# Transition Edge Sensors at the APS

**Orlando Quaranta, Lisa Gades, Antonino Miceli, Umesh Patel And Daikang Yan**
Detector Group
Advanced Photon Source

In collaboration with

06/23/2018
5-Way Light Sources Meeting 2018 – Berkeley (CA)

# Detector Landscape & Requirements for APS-U Era

APS/XSD R&D Focus

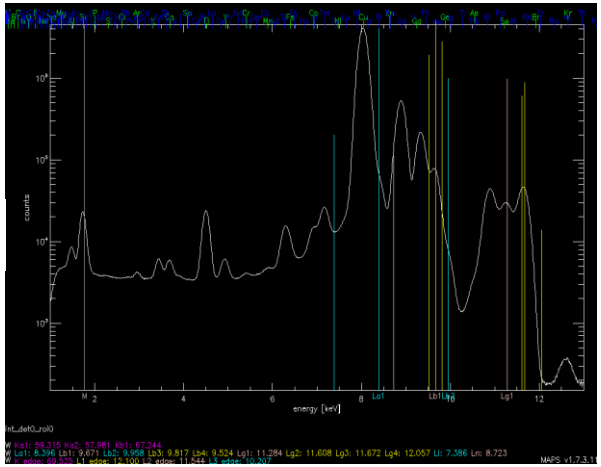
| Requirement | Detector Technologies | Beamlines |
|---|---|---|
| High Dynamic Range, Integrating Area Detectors (< 20 keV, Silicon Sensors, 50-150-um Pixels) | 1. MM-PAD v1.0 (Cornell/Sydor)<br>2. Jungfrau (PSI)<br>3. ePix (SLAC) | CSSI, 3DMicroNano/Atomic, Ptycho, CHEX, etc. |
| High Dynamic Range, Integrating Area Detectors (> 20 keV, High-Z Sensors, 50-150-um Pixels) | **1. MM-PAD v2.0 (Cornell/APS)**<br>2. Jungfrau v2.0 (PSI) | HEXM, HE Diffraction (1-ID, 6-ID, etc.) |
| High-Energy Bragg CDI (> 20 keV, ≤ 5 mm and High Dynamic Range) | 1. Scintillator-based Systems<br>2. MÖNCH Detector (PSI)<br>3. CMOS ISensor + Selenium (Waterloo) | HEXM |
| High-Speed Diffraction | 1. Keck PAD (Sydor/Cornell)<br>2. AGIPD, LPD (EU-XEFL)<br>3. UXI for National Ignition Facility (Sandia) | 32-ID, 35-ID, 14-ID, 7-ID |
| XPCS<br>(Counting with ~ 1-us Resolution) | **1. VIPIC (APS/BNL/Fermilab)**<br>2. Timepix-3 (Europe) | WAXPCS, SAXPCS, CHEX, CSSI |
| Imaging (< 20 keV, High-Speed) | 1. High-Speed CMOS Imaging Sensors (Industry)<br>2. Scintillators (ESRF, RMD/SBIRs) | 2-BM, 32-ID, 35-ID |
| Imaging (> 20 keV, 1-um Resolution) | 1. Scintillators (ESRF, RMD)<br>2. MÖNCH Detector (PSI) | HEXM, 1-ID, 2-BM, 32-ID, 35-ID, 13-BM, 16-BM |
| Fluorescence Detection<br>(~ 100-eV Resolution) | 1. Commercial SDD Arrays<br>2. MAIA v2.0 (BNL) | All XAS and XRF Nano/Micro-probes |
| High-Energy Spectroscopy<br>(> 20 keV) | **1. Germanium Strip Detector (APS/BNL)**<br>2. Hexitec (Diamond) | Energy-dispersive Diffraction, Powder Diffraction |
| Emission Detection<br>(~ 1-eV Resolution) | **1. Transition Edge Sensors (APS/NIST/SLAC)** | ISN, Ptycho, Polar<br>All XAS, XES, XRF Nano/Micro-probes |

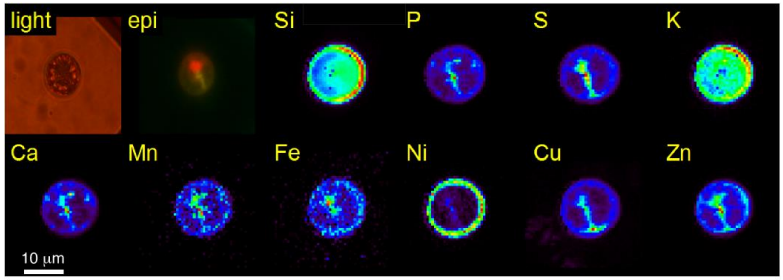
# Hard X-ray Transition Edge Sensors (TES)

## Why we are doing it?

- TESs offer energy resolution one to two order of magnitude better than any commercial solid-state detector.
- TES detectors offer great potential for applications in X-ray science including **chemically sensitive X-ray microscopy at nanoprobe beamlines, dilute sample XAFS, energy-dispersive diffraction, and Compton scattering**.
- Three of the nine flagship APS-U beamlines would benefit from a high-resolution hard X-ray TES detector, i.e. In-situ Nanoprobe, Ptychoprobe, Polarization Modulation Spectroscopy, in addition to the Sector 20 beamline relocation (Advanced Spectroscopy).
- **XRF of semiconductor samples**
  - Mapping heavy elements (L-lines) in integrated circuits.
  - For example Er, Hf, Ta, Tb, Tm, W.
  - Significant overlaps.
- **XRF of biological samples**
  - Differentiate Pt $L\alpha_1$ from Zn $K\beta$ signals (130 eV spacing).
  - Resolve $K\alpha/K\beta$ overlaps.

Tungsten ?




