Mitigation of Flux Trapping in Large-Format, Low-Tc Analog SQUID Arrays

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Detection and Mitigation of Flux Trapping in Superconducting Digital Electronics Workshop

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Outline

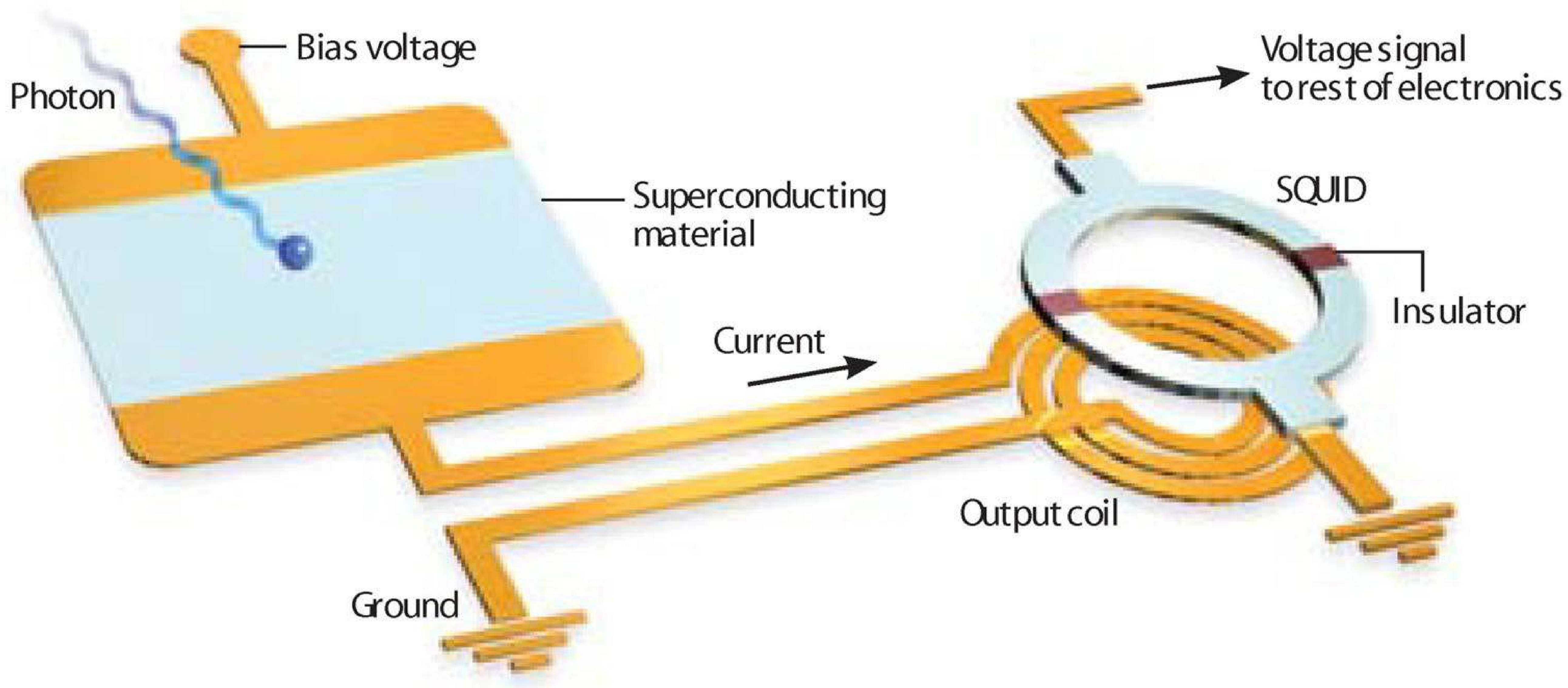
Mitigation of Flux Trapping in Large-Format, Low-Tc **Analog** SQUID Arrays

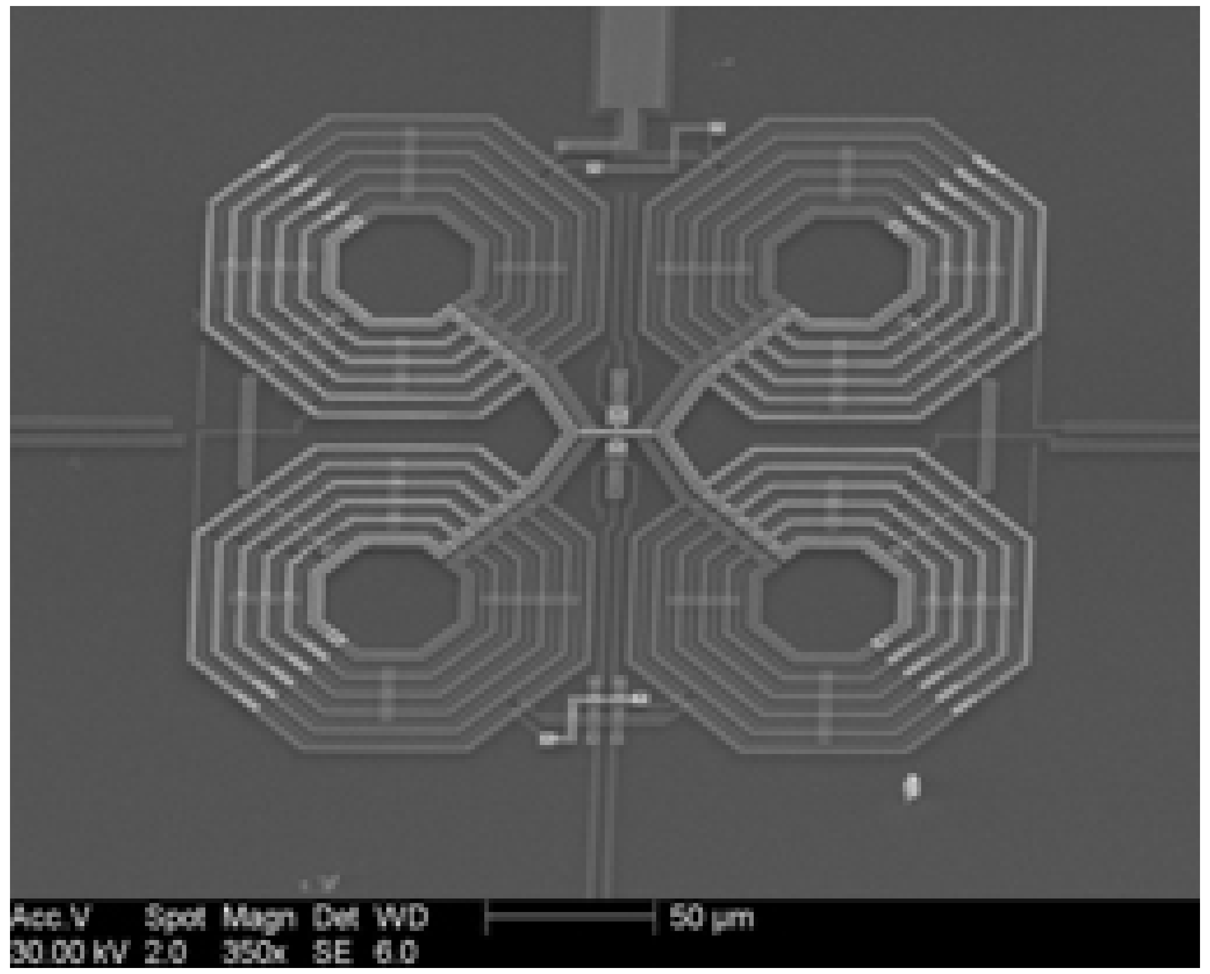
- Large format, multiplexed analog SQUID arrays
- Large-scale applications of multiplexed SQUID arrays reliable enough for use in complex environments (x-ray beamlines, South Pole, space, …)
- Techniques to control and mitigate flux-trapping in **analog** arrays
- SLAC superconducting foundry

Some aspects of flux control in analog SQUID circuits may present differently than in digital circuits

