Scanning SQUID Microscopy

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Superconducting Quantum Interference Device (SQUID)

„direct current“ (dc) SQUID

current

external magnetic flux $\Phi_e$

Josephson junctions

voltage $V_{dc}$

periodic response to external flux $\Phi_e$

period: $\Phi_0 = h/2e \approx 2.07 \times 10^{-15}$ Vs (magnetic flux quantum)

magnetic flux of the earth’s field: $3 \times 10^6 \Phi_0$ per cm$^2$

Josephson effect

Josephson junction = two weakly coupled superconductors („weak link“)

flux quantization

in a superconducting ring

+
dc SQUID: flux-to-voltage transducer

Periodic voltage-flux characteristics

Flux feedback electronics $\rightarrow$ linear voltage-to-flux response up to frequency $f \sim 20$ MHz

Magnetic flux noise:

$$\Phi_n \sim 1 \mu\Phi_0 \cdot (\Delta f/\text{Hz})^{1/2}$$

$\Delta f$: measurement bandwidth

Operation temperatures: $\sim 4$ K (liquid Helium) or $\sim 77$ K (liquid Nitrogen)
typical designs:

- thin film structures (~100 nm thick)
- lateral structures by micro-/nano-patterning

**field noise:**

\[ \Phi_n / A_{\text{eff}} = B_n \sim 1 \text{ fT} \times (\Delta f/\text{Hz})^{1/2} \]

\( A_{\text{eff}} = \text{effective sensor area} \)

@ \( f > 1 \text{ Hz} \)

1 fT \( \times 6 \times 10^9 = \text{earth magnetic field} \)

Paper thickness 0.1 mm \( \times 6 \times 10^9 = \text{radius of the earth} \)

**Important application:** Magnetoencephalography (MEG)
SQUID Microscopy
= scanning probe technique

sample is scanned relative to SQUID (or vice versa)
→ SQUID detects local magnetic field distribution
→ combines high flux sensitivity with spatial resolution

(a) sample in atmosphere

(b) sample in vacuum

SQUID

T=4 K or 77K

cold (variable T)

room temp.
SQUID Microscopy:
Sample in vacuum @ variable temperature

→ small sample-to-SQUID distance possible

spatial resolution determined by:
• sample-to-SQUID distance
• SQUID size

→ spatial resolution ~ 1 µm (~100 nm feasible → „nanoSQUID“)

$\Phi_n \sim 100 \, n\Phi_0 \cdot (\Delta f/\text{Hz})^{1/2}$

$B_n \sim 1 \, \text{nT} \cdot (\Delta f/\text{Hz})^{1/2}$

$\mu_B = \text{Bohr magneton}$
SQUID Microscopy: Sample in vacuum @ variable temperature

→ setup under construction
SQUID Microscopy
Sample in atmosphere @ room temperature

→ large sample-to-SQUID distance
determined by SQUID-to-window gap + window thickness

→ spatial resolution > 100 µm

1 Dollar bill
→ magnetic ink

J. Clarke, Scientific American 08/1994
Magnetic Relaxation ImmunoAssay (MARIA)

antibodies linked to magnetic labels (nanoparticles)

relaxation time for bound particles

\[ \tau_N \gg \tau_B \text{ (unbound)} \]

magnetic relaxation measured by SQUID

→ study of binding reactions between bio-molecules

no need for
- immobilization of targets
- separation of unbound tags

“Oh, no, he’s quite harmless. ... Just don’t show any fear. ... SQUIDs can sense fear.”