Integrated Quantum Memories at 1.3 K with Tin-Vacancy Centers and Photonic Circuits

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Abstract: We present an efficient microwave and optical interface for quantum memories at 1.3 K based on tin-vacancy color centers in diamond and scalable integrated photonics.

1. Introduction

Generating and maintaining quantum entanglement at distance remains a central challenge in quantum information science. A major goal is to leverage the same scalable techniques and technologies that underpin Moore's Law to scale quantum devices to system sizes necessary for high rates and fidelities. In this work, we expand upon Wan et. al. 2020 [1] by demonstrating and manipulating long-lived spin degrees of freedom in atomic memories as part of an immediately-scalable platform based on silicon-nitride (SiN) photonic integrated circuits (PICs).

Atomic memories in solids such as the nitrogen-vacancy (NV) center in diamond have enabled excellent advances in the generation of remote entanglement [2], though lack of optical stability—especially in nanofabricated structures—has stymied efforts to scale. Group-IV color centers such as the silicon-vacancy (SiV) center have attracted interest due to their symmetry-protected optical stability [3]. However, phonon-bath-limited coherence requires most SiV centers to operate around 100 mK. The order-of-magnitude larger orbital splitting of the tin-vacancy (SnV) center enables operating temperatures on the order of 1 K [4], as we demonstrate in this work.

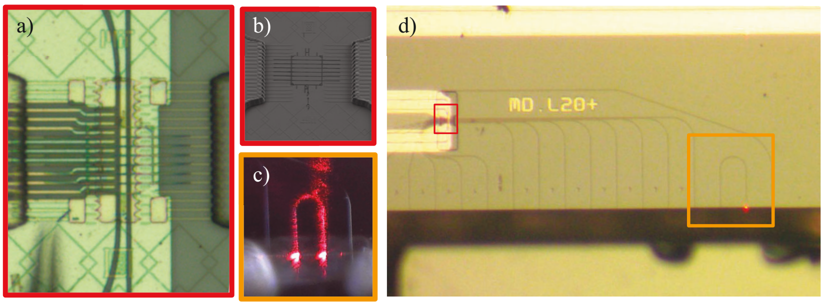

Fig. 1. Architecture and PIC. a) An optical image of a six-waveguide diamond microchiplet integrated onto SiN waveguides, with aluminum metal for microwave control (thin vertical wire) and strain control (left wires) underneath. b) SEM image of a). c) Loopback for fiber array alignment. d) An optical of our system with SiN waveguides connecting the diamond to a fiber array with 630HP single mode optical fiber (bottom).

2. Architecture & Spin Lifetime

We fabricate custom SiN PICs based on the platform described in Ref. [5]. SnV color centers in fabricated diamond waveguides are adiabatically coupled to SiN waveguides via heterogeneous integration. These SiN waveguides act as an optical interposer between the diamond and the modes of an optical fiber array (Fig. 1d), along with enabling more novel passive photonic components. A permanent neodymium magnet positioned above the chip by an attocube stage is used to controllably split the spin levels (Fig. 2a), allowing spin-selective optical addressing and targeted microwave driving without the complexity of a vector magnet. We measure T_1 times exceeding 50 ms in our 1.3 K system (Fig. 2b). We are working toward measuring and enhancing the T_2 coherence. While T_2

times have been demonstrated with optical control of the SnV [6], we aim to achieve higher fidelities and greater dynamic decoupling via efficient microwave control.

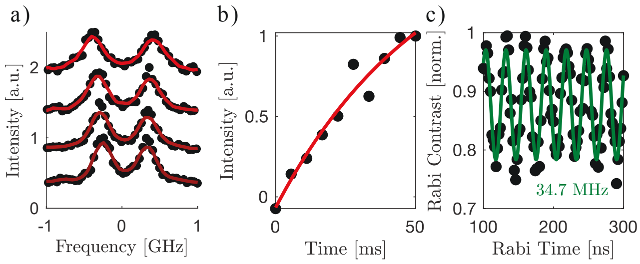

Fig. 2. Spin measurements. a) Optical splitting in SnV, depending upon the position $z = \{663, 555, 460, 350\}\,\mu$m (from the bottom) of the attocube-mounted magnet (arbitrary $z = 0$). The x-axis is relative to 484.1242 THz. b) T_1 spin lifetime exceeding 50 ms at 1.3 K. c) NV center Rabi oscillations at room temperature with 6 mW microwave power, representative of the achievable SnV Rabi rate.

3. Efficient Microwave

Cooling power in ultracold systems imposes a limit on the number of microwave control pulses that can be applied without heating the system and thermally limiting the memory lifetime [3]. Notably, when scaling to many memories in a cooling-power-limited system, this heating-limited maximum number of pulses is distributed across all memories, leading to fewer available pulses per memory. Our platform addresses this challenge in a twofold approach by maximizing available cooling power while minimizing microwave heating.

First, the choice of SnV as our memory allows us to use less expensive, higher cooling power 1.3 K systems than other group-IV color centers such as SiV. The immense 200 mW cooling power of our 1.3 K system—more than 2 orders of magnitude greater than that of a dilution refrigerator at 100 mK—is directly proportional to the number of qubits which can be simultaneously addressed inside a single system.

Second, the efficiency of our microwave delivery minimizes the thermal load to the low temperature stage. Our PIC platform buries aluminium electrodes underneath the SiN waveguiding layer, allowing us to bring a low loss 1 μm-thick microwave wire close to the memory ($\sim$800 nm distance) without inducing excessive optical loss. We engineered the width and thickness of this wire to maximize driving efficiency while minimizing resistive heating. We measure sub-dB microwave losses on-chip at room temperature, an upper bound for cryogenic temperatures. By applying microwave power at room temperature and measuring the thermally-induced resistance increase—assuming in the worst case that the heating is localized at the narrow microwave wire under the diamond pictured in Fig. 1a—we estimate an upper bound for local heating occurring under the diamond to be of order 100 mK for a full watt of applied microwave power. This is a negligible increase in temperature at our 1.3 K operating point.

4. Outlook

Our PIC-integrated platform simultaneously demonstrates scalability and long color center lifetimes, in a system unrestricted by microwave heating. The demonstrated lifetimes are expected to be sufficient to swap entanglement with ^{13}C or ^{117}Sn nuclear degrees of freedom. When combined with measurements of NV Rabi frequency of 35 MHz for only 6 mW of applied microwave power in this platform (Fig. 2c), the prospects for scaling are promising indeed even when accounting for the expected difficulty of driving SnV compared to NV [6]. All of this together suggests that our architecture will not be limited by cooling power, even in the target limit of scaling to thousands of memories with simultaneous individual addressing.

References

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