SNOWMASS 2021 (IF02)

TRANSITION EDGE SENSORS (TES) FOR PHOTON DETECTION

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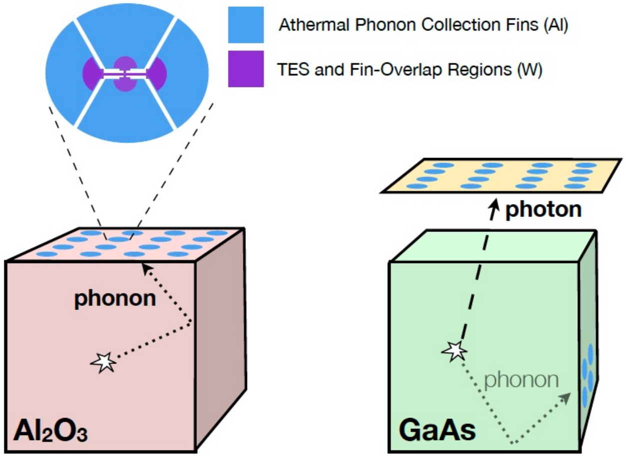
OUTLINE

- Drivers for low energy (single) photon detection (and energy resolution)
  - Dark matter detection
- Introduction to TES photodetectors
  - Detector configuration, energy resolution
- Examples of TES photodetector researches and applications
  - Large area TES photodetectors, single photon counting TES sensors, and Quasiparticle-trap-assisted Electrothermal-feedback Transition-edge-sensor (QET)
- Example of future directions:
  - Ir/Pt bilayer TES photodetectors
- Summary

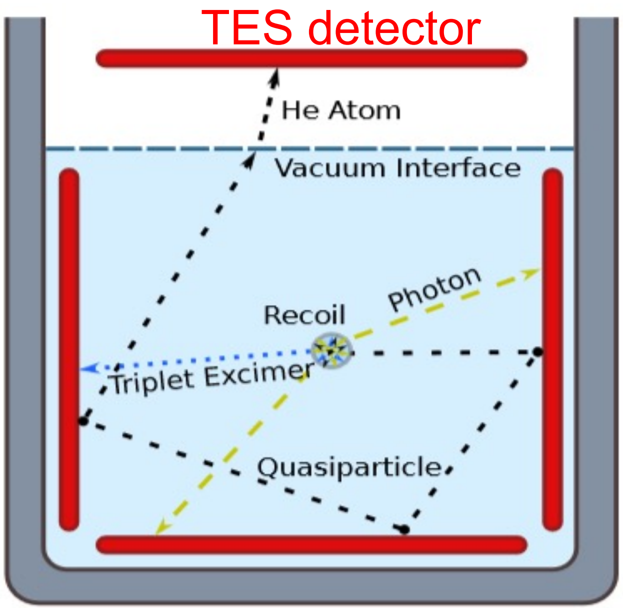
DARK MATTER DETECTION WITH CRYSTALLINE TARGETS AND LARGE AREA PHOTON (PHONON) DETECTORS



One cm^3 crystals.
Graph from SPICE/HeRALD proposal.

- Sapphire and gallium arsenide crystals are optimal for electron recoils (ER)
  - Hidden sector dark matter
- Measure athermal phonons in sapphire with TES detectors on surface
  - 0.35 eV
- Measure scintillation photons from gallium arsenide with TES photon detectors
  - 1.4 eV
- Measure athermal phonons in gallium arsenide with TES detectors on surface
  - 0.35 eV

DARK MATTER DETECTION WITH SUPERFLUID HELIUM AND LARGE AREA PHOTON (PHONON) DETECTORS



Hertel *et al*., arXiv, 1810.06283

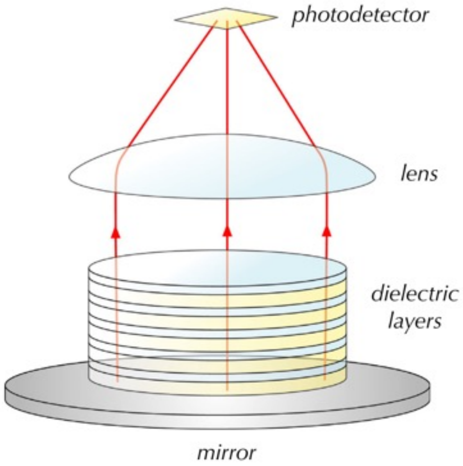
- Optimal for nuclear recoils (NR)
  - Light helium nucleus
- TES detectors in liquid helium
  - Triplet excimers, UV and IR photons, and quasiparticles (phonons and rotons)
- TES detector above liquid helium
  - Evaporated helium atoms kicked off by quasiparticles at surface