B. Twining, S. Baines, N. Fisher, J. Maser, S. Vogt, C. Jacobsen, A. Tovar-Sanchez, and S.Sañudo-Wilhelmy, *Anal.. Chem.* **75**, 3806 (2003)



Argonne NATIONAL LABORATORY

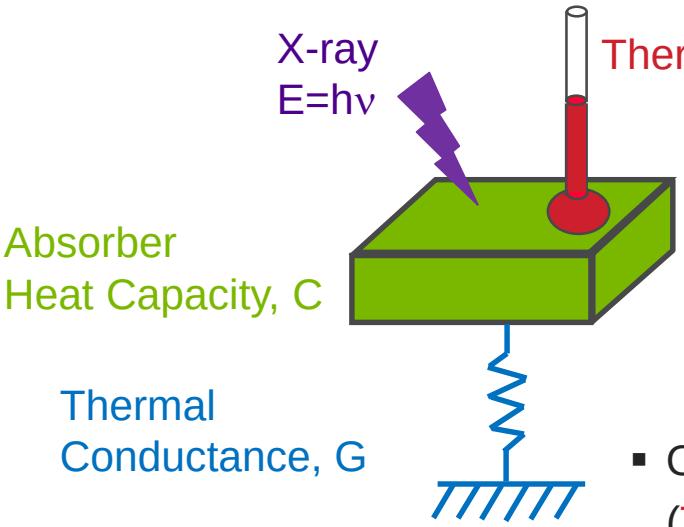
# Hard X-ray Transition Edge Sensors (TES)

## What we are doing?

- Our goal is to design and fabricate an instrument based on a TES array, together with the necessary cryogenic system, readout electronics, and software. This system will be made available to APS beamlines through the APS Detector Pool.
- The project is aim to produce two sensor arrays of ~100 pixels for X-ray photons between 2-20 keV:
  - One optimized for high energy resolution (< 10 eV) at low count rate (~ 100 counts/s per pixel).
  - One optimized for higher count rate with moderate energy resolution (10-20 eV), to explore the tradeoff between speed and resolution.
- The project uses established approaches and detector components:
  - TES sensors: Mo/Cu bilayer – $T_C$~100 mK, sidecar absorber composed of sputtered Au and electroplated Bi, SiN suspended membrane.
  - SQUID amplification/readout: Microwave SQUID multiplexer readout chips developed at NIST; one set for high resolution (~ 300 kHz bandwidth/pixel) one set for high speed (3 MHz bandwidth/pixel).
  - Cryogenics: HPD Cryostat is a system composed of an Adiabatic Demagnetization Refrigerator, backed by a 300 mK He3 sorption fridge and a 3.4 K cryocooler, with 3-4 days of hold time at operation temperature (~ 75 mK).
- First beamline testing to assess the system capabilities will take place at 1-BM. Pilot XAFS and XES experiments with real samples and data analysis are expected to take place consequently.

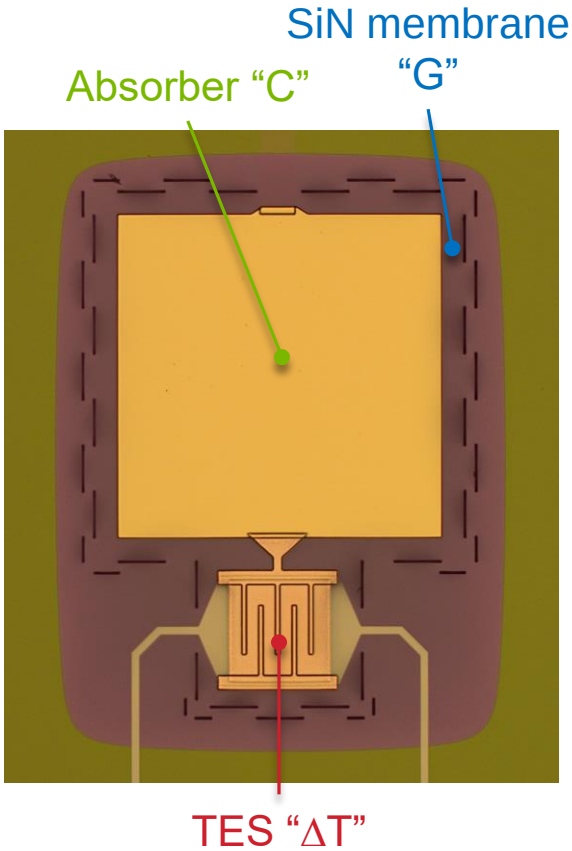
# Transition Edge Sensors (TES)

## Introduction

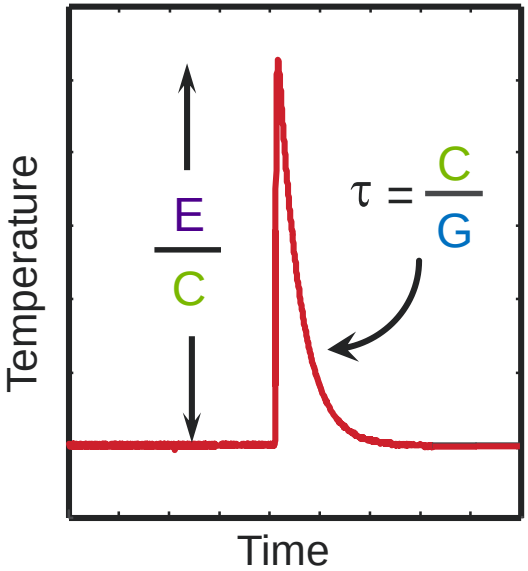


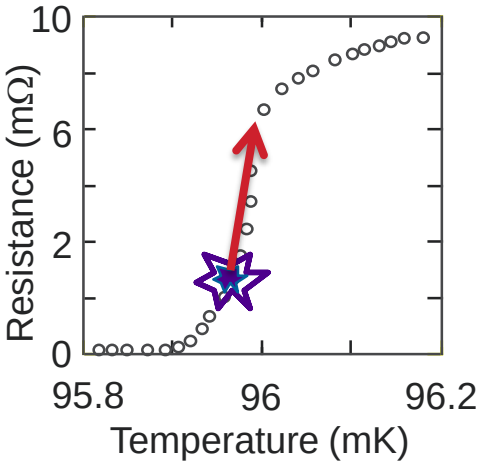

$E = C \times \Delta T$

$\Delta E = (k_B \times T^2 \times C)^{1/2}$




- Operate at low temperatures (T~ 0.1K) where C, G and thermodynamic fluctuations are small.
- Voltage bias the film on the transition.
- The signal is very small. Low noise, cold amplification is needed - Superconducting Quantum Interference Device (SQUID) amplifier.



