# Magnetic Calorimeter Arrays with High Sensor Inductance and Dense Wiring

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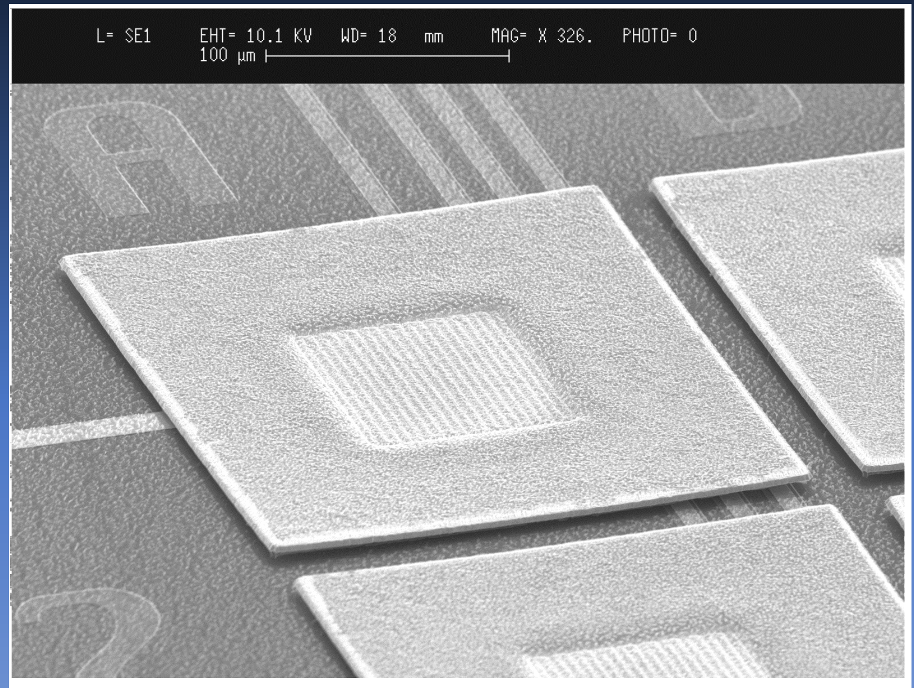
# Magnetically-Coupled Microcalorimeter arrays for x-ray astrophysics

- NASA Astrophysics Roadmap: "… breakthroughs in our understanding of accretion will come from the next-generation X-ray Surveyor, combining high-resolution spectroscopy with a large collecting area. X-ray absorption line studies of both stellar-mass and SMBHs with energy resolutions of ΔE < 4 eV will characterize the mass, energy and momentum of outflows from the accretion disk … "

- For X-ray Surveyor (renamed "Lynx"), goals include 100,000 pixel microcalorimeter arrays with energy resolution < 3 eV and pixel sizes 25 to 250 µm.
- See LTD17 poster: PE-46 "The Design of Whiskers, the Lynx X-ray Microcalorimeter," Simon Bandler, et al.

- AuEr Metallic Magnetic Calorimeters (MMCs) have demonstrated excellent energy resolution, e.g. 1.56 eV [FWHM] at 6 keV [A. Fleischman at LTD-16 (2015)].
- How can MMCs be scaled to Lynx array sizes?




*Example of previous type of MMCs fabricated at GSFC. Resolution 1.7 eV @ 6 keV. Pixel size 250 µm square. Sensor coil pitch 5 µm (2.5 µm lines and spaces). Insulator: $Nb_2O_5 + Al_2O_3$ 300 nm. Sensor Au:Er 900 ppm, 0.8 µm thick, 100 µm square.*
*J.P. Porst, S.R. Bandler, et al., J. Low Temp. Phys.* **176**(5) 617-623 (2014).