Devices shown in this presentation were fabricated at NIST/Boulder

SQUID-coupled detector readout



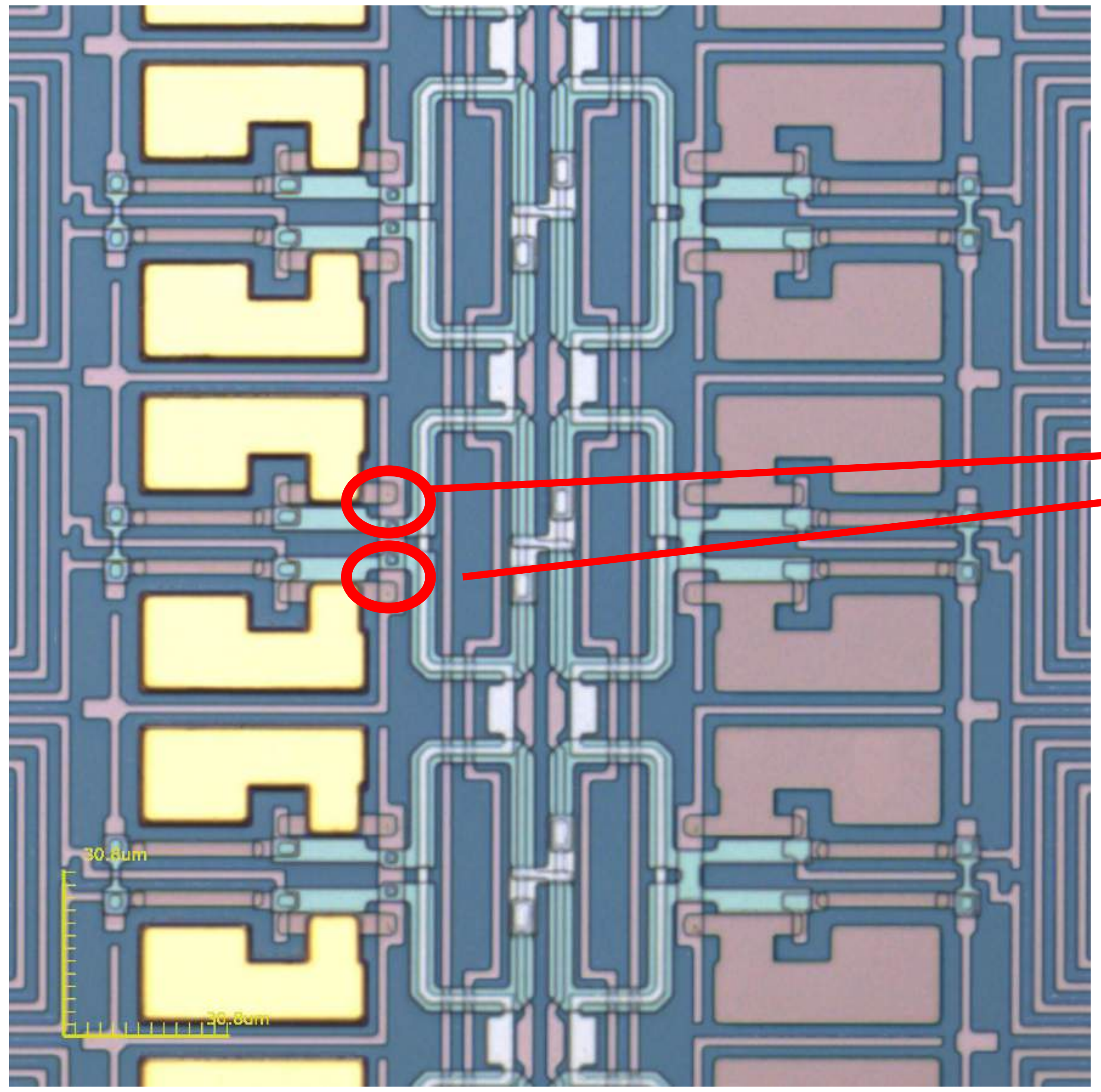


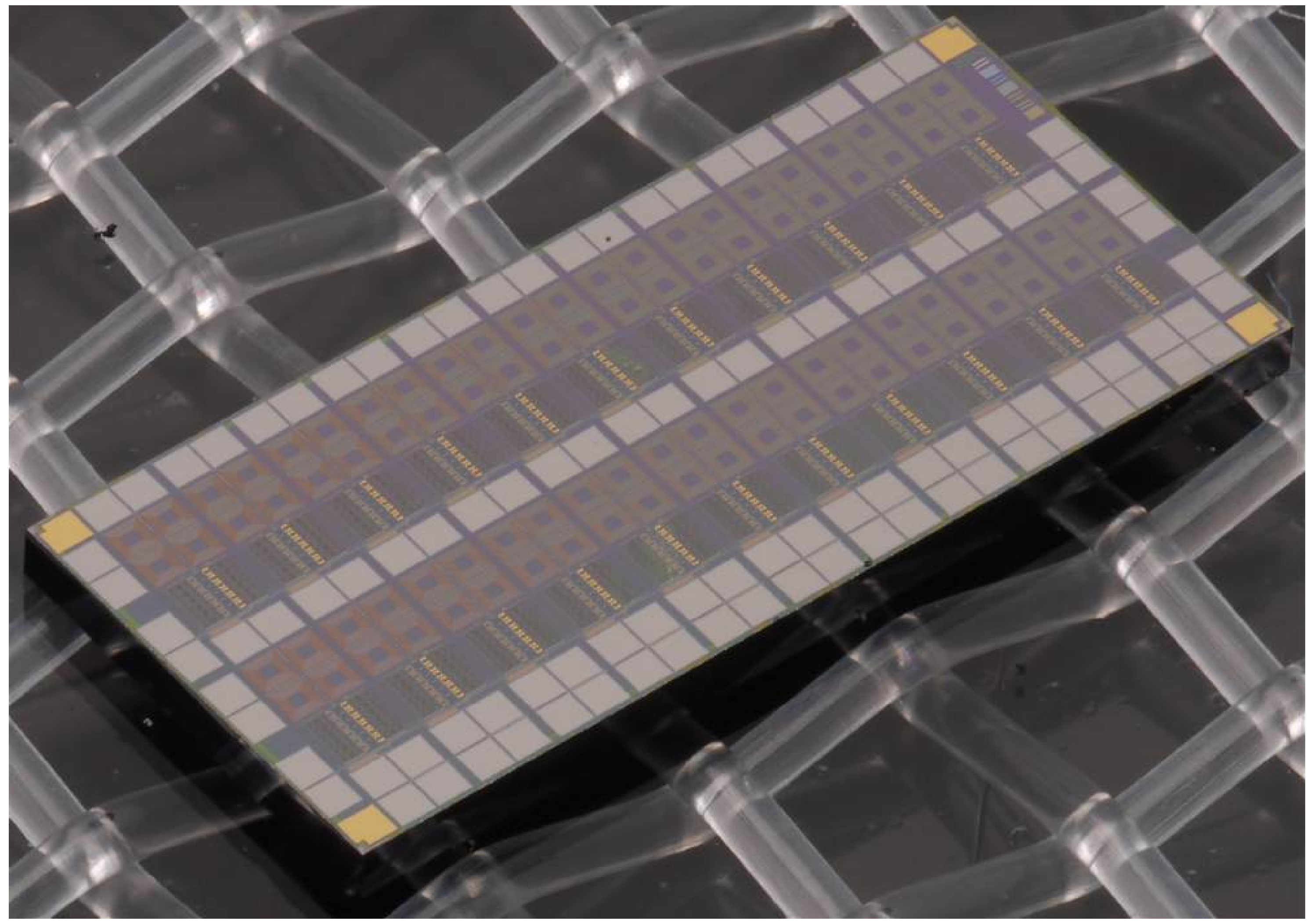
Niobium trilayer SQUID

- SQUIDs can be used to read out superconducting transition-edge sensors for x-ray, CMB, visible photon, gamma-ray, alpha particle, and other detection applications
- Robust arrays of SQUID of scale ~100,000 are being deployed, with plans for even larger arrays.
- Robust deployment at this scale has required the implementation of features to mitigate and control flux trapping.

