Development of large-scale magnetic calorimeter arrays

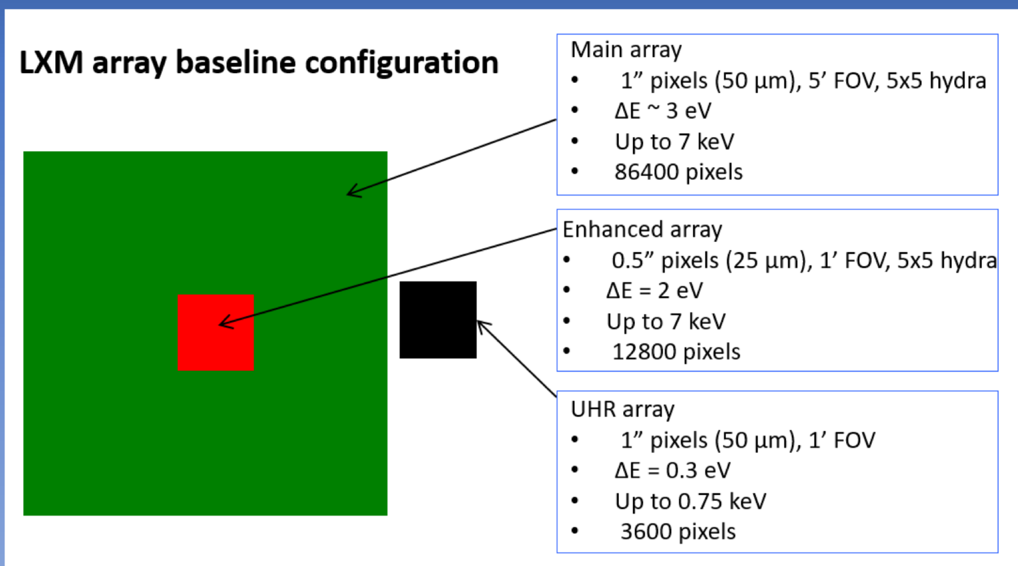
Thomas R. Stevenson[1], Manuel A. Balvin[1], Simon R. Bandler[1], Archana M. Devasia[1,2], Peter C. Nagler[1], Kevin Ryu[3], Stephen J. Smith[1,2], and Wonsik Yoon[1,4]

[1]NASA Goddard Space Flight Center, [2]CRESST, University of Maryland, Baltimore County,

[3]Lincoln Laboratory, Massachusetts Institute of Technology, [4]Science Systems and Applications Inc.

Introduction and Motivation

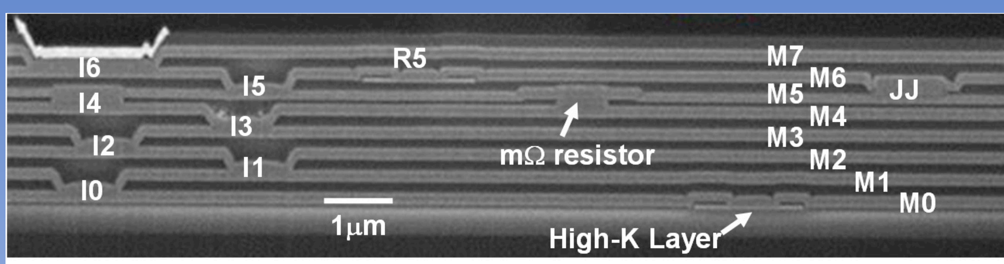
- Metallic magnetic calorimeters (MMCs) use paramagnetic sensors such as Au:Er to detect temperature changes produced by absorption of X-rays
- MMC is a potential sensor technology for the Lynx X-ray Microcalorimeter (LXM) on the Lynx mission concept



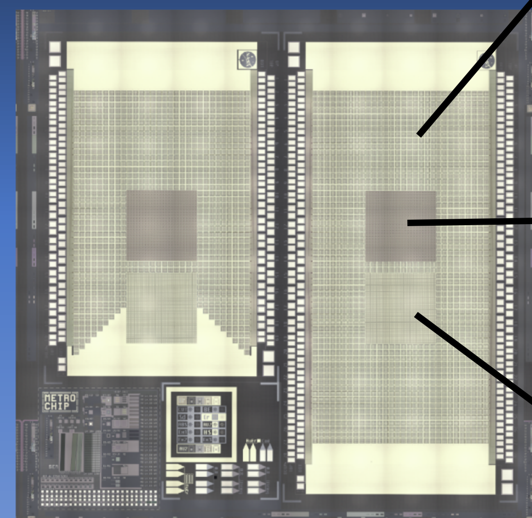
- As array size increases
  - Stray inductance of wiring increases
    - between pixels & fanout to amplifiers
  - Routing of wiring between pixels and readout challenging due to requirements of low inductance, low crosstalk, high critical currents & high yield
- MMCs can be scaled to large array sizes by,
  - Maximizing the sensor inductance by decreasing sensor meander coil pitch
  - Maximizing the magnetic coupling by scaling the sensor & insulator thicknesses with pitch
  - Maintaining the Nb thickness with pitch in order to keep sufficient critical current
- Buried layers can be used to achieve large scale, high density wiring
  - Well suited for connecting thousands of pixels on large focal plane to readout chips with high yield
  - Planarization allows use of top surface of wafer exclusively for pixels & heat sinking
    - allows new pixel geometries
  - Alleviates crosstalk