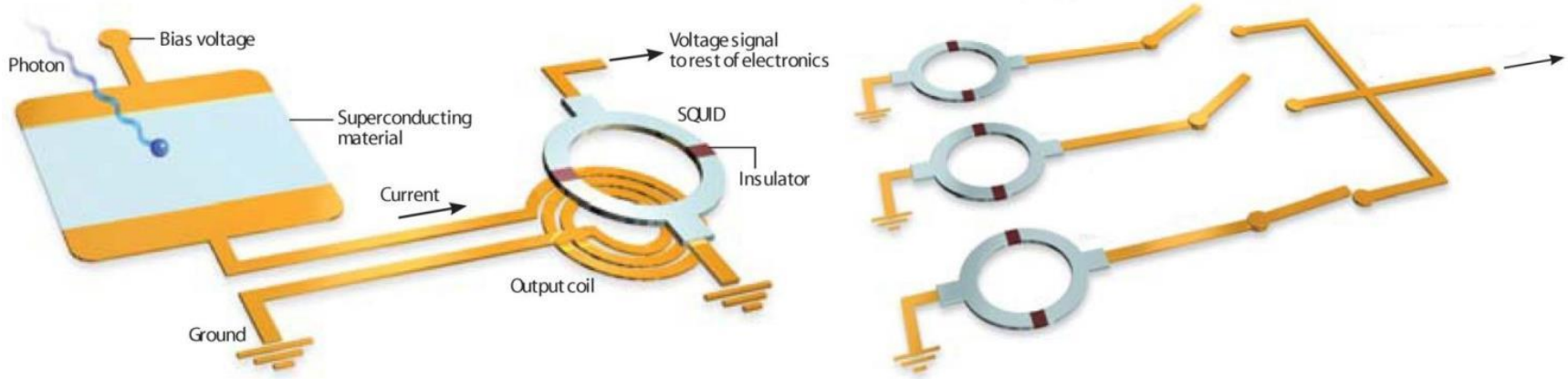




Argonne NATIONAL LABORATORY

# TES Readout

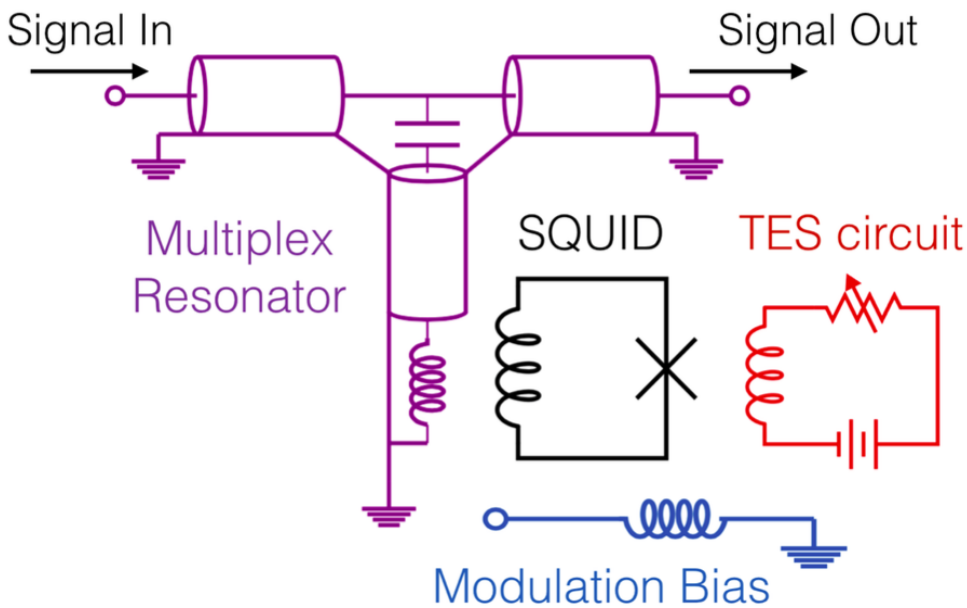
## SQUID Readout

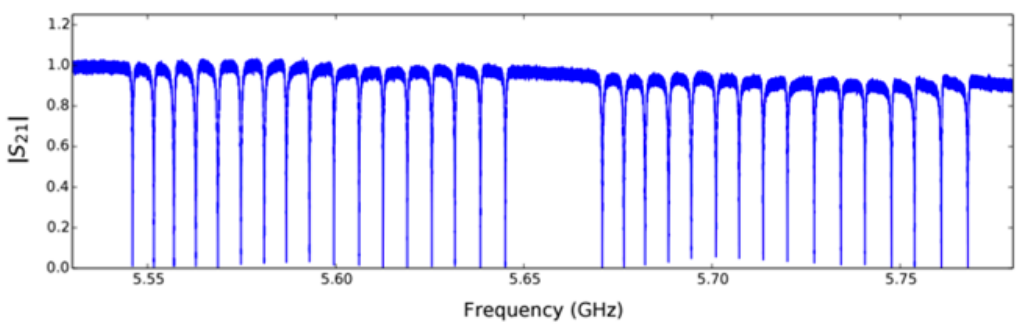
- One SQUID per TES is needed. This strongly limits the number of devices that can be directly addressed. Some multiplexing scheme is needed.
- Time-Division Multiplexing (TDM) represent the state of the art:
    - Each TES in a column is connected to a single SQUID.
    - SQUIDs in the column are turned on and off in a sequential order
    - The entire column is connected to a second stage SQUID
    - √N noise penalty
    - Count rate is limited by cross-talk between SQUIDs: ~ 10 cps/pixel