These techniques are used at scale in both dc SQUIDs and rf SQUIDs arrays

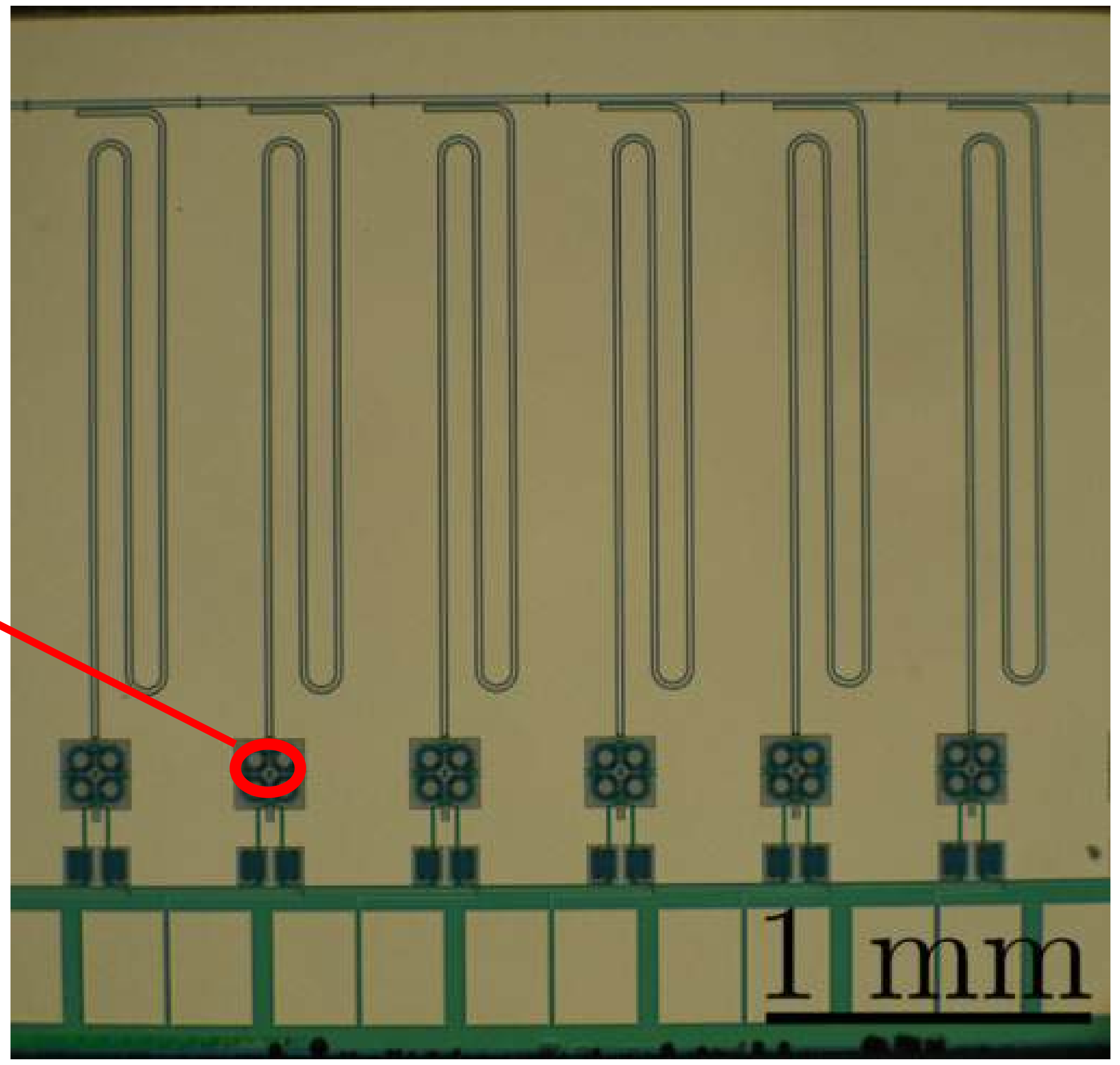
DC SQUID array

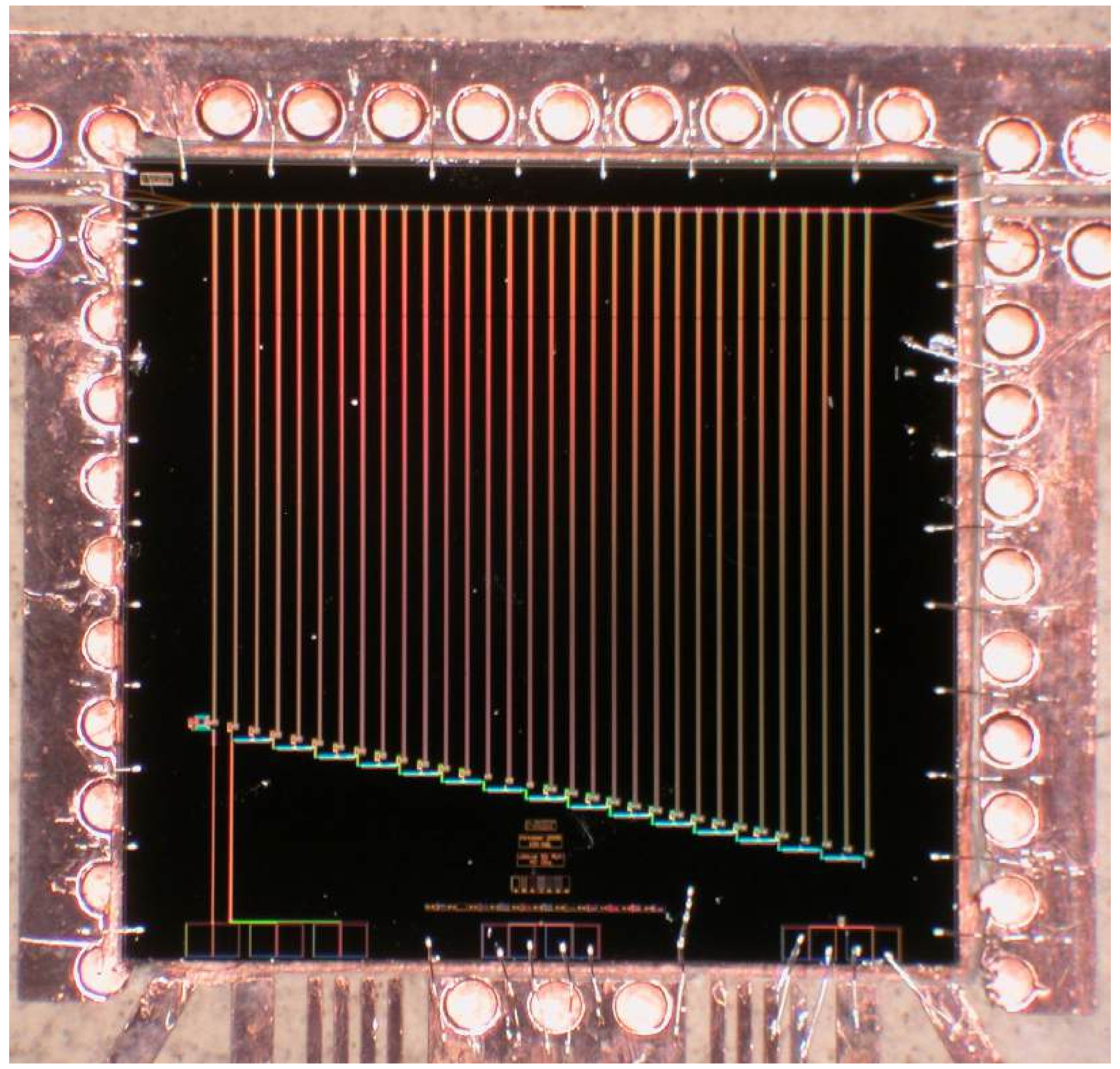




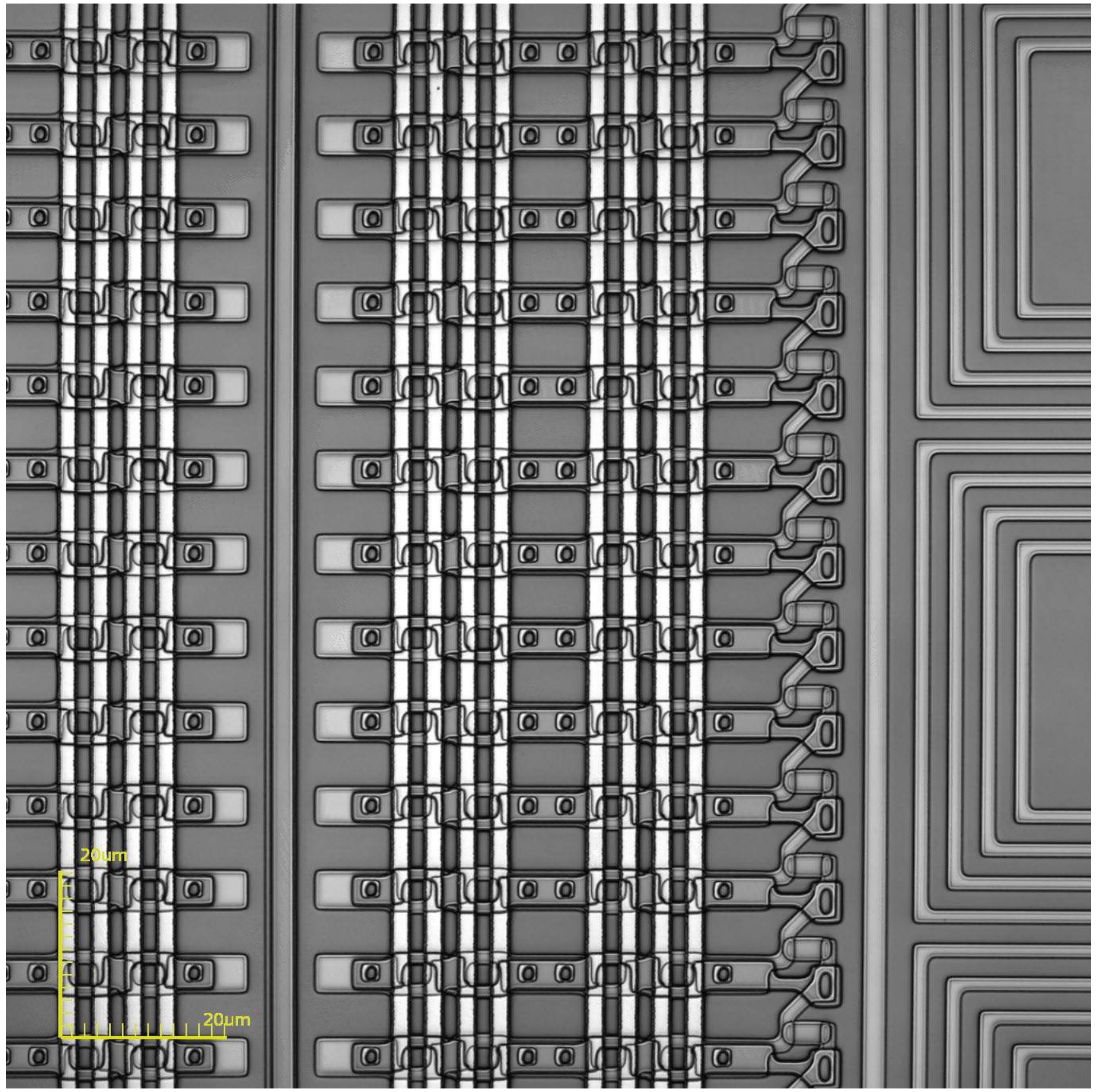
Josephson junctions

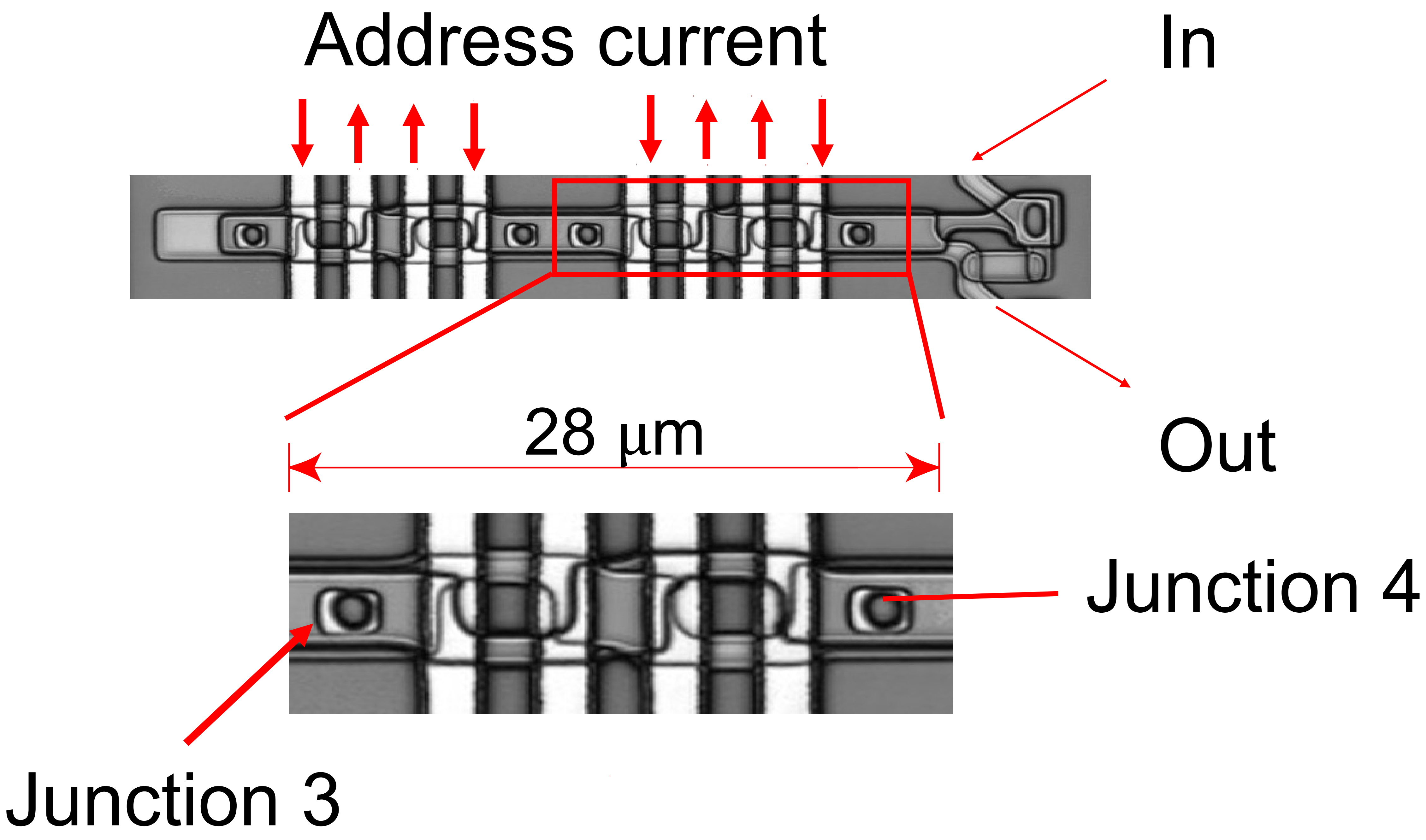
RF SQUID array





On-off switches used in multiplexing

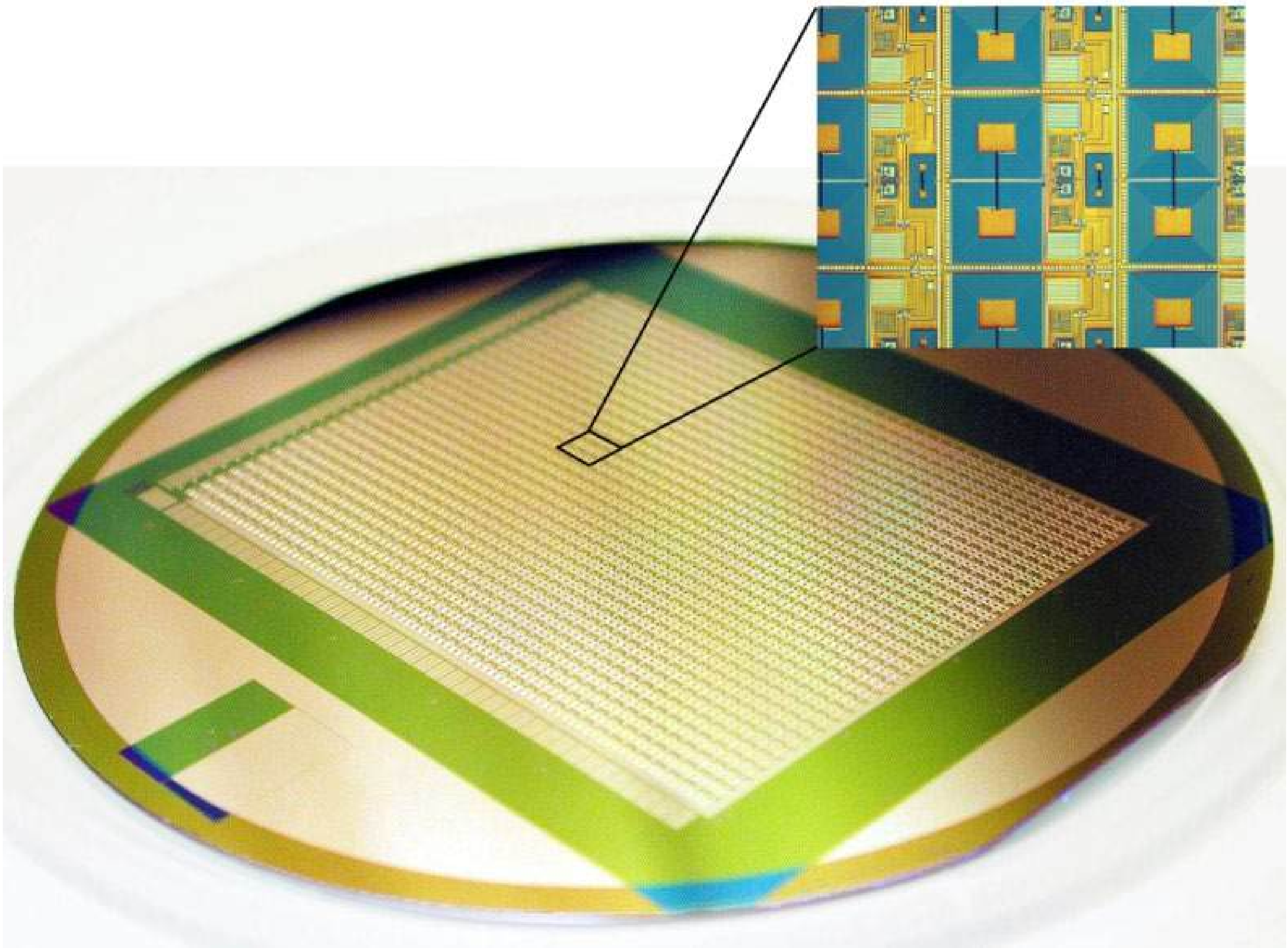




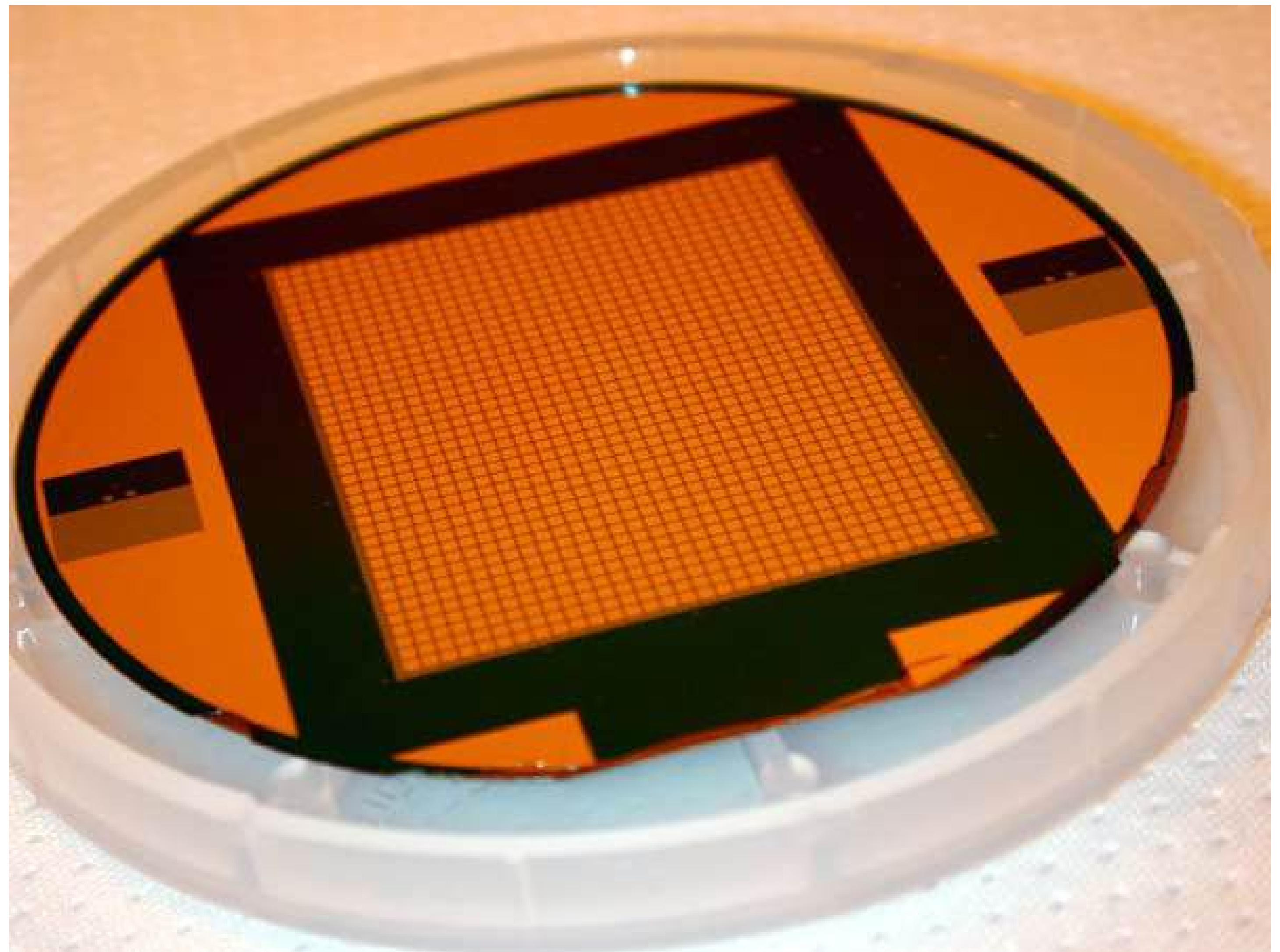
Photograph of four-junction interferometer switch