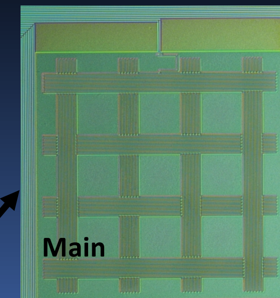
Fabrication of high sensor inductance MMC arrays with buried wiring

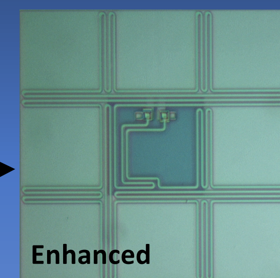
- Buried wiring & sensor meander coil layers
  - Nb deposition by dc magnetron sputtering
  - Nb patterning by DUV (248 nm) and plasma etch
  - SiO_2 ILD deposition by PECVD
  - CMP of ILD to desired thickness
  - ILD patterning by DUV lithography and plasma etch
- Au:Er deposition by sputtering & patterning by lift-off
- Thermalization Au deposition by e-beam evaporation
- Au heat sink deposition by e-beam evaporation
- Stems electroplated through photoresist mold on Au seed layer
- Absorbers electroplating and etch by ion milling

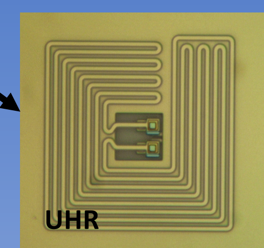


Die layout of prototype MMC LXM array



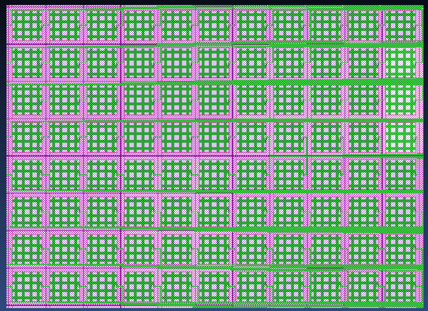






- 22 mm x 22 mm reticle consists of 2 chips, different sizes
- Each chip comprises of Main array, Enhanced array and UHR array with ***4 buried Nb layers***
- Larger chip consists of ***55,800 pixels, 5688 sensors***

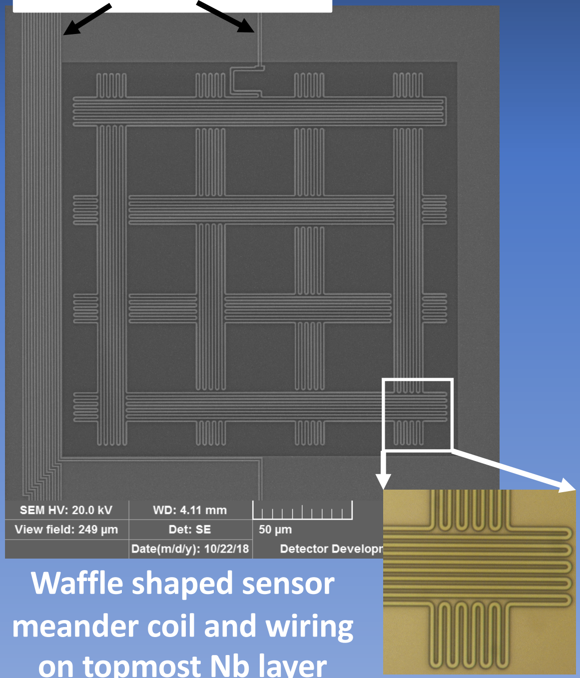
Components of Main Array



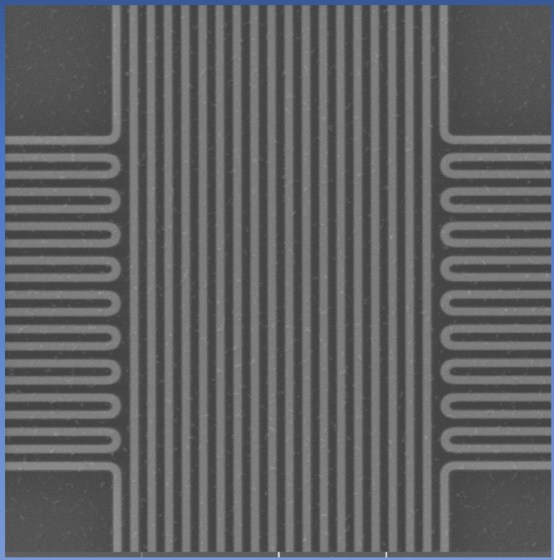
Main array

Main Array

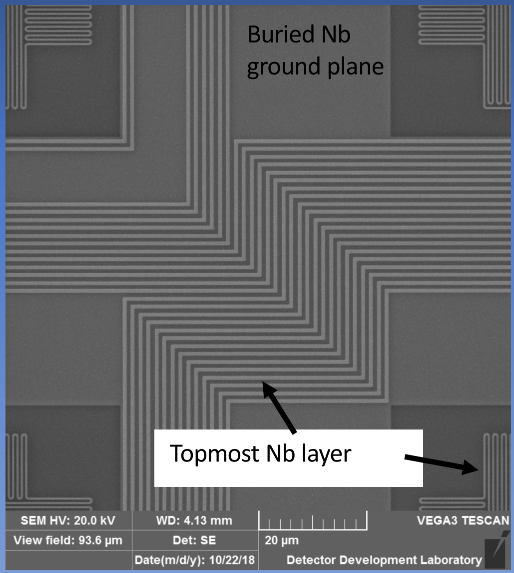
- 60 x 30 sensor array with waffle shaped, multi absorber sensors (5 x 5 Hydra)
- Sensor meander coils and twin microstrip wiring are both patterned on topmost Nb layer



