Superconducting Sensor Development in Support of the Search for the Neutron Electric Dipole Moment

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OUTLINE

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- SQUID Tutorial
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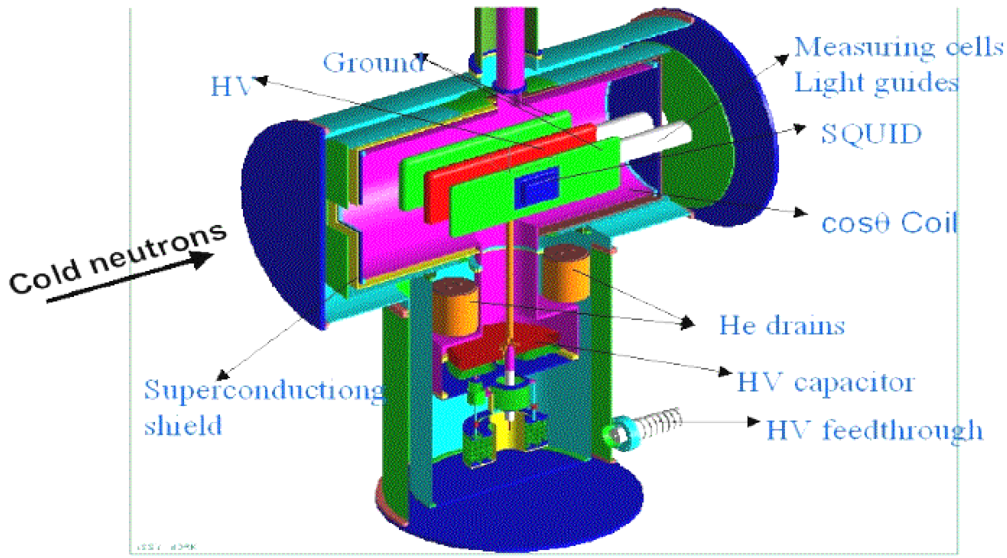


Work supported by DOE under Contract No. DE-FG02-08ER84990

STAR Cryoelectronics

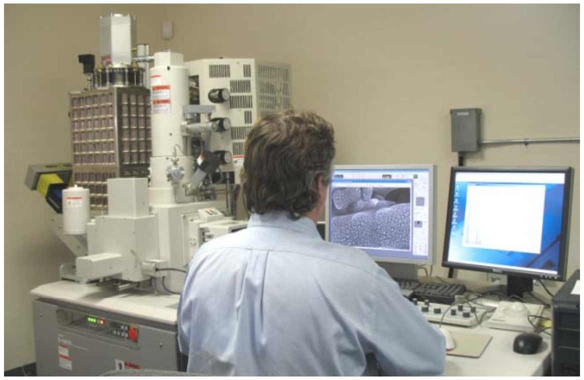
Company Overview

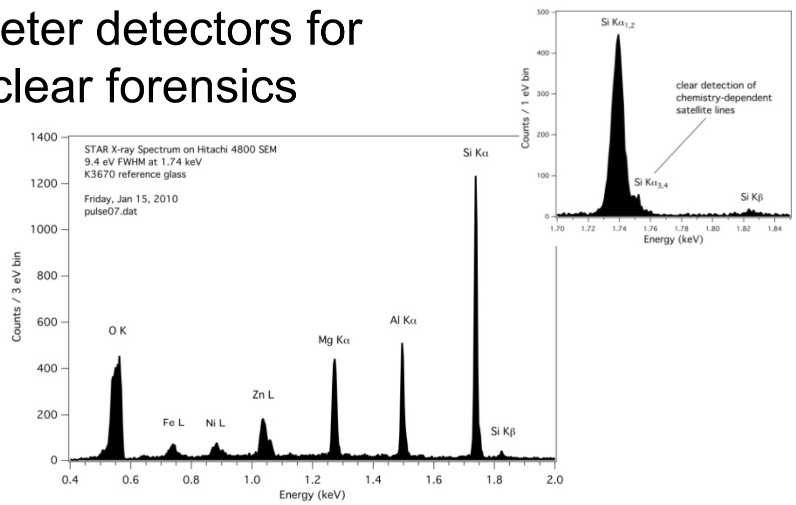
- Founded April 1999
- Licensed magnetic sensing technology, acquired production inventory, and thin-film manufacturing infrastructure from Conductus, Inc. (Sunnyvale, CA) in July 1999
- Acquired building in Santa Fe, NM June, 2001

