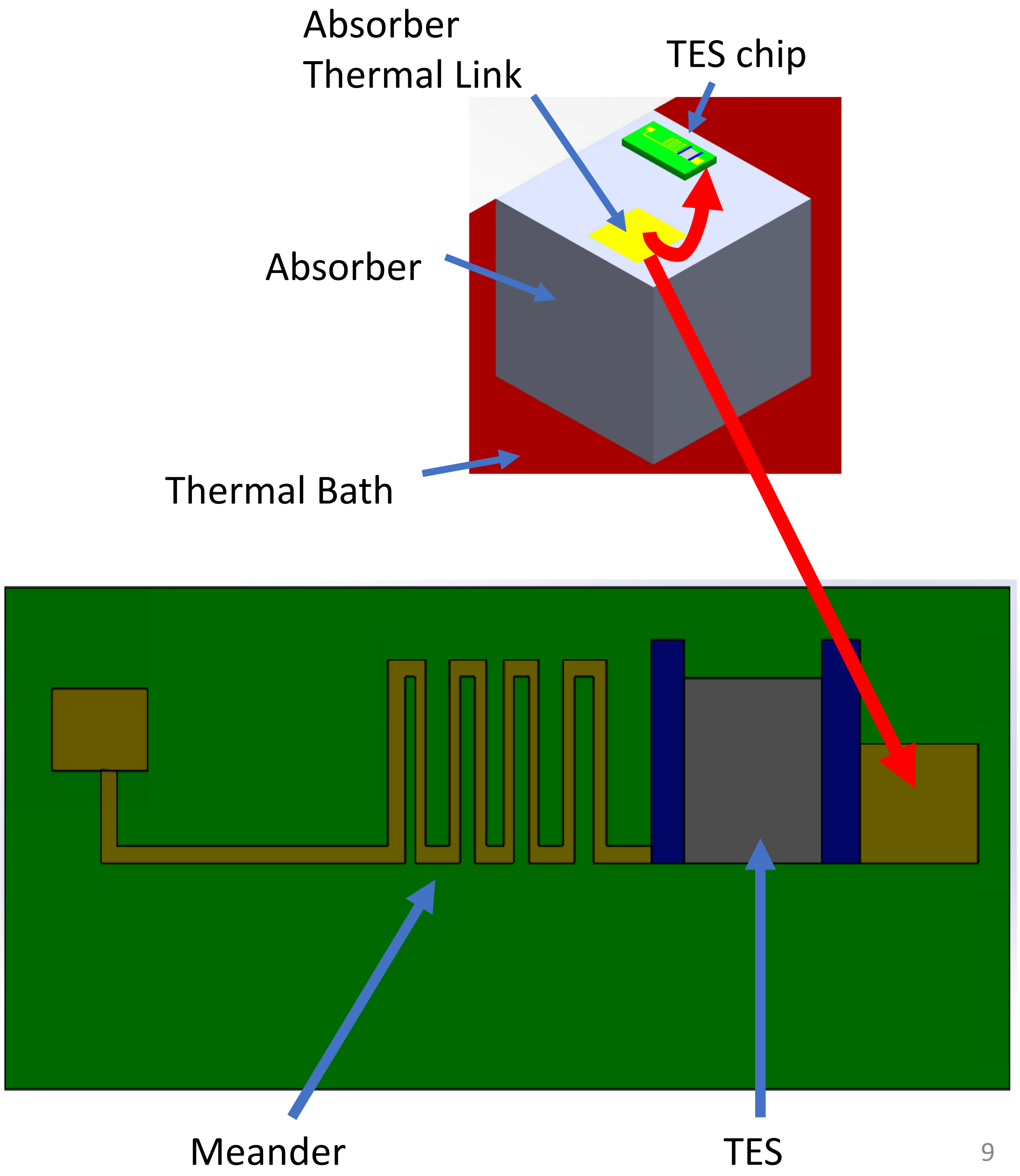
1. Energy absorbed





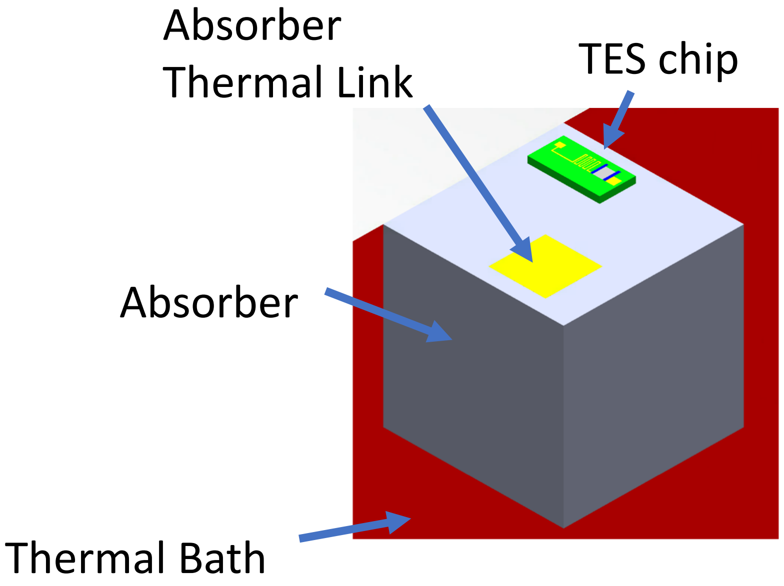
Thermal Circuit

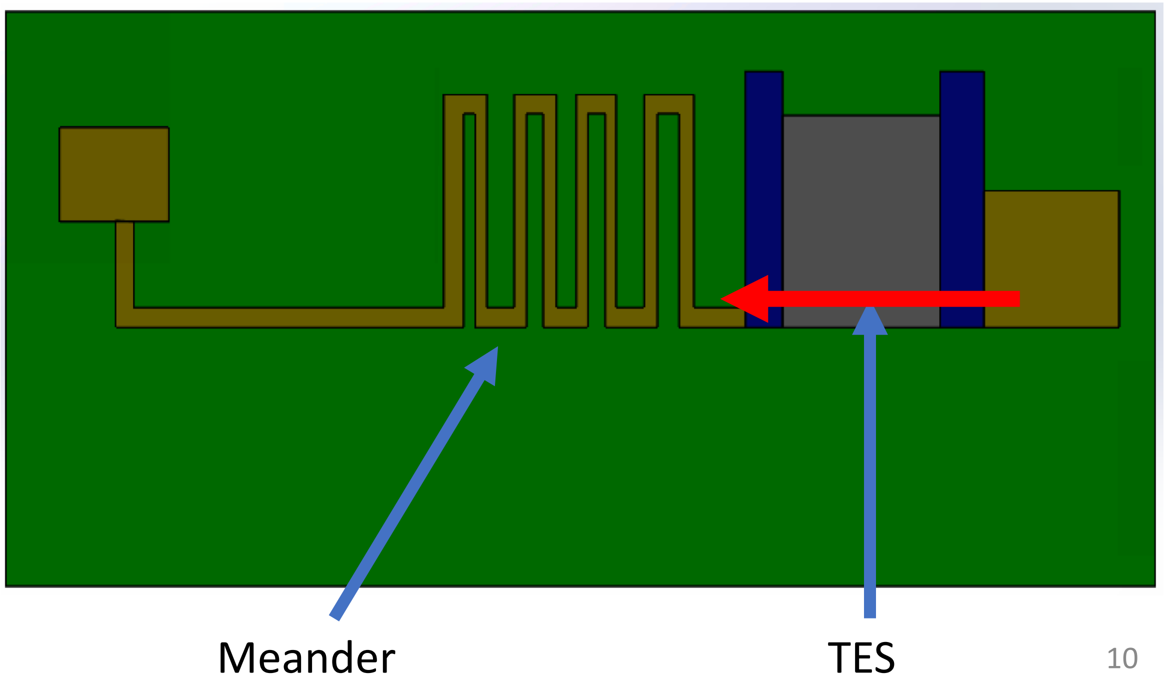
1. Energy absorbed
2. Energy flows through absorber gold pad and wire bond to thermal chip



Thermal Circuit

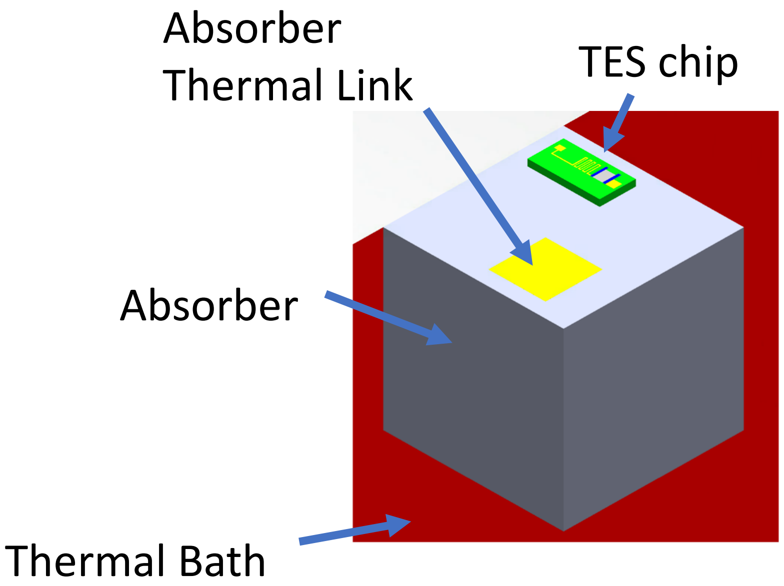
1. Energy absorbed
2. Energy flows through absorber gold pad and wire bond to thermal chip
3. Energy flows through TES