Waffle shaped sensor meander coil and wiring on topmost Nb layer

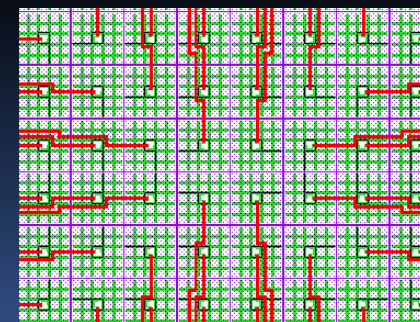


0.8 µm pitch Nb meander coil (1.2 and 1.6 µm pitch also used)



Main array twin microstrip wiring patterned on topmost Nb layer runs over a buried Nb ground plane layer

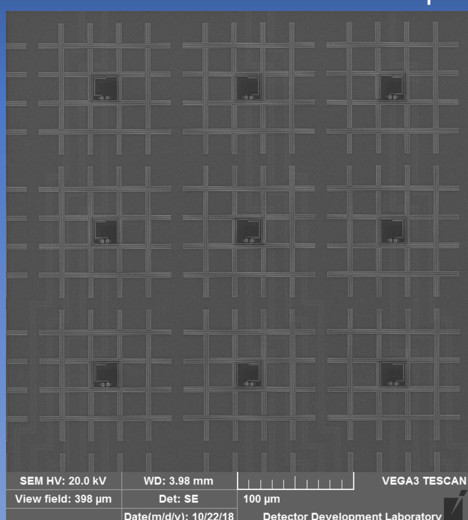
Components of Enhanced Array



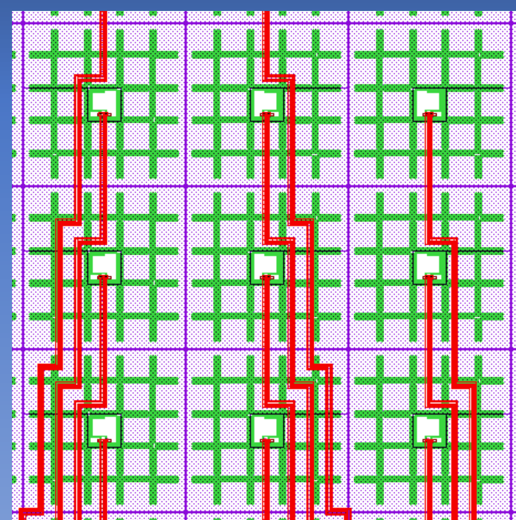
Enhanced array

Enhanced Array

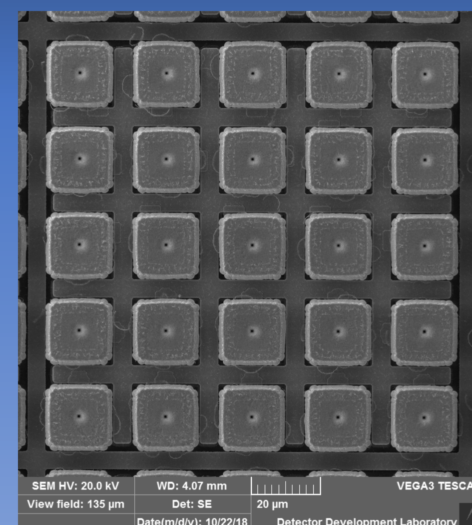
- 24 x 24 sensor array with waffle shaped sensor in a 5 x 5 Hydra configuration
- Sensor meander coils patterned on topmost Nb layer are connected through superconducting vias to twin microstrip wiring on bottom-most Nb layer
- Using multiple layers of buried wiring, the twin microstrip wiring is laid out on bottom-most Nb layer on a relaxed pitch, without the need for aggressively packing it on the top most Nb layer. This reduces crosstalk between pixels.



