Development of Iridium Platinum Bilayer-based Athermal Phonon Detectors

Gensheng Wang[1], Thomas Cecil[1], Clarence Chang[1], Marharyta Lisovenko[1], Valentine Novosad[1], Philip Strons[1], Vlad Yefremenko[1], Matt Pyle[2], Maggie Reed[2], Roger Romani[2], Bruno Serfass[2], Vetri Velan[3], Michael Williams[3]

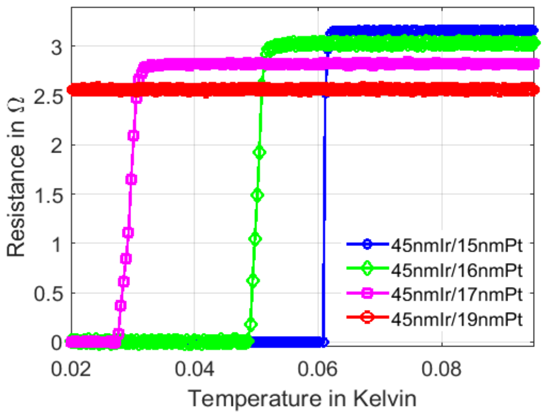
[1] Argonne National Laboratory, [2] UC Berkeley, [3] Lawrence Berkeley National Laboratory

Outline

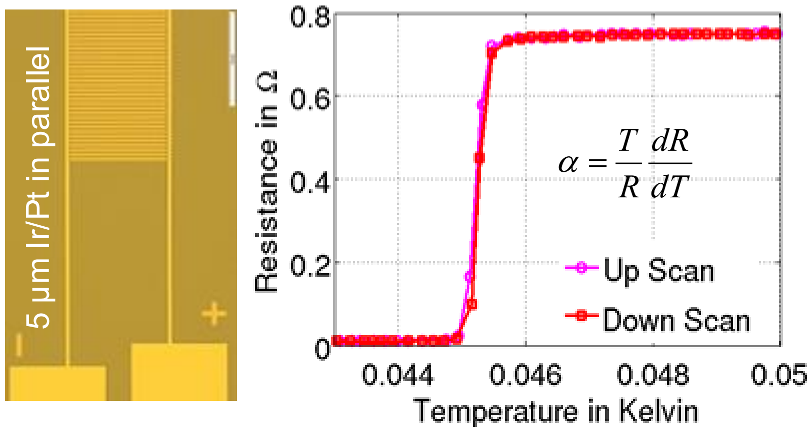
- Motivation of an Ir/Pt TES
- Performance of an Ir/Pt TES
- Athermal Phonon Detectors (APD) made of Ir/Pt
  - Thermal conductance
  - Time constant
- Summary

Introduction to Ir/Pt Transition-Edge-Sensor (TES)

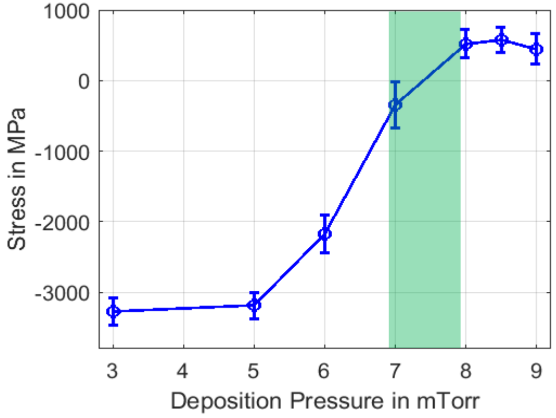
- Ir/Pt bilayer TES
  - Tc can be tuned to be low by changing the thicknesses of the two films
  - Stress can be independently tuned to be low by controlling films deposition pressure
- Potential impacts to phonon detectors for dark matter searches
  - Improve energy resolution ($\sigma_{\mathrm{E}}^2 \propto T_C^2 C/\alpha$) because of its low-Tc and sharp transition
  - Reduce Low Energy Excess (LEE) events due to stress in TES itself



