The BaRBE project and the perspectives of TES sensors in WISP searches

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Summary

- BaRBE project
- Low background detectors for WISP searches
  - Transition Edge Sensors (TES)
  - TES-based detector prototypes
- BaRBE activities with TES
- Future developments

BaRBE collaboration

- BaRBE (stands for "Low rate low energy") was started in 2009 and is funded by the italian INFN
  - University and INFN - Trieste (G. Cantatore, A. Rachevski)
  - University and INFN - Camerino (G. Di Giuseppe, M. Karuza, M. Lucamarini, R. Natali, P. Tombesi, D. Vitali)
- BaRBE is participating in CAST and is supported, for the TES studies, by ALPS

BaRBE quick overview

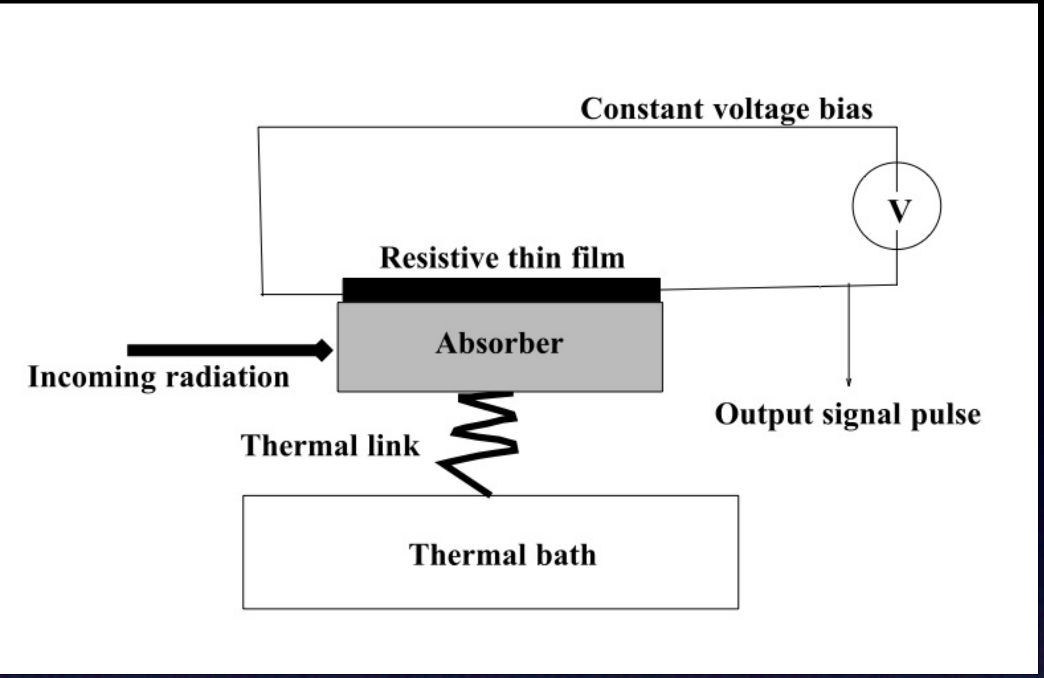
- BaRBE goal
  - Develop a very low background single-photon counting system, in the energy interval 1-100 eV, having spectroscopic capability. The system should be adapted to the low expected rate environment typical of WISP search experiments.
- BaRBE brief history
  - 2009-2010
    - project starts by testing a cooled photomultiplier sensitive at 2 eV and by designing and installing a switched fiber-optic system to couple the PMT to one of the CAST beamlines
    - coupling to CAST is made permanent by means of a semitransparent foil mirror
    - a LN2 cooled Avalanche PhotoDiode is tested with encouraging results
  - 2011 ...
    - the importance of Transition Edge Sensors is realized and the focus is shifted on implementing TES-based counters in WISP searches
    - a TES procurement and preliminary test program is launched in collaboration with the ALPS group from DESY. Application of TES counters to the BaRBE beamline at CAST is also foreseen.

Low background detectors for WISP searches

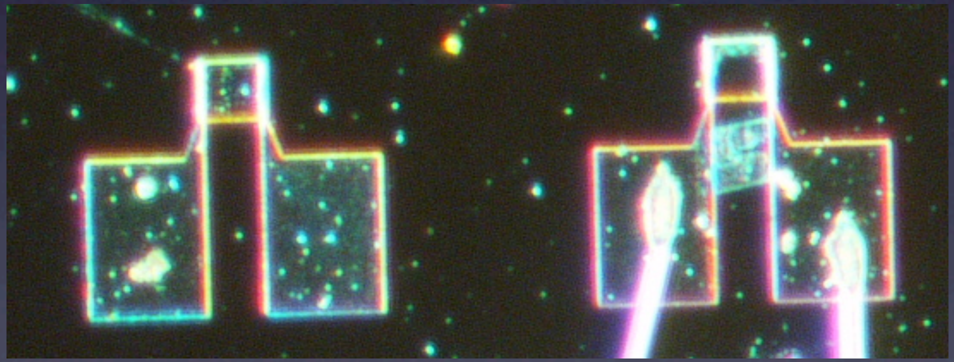
- The availability of low background photon detectors in many spectral intervals is crucial for the success of WISP searches of all kinds
- Low background must also be coupled to single-photon counting capability
  - Observatories such as CAST depend critically on the detector background (magnet parameters are strongly constrained by the available technology)
  - The sensitivity of laboratory-based experiments, such as ALPS, is also deeply affected by detector noise
- No single device is however capable of covering all the main energy intervals explored in WISP searches
  - 2-4 keV for solar ALPS
  - ~ 1 keV for solar chameleons
  - 1-2 eV for optical LSW experiments
  - sub-eV for relic axion searches
    - 5-10 keV might be needed for X-ray LSW experiments and 1-100 eV for paraphoton searches

Transition Edge Sensor (TES) working principle

- Incident energy heats an absorber (the choice of absorber material sets the spectral range of the sensor)
- A thin film (normally Ir or Ti) at the transition temperature between normally-and super-conducting measures the temperature change of the absorber
- The thin film (the actual TES) is biased by a voltage: a change in its resistance is sensed as a change in current with amplitude proportional to the energy deposited in the absorber
- At the end of an event the absorber slowly thermalizes towards an heat-sink
- The background noise is virtually zero since at the operating temperature, 50-100 mK, there are no “internal” heat sources