Sensor meander coils on top most Nb layer

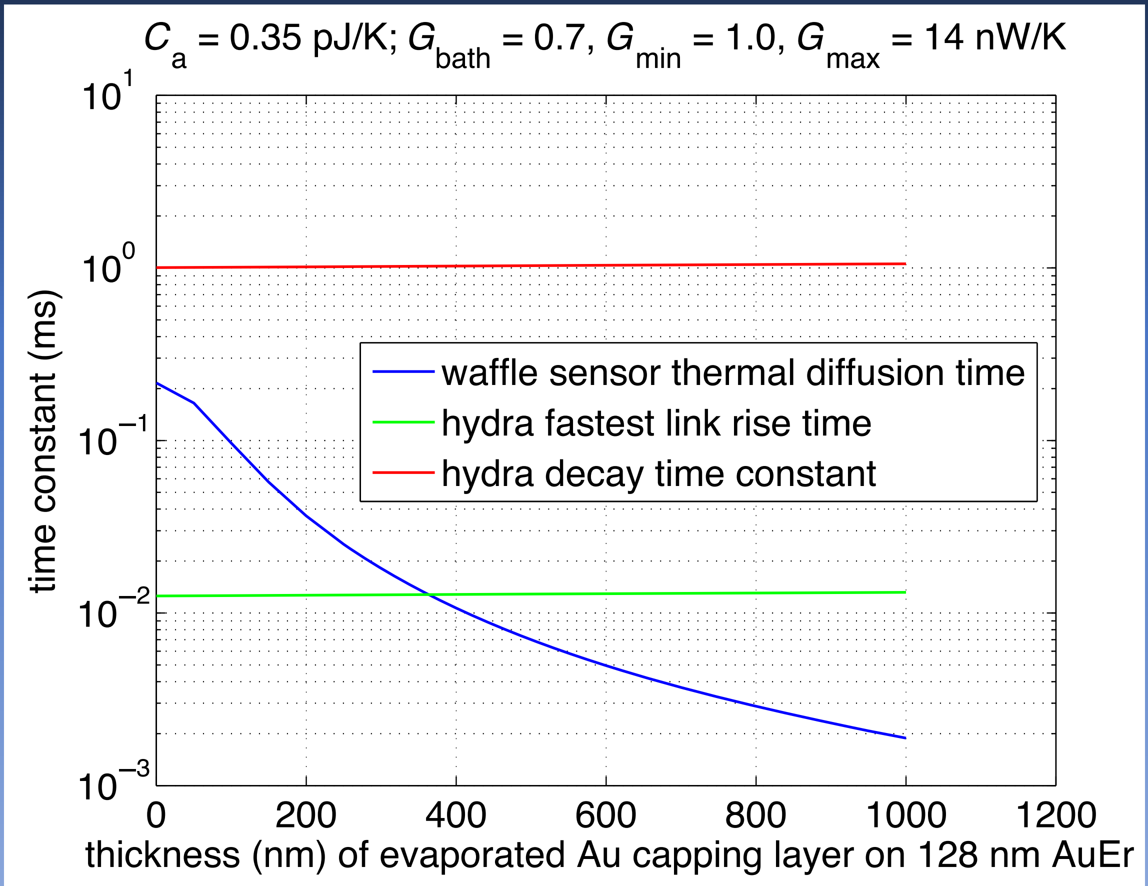


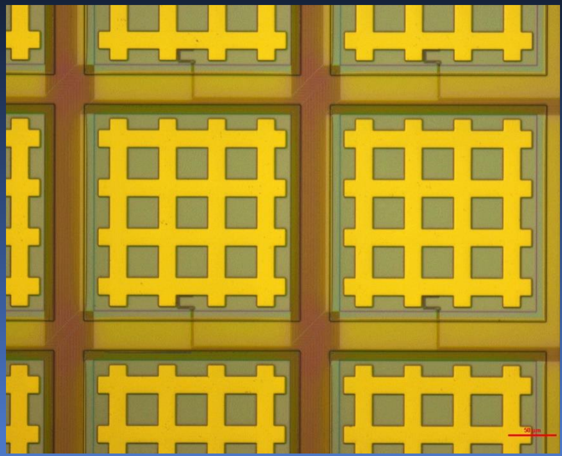
Top Nb sensor meander layer (green) is connected through two intermediate metal layers to bottom wiring layer (red)



125 µm x 125 µm sized composite Hydra absorber partitioned into a 5 x 5 array

Thermalization of Au-Er "Waffle"





- Thermal diffusion time across Au:Er main array waffle sensor as a function of thickness of Au capping layer

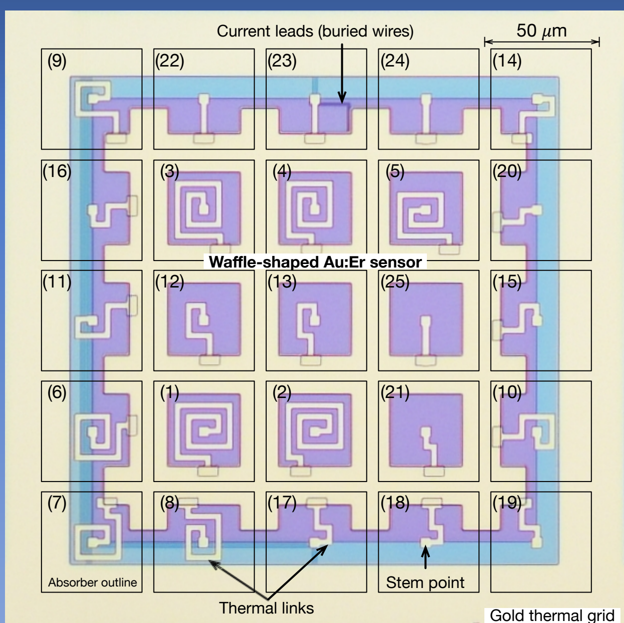
  - added to speed thermalization.