Tc tuning of Ir/Pt bilayers



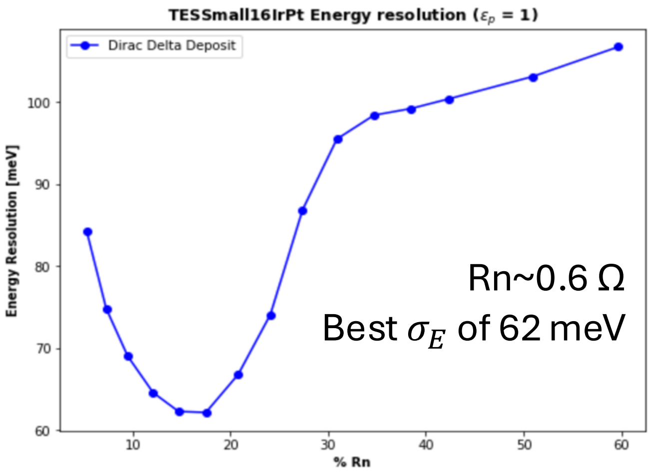
Transition of 5 μm wide Ir/Pt stripes

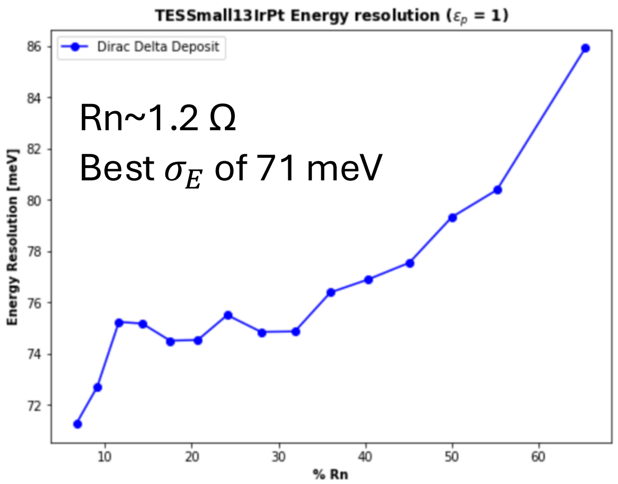


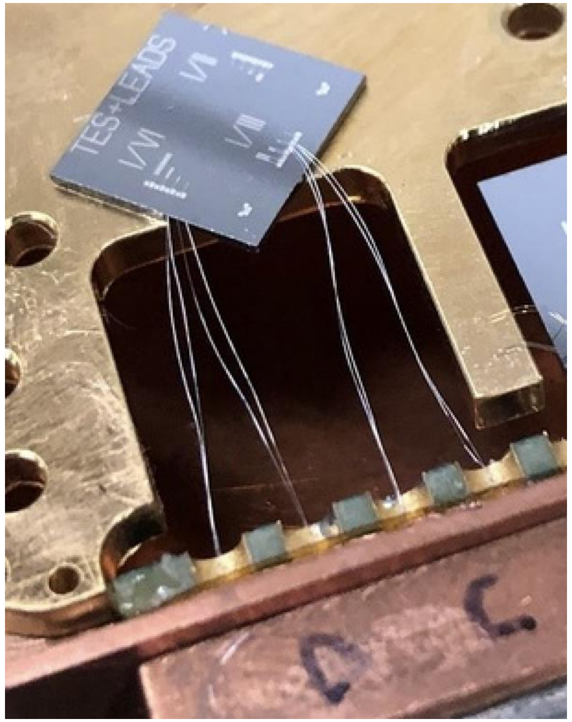
Stress tuning of Ir/Pt bilayers

Demonstrated performance of Ir/Pt TES

- Low-stress TESs with Tc of 50 mK
- Measured by Pyle's group at UCB
- TESSmall16: 50 μm long and 300 μm wide
- TESSmall13: 50 μm long and 150 μm wide
- A sensitivity resolves single infrared photons





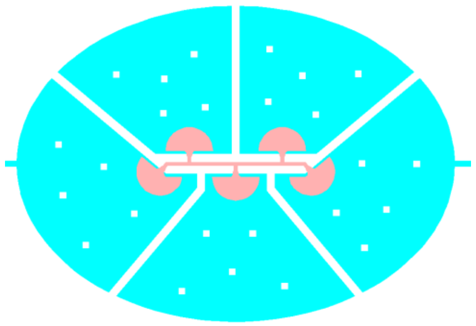


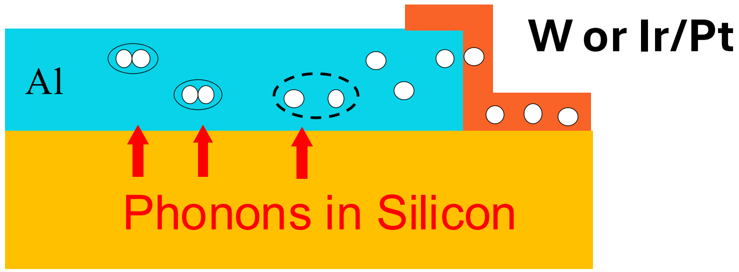
Detectors mounted for testing at UCB

Athermal Phonon Detector (APD)

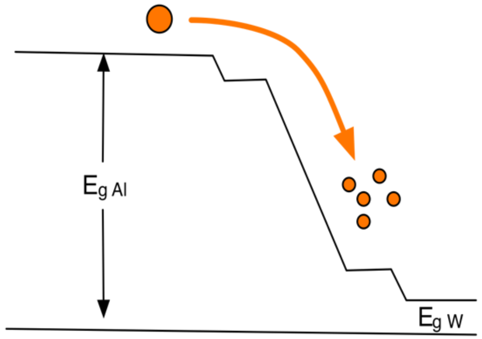
- QET: Quasiparticle-trap-assisted Electrothermal-feedback Transition-edge-sensor

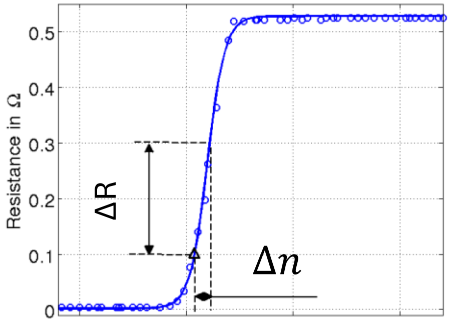
Al in light blue
TES in red





- QET cell of an Athermal Phonon Detector (APD)
  - Large Al phonon collection fins to increase detection area
  - Small TES volume for sensitivity





Quasiparticle density n

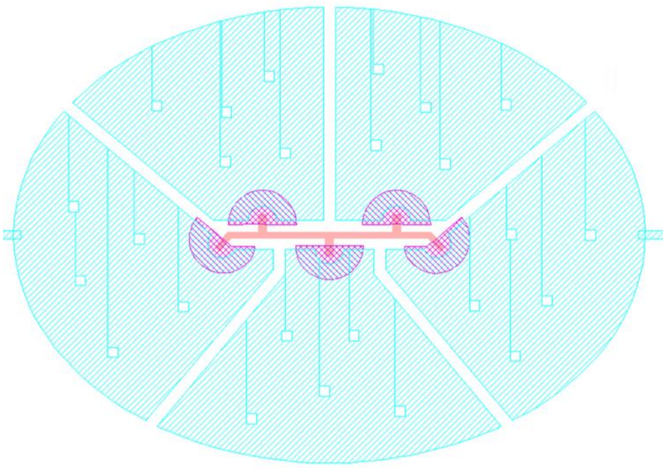
- Historically, tungsten TES has been the choice in APDs. See William Matava's talk on Thursday at 10am and Matt Pyle's talk on Thursday at 3:40pm.
- **Ir/Pt TES with not only low-Tc but also low-stress is new. Detector R&D for dark matter searches.**

