1. Northwestern University
2. Argonne National Lab
3. University of Massachusetts Amherst

DEVELOPMENT OF CRYOGENIC THERMAL DETECTORS FOR SUB-GEV DARK MATTER

Noemie Bastidon[1], Clarence Chang[2], Enectali Figueroa-Feliciano[1], Ziqing Hong[1], Valentine Novosad[2], **H Douglas Pinckney[1,3]**, Gensheng Wang[2], Volodymyr Yefremenko[2]

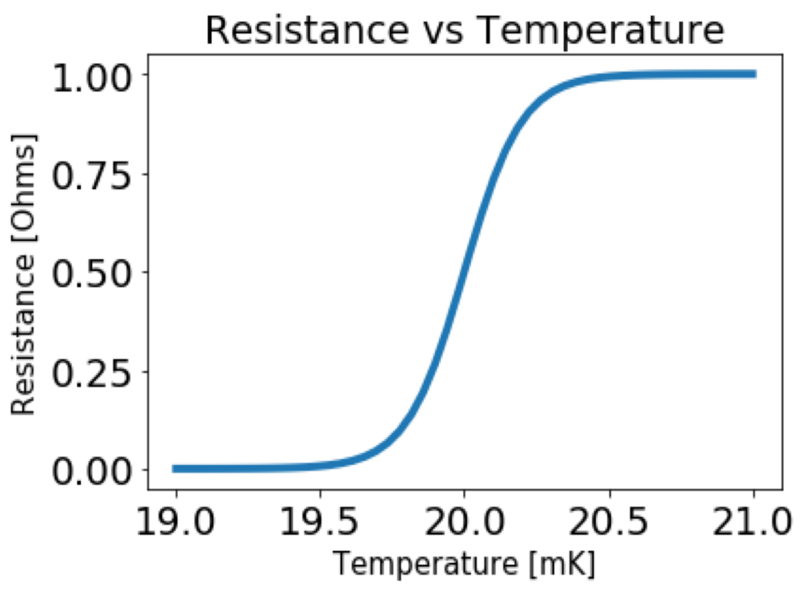
Motivation

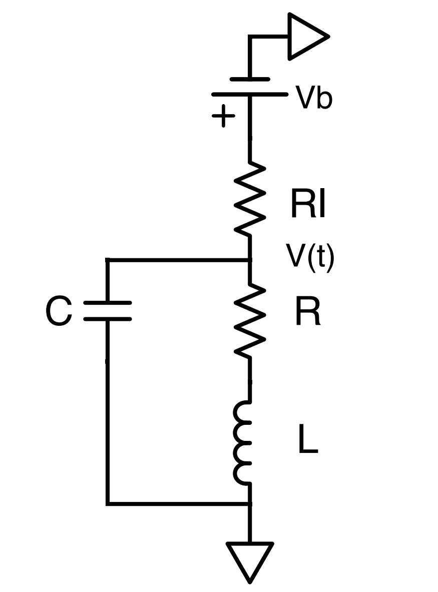
- Low mass dark matter (M_{DM} < 1 GeV) is an interesting problem to solve
- Could be detected via collision with Silicon nuclei with detector threshold of around 10 eV
- Will describe the design/fabrication efforts of such a cryogenic detector

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

Transition Edge Sensor (TES) Basics

- Use the sharp temperature-resistance transition of a superconductor to convert thermal to electrical signals
- Electrical signals read out with inductively coupled SQUIDs





Thevenin equivalent of the readout circuit

Figueroa-Feliciano JAP (2006)

Formaggio et al. Phys. Rev. D 85, 013009 (2012)

Using the TES

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

Formaggio et al. Phys. Rev. D 85, 013009 (2012)

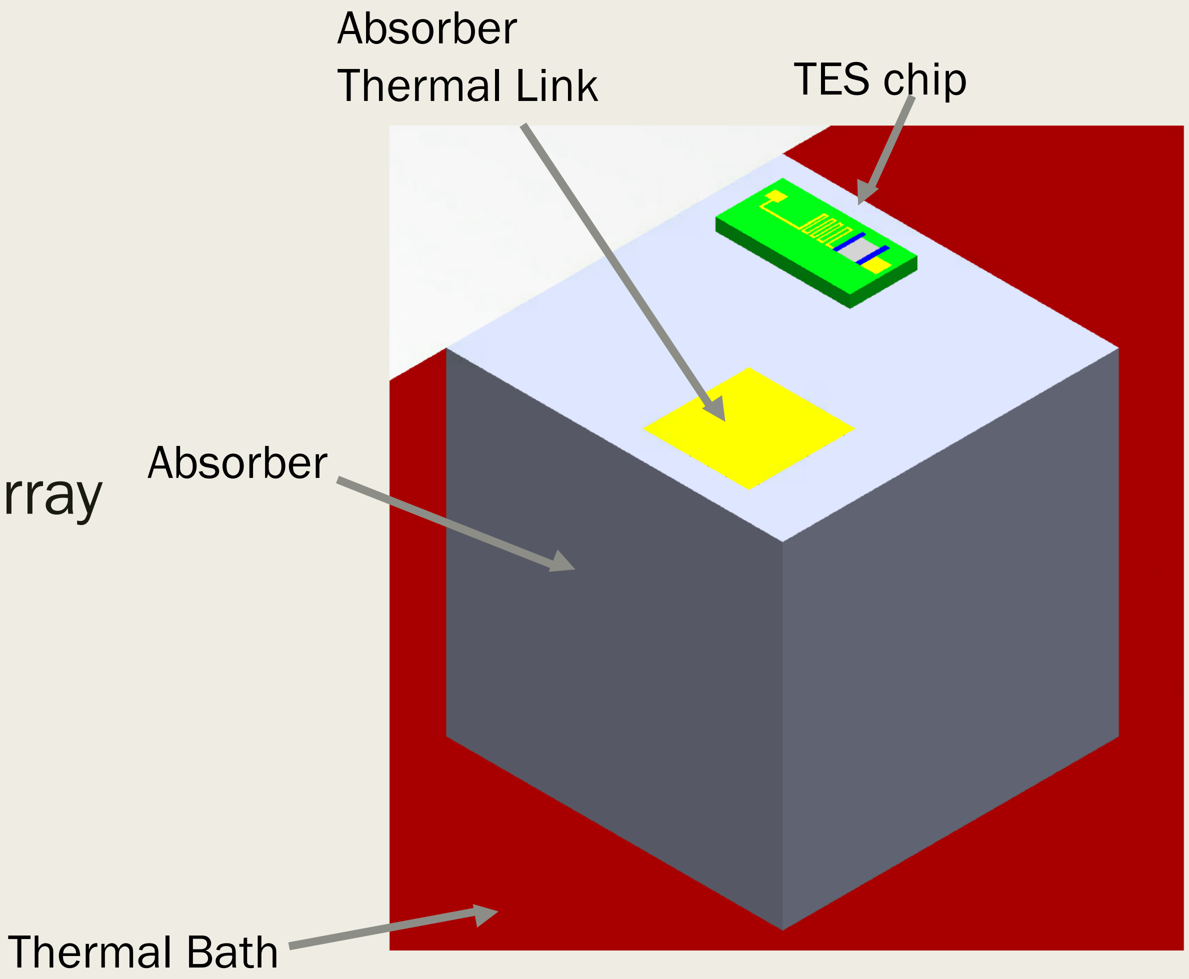
Using the TES

- How can we reach 10 eV threshold with this method?
  - *Low heat capacity*
  - *Lowers exposure mass*
- Idea: Use an array of smaller absorbers, ~2 g
- Challenge: Tedious fabrication

