A high energy resolution gamma-ray TES calorimeter with 0.5ms response time

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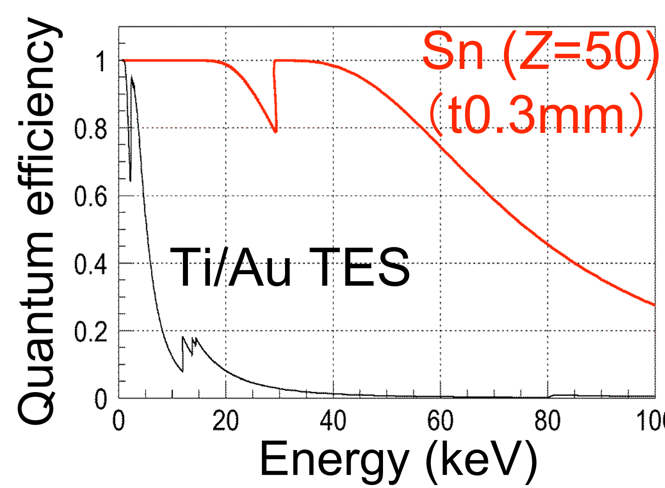
Applications & requirements

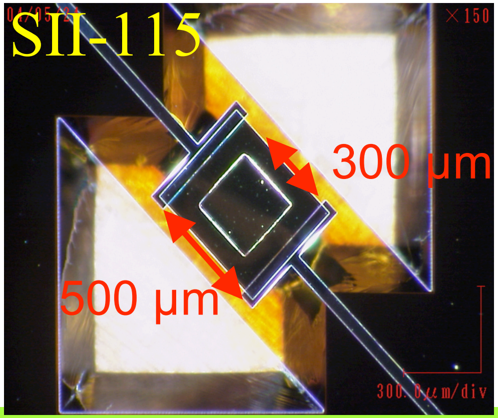
- Astrophysics
  - ^{44}Ti (68.9/78.3 keV, $T_{1/2}$~ 59 yr) γ-ray emission from supernova remnants
    - direct information on the radioactive isotopes produced by the explosions
    - not obscured by galactic dust

  ⇒ provides a stringent test of theories of supernova nuclear reactions.

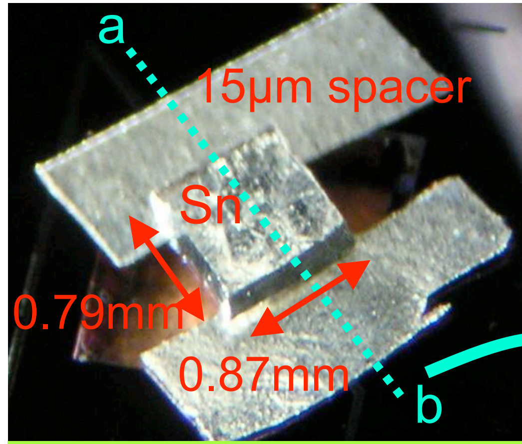
  Fly γ-ray calorimeters on balloons!
- Material analysis (EDXRD)
  - γ-ray diffraction spectroscopy of crystals under ultra high pressure(~MPa) → Poster by A. Hoshino
  - interesting structures ~80keV
  - time evolution ⇒ fast response time
- Our GOAL
  - Bandwidth ~ 100 keV
  - Energy resolution ΔE ~ a few times 10 eV
  - Fast response time τ << 1ms
  - High Efficiency @ ~80keV



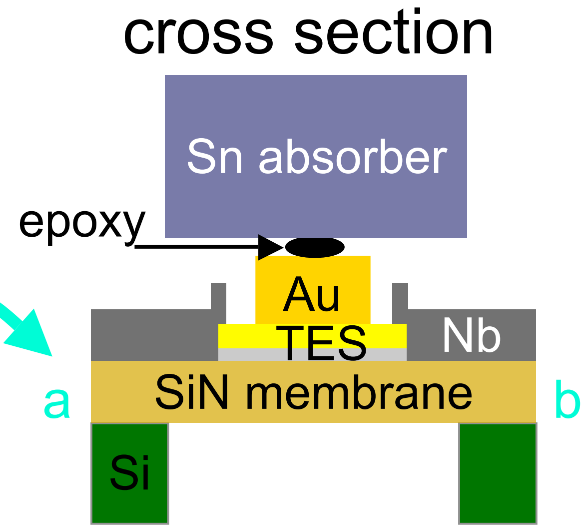
Our first trial (SII-115)



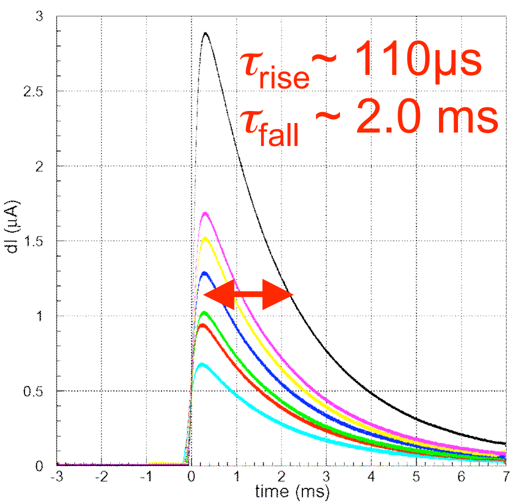
TES: Ti/Au(40/70nm)
X-ray absorber: Au(500nm)
Membrane: SiN bridge
T_c: 151 mK



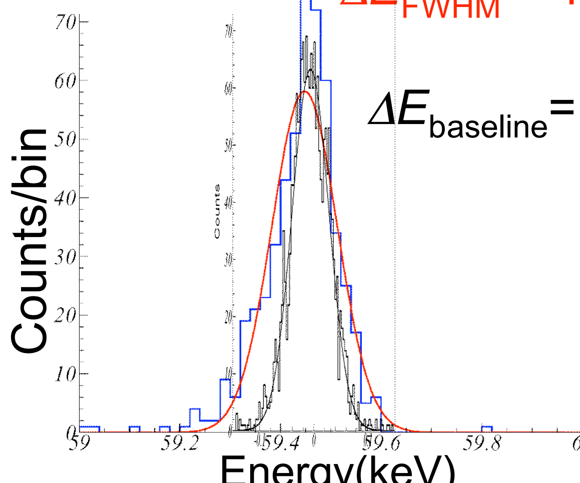
C_a =11.2 pJ/K



Response:



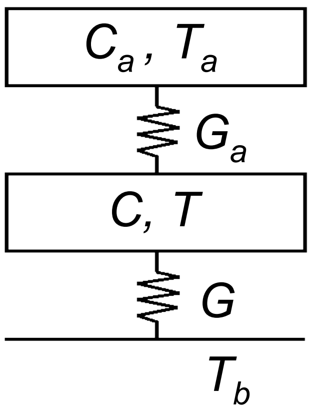
Energy resolution:



Pulse shape analysis shows no significant fluctuation of τ_{rise} .
Let's try a faster one!

Trade off

- Trade off between the signal loss and the position dependence.
  - $\tau_{fall} \downarrow (\cong G \uparrow) \Rightarrow \tau_{fall} / \tau_{rise} \downarrow \Rightarrow \Delta T_{TES} \downarrow \Rightarrow$ signal loss
  - $\tau_{rise} \downarrow (= G_a \uparrow) \Rightarrow$ Position dependence in the absorber $\uparrow$



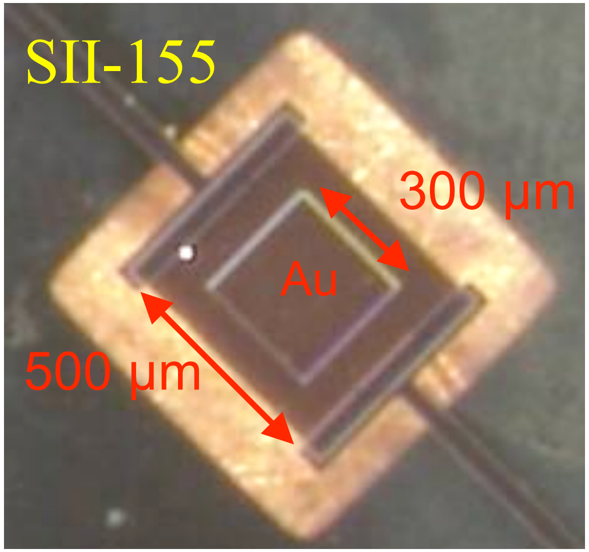
- How fast can we make?

$\Rightarrow$ SPICE simulation

- Boundary conditions:
  - Limited G_a : @150mK (@100mK)
    - Stycast 2850FT ~ 100nW/K (30nW/K) for r =100μm, h=20μm
    - Kapitza ~ 170nW/K (50nW/K) per r =100μm boundary (2 boundaries)
    - electron-phonon ~ 450nW/K (85nW/K)

    $\Rightarrow G_a$ ~ 50nW/K (~20nW/K)
  - Saturation at the transition edge:
    - lower limit to C_a

Our Second trial (SII-155)



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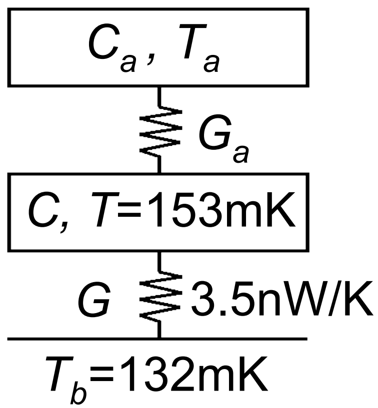
X-ray absorber: Au(500nm)
Membrane: SiN square
T_c: 151 mK
C = 2.0 pJ/K
G = 3.5 nW/K
ΔE = 12 eV @ 5.9 keV

Saturation

Thermal model



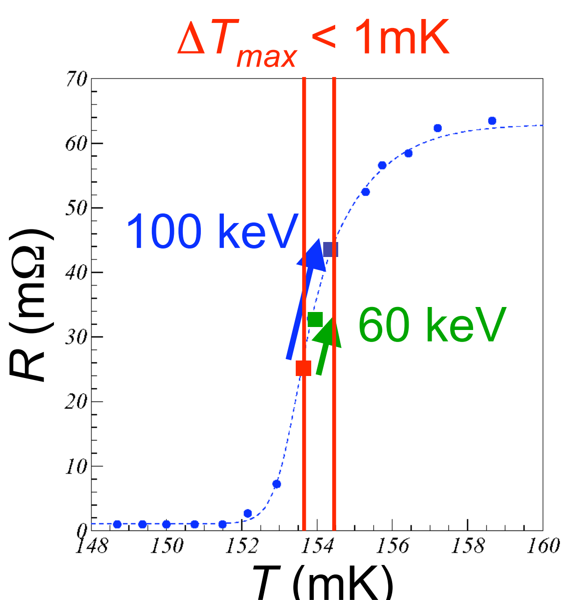
Temperature change of the TES

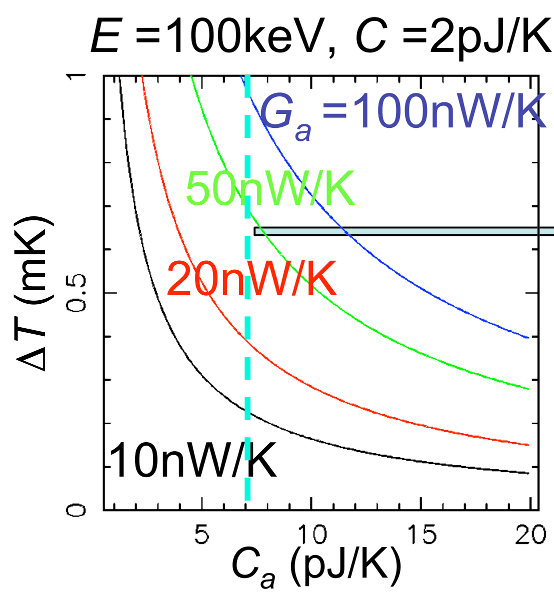
$$\tau_{\pm} = \frac{2\tau_0\tau_a}{\gamma\tau_0 + \mathcal{L}\tau_a \pm \sqrt{(\gamma\tau_0 + \mathcal{L}\tau_a)^2 - 4\tau_0\tau_a\mathcal{L}}}$$