# TES Readout

## Frequency Division Multiplexing (i.e. μ-mux from NIST)



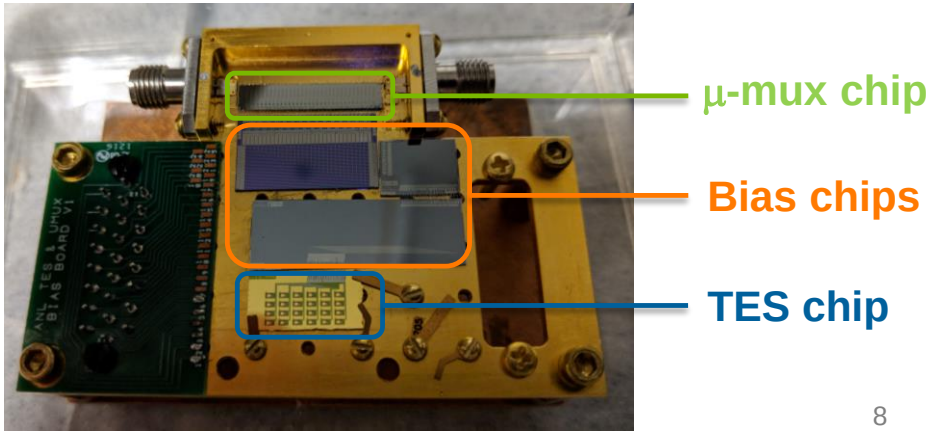

- Each TES detector is coupled to a SQUID amplifier and a microwave resonator.
- The photon absorption in a TES causes a temporary variation in the TES current. This is coupled to the SQUID via the coupling inductance, which amplifies this variation. This then induce a measurable shift in the superconducting resonator frequency, via the inductive coupling between the SQUID and the resonator.
- The TESs are multiplexed in frequency via the corresponding resonator frequency and read out all at the same time.
- Possible to multiplex ~ 500 TESs with single pair of coax and 4 DC lines.

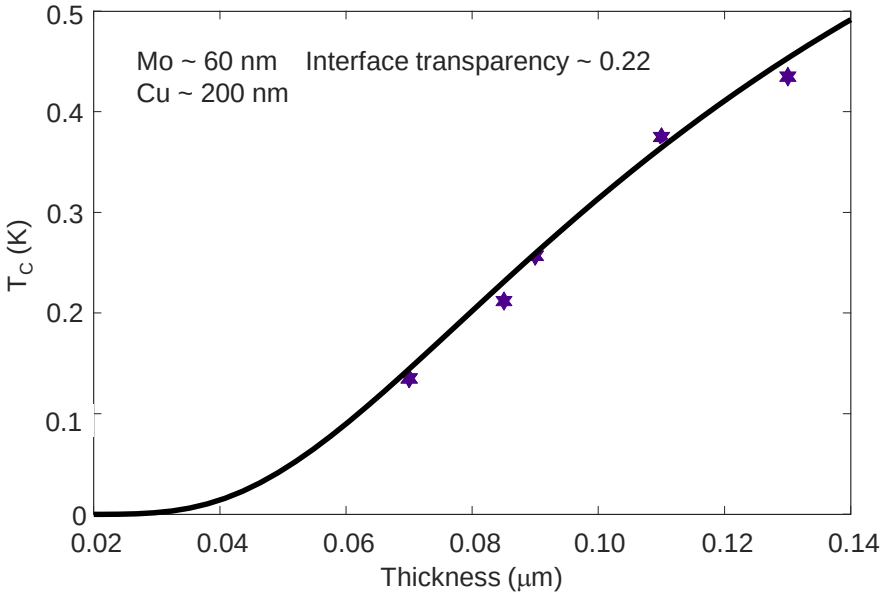
B. Mates, et al, *Appl. Phys. Lett.* 92, 023514 (2008)

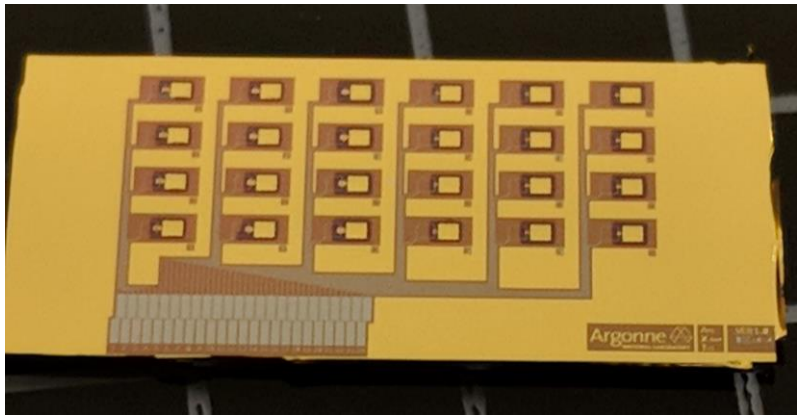
# TES Development at APS

## Application-specific sensors

- TES made of Mo/Cu bilayers:
  - $T_C$ ~ 100 – 110 mK.
  - $R_n$ ~ 10 mΩ.
- First prototype wafers contain multiple variations on the design:
  - TES dimensions, shape and number of bars to tune the resistance and the transition steepness.
  - TES with and without absorber to measure separately the different contributions to the total C.
  - Different SiN membrane designs to address the scalability of G.
- Testing via m-mux in an existing cryostat.