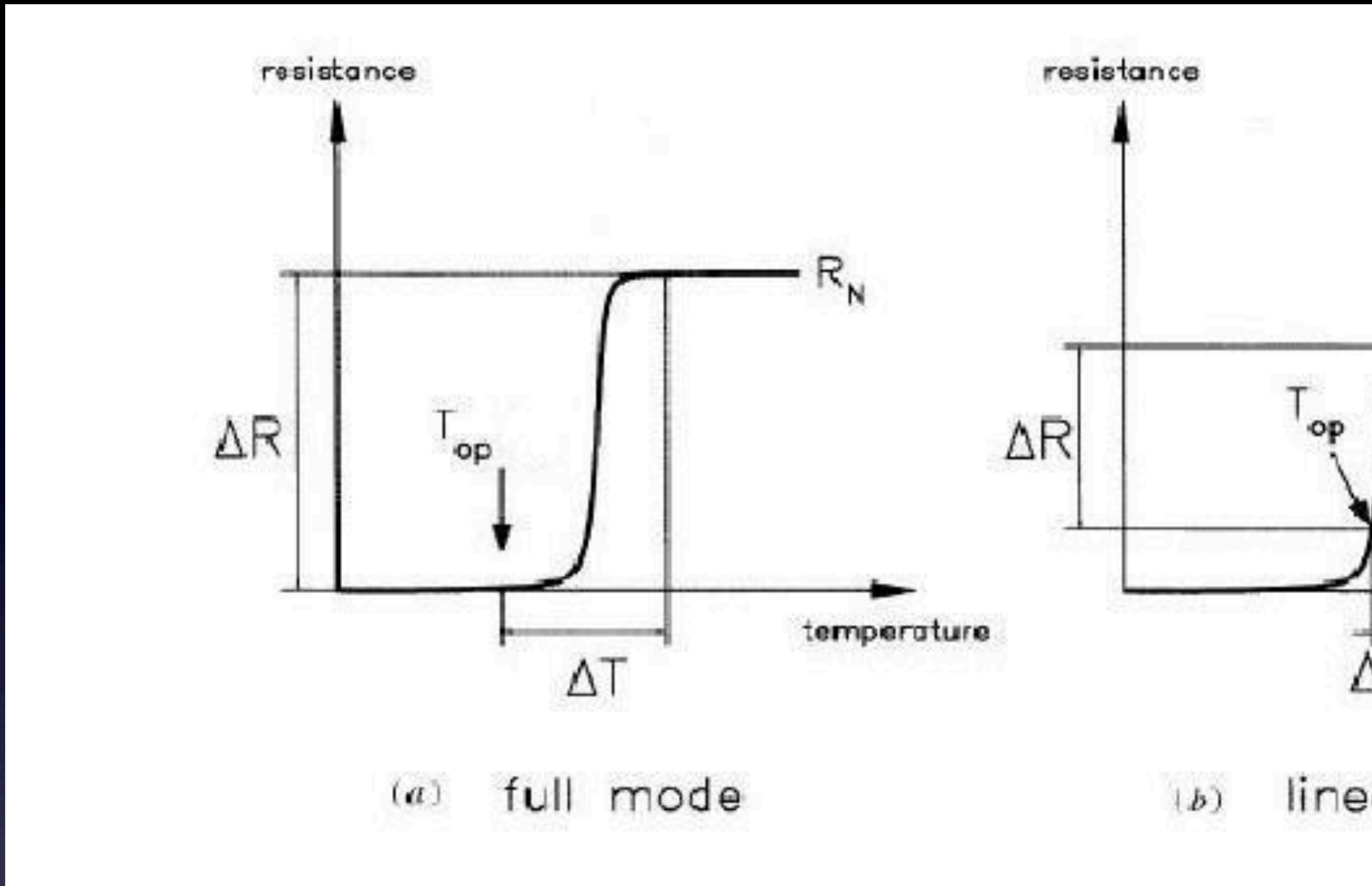


TES working principle schematic



View of two sample sensors: the small (50 μm)x(50 μm) square is the actual TES, and the rectangles are Al contact pads.

TES transition curve

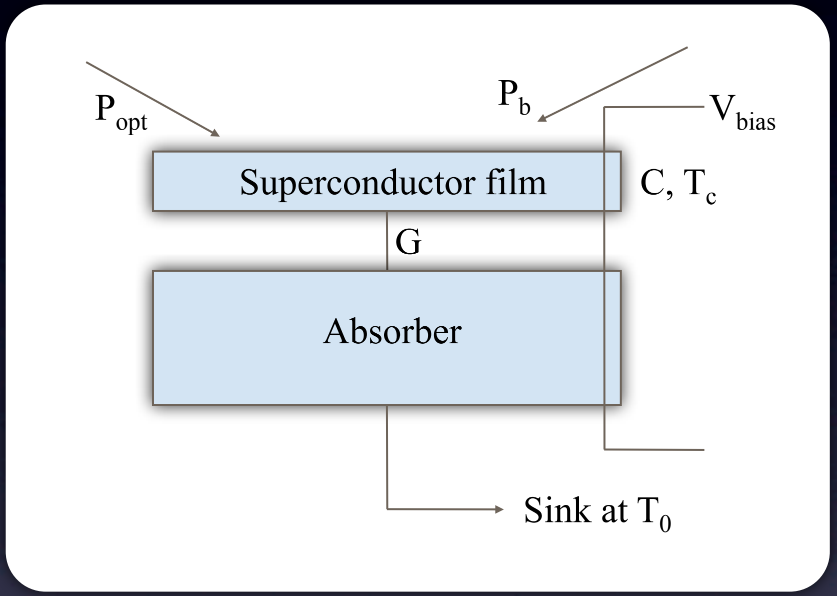


Taken with permission from F. Brunetto, Thesis, University of Genova 2009

- In full mode the temperature change ΔT of the absorber is such that the resistance changes fully from zero to normal almost independently of the incident energy ➔ equivalent to a Geiger counter
- In linear mode ΔT is proportional to ΔR and therefore to the incident energy ➔ the detector operates as a calorimeter
- The choice of mode is done by setting the operating temperature T_{op} and by dimensioning the absorber to undergo a certain ΔT in response to a given incident energy

TES Electro-Thermal Feedback

- The power absorbed by the sensor is the sum of the incident radiation power and of the Joule heating power due to the bias, $P = P_{opt} + P_b$
- The temperature of the sensor is given by $T = T_0 + C/G$, where C is the thermal capacity and G is the thermal conductance
- If the sensor is biased at a constant voltage V, then $P = V^2/R$, therefore
  - increase in T → increase in R → decrease in P → decrease in T → decrease in R → increase in P → increase T → .....
  - the system reaches stability
- This is called Negative Electro Thermal Feedback (NETF)
- In a NETF state the heat flow between film and ansborber is kept constant and temperature changes can be read quickly without the need to wait for the absorber to thermalize