$$\Delta T = \frac{E}{C_a}\frac{(\tau_a - \tau_+)(\tau_- - \tau_a)}{\tau_a(\tau_- - \tau_+)}\left(\exp(-\frac{t}{\tau_-}) - \exp(-\frac{t}{\tau_+})\right)$$

$$t_{pk} = \frac{\ln(\tau_-/\tau_+)}{(1/\tau_+ - 1/\tau_-)}$$

$\tau_a \equiv C_a/G_a$ $\gamma \equiv 1 + C_a/C$
$\tau_0 \equiv C/G$ $\mathcal{L} \equiv 1 + P\alpha/GT$
approx. $\alpha \sim (T/R)(\Delta R/\Delta T)$





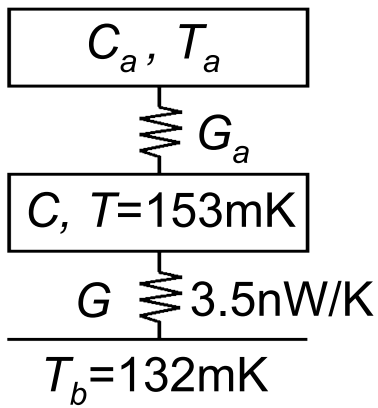
$C_a \sim 7$pJ/K

$(C > \alpha E_{max}/Tc = 21\mathrm{pJ/K})$

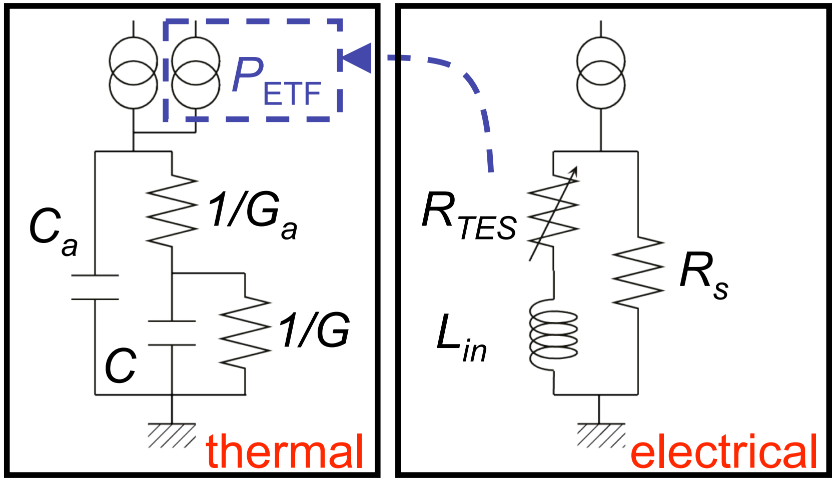
⇒ size ~ 700μm

SPICE Simulation: Noise spectrum

Thermal model

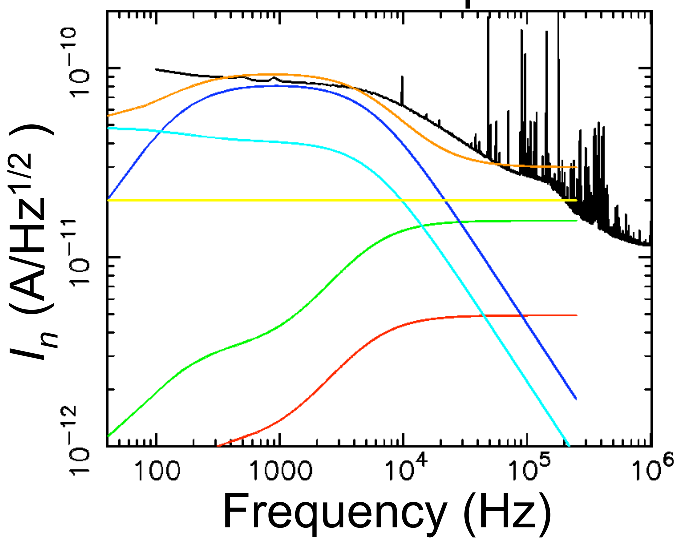


Equivalent circuit



(LLNL: Miyazaki et al.)

Current noise spectrum



Johnson noise of
- Shunt resistor R_s =3mΩ
- TES R_{TES} = 25.58mΩ

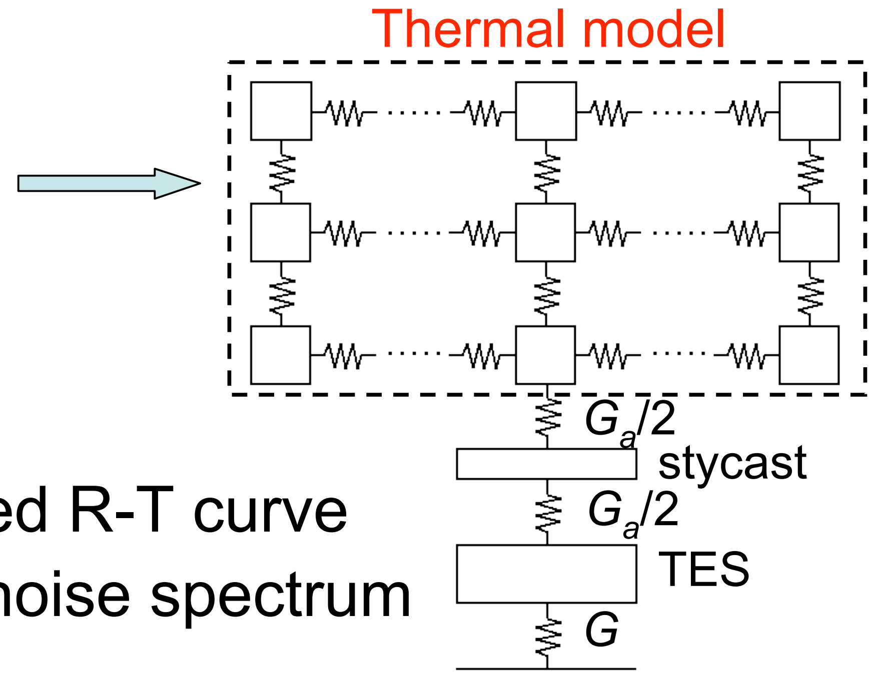
Phonon noise at
- G = 3.5nW/K
- G_a = 10nW/K
- Readout (SQUID) noise 20pA/$\sqrt{\text{Hz}}$
- Total

