Nanomagnetometry: microSQUID, Hall microprobe…

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1 The microSQUID

Standard SQUID

The SQUID *per se* is a superconducting loop with two Josephson junctions. The tunneling current through each junction is a function of the difference in the phases of the superconducting wave-function between the two sides of the junction. When a current is applied to it, the SQUID is superconducting up to a critical current periodic on the magnetic flux ϕ through the loop, with period $\phi_0 = h/2e$. It's $I(V)$ curve beyond the critical current has also a ϕ_0-periodic dependence on ϕ, which is a means of indirectly measuring ϕ.

The SQUID is coupled to the sample through a pick-up coil mounted as a gradiometer. The large diameter of the coil (a few cm) makes it a very sensitive field sensor, but a not so good magnetic moment sensor.

MicroSQUID

It is an hysteretic DC-SQUID with a multi-valued $I_c(\phi)$. A periodic measurement of I_c allows the determination of ϕ. The direct coupling to the sample, without a pickup-coil, makes it a poor field sensor but also an outstanding magnetic moment sensor. The key to high sensitivity is a good coupling to the sample. Coupling can be achieved by:

far-field: in the case of large samples with big total moment (crystals of single-molecule magnets)

deposition of the sample on the SQUID: for samples of a few tens of nm to a few hundreds of nm

embedding the sample in the SQUID: for samples as small as 3 nm ($\approx 10^3 \mu_B$)

Measurement modes

In *feedback mode*, a feedback loop applies an external flux to the SQUID. The variations of this flux compensate the variations of the flux made by the sample in order to keep the total flux on the SQUID (and therefore I_c) constant. In this mode we can measure hysteresis loops for an applied field in the plane of the SQUID: the applied field does not contribute to the flux in the SQUID. This mode is used to study micron-sized particles and crystals of single-molecule magnets.

In *cold mode*, the SQUID is kept at constant current below I_c. The magnetic switching of a nanoparticle induces a SQUID transition. This mode is therefore adapted to the study of switching field statistics of nanoparticles.

In *blind mode*, a "probe" field is first applied that may (or may not) reverse the magnetization of the nanoparticle, with the SQUID switched off. The final state of the particle is then measured with the cold mode. This mode allows the measurement of magnetic astroids in situations where the SQUID would not normally work (with an out-of-plane applied field, at high temperature, in the presence of RF field).

2 Other techniques

The Hall microprobe

Electrons in a two-dimensional electron gas (2DEG) patterned in a double-cross shape feel the Lorentz force induced by a field perpendicular to the 2DEG plane. The Hall voltage on each cross is amplified, then the two voltages are subtracted. This makes a gradiometer setup sensitive to the field of a sample close to one of the crosses, but insensitive to the uniform applied field.

The Hall microprobe is less sensitive than the microSQUID but has broader working conditions (total field, perpendicular field, temperature).

Electron spectroscopy

A conducting sample of a few nm is coupled to two leads via tunnel junctions. In order to put an electron into the sample, the generator has to provide the Coulomb energy needed to charge the capacitances of the junctions and extra Kinetic energy to have the electron reach one of the discrete energy levels in the sample. The discrete spectrum of the sample is reflected in discrete current steps in the $I(V)$ curve.

On a magnetic sample, the levels are not degenerate at zero field. Due to spin-orbit interactions, they depend in a non-trivial way on the magnetization of the sample. A magnetization reversal appears as a discontinuity in the positions of the current steps as a function of the applied field.