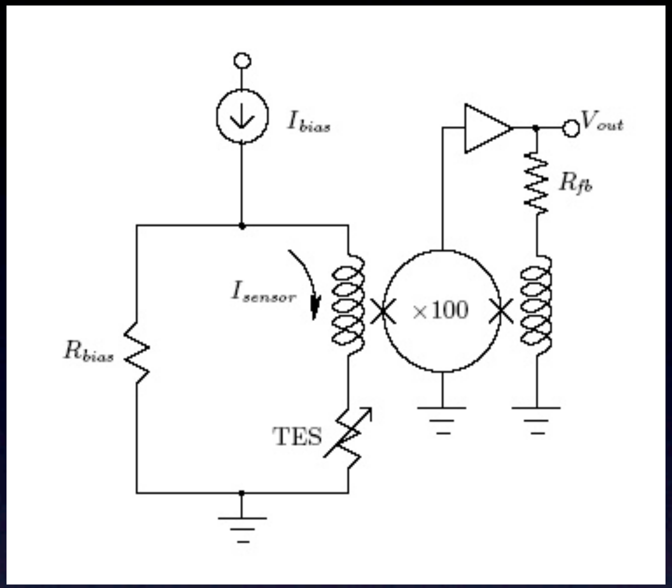


Electro-thermal feedback schematic

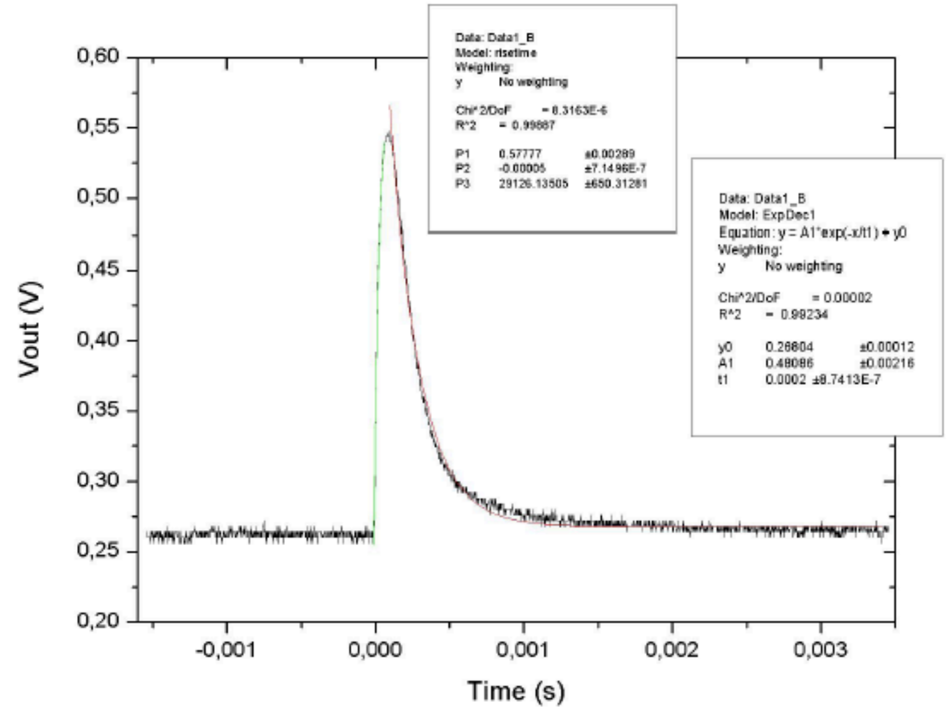
TES Voltage Bias

- The TES is biased by a constant voltage applied in parallel to a shunt resistance R_{bias} (typically < 0.5 Ω)
- When the TES resistance changes in response to an energy deposition event, the current through the sensor decreases and this negative pulse is detected by a SQUID and converted to an output voltage pulse
- The total energy deposited is given by the time-integral of $I_{sensor}(t)$

TES voltage bias



Output pulse sample, 60 keV photons



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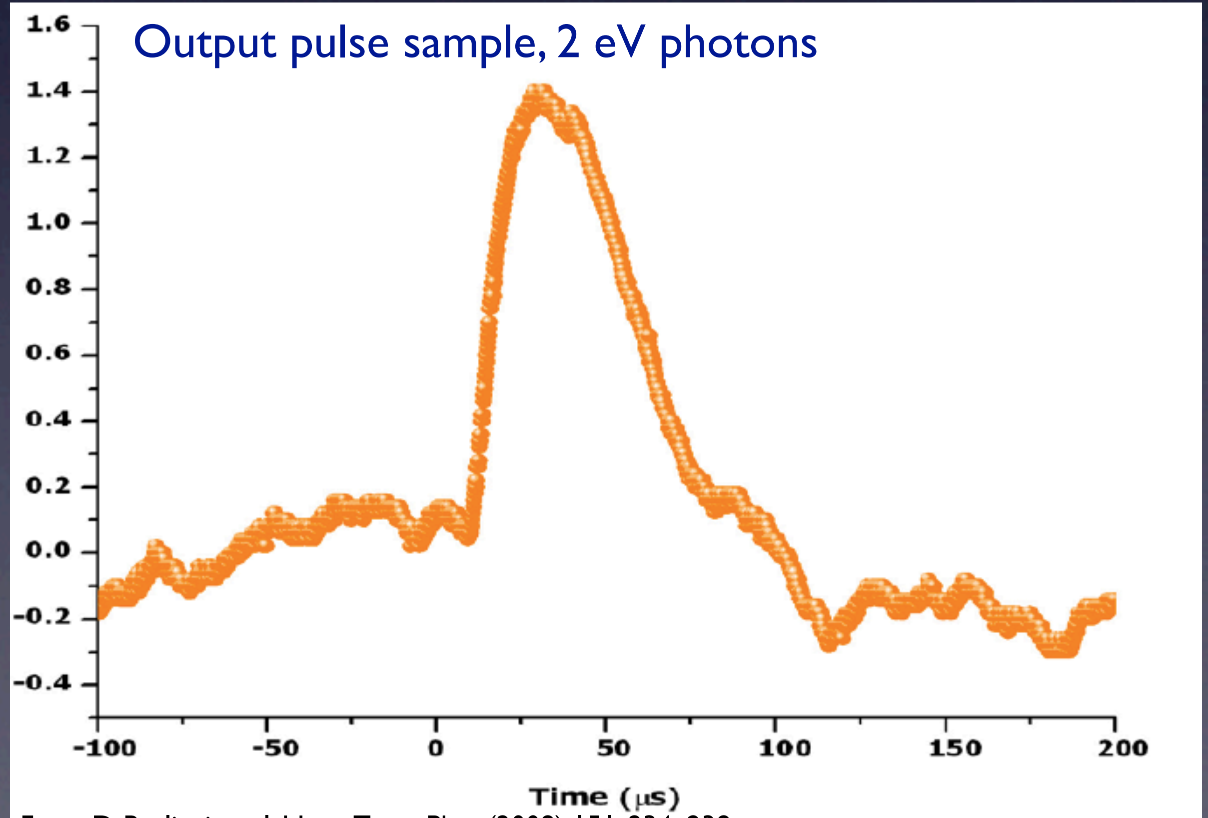
Output pulse sample, 2 eV photons



