High-density arrays of x-ray microcalorimeters for Constellation-X

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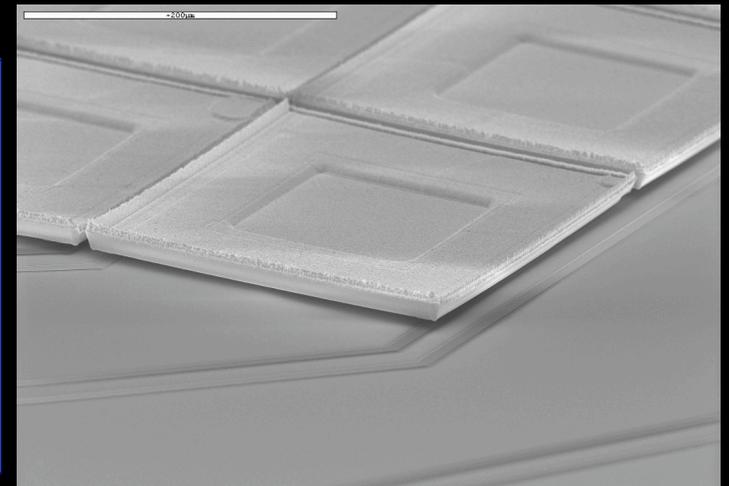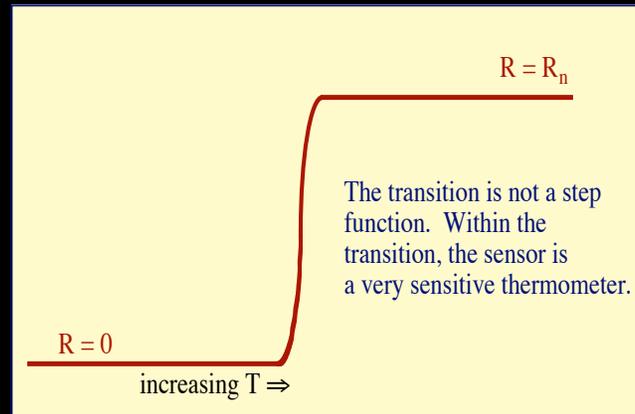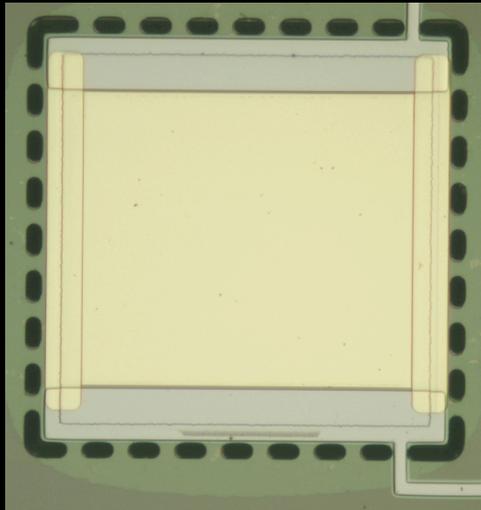
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Arrays of Superconducting Transition-Edge Sensors

- Superconducting thermometer: stable operation in the transition via electrothermal feedback
- Use Mo/Au bilayers for $T_c \sim 0.1$ K
- Si and Si-N used as structural materials
- Arrays are fabricated at the highest level of integration
- Read out with SQUID amplifiers

$R = R_n$

The transition is not a step function. Within the transition, the sensor is a very sensitive thermometer.