OTHER PARTICLE DARK MATTER DETECTION CANDIDATES

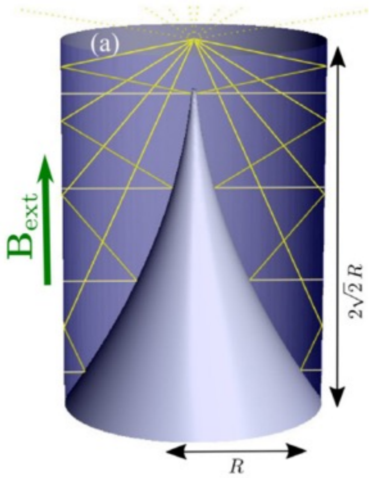
- Interactions with molecular targets
  - Bosonic DM interacting with molecular gas (A. Arvanitaki et al., Phys. Rev. X 8, 041001)
  - Light DM scattering off CO gas (R. Essig et al., PRR 1, 033105 (2019))
  - Spin-dependent light DM interaction with molecular crystals (G. Wang et al., arXiv:2201.04219)
- Interactions generate long wavelength photons
  - Faint signal requires low DCR
  - Well defined energy motivates spectral resolution for background rejection

WAVE DARK MATTER

- Conversion of wave dark matter (higher mass axions/dark photons) into a long wavelength photon
  - Faint signal requires low DCR
  - Well defined energy motivates spectral resolution for background rejection



M. Baryakhtar et al., Phys. Rev. D 98, 035006



J. Liu et al., PRL 128, 131801 (2022)

SUPERCONDUCTING TECHNOLOGIES

- Multiple drivers and applications for good detectors at long wavelengths
  - Dark matter
  - Space applications
  - Terrestrial imaging
- Long wave photons are challenging to detect
  - Superconducting systems are an attractive approach with typical excitation in superconducting systems is smaller than photon energy
- Transition Edge Sensor (TES) is a mature technology
  - Well developed noise theory
  - Thermal operating principles
  - Demonstrated multiplexing for scaling up mass and/or channels

VINTAGE TRANSITION EDGE SENSOR

JULY, 1942 R. S. I. VOLUME 13

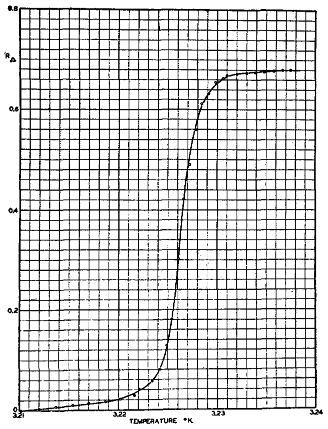
Attenuated Superconductors

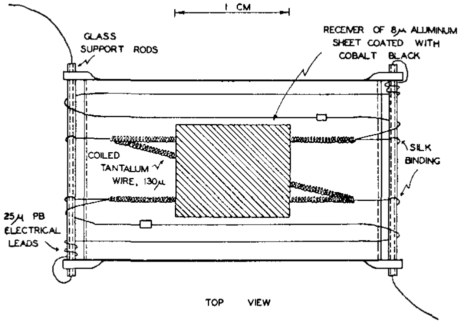
I. For Measuring Infra-Red Radiation

D. H. ANDREWS, W. F. BRUCKSCH, JR., W. T. ZIEGLER, AND E. R. BLANCHARD
Chemistry Department, The Johns Hopkins University, Baltimore, Maryland

(Received February 27, 1942)

An apparatus for measuring infra-red radiation has been constructed of fine tantalum wire, operating at a temperature of 3.22–3.23°K in the transition zone between superconduction and normal conduction. The tantalum coil is mounted on a thermostated plate with temperature electrically controlled and operates in a special self-regulating shunt circuit by which its own temperature is automatically maintained constant. The ratio of developed electrical potential to radiation flux received is 150 μv (erg cm^{-2} sec.$^{-1}$)$^{-1}$. Minimum detectable flux is *ca.* 10^{-3} erg sec.$^{-1}$. Absolute measurements of intensity of radiation from sources at temperatures between 24° and 55° are consistent with the Stefan-Boltzmann law showing that instrument corrections for reflectivity, window-absorption, and changes with wave-length are very small.