- 6,000 sq-ft of office, lab, cleanroom and warehouse space; lab and cleanroom expansion in progress
- Total investments in infrastructure over $3,000,000
- 5 employees and 5 contract consultants

Products

- LTS and HTS dc SQUID sensors
- pcSQUID™ - Advanced PC-based SQUID readout electronics
- TES and STJ X-ray and alpha particle detectors
- Mr. SQUID® Educational Demonstration System
- Custom SQUID and thin-film fabrication services
- Next-generation energy dispersive spectrometers based on TES microcalorimeter detectors for X-ray microanalysis and nuclear forensics



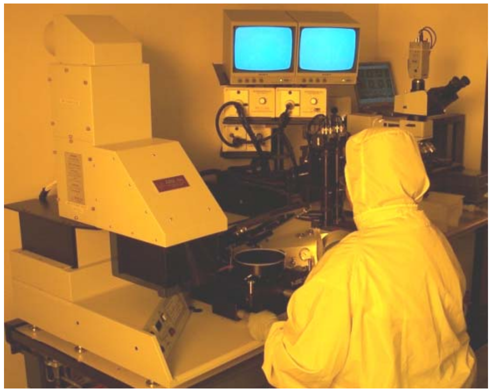
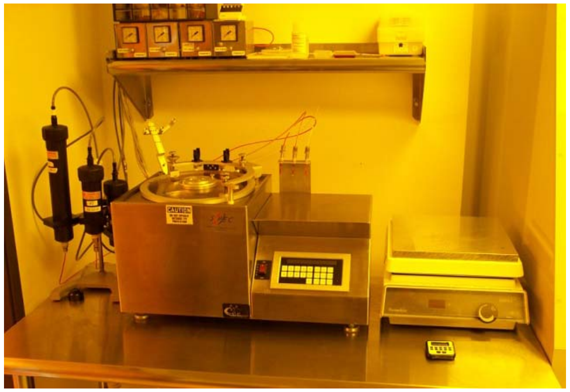


Thin-Film Facilities

- 650 sq-ft clean room; Class 1,000 Deposition, Class 100 Photolithography
- Two multi-target sputter deposition systems (Lesker and UniFilm Tech.)
  - Configured for dc and rf sputtering, 2”, 3”, 4” and 6” wafers
  - *In situ* ion mill for controlled pre-sputter etch, film patterning
  - 99% film thickness uniformity over entire wafer
- Thermal evaporator (Bi), magnetron sputter system (magnetic alloys)
- Ion and Plasma Technologies PECVD system for oxide and nitride
- Plasma-Therm 790 Reactive Ion Etch (RIE) system
  - Etch up to 8” wafers; config. with CF_4, SF_6, C_4F_8, CHF_3, O_2, Ar, H
- Ion Tech Ar ion mill with PBN, up to 6” wafers
- Technics PE-II for oxygen plasma ash and descum, up to 8” wafers
- XeF_2 etcher for Si micromachining
- Dektak III Step Profilometer, FSM 8800 Thin Film Stress Gauge, Hitachi S-4800 II SEM Tencor 6200 Surfscan, Prometrix FT-750