$R = 0$

increasing T $\Rightarrow$

X-ray Calorimeter Principals

- **Three basic components**
  - Thermalizing x-ray absorber
  - Thermometer
 - Thermal link to heat sink
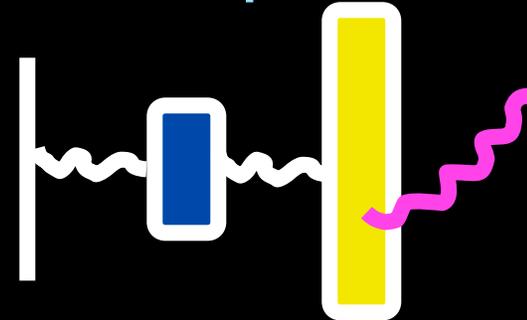
- **Link between absorber and thermometer can be a fourth important component**
  - Can mask the effects of position dependent thermalization in the absorber
  - Rolls off high-frequency input response and adds thermal fluctuation noise
    - Noise from a decoupled absorber is a particular concern for TES's because these tend to be high α devices with most the the heat capacity in the absorber
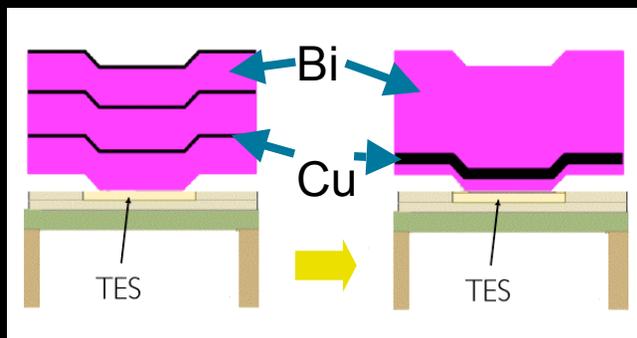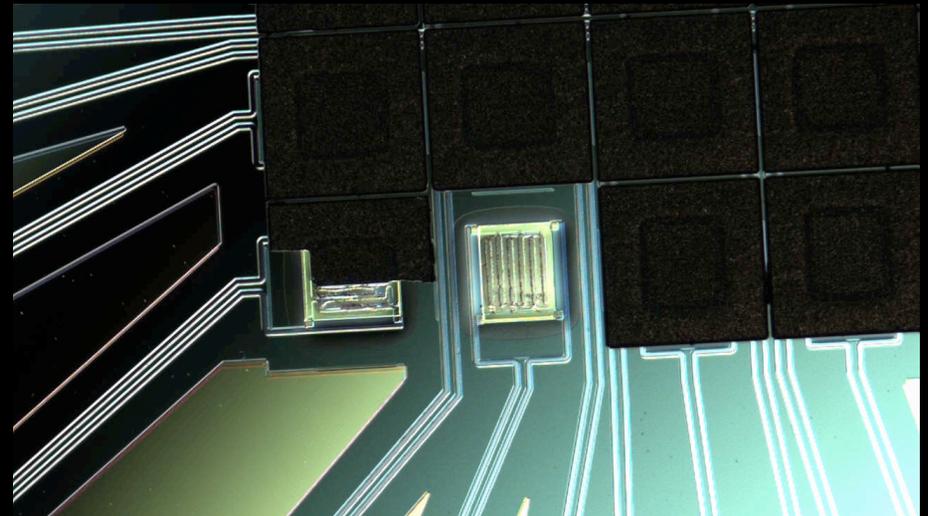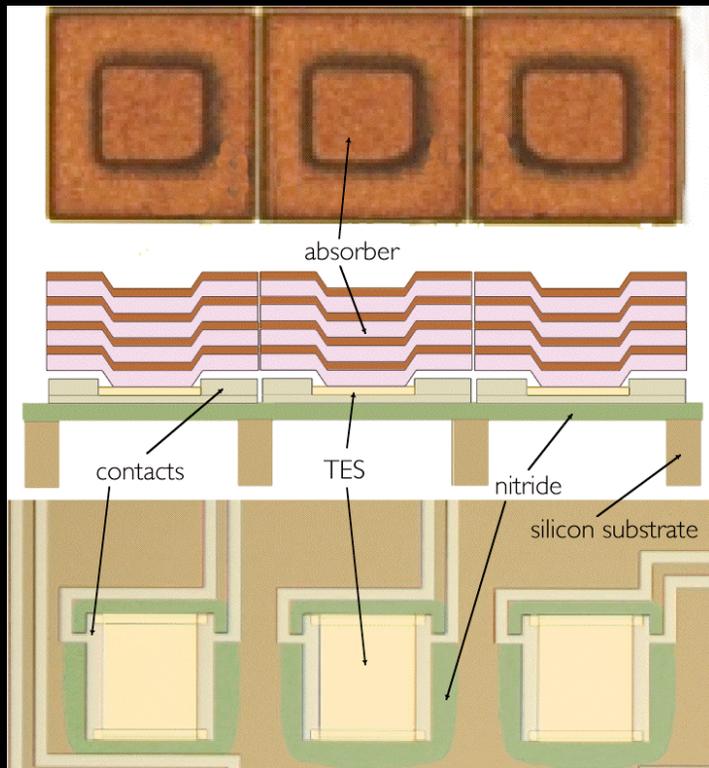
