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3D Integration for Modular Quantum Computer based on Diamond Spin Qubits

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***Abstract*—Quantum computer chip based on spin qubits in diamond uses modules that are entangled with on-chip optical links. This enables an increased connectivity and a negligible crosstalk and error-rate when the number of qubits increases on-chip. Here, 3D integration is the key enabling technology for a large-scale integration of the diamond spin qubits with photonic and electronic circuits for routing, control and readout of qubits. There are several engineering challenges to integrate the large number of spins in diamond with the on-chip circuits operating at a cryogenic temperature. In this paper we will address challenges, present recent results and discuss future outlook of the integration technology for realization of a scalable quantum computer based on diamond spin qubits.**

Keywords—Quantum computer, 3D integration, Photonic circuits, Flip-chip bonding

I. INTRODUCTION

In quantum computer (QC) chips, attentions have recently been focused on scaling to larger qubit numbers that are capable of complex computing algorithms. Here it is preferable to have a high connectivity and low crosstalk between the qubits. The architecture that uses a network of modules having many qubits through entangled channels [1,2] using photon [3] will provide a low crosstalk and hence low error-rate. It also increases the connectively via a beyond nearest neighbor connectivity.

The modular QC chips could be devised with optically linked modules having a single color-center in diamond with an electron spin and associated nearby carbon-13 nuclear spins as shown in Fig. 1. Color centers are localized defects in the diamond lattice created by the combination of vacancies, and substitutional atoms like nitrogen [4] or tin [5]. The color-center has an optically active spin and features spin-selective optical transitions and using photon detection with beam splitter interference, two electron spins in diamond at separate positions can be entangled [6]. In diamond, there are ^{13}C isotopes which has a nuclear spin with coherence time of over ten seconds [7] and can be coupled with the color-center. Color-centers can operate relatively high operation temperatures (>1K) enabling a smaller form factor than systems with many other qubits.

For routing and detecting photon for the qubits in diamond on-chip, integrated photonics [8] will be the enabling technology. Integrated waveguides and single photon detectors will not only pack the devices compactly but also improve overall performance because of the low loss and better phase control compared to the optical fiber and open space solutions. For controlling multi qubits with a reduced number of cables, cryo-CMOS electronics [9] will facilitate classical analog and digital electronic infrastructures, such that it is no longer necessary to address individual circuit from outside of the chip.

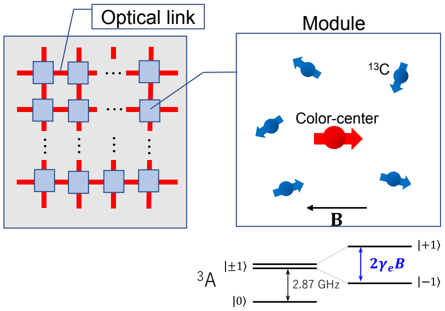

Fig. 1. Modular quantum computer chip with spins in diamond

In order to integrate those functional layers with a large number of qubits, it becomes necessary to go beyond planar geometries. The key enabling technology is 3D integration of an array of diamond spin qubits, electronic and photonic integrated circuits which will be a viable pathway to meet the increased interconnect needs of the system, improving the performance and realize a compact overall system. We will review trends, address challenges, and discuss future outlook of the 3D integration in QC chip based on spins in diamond.

II. 3D INTEGRATION

In this work, we propose a 3D integration process for implementing modular QC chip with diamond spin qubits in a combination of monolithic and flip-chip integration techniques. As provided in Fig. 2, the proposed integration scheme is based on using heterogeneously integrated diamond devices on a wafer. A monolithic integration of photonic circuits, waveguide coupled single-photon detectors [10], local magnetic field generators is carried out on the substrate. The cryo-CMOS control chip is separately manufactured and then bonded with the photonic chip with a flip-chip technique with bumps.

