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Quantum Sensing with Superconducting Flux Qubits

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***Abstract*—Recent advances in quantum technology allow the precise manipulation of quantum states. This capability can be applied to many fields of application. In particular, quantum computation, quantum sensing, and quantum cryptography are the fields under intense research. Among the various types of qubits for these applications, superconducting qubits are one of the most promising candidates as a building block for realizing large-scale quantum computers [1]. Such a superconducting quantum technology is also applied in the field of sensing. For example, microwave parametric amplifiers based on Josephson junctions achieve the noise performance bounded by quantum theory. This amplifier can be applied to any field requiring ultra-low noise microwave amplifiers, such as radio astronomy [2] or electron spin resonance (ESR) spectroscopy [3].**

Superconducting qubits themselves can also be applied to sensing. Among many types of superconducting qubits, we especially focus on a superconducting flux qubit as a sensitive detector of magnetic field [4, 5] because of the strong interaction between a circulating current in the qubit and the magnetic field. The magnetometer based on a superconducting flux qubit is shown in Fig. 1(a). The flux qubit is connected to a readout circuit, namely a superconducting quantum interference device. The transition frequency of a superconducting flux qubit can be controlled by an out-of-plane magnetic field $B_\perp$ [Fig. 1(b)]. This is because the balance of the two eigenbases of the flux qubit, the clockwise and counterclockwise currents through the loop, is changed by the interaction with the out-of-plane magnetic field. A flux qubit is designed to have a transition frequency in the microwave range and an operating flux range of 0.1% of the magnetic flux quanta. This means that a small magnetic perturbation will change the transition frequency of the flux qubit. Thus, the flux qubit works as a transducer from the magnetic flux to the resonance frequency [Fig. 1(b)].

To use the flux qubit for the magnetometry of materials, the target sample should be placed in the vicinity of the flux qubit. To polarize electron spins in the sample, an in-plane magnetic field $B_{||}$ is applied in addition to $B_\perp$. In the absence of sample magnetization, the transition frequency of the flux qubit remains the same as in the stand-alone case. In contrast, in the presence of sample magnetization, the transition frequency of the flux qubit is shifted, depending on the intensity of the magnetization [(Fig. 2(b)].

This magnetometer can also be used as an ESR spectrometer, because the magnetization of the target sample can be controlled by microwave irradiation, namely the spin resonance phenomenon. For this purpose, microwave excitation lines are designed on the flux qubit chip [Fig. 1(a)] to flip the electron spins in the sample.
As a demonstration of the ESR spectroscopy, impurities in semiconductors are analyzed using a flux qubit magnetometer. The target sample here is a type-IB diamond crystal with high concentration of compound defects formed by a nitrogen impurity and a vacancy (NV center). Corresponding to the zero-field splitting of the NV center (2.88 GHz), we successfully observed dips in the ESR spectrum [Fig. 1(c)] [4]. From the qubit design and parameters, we can estimate the sensitivity and sensing volume of the spectrometer to be 12 spins/√Hz and of 5 fL [6].
The target sample is not limited to solid state materials as in the previous case. As an example of biological applications, rat hippocampal neurons are characterized [7]. In this case, we qualitatively extract the concentration of ferric ion in the neurons to be 8 μg/g from the magnetometry results.
In this talk, we will discuss in detail the experimental setup, the design of the qubit and the measurement system, the limitation of the sensitivity, and the applications. Future research directions will also be discussed.

***Keywords (Index Terms)*—Superconducting qubit, Quantum sensing, Biosensing, Electron spin resonance spectroscopy, Magnetometry, Thermometry**

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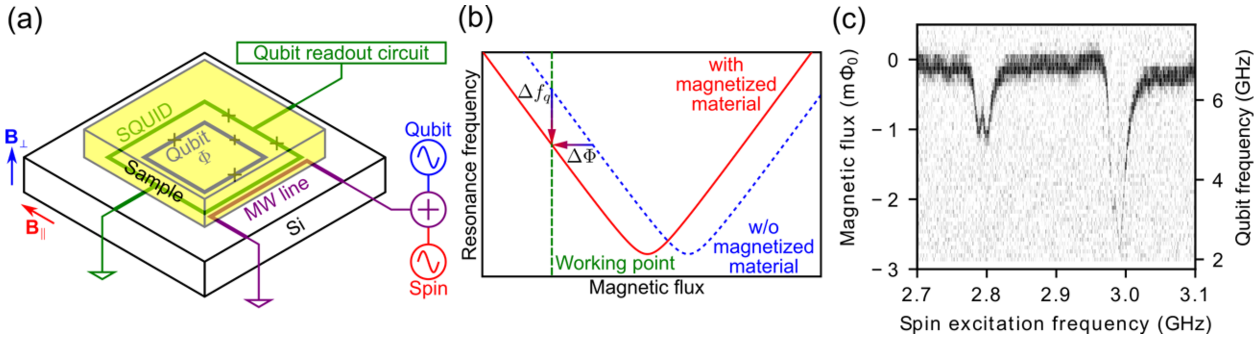

Figure 1. (a) Experimental setup. (b) Principle of the magnetometer. (c) Example of an ESR spectrum using a superconducting flux qubit. These figures are adaptation (some labels are modified) of the published work [3] under a Creative Commons Attribution 4.0 International License.