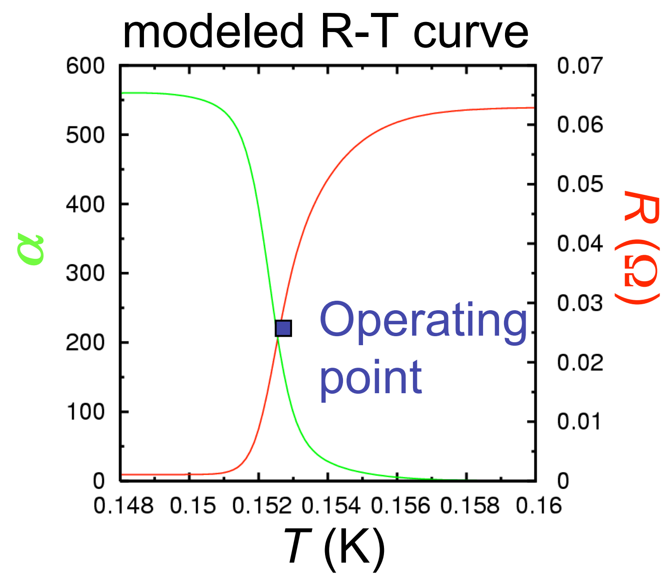
SPICE Simulation: Position dependence (1)

- FEM-like model with SPICE
  - Absorber: 3D network of *C* and *G*
    7 x 7 x 3 elements
    (Please imagine a 3D picture!)
  - stycast: 1 element
  - TES: 1 element
- generate pulses using a modeled R-T curve
- optimal filtering with simulated noise spectrum

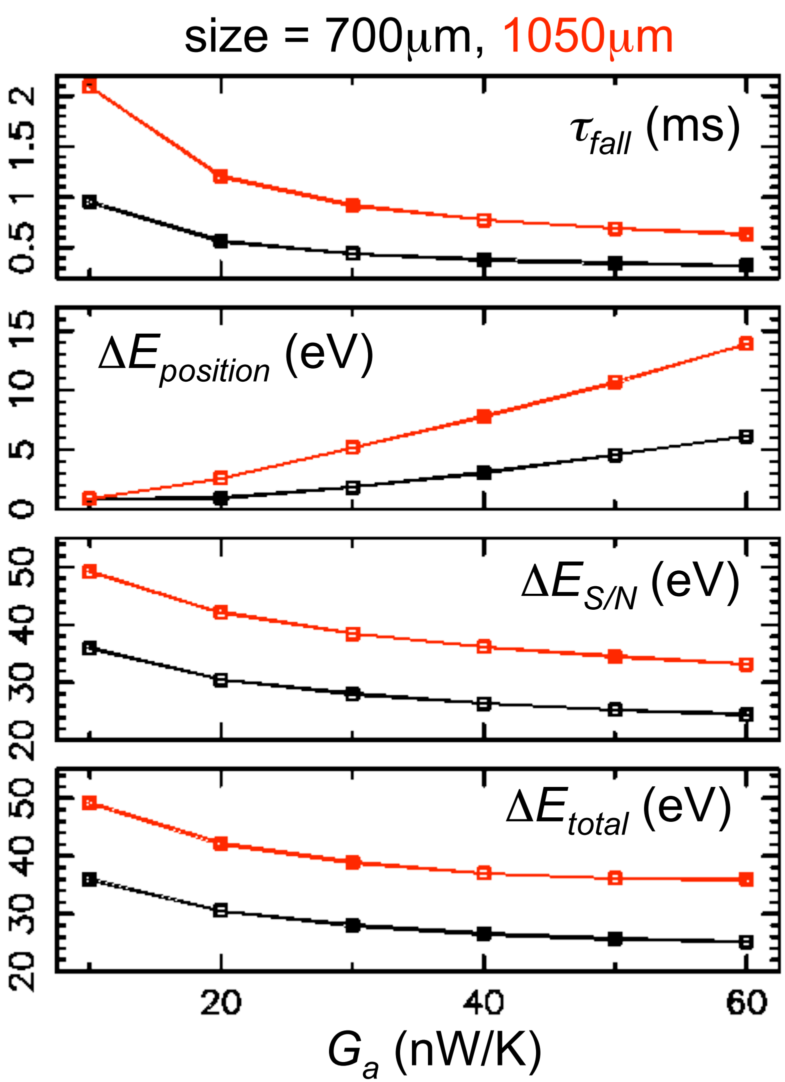
$\Rightarrow$ pulse height $\Rightarrow \Delta E_{FWHM}$

- Material Parameters of Sn:
  - $\kappa_{Sn} = 1.24 T^{3.1}$ W/K/m (foil)
  - $c_{Sn} = 0.054$ pJ/K
- Scan parameters: G_a , absorber area



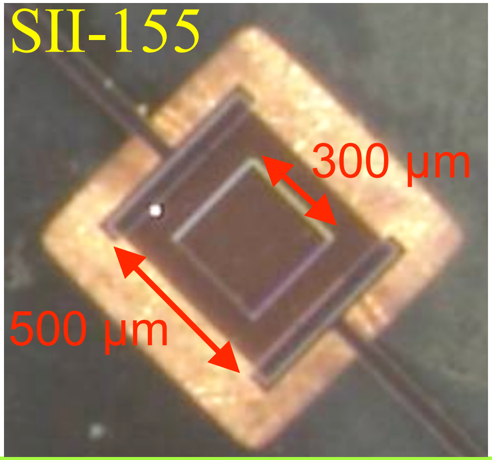


SPICE Simulation: Position dependence (2)



Make G_a as large as possible!
700μm 25 eV && τ_{fall} = 300μs
1050μm 36 eV && τ_{fall} = 600μs
achievable.