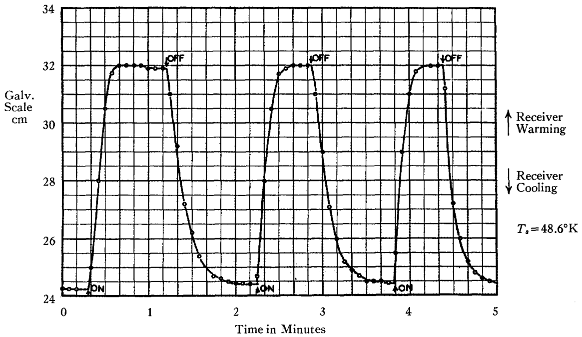
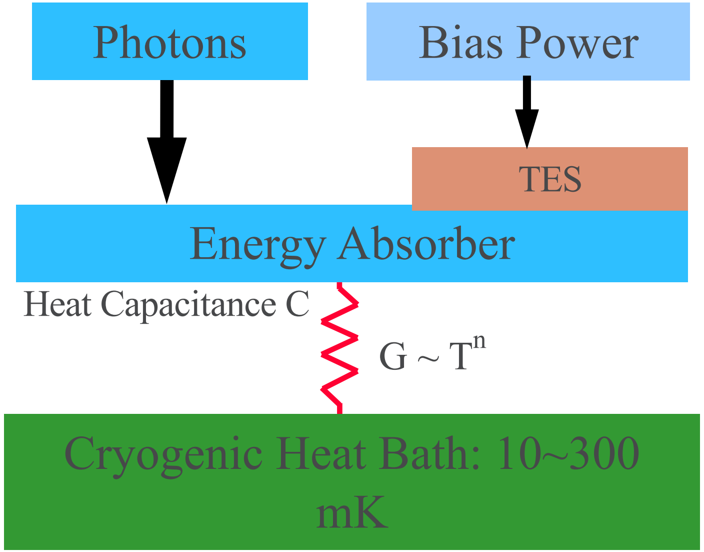
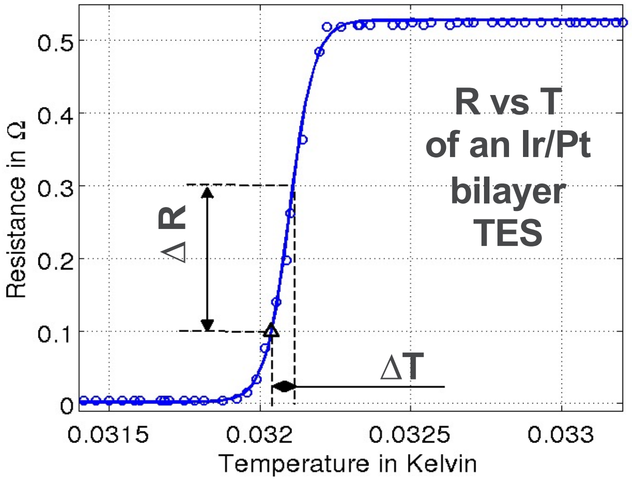


FIG. 6. Galvanometer response to radiation.

MODERN TES

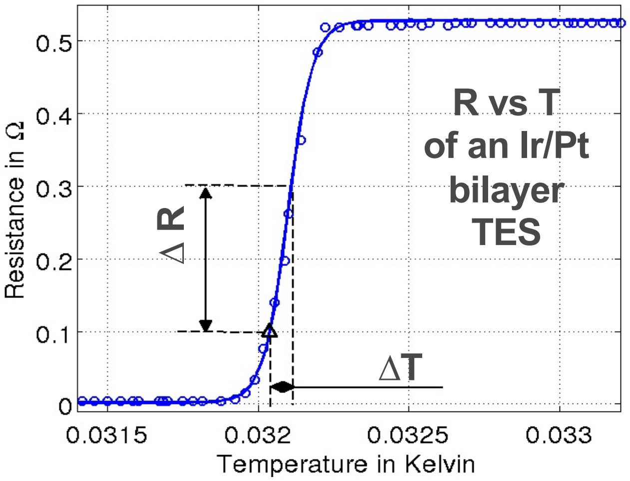




- Heat capacity thermally stood-off from heat sink
- Voltage bias into superconducting transition
- Low-impedance current measurement via SQUID