From D. Bagliani et al, J Low Temp Phys (2008) 151: 234–238

TES-based photon counters

- Transition Edge Sensor (TES)-based photon counters hold the promise of becoming the detectors of choice for WISP searches
- Main advantages
  - VERY LOW background (at least < 1 mHz measured over short acquisition times, potentially "zero" over long exposure times)
  - single-photon counting capability even at low energies (1 eV or less)
  - spectroscopic capability
  - can be optimized, in the design stage, for specific wavelengths in a wide range up to tens of keVs
- Main drawbacks
  - relatively small active area (typically 100x100 μm^2 or less for a single sensors)
  - need ultracryogenic environment (T around 100 mK)
- However ....
  - researchers are already working on TES arrays with active surfaces up to 1 cm^2
  - the required cooling power is very low (< 1 mW) and suitable refrigerators are commercially available

TES-based detector prototypes

- TES sensors are NOT available commercially: one must procure them through groups researching TES design and manufacture
- BaRBE has teamed up with ALPS to procure, mount and test in the proper cryogenic environment TES detector prototypes
- TES source contacts
  - INRIM Torino
    - TiAu film TES chip with several sensor pads of different sizes
  - NIST (USA) and PTB (Germany)
    - W film TES chip with several sensor pads of different sizes
  - INFN Genova
    - Ir film TES chip with single sensor and 10x10 TES array

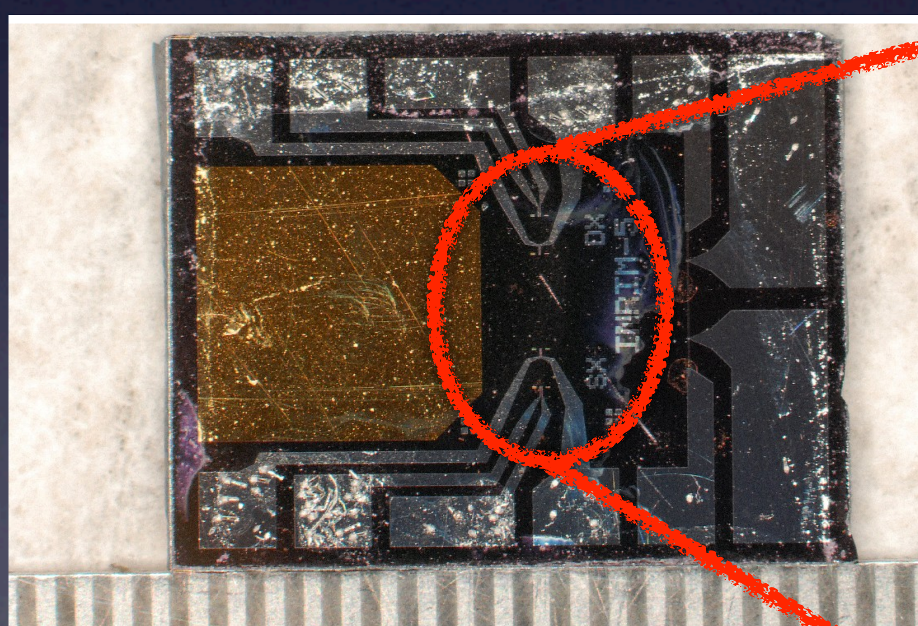
BaRBE activities with TES (in collaboration with ALPS)

- Sensor mounting
  - Cu baseplate preparation
  - PCB design and manufacture
  - TES bonding
- Refrigerator and SQUID set-up
  - Cold finger preparation
  - Fiber-optic coupling
  - Sensor-SQUID assembly
- Sensor tests
  - SQUID tests
  - TES cooling tests and transition curve measurements
  - Photon counting tests
  - Long background measurements

TES sensors from INRIM - Torino

- Ti-Au set of 4 sensors made by INRIM (Italian Metrology Research Institute)
- Two 20x20 micron^2 and two 10x10 micron^2 sensors in the set
- Sensors were characterized thermally (transition temperature at 300 mK) but never used for photon counting

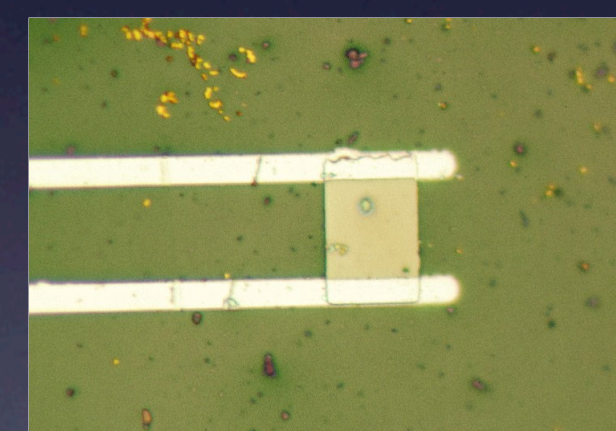
Picture of the INRIM TES chip with bonding pads and test structures