Our Second trial (SII-155)



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C = 2.0 pJ/K
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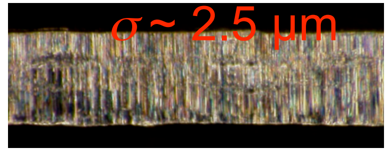
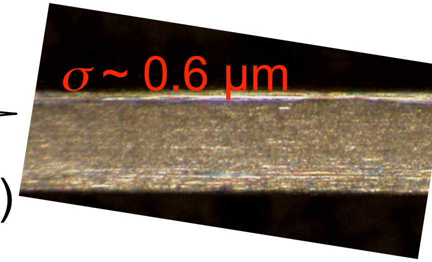
ΔE = 12 eV @ 5.9 keV

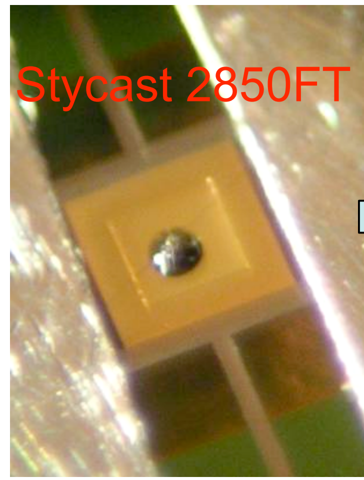
C_a = 6.9 pJ/K

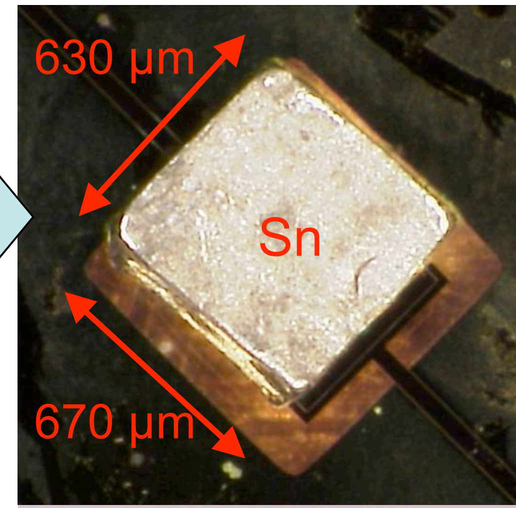
Surface roughness of Sn:



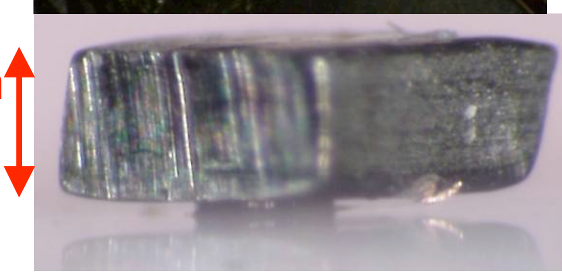
Polished with alumina powder(~3 µm)