ELECTROTHERMAL FEEDBACK

- Shape of R(T) curve together with voltage bias establishes natural negative feedback
- TES temperature stabilizes at T_c
- Increases bandwidth
- Linearizes response:
  - $\Delta P_{absorbed} \approx \Delta P_{bias} = V_{bias} \times \Delta I_{TES}$
- "Loop gain" determined by slope of R(T), which can be steep making feedback strong.



$$\delta P_{Joule} = \delta\left(\frac{V_0^2}{R(T)}\right) = -\left(\frac{V_0}{R}\right)^2 \frac{dR}{dT}\delta T$$

SENSITIVITY

- Fundamental noise comes from thermal fluctuations (~kT), which can be made small by choosing suitable T_c
- Energy resolution:

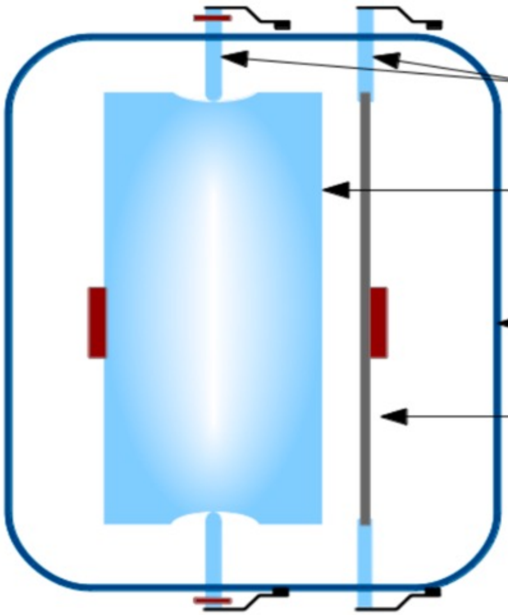
$$\Delta E \approx 2\sqrt{2\,ln2}\sqrt{\frac{4k_B T_C^2 C}{\alpha}\sqrt{\frac{n}{2}}}$$

$$C \propto T_C \qquad C \propto A \cdot d \qquad \alpha = \left(\frac{T}{R}\frac{dR}{dT}\right)_{T=T_C} \qquad n{\sim}3-5$$

- Improve by reducing T_c
- Incorporating athermal techniques can further reduce volume

A LARGE AREA PHOTON DETECTOR IN CRESST

Cryogenic Rare Event Search with Superconducting Thermometers

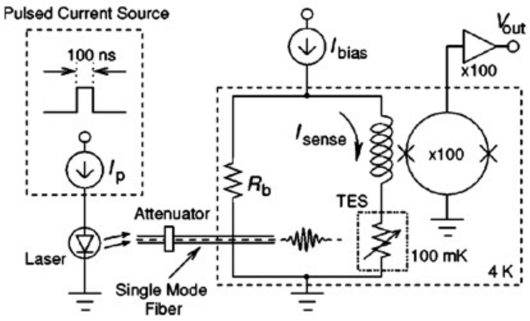


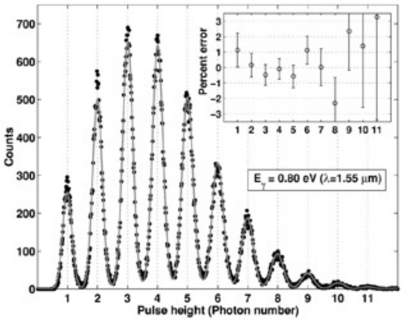
- Evaporated W TES thermometer with a Tc of 15 mK
  - Measure heat of target calcium tungstate
  - Measure scintillation light with a silicon-on-sapphire light detector of 20 × 20 × 0.4 mm^3
  - The light yield is used to discriminate between electron recoils and nuclear recoils in the target
- Baseline noise energy resolution lies between 4.1 eV and 6.7 eV

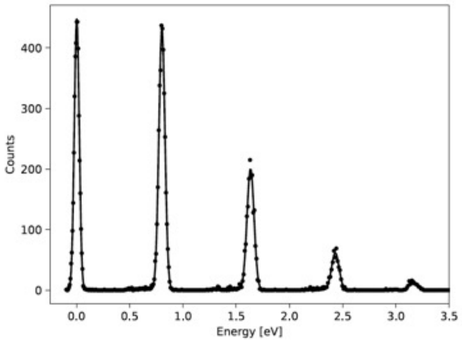
A. H. Abdelhameed *et al.* (CRESST Collaboration), Phys. Rev. D 100, 102002