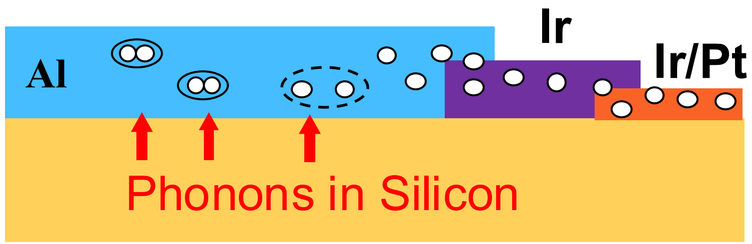
Innovative APD design

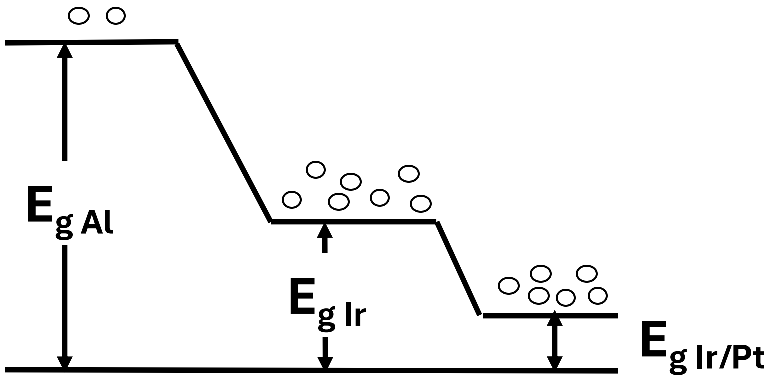
Red: 3 μm wide Ir/Pt

Hatched purple: Ir

Hatched blue: Al

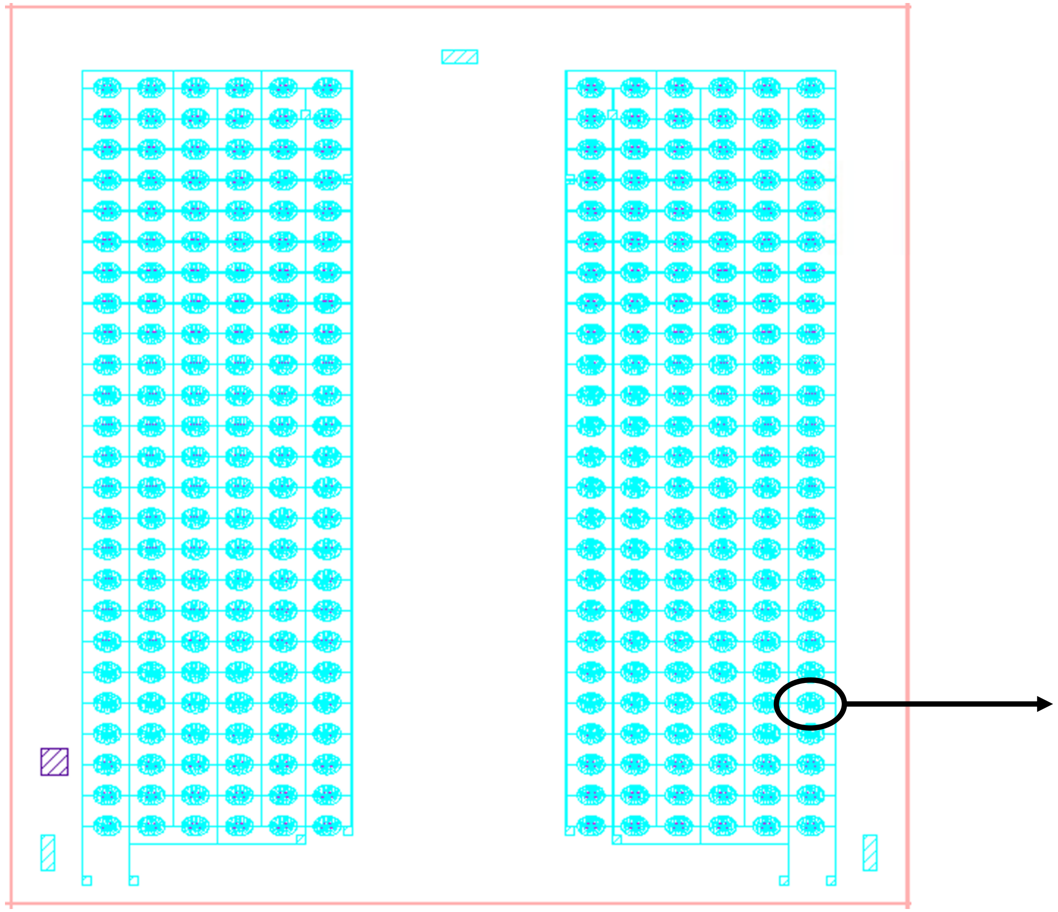




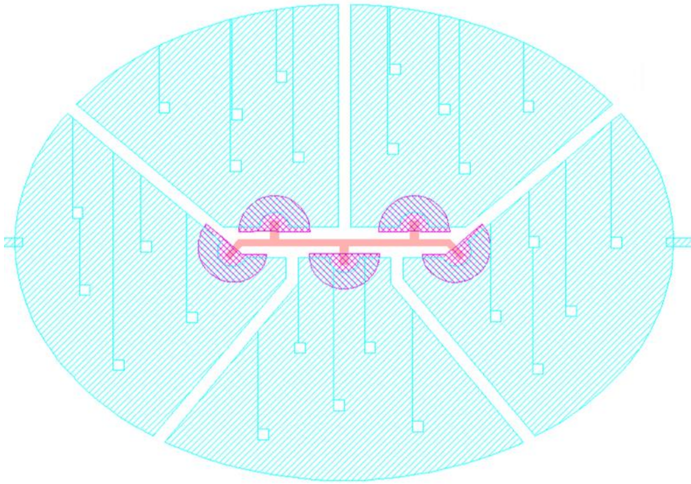


- Use **Ir** with a Tc of 300 mK between Al fins and Ir/Pt TES as **quasiparticle reservoirs**
  - Initially envisioned to optimize QP-TES coupling for an enhanced quantum efficiency
  - Would also optimize Ir/Pt volume for a controlled heat capacitance and thermal conductance

Large area APDs with Iridium QP reservoir



- 10mm×10mm×675μm silicon chip
- Two identical channels
- 25×6 QET cells in each channel
- Each QET cell is made of Ir/Pt-Ir-Al