Formaggio et al. Phys. Rev. D 85, 013009 (2012)

Solution: Separate Thermal Circuitry

- Manufacture many at once
- Minimal manufacturing on absorber
  - *Gold pad for thermal link to TES deposited by shadow mask*
- Rest of talk discusses design of one array element

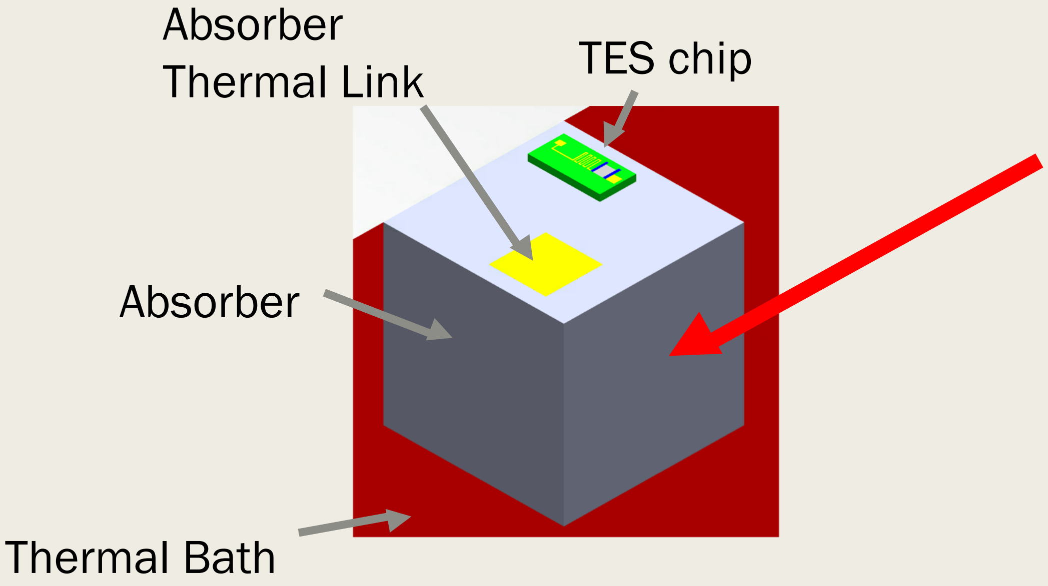


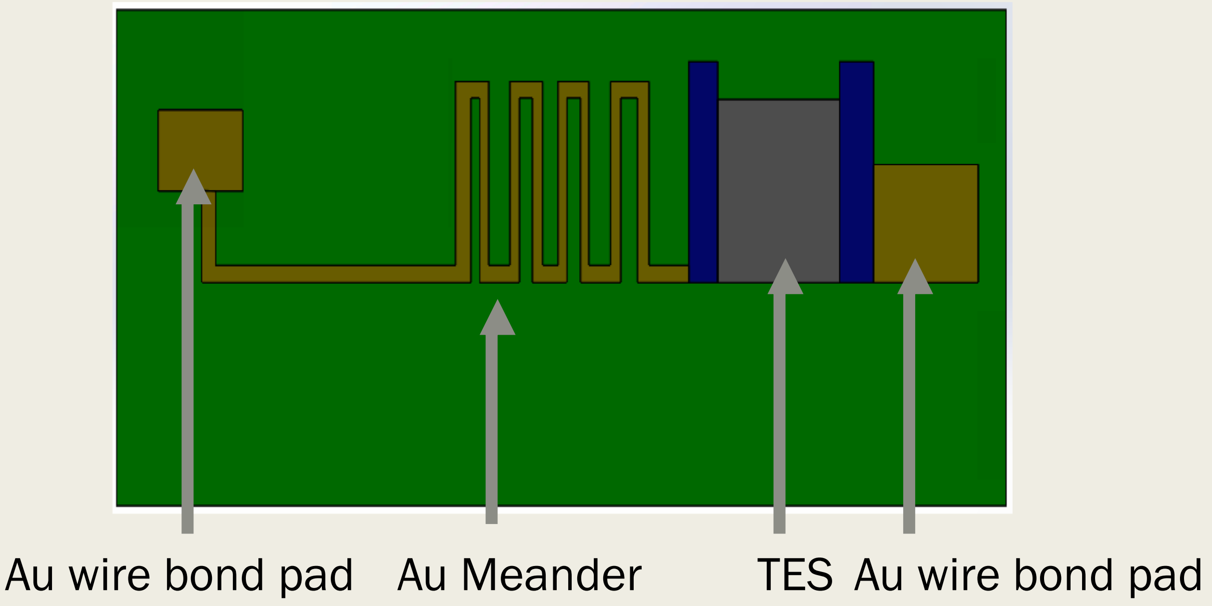
Pyle et al. arXiv:1503.01200v2

Formaggio et al. Phys. Rev. D 85, 013009 (2012)