Some arrays use superconducting bump-bond hybridization

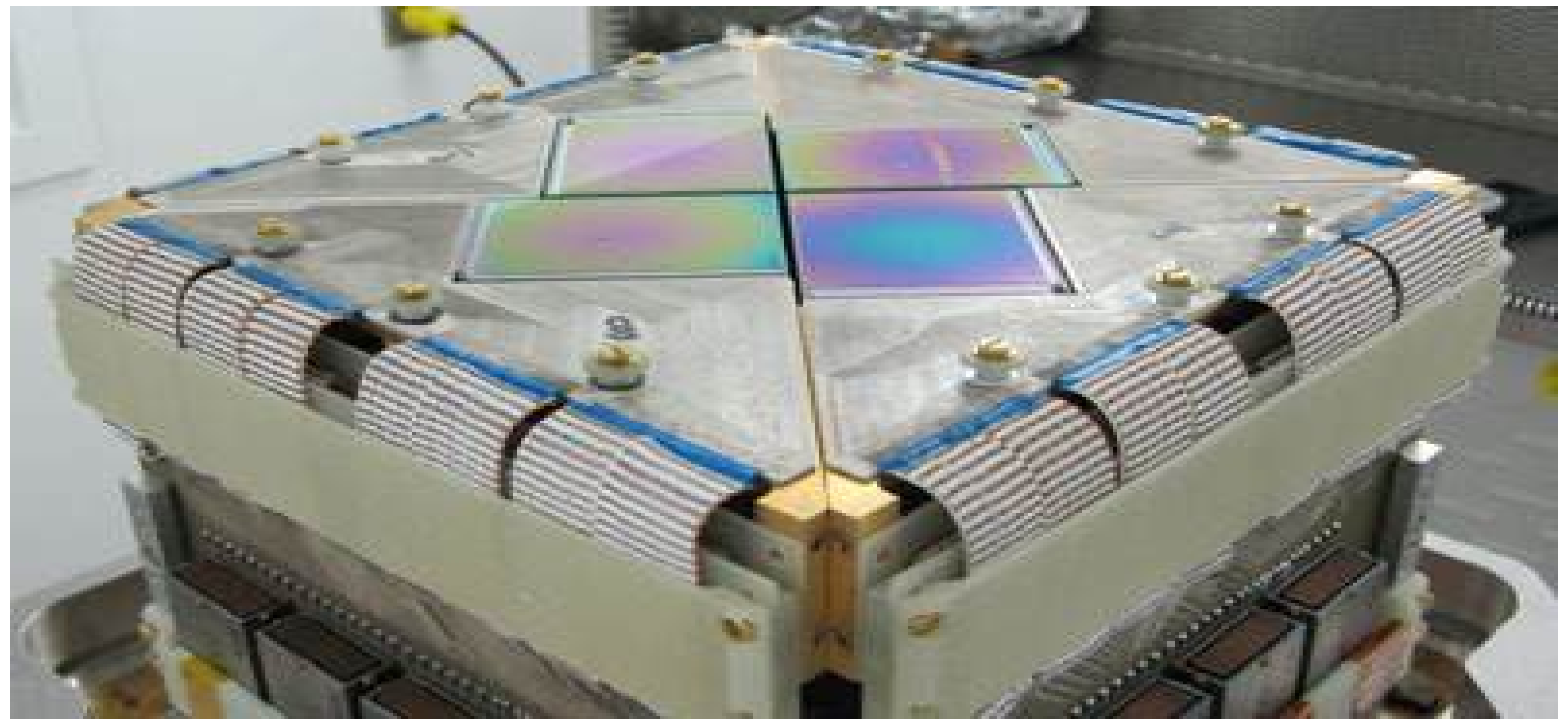
1,280-pixel SQUID Multiplexer



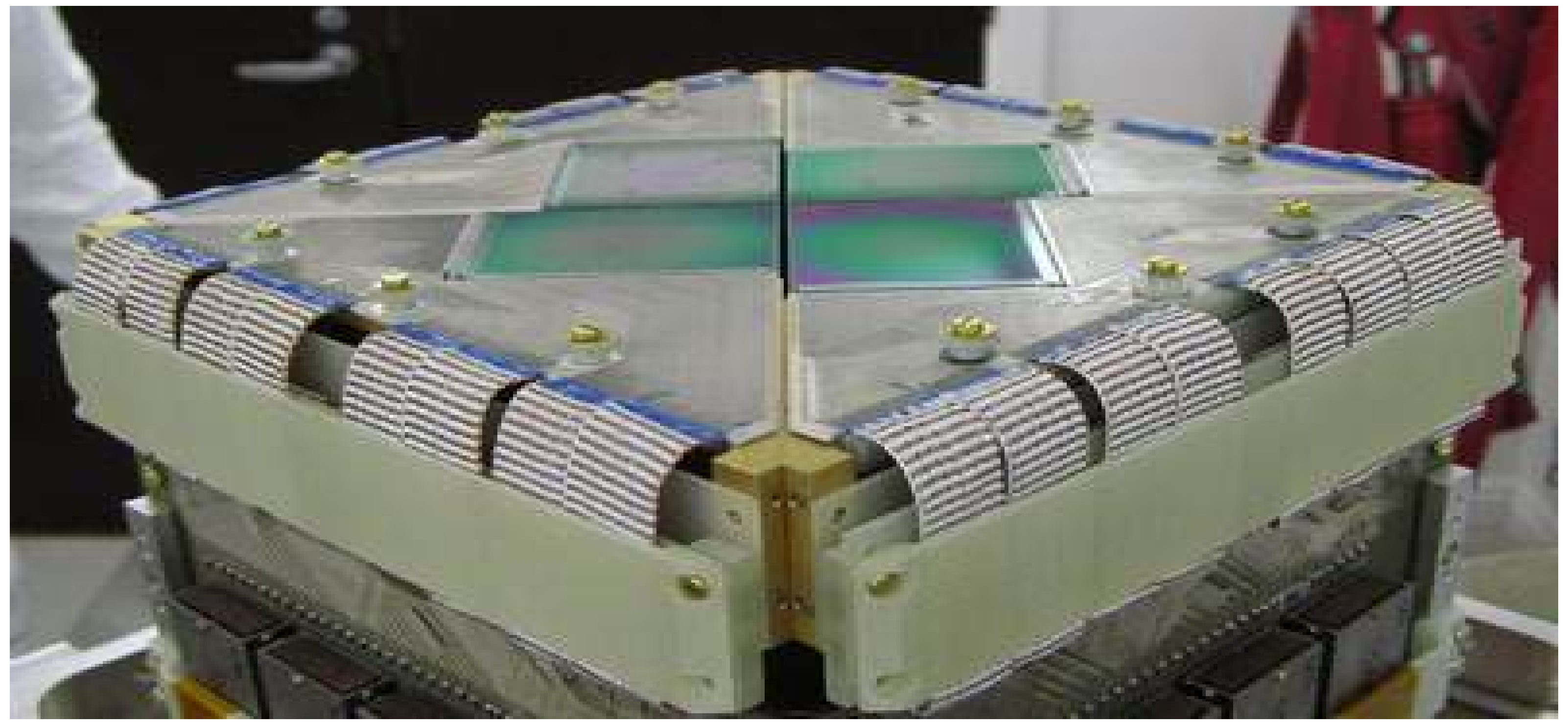
1,280-pixel TES bolometer



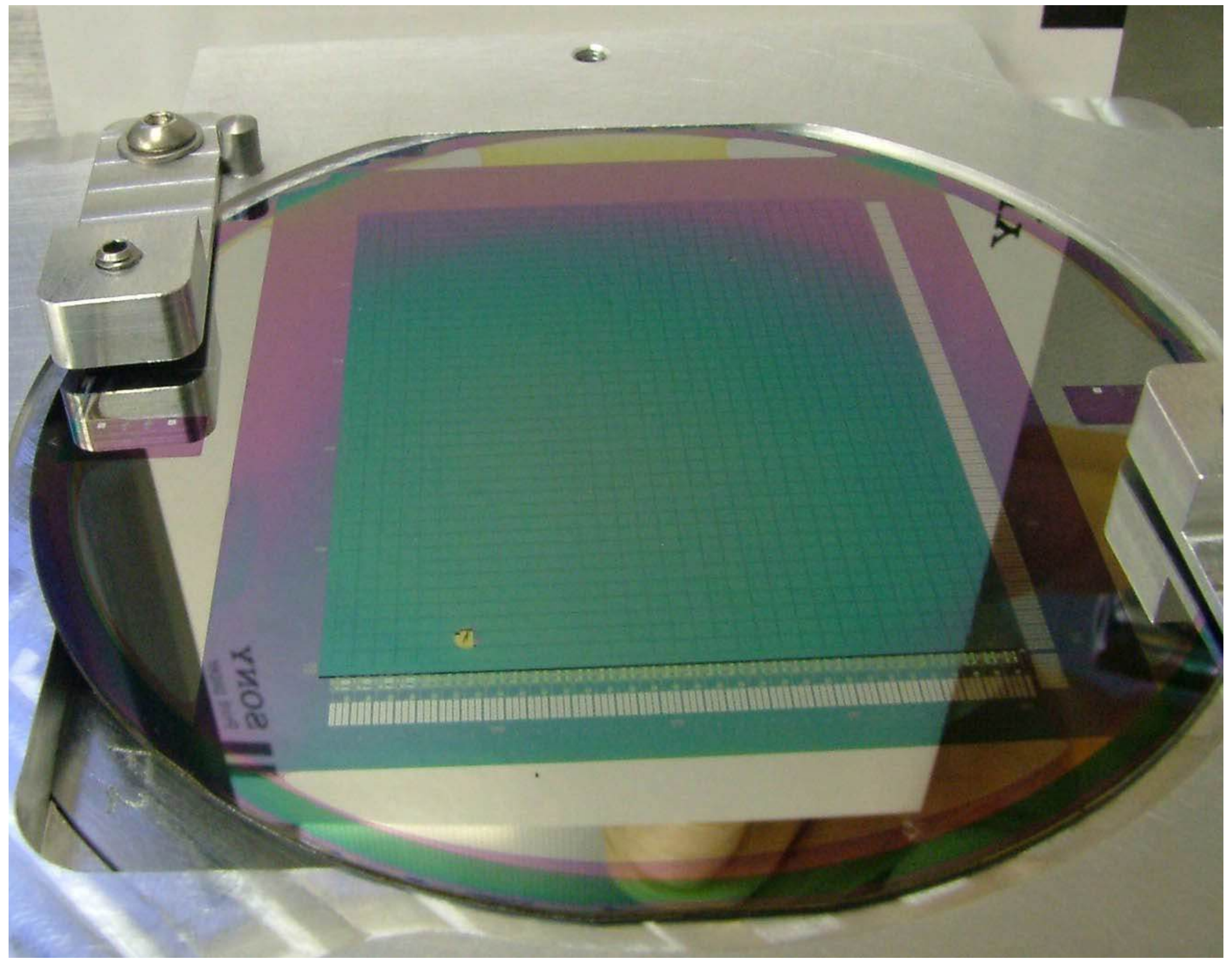
5,120 pixels at 450 um



5,120 pixels at 850 um



bump-bonded
subarray
(TES+MUX)

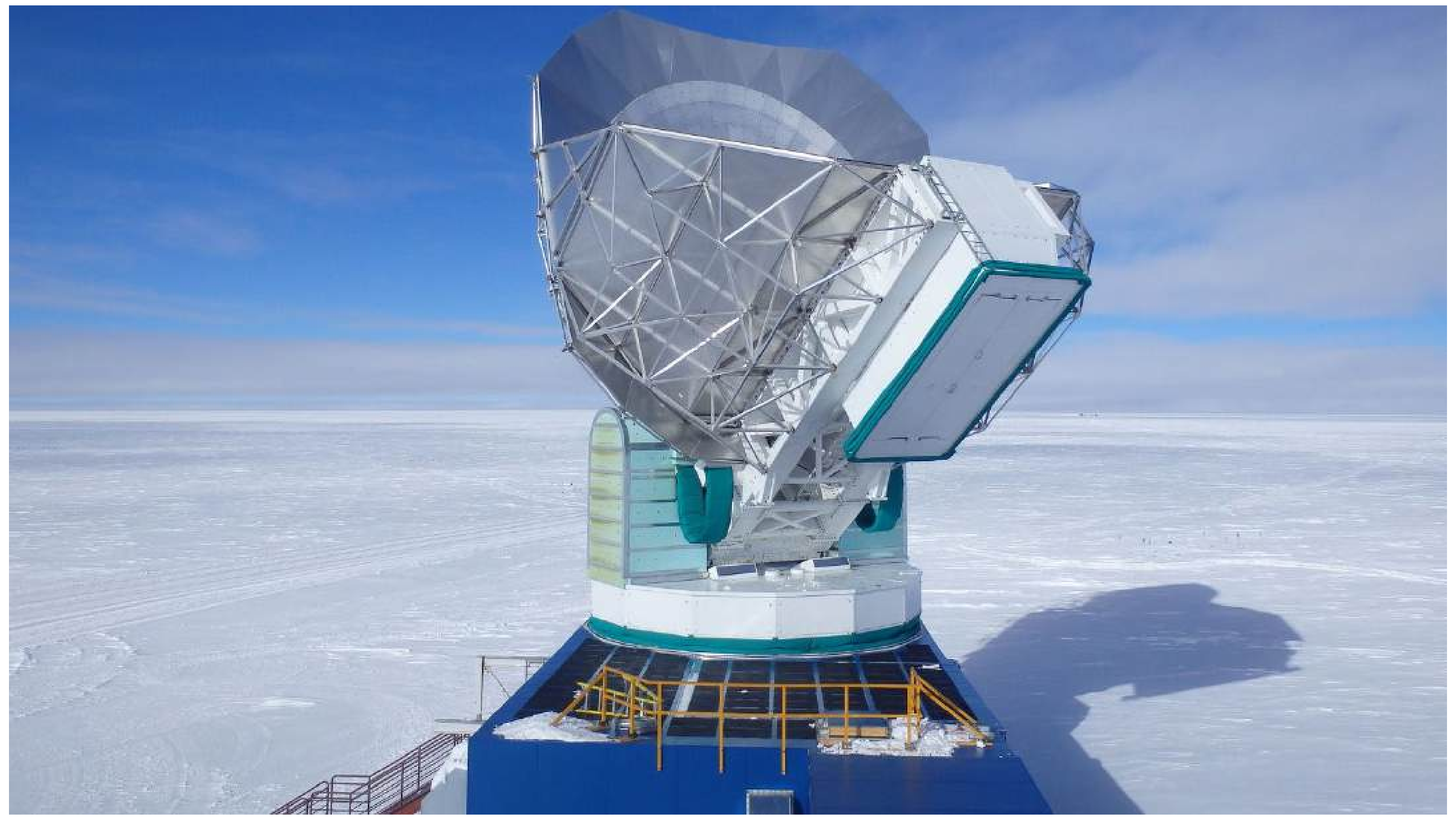


Applications of these techniques

Reliable enough for use in complex environments (x-ray beamlines, South Pole, space, etc)

