Coupling G4CMP Athermal Phonon Transport to TES Readout for SuperCDMS Detectors

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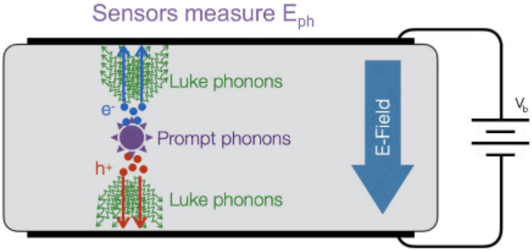
Energy deposition under bias

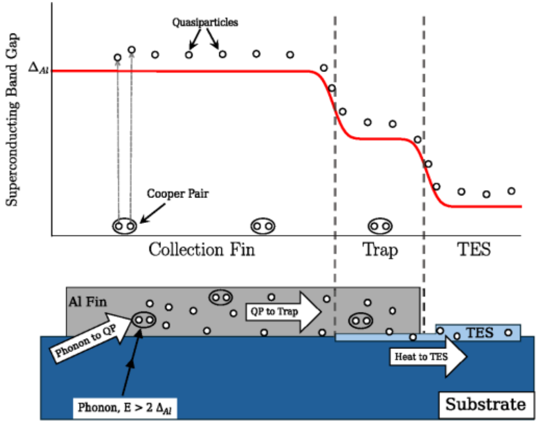
A particle interaction in Si/Ge makes prompt phonons and ionization.

The bias field does work on the charges. Fast carriers emit NTL/Luke phonons.

$$E_{\text{tot}} = E_r + eN_{eh}V_b$$



Quasiparticle collection in the QET



- Al fins overlap a W TES, biased mid-transition.
- Phonons above $2\Delta_{\mathrm{Al}}$ break Cooper pairs.
- Quasiparticles down-convert and cascade.
- The Al-W gap step funnels QPs into the TES.
- They heat up the TES, changing its resistance and current.

Electrothermal feedback

Single thermal block, two coupled ODEs.

$$L\,\frac{dI}{dt} = V_b - I\left(R_p + R_{\mathrm{sh}} + R_{\mathrm{TES}}\right)$$

$$C\,\frac{dT}{dt} = I^2 R_{\mathrm{TES}} - \Sigma_W \mathcal{V}_W \left(T^n - T_b^n\right) + P_{\mathrm{ph}}(t)$$

$n = 5$, tungsten electron-phonon; one bath link.

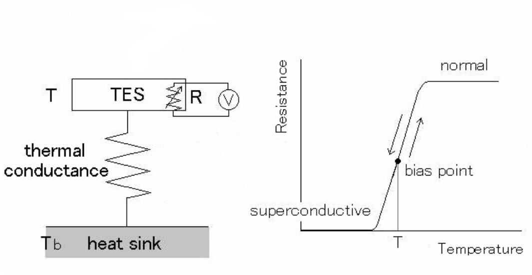
Transition with current:

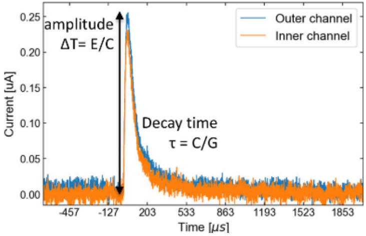
$$R_{\mathrm{TES}} = \frac{R_n}{2}\left[1 + \tanh\frac{T - T_c\left(1 - |I|/I_c\right)^{2/3}}{T_w}\right]$$

Under constant voltage bias, roughly,

$$\Delta I = -\frac{I_0}{R_0}\,\Delta R \propto \Delta T \approx \frac{\Delta E}{C}$$

Inputs: $P_{\mathrm{ph}}(t)$ from the crystal, TES parameters from the sensor.

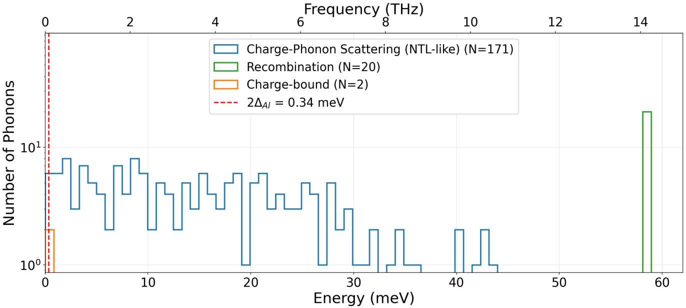




Amplitude $\Delta T = \Delta E/C$, decay $\tau = C/G$.