Thermal Circuit

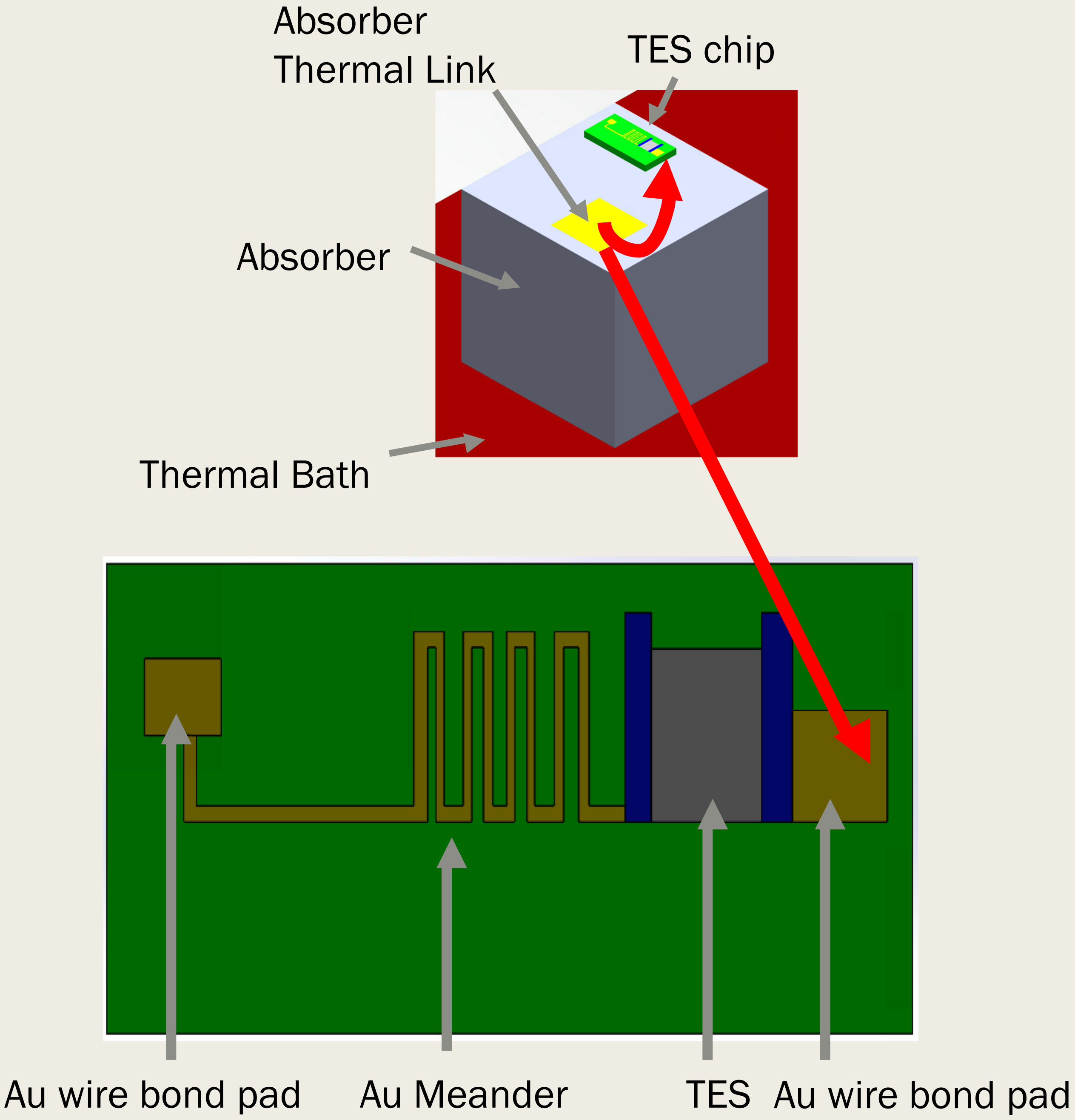
1. Energy absorbed





Thermal Circuit

1. Energy absorbed
2. Energy flows through absorber gold pad and wire bond to thermal chip
    1. Rate controlled by area of gold pad



Thermal Circuit

1. Energy absorbed
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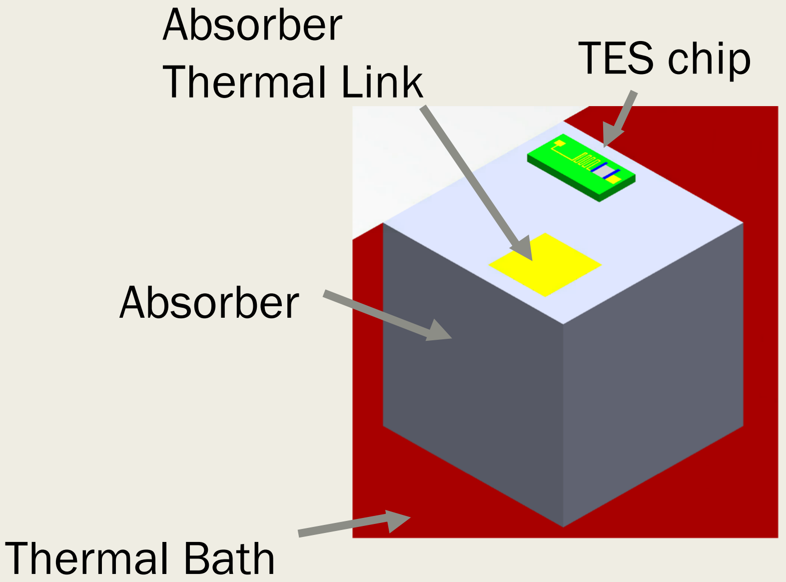
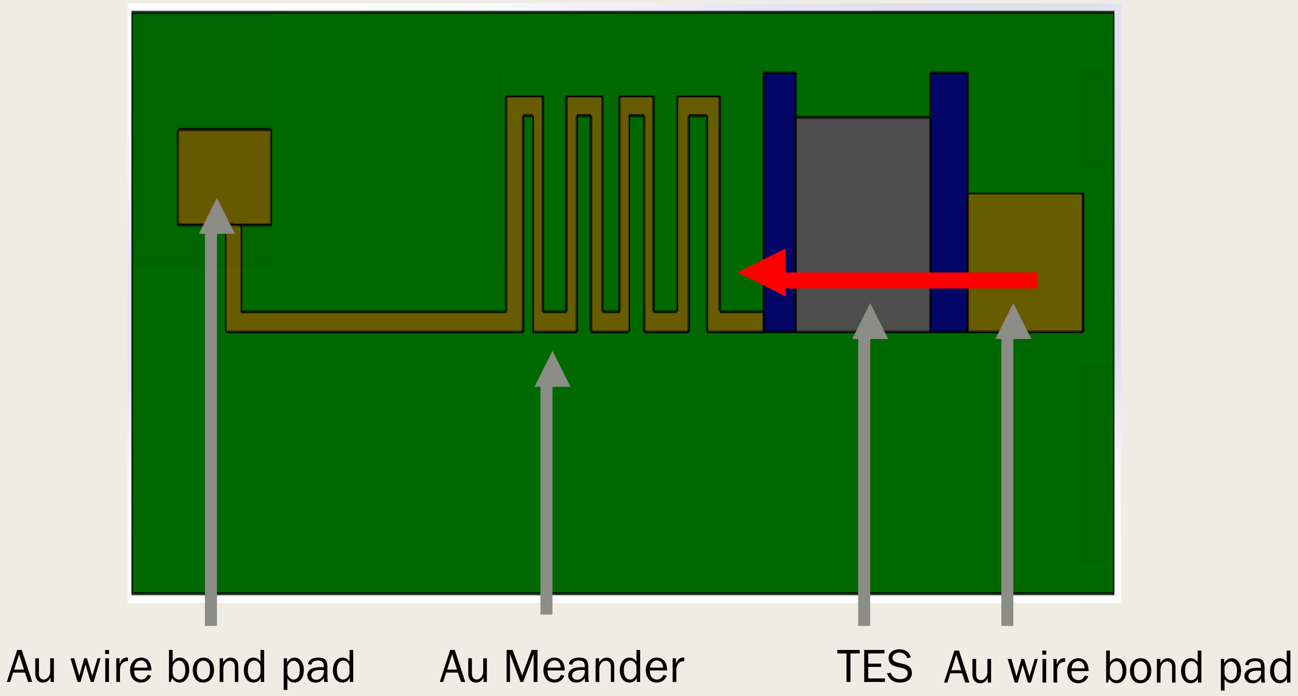
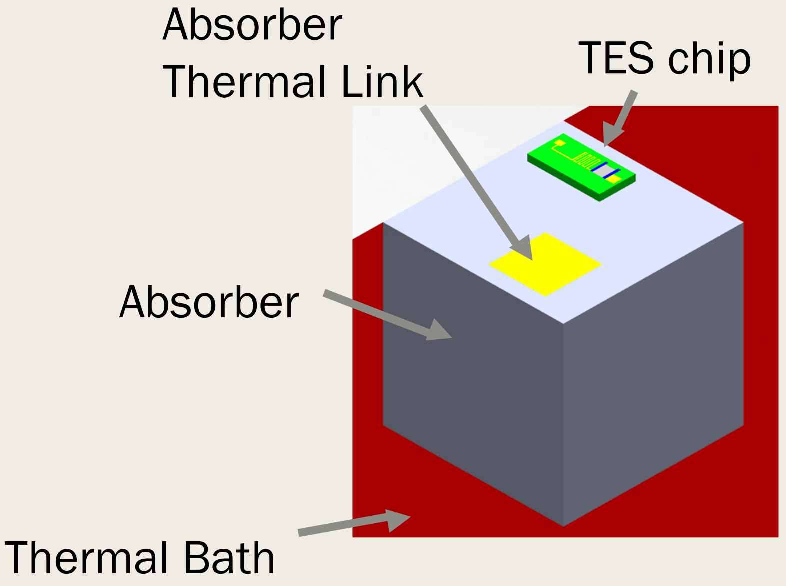
3. Energy flows through TES