Lines are spaced by 0.5 mm, long side of the chip is 9 mm

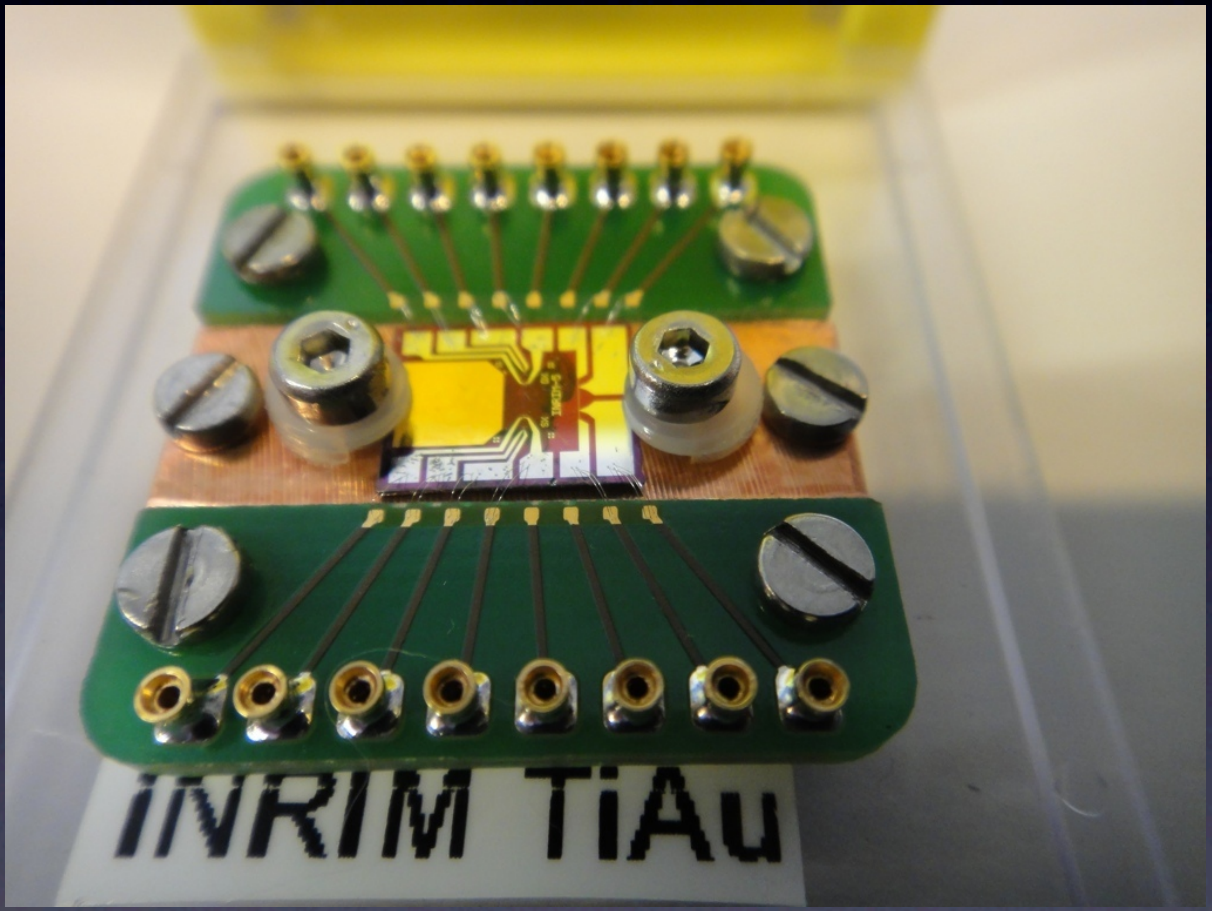
Zoom on the sensor area

TES sensor pad

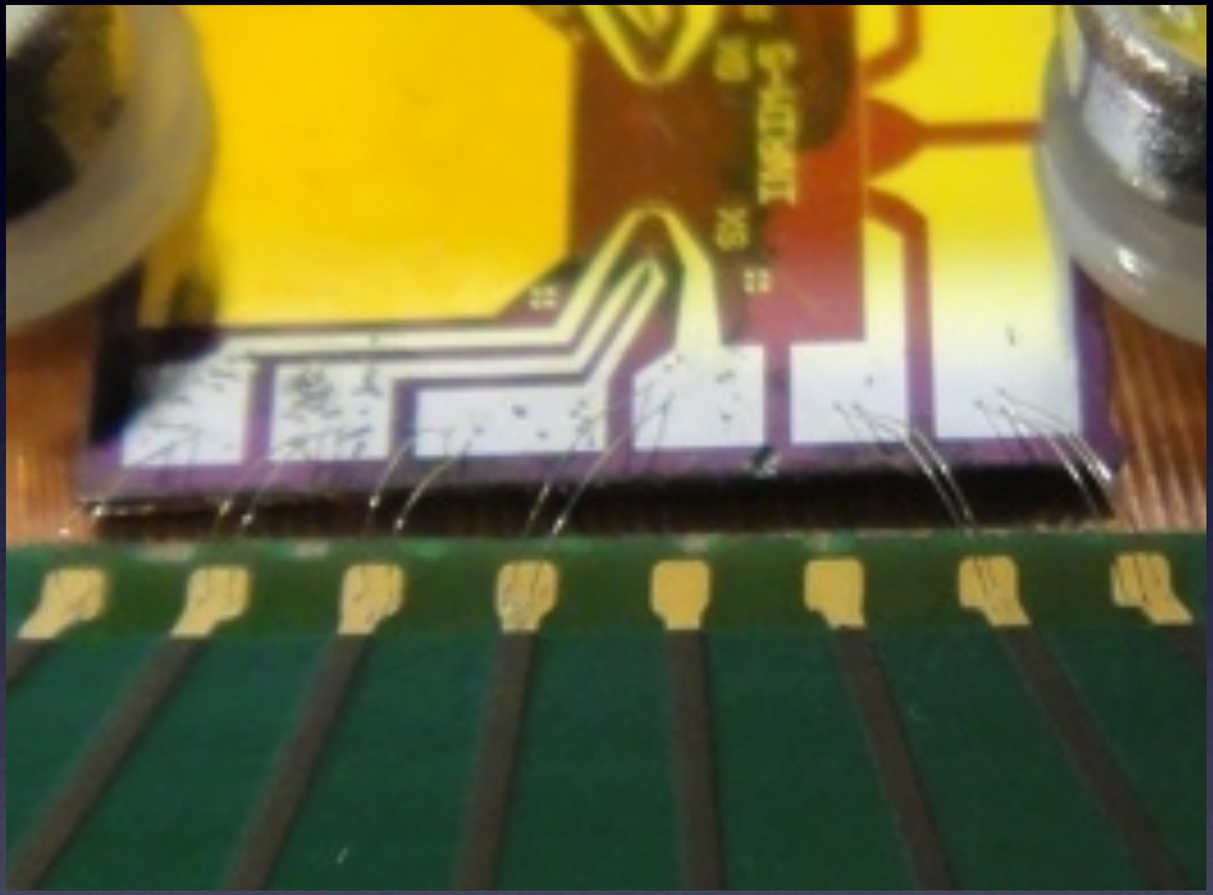