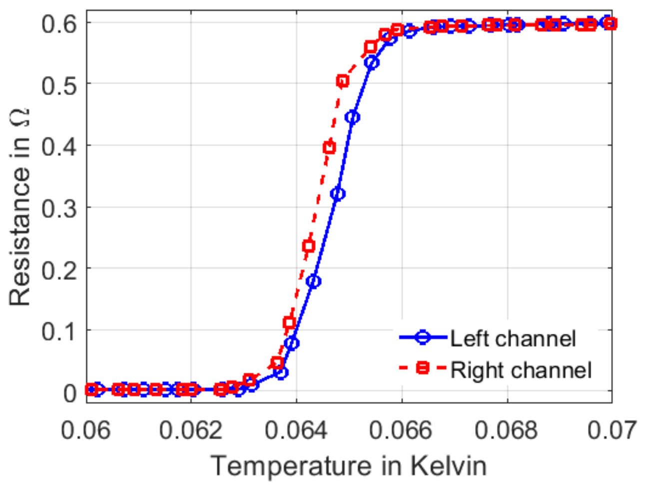
Red: 3 μm wide Ir/Pt

Hatched purple: Ir

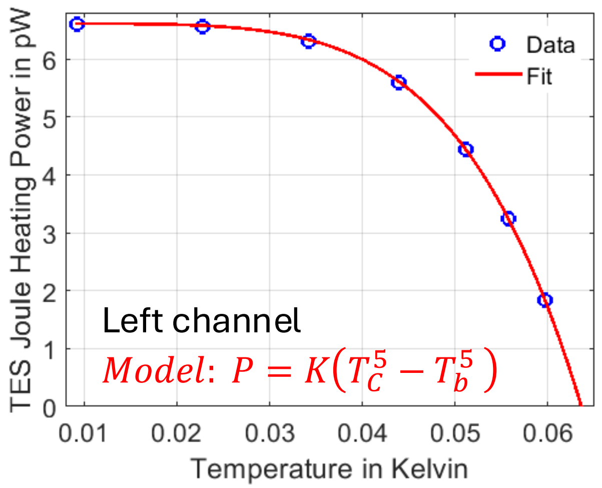
Hatched blue: Al

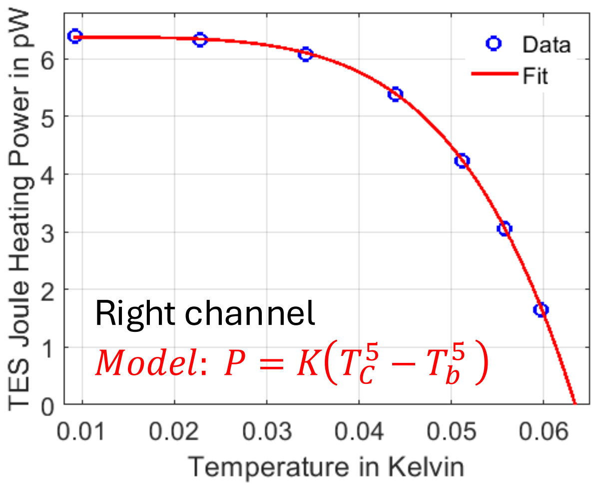
R-T curves and P-T curves of APDs

- Tc of ~65 mK with a transition width of ~1.5 mK
- TES saturation power is measured with I-V curves at a variety of bath temperatures
- Large saturation powers (~4x more than expected) on both channels



R-T curves



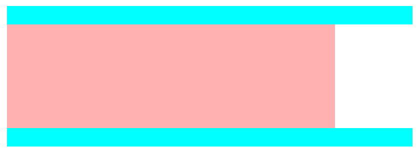


APD saturation power vs bath temperature

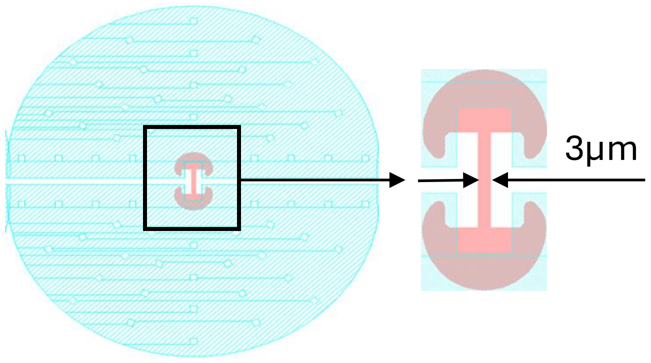
Comparison of thermal conductance of Ir/Pt in three detectors:

- TES saturation power follows $P = K\left(T_C^5 - T_b^5\right)$, where T_b is bath temperature, $K = \Sigma V$, Σ is electron-phonon decoupling coefficient and V is Ir/Pt TES volume.
- Σ is enhanced using the Ir/Pt not covered by Al or Ir
- Ir/Pt underneath Al or Ir cannot fully explain the large thermal conductance of APD2

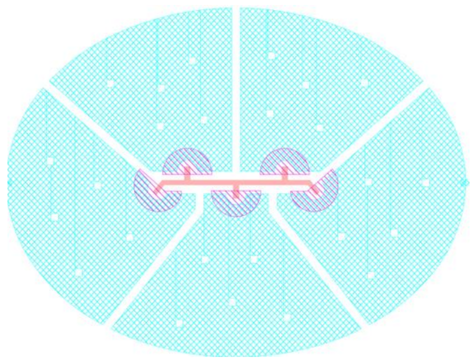
Detector	Tc in K	K in W/K^5	Ir/Pt Vol. (in μm^3) not under Al or Ir	Total Ir/Pt Vol. in μm^3	Σ in $W/K^5/m^3$ with uncovered Ir/Pt	Σ in $W/K^5/m^3$ with total Ir/Pt
TES1	0.0630	3.88×10^{-7}	1054.7	1195.3	3.68×10^{8}	3.25×10^{8}
APD1	0.0575	4.22×10^{-7}	346.9	2334.4	12.3×10^{8}	1.81×10^{8}
APD2	0.0645	62.2×10^{-7}	3572.3	4509.1	17.4×10^{8}	13.8×10^{8}