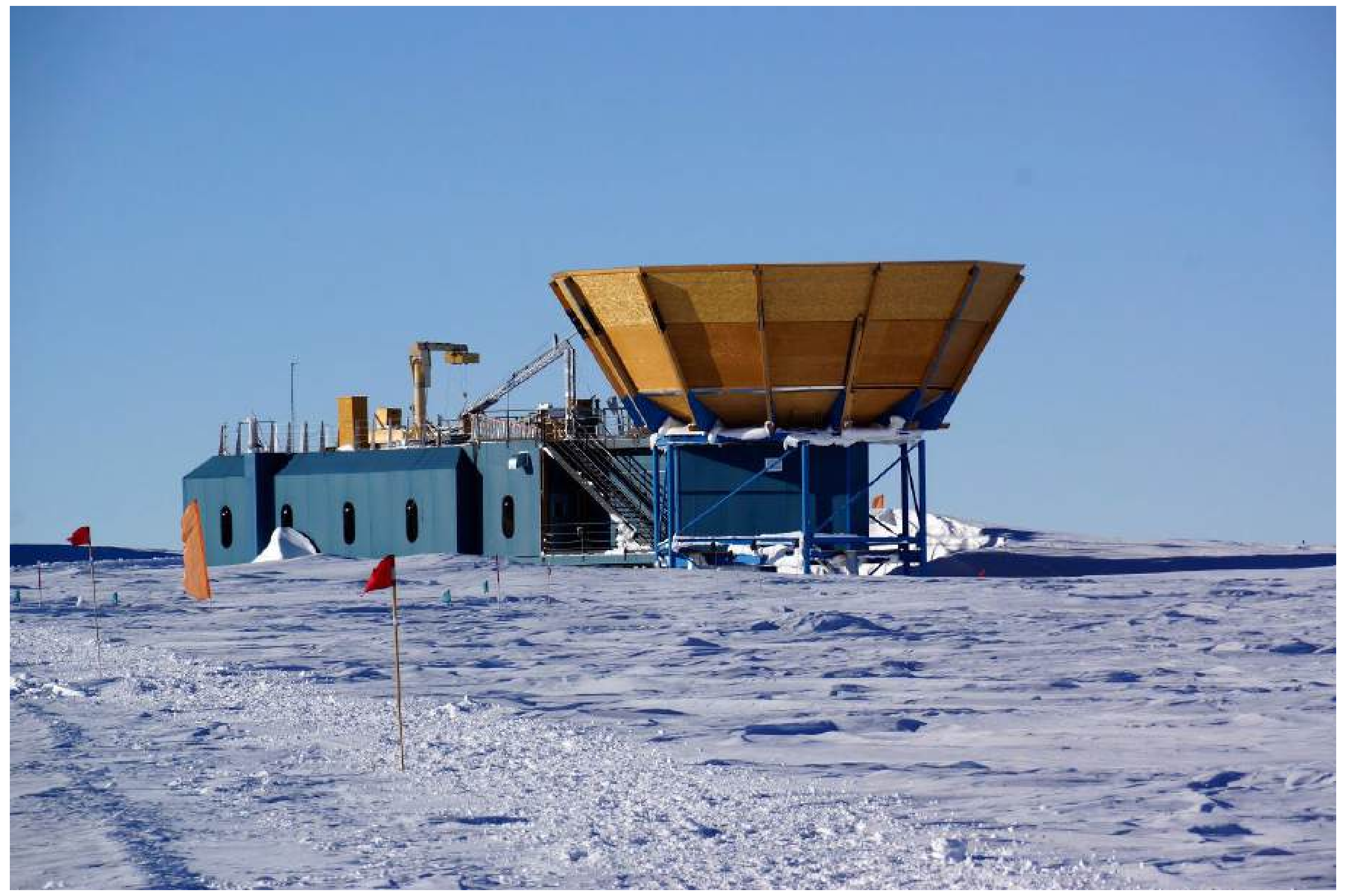
- Cosmic Microwave Background
- THz imaging
- Dark-matter searches
- Visible photon detection for quantum communications / key distribution / loophole-free Bell
- X-ray imaging spectroscopy
- X-ray astronomy
- Submillimeter astronomy
- Gamma-ray detection for nuclear non-proliferation, forensics, nuclear security, and mixed-actinide analysis
- Alpha-particle detection for nuclear forensics