Magnified picture of a single 20x20 micron^2 sensor

Mounted INRIM TES



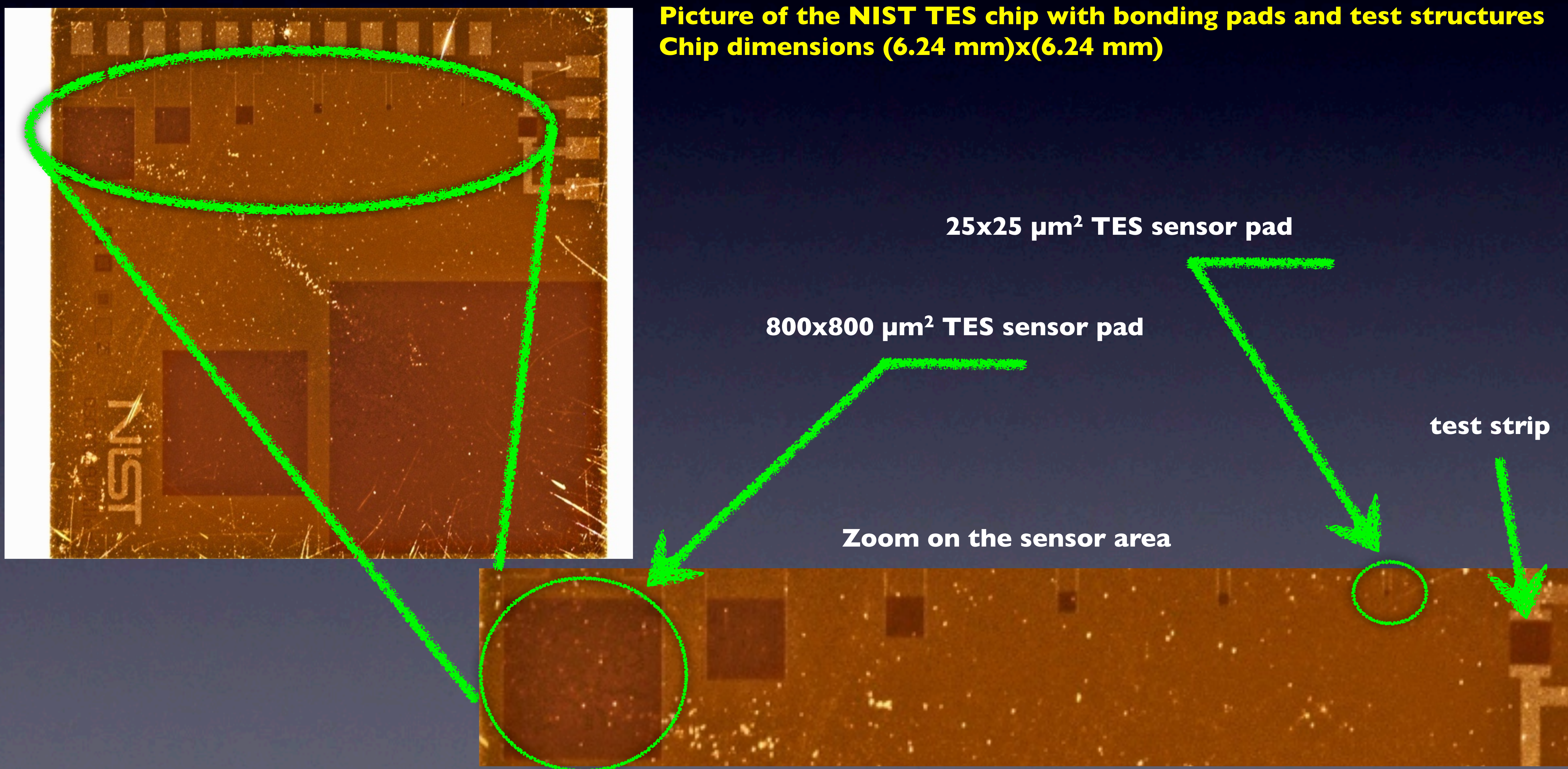
INRIM chip mounted on copper baseplate and bonded to PCB contact pads