TES1: A rectangular Ir/Pt with Al leads



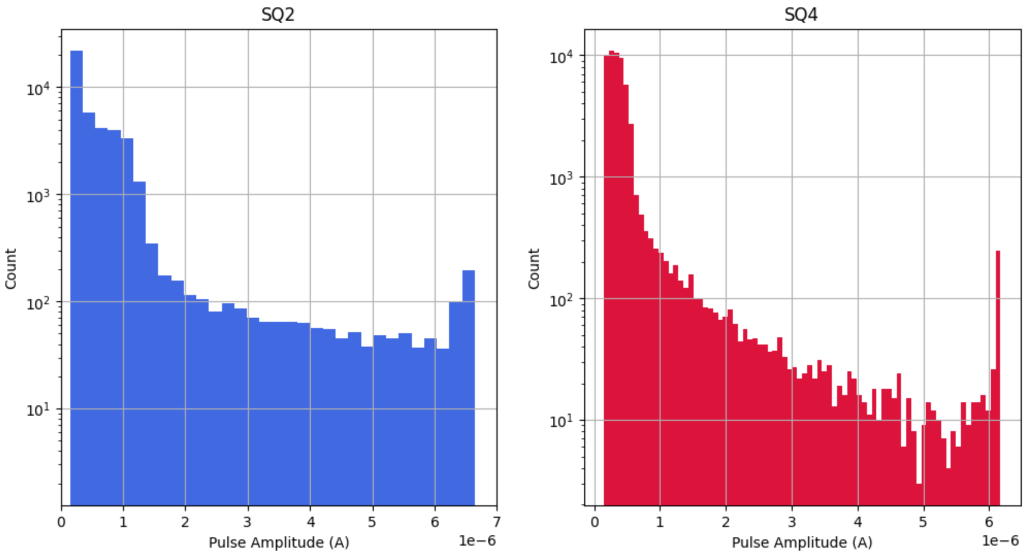
APD1: 25 QET cells made of Ir/Pt-Al



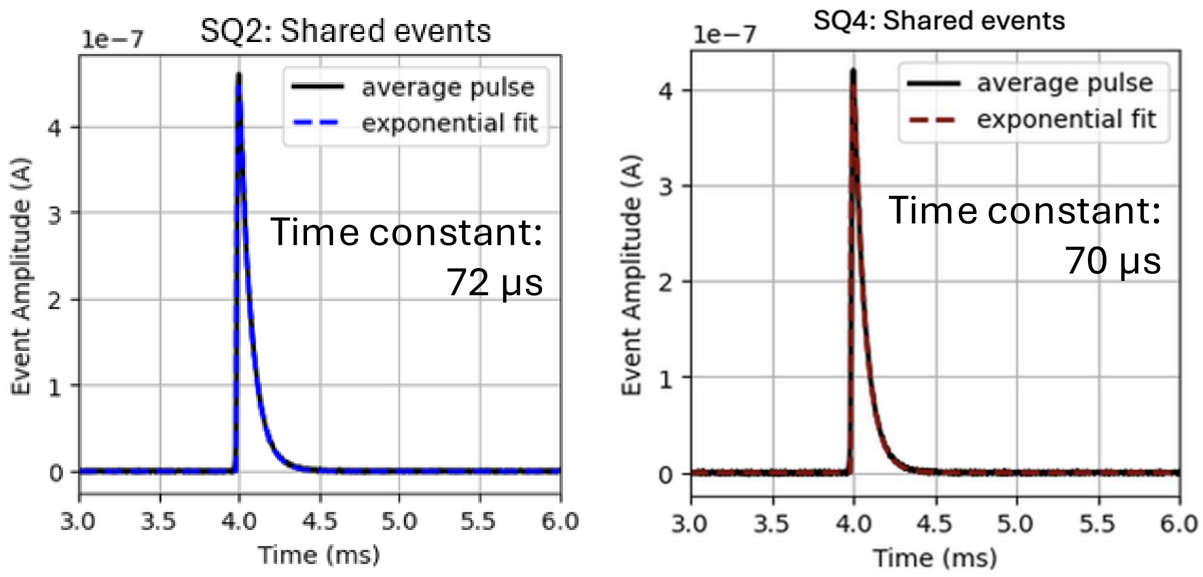
APD2 (shown in slide 7): 25×6 QET cells made of Ir/Pt-Ir-Al

Background data of APD2

- High event rate, ~100 events per minute. These events are shared between the two channels.
- The detector chip is glued onto a metal with rubber cement. These events are from stress in silicon due to gluing.
- APDs made of Ir/Pt TES are functional for phonon measurement
- The APDs have a small time constant (of ~72 μs in SQ2)



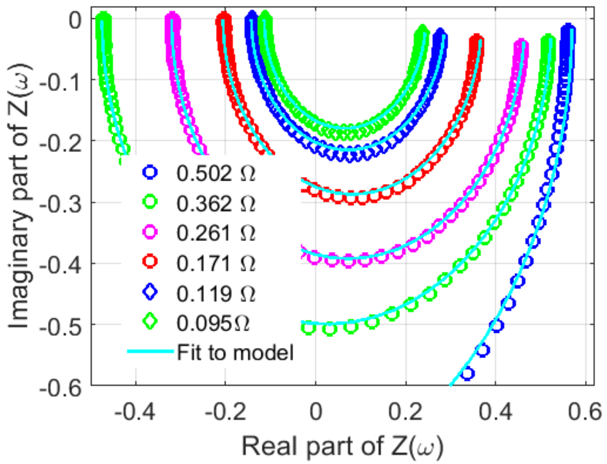
Histograms of event amplitude



Exponential fits to average pulses of shared events

Time constants of SQ2 using complex impedance

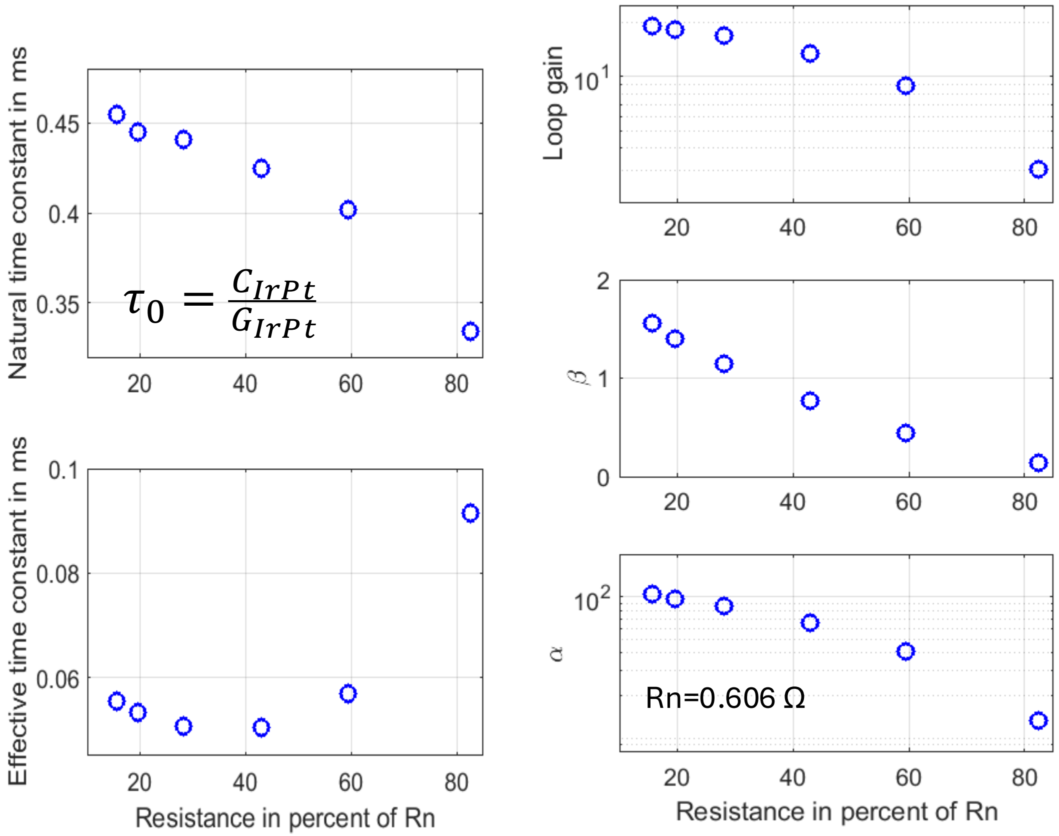
- Complex impedance is measured with a small AC (<1%) on the top of a DC bias on TES
- Applying one block model approximation to complex impedance data for resistance R_0, loop gain $\mathcal{L}$, current dependence parameter β and natural time constant τ_0.
- The effective time constant of 58 μs is close to 72 μs from pulse data