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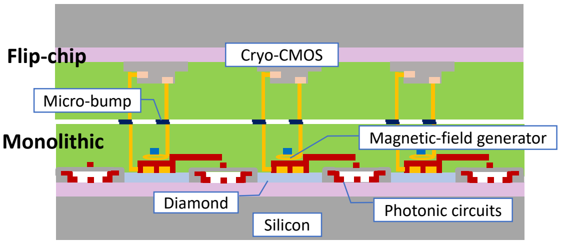

Fig. 2. 3D integration of modular quantum computer chip with spins in diamond

A. *Diamond on Insulator*

Most diamond substrates are made by high pressure and high temperature diamond (HPHT) methods, where the maximum size of readily available single crystalline diamond substrate with a low impurity level is very small: in the order of mm^2. The small size prevents the use of advanced semiconductor manufacturing line which accepts a wafer size of at least 2 inch. Direct bonding of single crystalline diamond substrate on insulator (DOI) [11] is a promising approach. With improved process conditions, we have successfully bonded a (100) diamond substrate on a CVD deposited and oxygen plasma treated SiO_2 on a silicon substrate without pressure under atmospheric conditions (Fig. 3) and annealed at 200 °C to strengthen the bonding to the shear strength of 9.6MPa. Alternatively, we have also successfully bonded a diamond substrate directly on a sapphire substrate by fast ion beam (FAB) irradiation and the shear strength of 14.4MPa has been obtained. [12] Those methods are encouraging for preparation of DOI wafer, which enables large-scale nanostructure fabrication in diamond. The rest of active layers could be fabricated monolithically or vertically stacked in a chip level.

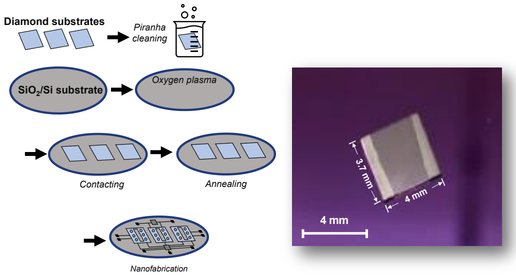

Fig. 3. Process flow (left) and image (right) of direct bonding of (100) diamond on CVD-SiO_2/Si wafer

B. *Diamond chiplet assembly*

Alternatively, pre-fabricated diamond chiplets could be released and picked from the diamond wafer and heterogeneously placed on a receptor chip or wafer having photonic circuit [13]. The pick-and-place assembly method has an advantage that pre-testing of diamond chiplets can select good devices to be integrated on the photonic circuit. In order to optically interconnect the diamond chiplet to the waveguides on the optical chips, the adiabatic couplers appear to be the most promising solution. Different shapes of adiabatic couplers have been simulated using FDTD method. Different taper profiles have been compared and assessed on their performance related to coupling efficiency, alignment sensitivity and insertion loss. An FDTD simulation has been done for the optimum dimensions (taper length 9 μm and taper tip width 70 nm). The diamond waveguide dimensions are 200 nm in thickness and 340 nm in width, which support single mode operation. The SiN dimensions are 150 nm in thickness and 500 nm in width. The mode coupling efficiency is 98.7% and the total transmission is 80%.

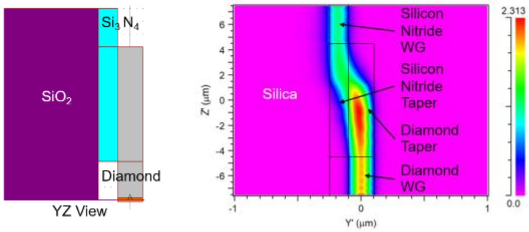

Fig. 4. Geometry (left) and simulated contour plot (right) of the electric field of diamond on SiN with a linear taper.

C. *Optical switch*

Optical switches are the essential component of integrated photonics for routing excitation and emitted photons to and from color-centers in diamond. Use of MEMS in the switch gives a relatively fast switching time in the order of 1 μs and is also compatible with CMOS technology. Previous design of MEMS photonic switches [14] uses silicon as waveguide material to support a 300 nm broadband centered at 1550 nm. However, due to the excitation and emission spectrum of the color centers in diamond, the switch must operate in visible wavelength where silicon nitride (SiN) is an attractive material as the waveguide is well matured in Si photonics foundries.