- Thermal diffusion time (curve) is sufficiently fast compared with fastest expected hydra pulse rise time and overall hydra decay time constant

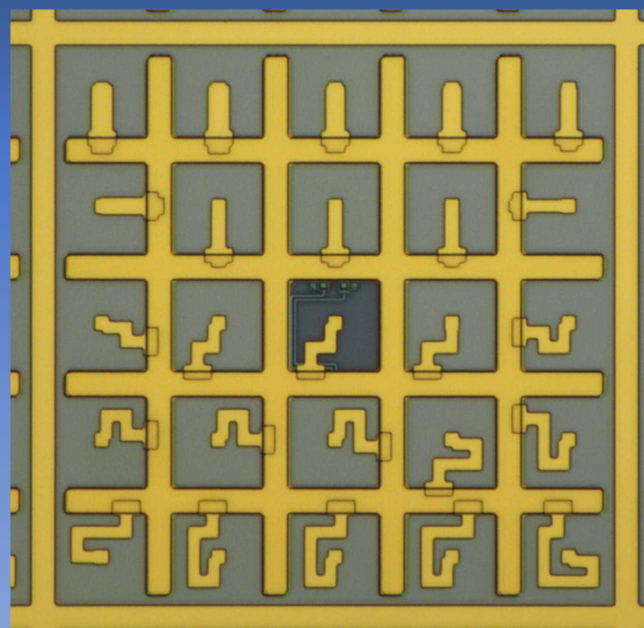
- 600 nm added does not significant affect total heat capacity

Thermal multiplexing with hydra links

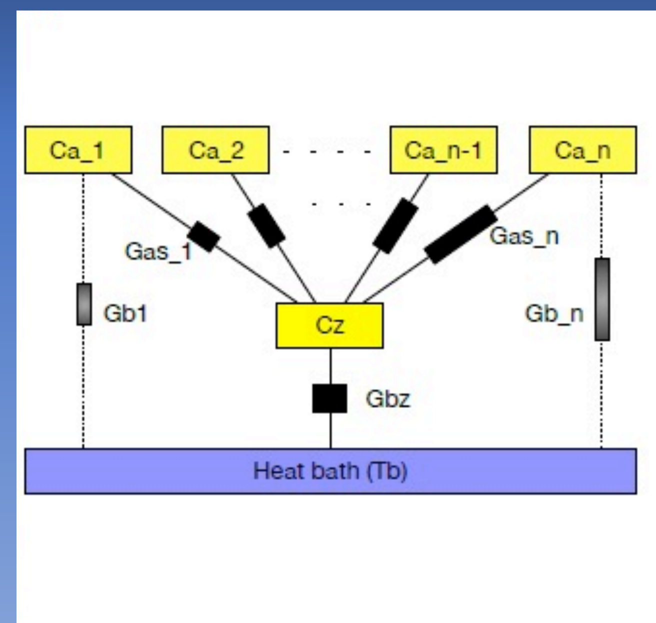
- Hydra design of Main and Enhanced Main Arrays allows 25 different pixels read out by single sensor
  - Achieved by coupling 25 absorbers in 5 x 5 configuration to single sensor through Au thermal (hydra) links of varied thermal conductance
  - Thermal conductance is varied by maintaining the same film thickness but varying the geometry (length) of the link



Arrangement of Main array hydra links.

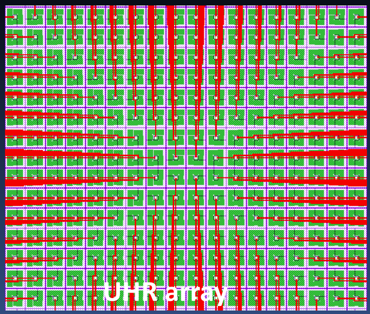


Arrangement of Enhanced Main Array hydra links.

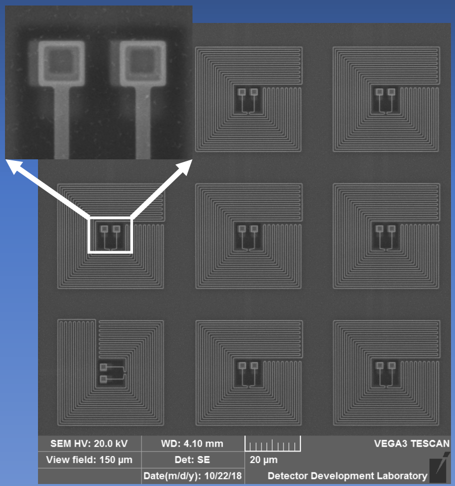


Schematic diagram of hydra device

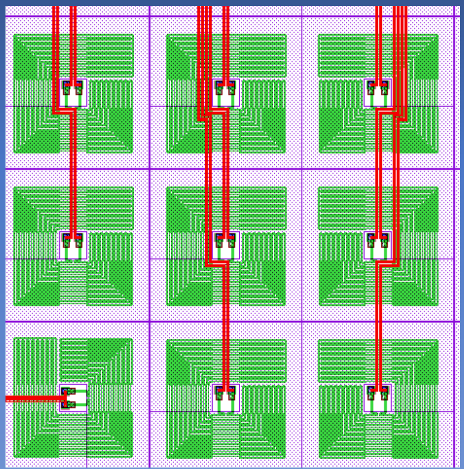
Components of UHR array



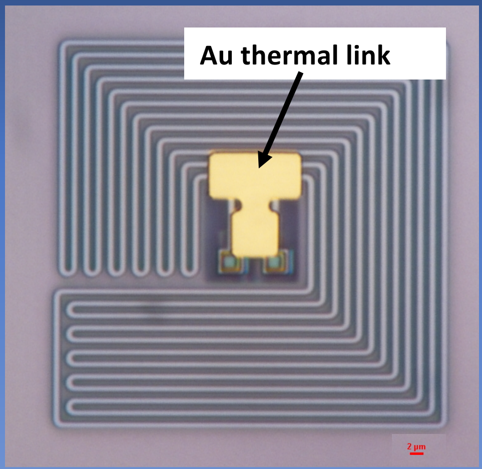
- 60 x 60 sensor array with a square annulus shaped sensor