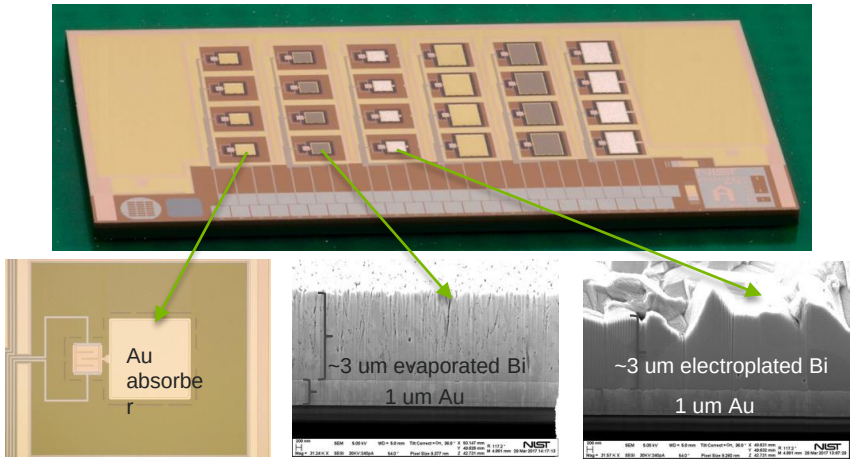



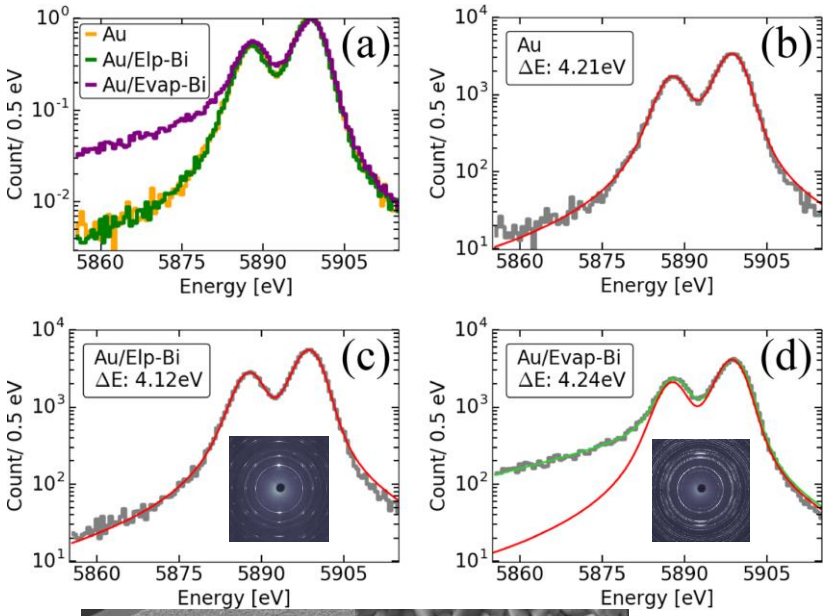



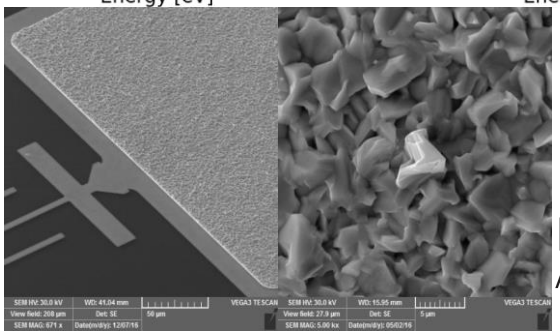
# TES Development at APS

## Absorber

- Absorbers with high Z and low C are needed for high detection efficiency and energy resolution.
- Bi is dense and its semimetal nature limits its C at these temperatures. Together with a Au underlayer for thermalization it is a good candidate for the absorber.
- Evaporated Bi (Evap-Bi) absorbers are widely reported to have non-Gaussian low-energy tails.
- Electroplated Bi (Elp-Bi) was integrated in existing TESs from NIST. No sign of non-Gaussian low-energy tails.
- The energy resolution was not affected by the presence of Bi, confirming its low C.
- Scanning electron microscopy and X-ray diffraction microscopy show grain size of the Evap-Bi ~ 30 nm while for Elp-Bi was ~ 1.4 μm.
- Average secondary electron cloud size span easily many grains in Evap-Bi while it can be contained in one Elp-Bi grain. This can indicate that the tails are due to energy trapping at grain boundaries.