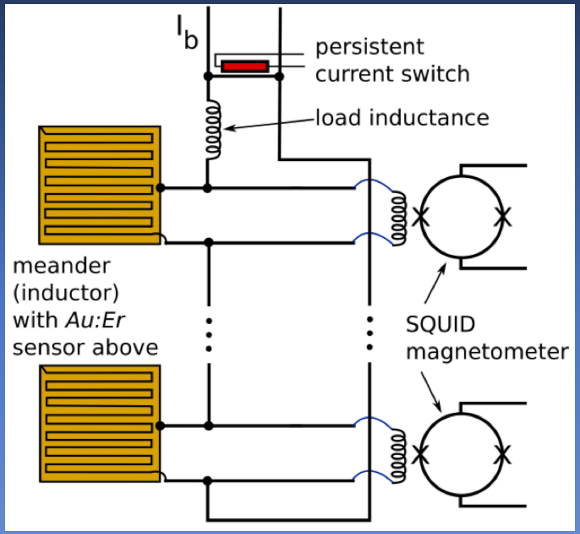
# Scaling of inductances & coupling with array size

- As array size increases, the stray inductance of the wiring, both between pixels and in fanout to amplifiers, will increase.
- The ratio of signal energy in the SQUID amplifier to that in the MCC sensor is a product of inductance factors,

$$\frac{M_i^2}{LL_i}\frac{L_i L_m}{(L_m+L_s+L_i)^2} = k^2\frac{L_i L_m}{(L_m+L_s+L_i)^2}$$

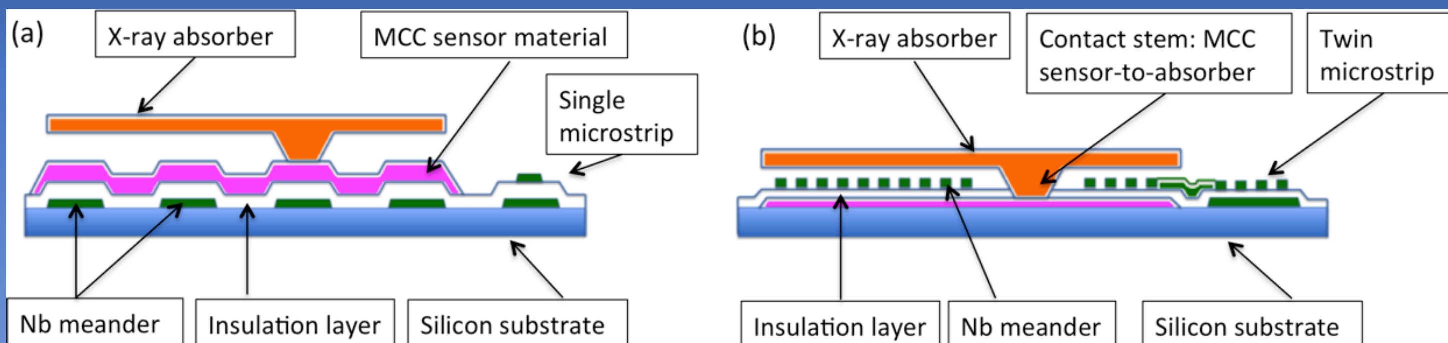
where $L$ is the SQUID loop inductance, $L_i$ is the SQUID input inductance, $L_m$ is the sensor meander coil inductance, and $L_s$ is the stray wiring inductance.

- Maximization of sensor signal energy requires maintaining optimal magnetic field bias, and largest active AuEr volume possible, with close proximity of all Er spins to Nb coil.
- Consequently, in scaling up to the X-ray Surveyor array size, our goals are:
  - maximize sensor inductance -> decrease meander coil pitch
  - minimize wiring inductance -> decrease microstrip insulator thickness as wiring linewidths decrease
  - maximize sensor signal energy -> scale AuEr and sensor insulator thicknesses with pitch, but not Nb thickness (keep high critical current/width)
  - connect to a multiplexed microwave SQUID array having good coupled energy sensitivity and an input inductance matched to the sensor plus stray inductance.



# MMC with high sensor coil inductance and dense, low inductance wiring

- For maximal critical current, we desire anisotropic etching of the niobium to produce vertical edges, resulting in an approximately square cross-section
- This motivated us to move the coil and fine sensor wiring on top of the sensor and insulation. In contrast, our existing process has the sensor coil under the Au:Er layer, requiring sloped Nb edges in order to have continuity of the insulator over Nb step edges.