- **Thus the link between the absorber and the thermometer must be tuned to the absorber thermalization time**
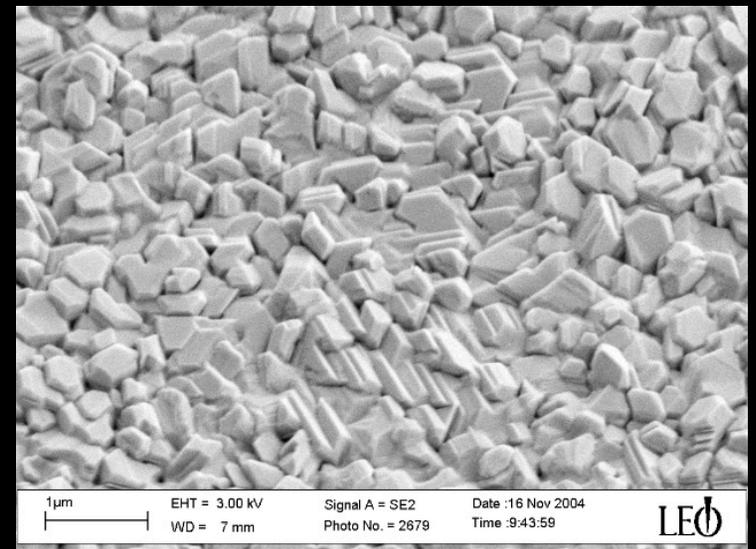
Standard 8x8 arrays
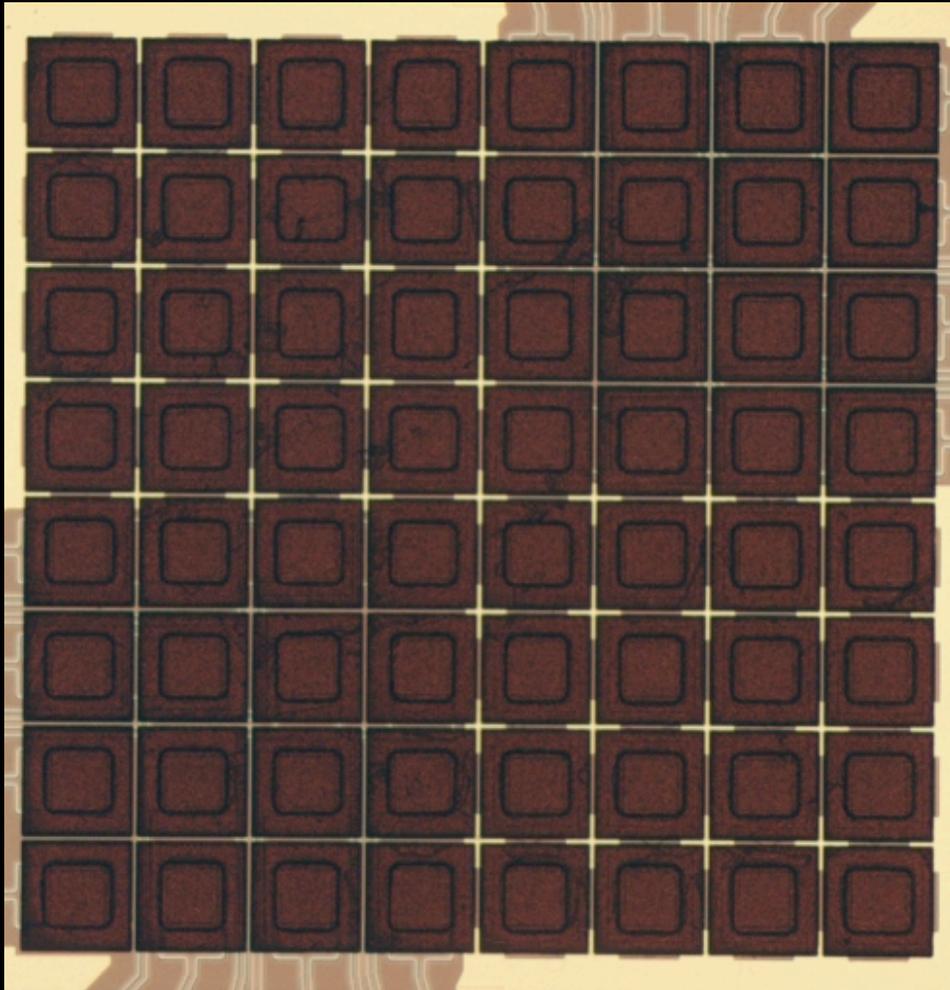
- Mo/Au TES
  - Electron-beam deposited
  - $T_c \sim 0.1$ K
- Bi/Cu absorber
  - High Z semi-metal
  - Normal metal to tune C and aid thermalization
- Matched to Constellation-X reference design
  - 0.25 mm pitch
  - 92% fill factor
  - 95% QE at 6 keV
- Pulse fall times typically several 0.1 ms
  - Depending on where in the transition biased
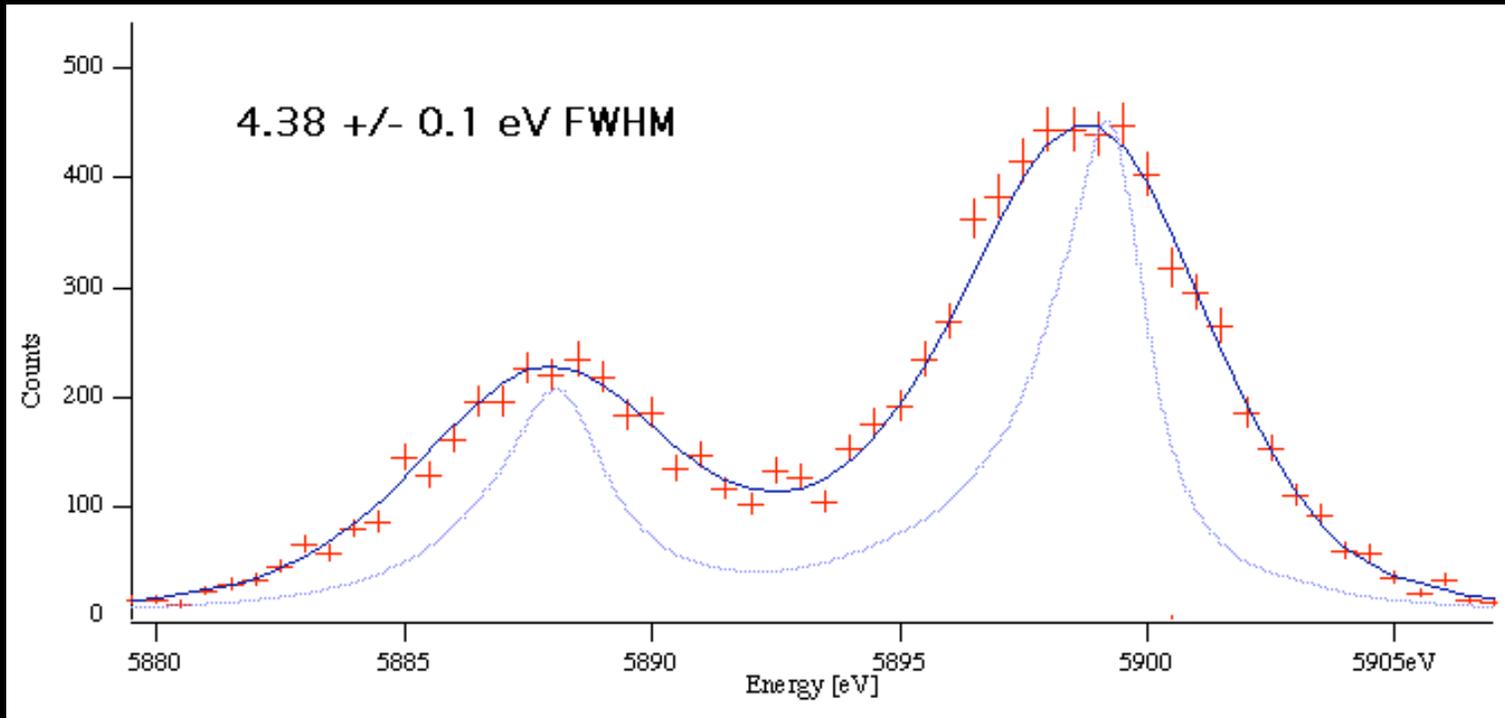
Array components