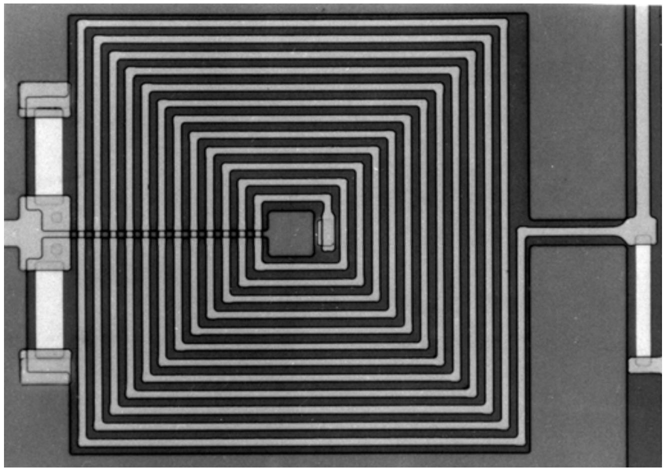
Photolithography

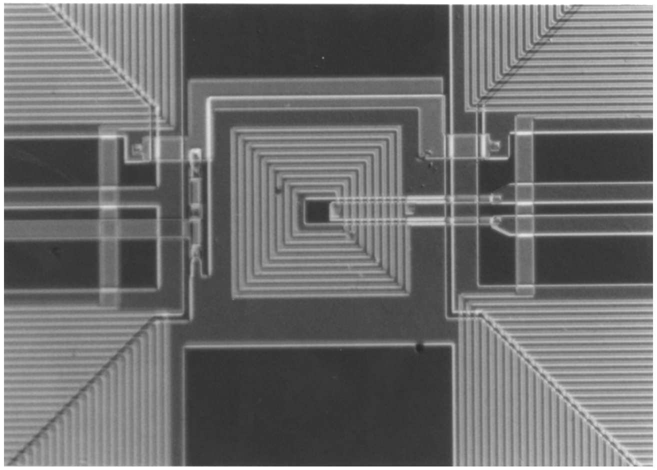
- Brewer Science 100 Coater with multiple auto-dispense controls
  Chucks for 6”, 4”, 3", and 2” wafers, 1 cm^2 substrates
- AB-M Contact Mask Aligner
  Tooling for 6”, 4”, 3", 2”, 1 cm^2 substrates, capability for up to 8” wafers
  Sub-micron resolution, better than 0.5 micron accuracy
  IR camera for backside alignment
- Wet bench with Tek-Vac PRC-2000 Photoresist Curing System, and ultrasonic and DI dump rinse stations
- M150-PC UV Resist Cure Station

LTS SQUID Process

- Nb/Al-AlO$_x$/Nb trilayer process, 100 A/cm^2 typical J_c
- AuPd resistors, 1.3 Ω/sq typical sheet resistance at 4 K
- SiO_2, Si_3N_4 dielectrics
- Four-layer (SNAP) and twelve-layer (SNEP) Josephson junction processes
- Standard processes compatible with 6” wafers for improved throughput
- Patented static dissipative passivation to improve robustness against ESD damage
- HTS bicrystal SQUID process available, step-edge process under development



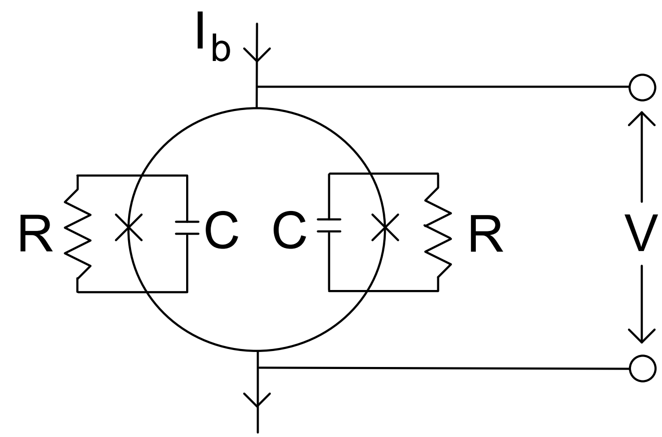


Neutron Electric Dipole Moments (nEDM) Experiment

- Fundamental experiment in nuclear physics research to test Standard Model prediction that $|d_n| < 10^{-32}$ e-cm
- The existence of nEDM would violate Time-Reversal Invariance and Charge Conjugation-Parity (assuming CPT invariance). For $|d_n| \sim 10^{-27}$ e-cm, this would be sufficient to explain the matter-antimatter asymmetry currently not accounted for by the Standard Model
- Experimental cell consists of a three-component fluid of neutrons and ^{3}He atoms dissolved superfluid ^{4}He at ~ 300 mK
- The superfluid ^{4}He moderates a beam of cold neutrons, scattering them to produce a low concentration of ultra-cold neutrons
- The ^{3}He atoms polarize the ultra-cold neutrons via spin-dependent absorption. When an external magnetic field $\boldsymbol{B}_{\text{ext}}$ is applied, the ultra-cold neutron and ^{3}He magnetic dipoles precess in the plane perpendicular to $\boldsymbol{B}_{\text{ext}}$
- A static electric field $\boldsymbol{E}_{\text{ext}}$ applied parallel or anti-parallel to $\boldsymbol{B}_{\text{ext}}$ causes the Larmor precession frequency of the ultra-cold neutron to change proportionally to the neutron electric dipole moment; in particular, if $\boldsymbol{E}_{\textbf{ext}}$ is reversed, $\Delta f \propto |d_n| \cdot E_{\text{ext}}$
- Goal: 100-fold improvement in sensitivity using SQUID sensors