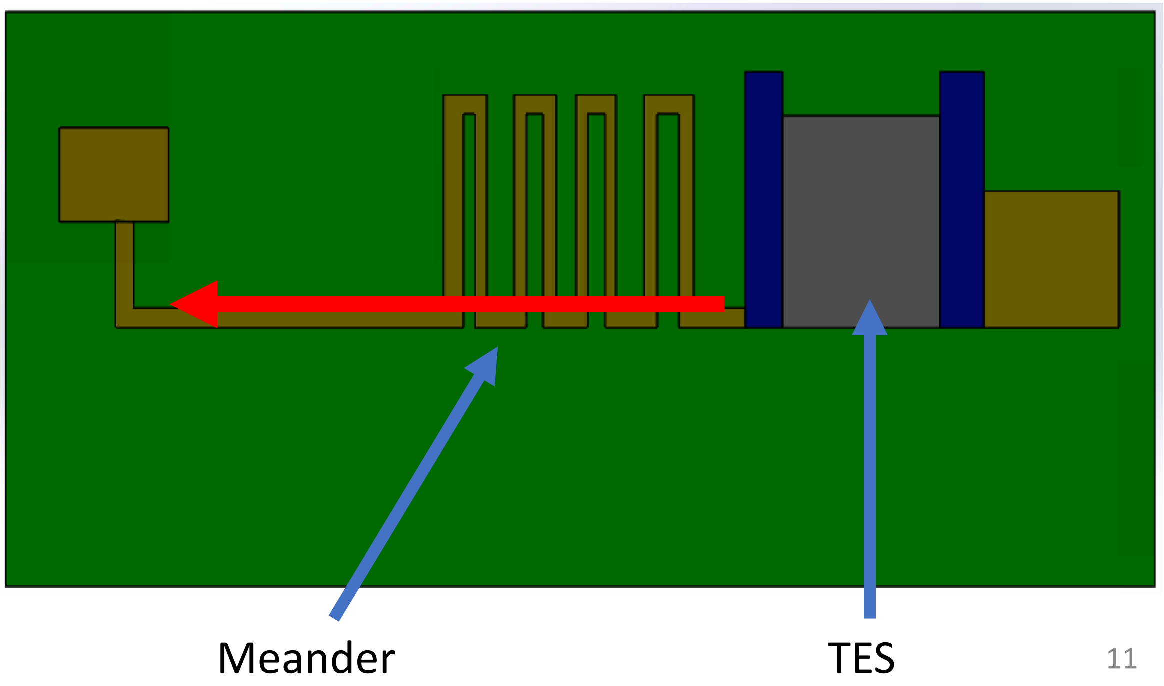




Thermal Circuit

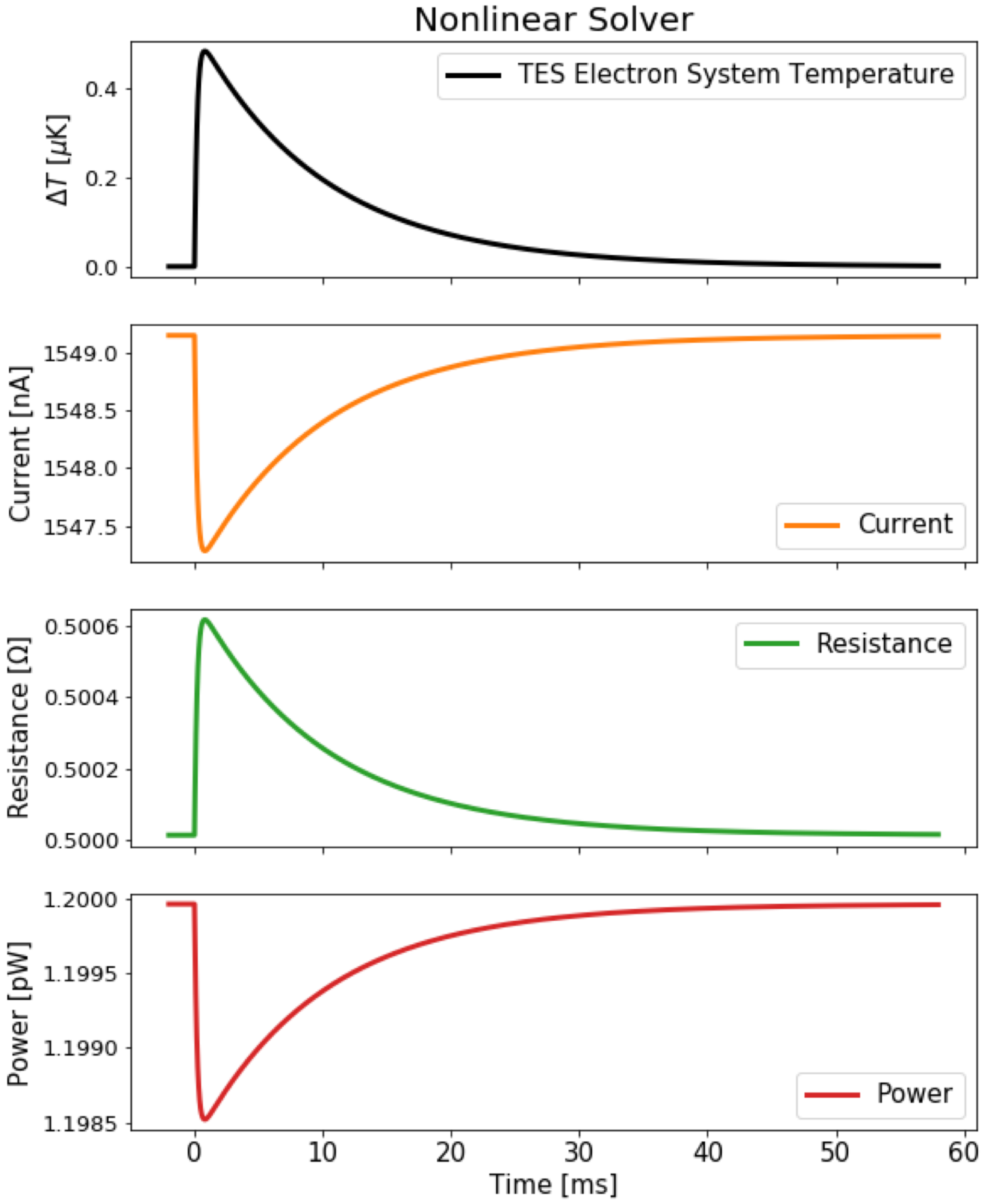
1. Energy absorbed
2. Energy flows through absorber gold pad and wire bond to thermal chip
3. Energy flows through TES
4. Energy flow out of TES controlled by geometry of gold meander





Theoretical Results

- 5 eV threshold
  - Tungsten TES
  - 1 cm^3 Silicon Absorber
  - 20 mK transition temperature

