

Highly Sensitive Nanoscale Scanning Magnetic and Thermal Sensor

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Overview

A new technology developed by a group of researchers from the Weizmann Institute is a nanoscale sensor-on-tip for local magnetic signals and thermal dissipation with state-of-the-art sensitivity and spatial resolution.

Detecting a signal as low as the magnetic moment of a single electron is of key technological importance for applications ranging from electronics (e.g., hard discs, magnetic RAM and spin valves) to biotechnology applications, including enhanced tissue and organ imaging and MRI. Furthermore, investigation of energy dissipation on the nanoscale is of major interest in quantum systems in which the dissipation mechanism is related to preservation of quantum information, which is of particular importance in the field of quantum computing.

To date, there are several local magnetic imaging methods, such as scanning superconducting quantum interference devices (SQUID), magnetic force microscopy and Lorentz microscopy. Scanning SQUID microscopy is a promising technology, having the highest field sensitivity (1 micro-Gauss), however, it has a rather poor spatial resolution (of several microns). Energy dissipation is another important imaging parameter, which is not readily measurable on the nanometer scale and existing thermal imaging methods are not sensitive enough for studying quantum systems and are unsuitable for low temperature operation.

Here, we propose a novel sensor device comprising a nanoscale SQUID-based probe. The fabrication method, enables the miniaturization of the sensor to an effective diameter of <50 nm and its integration onto the apex of a very sharp tip that is ideally suited for scanning probe microscopy. The extremely small size of the SQUID-on-tip sensor and the ability to very closely approach the sample surface, provide for nanometric spatial resolution, very high spin sensitivity ($>1 \hat{1}/4 B/Hz^{1/2}$) and micro-Kelvin thermal resolution, whereas commercially available thermal scanning systems are limited to an order of 10 milli-Kelvin.

The Need

In light of the rapidly developing scanning-probe based technologies including nanomagnetism, spintronics, energy-efficient computing and quantum computing, there is a pertinent need for the development of nanoscale sensor devices for direct magnetic field and thermal imaging with high sensitivity and spatial resolution. The effective spatial resolution is determined by the size of the sensor and its proximity to the sample. The existing superconducting quantum interference (SQUID) sensors based on planar technology are limited in their size and in ability to closely approach the surface of a sample.

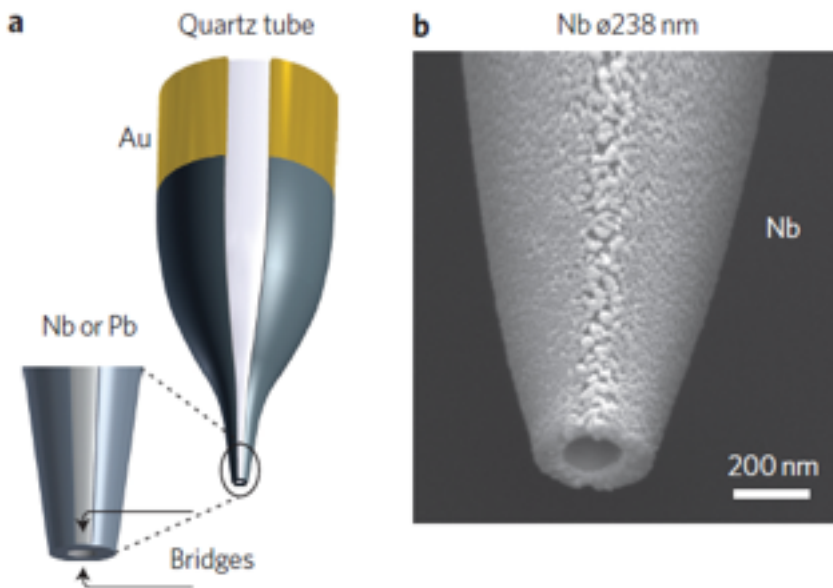
In addition, owing to the detrimental effect of dissipation on quantum information, study of the underlying mechanisms is of particular importance. In order to preserve a quantum state, for instance, in the case of a qubit, the dissipation has to be extremely weak, i.e., at magnitudes several orders below the best sensitivity (several mK/Hz^{1/2}) of any of the existing thermal imaging techniques. Moreover, none of these imaging techniques has been demonstrated to operate at the low temperatures that are essential for study of quantum systems.

The Solution

Nanoscale SQUID-on-tip device that enables high spatial, magnetic and thermal resolution for local measurements by minimizing the sensor size and the distance between the sensor and the sample.

Technology Essence

The present invention is a novel sensor device, based on nanoscale two-junction or multi-junction SQUIDs fabricated on the edge of a sharp tip in a three-dimensional geometric configuration. In such a setup, the SQUID can approach the sample to a distance of several nanometers. The small size of the sensor device and its ability to be placed at a short distance from the sample surface, result in extremely high sensitivity. The novel three-dimensional geometrical configuration of the SQUID-on-tip is obtained by focused ion beam milling, which enables measurement of both in-plane and out-of-plane components of the magnetic field with a remarkable sensitivity. The capability to measure in-plane fields enables use of this novel sensor device for applications such as in-plane spin detection and transport current distribution in complex systems. The unique nanoscale cross-section geometry of the device allows for non-contact, nanoscale-resolution sensing of the local temperature of a sample. This tool enables scanning cryogenic thermal sensing that is 4 orders of magnitude more sensitive than other devices, allowing for the detection of $<1 \text{ } \mu\text{K}$ temperature variations. Furthermore, it is non-contact and non-invasive and allows for thermal imaging of very low intensity, nanoscale energy dissipation down to the fundamental Landauer limit of 40 fW for continuous readout of a single qubit at one gigahertz at 4.2 Kelvin.



The nanoscale SQUID-based probe. a) Schematic presentation of the pulled quartz tube with two Nb or Pb superconducting leads connected to Au electrodes. b) SEM image of the Nb SQUID-on-tip.

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Applications and Advantages

Advantages

- Simple fabrication process
- High field sensitivity and bandwidth
- Nanoscale sensor (down to 46 nm in diameter)
- Tip-sample distance can be as small as a few nanometers
- High spin sensitivity ($> 1 \text{ } \mu\text{B}/\text{Hz}^{1/2}$)
- High thermal resolution ($< 1 \text{ } \mu\text{K}$).

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Applications

- Scanning probe microscopy for magnetic and thermal characterization
- Inspection and probing equipment for quantum computing

Development Status

SQUID-on-tip devices were fabricated and tested, under laboratory conditions, to measure local magnetic signals and thermal dissipation processes in model systems (Published in: [Nat. Nanotechnol. 2013, 8: 639:644](#) [1]).

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Market Opportunity

Various industries use scanning probe microscopes to improve quality control and assurance and enhance overall product development. Key end-use industries include semiconductor, personal care and food science industries. According to a recent market report, the scanning probe microscope market is expected to grow at a CAGR of 7.1% during 2017-2026. Nanomechanical characterization with the help of scanning probe microscopy is quickly gaining traction, further promoting growth of the market.

The constant research advancements in the quantum computing field is projected to rapidly grow the market at a CAGR of 29% during 2017-2023. The quantum computing processor, a physical device enabling the principle of quantum computing, is still a rather theoretical concept than a ready-to-implement engineering solution. At the same time, this rapidly evolving market is one of the most active R&D fields, attracting substantial government funding that supports research groups at internationally leading academic institutions, national laboratories, and major industrial-research centers. The governments are the major driving force behind investments in quantum computing R&D, fiercely competing for what is perceived as one of the most promising technologies of the 21st century.

Patent Status

USA Granted: 8,723,514 USA Granted: 10,481,174