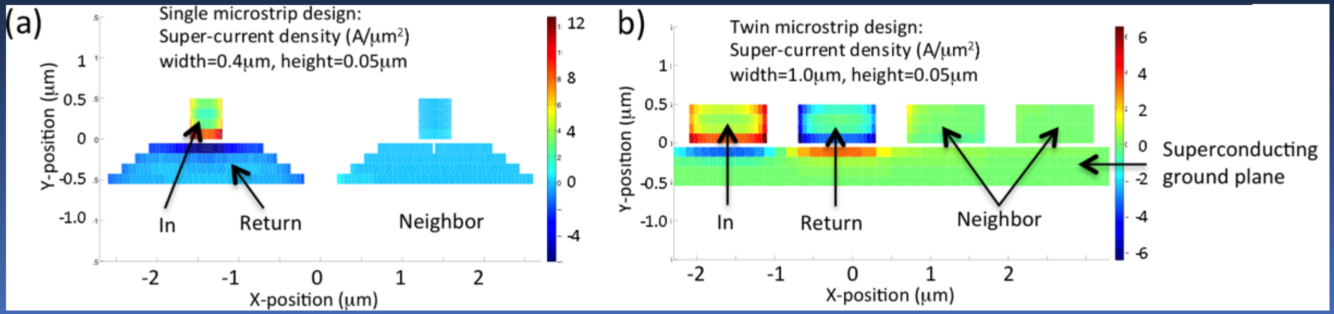



(a) Previous geometry. Nb coil is under Au:Er magnetic sensor layer, separated by an insulating Al2O3 layer. Au X-ray absorber contacts sensor from top. Wiring uses two layers of Nb in a individual microstrip configuration. Bottom Nb etch needs sloped edges to ensure good step coverage by insulator, sensor, and wiring.

(b) New configuration with twin microstrip leads per sensor coil and a common ground plane for all wires in a street.

# Magnetic field simulations

- Advantages of twin microstrip geometry:
  - no extra space needed for alignment tolerance and sloped edge
  - single layer projection lithography (5x stepper i-line 365 nm)
  - relative cross-talk between x-ray signals is still small, will be < 1%

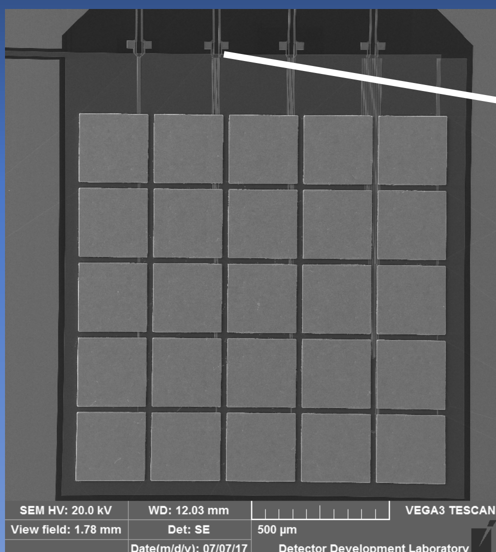



(a) Single microstrip design on pitch of 2.8 μm with thickness 0.5 μm and insulation thickness 0.050 μm. Colors depict current density. dL/dx = 0.242 $\mu_0$. dM/dx = 0.004 $\mu_0$.
(b) Twin microstrip design with two adjacent 1.0 μm wide Nb wires above a continuous Nb ground plane, with same total width per pair. dL/dx = 0.235 $\mu_0$. dM/dx = 0.011 $\mu_0$.