Basic DC SQUID Operation

- Two Josephson junctions connected in parallel, represented by resistively shunted junction (RSJ) model



- **Optimal design parameters**:

  Stewart-McCumber parameter $\beta_c = \frac{2\pi}{\Phi_0} I_c R^2 C < 1$

  Modulation parameter $\beta = \frac{2 L I_c}{\Phi_0} \approx 1$

- **Figure of merit**:

  Energy resolution $\varepsilon = \frac{S_\Phi}{2L} \approx 12 k_B T \sqrt{LC} \propto \sqrt{\frac{C_s}{J_c}}$

- **For lowest noise performance require**:

Low SQUID inductance L	~ 10 pH
Low capacitance C	< 1 pF
High critical current density J_c	> 1 kA/cm^2

I_c: Critical current

J_c: Critical current density

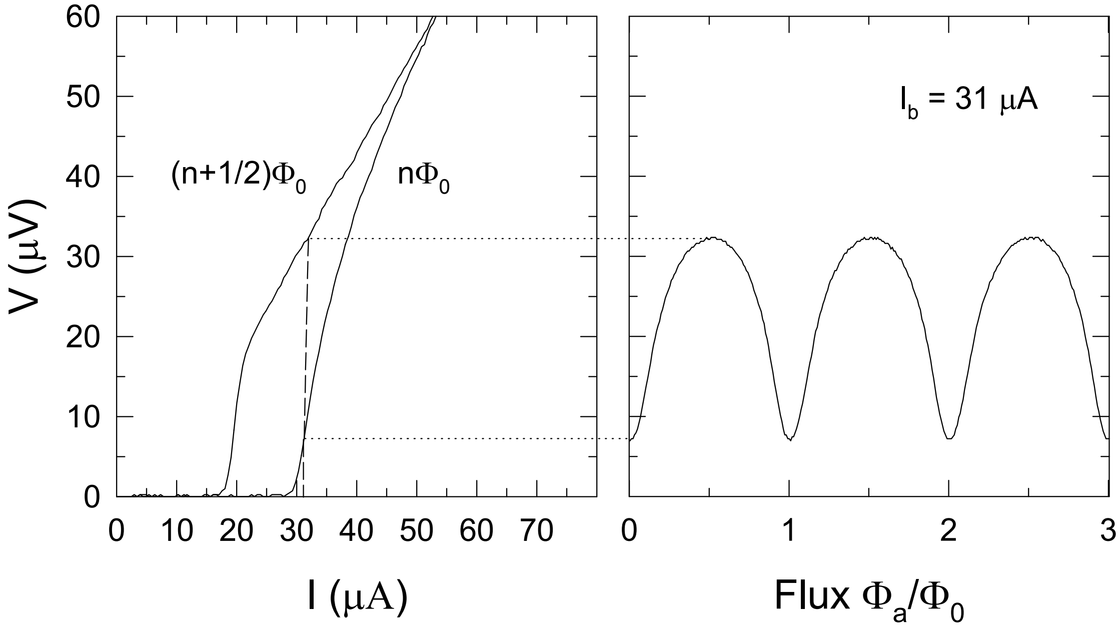
C_s: Specific capacitance

$\Phi_0 = 2.068 \times 10^{-15}$ Wb

Basic DC SQUID Operation

Operation with constant current bias I_b

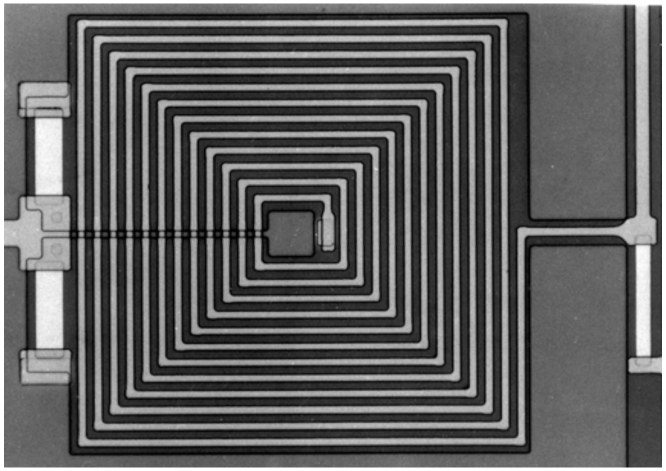
- Voltage output is a period function of applied flux
- Use flux-locked loop feedback electronics to linearize output



