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Irfan Siddiqi

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of California, Berkeley
2150 Shattuck Avenue, Rm 313
Berkeley, CA 94704-5490

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14. ABSTRACT
We have successfully developed a superconducting quantum interference device magnetometer employing nanoscale weak links (nanoSQUIDs) with a dispersive microwave readout. These sensors have a flux sensitivity of 25 nano□/Hz1/2, which translates into single Bohr magneton resolution (for a 1 Hz bandwidth) for magnets placed within 100 nm of the sensor—a very reasonable task for current e-beam and scanned probe lithography. In our nanoSQUID magnetometer, the SQUID is incorporated into a 5 GHz microwave tank circuit. The magnetization of a spin signal under study shifts the resonant frequency of the resonator which is readily detected using microwave reflectometry. The weak links are made of aluminum and have been optimized for maximum nonlinearity by contacting the narrow (25-50nm), thin (6nm) bridge with think (>50nm) contacts, which serve as good phase reservoirs. The measured current phase relation and inductance modulation is in excellent agreement with our numerical simulations based on a solution of the Usadel equations. Both our observed the flux sensitivity and instantaneous bandwidth of ~ 10-40 MHz are several orders of magnitude higher than other types of nanoSQUID sensors currently reported in the literature. This sensor is now a robust device w

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Single Bohr Magneton Detector

Irfan Siddiqi

Quantum Nanoelectronics Laboratory

UC Berkeley, Berkeley CA

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1 Introduction

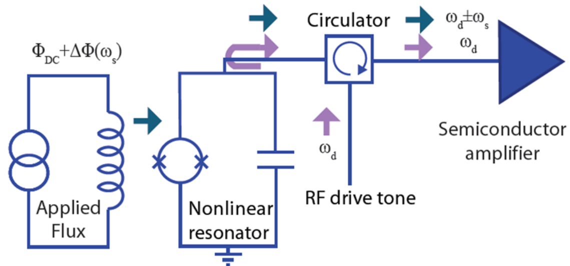
Over the past decade, there has been tremendous interest in unraveling the physics governing the interaction between micro and nanoscale spin systems, and spin relaxation to the environment. In the classical domain, spin systems are used currently as memory elements. With respect to information processing, there is a broad spectrum of research activity that falls under the heading of ”spintronics” [1] and is aimed at realizing logical functions using spin based bits. If individual spins can be harnessed for both of these functions, then it may be possible to realize extremely high device density and reduced dissipation, approaching the Landauer limit of $k_B T ln 2$ per bit. During the 1990s, interest in quantum computation grew after the development of Shor’s algorithm for the prime factorization of large numbers [2]. Isolated spins are also a candidate quantum bit for employing such quantum algorithms. Thus, spin based circuitry has the potential for use as information storage and processing elements, both quantum and classical, with significantly increased density and computational power over the current state-of-the-art.

The primary reason individual spins are challenging to detect and address with high fidelity is also one of the reasons why they are so attractive for information storage and processing: weak coupling to the electronic environment. This fact makes measurement difficult but it also preserves state coherence, and indeed many semiconductor spin species, such as donor electrons in Si and NV centers in diamond, have spin lifetimes in the millisecond to second range. The magnetic signature associated with the flip of a single spin or the magnetization reversal of a small spin ensemble decays rapidly on the micrometer size scale of a typical electrical circuit, thereby preventing efficient coupling. As such, local probes based on optical manipulation or atomic force microscopy have been the most successful in addressing small numbers of spins. We have developed superconducting circuitry specially designed for interfacing with nanoscale spin systems to realize an all electrical platform to study the fundamental interactions governing relaxation in spin ensembles of varying density. From an applications point of view, such an architecture is attractive for large scale integration and coupling to other solid state circuits–classical and quantum bits for example.