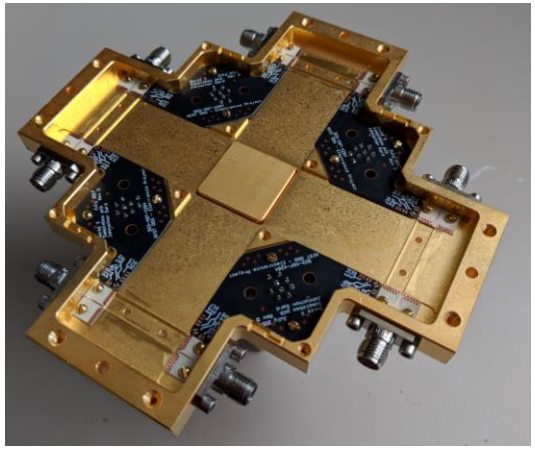



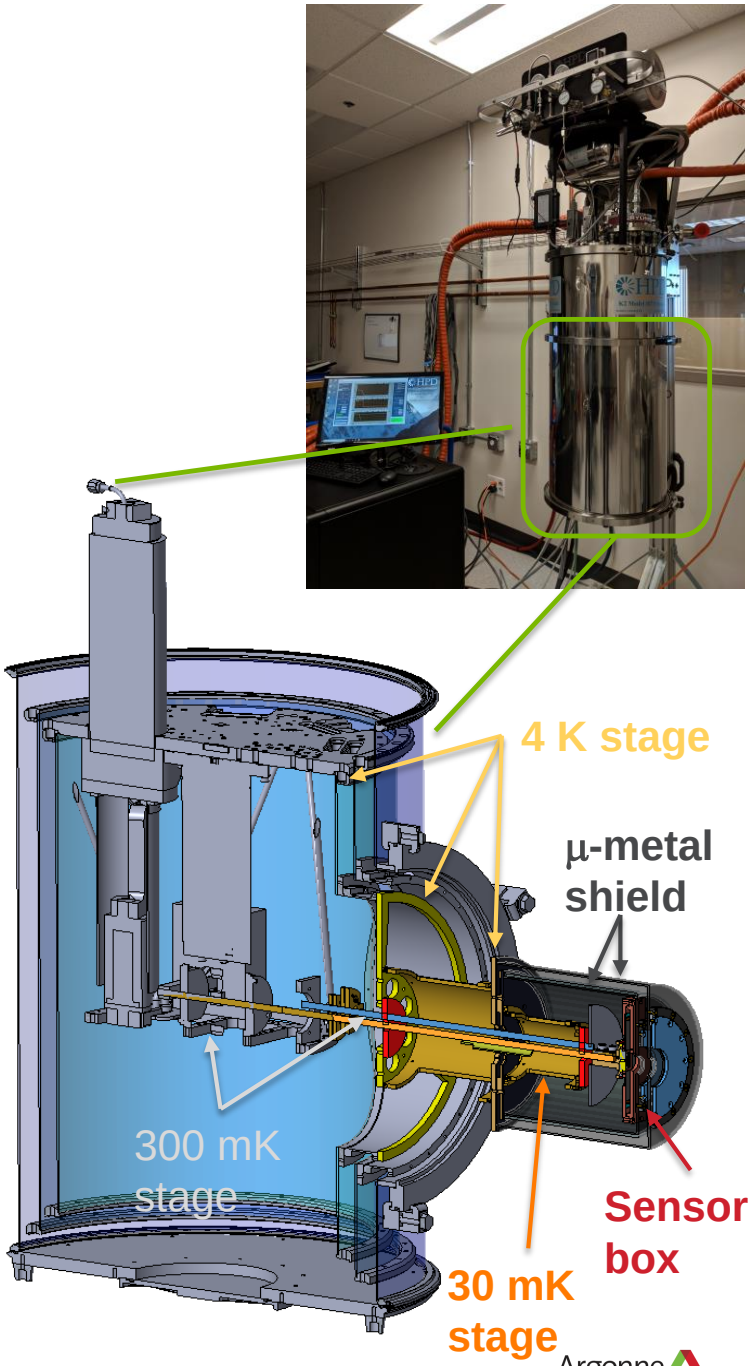
D. Yan, et al, *Appl. Phys. Lett.* 111, 192602 (2017)

# Cryogenics System

## Cryostat and Sensor Box

- Cryostat with a base temperature of ~ 30 mK and hold time of 3-4 days at 75 mK. The cryostat control is completely automated and cryogenic liquid free.
- Low thermal conductance wires and cable for bias and readout.
- Thermal and magnetic shielding while keeping photon access.
- Snout structure to bring the sensor as close as needed to the sample under investigation.
- The sample box mounts the TES array in the center, surrounded by 4 quadrats with the readout chips: bias and μ-mux SQUIDs.