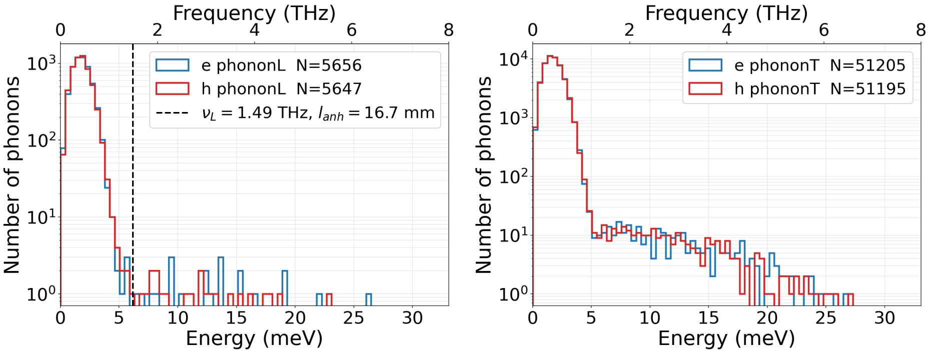
Phonons at zero bias

- G4CMP simulation of one e-h pair, $\varepsilon = 3.81$ eV.
- HVeV, a gram-scale Si detector, 1 cm $\times$ 1 cm $\times$ 4 mm.
- For electron recoil, no prompt phonons. Only ionization.
- At 0 V charges drift $\sim \mu$m.
- They shed NTL phonons by charge-phonon scattering.
- Recombination emits the gap near the Debye energy.
- Leftover kinetic energy makes a few charge-bound phonons.



NTL phonons in the Si HV detector

The HV detector is a cylinder, 5 cm radius and 3.33 cm thick, instrumented on both sides. 10 single e-h events with 2 eV deposit each at the center, field ≈ 6 V/cm.



Longitudinal modes on the left, transverse on the right. NTL emission is mostly transverse. The peak depends weakly on the applied field.

Phonon mean free path

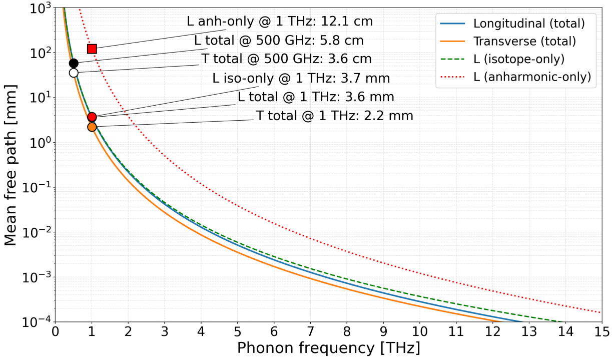
Two processes limit the path length.

$$\Gamma_{\text{anh}} = A\,\nu^5$$

$$\Gamma_{\text{iso}} = B\,\nu^4$$

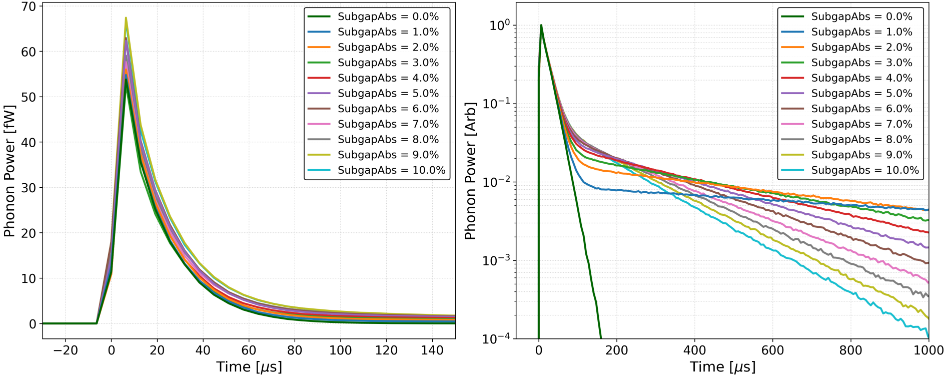
$$\ell = \frac{v_g}{\Gamma_{\text{anh}} + \Gamma_{\text{iso}}}$$

- Isotope scattering sets the path length.
- Transverse phonons have no anharmonic channel in G4CMP.
- They convert only by mode mixing into longitudinal.



Phonon arrival in the HVeV detector

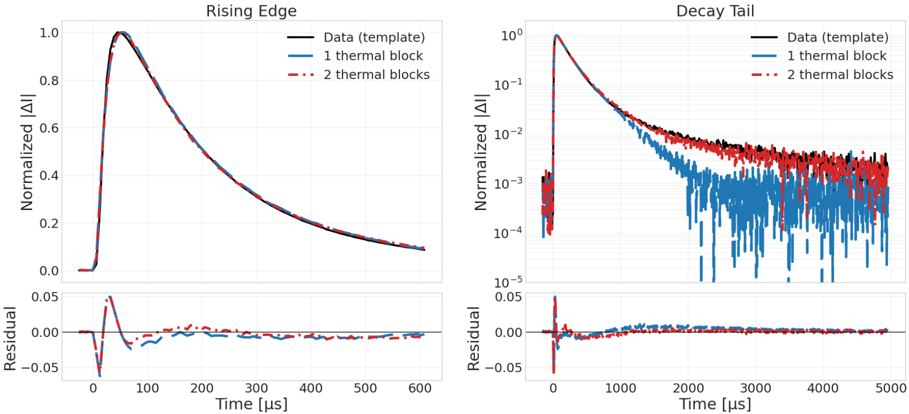
Arrival power fed to the TES, as `TESSubgapAbsorption` runs 0% to 10%.