absorber
contacts TES nitride
silicon substrate

Bi
Cu
TES → TES

0.6 microns Cu
6.5 microns Bi

1μm   EHT = 3.00 kV   Signal A = SE2   Date :16 Nov 2004
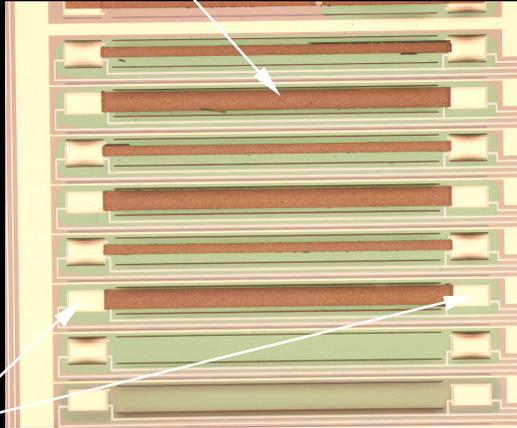   WD = 7 mm   Photo No. = 2679 Time :9:43:59   LEO

Performance

- 4 - 5 eV resolution at 6 keV was measured on several different pixels, on several different 8x8 arrays, on the first wafer after absorber redesign that redistributed the Cu into one thick layer instead of three or four thinner layers

Diffusion studies

Bi or Bi/Cu strip on nitride

TES

- Resolution predicted from signal and noise typically better than actual linewidth. How much of the broadening is due to the absorber?