INRIM chip - detail of 25 μm dia. Al bonding wires

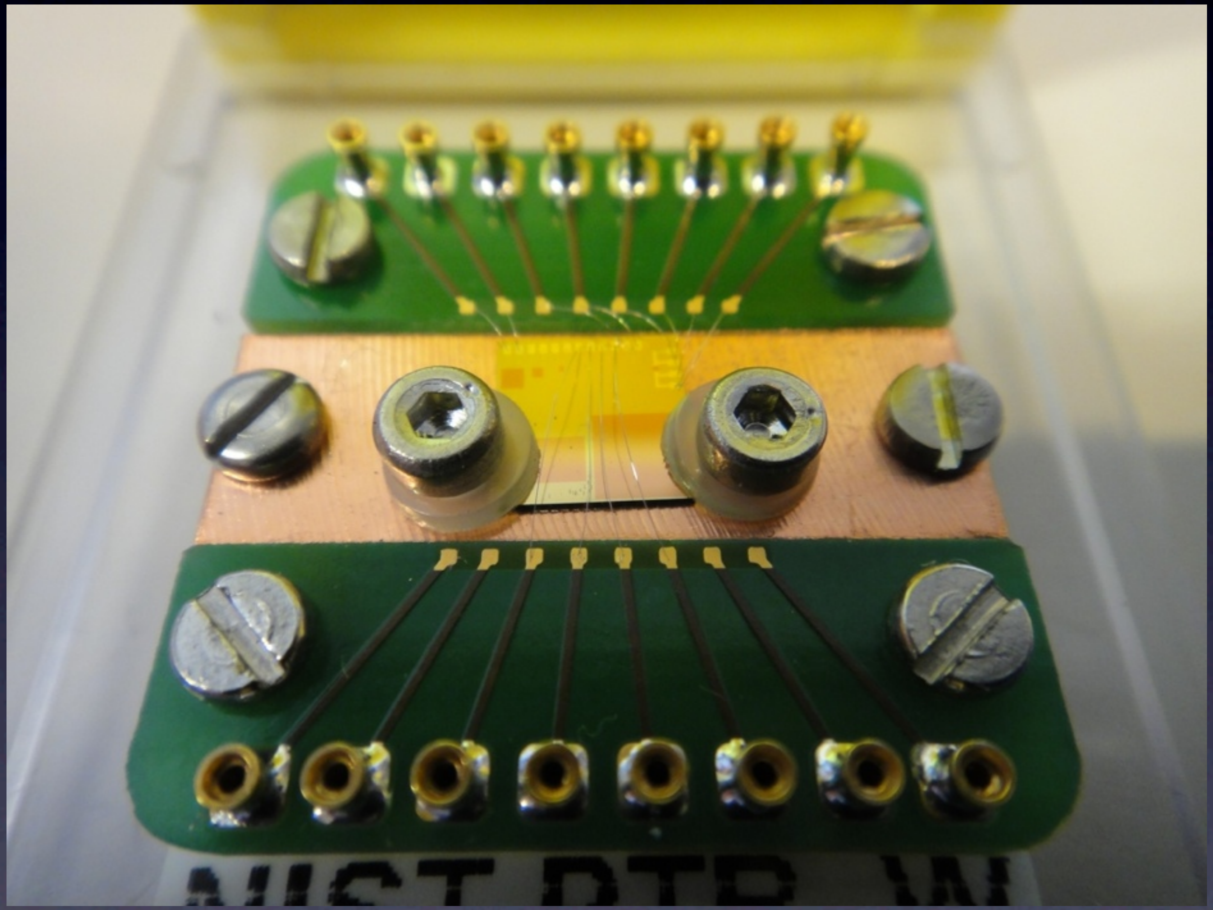
TES sensors from NIST

- W film TES from NIST - USA
- 6 single TES square pads with different sizes (doubling in size from 25 μm up tp 800 μm) plus test strip

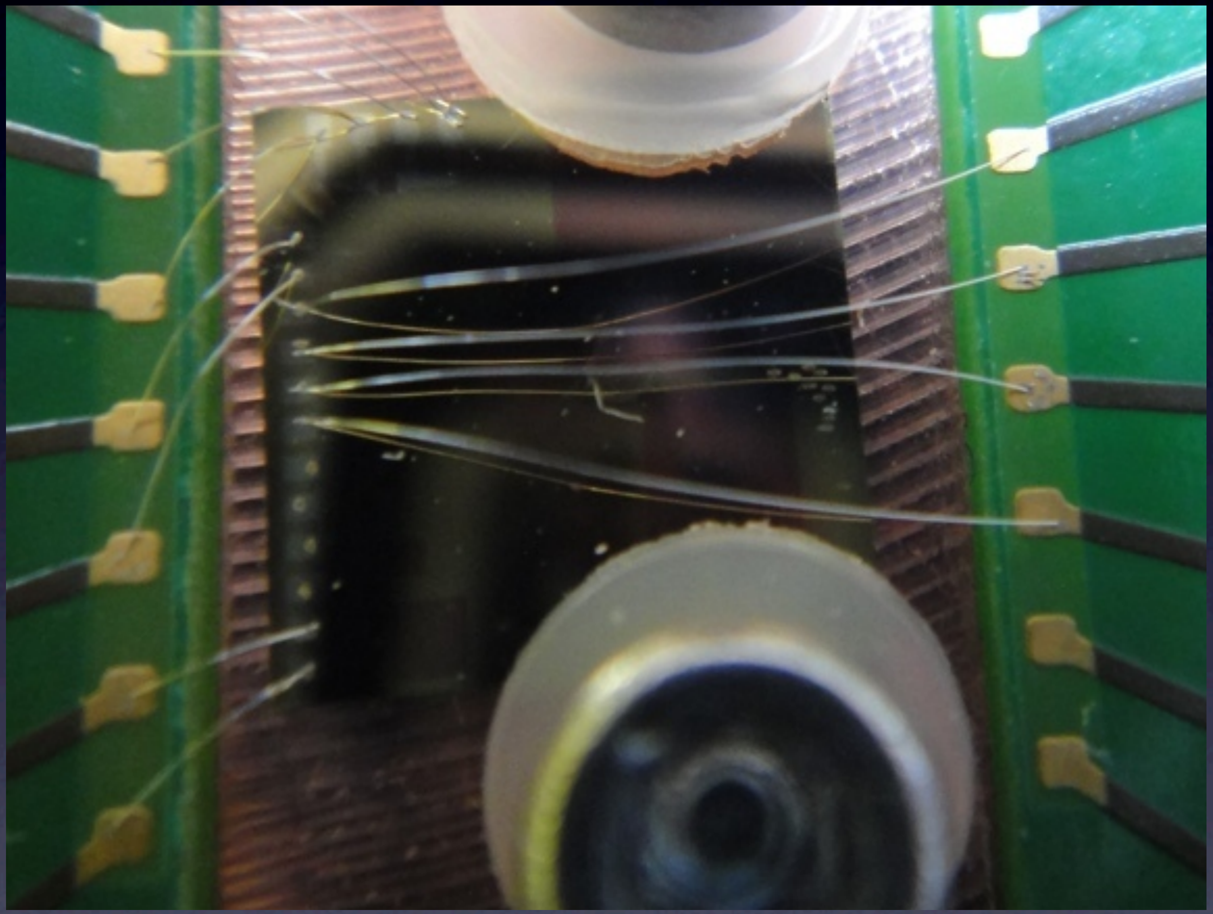


Picture of the NIST TES chip with bonding pads and test structures
Chip dimensions (6.24 mm)x(6.24 mm)