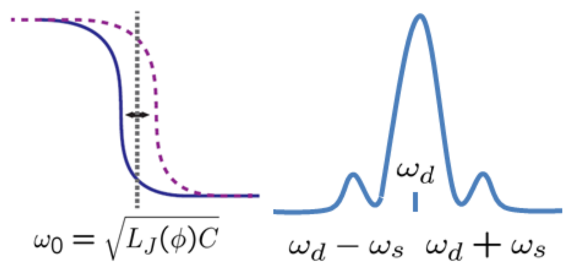
In particular, we have developed a nanoSQUID magnetometer with a dispersive microwave readout which can directly measure the magnetization of both metallic and semiconductor spin ensembles. This technique is well suited to address ensembles ranging from bulk crystals down to the single spin level. In this geometry the spin system is coupled to a microwave transmission line. As such, we envision transferring the spin information in the ensemble to a microwave photon field which can subsequently interface with other circuitry–such as a logical bit or even a circuit to upconvert to the optical domain.

2 Nanobridge SQUID Magnetometer

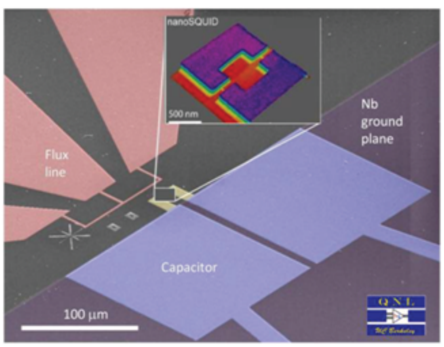
We have developed a magnetometer capable of measuring small numbers of spins. Having characterized this magnetometer [3], we now plan to use it to study spin physics. There are many possible spin species to measure with this versatile device. We can study single molecule magnets, as previously proposed, like those made by Prof. J. Long at UC Berkeley. Dr. T. Schenkel at LBL has the capability to implant NV centers in diamond in very precise locations [4]. In this case we would fabricate the magnetometer on top of the implanted diamond sample. As well, we plan to measure $N@C_{60}$, nitrogen atoms enclosed by carbon buckyballs, that are made by Prof. J. Morton at Oxford University [5]. These $N@C_{60}$ molecules are made in solution, and could be dropped onto the magnetometer with a micropipette. We also have additional methods to place small numbers of spins next to the magnetometer. It is possible to use our AFM to place the spins, and here we would leverage the experience of Prof. M. Crommie's group at UC Berkeley. Another possibility is to mask the sample with resist, and then spin a solution of the species onto the surface. Each of these systems has a very different magnetic structure, ranging from a simple atomic spin to a complex, collective molecular magnet, and thus provides a chance to investigate many different types of magnetic interaction.



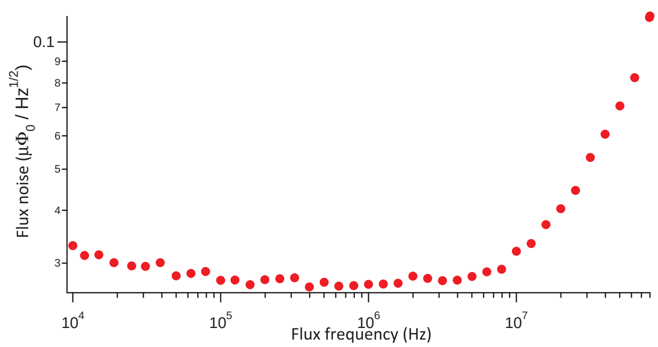
(a)



(b)



(c)



(d)

Figure 1: (a) The magnetometer measurement scheme. (b) A flux signal changes the SQUID inductance, modulating the resonant frequency, which manifests as sidebands on the drive tone. (c) A picture of the magnetometer LC circuit. (d) Sensitivity of the detector versus frequency of the flux signal. Lower flux noise means higher sensitivity, ie. the signal to noise ratio will be higher for a given bandwidth.