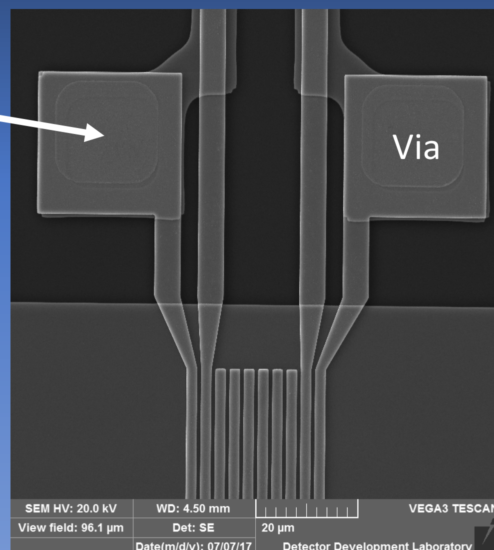
- Values for 102,400 pixel array implemented as 5x5 hydras with 50 μm absorbers:
  - meander inductance $L_m$ = 7.9 nH, stray inductance $L_s$ = 5.8 nH, optimal SQUID input inductance will be $L_i$ = 13.6 nH.
  - assuming a coupled energy sensitivity of 100 hbar for future microwave SQUIDs, we expect energy resolution < 3 eV.

# Fine-Wire MMC test devices

- Fabricated 5x5 arrays of MMC 250 µm x 250 µm x 4 µm Au absorbers (8 pixels/ array connected to SQUID input pads).
- Projection lithography (5x reduction, i-line 365 nm) and Reactive Ion Etching gave resolution and etch anisotropy needed for 0.8 µm pitch coils.
- Thin insulation layers were 50 nm anodic $Nb_2O_5$ + 40 nm evaporated $Al_2O_3$ between Nb microstrip layers, and $Al_2O_3$ between AuEr and Nb coil.

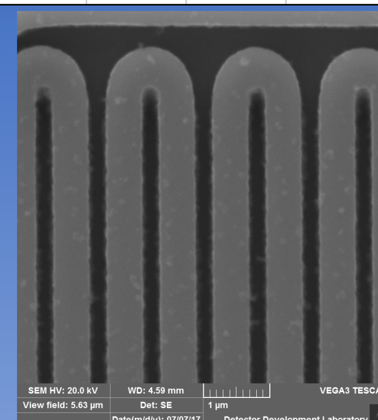



5x5 array of MMCs



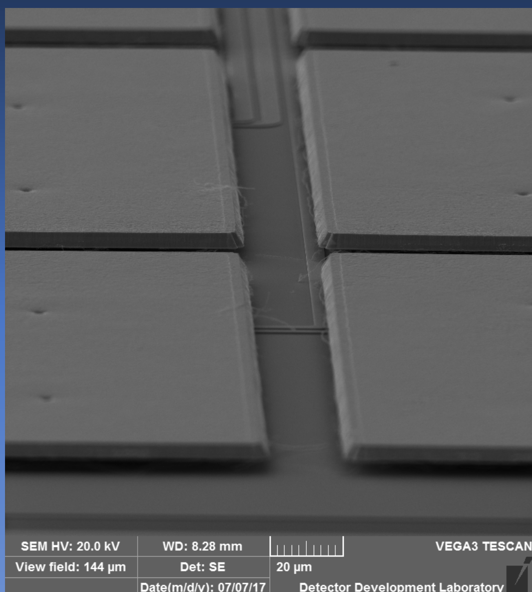

Individual microstrips in fanout (at top) change to twin microstrips within array (at bottom) with line/space = 1/0.4, 2/0.8, or 5/2.5 µm.

| Meander Pitch (µm) | Nb Line Width (µm) | Thickness (µm) | Critical Current (mA) @4K |
|---|---|---|---|
| 0.8 | 0.46 | 0.56 | 40 |
| 1.2 | 0.66 | 0.52 | 52 |
| 1.6 | 0.86 | 0.56 | 61 |
| 5 | 2.56 | 0.52 | 101 |