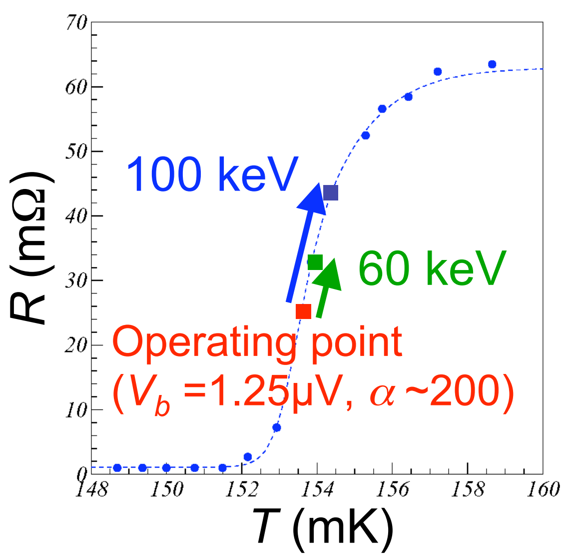


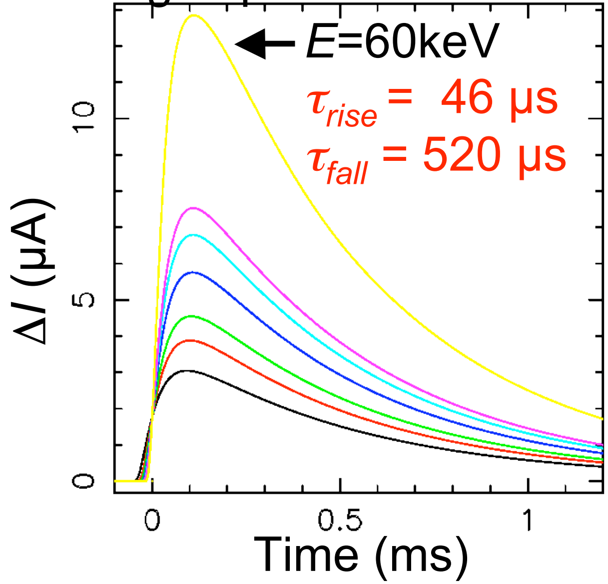


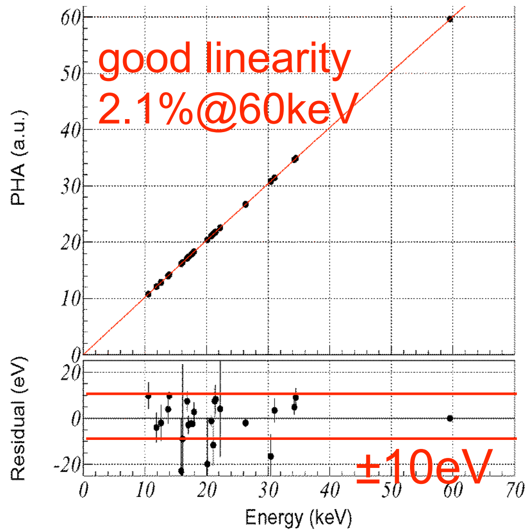
300µm



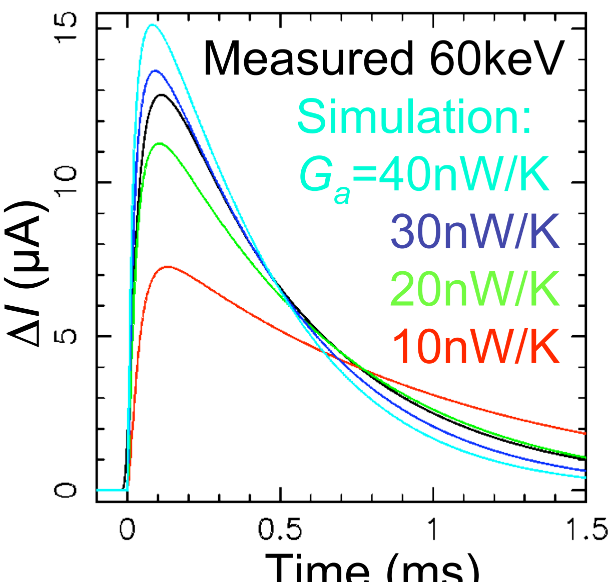
SII-155+Sn results (1)