Basic DC SQUID Operation

Optimization for practical applications

- Improve flux capture area using pickup loop transformer-coupled to SQUID inductance
- Integrated magnetometers for magnetic field measurements
- Integrated gradiometers for magnetic field gradient measurements



$$S_B^{1/2}(f) = B_\Phi \cdot S_\Phi^{1/2}(f)$$

$$B_\Phi = \Phi_0 \frac{L_p + L_{i,eff} + L_{par}}{M_i} \frac{1}{A_{eff}}$$

$$G_n^{1/2}(f) = S_B^{1/2}(f)/b$$

A_{eff}: Effective area of pickup loop

L_p: Pickup loop inductance

$L_{i,eff}$: Effective input coil inductance

L_{par}: Parasitic inductance

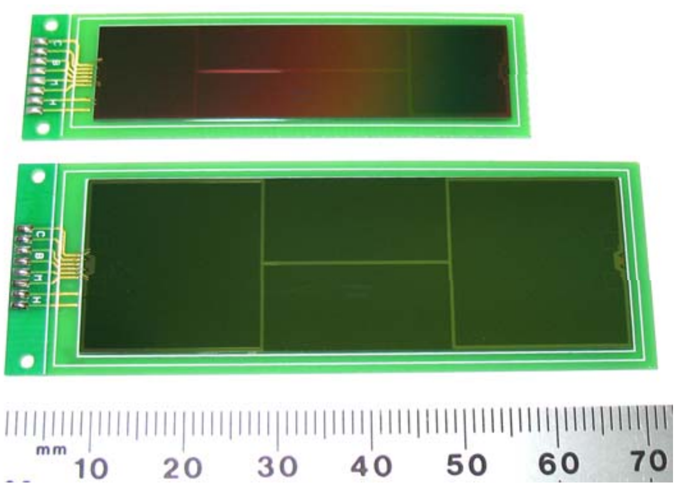
M_i: Mutual inductance of input coil

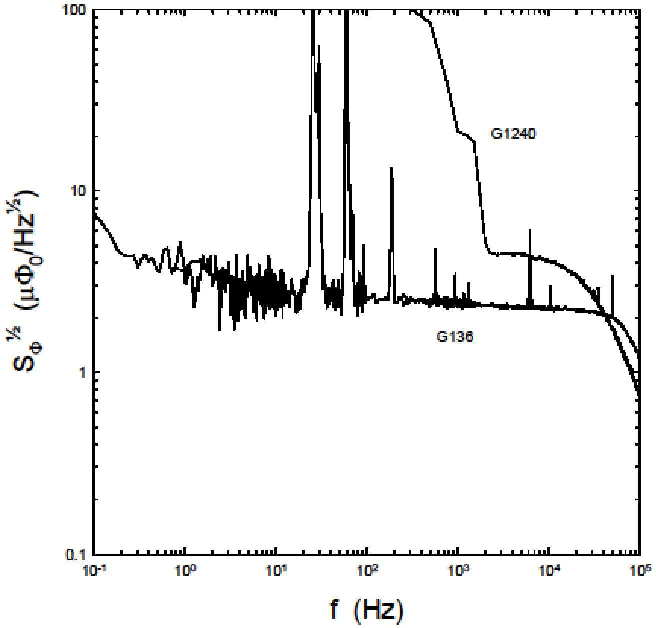
b: Gradiometer baseline

Integrated SQUID Gradiometer Development

Long baseline first-order planar gradiometers

- G136 with 3.6 mm baseline
  - $B_\Phi = 0.63\ \mathrm{nT}/\Phi_0$, $S_B^{1/2} = 1.5\ \mathrm{fT/Hz^{1/2}}$, $G_n = 0.42\ \mathrm{fT/cm\text{-}Hz^{1/2}}$
- G1240 with 4.0 mm baseline
  - $B_\Phi = 0.\ 3\ \mathrm{nT}/\Phi_0$, $S_B^{1/2} = 0.9\ \mathrm{fT/Hz^{1/2}}$, $G_n = 0.23\ \mathrm{fT/cm\text{-}Hz^{1/2}}$ (estimated values)

