NEED

Nano- and material science have led to a plethora of new smart materials with a variety of functional properties. Local details of surface current flow and variation of given current components are necessary to be identified for design, fault location and further technological improvement. These measurements are not well established or not accessible.

We intend to provide a **device which is capable of micron scale mapping of electric currents**. This is needed in the following systems:

- To investigate the poor conductivity of additively manufactured metals in 3D printed microchips.
- Conducting transparent media being developed for next-generation touch screens. (Transparent electrodes based on silver nanowires and graphene.)
- Percolation processes in electro-chemical batteries and chemical gas sensors.

These systems have similar needs in common, such as

- The simultaneous need for microscopically high spatial resolution without compromising the electrical current sensitivity.
- Rapid sample exchange, wide range of permissible sample sizes and shapes

APPROACH

Quantum gas microscopy: An elongated cold atom probe is placed close to the sample surface where its distribution directly maps the magnetic field induced by the current flowing in the sample. The atomic distribution is imaged and the surface currents can be reconstructed from the image.

Performance improvement and sample flexibility are under development. Key directions to address are improved optical imaging, closer atom-sample approach and choice of interaction-tunable atomic species.

We aim for the transformation of proof-of-principle quantum gas microscopy to a versatile instrument at a later stage of the development.

Ambient conditions for cryogenic and non-UHV compatible samples will be adjusted in advanced instrument components.

Performance tests and example sample measurements will be separated to allow for more efficient development.

BENEFITS

- Unique combination of spatial resolution and sensitivity to current variation measurement not directly accessible with any competing technique.
- Large 1D or 2D field of view in the mm-range
- Single-shot 1D or 2D measurements create instantaneous (~10 µs) field maps (snapshots) avoiding the need for time-consuming and signal-blurring scans.
- (Quasi-) homogeneous offset fields of tens of Gauss do not affect instrument.

Further benefits are feasible for advanced application needs:

- Dynamical processes can be captured in short dynamic imaging-sequences or stroboscopically due to short data acquisition times.
- (Quasi-) homogeneous offset fields of tens of Gauss do not affect the instrument performance.

COMPETITION

Bose-Einstein condensate/cold atom microscopy at Stanford, Cornell, Tübingen (similar development stage)

Highest sensitivity with SQUIDs and atomic vapour cells, but hard to reach spatial resolution

Scanning surface microscopy, e.g. magnetic force microscopy or nitrogen-vacancy centres in diamond have better resolution but do not reach sensitivity and cannot provide single-shot images or large fields of view

COLD ATOM MAGNETIC MICROSCOPE WITH SAMPLE-EXCHANGE FACILITY

Description

A cold atom magnetic microscope for 1D and 2D imaging on millimetre scales with micron resolution. The system consists of:

- "Sensor head":
  - Vacuum chamber, ion pump and alkali-source dispenser.
  - PCB based vacuum-compatible atom chip driven by current drivers. With a sample holder. (Developed by P. Krüger group.)
- Laser system: Tapered amplifier, high power laser system at 780/776 nm and optical components. Coupled to the sensor-head via optical fibres.
- Electronic control/sequencing software and data acquisition via a CCD.

Inputs to the device

- Computer for control (USB, Ethernet)
- 780/776 nm laser beam (free space)
- Electrical power hundreds of Watts as in a conventional cold-atoms lab.

Outputs of the device

Maps of 1D and 2D magnetic fields and/or electrical currents, including deviations.

Expected applications

Mapping and characterisation of samples relevant to materials science, such as:

- 3D printed conductors (Added Scientific Ltd)
- 2D materials such as graphene
- Silicon Nitride membranes
- Silver nanowires (Alan Dalton, Sussex)
- Electro-chemical processes e.g. battery charging-discharging cycles
- Chemiresistive gas sensors
- Topological insulators

Mapping and characterisation of samples relevant to biology / medical science, such as:

- Ion channels in cells
- Conductive pathways in tissue scaffolds for stem cell differentiation
- Magnetic bacteria for drug delivery

Performance

- High magnetic field/ current sensitivity for 1D images with micrometer resolution. Transversal scanning of these 1D images with submicron resolution. Alternatively, 2D single-shot images for mm^2 samples possible at reduced sensitivity.
- DC field imaging or microsecond timescale imaging of dynamic processes.

PARAMETERS	CURRENT VALUES	TARGET VALUES (2019)
Minimum detectable magnetic field variation	700 pT	10 pT
Spatial resolution	2.8 µm	500 nm
Minimum resolvable current variation in the transverse direction to the current flow (dI_x for any I_z)	7 nA	25 pA
Dynamic range	± 70 nT (Homogeneous offset field allowed)	± 1 µT (Homogeneous offset field allowed)
Field of view	1.3 mm x 0.1 µm (1D)	1.3 mm x 0.1 µm (1D) or Ø = 100 µm circular area (2D)
Number of simultaneous measurements	500 (1D)	8000 (2D)
Time resolution for imaging	DC field imaging	100 µs (~ 10 consecutive measurements) 1 µs in stroboscopic mode
Magnetic field sensitivity with spatial and temporal averaging	290 pT/√Hz/µm	1 pT/√Hz/µm
Conditions	UHV Room temperature	Bio-compatible / atmospheric pressure Compatible with 4 K
Special features	1 cm^2 sample size Large field of view in single shot 2D image Large homogeneous offset fields allowed Dynamic range could be larger, resulting in lower field sensitivity	