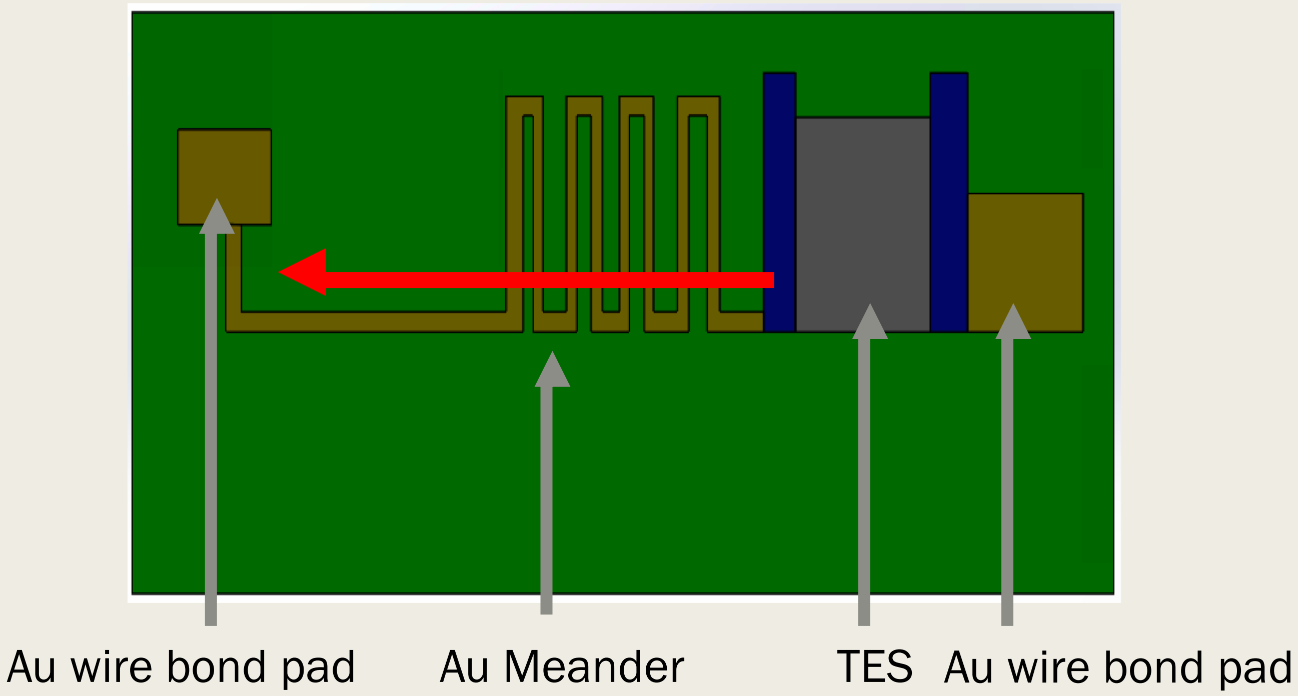




Thermal Circuit

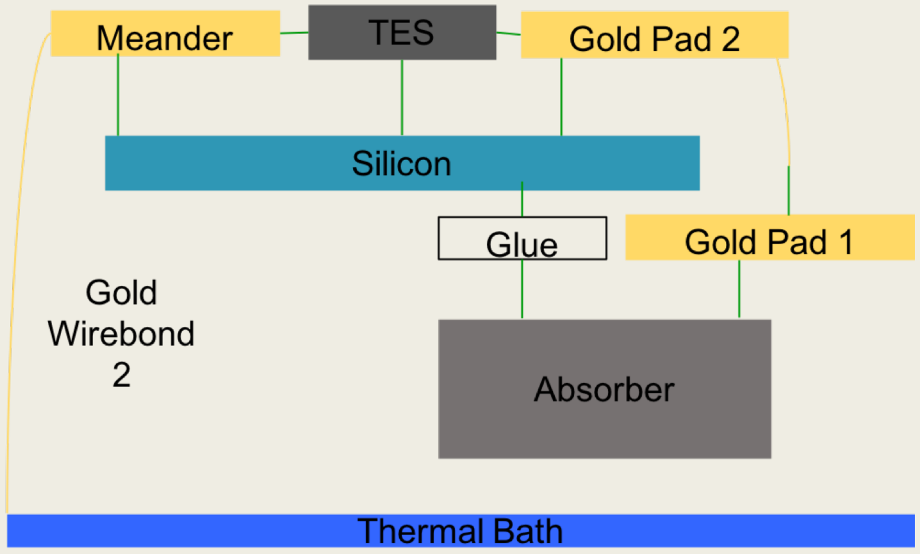
1. Energy absorbed
2. Energy flows through absorber gold pad and wire bond to thermal chip
   1. Rate controlled by area of gold pad
3. Energy flows through TES
4. Energy flow out of TES to bath
   1. Rate controlled by geometry of gold meander





Modeling and Assumptions

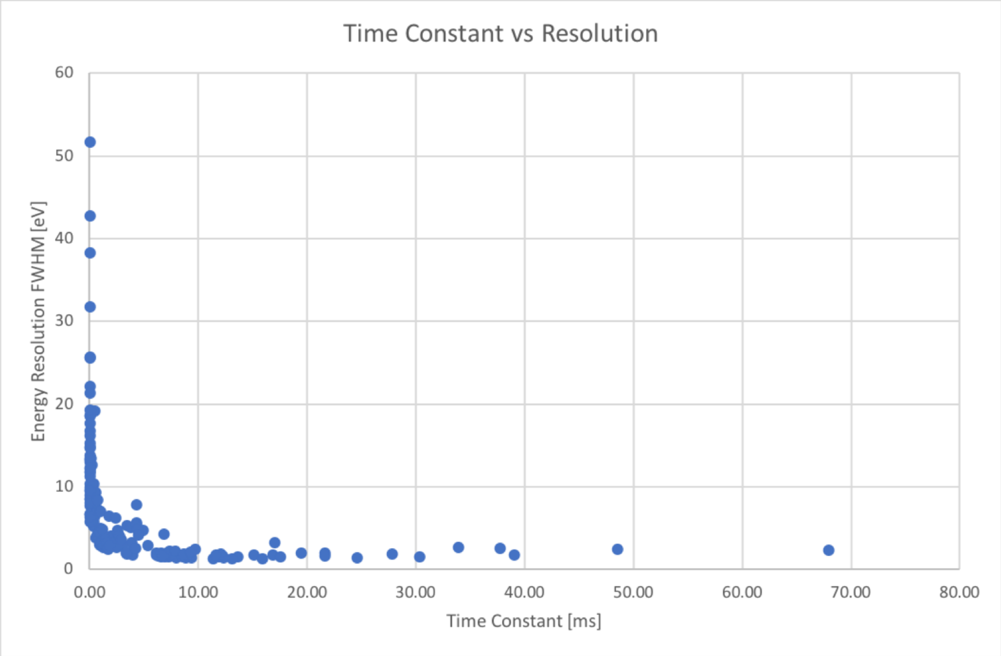
- Components as thermalized blocks
- Absorber thermally isolated from thermal bath
- Metal-metal and insulator-insulator connections are diffusive
- Metal-nonmetal connections are electron-phonon
- No Kapitza resistance incorporated
- Noise is assumed to come from thermal fluctuations and Johnson noise