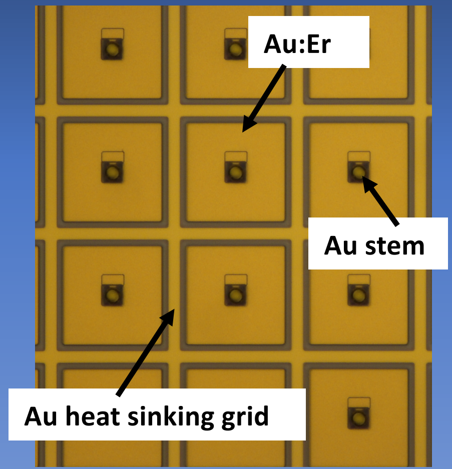
Array of sensor meander coils on topmost Nb layer. Superconducting vias located at center of meander coil connect coil to wiring



Top Nb sensor meander layer (green) is connected through two intermediate metal layers to bottom twin microstrip wiring layer (red)

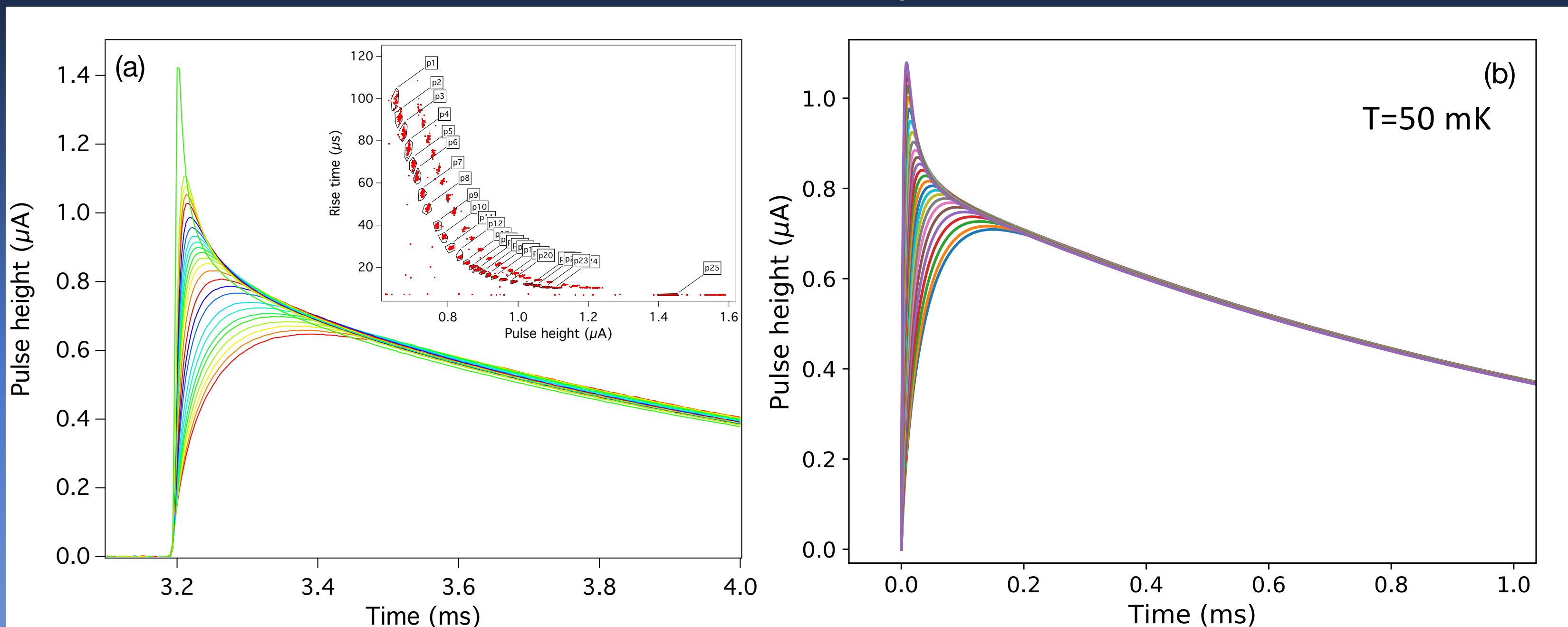


To control size of slew rate at readout a Au thermal link connects sensor to absorber stem