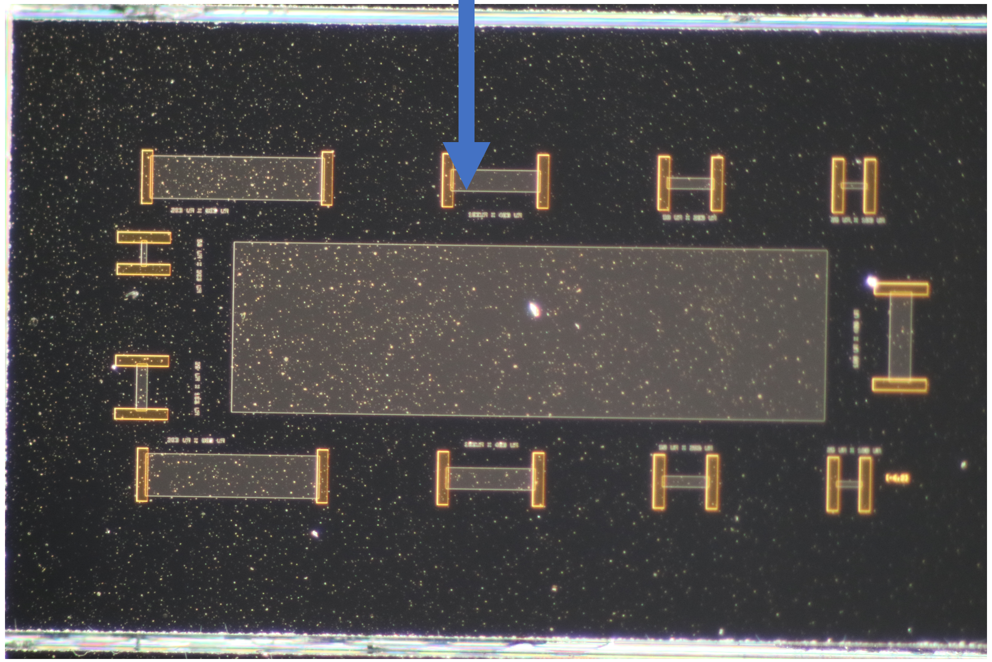


Practical Implementation

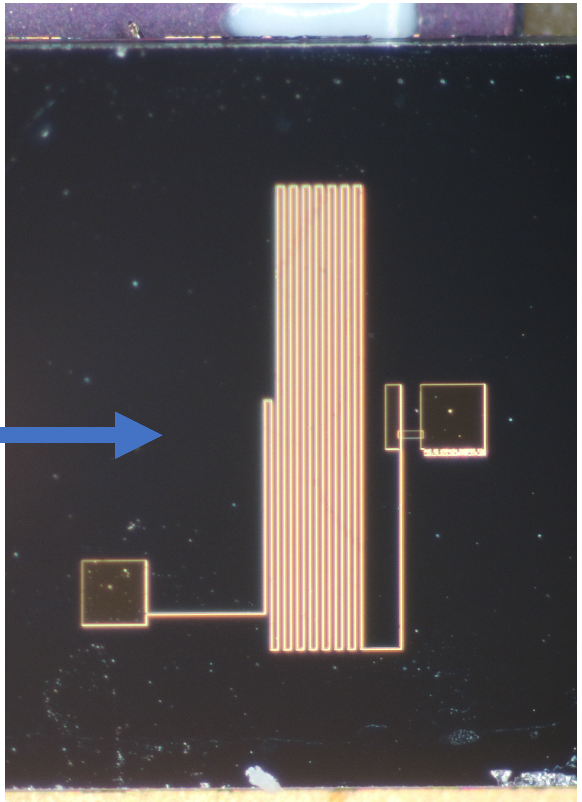
- Create a mask for initial tests
- Current testing apparatus has base temperature around 50 mK
    - Aim for transition temperature of around 85 mK
    - Mask design has contingency for transition temperatures of 60 mK – 100 mK
- Mask prepares for multiple absorber materials
    - Silicon
    - Germanium
    - Zinc
    - No absorber

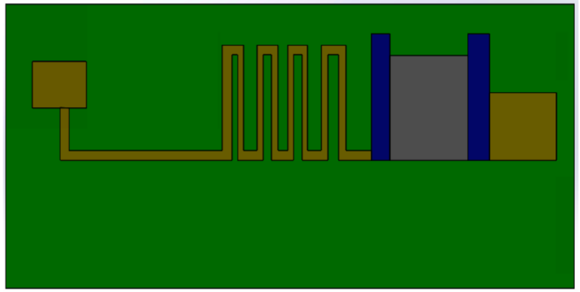
First Tests

- Transition temperature check
  - Observed at 85 mK and 80 mK



Transition temperature test structure





Future Tests and Goals

- Future Tests:
  - Measure gold thermal conductance
  - Observe pulses
    - Compare with the model
- Goal:
  - Move towards the lower transition temperature design for better performance

Conclusions

- Cryogenic thermal detectors can theoretically reach the sensitivity necessary for sub-GeV dark matter searches
- High temperature proof-of-concept tests are underway
- Low temperature tests should be in the near future

Acknowledgments

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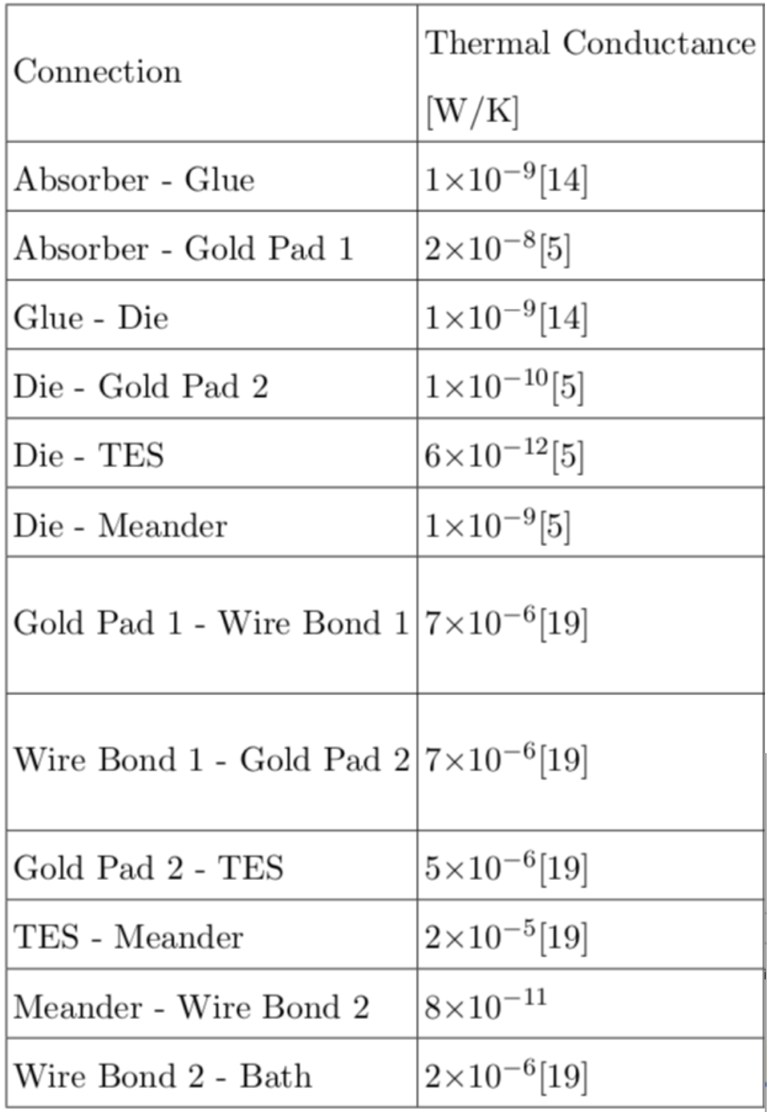
- Additional funding was provided through the NASA Illinois Space Grant