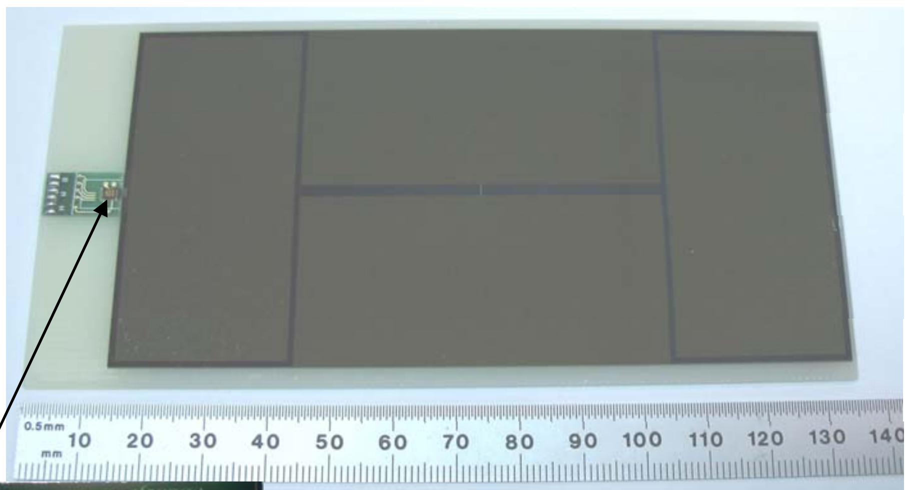


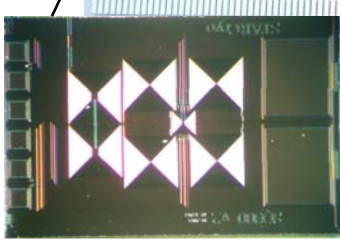


Ultra-Sensitive Gradiometer Development

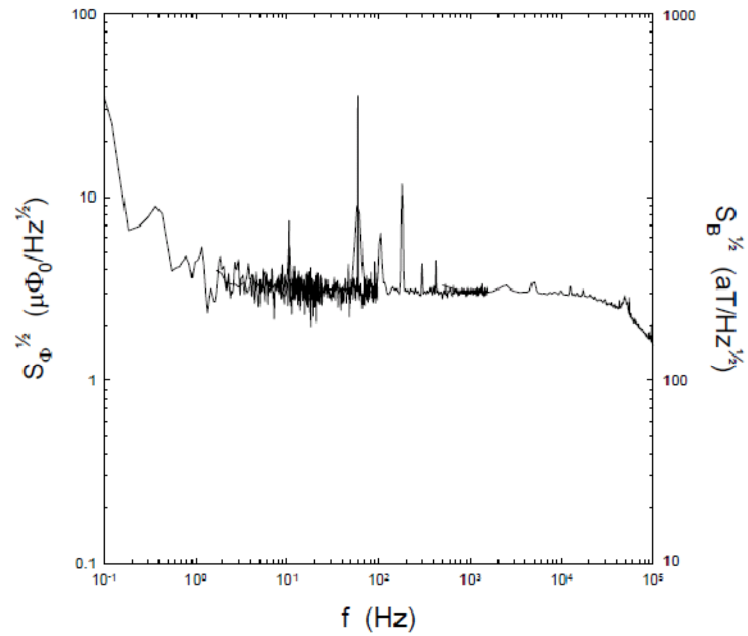
Multi-chip module with pickup loop chip and SQUID chip

- Fabricate four-layer pickup loop with 90 mm baseline on 150 mm wafer
- Wire bond to input of separate SQ300 SQUID chip with Nb ribbon
- B_Φ = 0.105 nT/Φ_0, $S_B^{1/2}$ = 0.3 fT/Hz$^{1/2}$, G_n = 0.033 fT/cm-Hz$^{1/2}$ (est. noise values)





SQ300 chip, 2 mm × 3 mm



Typical rms flux noise of SQ300 with open input (left axis), projected field noise with pickup loop (right axis)