- Is the Cu sufficient to allow this grainy Bi to thermalize?

- We have used absorber strips between TES sensors, combined with diffusion modeling, to determine the diffusivity of our absorber material. We have determined a diffusion constant of 2-4x10^4 μm^2/μs.

- Wiedemann-Franz scaling from electrical resistivity in another sample implied 2x10^4 μm^2/μs.

- Is this good enough?

Diffusion studies

- Numerically solved the diffusion equation for the geometry of a pixel
- Generated pulses for a grid of positions across the absorber
- Created a template pulse from averaging all the individual pulses.
- Used the template pulse and the theoretical noise response to construct an optimal digital filter
- Determined the estimated energy as a function of position
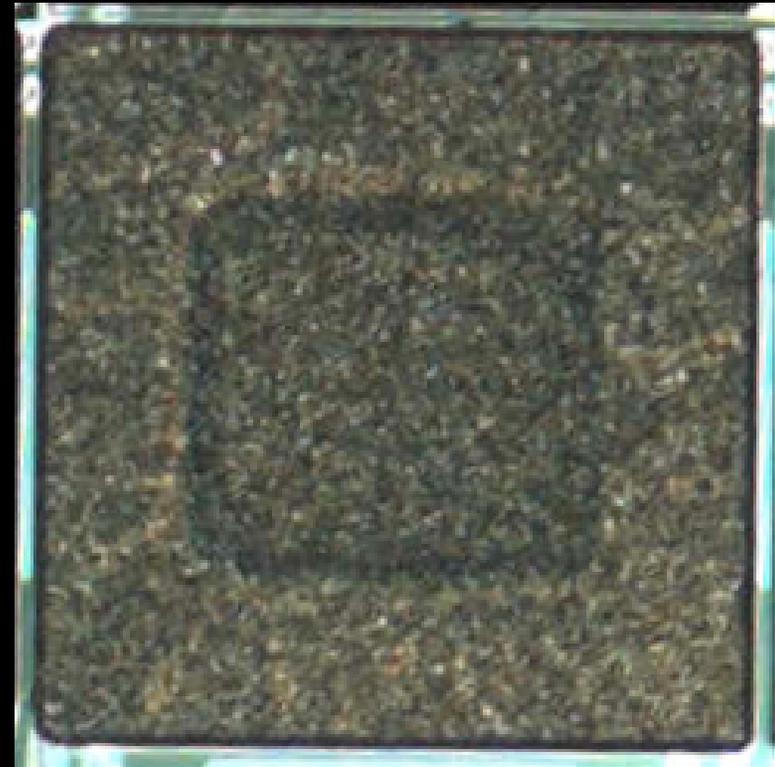
  - 2/3 of absorber area is in the overhang