References

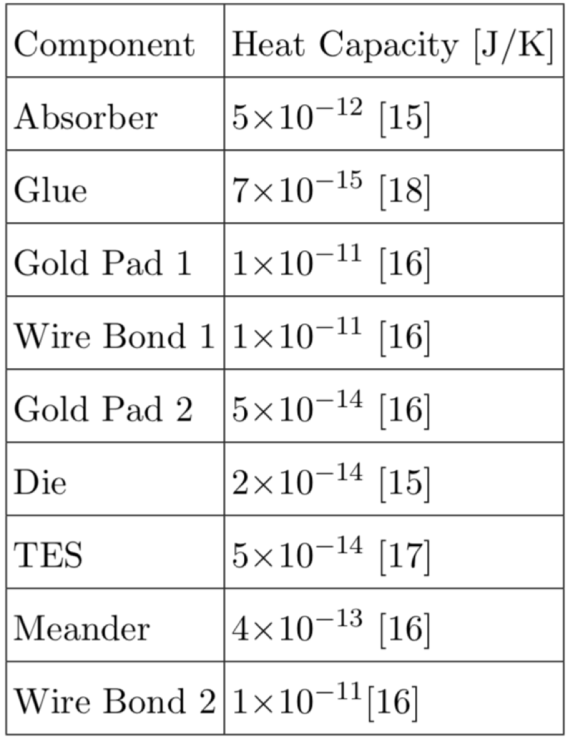
- E. Figueroa-Feliciano. *Complex microcalorimeter models and their application to position-sensitive detectors*. JAP (2006)
- M. Pyle et al. *Optimized designs for very low temperature massive calorimeters.*(2015) **arXiv:1503.01200v2**