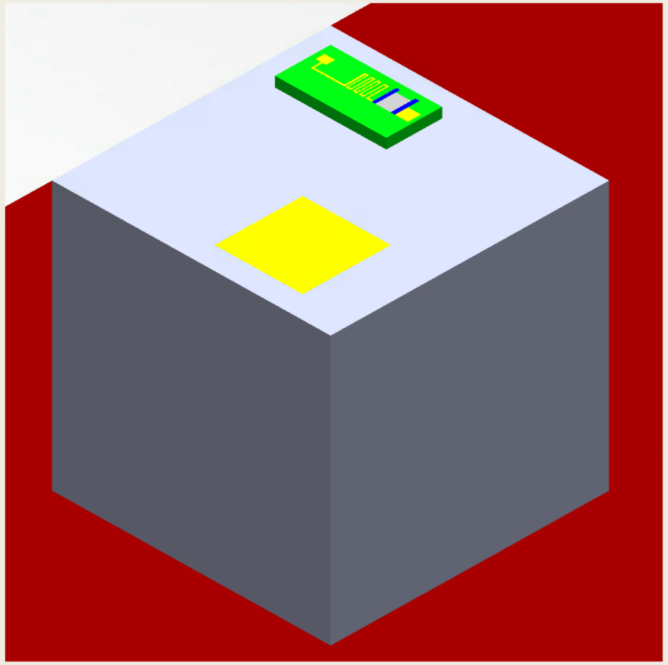


Figueroa-Feliciano JAP (2006)

Optimization

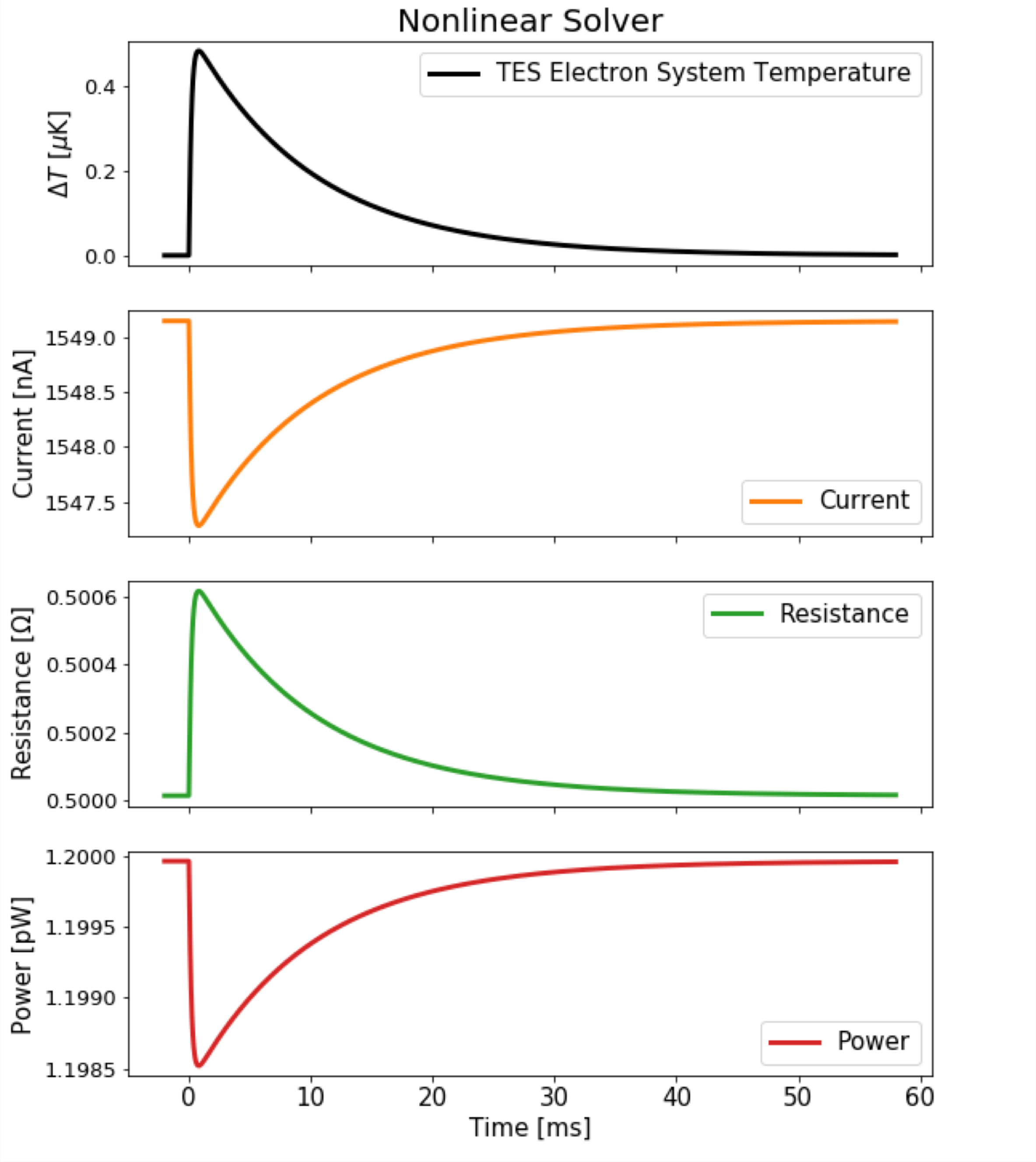
- Scan parameter space and monitor resolution and time constant
  - *Heat flow into TES governed by gold pad area*
  - *Heat flow out of TES governed by meander length*
- Set upper limit on time constant and minimize resolution





Theoretical Results

- 5 eV threshold
  - *Tungsten TES*
  - *1 cm^3 Silicon Absorber*
  - *20 mK transition temperature*
  - *10 ms decay time constant*
- Noise not shown on these pulses