Diffusion studies
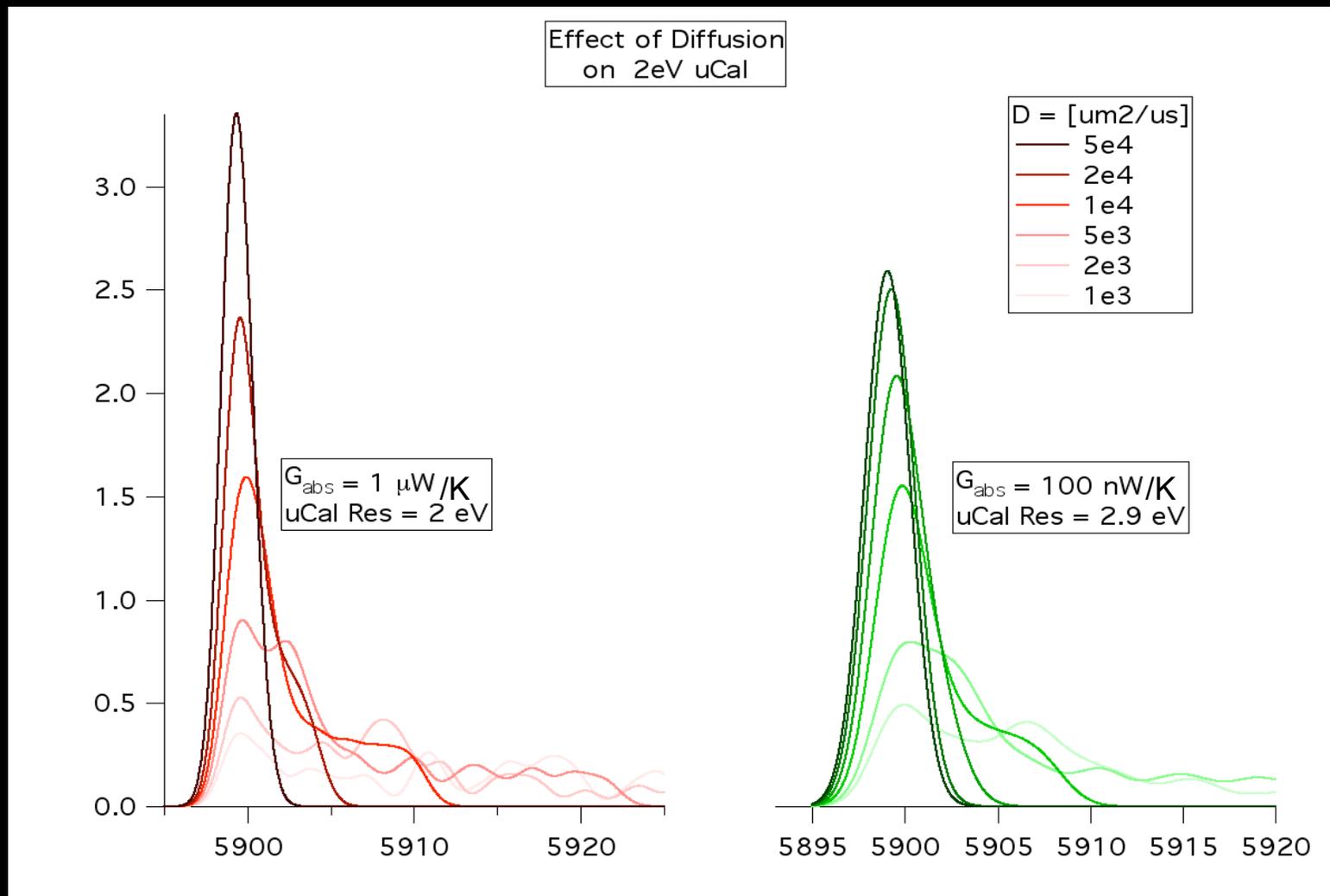
Interface issues

- Subsequent wafers did not match the 4 - 5 eV performance

- Formation of BiAu intermetallics at the interface or diffusion of Cu through the Bi and into the Au of the TES altered the superconducting transition in an uncontrollable manner
    - Good devices were immune to such interface chemistry, even when subsequently annealed

- Because of the variable nature of the phenomenon, we investigated designs that would prohibit damage to the critical interface

Barriers at the interface

- ## Ge
  - Compatible with Bi to > 120 °C, but not with Au

- ## Mo
  - Compatible with Bi and Au. E-beam tends to put down normal-conducting film if substrate not heated, but actual T_c (and its impact on the underlying TES) so far too hard to control

- ## Metallic and dielectric barriers under consideration

- ## Insulating films not necessarily bad
  - Open holes to normal-conducting (non-sensing) regions of the TES
    - Extreme case: insulator is VACUUM
  - Or phonon connection between metals with good e-ph coupling

Vacuum gaps

- Absorber makes contact only at normal-metal features or out on the membrane (for support)