Bonus Slides

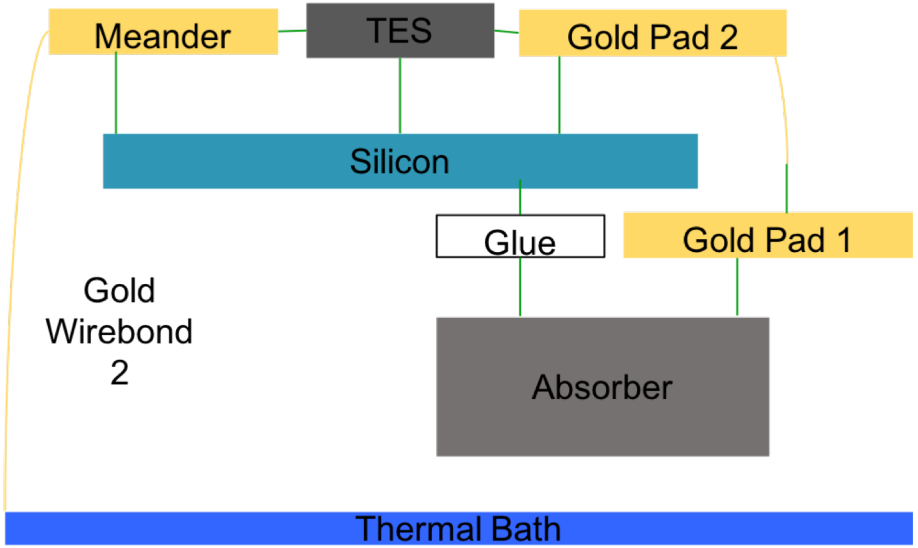
Model Parameters

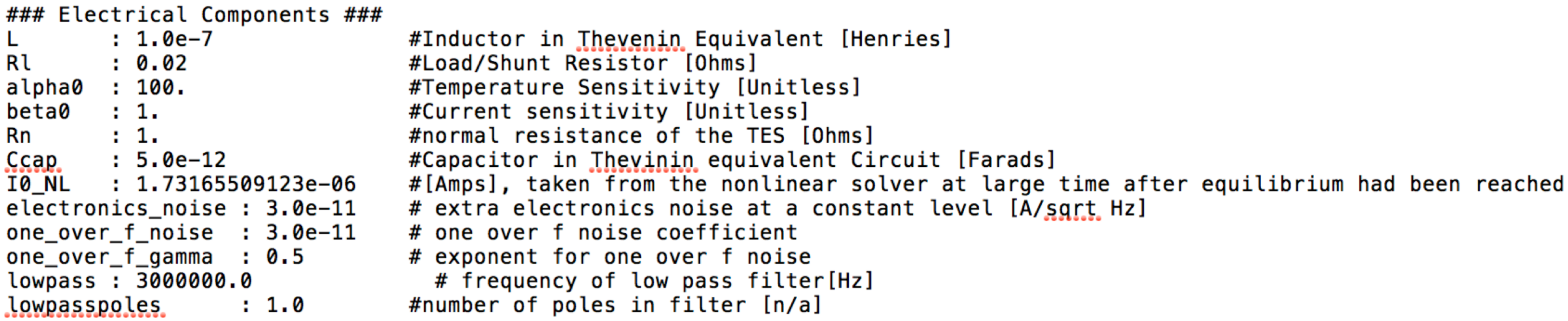


Connection	Thermal Conductance [W/K]
Absorber - Glue	$1{\times}10^{-9}$[14]
Absorber - Gold Pad 1	$2{\times}10^{-8}$[5]
Glue - Die	$1{\times}10^{-9}$[14]
Die - Gold Pad 2	$1{\times}10^{-10}$[5]
Die - TES	$6{\times}10^{-12}$[5]
Die - Meander	$1{\times}10^{-9}$[5]
Gold Pad 1 - Wire Bond 1	$7{\times}10^{-6}$[19]
Wire Bond 1 - Gold Pad 2	$7{\times}10^{-6}$[19]
Gold Pad 2 - TES	$5{\times}10^{-6}$[19]
TES - Meander	$2{\times}10^{-5}$[19]
Meander - Wire Bond 2	$8{\times}10^{-11}$
Wire Bond 2 - Bath	$2{\times}10^{-6}$[19]



Component	Heat Capacity [J/K]
Absorber	$5{\times}10^{-12}$ [15]
Glue	$7{\times}10^{-15}$ [18]
Gold Pad 1	$1{\times}10^{-11}$ [16]
Wire Bond 1	$1{\times}10^{-11}$ [16]
Gold Pad 2	$5{\times}10^{-14}$ [16]
Die	$2{\times}10^{-14}$ [15]
TES	$5{\times}10^{-14}$ [17]
Meander	$4{\times}10^{-13}$ [16]
Wire Bond 2	$1{\times}10^{-11}$[16]





