Scanning Magnetic Microscopy Using a Superconducting Quantum Interference Device On-a-tip with Single Spin Sensitivity

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October 21, 2013 (HP65). In the last decade the field of scanning probe magnetic imaging has yielded various new instruments, establishing numerous records in sensitivity to small magnetic dipoles or so-called spin sensitivity. The competing technologies include magnetic resonance force microscopy (MRFM) and sensors based on nitrogen vacancy (NV) centers in diamond[1,2]. The progress in scanning superconducting quantum interference device (SQUID) microscopy was stagnating due to the constraints imposed by the form-factor of the planar SQUIDs and the existing lithography techniques. The former restricts the sensor-to-sample distances smaller than ~ 0.5 μm and the latter restrict SQUID diameters smaller than ~ 200 nm. These two main limitations were overcome by the invention of a SQUID-on-tip device[3] and subsequent realization of a SQUID-on-tip microscope[4], which culminated in the creation of an ultra-small sensor with a spatial resolution of 50 nm and a sensitivity to less than a single electron spin (μ_B) per 1 Hz bandwidth[5] working in a range of magnetic fields up to 1 T. Here we report the latest advances of this work.

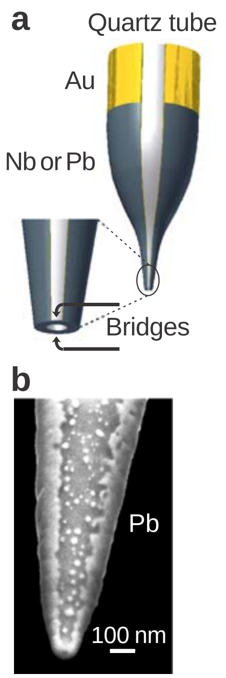

Fig. 1. SQUID-on-tip devices[5]. **a.** Schematic view of the SOT with two superconducting leads made from Pb or Nb. Inset: Magnified view showing the SQUID loop and two Dayem-bridges. **b.** Scanning electron microscopy image of the Pb SOT.

The Dayem-bridge-type Pb and Nb nano-SQUIDs with sizes as small as 46 nm in diameter were fabricated on the apex of sharp quartz pipettes using a self-aligned 3-step deposition technique[5] (see Fig.1). When combined with conventional tuning-fork-based atomic force microscopy techniques[3], this geometry is ideal for approaching the SQUID-on-tip (SOT) sensors within a few tens of nm above the sample surface.

The fabricated devices were characterized at 4.2 K. Since the current-voltage characteristics of current-biased Dayem-bridges are usually hysteretic, we used a quasi-voltage bias circuit to provide stable operation of the SOTs above the critical current[3-6]. In the absence of the compensation coil the working points of the SOTs were set by choosing the appropriate magnetic field and the SOT bias voltage. After setting the SOT at the working point, we measured the current through the SOT as a function of magnetic field using a SQUID array amplifier[6]. The lowest recorded field noise $S_B^{1/2}$ = 5 nT / Hz$^{1/2}$, flux noise $S_\Phi^{1/2}$ = 50 nΦ_0 / Hz$^{1/2}$ and the best spin sensitivity $S_n^{1/2}$ = 0.38 μ_B / Hz$^{1/2}$ at 10 kHz were achieved in Pb SQUIDs. Another distinct feature of the Pb SOTs is their low *1/f*

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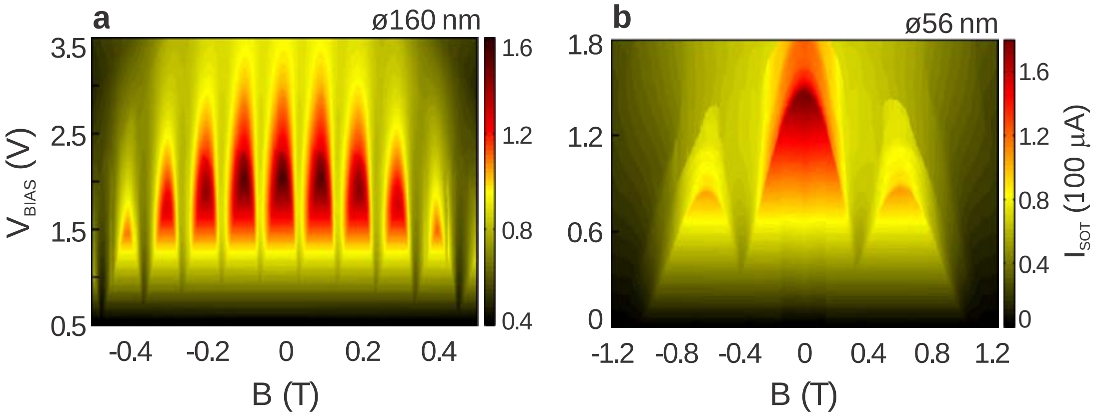

Fig. 2. Quantum interference patterns of Pb SOT devices of different sizes[5]. a. Quantum interference pattern of the ∅160 nm SOT. **b.** Current oscillations of the ∅56 nm SOT. The critical current is fully suppressed at B = ±1.2 T

noise, allowing even DC measurements with improved sensitivity[5]. Oscillations of the critical current were observed up to 1 T, at higher fields the superconductivity was fully suppressed[5] (see Fig. 2).

An in-house built scanning probe microscope utilizing the Pb SOT sensors was used to image magnetic vortices in a thin superconducting niobium film. The smallest measured inter-vortex separation was about 120 nm at ~ 0.2 T. We have also demonstrated the high sensitivity of our sensors by imaging magnetic fields of AC currents in Nb strip as small as 200 nA with 1 second integration time resulting in measured flux lower than 100 nΦ_0.

The obtained SOT characteristics set a record for scanning nano-SQUIDs in terms of spatial resolution, spin sensitivity, and operating magnetic field perpendicular to the SQUID loop. The low-cost fabrication, simple measurement technique, and the direct measurement of magnetic field renders the SOTs as promising step forward in nanoscale magnetic imaging.

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