The History of SQUIDs

Superconducting Quantum Interference Device

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Riverside, CA, USA
Post-WWII Innovations

- Microwave oven (1946)
- Magnetic resonance (1946) Nobel Prize (1952). Led to MRI
- Transistor (1947) Nobel Prize (1956). Enabled digital computers, etc
- Instant photography (Polaroid 1948)
- Maser (1953)
- Artificial satellites (Sputnik 1957) Eventually led to GPS, comsats, etc.
- BCS Theory (1957) Nobel Prize (1972)
- Laser (1960) Enabled CDs, DVDs, optical memory, etc.
- Xerography (1960) Led to copiers, laser printers, etc.
- Observation of the flux quantum (1961)
- Tunneling in superconductors (1960). Nobel Prize (1973)
- SQUID (1963)
- Cosmic background radiation (1964) Nobel Prize (1978)

SQUID Is Based on Earlier Research

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Description</th>
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<tbody>
<tr>
<td>1950</td>
<td>F. London</td>
<td>Electrodynamics of superconductors</td>
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<td>1957</td>
<td>J. Bardeen, L. Cooper, &amp; J.R. Schrieffer</td>
<td>Cooper pairs Microscopic theory of superconductors</td>
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<td>1961</td>
<td>I. Giaever</td>
<td>Observation of tunneling in superconductors</td>
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<td>1961</td>
<td>B.S. Deaver &amp; W.M. Fairbank M. Doll &amp; M. Neubauer</td>
<td>Direct observation of the flux quantum $\Phi_0 = h/2e$</td>
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<td>1962</td>
<td>W.A. Little &amp; R.D. Parks</td>
<td>Free energy of the flux quantum</td>
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<tr>
<td>1962</td>
<td>B.D. Josephson</td>
<td>Theory of supercurrent tunneling</td>
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<tr>
<td>1963</td>
<td>P.W. Anderson</td>
<td>Interpretation of Josephson effect</td>
</tr>
<tr>
<td>1963</td>
<td>P.W. Anderson &amp; J.M. Rowell</td>
<td>Experimental confirmation of Josephson tunneling</td>
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Early Technology of the 1960’s?

• Mostly analog, vacuum-tube electronics
  – Few equipment suppliers
  – Oscillators
  – Oscilloscopes
  – Polaroid cameras
  – Strip-chart and X-Y recorders

• Source of LHe an issue

• Glass LHe dewars with LN2 glass jacket dewars

• Manuscripts
  – Hand written
  – Literally “cut and paste” typewriter editing
  – “Carbon” copies
  – Limited availability of the new Xerox copiers
  – Hand-plotting on graph paper
  – Traced on vellum for presentations and publications

• Presentations like this used 3” x 4” photographic glass slides
Ford Research Team

Lambe, Zimmerman, Silver, Jaklevic, Mercereau
Phase One: Thin Film Devices 1963-64

- Started with Lambe’s observation of anomalous microwave signals during ENDOR experiments
  - LHe cryostat in a large electromagnet
  - Ultra-low power X-band heterodyne spectrometer
- *Periodic* in magnetic field *and* in microwave power
- Temperature dependent
- Attributed to indium solder contacts and flux quantization
- Lambe, Jaklevic, Mercereau, and Silver
First Thin-Film Tunnel-Junction “Interferometer”

December 23, 1963

Fabricated by Robert Jaklevic
Microscope slide substrates
Stainless-steel shim shadow masks
Formvar insulating aperture “A”
Sn thin films
Task Was to Measure and Record
Josephson Critical Current vs. Magnetic Field

- Hysteretic I-V characteristic on oscilloscope required current cycling
- Low resolution measurement on oscilloscope
- Background magnetic noise interference

- Sinusoidal current source produced voltage train of variable-width square waves
- Synchronous detector (Lock-In amplifier) generated DC voltage linear in critical current
- Automatic X-Y recording
PHYSICAL REVIEW LETTERS

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NUMBER 7

QUANTUM INTERFERENCE EFFECTS IN JOSEPHSON TUNNELING

R. C. Jaklevic, John Lambe, A. H. Silver, and J. E. Mercereau
Ford Scientific Laboratories, Dearborn, Michigan
(Received 18 January 1964)

Recorded on Monday
December 23, 1963
Superconducting Aharonov-Bohm Interferometer

- Influence of the vector potential in a magnetic-field-free region
- Miniature coil inserted in a small sleeve

\[ B = \text{curl} A \]
\[ \Phi = \oint A \cdot dl \]
Phase 2: Nb Point-Contact Devices 1964 – 68

Crossed 8 mil Nb ribbon

Tunnel Junction

Point contact

V (μV)

I (mA)

100 mg
Niobium Point Contact SQUIDs

- SQUIDs machined from bulk Nb
- Pointed 000-120 Nb screws
- Screws were adjustable in-situ with long wrench
- Devices were sealed in stainless steel tubing with He gas
- Moved to RF measurement
- Silver and Zimmerman
Typical RF SQUID Measurement System

- Gain of Q from LC resonance circuit
- Wideband response
- Single cable connection to SQUID
- Homodyne detection provides both amplitude and phase information
RF SQUID Multiple Exposure Data

Composite Data Provides Quantitative Calibration
SQUID Quantized States and Transitions

Theory

\[ \beta = \frac{2\pi LI_C}{\Phi_0} \]

Measurement

Distinguished presentation 1-SQ-D-1 given at ISEC, 28 July-1 August 2019, Riverside, USA.
Ford SQUID Summary

- Spurious microwave observations in P-doped Si
- First 2-junction interferometer (DC SQUID)
- deBroglie wavelength experiment
- "Point contact" DC SQUID
- London moment measurement
- "Point contact" RF SQUID
- Flux quantum model
- Resistive RF SQUID
- SQUID microwave oscillator
- SQUID oscillator-detector-parametric amplifier


Thin-film junction devices

Bulk Nb point contact devices
First MCG: 12/1969 at National Magnet Lab, MIT

Jim Zimmerman, NBS (NIST) Boulder: test subject
David Cohen, National Magnet Lab
Benjamin Lax, National Magnet Lab
Ed Edelsack, Office of Naval Research
SQUID vs. Josephson Junction

- The Josephson junction is the critical element of a SQUID since it is the non-linear part.
- It has a small but non-linear inductance
  \[ L_J = \frac{\Phi_0}{2\pi i_c \cos \theta} \]
- It is difficult to match the inherent Josephson inductance, parasitic capacitance, and resistance of the Josephson junction
- The SQUID inductance provides the most effective method of coupling to the junction inductance,
  \[ L_{SQ} \approx L_J \]
- Flux quantization is inherent in the physics of both the junction and the SQUID loop
Notable Developments

- IBM Josephson latching logic computer project
- IC lithographic processes
- Washer SQUIDs
- Nb AlOx tunnel junction process
- Japan computer projects
- A/D converters
- SFQ circuitry
- HTS technology
- Mixed-signal electronics
- SQUID Qubits
SQUIDs have impacted at least these areas

• Sensing magnetic fields from many sources
• A/D converters
• Cryogenic imagers
• Mixed-signal electronic devices and systems
• Digital computing
• Quantum computing
RF SQUID Video Recordings