Cosmic Microwave Background



South Pole telescope

Atacama Cosmology Telescope

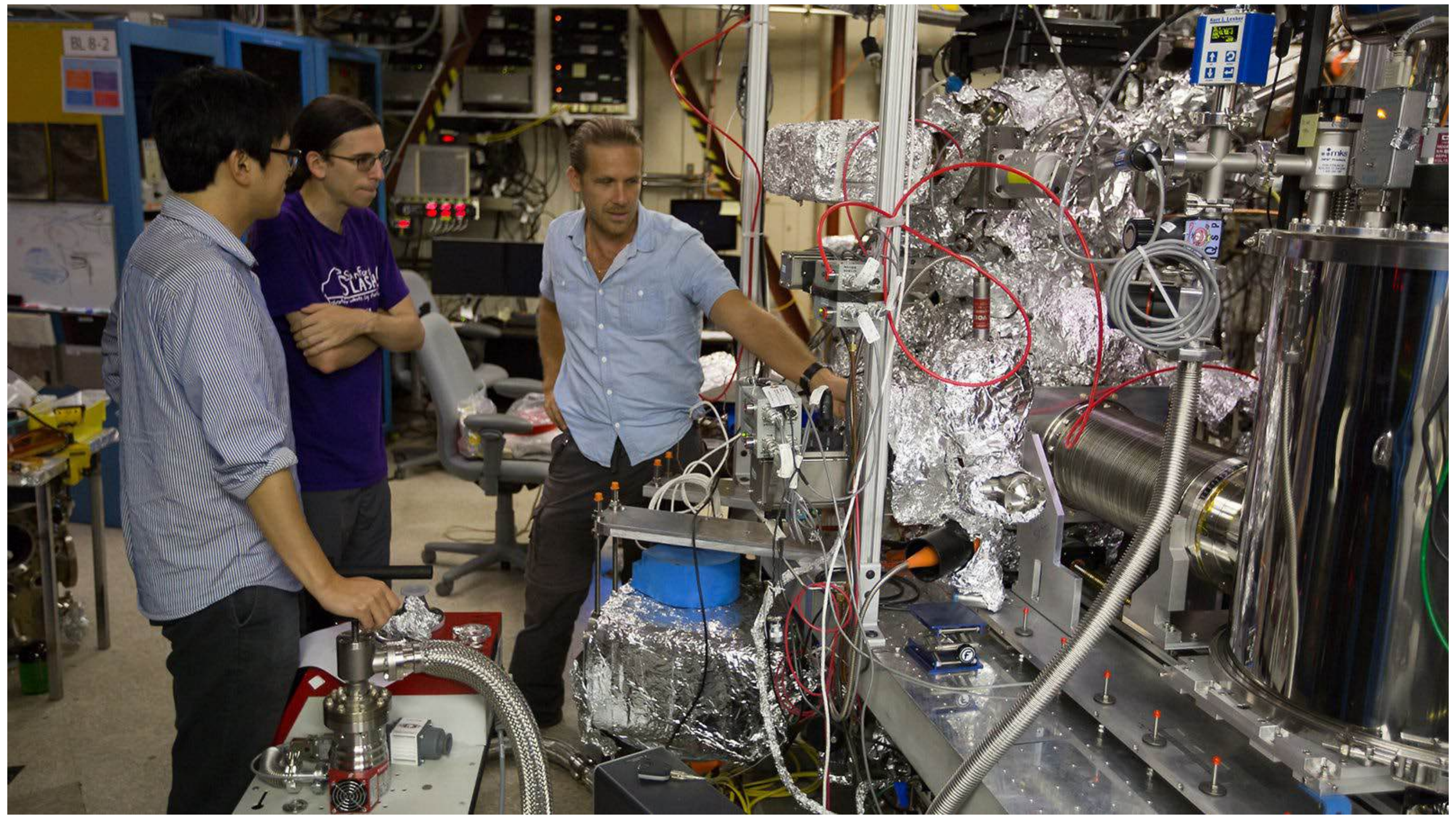


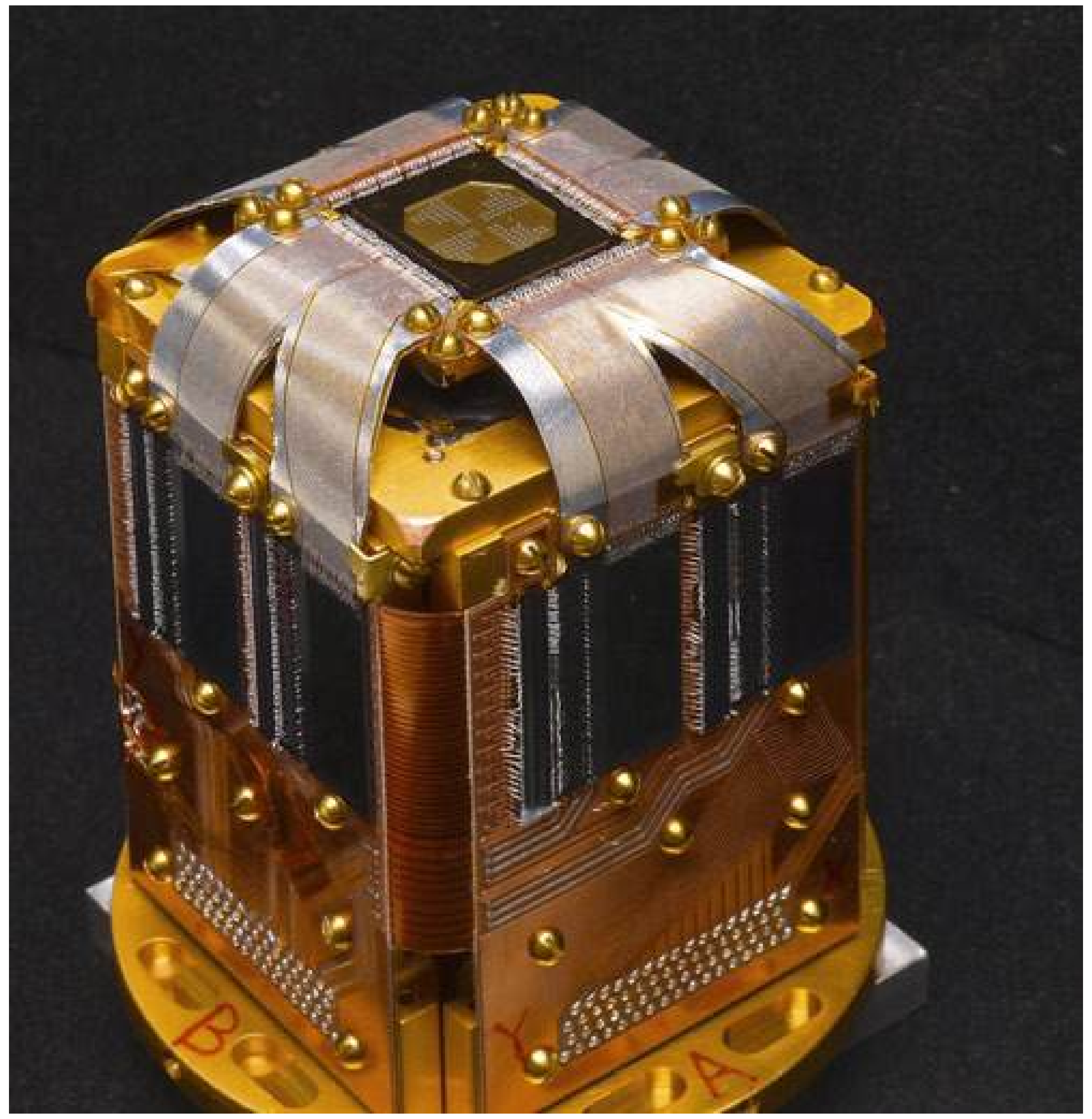
BICEP / Keck telescopes

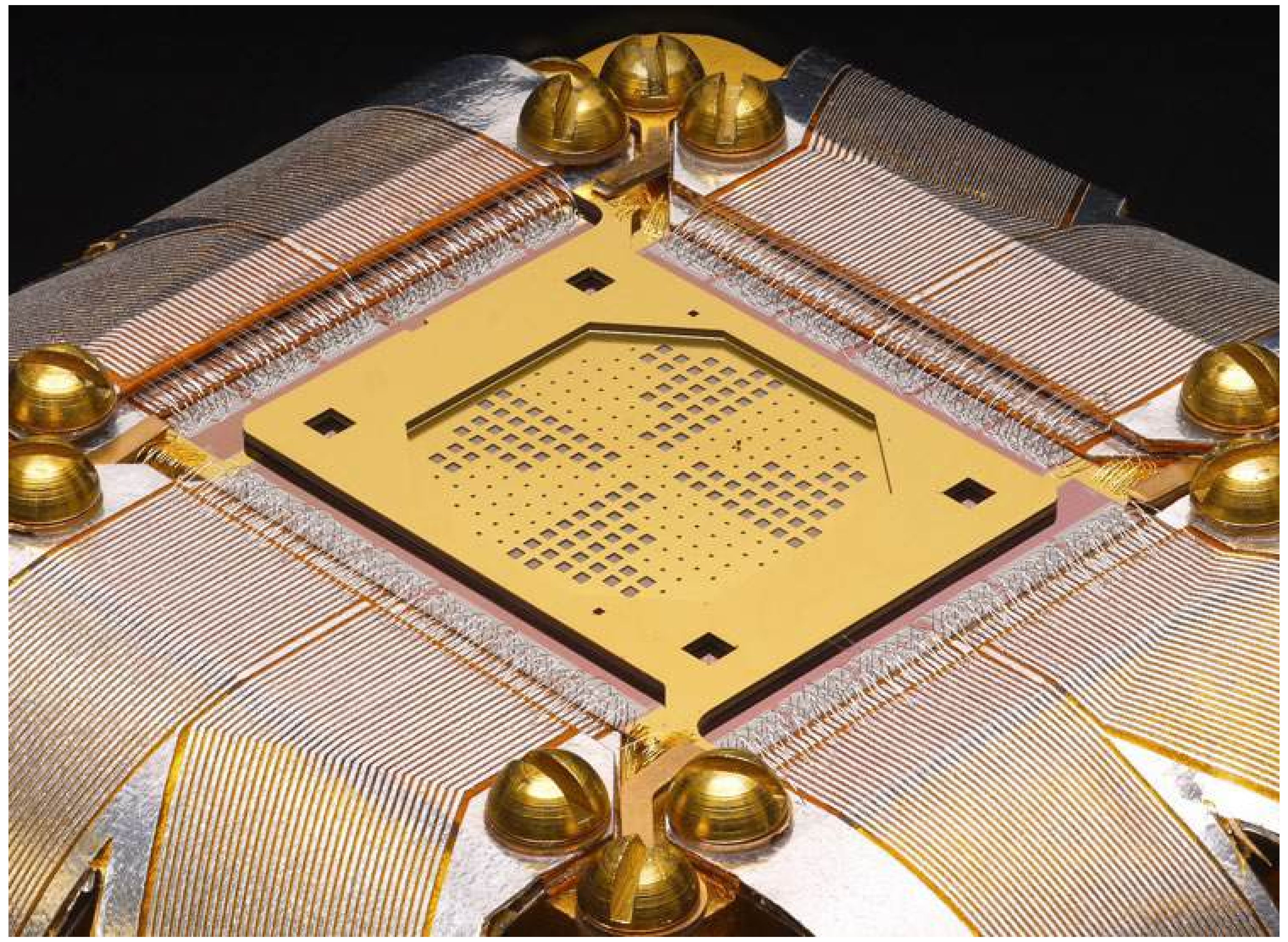
Arrays of SQUIDs using these designs and incorporating flux-trapping-mitigation features described here are used in all Cosmic Microwave Background telescopes currently operating.

Simons Observatory

X-ray spectrometers on beamlines





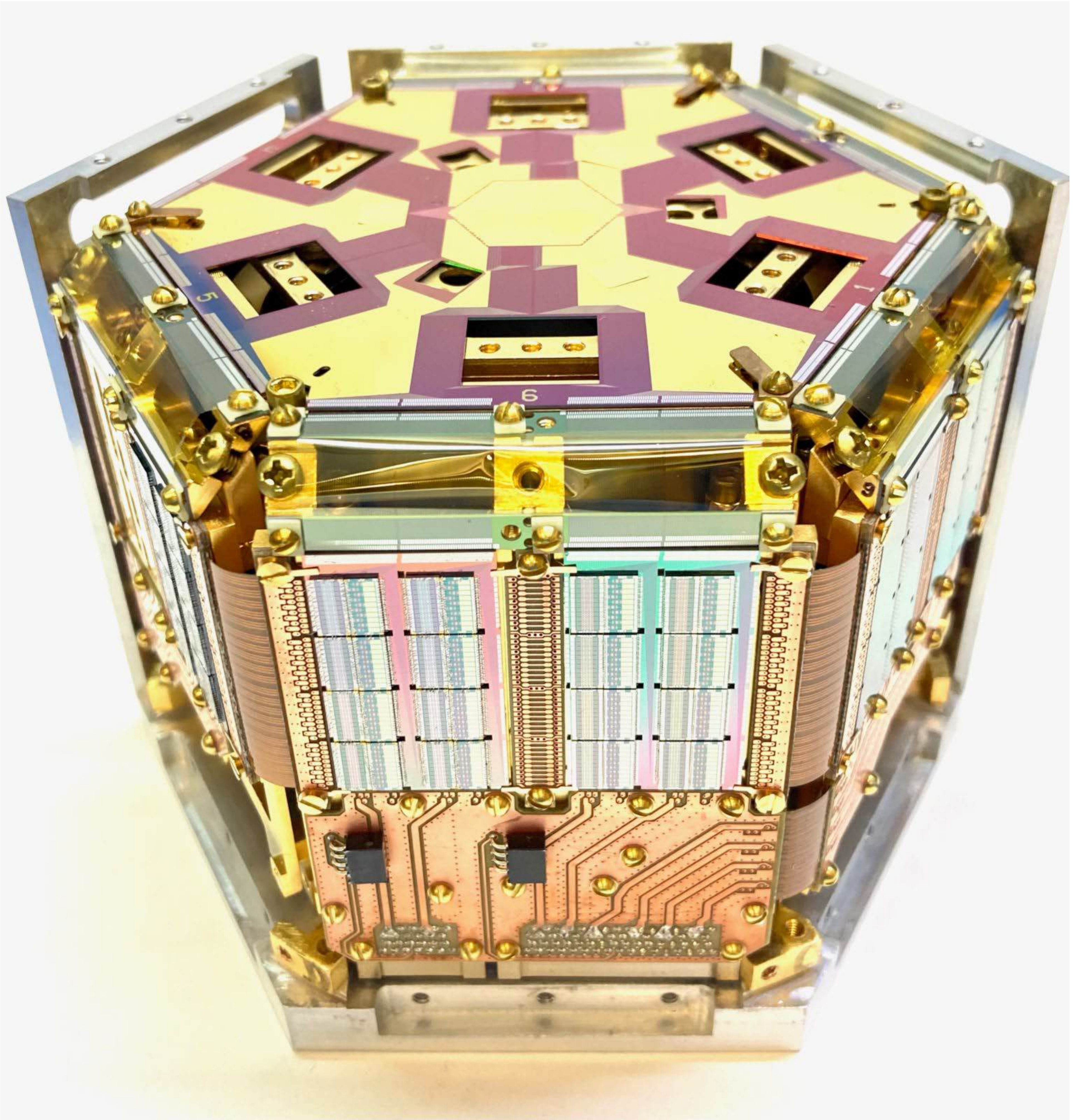


Arrays of SQUIDs are used in x-ray beamline instruments, including the BL10-1 instrument at SSRL shown here

Athena X-Ray Observatory

Athena will be the largest X-ray observatory ever built, investigating some of the hottest and most energetic phenomena in the Universe with unprecedented accuracy and depth.

- Planned **launch by ESA** in **2037**
- **NASA/GSFC, NIST, SRON, Toulouse**



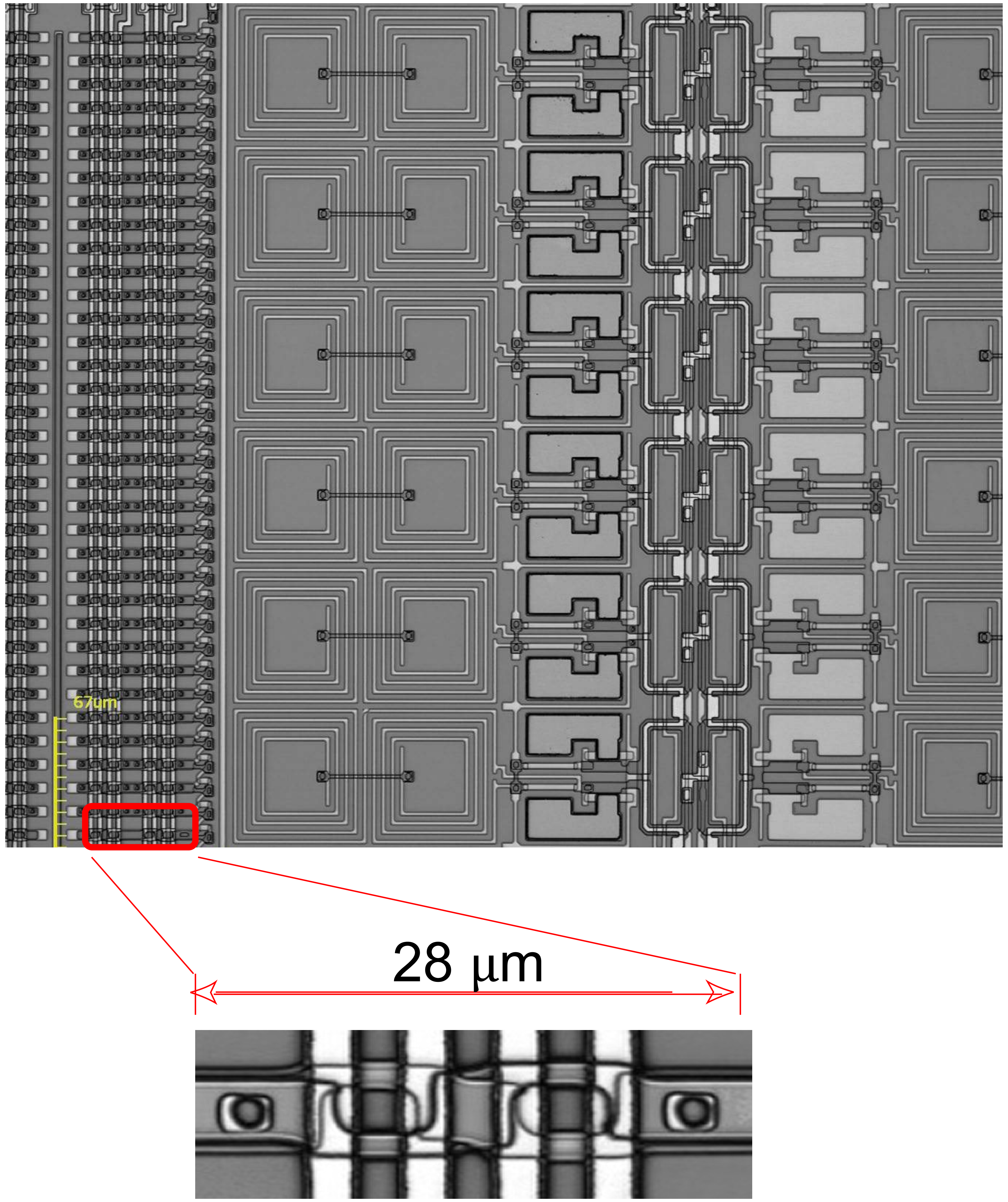
Multiplexed SQUIDs in X_IFU instrument

Flux-trapping control in analog SQUID arrays

- Narrow superconducting films (< 5 um is our rule)
- Slotted washers
- Serial gradiometer pickup loops to avoid trapping
- Second-order parallel gradiometers with high symmetry to avoid coupling to distant flux motion