Ultra-Sensitive Gradiometer Development

Issues

- Need extremely robust fabrication to reduce risk of damage in strong *E*-field, or remotely located SQUIDs (outside of main experimental cell)
- Remotely locating SQUID requires high input inductance design with very high input coupling (M_i)

$$B_\Phi = \Phi_0 \frac{L_p + L_{i,eff} + L_{par}}{M_i} \frac{1}{A_{eff}}$$

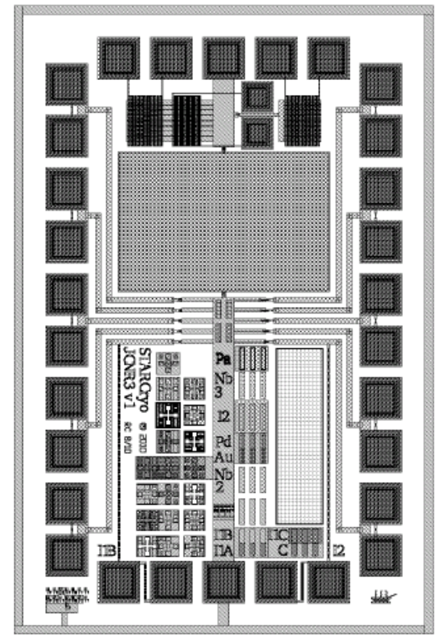
- Accomplished using large, multi-turn input coils
  - Introduces large parasitic capacitance that can degrade performance
  - Requires interlayer insulation with low dielectric constant

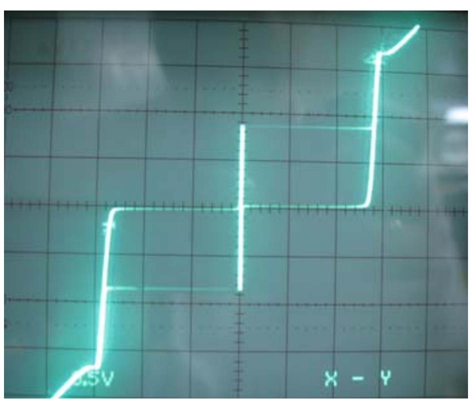
Improved SQUID Process Development

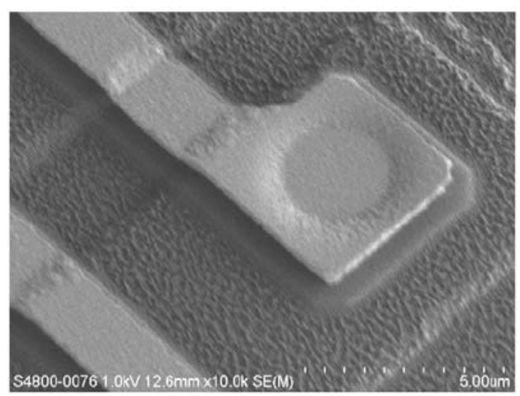
Key Improvements

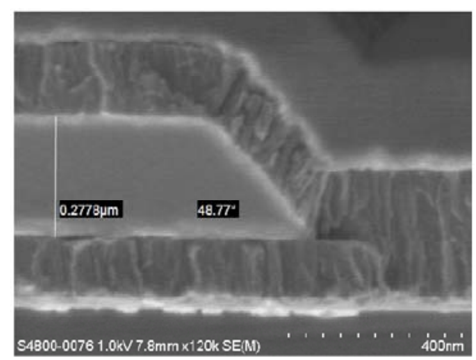
- Josephson junctions defined using dry etch (RIE) process
- PECVD SiO_2 used for all interlayer dielectrics
- New Nb and via RIE processes to improve cross-overs
- Dramatic results for via, cross-over I_c
  - Junction vias (2 μm) ~ 40 mA
  - Wiring vias (2.5 μm) ~ 200 mA
  - Wiring cross-overs ~ 200 mA (~10 MA/cm^2)