TES SINGLE PHOTON DETECTOR AT 1550 NM

- 25 μm × 25 μm x 35 nm single-moded fiber-fed W TES
- Pulse height proportional to photon number. The inset shows the measured probability distribution. ∆E=0.12 eV
- The graph on the right shows the measured distribution with a Au/Ti (10/20 nm) bilayer TES (8 μm × 8 μm and a Tc of 115 mK). ∆E=0.067 eV
- Ultra-low DCR: detection threshold > 2.3∆E + pulse shape discrimination







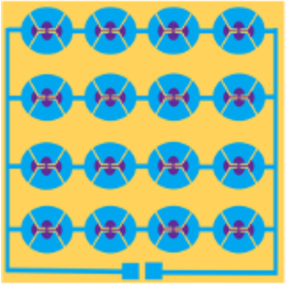
A. J. Miller et al., Appl. Phys. Lett. **83**, 791 (2003)

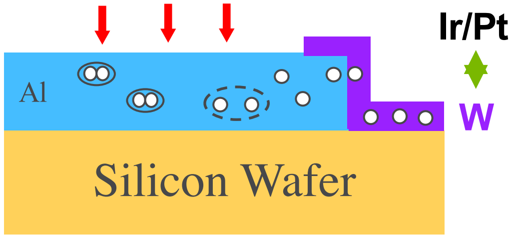
K. Hattori et al., arXiv:2204.01903v1

LARGE AREA PHOTON DETECTOR WITH A SUB-EV THRESHOLD

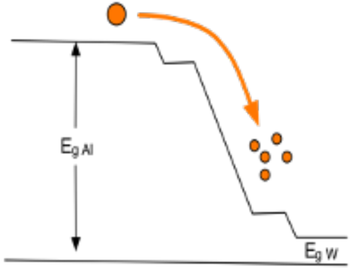
- Quasiparticle-trap-assisted Electrothermal-feedback Transition-edge-sensor (QET)
  - Superconductor Al as photon absorber + TES as quasiparticle readout sensor
  - Originally developed in the CDMS collaboration measuring phonon with a large area coverage