$Z_{TES}(\omega)$ data for the left channel SQ2 of the APDs.

Model
↓

$$Z_{TES}(\omega) = R_0(1+\beta) + \frac{\mathcal{L}R_0(2+\beta)}{1-\mathcal{L}+i\omega\tau_0}$$



$$\tau_{eff} = \frac{\tau_0(1+\beta+R_p/R_0)}{1+\beta+R_p/R_0+(1-R_p/R_0)\mathcal{L}}$$

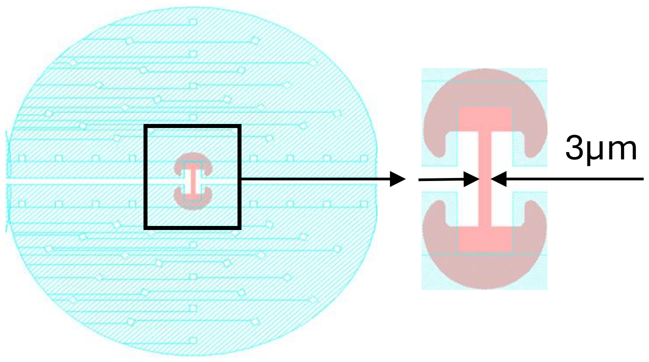
$$\mathcal{L} = \frac{P_0\alpha}{G_{IrPt}\,T_0}$$

Summary of time constants of the three detectors:

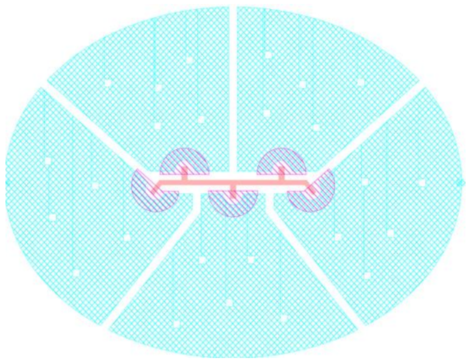
- Effective constants from two different measurements are similar
- Time constant maps to electron-phonon decoupling coefficient **Σ** estimated with bare Ir/Pt
  - APDs made of Ir/Pt stripes have enhanced **Σ** but reduced time constants
- Ir/Pt stripes have no specific heat (**c**) increase regardless of **Σ** enhancement

Detector	Tc in mK	Operation resistance R_0 in Ω	Σ in $W/K^5/m^3$ with uncovered Ir/Pt	Natural time constant from $Z(\omega)$ in ms	Effective time constant from $Z(\omega)$ in µs	Effective time constant from pulse data in µs	Specific heat c of Ir/Pt in J/Km^3
TES1	63.0	0.102	**3.68×10^8**	**2.25**	**435**	**620**	**65.2**
APD1	57.5	0.115	**12.3×10^8**	**0.64**	**155**	**165**	**43.0**
APD2	64.5	0.104	**17.4×10^8**	**0.45**	**58**	**72**	**66.3**

TES1: A rectangle TES with Al leads



APD1: 25 QET cells made of Ir/Pt-Al



APD2 (shown in slide 7): 25×6 QET cells made of Ir/Pt-Ir-Al

$$\tau_0 = \frac{C_{IrPt}}{G_{IrPt}} = \frac{cV}{5\cdot\Sigma V\, T_C^4} = \frac{c}{5\cdot\Sigma\, T_C^4}$$

Summary

- Ir/Pt TES has a good sensitivity to resolve single infrared photons
- Demonstrated functional APDs made of Ir/Pt
  - Ir/Pt stripes have an enhanced electron phonon decoupling coefficient and a reduced time constant, but do not have a specific heat increase
  - Using Ir between Al fins and Ir/Pt TESs as QP reservoirs allows us to make APDs with
    - A controlled thermal conductance
    - An optimized time constant

Acknowledgment

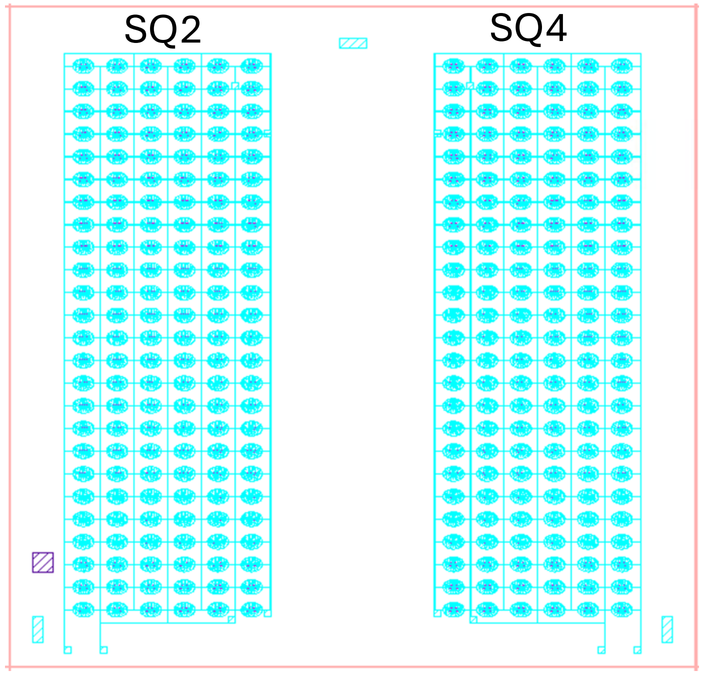
- Developing Ir/Pt based APDs was part of R&D program in TESSEARCT project. There are ~40 scientists from eleven institutions in TESSERACT collaboration, advancing the development and application of ultra-sensitive TES detectors and cryogenic targets for light dark matter searches.

