

Scanning SQUID-on-Tip Magnetic and Thermal Imaging: Nanoscale Probe of Superconductivity and Strongly Correlated Electronic Systems

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Abstract—Over the past decade we have developed a family of scanning probes based on a superconducting quantum interference device fabricated directly on the apex of a pulled quartz pipette—SQUID-on-tip (SOT). The self-aligned process yields SOT diameters down to 40 nm, extremely low flux noise of $50 \text{ n}\Phi_0/\text{Hz}^{1/2}$, and record spin sensitivity of better than $1 \text{ }\mu\text{B}/\text{Hz}^{1/2}$ [1]. The SOT geometry allows scanning at tip–sample spacing of few tens of nanometers, operation in elevated magnetic fields, and over a span of temperatures down to mK range. These capabilities enable quantitative, non-invasive mapping of magnetic textures, current distributions, dynamic responses, as well as scanning-gate microscopy.

Using SOT magnetometry of vortex matter, we resolved the pinning potential and nm-scale trajectories of individual vortices with displacement sensitivity down to $\sim 10 \text{ pm}$, directly imaging elementary depinning processes [2]. When the critical current is exceeded, we visualized super-fast vortex flow with velocities up to tens of km/s, uncovering channel flow with branching instabilities and dynamic transitions as the resistive state emerges [3]. Recently, we have extended vortex imaging beyond superconductors, providing the first direct observation of vortices in an electron fluid and hydrodynamic to laminar-flow transition in van der Waals materials [4].

The SOT microscopy provides a novel tool to study spontaneous time-reversal-symmetry-breaking that occurs in topological and strongly interacting electron systems including graphene and transition metal dichalcogenides. Our studies have revealed Berry-curvature-induced orbital magnetization in rhombohedral graphene [5] and Chern mosaic in magic-angle twisted bilayer graphene (MATBG) [6]. Moreover, it has provided the first measurement of thermodynamic quantum oscillations in magnetization in graphene systems, including trilayer [7], bilayer moiré [8], twisted trilayer [9], and MATBG structures [10], allowing very accurate reconstruction of the band structure, disorder, and interaction effects with nanoscale spatial resolution.

Finally, we transformed the SOT into an ultra-sensitive scanning nano-thermometer,

enabling the first thermal imaging at cryogenic temperatures with μK sensitivity and nanoscale resolution [11]. This platform visualized heat released by electron scattering off single atomic defect in graphene, separated “work” from “dissipation” at quantum Hall edges via simultaneous thermal and scanning-gate imaging [12], uncovered long-range non-topological edge currents in graphene [13], allowed cryogenic study of thermoelectric effects [14], and provided a new method for electron thermometry [15].

References

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