Theoretical Results

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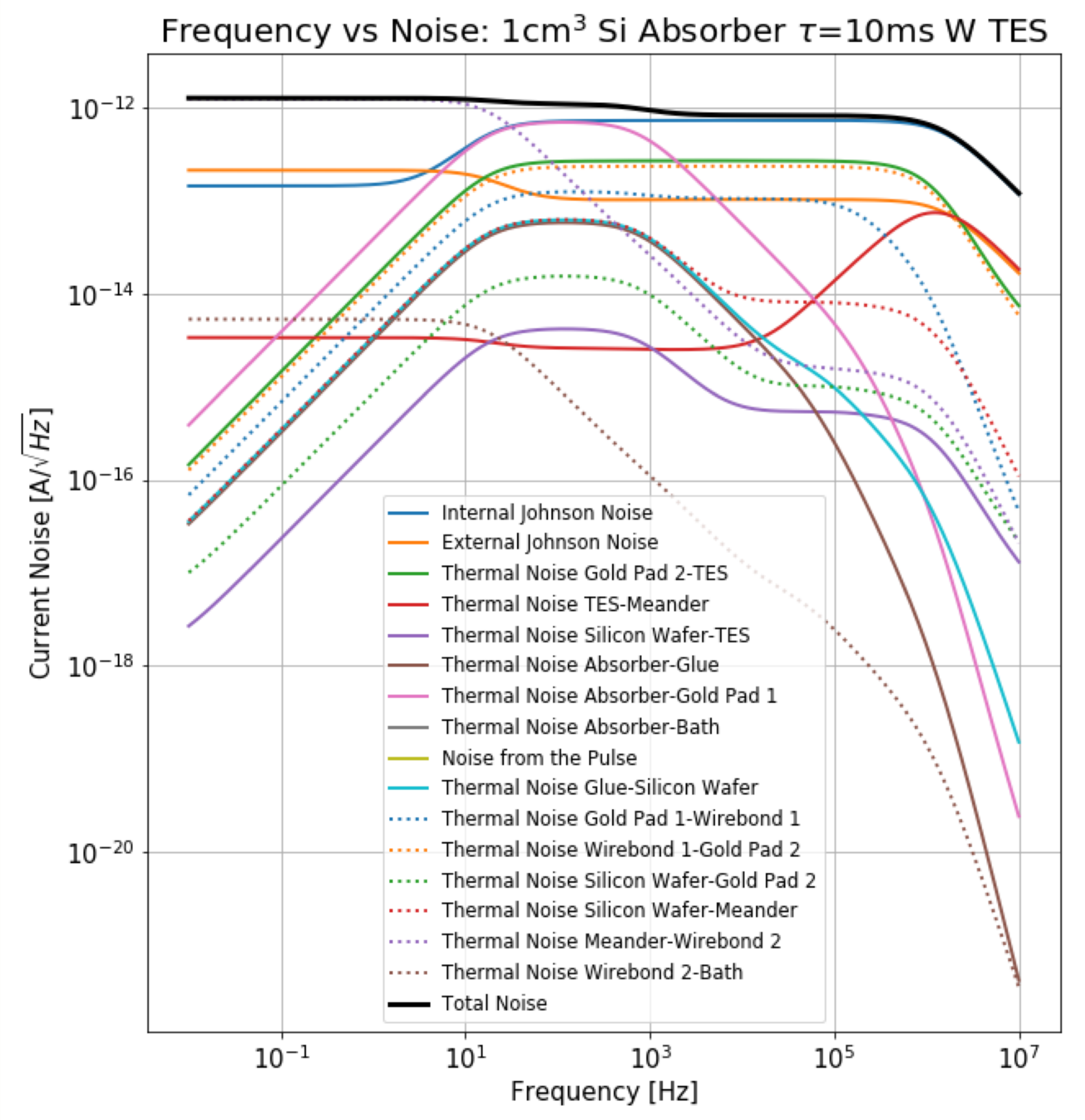
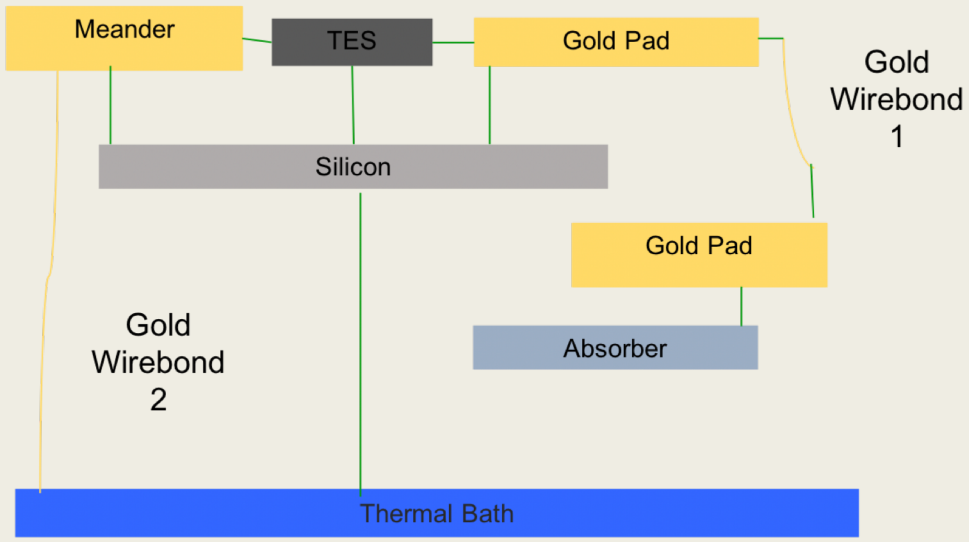


Model Variations

- Studied some variations on the model to probe different applications

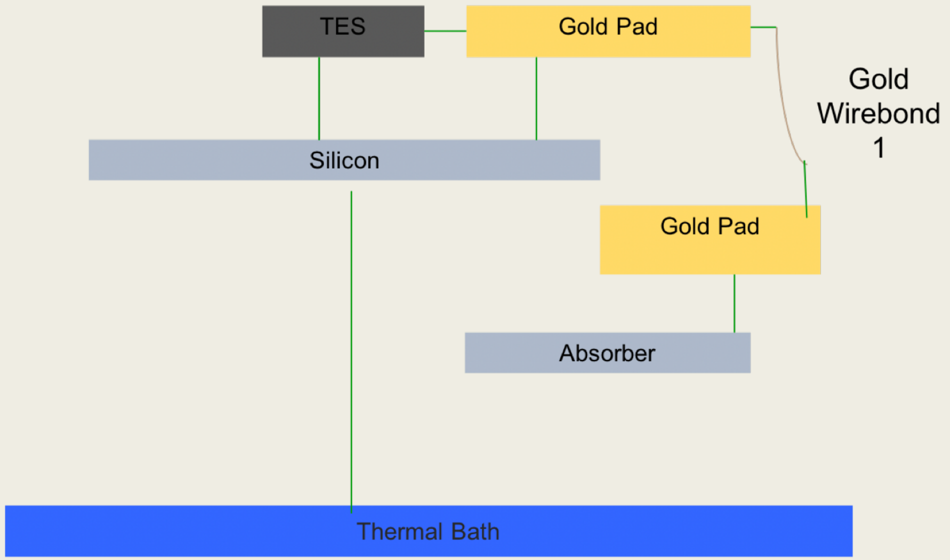
Placing Thermal Chip on Bath

- Connect chip to bath assuming perfect thermalization
- At longer time constants (~5 ms) heat preferentially flows to bath through silicon die rather than through the meander
- Threshold is 10 eV at 5.3 ms

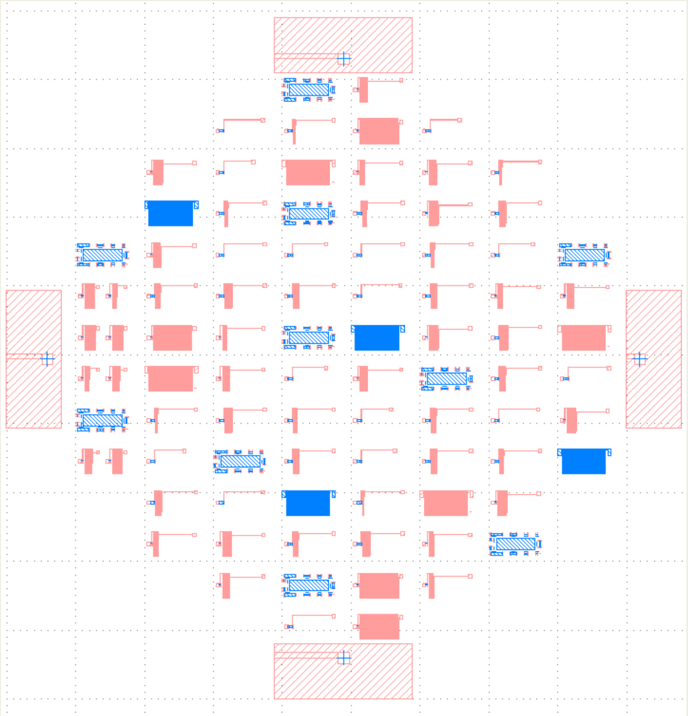


Removing Second Wire Bond

- Since heat flows through the wafer, we can remove the second wire bond
  - *Lowers heat capacity of detector by ~1/3*
- Threshold reduced to 5 eV for 10 ms decay time