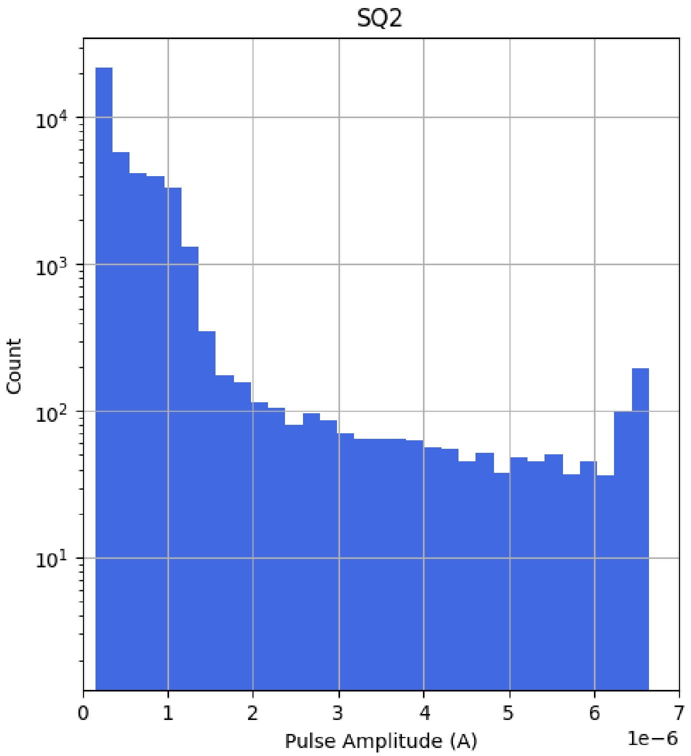
- Fabrication of a low-Tc Ir/Pt TES with a low stress was supported by Argonne National Laboratory LDRD program.

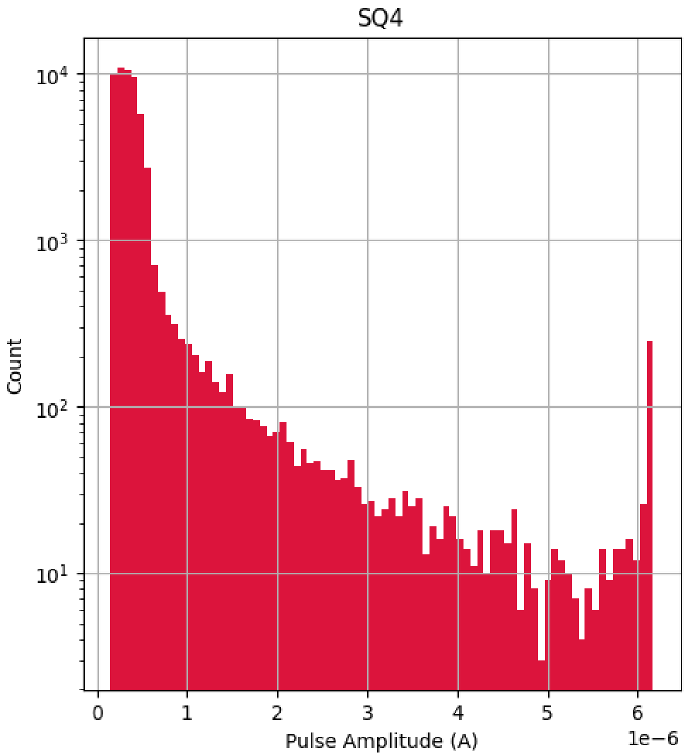
- The work at Argonne National Laboratory, including the use of facility at the Center for Nanoscale Materials (CNM), was supported by Office of Science and Office of Basic Energy Sciences of the U.S. Department of Energy, under Contract No. DE-AC02-06CH11357.