Mounted NIST TES

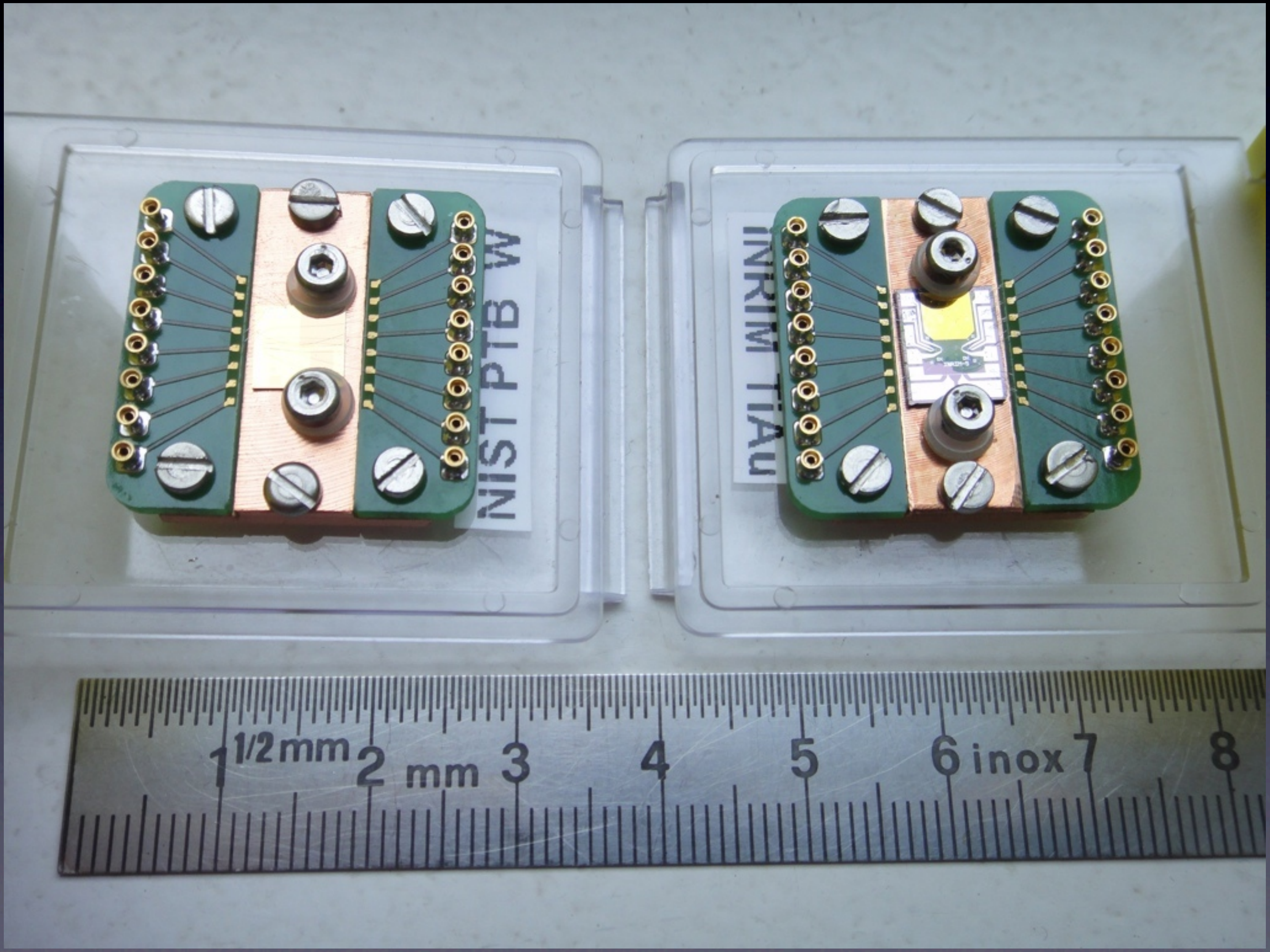


NIST chip mounted on copper baseplate and bonded to PCB contact pads



NIST chip - detail of 25 μm dia. Al bonding wires

Available sensors



INFN Genova TES

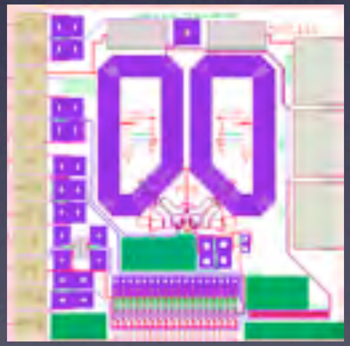
- Manufactured by INFN Genova, now under post production tests in Genova
- Not available to us yet , will be shortly (sorry no pictures!)
- Main characteristics
  - 30 nm thick Ir film with SiO_2 protective coating
  - single chip containing
    - single 10x12 μm^2 TES sensor optimized for low thermal capacity (faster response)
    - 10x10 array of 100 sensors, each 10x10 μm^2, to be biased in parallel and readout as a single device

Dilution refrigerator and SQUID amplifier

- A LHe dilution refrigerator capable of reaching 17 mK is being prepared for hosting TES measurements in the University of Camerino laboratories
  - copper holders with attached sensors are mounted on a cold finger to be inserted in the cryo-chamber
  - electrical connections are made
  - fiber optic coupling of the cryo-chamber to the outside is being prepared to allow photon counting tests using stray ambient light
- A SQUID amplifier chip with its associated electronics has been purchased from Magnicon and is being connected to act as the TES readout
- TES measurements will start in Camerino in mid July

Nb SQUID case and holder

SQUID chip schematic from MAGNICON



University of Camerino dilution refrigerator

TES testing schedule

- TES sensor tests at mK temperature will be carried out in Camerino in collaboration with the ALPS group from DESY starting mid-July
(Jan Dreyling-Eschweiler from ALPS is working at the tests in Camerino)
- Measurement draft agenda
  - SQUID preliminary check
  - Transition curve measurements
  - Stray light photon counting
  - Long background measurements
- We are now in the hands of the Gods ....

Boreas, Greek god of the cold ...

Detail of Boreas, the winged god of the north wind, from a painting depicting his pursuit of the Athenian princess Oreithyia. He is shown with winged shoulders and feet.

Future developments

- BaRBE @ CAST
  - put a TES visible detector on the BaRBE beamline at CAST
  - search for low energy solar ALPs and chameleons
    - TES sensors are at present limited by the small active area ➔ easily overcome in the 1-2 eV range using standard optical techniques
    - It is however desirable to move to higher energies
      - 100 eV to 1 keV (solar chameleons)
      - 4-10 keV ALPs detection at CAST, X-ray LSW experiments
      - move from visible to higher energy sensors
- BaRBE next
  - increase quantum effciency
  - move from visible to higher energy sensors
    - 100 eV to 1 keV or more
    - learn working with TES arrays
    - meet, if possible, the challenge of optics

BaRBE @ CAST

- Good news
  - optics already in place, a TES would occupy a free output of the BaRBE optical switch and share beamtime with the existing PMT
- Bad news
  - need ultracryogenic environment (LHe not enough!)
- However...
  - the Camerino dilution refrigerator could go to CERN for a short time for the initial measurements
  - for the longer term cooling solutions are commercially available
    - dilution refrigerators (needs LHe)
    - pulse-tube Adiabatic Demagnetization Refrigerators (no cryogenic fluids)

BaRBE next

- Quantum efficiency
  - anti-reflection coating on sensor surface
  - Fabry-Perot resonant micro-cavity
    - built with a suitable sequence of coatings
    - “traps” photons near the absorber and increases absorption probability
    - limits the sensor spectral response width
- Higher energy sensors
  - build a 100 eV (1 keV?) sensor by adjusting the film thickness and characteristics
  - test bare sensor vith UV or soft X-ray source (perhaps at a synchrotron)
  - study UV and X-ray optics

Conclusions

- Low background, single-photon detectors are essential components for laboratory-based searches (ex. ALPS) and valuable tools for observatories (ex. CAST)
- TES sensors can be applied at photon detection at several energies: mastering TES sensor operation and technology could impact directly on possible discoveries in particle physics and cosmology
- BaRBE, strongly supported by CAST and ALPS, is moving its first steps in this difficult territory. Goals:
  - TES sensor assembly, test and operation
  - sensor energy optimization
  - efficient coupling to the experimental environment