Process Test Chip, 2 × 3 mm







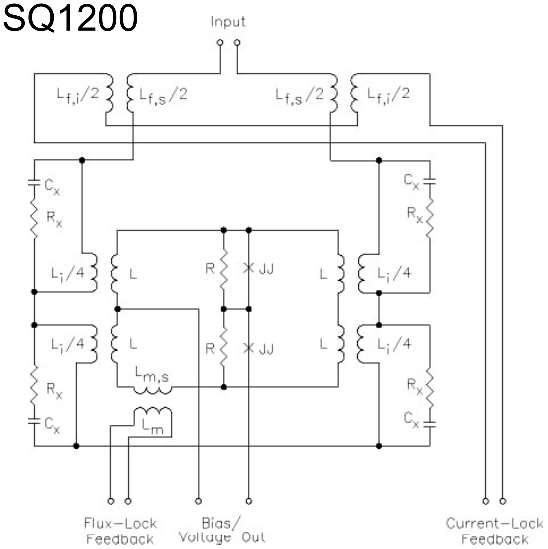


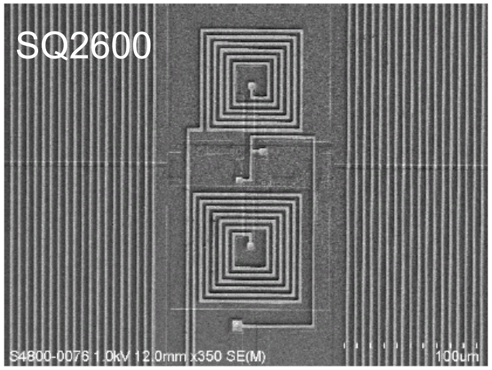
SQUIDs for High Inductance Loads

Two candidate designs:

- ► **SQ1200** (four-washer series-parallel, symmetric feedback)
- – 1200 nH input, 0.13 mA/Φ_0 input coupling
- – ~4 $\mu\Phi_0$/Hz^{½} flux noise with matched load
  (~500 fA/Hz^{½} current noise)
- ► **SQ2600** (two-washer parallel, symmetric feedback)
- – 2600 nH input, 0.096 mA/Φ_0 input coupling
- – ~3 - 4 $\mu\Phi_0$/Hz^{½} flux noise
  (~300 to 400 fA/Hz^{½} current noise; lowest available)

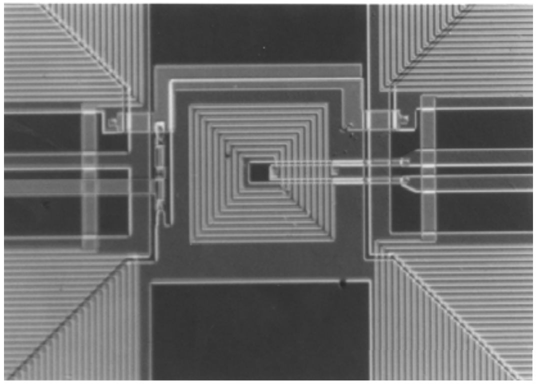
SQ1200





SQ300 Parameters

- 300 nH input inductance
- 0.44 mA/Φ_0 input coupling

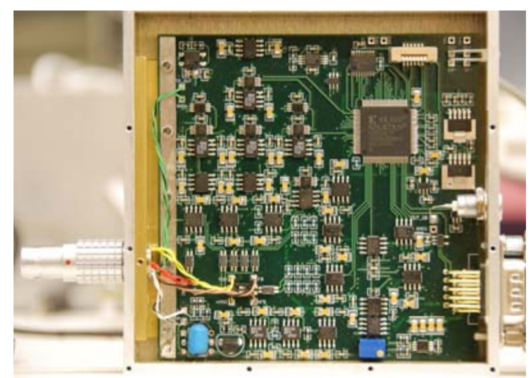


SQUID Readout Electronics Development

Overview

- Robust design based on flux modulation technique
- Current design developed at Conductus, released in 1996; many key components no longer available
- Updated design takes advantage of newly available high-performance amplifiers
- Useable bandwidth extended from 100 kHz to >1 MHz
- All drive signals and feedback loop parameters configurable via software
- Single-channel design successfully completed, eight-channel design underway

Current single- and eight-channel feedback loops



Prototype single-channel feedback loop assembly

Summary

SQUID Gradiometer Development

- Ultra-sensitive integrated SQUID gradiometers and magnetometers successfully developed
- New robust SQUID fabrication process implemented
- Successfully developed new high input inductance SQUIDs

SQUID Readout Electronics Development

- Developed next-generation designs for single-channel and multi-channel applications
- Bandwidth extended by more than order of magnitude
- Flexible design architecture with software control