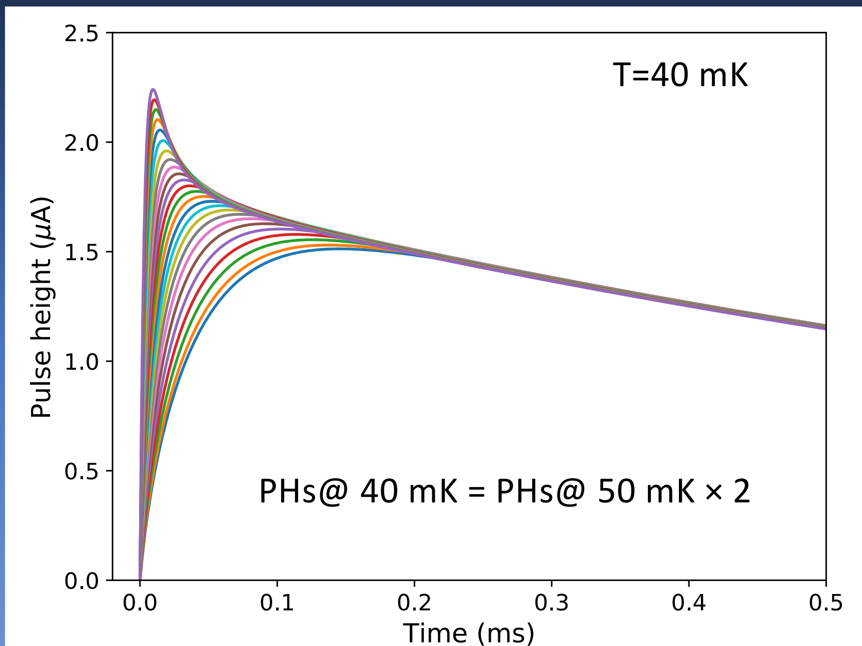
Pixels with absorbers uncovered

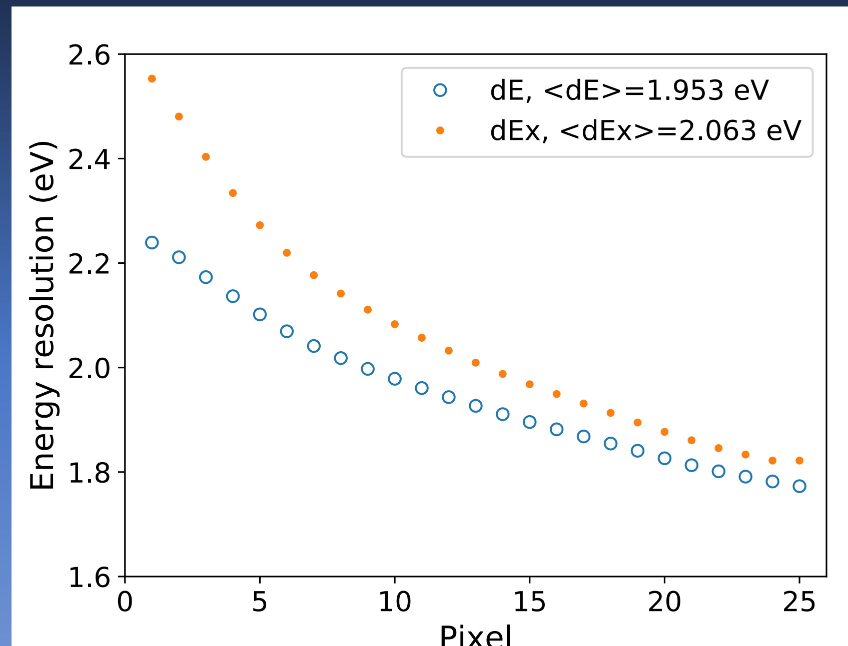
MMC results (Main array)



- (a) measured and (b) modeled pulse-shape of Main array MMC Hydra with 25 absorbers at 50 mK
  - 25 different pulse shapes are clearly separated by means of rise-time and pulse height
  - MMCs have high heat-capacity sensor, no need to add heat capacity to sensor for read-out optimization.
- Expected energy resolution based on signal and noise measurements: 2.8 – 3.7 eV for 6 keV @ 50 mK
  ➔Simulation results: 3.2 – 3.8 eV FWHM

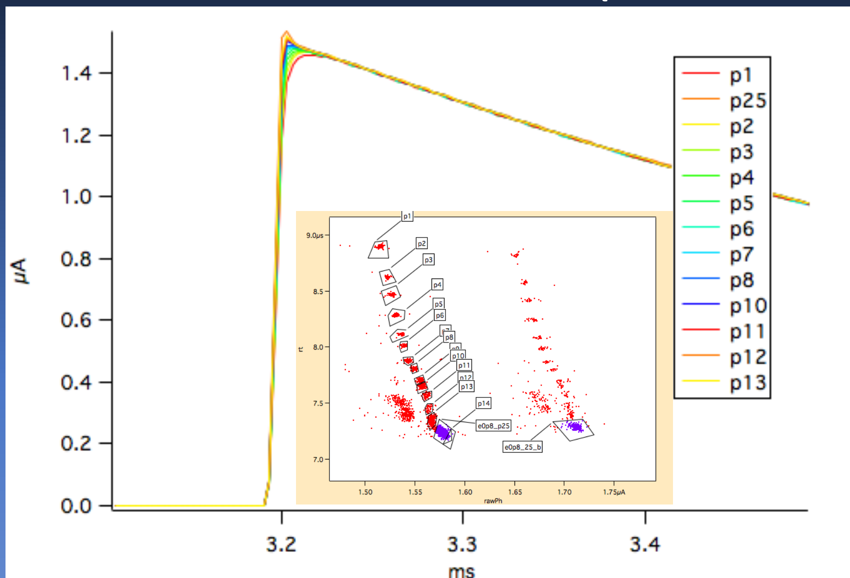
Modeling result (Main array)