Flux expulsion when passing through the transition

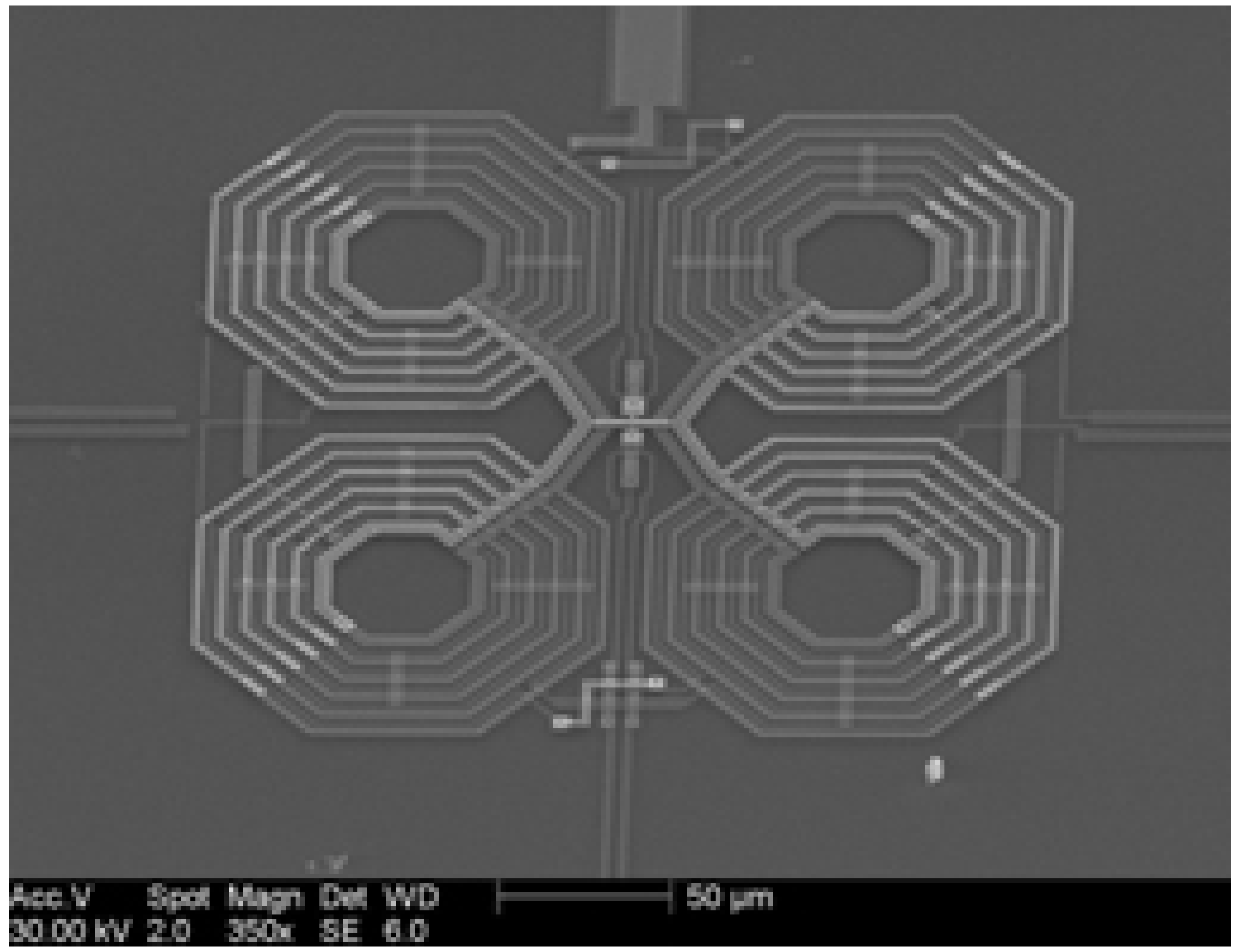
All superconducting films < 5 um wide

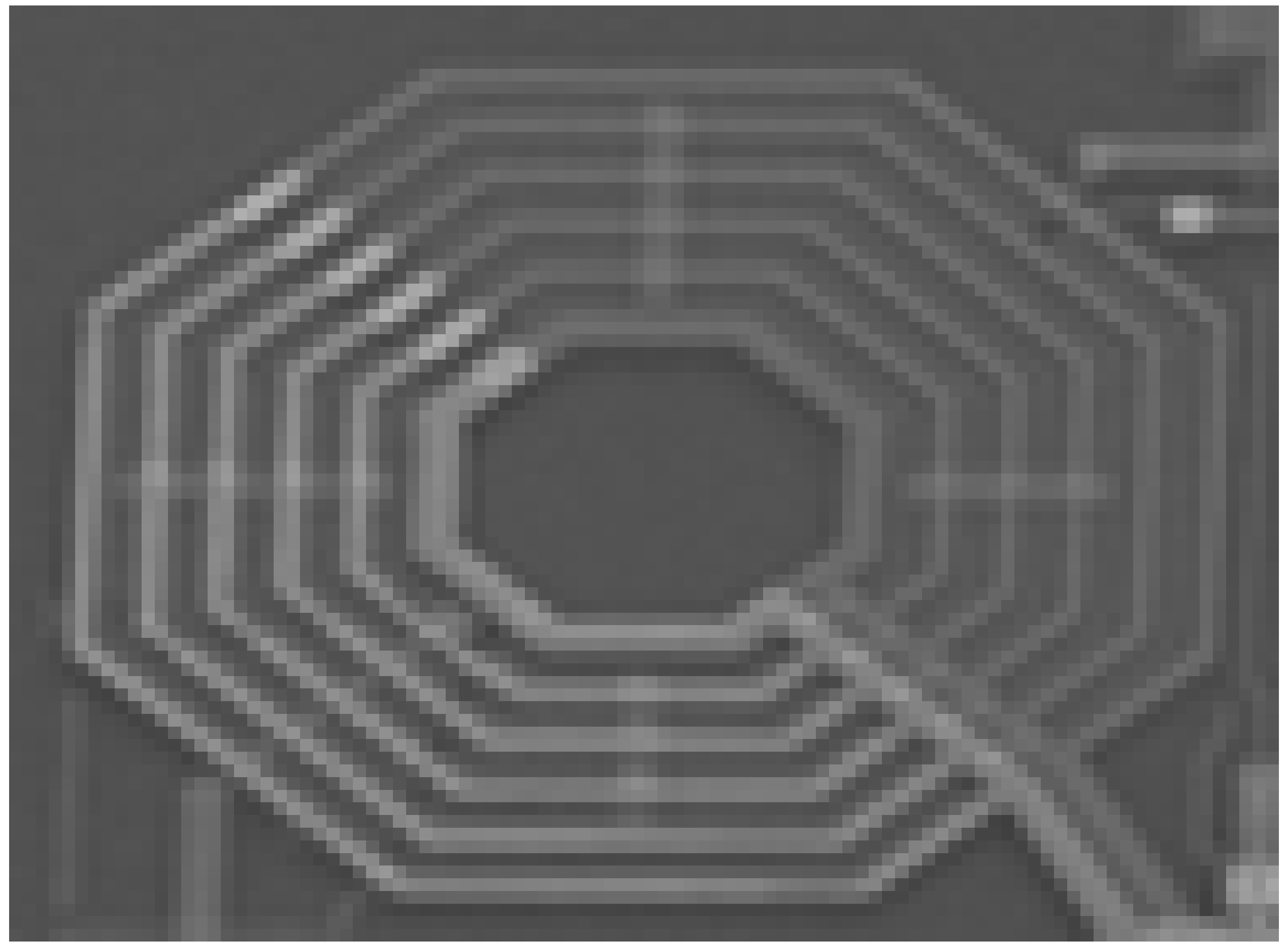


We want flux to be preferentially expelled while passing through the superconducting transition.

1) We keep all superconducting films no wider than 5 um
2) Cool single devices in < 50 uT. Even though the “universal rule” predicts full flux expulsion, we do see a small amount of flux trapping in large arrays of devices
3) Cool large device arrays in < 5 uT.
4) Cool slowly
5) If necessary, reheat just above the transition and slowly cool a second time

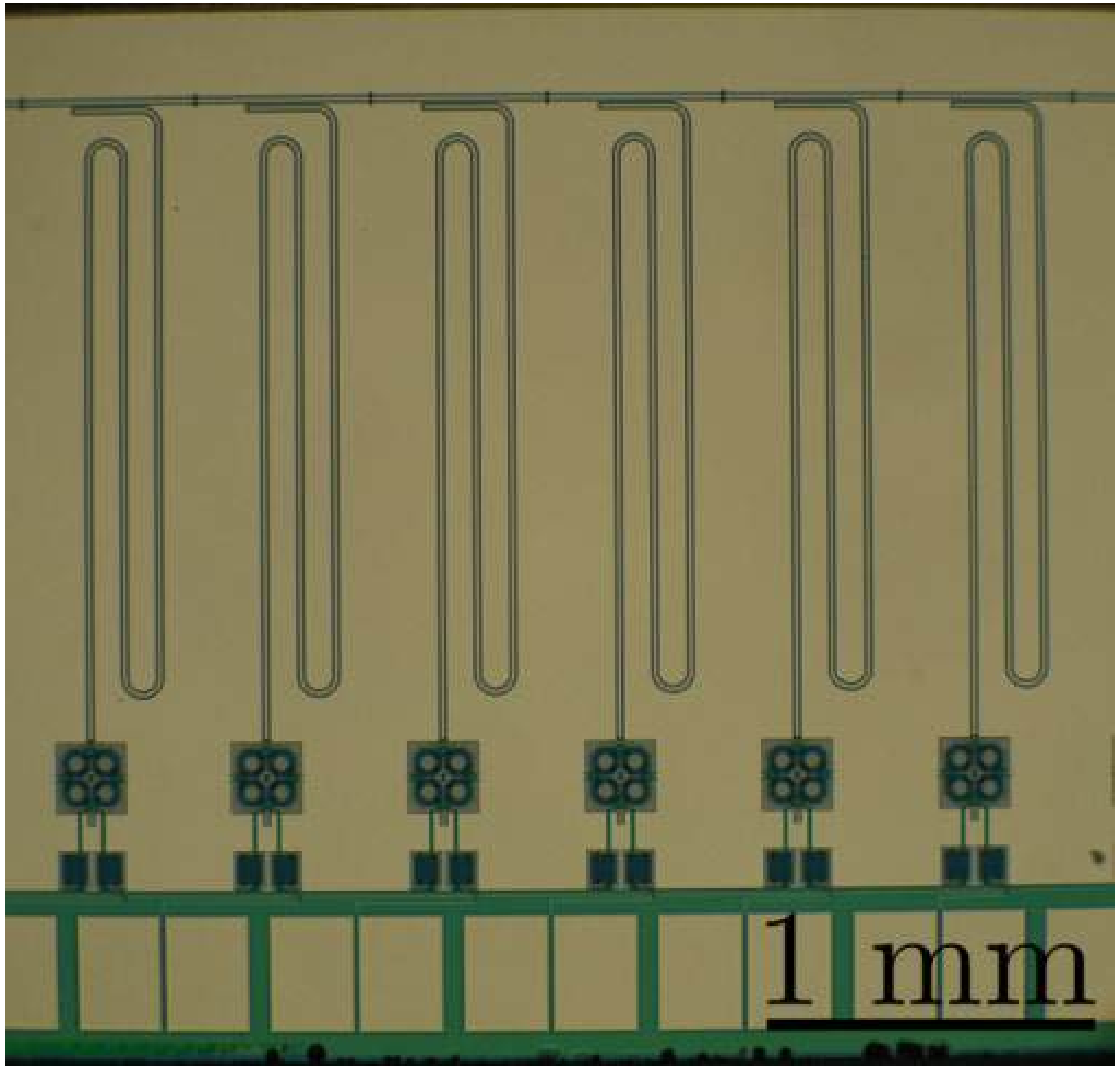
Slotted washers and second-order gradiometers





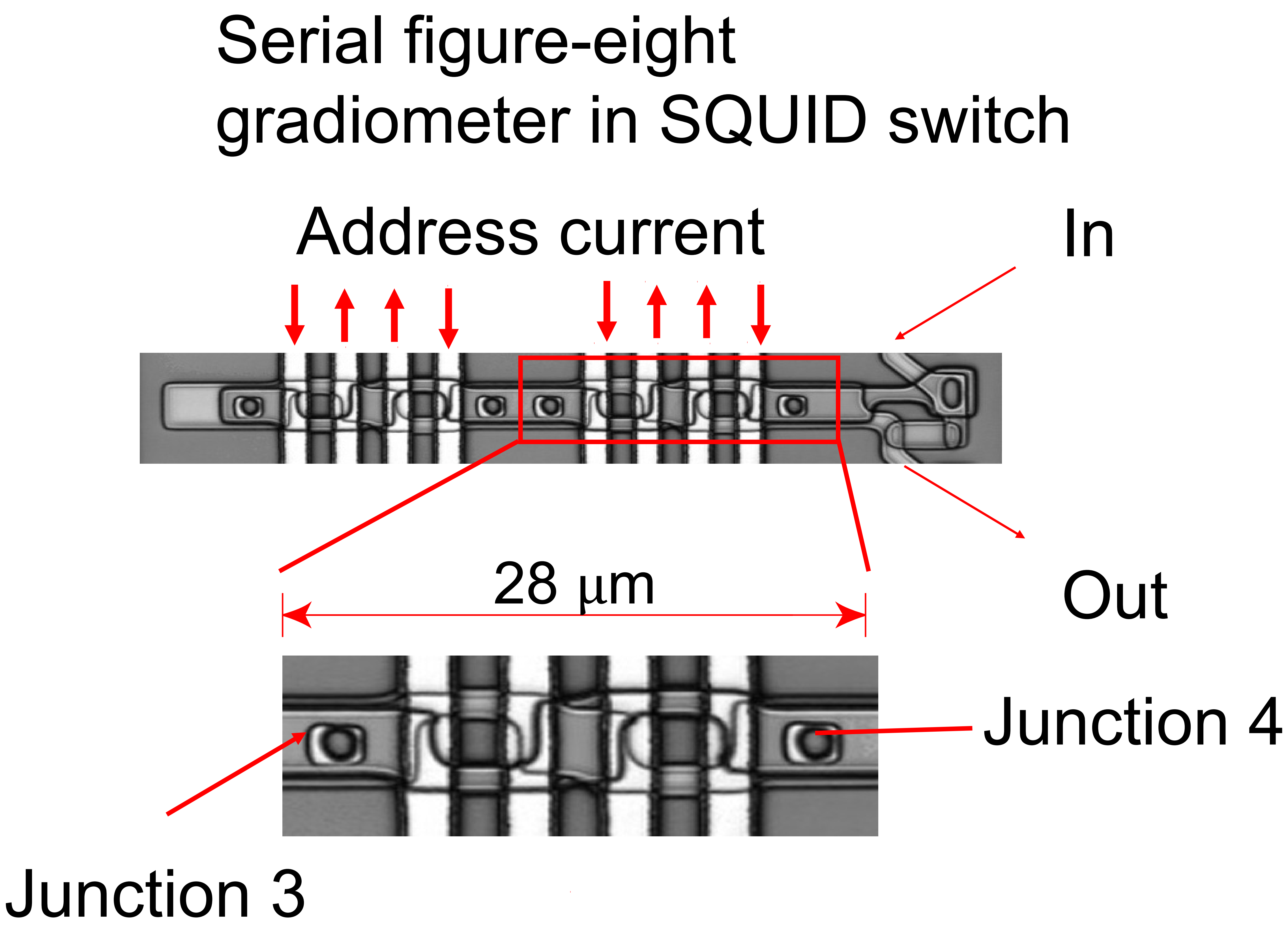
Wide flux-focusing washers are slotted, rather than solid. This serves to:

