Scanning Hall-Probe Microscopy

At the Institut NÉEL, we develop many highly sophisticated scanning probes to use for a large variety of experiments under extreme conditions of magnetic field, low temperature and vacuum, as well as microscopes sensitive to charge, to currents, to magnetic fields, forces, electrical potential, to name just a few. Here, we wish to highlight a microscope which does not operate under extreme conditions but has the advantage of being extremely versatile. This microscope is a “Scanning Hall-Probe Microscope” (SHPM) which allows us to do direct, quantitative measurements of the spatial variation of a magnetic field, that is to “map” the field.

Our sensor uses the Hall Effect, the transverse voltage induced when a magnetic field is applied perpendicular to the flow of an electric current. It can measure over a large magnetic field range while giving a simple, quantitative relation between the measured transverse voltage and the magnetic field deflecting the electric charges. It was developed in particular for the quantitative study of the stray magnetic fields produced by high performance micro-magnet samples but can have many other uses. The scanning probe, being sensitive to a sample’s long-range stray field can survey encapsulated and somewhat rough surface states as it can maintain sufficient resolution while scanning at a moderate distance above the sample’s surface.

The spatial resolution of the Hall probe microscope is determined by several factors: the size of the sensor (which is a “Hall cross”), the intrinsic electrical noise of the material used to form the Hall cross, the distance between it and the source of the stray magnetic field, and the distance between adjacent field sources. Evidently, the closer the Hall cross can be brought near the sample, the better the spatial resolution.

Our Hall probes are fabricated in a GaAs/AlGaAs semiconductor heterojunction grown on a gallium arsenide substrate. A very high mobility, two-dimensional electron gas (2DEG) lies at only 50 nm below the surface of the semiconductor chip. Using laser lithography, a photomask is structured to allow a wet chemical etch of 100 nm depth that leaves intact a “+” shaped 2DEG, the Hall cross. Four ohmic contacts are created by diffusing a metallic AuGe alloy into the ends of the bars of the 2DEG forming the Hall cross. Four ohmic contacts are created by diffusing a metallic AuGe alloy into the ends of the bars of the 2DEG forming the Hall cross. Four ohmic contacts are created by diffusing a metallic AuGe alloy into the ends of the bars of the 2DEG forming the Hall cross. An additional deep etch, the “mesa etch” of at least 10 microns depth, is made in order to place the Hall cross exactly at the corner of the chip (see Fig. 1).

The sensitivity of a Hall probe is expressed by the “Hall resistance” (the ratio of the transverse voltage to the electron current). Our 2DEG has a Hall sensitivity of 200 Ω per Tesla. Hall probes of size 1 to 5 microns have been prepared. A limiting factor is the in-line resistance of the bars that form the Hall cross; the narrower the cross’s bars, the higher the longitudinal resistance and thus the higher the Johnson noise.

The Hall probe is inclined at a slight angle (<5 deg.) as we approach it to the sample surface. Keeping the probe as close as possible to the surface during scanning is a challenge that we tackle by coupling a sensitive force sensor with it. The probe is attached to a piezoelectric-quartz tuning fork, similar to those used in watches. The resonance frequency of the tuning fork shifts as the Hall probe comes into close proximity with the sample surface, and this frequency shift is used in a control loop to retract or approach the GaAs chip as necessary, in order to maintain the proximity force constant while scanning. The scanning-microscope uses high resolution, long-range stepper motors for its displacement. The smallest step size is of the order of 100 nm.

The development of this new generation of mesa-etched and precision-diced Hall sensors enables close approach to the sample surface (<2 microns) resulting in images with highly resolved features (Fig. 2). The spatial resolution of the magnetic field distribution is limited by the size, ~1 micron, of the Hall probes. Depending on the acquisition time, the magnetic field resolution in our measurements is about 100 μTesla/√(Hz).

Our Scanning Hall-Probe Microscope SHPM system demonstrates the usefulness of a combination of concepts formerly used separately, namely tuning-fork feedback-based height control, scanning with stepper motors, Hall probe measurements, and customized nanofabrication. It is the tool of choice for quantifying the stray fields produced by micro-magnets, which have many applications in bio-medical studies and MEMS (micro-electromechanical systems).

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FURTHER READING...
“A scanning Hall probe microscope for high resolution, large area, variable height magnetic field imaging”
G. Shaw, R.B.G. Kramer, N. Dempsey and K. Hasselbach