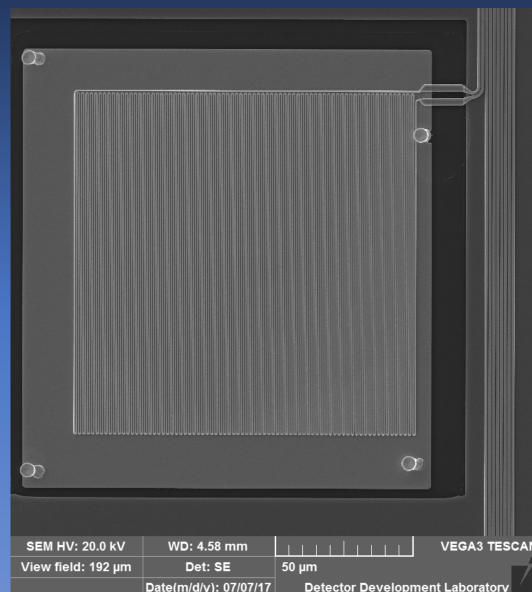



0.8 µm pitch, 0.5 µm thick Nb coil (w/o absorber) on $Al_2O_3$ insulated AuEr sensor.

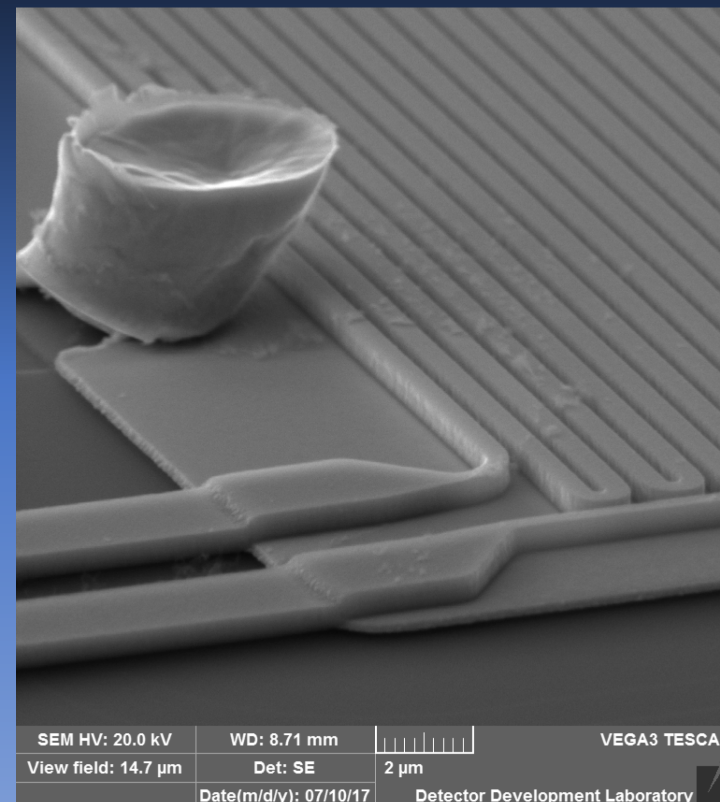
# Fine-Wire MMC test devices




Tilted view of array of MMCs with electroplated gold absorbers suspended above sensors and wiring.




Plan view of one 0.8 µm pitch sensor that has had its absorber pried off of its four 5 µm diameter Au support stems.




Tilted view shows non-planar coil surface.

# Summary and Next Steps

- MMC dimensions can be scaled to maintain signal coupling and energy resolution in arrays sized for the Lynx mission concept, despite the increase in stray inductance in a large array.
- Used projection lithography to create submicron patterns (< 400 nm) in niobium sensor meanders and wiring, integrated with gold-erbium sensor films and gold x-ray absorbers.
- Demonstrated highly anistropic reactive ion etching of niobium films.
- Combination of $Nb_2O_5$ and $Al_2O_3$ gave thin insulators (50 nm) for maximizing magnetic coupling, minimizing stray inductance, and providing an etch stop.
- Critical currents were low in first prototype circuits because of second layer Nb step coverage over too-steep first layer Nb edges; new batch under fabrication.
- Arrays include devices with a variety of pitch values, 0.8 to 5 µm for sensor and microstrip wiring (down to 1 µm lines with 0.4 µm spaces).
- We will explore the device physics of Metallic Magnetic Calorimeters as feature sizes are reduced to sub-micron values.

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