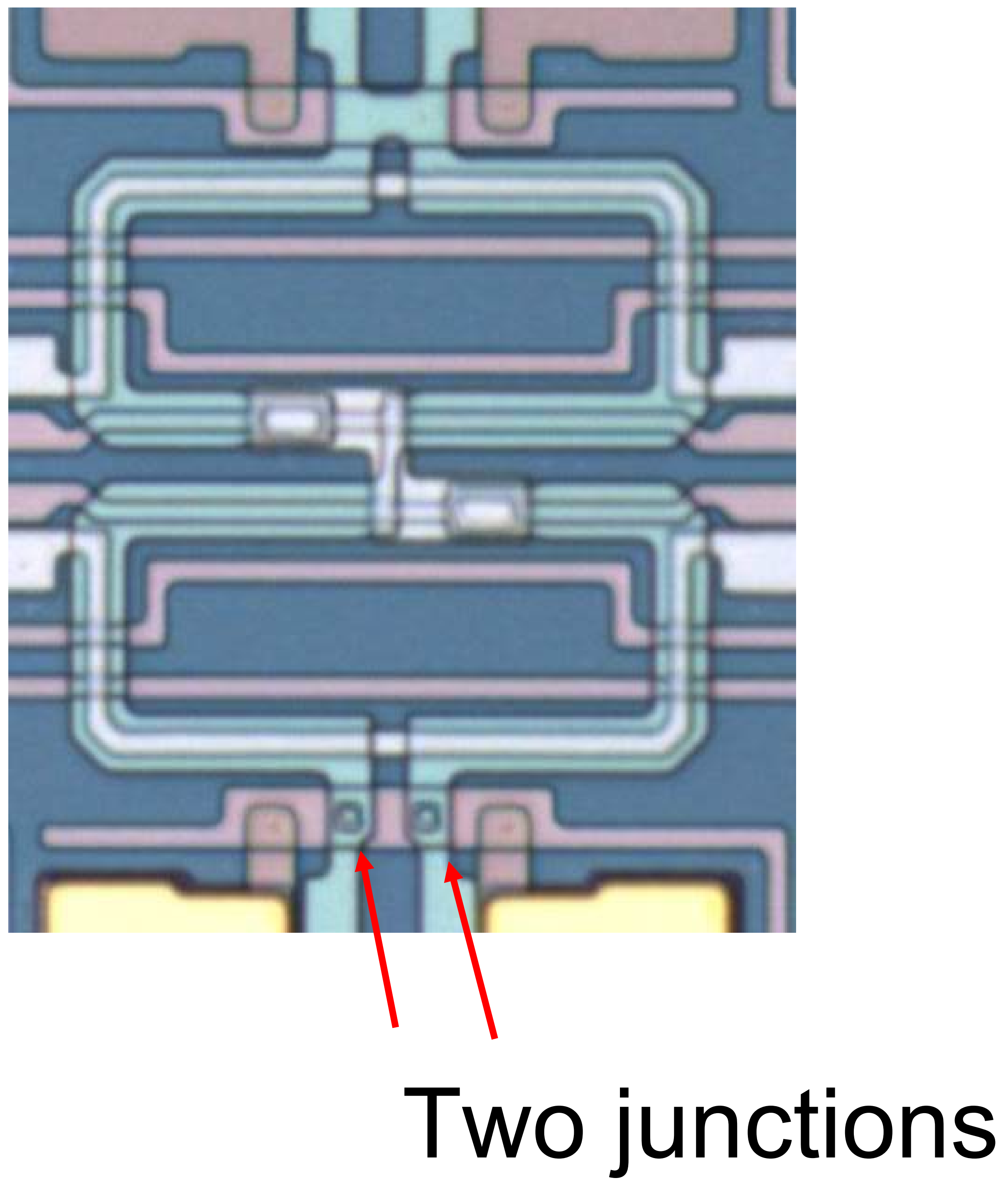
1) Preferentially trap flux in the slots, rather than pinning it in the superconductor.
2) Reduce parasitic capacitance between input wire coils and washer, which is important at ~10 GHz Josephson frequencies
3) This SQUID is also a parallel second-order gradiometer to mitigate pickup from motion of distant trapped flux



RF SQUID using slotted flux-focusing washers

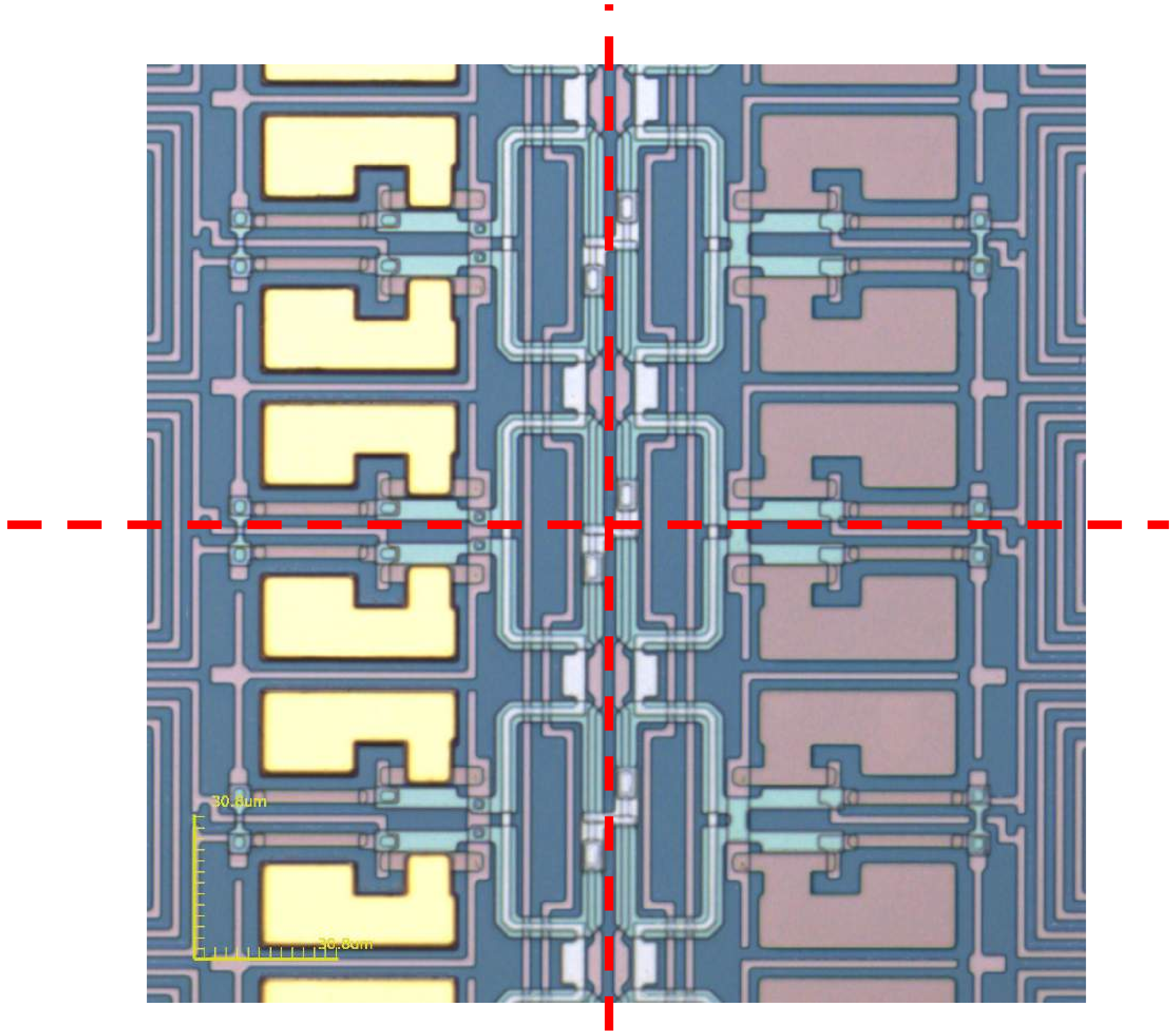
Serial gradiometer pickup loops

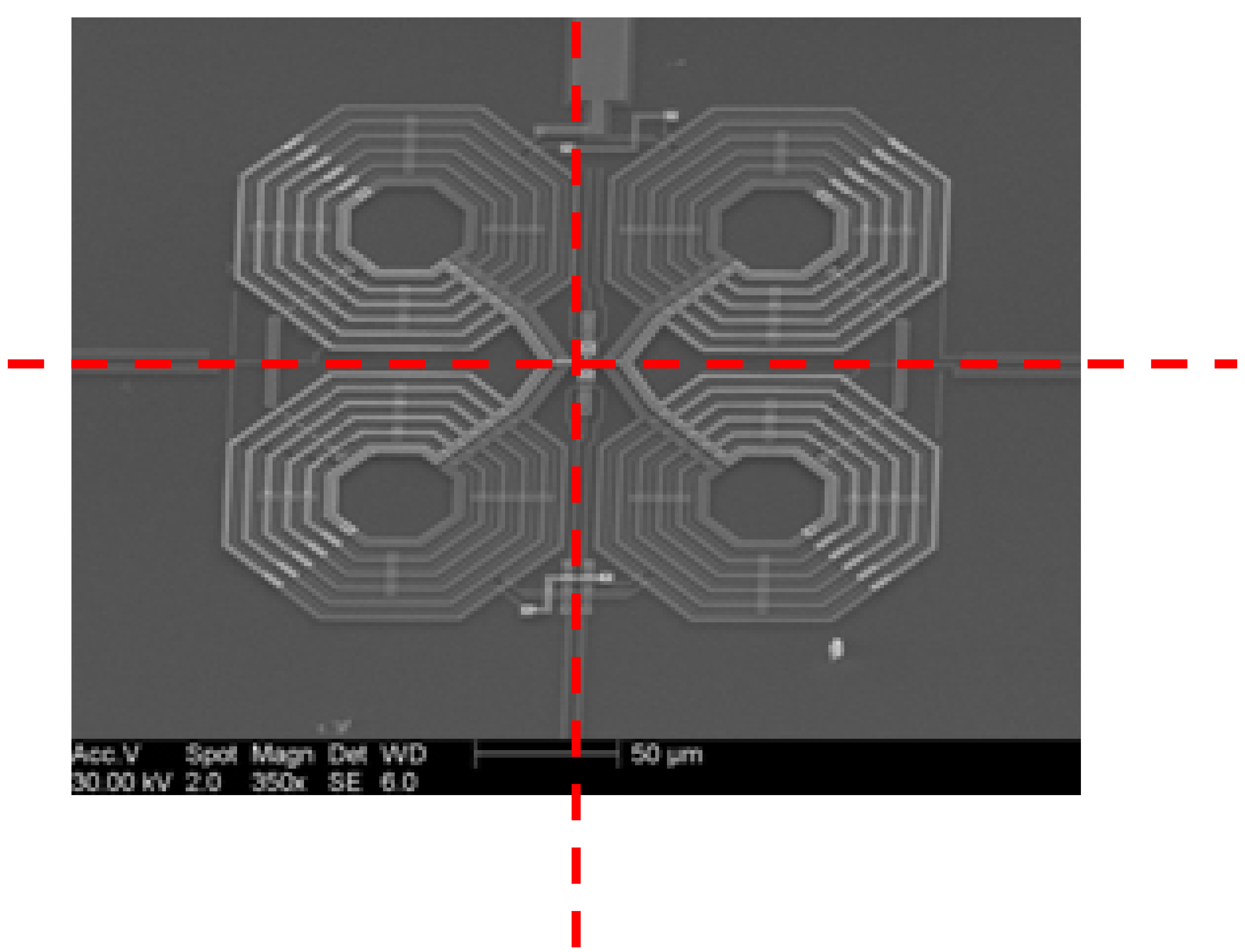




- Analog SQUID circuits are sensitive both to vortex trapping in films / junctions and also to non-zero flux quanta in pickup loops.
- Flux-trapping can be reduced in pickup loops by the use of figure-eight serial gradiometers.
- A serial gradiometer has net zero flux through the loop if the field is uniform. We see no flux trapping in very large arrays of devices at 5 uT.

Highly symmetric designs





- All flux pickup loops are first- or second-order gradiometers.
- We preserve lines of symmetry as much as possible so that uniform fields are not picked up by input loops.
- Distant moving flux presents as a uniform field at the pickup loop, with null coupling.

SLAC Superconducting Foundry

- Devices shown in this talk were fabricated in the NIST Boulder clean room.
- SLAC is now commissioning a superconducting foundry that will produce similar devices

Detector Microfabrication Facility (DMF)
SLAC Arrillaga Science Center

SLAC NATIONAL ACCELERATOR LABORATORY

Director
Hsiao-Mei Sherry Cho

SLAC Superconducting Quantum Foundry

All tools and processes compatible with 150 mm wafers

Lithography	. Stepper - **ASML PAS 5500/100** . Coating/develop Track - **PicoTrack** . Direct Writing Lithography- **Heidelberg DWL66+**
Deposition Tools	. IPCVD/PECVD- **Oxford Cobra** . E-Beam Evaporator - **Lesker** . Double-Angle Evaporator - **Plassys** . Nb, AlOx, Nb Sputtering -**Lesker** . AlMn Sputtering - **Lesker** . Ti, Au, PdAu Sputtering - **Lesker**
Etch Tools	. Florine/Chlorine ICP Metal Etcher – **Oxford Cobra** . Florine ICP Dielectrics Etcher – **Oxford Cobra** . Deep Etcher – **SPTS Rapier** . O2 Plasma Etcher – **Technics**
Metrology	. Profilometer – **KLA P-17** . Film Stress –**K-space** . Auto Wafer Inspection and Probe –**FormFactor-summit** . Ellipsometer - **Woollam** . Spectrophotometer - **Filmetrics** . 4 Microscopes – **3 of Leica microscopes**
Wet benches	. Acid Etching- **JST** . HF Etching -**JST** . Solvent Liftoff -**JST** . Solvent PR Removal- **JST** . Solvent MEMS Release - **JST** . LOR Spin Coating - **JST** . MF26A Wet Bench - **JST** . 6 Spin Rinse Dryers – **1 semitool and 5 Shellback**

Summary

- We have a set of design rules that allow robust performance of single analog SQUID devices in < 50 uT, and large format analog SQUID arrays when cooled < 5 uT.
- It would be valuable to enable operation in Earth’s field (~50 uT) with even large-format analog SQUID arrays.
- I hope that lessons learned from flux engineering in large-format analog SQUID arrays will have some relationship to digital circuits