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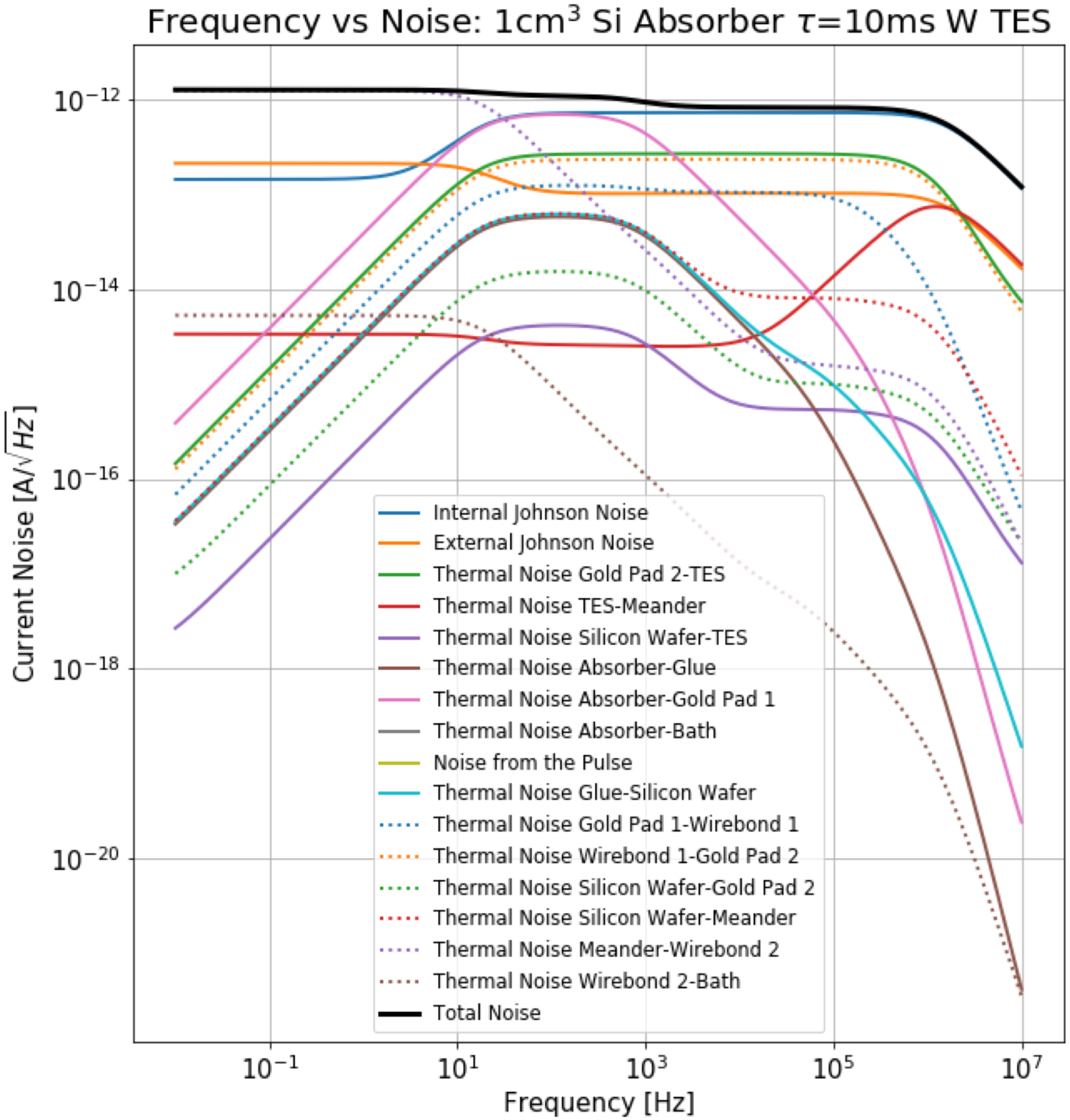
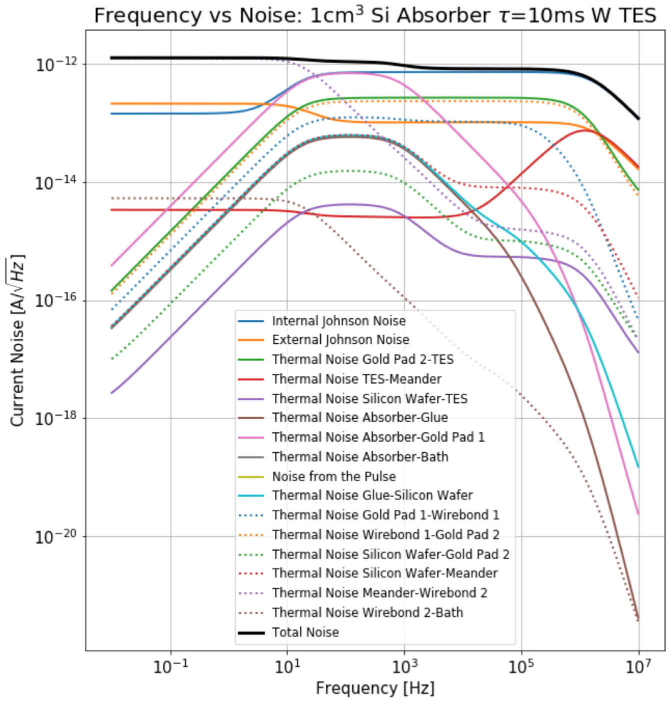
### Electrical Components ###
L        : 1.0e-7              #Inductor in Thevenin Equivalent [Henries]
Rl       : 0.02                #Load/Shunt Resistor [Ohms]
alpha0   : 100.                #Temperature Sensitivity [Unitless]
beta0    : 1.                  #Current sensitivity [Unitless]
Rn       : 1.                  #normal resistance of the TES [Ohms]
Ccap     : 5.0e-12             #Capacitor in Thevinin equivalent Circuit [Farads]
I0_NL    : 1.73165509123e-06   #[Amps], taken from the nonlinear solver at large time after equilibrium had been reached