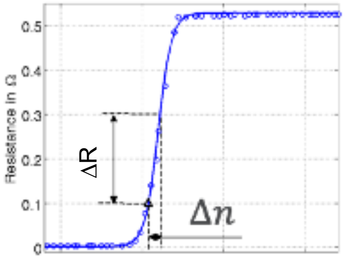
A large area TES photon detector





- Detector sensitivity depends on
  - TES volume (heat capacity)
  - TES Tc

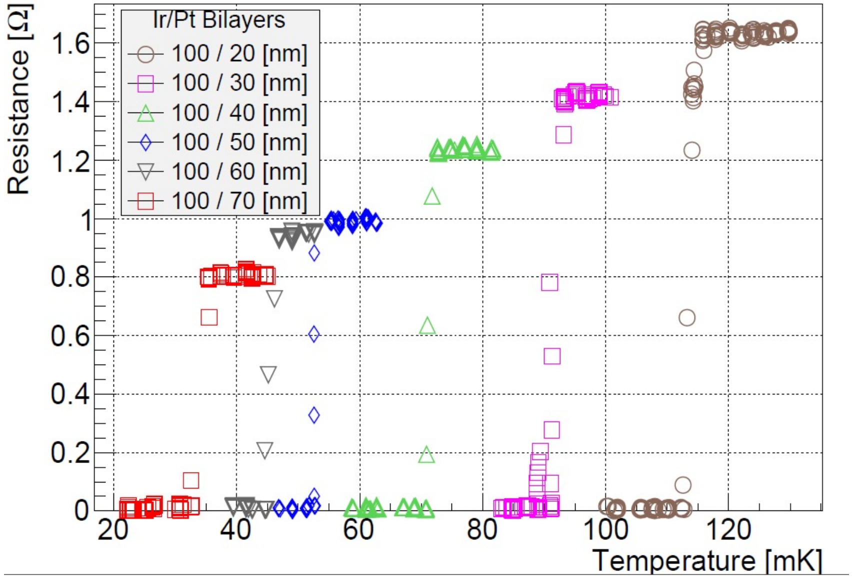


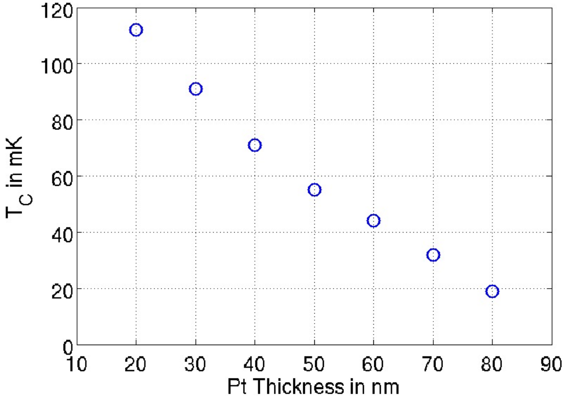


Quasipartiple density n

IR/PT BILAYERS

Fabricated at Argonne and tested at UC Berkeley

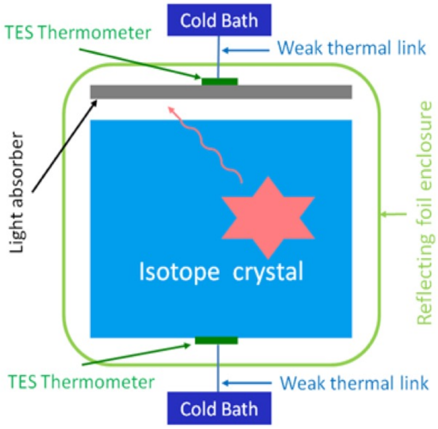




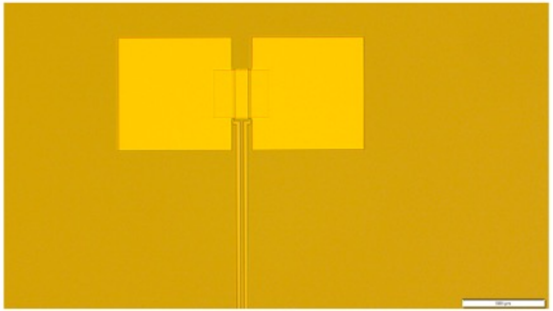
Tc of 100 nm Ir film: 195 mK

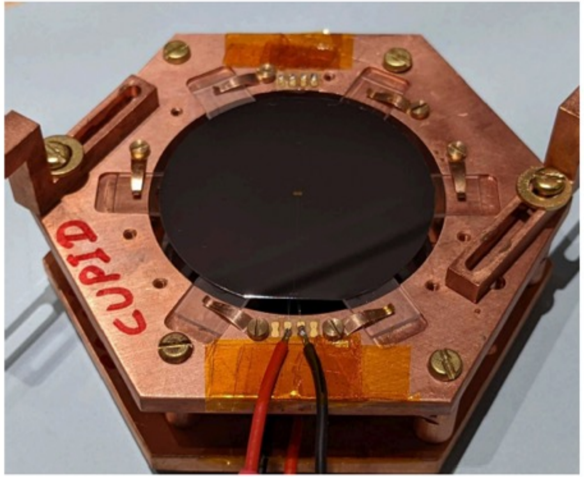
R. Hennings-Yeomans, C. L. Chang, J. Ding, et al., J. Appl. Phys. 128, 154501 (2020);

A LARGE AREA TES PHOTON DETECTOR FOR NLDBD



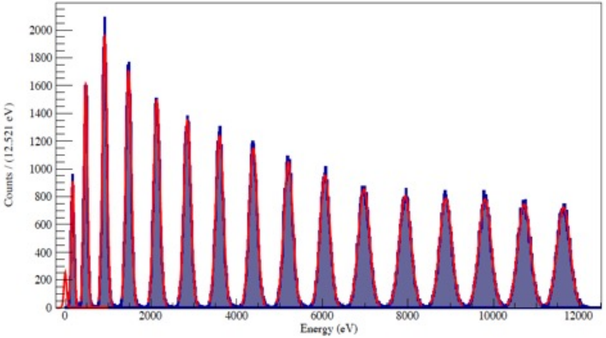
- Working with the CUPID collaboration, to develop a large area photon detector to measure the scintillation light from Li2MoO4 crystals
  - Measure heat & light to reject background
- 45nm/20nm Ir/Pt TES at the center of a 2-inch silicon wafer, Tc~33 mK, Rn=0.75 Ω
- Two large Au pads (900 μm × 900 μm × 0.2 μm) thermalize contact between the Si wafer and the TES