Left: absolute power, the amplitude peak shifts vertically with the parameter. Right: normalized, the long tail is a single slope set by subgap absorption.

Reproducing the long tail

- The data template is the average of carefully selected pulses from single e-h pair events.
- One thermal block matches the rising edge but misses the decay tail.
- A second thermal block, the substrate, recovers the tail.



HVeV model parameters

Fixed circuit: $L = 363$ nH, $R_n = 324.7$ mΩ, $R_p = 11.5$ mΩ, $R_{\mathrm{sh}} = 18.6$ mΩ, $\gamma_e = 108\,\mathrm{J/(m^3K^2)}$.

Parameter	Symbol [unit]	Type	1-block	2-block
Critical temperature	T_c [mK]	Fixed	49	49
Substrate / bath temperature	T_{subst} [mK]	Fixed	15	15
Transition width	T_w [mK]	Fixed	1.27	1.27
Electron-phonon coupling	Σ_W [W/m^{3}K^5]	Fitted	3.6×10^8	6.0×10^8
Electron-phonon conductance	$G_{\mathrm{eph}}(T_c)$ [pW/K]	Derived	79.6	132.7
Kapitza coefficient	$K_{\text{s-b}}$ [nW/K^4]	Fitted	—	250
Kapitza conductance	$G_K(T_{\mathrm{subst}})$ [pW/K]	Derived	—	3.4
Substrate heat capacity	C_{subst} [pJ/K]	Fitted	—	0.30
TES heat capacity	$C_{\mathrm{TES}}/f_{\mathrm{SC}}$ [fJ/K]	Fixed	40.6	40.6
`TESSubgapAbsorption`	[%]	Fitted	4.6	4.6

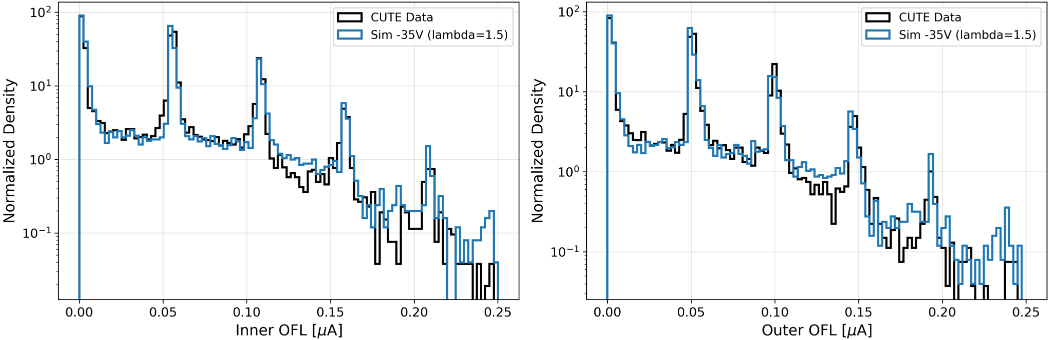
$G_{\mathrm{eph}} = n\,\Sigma_W\,\mathcal{V}_W\,T_c^{n-1}$ with $n = 5$. $G_K = 4\,K_{\text{s-b}}\,T_{\mathrm{subst}}^3$. Highlighted rows are fitted.

Σ_W and $K_{\text{s-b}}$ are degenerate. Σ_W differs by nearly $2\times$ between the fits. Both stay unconstrained.

HVeV detector, arXiv:2601.16307.

Energy spectrum

Simulated events are fitted with MCMC to the template scaled to the one e-h pair peak amplitude. The spectrum matches LED calibration data from HVeV run at the Cryogenic Underground TEst facility (CUTE) at SNOLAB.



Inner and outer optimal filter amplitude. CUTE data in black, simulation at -35 V with Poissonian $\lambda = 1.5$ in blue.

Conclusions

1. The two thermal block model reproduces the long tail in the HVeV pulse.
2. The best-fit $C_{\mathrm{subst}} = 0.30$ pJ/K is within ∼3× of the Debye value at $T_{\mathrm{subst}} = 15$ mK (0.85 pJ/K).
3. $K_{\text{s-b}}$ is degenerate with Σ_W. Both stay unconstrained.
4. The long tail is also degenerate with `TESSubgapAbsorption`. Heat leaves the model faster than the data shows.

Thank you

on behalf of the SuperCDMS Collaboration