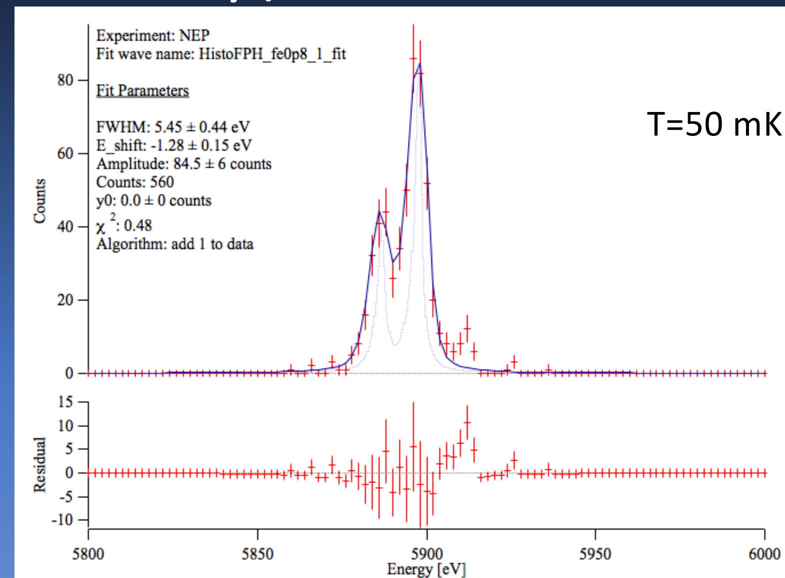




- Modeled FWHM energy resolution of Main array MMC Hydra with 0.8 μm pitch meander coil with optimized read-out
  - *dE* is energy resolution without errors in position correlation
  - *dEx* includes the effect of uncertainty in determining the pixel location that X-ray hit at 200 eV
- For X-ray energy larger than 200 eV, the position error converges to zero, *dEx* approaches *dE*

MMC results (Enhanced array)





- X-ray pulse data for Enhanced Array Hydra with 25 absorbers at 50 mK
    - Only 13 of 25 different pulse shapes were clearly separated by means of rise-time and pulse height
    - Hydra thermal links were fabricated with higher thermal conductance range than optimized design
    - Thermal and electrical cross-talk effects were worsened by experimental details: need to float heatsinking grid, lack of x-ray mask over ballast inductor, and use of relatively high x-ray flux
- Expected energy resolution based on signal and noise measurements: 2.0 eV for 6 keV @ 50 mK
- Measured energy resolution from pulse histogram: 5.5 ± 0.4 eV @ 50 mK

Experimental performance of pixel types

- Cooling system limited temperature of operation to 50 mK instead of 40 mK as designed
  - Performance worse by about a factor of 1.2.
- Each sensor not coupled to optimized SQUID (input inductance lower than optimum for design)
  - Performance worse by about a factor of 1.6.

- Main Array performance Integrated NEP @ 50 mK
  - 0.8 um pitch : 2.8 – 3.7 eV
  - 1.2 um pitch : 3.0 – 4.0 eV
  - 1.6 um pitch : 4.1 – 5.8 eV
  - $\Rightarrow$ < 3 eV is achievable, even before incorporating sandwich design and improving noise.

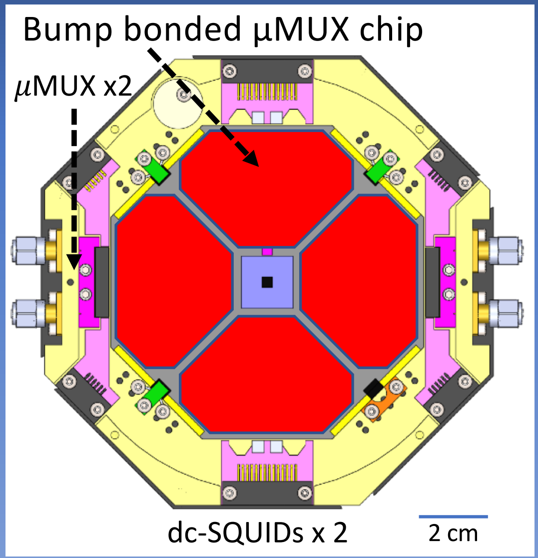
- Enhanced Main Array performance Integrated NEP @ 50 mK
  - 0.8 um pitch : 1.96 – 1.99 eV
  - 1.2 um pitch : not available
  - 1.6 um pitch : 6.3 – 6.4 eV
  - $\Rightarrow$ < 2 eV is achievable, even before incorporating sandwich design and improving noise.

- Ultra-Hi-Res performance Integrated NEP
  - 0.8 um pitch : 4.8 eV – even more highly unoptimized – needs “flux transformer”.

Summary and plans

- Demonstrated large-scale, multilevel wiring to MMC sensors with high yield and high critical current.
- Demonstrated fine-pitch MMC meander coils with high inductance suitable for large arrays.
- Demonstrated the 25-pixel position-sensitive Hydra detector.
  - 25-pulse shapes are clearly separated and pulse heights agree well with the modeling
- Estimated energy resolution (NEP): 2.8-3.7 eV for 6 keV @ 50 mK.
- Modeling result for the Main array assuming SQUIDs with optimal input inductance:
  - 1.8 – 2.3 eV FWHM at 40 mK
- Next generation of MMC Arrays currently being designed

- New MMC arrays:
  1. A full-size LXM MMC array with all pixels wired out on a full-size support wafer
     - Requires "stitching" small-field (highest feature resolution) & large-field (for wiring out to read-out) mask-sets.
  2. New MMC "sandwich" geometries to improve coupling of sensor to pick-up coil – will improve energy resolution performance of all pixel types!
  3. Integration of "flux-transformers" to optimize performance of MMC UHR pixels.
  4. Allows testing of bump-bond connections to microwave read-out
     - as well as wire-bonds to current dc SQUIDs.



Package for testing full size arrays with dc and microwave readout SQUIDs