- Contacts placed to avoid diverting current away from the sensor

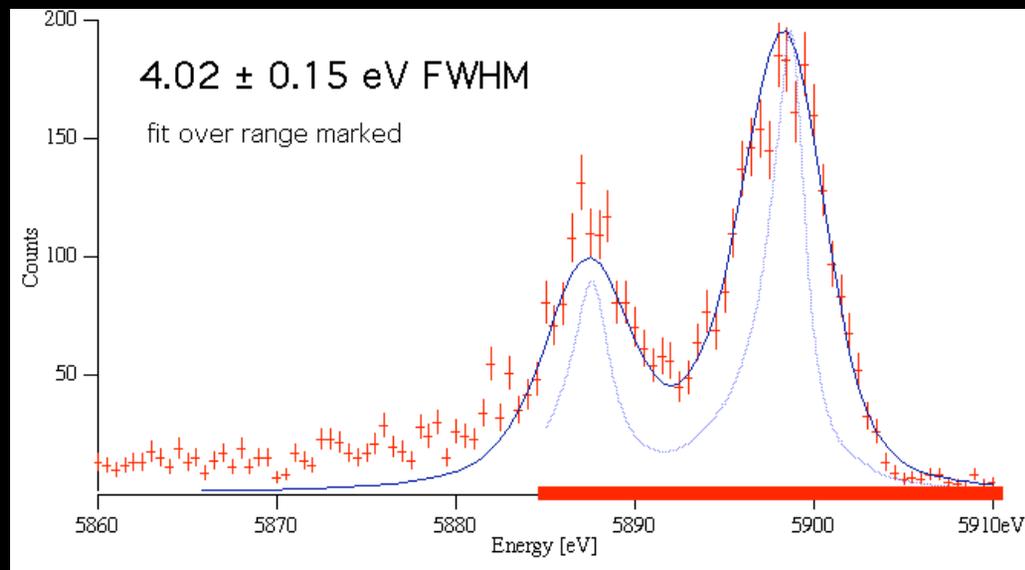- Permits deposition of good thermalizing layer first
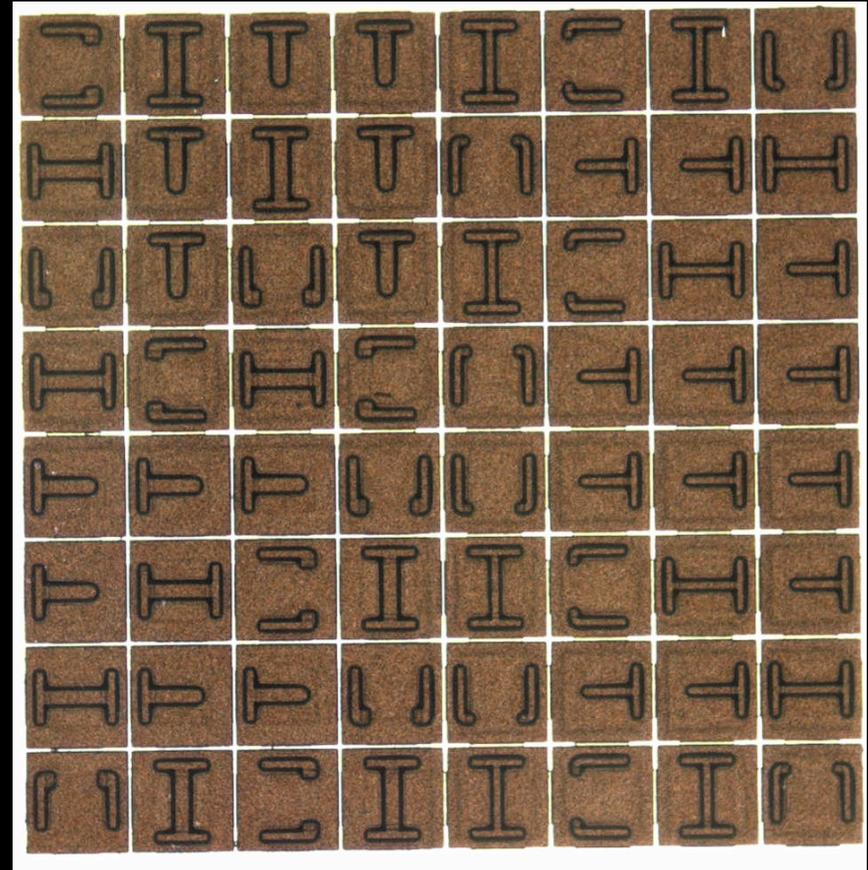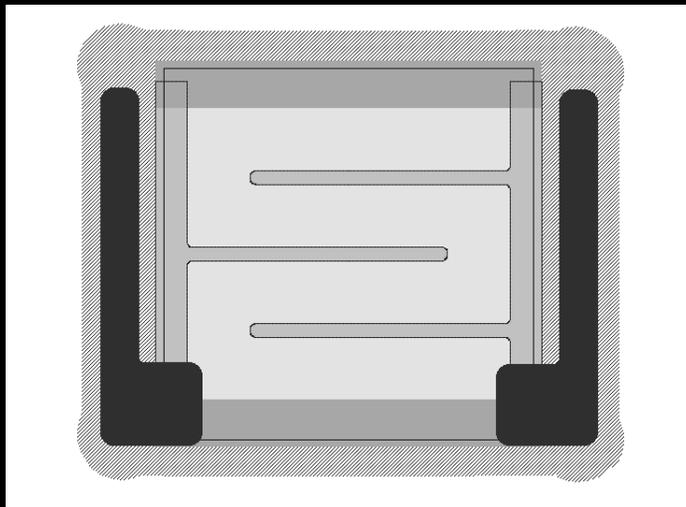
Au/Bi
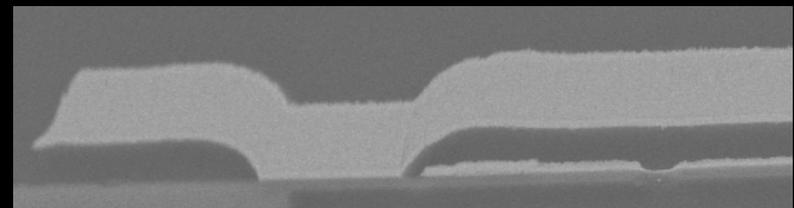
Au/Bi results ("T" and "H" designs)

