Cryo-CMOS Controller for Solid-State Color-Center Qubits Towards Scalable Quantum Processors

Mohamed I. Ibrahim, and Ruonan Han

***Abstract*—Solid-state color-center in diamond has emerged as a good candidate for quantum networks. However, scalability to a large number of qubits is a key challenge. This article introduces a novel scalable complementary metal-oxide-semiconductor (CMOS) architecture that can perform the microwave control of multiple solid-state color-centers in diamond. The color centers are integrated into diamond waveguides (quantum micro-chiplets (QMC)) and attached to the top of the CMOS chip. A demonstration for the control of one qubit at room temperature is also presented. This hybrid integrated system opens the door for scalable integration of solid-state color-centers for quantum information processing applications.**

***Index Terms*—color-centers in diamond, cryo-CMOS, quantum information processing.**

I. Introduction

Quantum systems are gaining increased interest with applications in high-performance computing, advanced sensing and secure communication. However, building a scalable quantum system is a challenge. For instance, thousands to millions of qubits are required to achieve practical quantum computing systems. Complementary metal-oxide-semiconductor (CMOS) integrated circuits stand out due to their scalability and reduction of cost, size and power. CMOS-based control and readout circuitry, operating at cryogenic temperatures (∼4K), has been demonstrated recently to interface with a few superconducting or spin qubits working at mK temperature [1], [2].

The qubits based on solid-state color-centers are also good candidates for quantum systems. For example, Nitrogen-vacancy (NV) centers in diamond have emerged as a leading room-temperature platform for sensing and imaging of temperature, electric fields and magnetic fields [3]–[6]. Moreover, since diamond color-centers act as spin-photon interfaces, they are promising for the realization of quantum networks. These networks are expected to play an important role in the future of information technology as carriers of secure classical information and as links between quantum computers [7], [8].

Conventional approaches for the control of solid-state color-centers involve bulky and discrete instruments for spin state manipulation and readout, leading to impractical systems that are hard to scale up due to the large number of wires, complexity and thermal load. To address this challenge, we have been developing custom chip-scale CMOS platforms that tighly integrate electronics and solid-state qubits. We demonstrated the first hybrid CMOS platform that controls and detects the spin-states of nitrogen vacancy (NV) centers in diamond for magnetometry. Two mm-scale room-temperature magnetic field sensors were demonstrated [9], [10]. This article introduces a novel scalable cryogenic-CMOS (cryo-CMOS) architecture to perform the simultaneous microwave coherent control of multiple solid-state color-center qubits (e.g., nitrogen-vacancy centers in diamond). These color centers are integrated into diamond waveguides (quantum micro-chiplets (QMC) [11]) attached to the top of the CMOS chip. This opens the door for scalable integration of solid-state color-centers for quantum information processing applications.

M. I. Ibrahim, and R. Han are with the Department of Electrical Engineering and Computer Science (EECS), Massachusetts Institute of Technology (MIT), Cambridge, MA, 02139, USA.

Other contributors are Isaac Harris, and Dirk Englund from EECS Department, MIT, Cambridge, MA, 02139, USA.

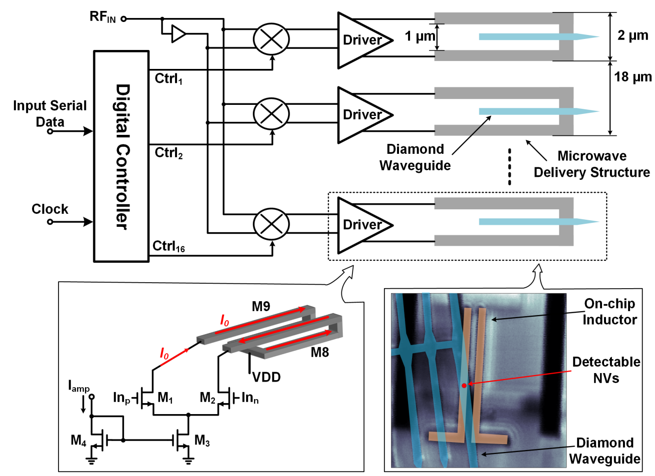

Fig. 1. Hybrid CMOS-diamond architecture to perform the microwave control of the diamond color-centers