electronics_noise : 3.0e-11    # extra electronics noise at a constant level [A/sqrt Hz]
one_over_f_noise  : 3.0e-11    # one over f noise coefficient
one_over_f_gamma  : 0.5        # exponent for one over f noise
lowpass : 3000000.0              # frequency of low pass filter[Hz]
lowpasspoles      : 1.0        #number of poles in filter [n/a]
```

Noise Spectrum



Resolution Calculation

$$\mathrm{Resolution_{FWHM}} = 2.35\left(\sqrt{\int_0^{\infty}\frac{4df}{\mathrm{NEP}(f)^2}}\right)^{-1}$$



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Responsivity

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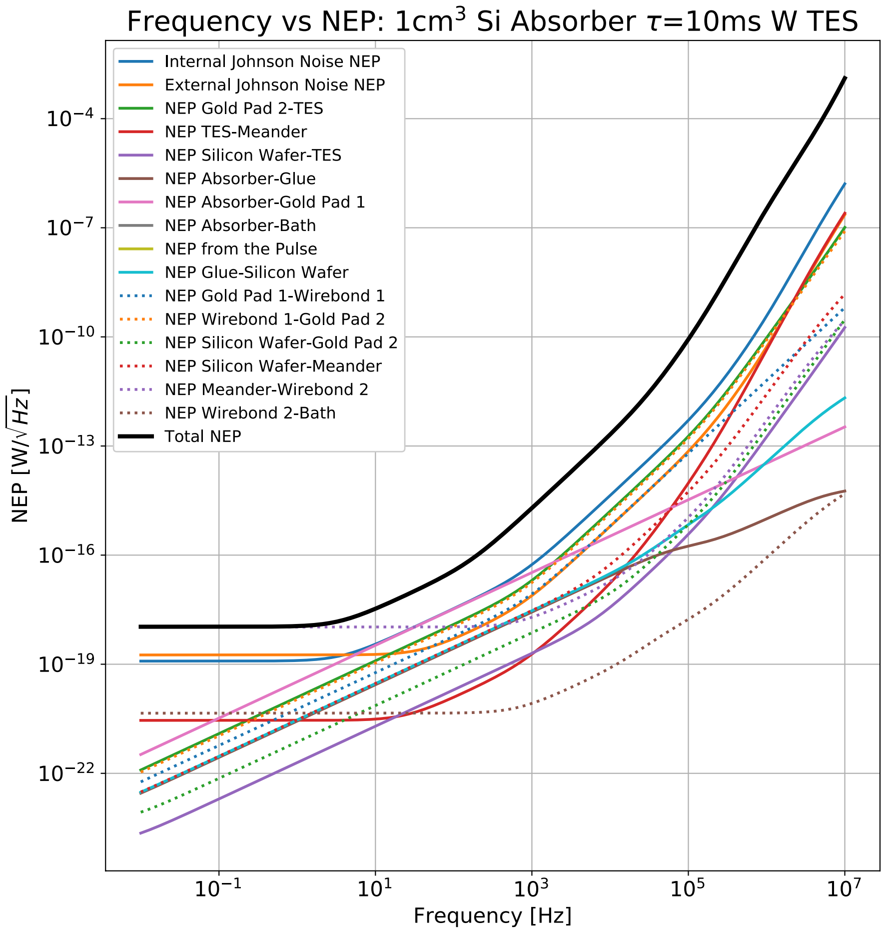
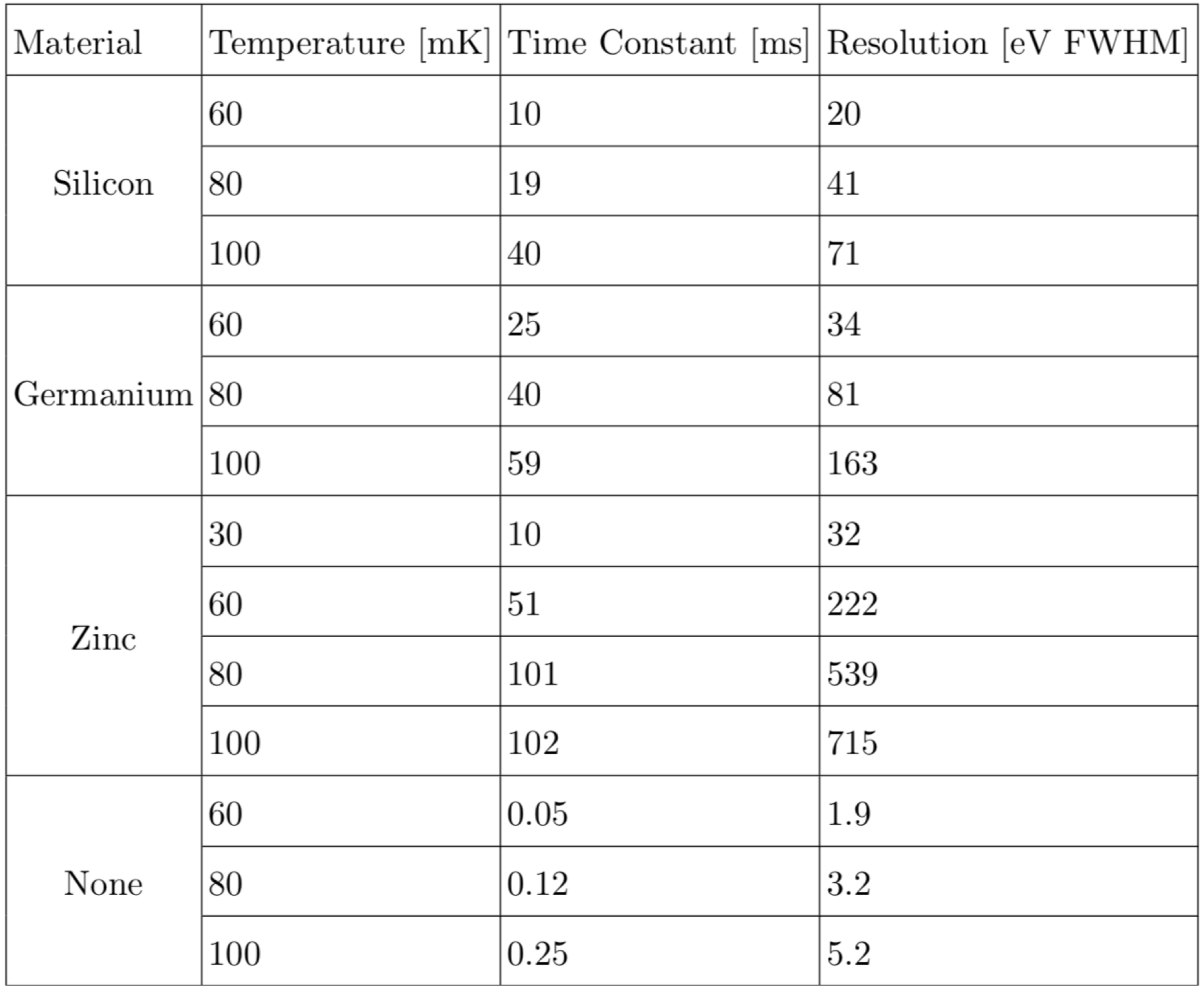


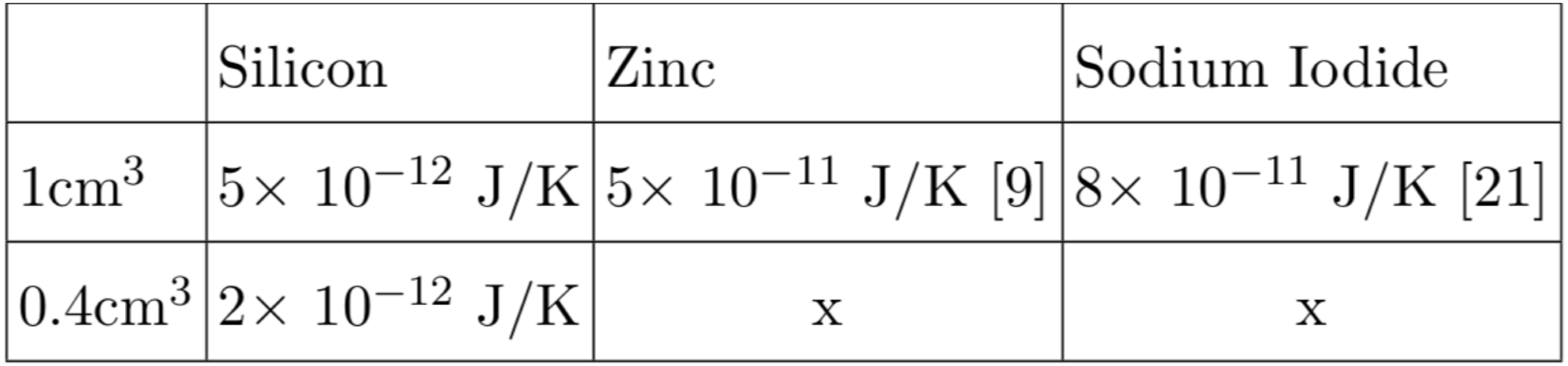
Mask Design Optimization Results



Material	Temperature [mK]	Time Constant [ms]	Resolution [eV FWHM]
Silicon	60	10	20
	80	19	41
	100	40	71
Germanium	60	25	34
	80	40	81
	100	59	163
Zinc	30	10	32
	60	51	222
	80	101	539
	100	102	715
None	60	0.05	1.9
	80	0.12	3.2
	100	0.25	5.2

$$\text{Threshold} = 7.5\left(\frac{\text{Resolution}_{\text{FWHM}}}{2}\right)$$

Absorber Heat Capacity at 20 mK



	Silicon	Zinc	Sodium Iodide
1cm^3	5×10^{-12} J/K	5×10^{-11} J/K [9]	8×10^{-11} J/K [21]
0.4cm^3	2×10^{-12} J/K	x	x