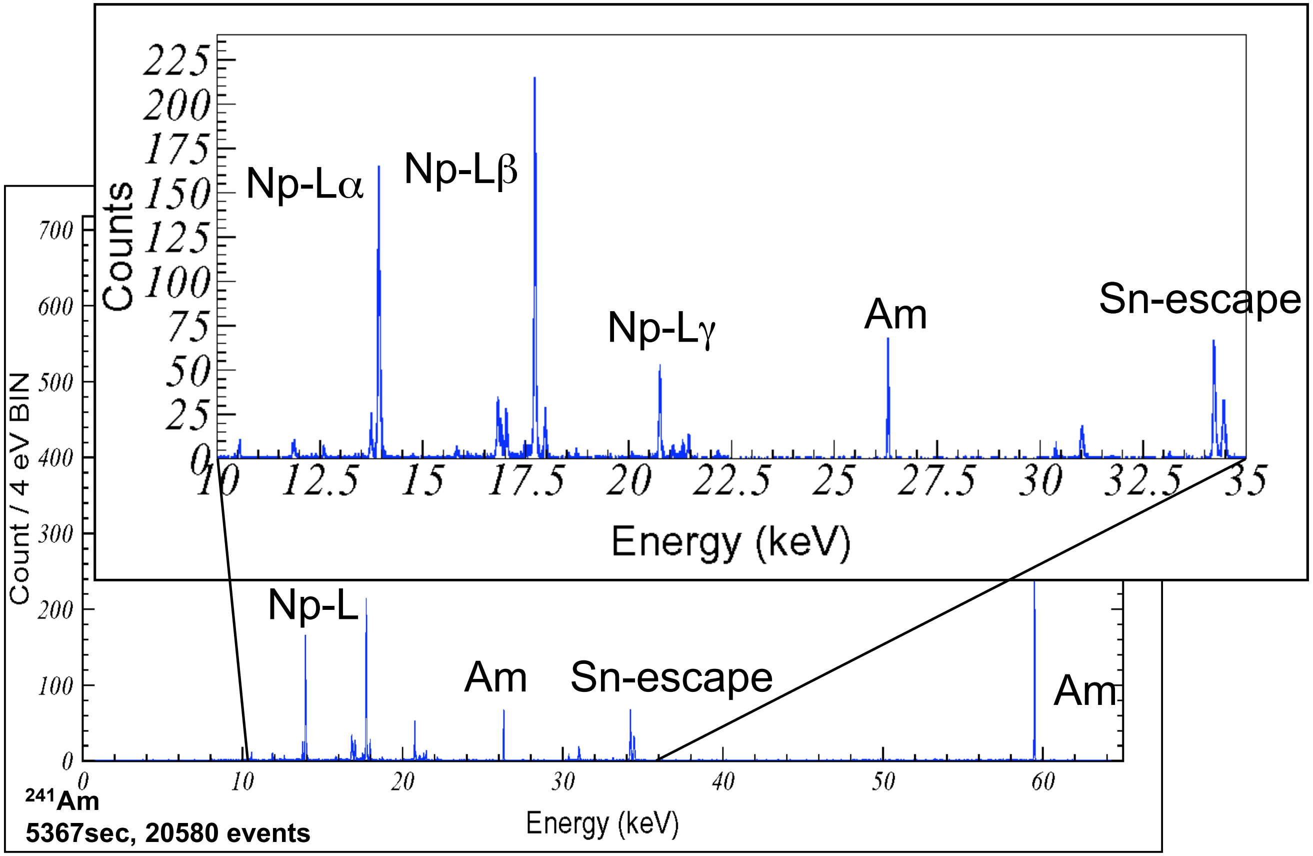


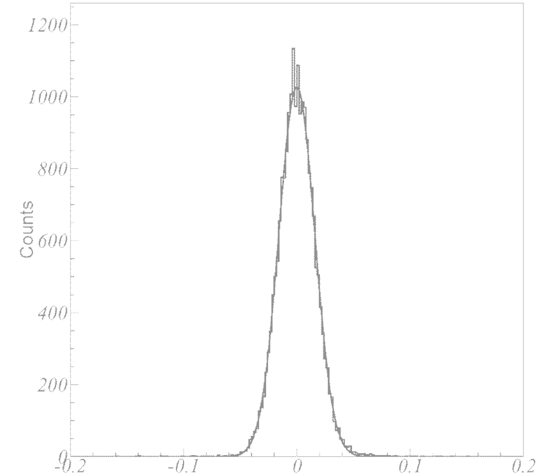
Comparison with the SPICE simulation



G_a ~ 30nW/K

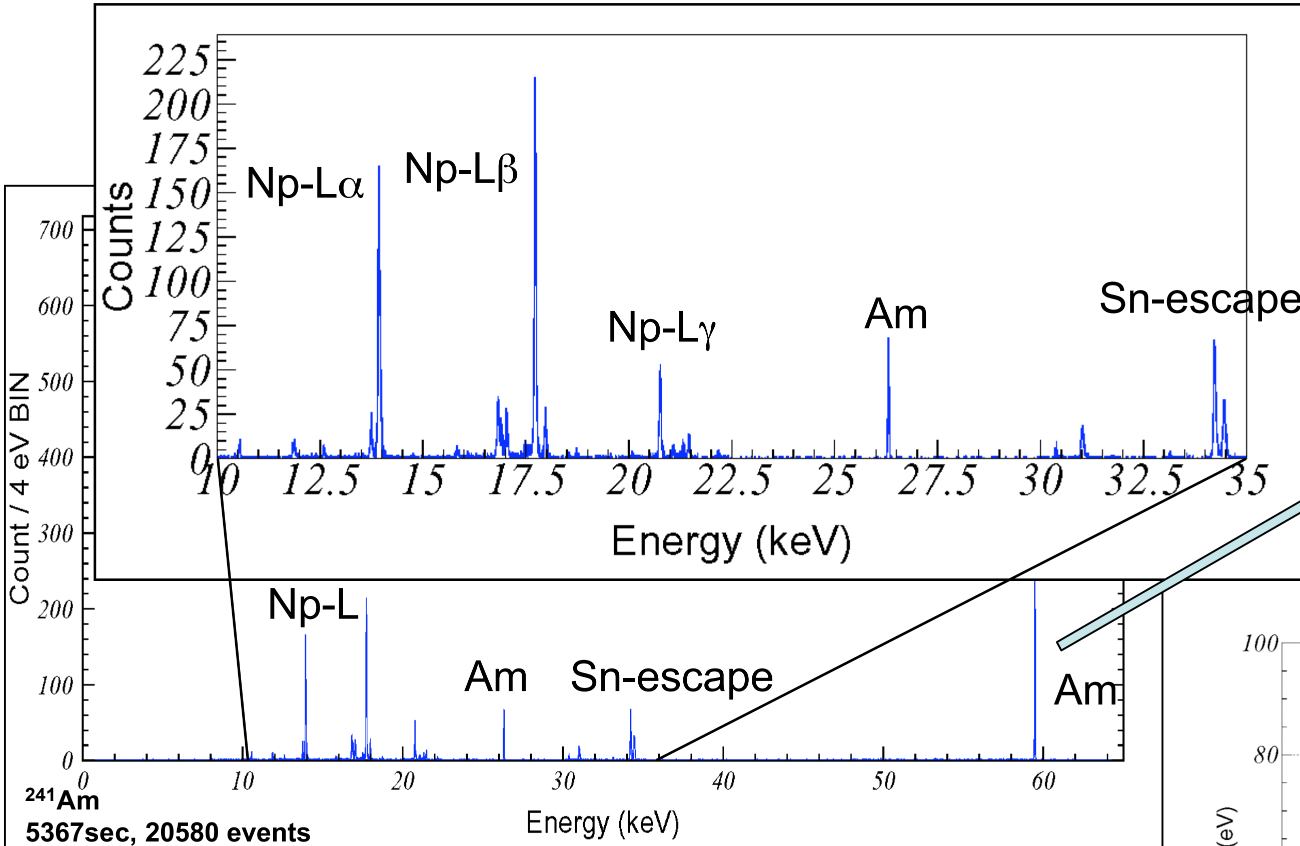
SII-155+Sn results (2)

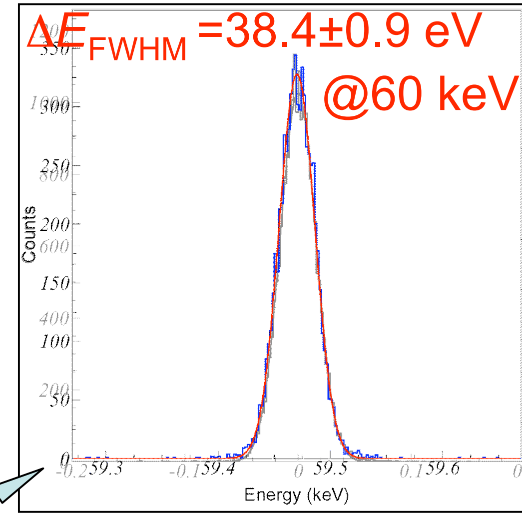




$\Delta E_{baseline}$=37.9±0.7 eV

SII-155+Sn results (2)





