MICROWAVE RESONATORS FOR GLOBAL CONTROL OF ELECTRON SPIN QUBITS

SUMMARY: We show preliminary results for a microwave resonator for global control of single-qubit operations on semiconductor spin qubits.

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INTRODUCTION

Electron spins in semiconductor quantum dots are excellent candidates for qubits for a scalable quantum computer due to their addressability and electrical control. Silicon, in particular, is a promising host material due to the possibility of isotopic purification, leading to decreased nuclear magnetic noise, and integration with classical control by leveraging conventional CMOS electronics. In order to implement single-qubit rotations on such a quantum processor, electron spins must experience a resonant, oscillating magnetic field. The two conventional methods used for creating this oscillating magnetic field are micro-striplines, which produce an oscillating magnetic field directly on-chip [1], and micromagnets, where the magnetic field gradient produced by the micromagnet and an oscillating gate voltage lead to an oscillating magnetic field in the reference frame of the electron [2]. Both methods require on-chip components that are bulky (> 1 µm) compared to the footprint of an individual quantum dot (<100 nm), reducing the possibility for the dense packing of qubits. Furthermore, the oscillating field produced by both methods is local, limiting single-qubit rotations to only a few quantum dots per micro-stripline or micromagnet.

For long-term scalability, there is a clear need for generating a global oscillating field for spin-qubit operations. A macroscopic microwave resonator is an obvious solution, however, there is a key challenge: the electric field component generated by such a resonator can excite the electron to higher orbital states or even out of the dot, which is detrimental to the spin qubit.

Here, we show preliminary results for a 'bowtie' microwave resonator (see Figure 1) that produces a strong magnetic field in a central region while also minimizing the electric field in this region. The resonator will be placed above the quantum device layer, allowing for dense packing of qubits. Individual qubits can be tuned into and out of resonance with this global field electrically by the Stark effect: the electronic g-factor, which controls the spin's resonance frequency, has been shown to vary with an applied electric field [1].

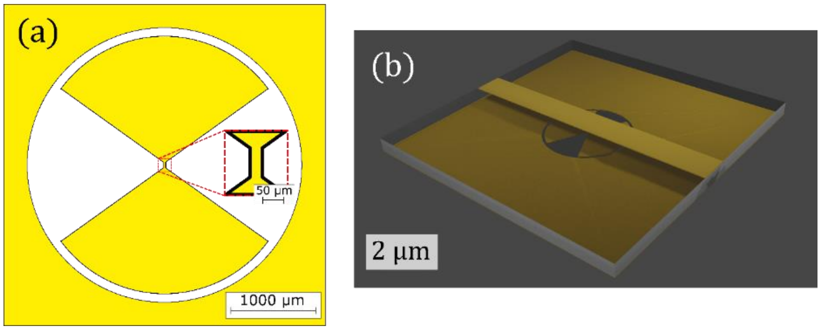

Figure 1. (a) Top-view schematic of the 'bowtie' resonator. Inset: Enlarged view of the device region. (b) 3D rendering of the resonator, showing the stripline used to couple an input microwave signal.

RESULTS

Simulations of the magnetic and electric field profile of the resonator are shown in Figures 2 (a) and (b), respectively. In an area roughly 40 x 60 μm near the center of the resonator, the magnetic field intensity is within 75% of the peak value of 1.75 mT, which could allow for manipulation of over $2x10^5$ qubits, assuming a 100 nm device pitch. The electric field is expelled towards the edges of the resonator, away from the central region where the magnetic field is strongest. We also simulated the resonator response as a function of frequency, shown as the blue trace in Figure 3, which indicated that the resonance frequency is near 16 GHz with a quality factor Q≈10. The theoretical Rabi frequency

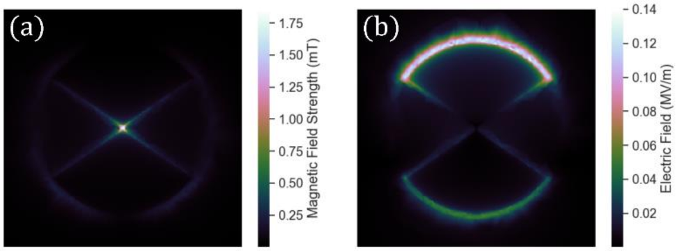

Figure 2. Simulated (a) magnetic field and (b) electric field distribution generated 10 μm below the resonator plane, with a 1 W input power to the stripline.

(how fast the spins can be rotated) is roughly 775 kHz/(mW)^{½}. All simulations were performed using Ansys® HFSS, revision 2020 R2.

EXPERIMENTS

We fabricated a copper resonator with the same dimensions as the schematic in Figure 1 (a) and measured the transmission response of the nearby stripline as a function of frequency, shown as the orange trace in Figure 3, showing a coupling qualitatively similar to the simulated response with a similar quality factor of Q~10, albeit with a shifted resonance frequency. A possible explanation for this difference in frequency is due to using a plane-wave excitation model in the simulations, which is known to cause overestimation of the resonant frequency in comparison to experiment [3], however, further investigation is required.

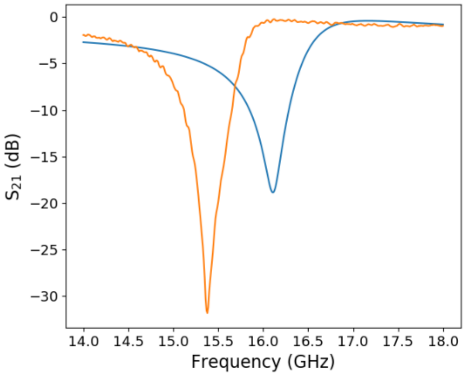

Figure 3. Simulated (blue) and measured (orange) transmission through a coupling stripline, showing strong resonance near 16 GHz.

CONCLUSION AND FUTURE WORK

The results presented here are promising, but preliminary, and much work remains before we can demonstrate spin qubit control with these resonators. The experiment presented above was performed using a copper resonator at room temperature, but we intend to use a niobium resonator at cryogenic temperatures. Niobium is a type-II superconductor with a critical temperature above 9 K, well above the typical temperatures for experiments on gate-defined quantum dots. Superconducting resonators tend to have higher Q-factors than those with finite conductivity, which would improve the Rabi frequency achievable with the global field. We have already fabricated niobium resonators, and measurements of the magnetic and electric field distribution of these resonators is currently underway.

In parallel, we have been developing single-electron transistors (SETs), both to be integrated as charge sensors for quantum dots, and also as a testbed for the resonators. We can gauge the strength of the electric field produced by the resonator by observing the onset of photon-assisted tunneling through a

SET, as a function of microwave input power.

Finally, we have also been working on strategies to shield the quantum device layer from the remaining stray electric field, to minimize the voltage fluctuations on the metal gates used to define the quantum dots. The ultimate goal of our efforts in this direction is the demonstration of a scalable node-network architecture for spin qubits [4]. With the results presented herein, we are confident that these resonators are promising candidates for global spin control in quantum processors based on lateral semiconductor quantum dots.

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