Backup slides

Background data of APD2



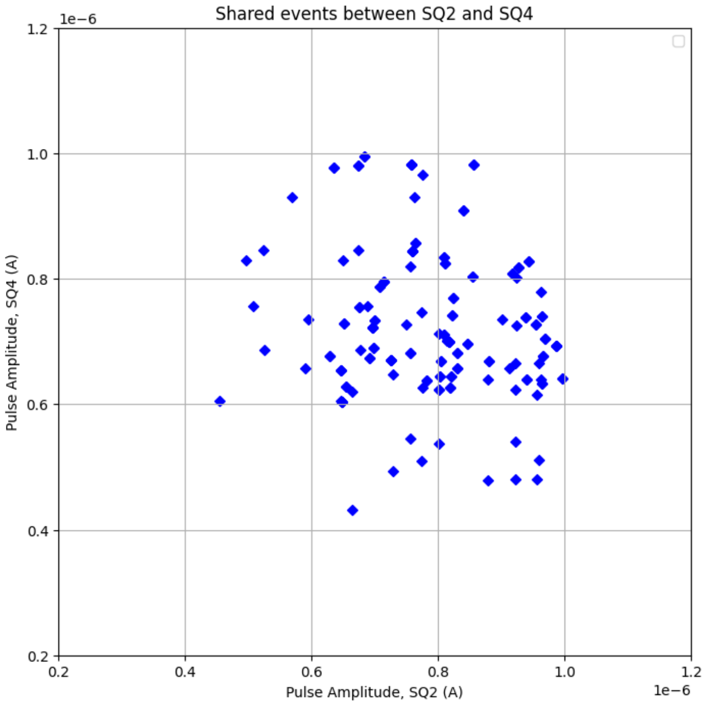


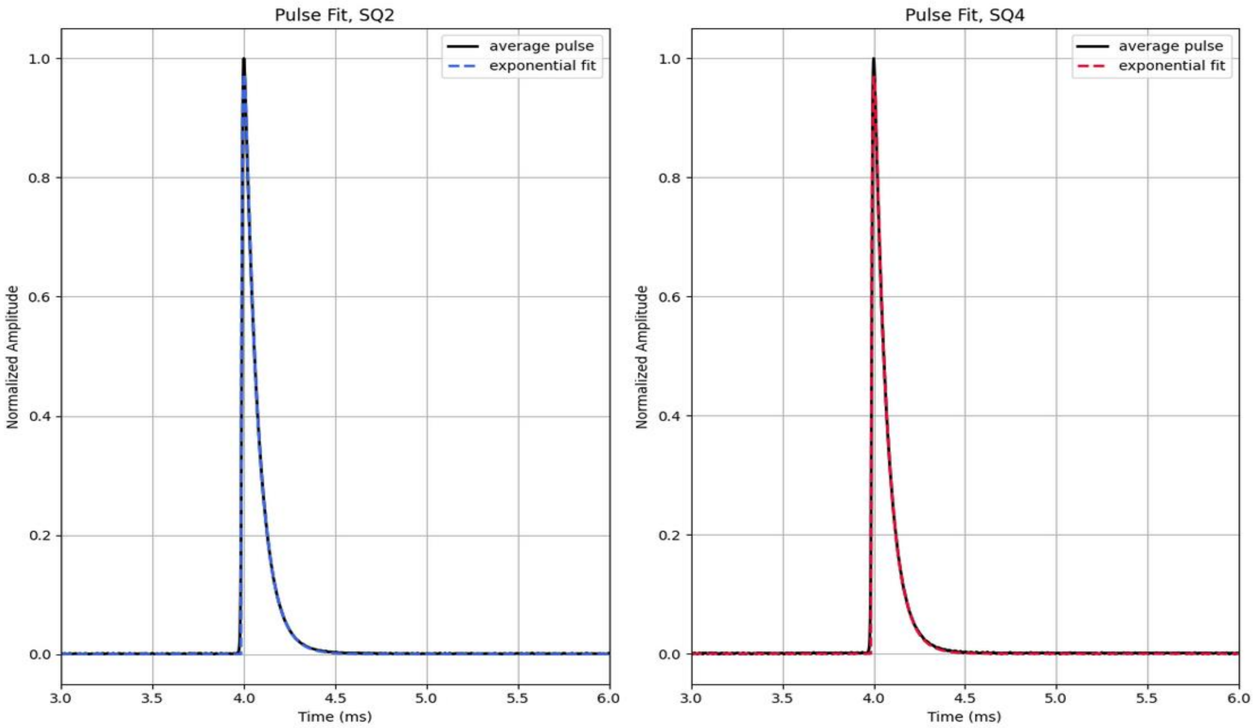


Two APDs on a 10mm×10mm silicon chip, which was glued on a copper plate

Histograms of event amplitude above selected threshold in both channels

Time constant of shared events of APD2

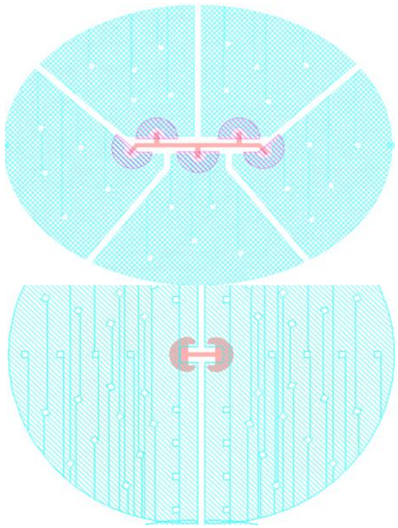


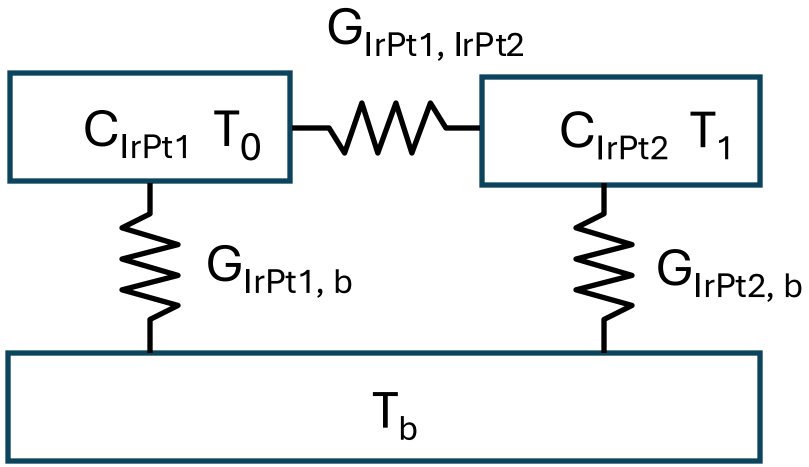


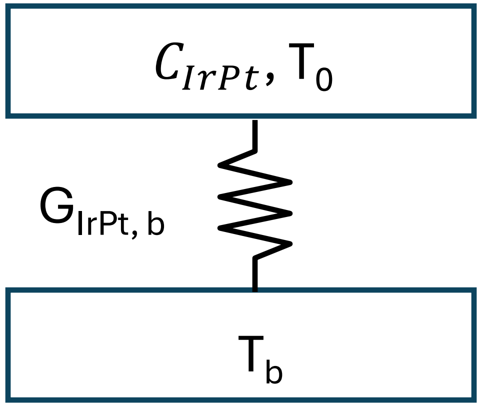
Select a small number of shared events

Normalized averaged pulses for time constant fit:
SQ2, time constant of 72 us;
SQ4, time constant of 70 us.

One block model approximation







- IrPt1: Ir/Pt not covered by Ir or Al
- IrPt2: Ir/Pt underneath Ir or Al

Assume that $G_{IrPt1, IrPt2} \gg G_{IrPt2, b}$ and $T_1 \approx T_0$.

Then two blocks in parallel can be approximated with one block model :

$$G_{IrPt, b} \approx G_{IrPt1, b} + G_{IrPt2, b}$$

$$C_{IrPt} = C_{IrPt1} + C_{IrPt2}$$

Fabrication

- Detector fabrication was done at MSD and CNM of Argonne National Laboratory.
- Detectors were made on high resistivity 6-inch silicon (675um thick) wafers and then diced into 10 mm square chips.
- The films of 45nmIr/17.5nmPt, 100nmIr and 600nmAl were fabricated using DC magnetron sputtering with an AJA system.
- Deposition rate for Ir – 0.75A/s and for Pt – 0.73A/s.
- The base pressure in the sputtering chamber was $\sim 3.4\times10^{-8}$ Torr.
- The sputtering was performed with Ar gas pressure of 3mTorr for the measured detectors presented here.
- We used 4N targets for Pt, Ir and Al.
- Detectors were patterned with liftoff technique.