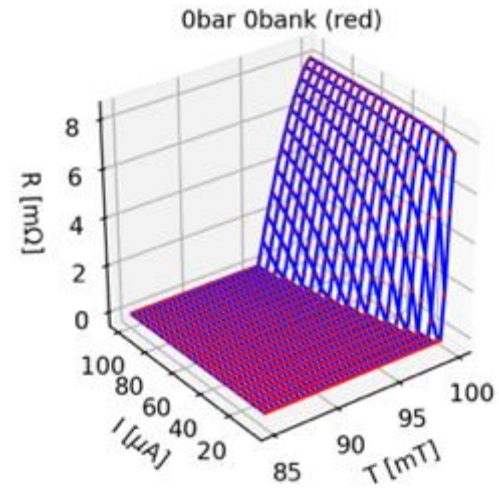


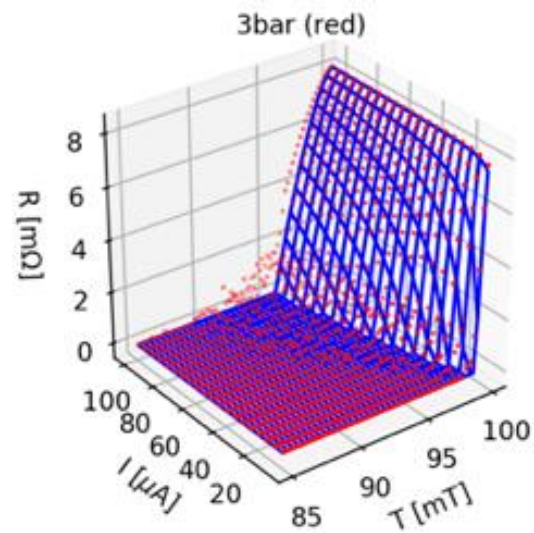


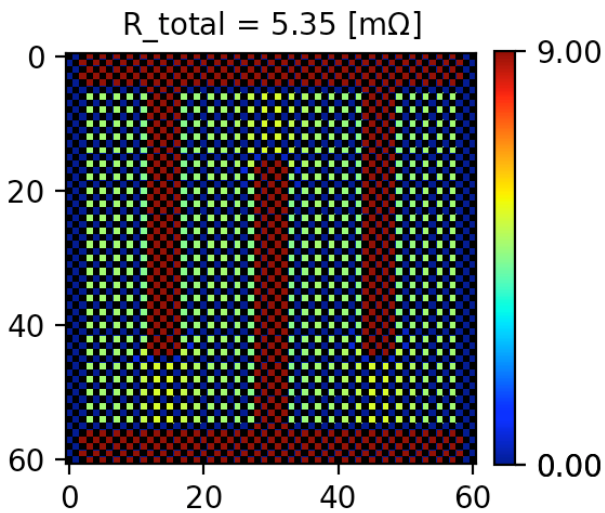
# Simulations

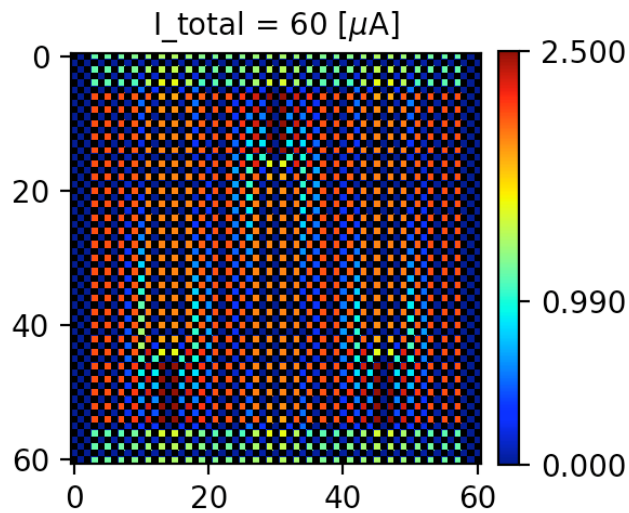
## Tools to guide device designs

- To better understand the TES behavior an accurate understanding of the relationship between R vs I and T is needed.
- One of the most promising models for TES is based on the two-fluid model of superconductivity.
- We are applying this model to an arbitrary mesh that can resemble any TES design.
- The aim is to simulate and predict the effect of typical TES features like normal metal bars used to tune the TES behavior.





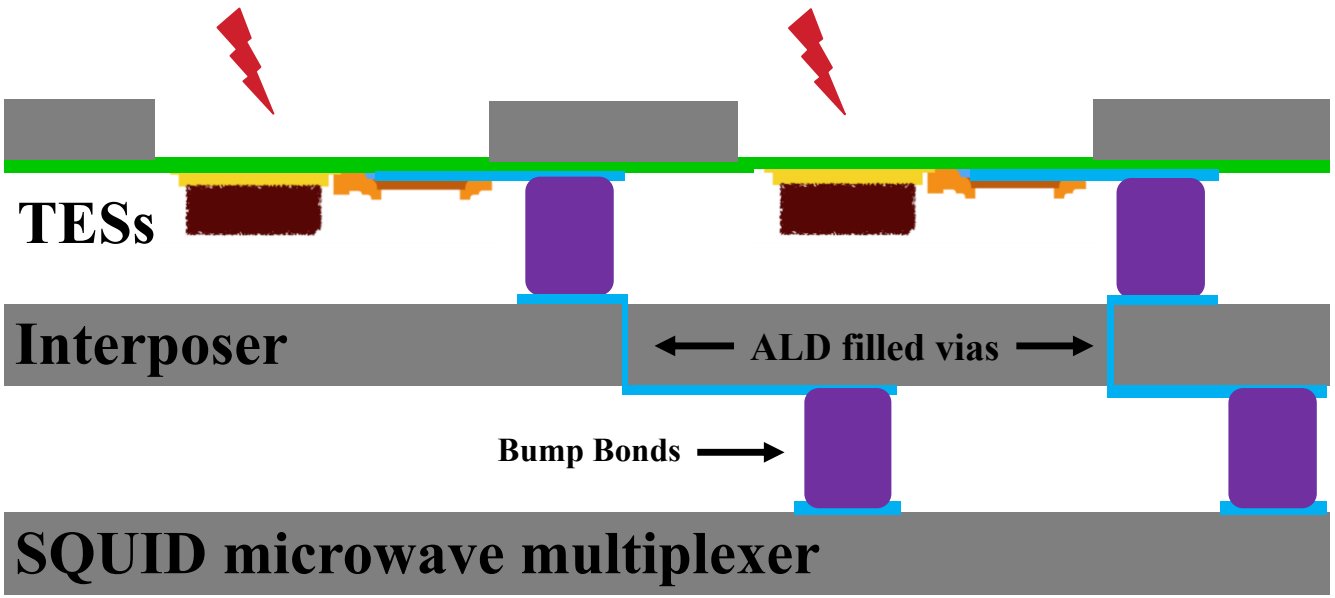

Argonne NATIONAL LABORATORY

# Future Endeavors?

Argonne NATIONAL LABORATORY

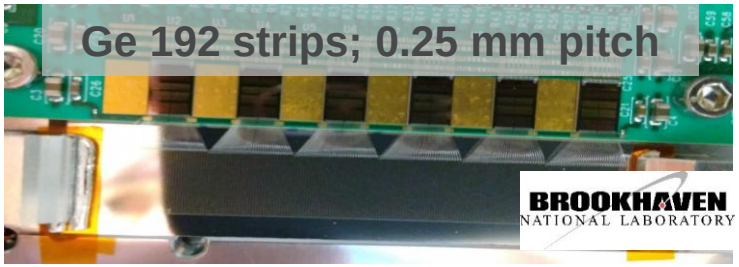
# 3D Superconducting Interconnects

- 3D interconnects/vertical integration is very common for semiconducting detectors and electronics.
- Propose to develop superconducting interposers as a versatile component for 3D integration of TES detectors.
- Superconducting interconnects requires conformal deposition in thru-silicon vias (e.g., atomic layer deposition, ALD) while maintaining the superconducting properties.
  - Interposer with ALD filled thru-silicon vias from ANL.
  - Bump bonding capabilities from NIST.