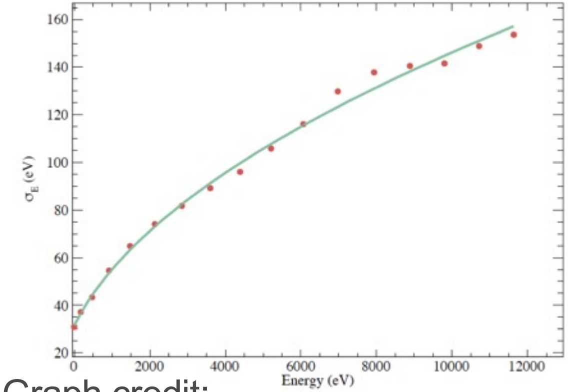




PERFORMANCE OF THE LARGE AREA TES PHOTON DETECTOR

- Operated at a bath temperature of 15 mK and at R=0.3Rn
- Excited back of the wafer with varying amplitudes of blue LED (475nm) pulses
- Pulse height is proportional to the number of photons impinging on the wafer
- Used photon statistics to calibrate the LED spectra
  - Statistics derived energy resolution is better than 40 eV

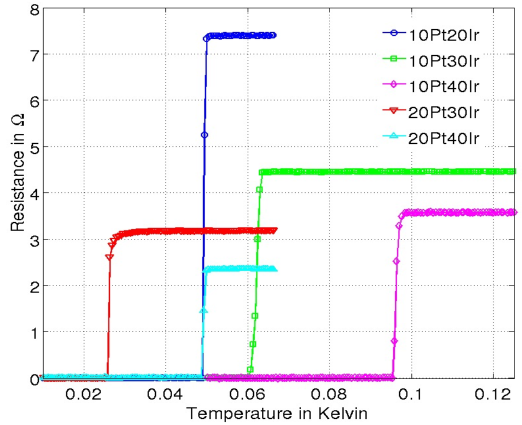


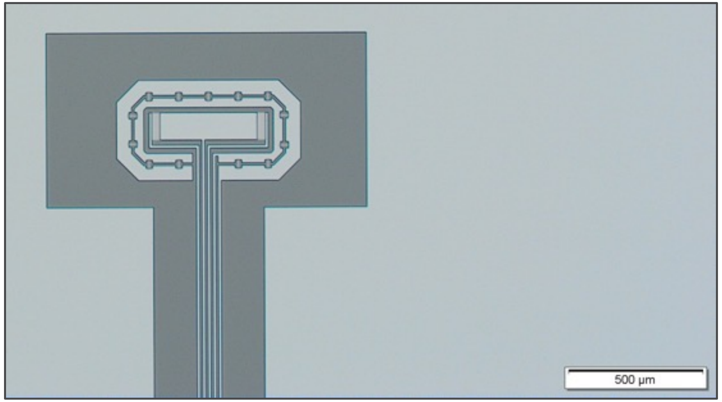


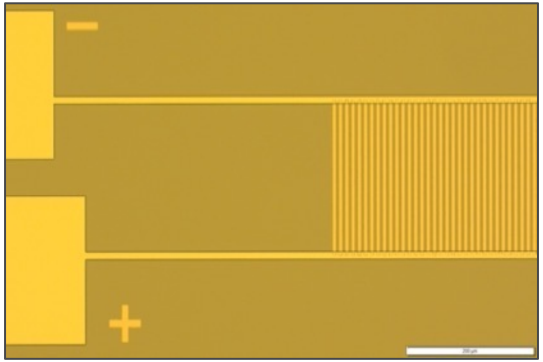
Graph credit: Vivek Singh at UC Berkeley

IR/PT QET

- Developing athermal coupling
  - Reduce TES Tc and volume.
    - Thin IrPt bilayers
    - Narrow TES lines
  - Al QP collector fins







SUMMARY

- Applications:
  - particle & wave dark matter searches
  - single photon spectroscopy
- TES photodetector has a high resolution and low dark counting rate
- Reviewed three kinds of TES photodetectors
  - A large area TES photodetector: a large dielectric photon absorber + a TES sensor for temperature readout
  - Sensitive large area QET: Superconducting photon absorbers + TES sensors for quasiparticle readout
  - Single photodetector: TES is used both as an absorber and a readout sensor
- Future development aims to use lower Tc materials to improve detector sensitivity

THANK YOU.

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