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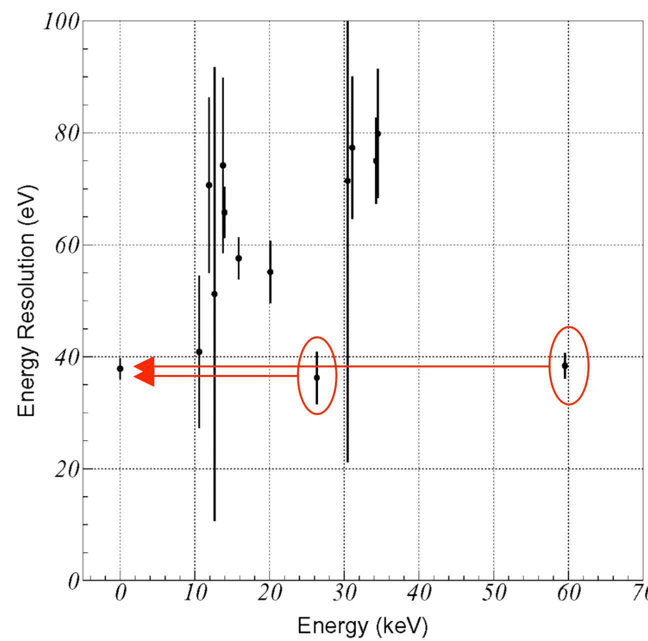
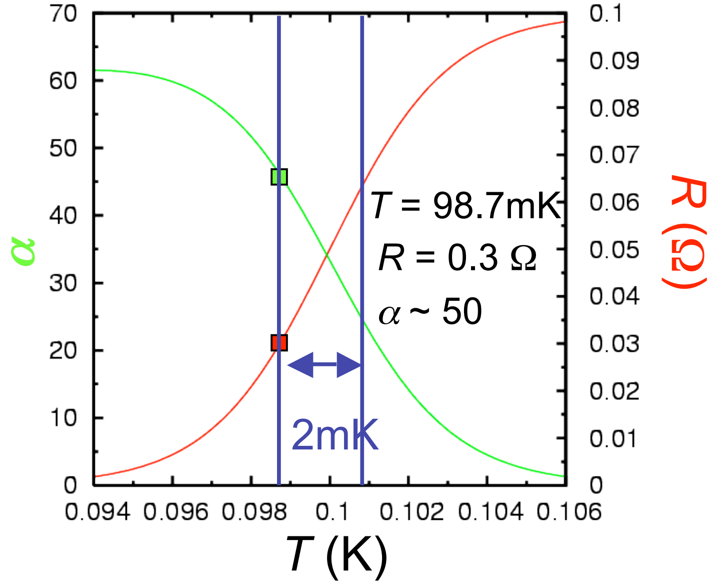
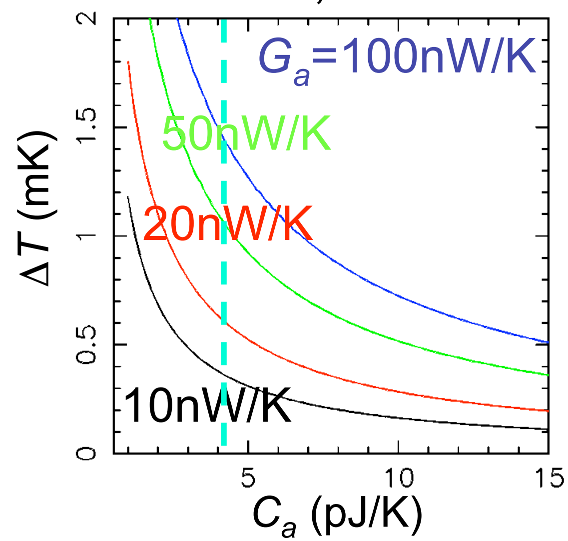


Energy resolution of the
nuclear γ-ray lines (26, 60 keV)
agrees with $\Delta E_{baseline}$
⇒ no degradation by the position dependence

SPICE simulation: Ideal 100mK device





C_a ~ 4pJ/K
⇒ size ~ 1000μm

Results for E=60keV signal
Scan parameters: G_a = 10 - 50nW/K, G = 1 - 5nW/K
Hard to list all. Results for some parameters are shown.

Size(μm)	G(nW/K)	G_a(nW/K)	τ_{fall} (μs)	$\Delta E_{S/N}$(eV)	ΔE_{pos}(eV)	ΔE_{tot}(eV)
700	5	40	160	9.1	3.5	9.7
1050	3	40	420	10.8	6.8	12.7
1400	1	30	970	14.2	5.0	15.1

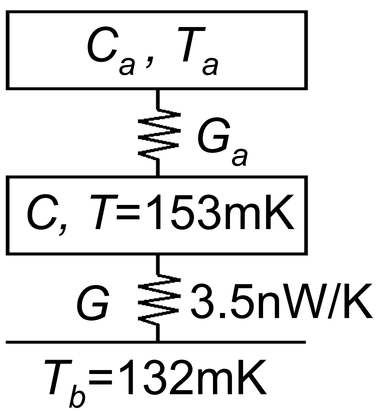
Summary

- Designed a fast response γ-ray TES calorimeter using SPICE simulation.
- 150mK device with 700μm x 700μm x 300μm tin absorber demonstrated
  - τ_{fall} = 520 μs, τ_{rise} = 46μs
  - ΔE= 38.4±0.9 eV eV@60keV, $\Delta E_{baseline}$=37.9±0.7 eV
  - No degradation of ΔE due to the position dependence seen as the simulation tells.
- SPICE simulation for 100mK device shows
  - τ_{fall} < 500 μs
  - ΔE < 15 eV

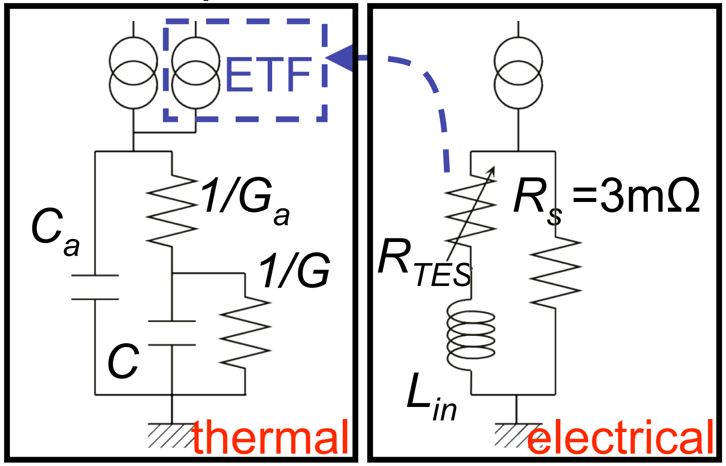
  is achievable with 1mm^2 x 300um absorber

SPICE Simulation: non-linearity

Thermal model



Equivalent circuit



- Generate simulated pulses using a modeled R-T curve
- Apply optimal filtering

⇒ pulse height