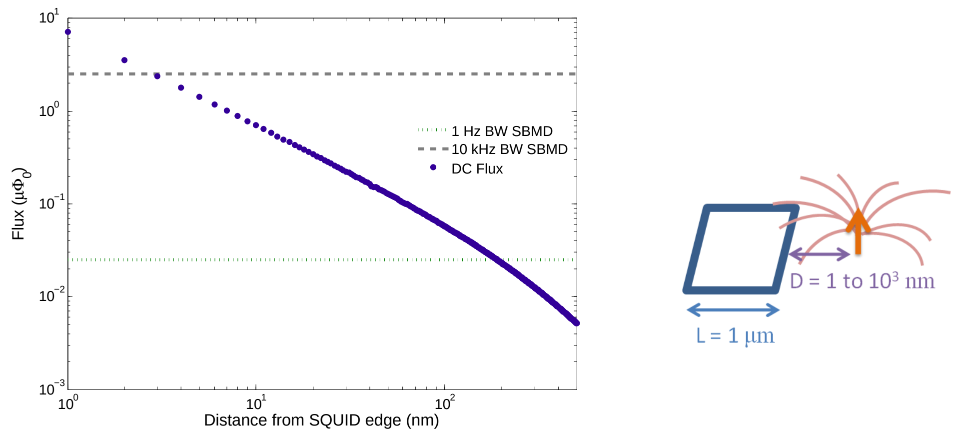
In Figure 1 we show a schematic of the operation of the nanobridge magnetometer, as well as a scanning electron micrograph of the device. The magnetometer is in essence a nonlinear LC circuit, where the nonlinearity is provided by a nanobridge SQUID, which acts as an inductor. A nanobridge SQUID is a loop of a thin superconducting film, in this case aluminum, interrupted by two nanoscale geometric constrictions. These nanobridge constrictions can act quite well as Josephson junctions [6], approaching the nonlinearity of traditional tunnel-type Josephson junctions with an insulating barrier. The inductance of the SQUID changes with the magnetic flux threading the loop, changing the resonant frequency of the circuit. When probed with a microwave carrier tone, the magnetometer transduces an input magnetic flux signal into a microwave voltage which mixes with the carrier and appears as sidebands on the fundamental tone [7]. These sidebands can then be amplified, mixed back down to low frequency, and read out, giving us the flux signal. For nanoscale magnetometry experiments the spins will be placed in close proximity to the detector. They will then be excited by a microwave fast flux line, which is a coplanar wire that is shorted on chip in order to produce strong alternating magnetic fields near the spins. We have used the fast flux line to generate "'dummy"' flux signals in order to characterize the detector, and its operation is well understood.

The measured flux sensitivity of this device for a range of input flux signal frequencies is shown in Figure 1(d). Sensitivity can be converted to signal to noise ratio (SNR) by taking:

$$\mathrm{SNR} = \frac{\mathrm{Signal}\,[\mu\Phi_0]}{\mathrm{Flux\ Noise}\left[\mu\Phi_0\mathrm{Hz}^{-1/2}\right] \times \sqrt{\mathrm{Bandwidth}}\left[\mathrm{Hz}^{1/2}\right]} \tag{1}$$

The sensitivity is 30 $n\Phi_0/\sqrt{Hz}$ over a wide band of signal frequencies, which is a record for comparable nanoSQUID devices [3]. Nanobridge junctions are also attractive for magnetometry applications because they can tolerate higher in-plane magnetic fields, often required to achieve the desired energy level structure, and their geometry is conducive to placement of single spins near the junction for maximum coupling of the flux signal.

We have performed calculations to estimate the sensitivity of the device to a single spin at a range of distances from the SQUID loop, as shown in Figure 2(b). These numerical models suggest that for a 1 μm^2 loop, the magnetometer will be sensitive to the signal from one spin at 180 nm with 1 Hz bandwidth. For a 10 kHz bandwidth, the spin needs to be 2 nm away. Thus, using selective ion-implantation, AFM manipulation of small ensembles, and direct mechanical placement of larger doped crystals, we should be able to position our spins within the active area of the nanoSQUID magnetometer and study resonant spin dynamics under microwave excitation.



(a) (b)

Figure 2: (a) Flux through the SQUID loop from a spin at varying distance from the edge. Horizontal lines indicate the flux that yields an SNR of 1 for a 10 kHz and 1 Hz detection bandwidth respectively. (b) Cartoon of the calculation.

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