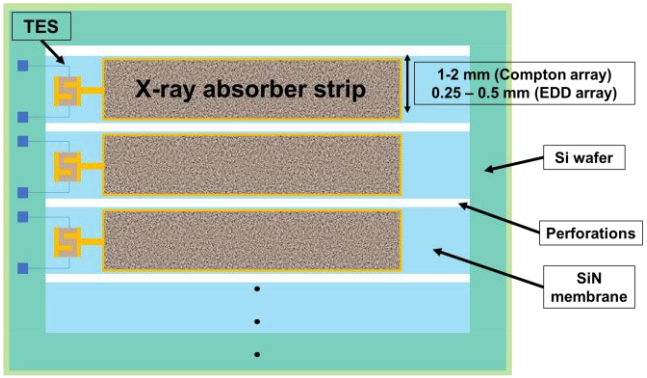


# High-energy X-ray TES

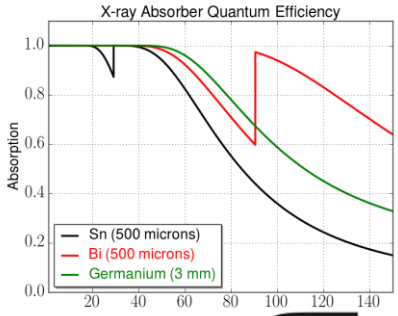
- TES efficient to 150 keV can provide energy resolutions unprecedented for solid state detectors:
  - TES: DE < 55 eV at 100 keV
  - Germanium: DE = 500 eV at 60 keV




- **Energy-Dispersive Diffraction**
  - Resolution gives structural information.
  - Pixelated detectors also provide imaging capabilities:
    - Pencil beam illuminates line in the sample; pixelated detector plus pinhole, polycapillary or coded aperture provides 3D information




- **Compton Scattering**
  - A bulk-sensitive probe of Fermi surfaces in strongly correlated materials; a complementary approach to ARPES.
  - Fluid dynamics, catalysis, etc.
  - Probe low-Z materials in real-world environment chambers
  - Pixelated detectors also provide imaging capabilities




- **Develop TES strip detectors**
  - Pitch ~ 0.25 - 2 mm (TBD)
  - Energies up to 150 keV
  - Strips: > 200 (straightforward to scale to 1000-pixels)
  - Up to 500 microns (TBD) thick of electroplated Bi (or Au or Sn) to provide fine pitch
  - Co-developed by ANL and NIST

SXS

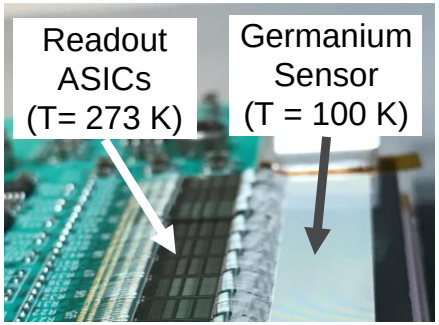
NIST SLAC NATIONAL ACCELERATOR LABORATORY Argonne NATIONAL LABORATORY

# Cryo-ASICs

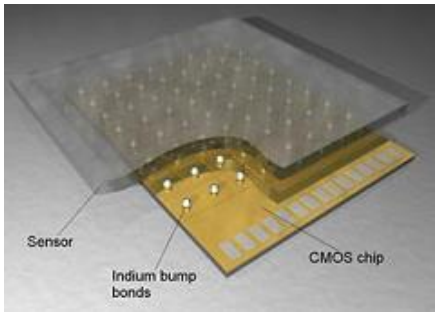
## A provocation

- Germanium (hybrid) pixel array detectors (T= 100 K):
  - APS-U (E > 30 keV) – High-energy diffraction
  - High-flux XFELs (e.g., HE-LCLS-II, MaRIE).
  - Ge is an ideal sensor for HE and high-flux (compared to CdTe, GaAs).
- (SNSPDs) Superconducting nanowire photo/particle detectors arrays (T= 4K):
  - Ultra-fast (ps-jitter) detectors with applications from infrared photon counting to X-rays to particle detection (e.g., Electron-Ion Collider).
  - Each pixel needs high bandwidth readout signal chain (e.g., GHz amp, CFD, TAC, etc).
- Transition-Edge Sensors (T < 0.5 K):
  - Fast X-ray TESs need > 10 MHz BW/pixel.
  - Hybrid CMOS & SQUID approach.
- Commercial deep-submicron CMOS process works at cold temperatures:
  - DUNE LAr TPC cold electronics at BNL, etc.
  - Quantum computing readout at TU-Delft.

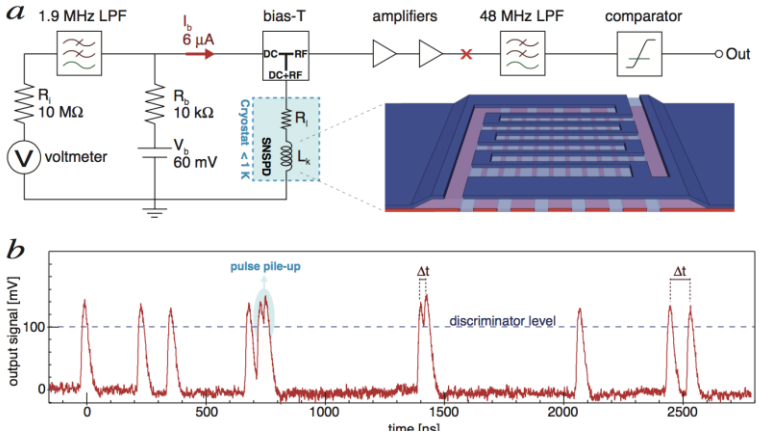
APS/NSLS-2 Ge Strip/1D Detectors




Ge pixel detectors




Superconducting nanowire photon detectors arrays





https://doi.org/10.1109/TNS.2014.2365358
https://dx.doi.org/10.1117/12.2274567
R. Valivarthi, S.W. Nam, et. al., DOI:10.1364/OE.22.024497


Argonne NATIONAL LABORATORY

# Conclusions

- APS is developing a 100-pixel TES instrument for energies up to 20 keV:
  - It will be based on Mo/Cu TES in conjunction with electroplated Bi/Au absorbers.
  - It will become available to beamline scientists via the Detector Pool.
  - It will represent a pathfinder for future instruments developments, with application-specific sensor designs.
- APS is also working on developing the TES technology in collaboration with NIST and SLAC:
  - Packaging – superconducting TSV and interconnects.
  - TESs for high-energies – up to 100 keV.
  - General TESs performances improvement – resolution and speed.