II. Hybrid CMOS-Diamond Scalable Quantum Controller

The novel hybrid CMOS-diamond architecture to perform the microwave control of the diamond color-centers is shown in Fig. 1. These color centers (e.g., NV centers in diamond) are integrated into diamond waveguides attached to the top of the CMOS chip (see Fig. 1), where each waveguide is considered a single qubit. Our hybrid integration approach can be easily scaled up, since the qubits are directly attached to the top of the chip. The whole system is designed to work at ∼1-4 K, which eliminates the need for another mK stage.

The multi-qubit controller is designed and fabricated using TSMC 65-nm process. The high integration density of CMOS technologies enables closely spaced array of inductors; each addresses one qubit, together with the active control circuits. The inductors deliver the microwave control signals (∼3 GHz) to the diamond waveguides. Each inductor is designed with an outer width of 2µm and using two stacked metal layers (M9 and M8). In order to address multi-qubits simultaneously, the coupling between the closely spaced adjacent inductors (pitch = 18μm) has to be reduced. Therefore, the inductor is designed to flip the current polarities between M8 and M9 (Fig. 1). The field due to the current flowing in M8 reduces that due to the opposite current of M9 at the location of the adjacent inductors. Besides, this cancellation mechanism has a minimal effect on the field at the top of the inductor, since the vertical separation between M8 and M9 is closer to the inner width of the inductor.

The microwave signals are fed to the inductors through on-chip current differential drivers (Fig. 1). To achieve the microwave control of a large number of individual qubits simultaneously with a reduced number of control signals to the cryostat, we use an integrated digital controller (Fig. 1). The controller consists of a deserializer that allows a single serial digital input to be converted to multiple (16) parallel digital lines to control the qubits simultaneously. Each of these parallel signals is then mixed with the microwave input (RF_{IN} =∼3 GHz) fed from outside the cryostat using a passive mixer. Therefore, the resulting modulated signals represent the pulsed sequence that performs the qubit control.

The diamond waveguides, fabricated at MIT, are attached to the top of the chip using pick-and-place machine (Fig. 1). However, the chip's passivation layer, which emits unwanted background red fluorescence, is etched first using CF4 plasma [10]. The passivation etching also reduces the distance between the inductors and the waveguides to increase the strength of the microwave field delivered to them. Then the system operation is verified using single qubit control test structures at room-temperature. The optical detected magnetic resonance (ODMR) response [9], [10] of the NV centers in the diamond waveguides is measured. By sweeping the microwave frequency (RF_{IN}) around 2.87 GHz and using off-chip optical pumping and detection, an ODMR spectrum with a contrast of 8% is successfully obtained (See Fig. 2). We also conducted pulse-based spin control experiments (e.g. Rabi oscillations [12]) using a similar setup to the ODMR experiment. The measured Rabi oscillations data is shown in Fig. 3.

The measurements shown in Fig. 2 and Fig. 3 confirms the functionality of our microwave control architecture at room temperature. The cryogenic experiments and the simultaneous multi-qubit control are carried out currently towards the first demonstration of CMOS-integrated multi-qubit control for diamond color-centers. The next step for a more complex scalable solid-state quantum processor is the integration of

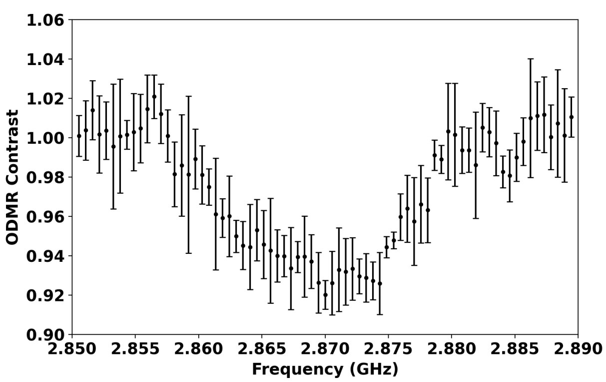

Fig. 2. Measured ODMR curve of a single qubit at room temperature.