Practical Implementation

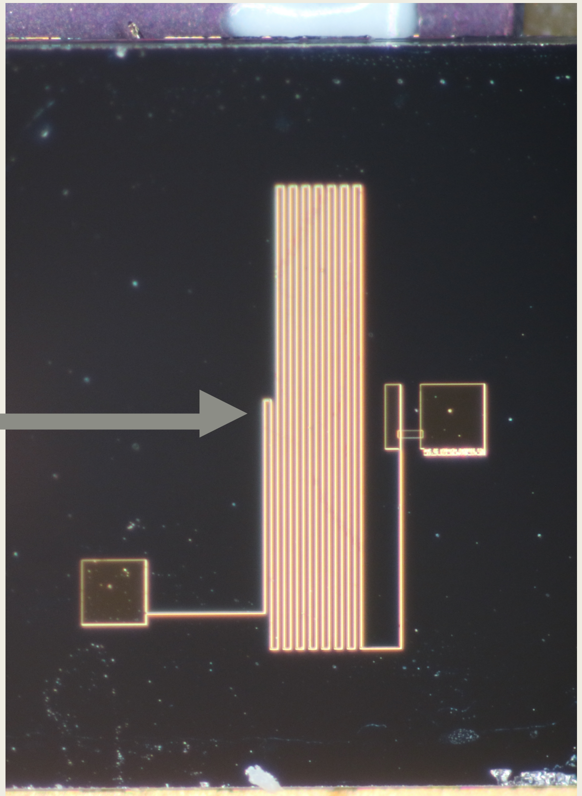


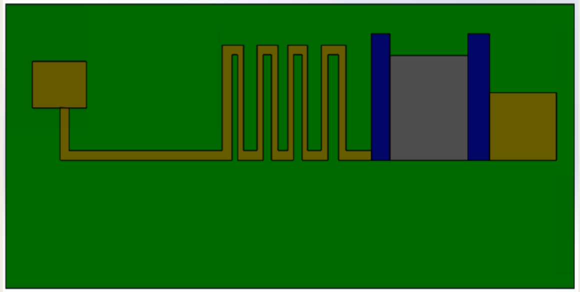
- Create a mask for initial tests
- Lab ADR has base temperature around 50 mK
  - *Aim for transition temperature of around 85 mK*
  - *Ir(100 nm)/Pt(20 nm) bilayer*
  - *Mask design has contingency for transition temperatures of 60 mK – 100 mK*
- Mask prepares for multiple absorber materials
  - *Silicon*
  - *Germanium*
  - *Zinc*
  - *No absorber*

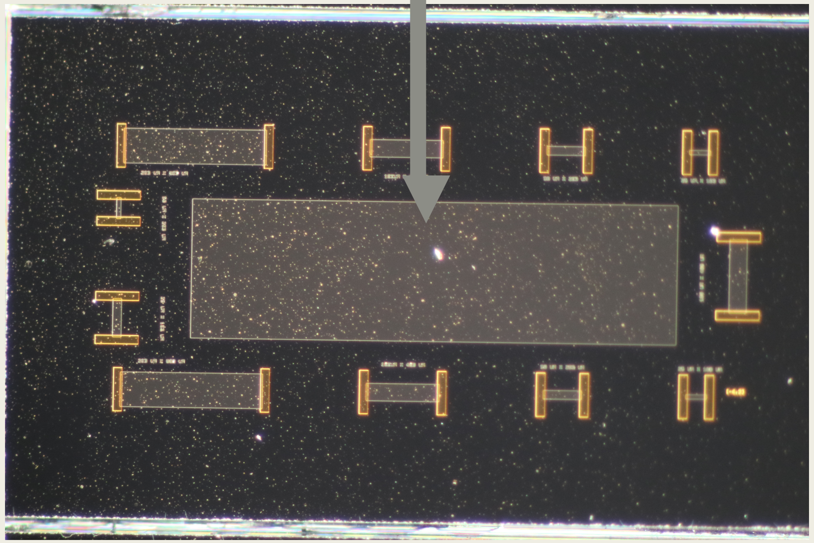
First Tests

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

High temperature device
(3 mm x 2.5 mm)







Transition temperature test structure
(3mm x 5mm)

Future Tests and Goals

- Future Tests:
  - *Observe pulses*
    - Compare with the model
  - *Measure gold thermal conductance*
- 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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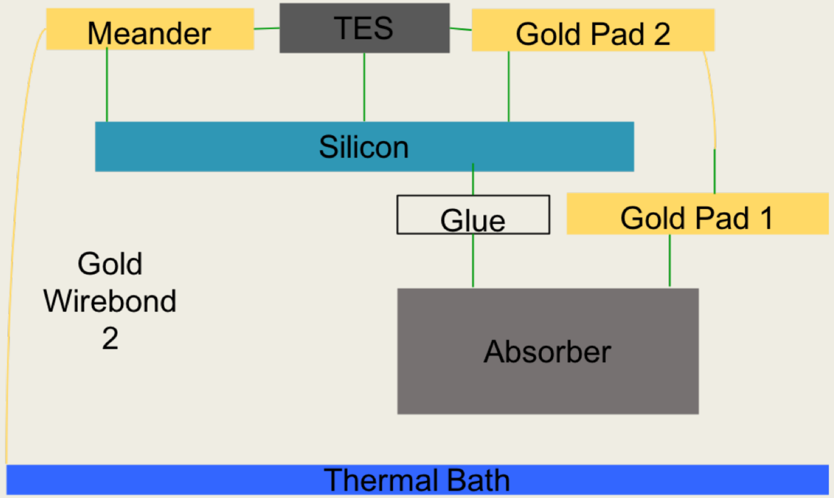
- Additional funding was provided through the NASA Illinois Space Grant

Questions?