- ## Three devices with 4.0 - 4.5 eV resolution at 6 keV
  - ~15% of the counts in a low-energy shoulder
    - In both designs, so not consistent with loss to the membrane
    - Still being studied; application of diffusion model should help
      - Electrical conductivity factor of 2 higher than Bi/Cu/Bi devices
      - But extent of cantilevered regions much greater
  - $G(0.1) = 1.9 \times 10^{-10}$ W/K
    - In range obtained for conventional design

4.02 ± 0.15 eV FWHM

fit over range marked

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Electroplated Gold Absorbers

- 0.2-micron evaporated Au seed layer and 4-micron electroplate

- Factor of 4 higher heat capacity than other designs
  - May be offset by simpler and better behaved system

- Testing for the first time this week!
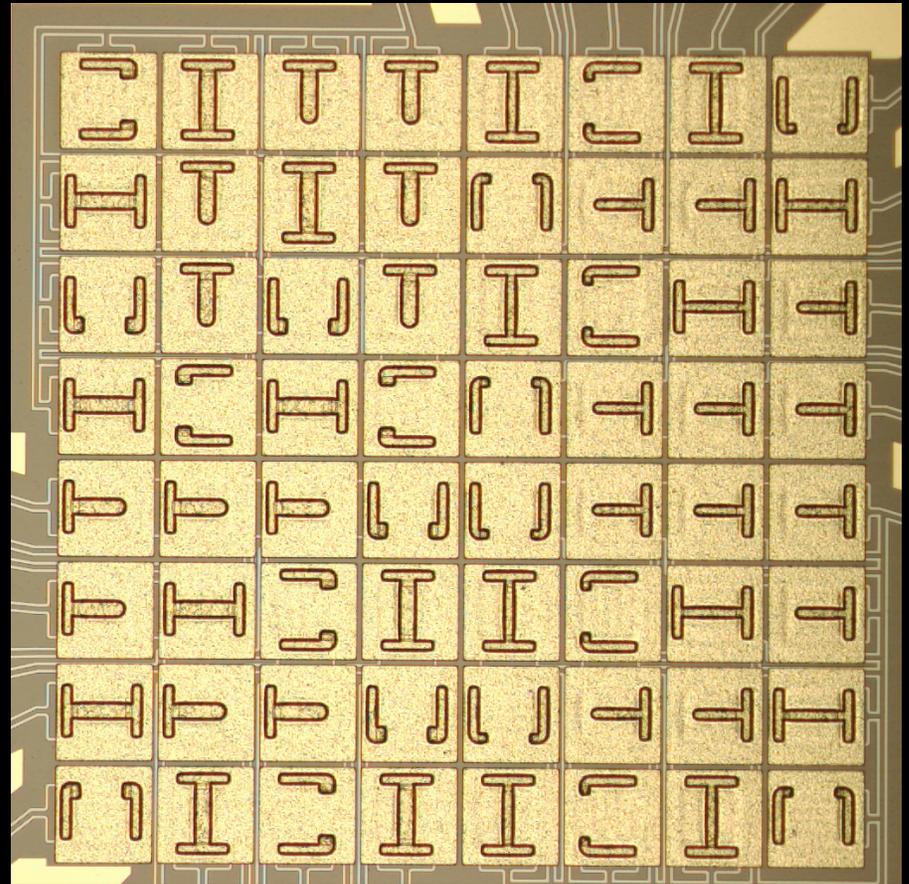
Next steps

- Through variations of new absorber design (including solid-Au), address low-energy shoulder in "vacuum gap" design
  - Characterize and optimize contact conductance and placement

- Resume barrier layer studies

- Optimize for reproducibility, robustness, uniformity, as well as best-achievable resolution and speed

- Constellation-X XMS requirement in a "flight-like" design now in our grasp