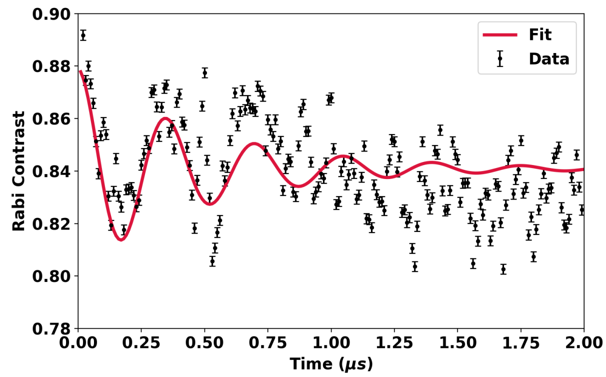

Fig. 3. Measured Rabi oscillations of a single qubit at room temperature.

silicon-photonics platforms to control the optical pumping. In addition, integration of optical readout using single-photon detectors is another possible direction in the future.

III. Career Plan and Fellowship Impact

I would like to sincerely thank the Microwave Theory and Technique Society (MTT-S) for this prestigious fellowship award in support of my Ph.D. research work. With the help of this fellowship award and the success of this project, I graduated from the Massachusetts Institute of Technology with a Ph.D. degree in electrical engineering and computer science. I look forward to further contributing to the MTT-S from academia and industry through exciting microwave research in integrated quantum systems and wireless/wireline transceivers.

References

[1] B. Patra et al., "Cryo-CMOS circuits and systems for quantum computing applications," *IEEE Journal of Solid-State Circuits*, vol. 53, no. 1, pp. 309-321, Jan. 2018.
[2] J. C. Bardin et al., "Design and characterization of a 28-nm bulk-CMOS cryogenic quantum controller dissipating less than 2 mW at 3 K," *IEEE Journal of Solid-State Circuits*, vol. 54, no. 11, pp. 3043-3060, Nov. 2019.
[3] G. Kucsko et al., "Nanometre-scale thermometry in a living cell," *Nature* 500, no. 7460, pp. 54-58, 2013.
[4] F. Dolde et al., "Electric-field sensing using single diamond spins," *Nature Physics* 7, no. 6, pp. 459-463, 2011.
[5] G. Balasubrmanian, et al., "Nanoscale imaging magnetometry with diamond spins under ambient conditions," *Nature* 455, no. 7213, pp. 648-651, 2008.
[6] D. Le Sage et al., "Optical magnetic imaging of living cells," *Nature* 496, no. 7446, pp. 486–489, 2013.
[7] G. Wolfowicz, F.J. Heremans, C.P. Anderson, S. Kanai, H. Seo, A. Gali, G. Galli, D.D. Awschalom, "Quantum guide-lines for solid-state spin defects," *Nature Reviews Materials* 6, no. 10, pp. 906–925, 2021
[8] H. Choi, M. Pant, S. Guha, D. Englund, "Percolation-based architecture for cluster state creation using photon-mediated entanglement between atomic memories," *npj Quantum Information*, 5, no.1, pp. 1–7, 2019
[9] M. I. Ibrahim, C. Foy, D. R. Englund and R. Han, "High-Scalability CMOS Quantum Magnetometer With Spin-State Excitation and Detection of Diamond Color Centers," *IEEE Journal of Solid-State Circuits*, vol. 56, no. 3, pp. 1001-1014, March 2021.
[10] D. Kim, M. I. Ibrahim, C. Foy, M. E. Trusheim, R. Han, and D. R. Englund, "A CMOS-integrated quantum sensor based on nitrogen–vacancy centres," *Nature Electronics*, vol.2, no.7, pp. 284-289, July 2019.
[11] N.H. Wan, et al., "Large-scale integration of artificial atoms in hybrid photonic circuits," *Nature* 583, no. 7815, pp. 226–231, 2020
[12] F. Jelezko et al., "Observation of coherent oscillations in a single electron spin," *Physical review letters* 92, no.7, p. 076401, 2004