Bonus Slides

Model Parameters



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

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

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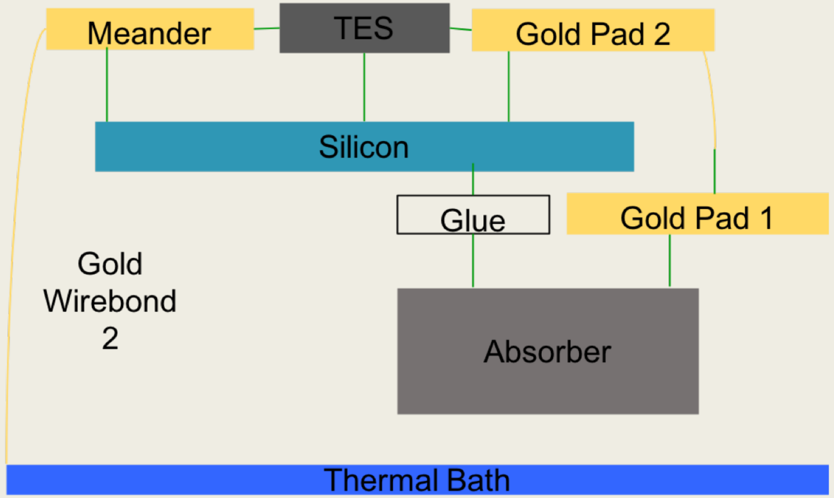
### Electrical Components ###
L        : 1.0e-7                #Inductor in Thevenin Equivalent [Henries]
Rl       : 0.02                  #Load/Shunt Resistor [Ohms]
alpha0   : 100.                  #Temperature Sensitivity [Unitless]
beta0    : 1.                    #Current sensitivity [Unitless]
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]
```

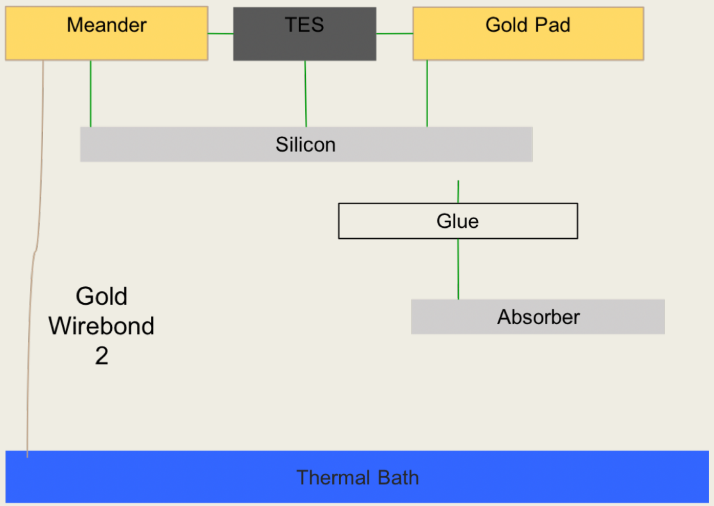
Component Geometry

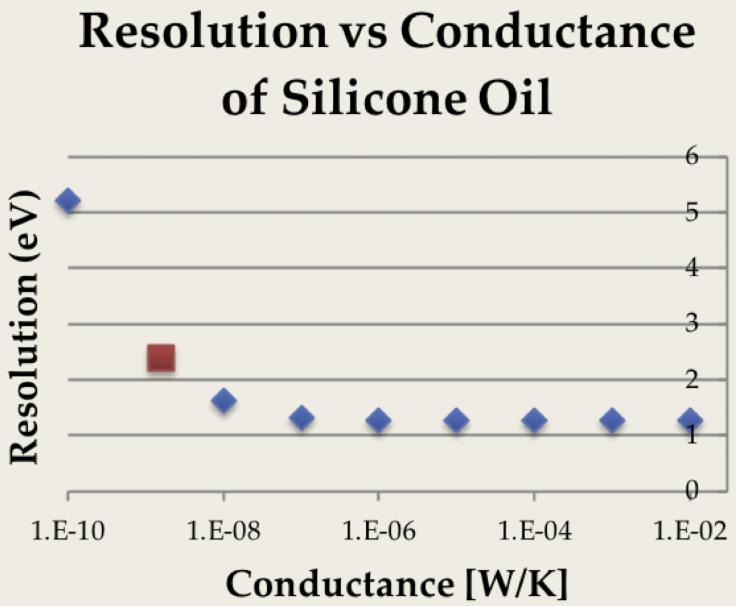


Component	Geometry	Material
Absorber	1cm^3	Silicon
Glue	$1\text{ mm} \times 1\text{ mm} \times 200\ \mu\text{m}$	Polydimethylsiloxane (Silicon Oil)
Gold Pad 1	$20\text{ mm}^2 \times 400\text{ nm}$	Gold
Wire Bond 1	$50\ \mu\text{m} \times 5\text{ mm}$	Gold
Gold Pad 2	$250\ \mu\text{m} \times 250\ \mu\text{m} \times 600\text{ nm}$	Gold
Die	$2\text{ mm} \times 4\text{ mm} \times 375\ \mu\text{m}$	Silicon
TES	$200\ \mu\text{m} \times 200\ \mu\text{m} \times 600\text{ nm}$	Tungsten
Meander	$5\ \mu\text{m} \times 167\text{ mm} \times 600\text{ nm} + 250\ \mu\text{m} \times 250\ \mu\text{m} \times 600\text{ nm}$	Gold
Wire Bond 2	$50\ \mu\text{m} \times 5\text{ mm}$	Gold

No Absorber Deposits

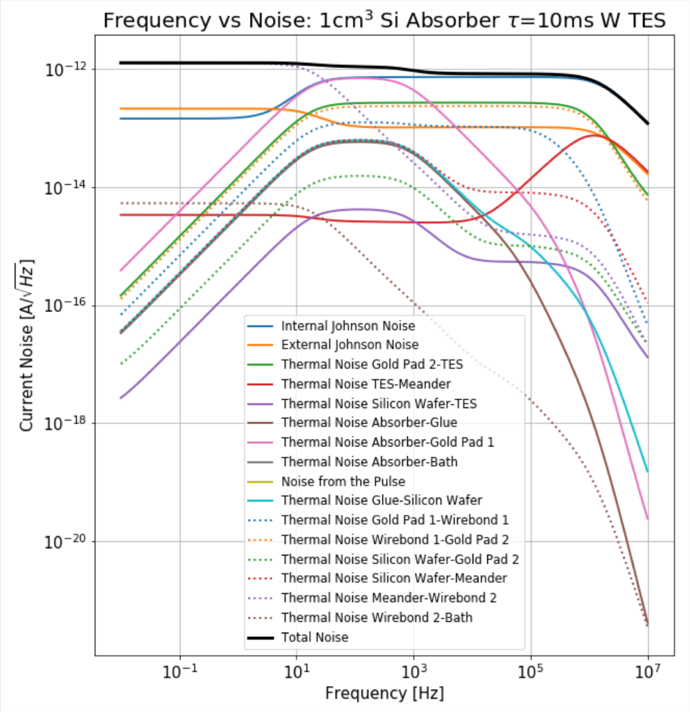
- Heat can flow directly through the glue
- In the case we do not want to manufacture on the absorber
- Uncertain assumption of the glue thermal conductance
- Threshold 5 eV at 10 ms decay time





Resolution Calculation

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



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Responsivity

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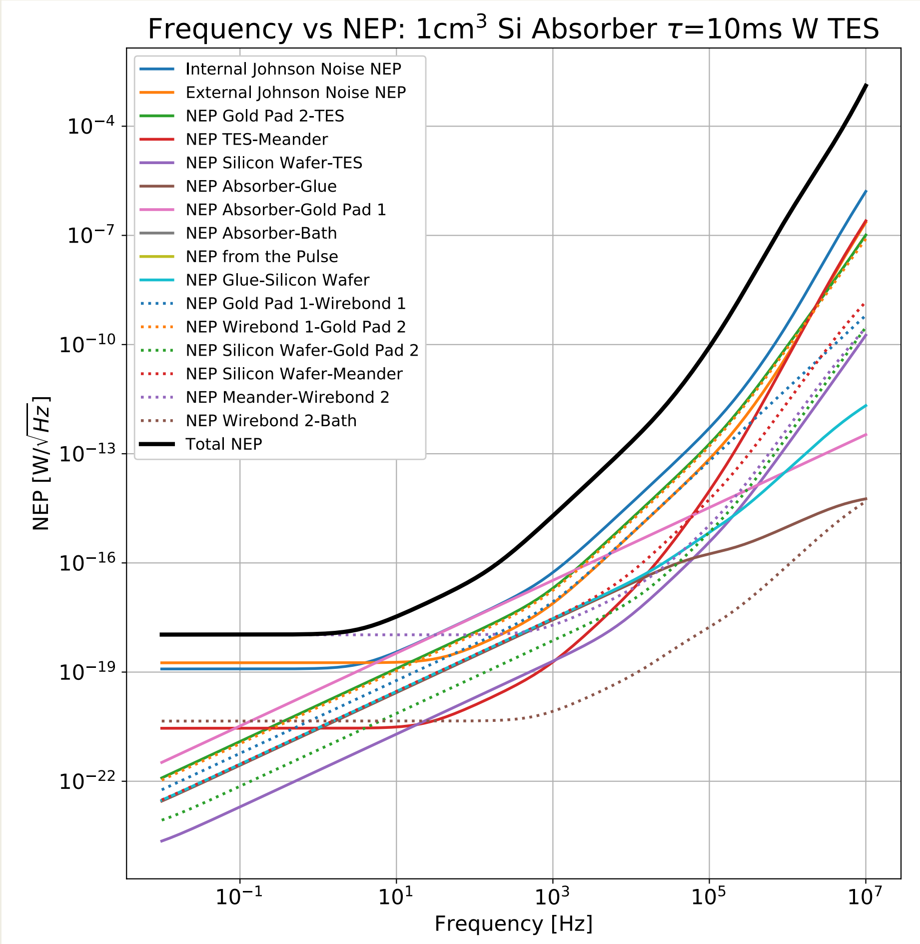

Mask Design Optimization Results

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