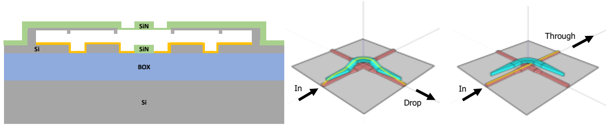

Fig. 5. Cross sectional view of MEMS optical switch (left) and the configurations for ON and OFF states of adiabatic couplers (right).

Two orthogonal sets of bus waveguide with a low-loss multimode interference (MMI) crossing defines two propagation paths. The switching is controlled by L-shaped waveguide having two adiabatic couplers at the ends that are vertically moved by two MEMS-actuators. When the switch is in ON state, the first adiabatic coupler couples the light from the bus waveguide and takes a 90-degree bend, and the second adiabatic coupler couples light back into the orthogonal bus to the drop port.

D. *Direct bonding bump*

Cryo-CMOS chip can be stacked on top of the monolithic integrated DOS chip by flip-chip bonding. The conventional

CMOS flip-chip bonding involves the formation of solder bumps using solider alloy of Sn/Ag/Cu, which will undergo a ductile to brittle transition due to a phase change resulting in catastrophic failure of the interconnect. There are a few demonstrations of bump bonds that are compatible with qubit operation at a cryogenic temperature. Indium [15] is reported to be a good bonding at cryogenic temperature due to its good wettability, low melting point and softness at a low temperature. However, the critical temperature (Tc) of indium is typically around 3.4K, which is lower than qubit working temperature of above 4K for NV-centers in diamond. Furthermore, an extra layer of adhesive used to join two planes of indium bumps increases the degree of misalignment.

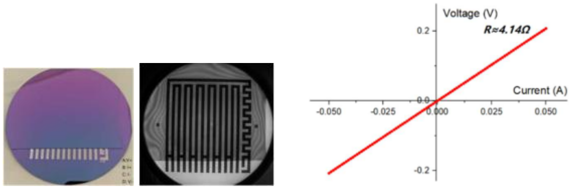

Fig. 6. Wafer scale daisy chain pattern (left) and I-V characteristics with 80 contact stops of NbN direct bonded bumps.

The first approach in this work is to use NbN for direct bonding bump in 3D structure for the modular QC chip [16]. NbN provides a higher critical temperature and the direct bonding allows joint without any extra adhesive, hence a high alignment accuracy. Two NbN films are deposited on Si wafers in a magnetron sputtering system at a temperature of 350°C and the critical temperature of 15.2K was obtained. After pattering resistive daisy chain patters of NbN on wafers, the two wafers are aligned and bonded with thermo-compression bonding at an elevated temperature of 550°C and a pressure of 15kN. Fig. 6 shows the bonded wafers by the thermo-compression. In the figure, the daisy chain rectangular patterns from the top wafer aligns perfectly with those on the bottom wafers. The I-V measurement at RT of NbN-NbN daisy chain resistor with 80 contact spots in Fig. 6 shows ohmic behavior with a total resistance of 4.14 Ω, indicating that the contact resistivity of a single contact spot is on average is $2.36\times10^{-3}\ \Omega\cdot cm^2$.

III. CONCLUSION

3D integration of modular quantum computer chip based electron and nuclear spins in diamond has been proposed as a key enabling technology for large scale integration of qubits in diamond with integrated photonics and CMOS electronics. Trends and challenges in each individual layers and integration of them are reviewed and discussed. Combination of monolithic integration on diamond on silicon and flip-chip integration techniques was proposed as a viable process. Recent results on direct bonding of diamond with SiO_2 and direct bonding metal bumps provide a step towards a realization of modular quantum computing based on spins in diamond, which will provide a high connectivity and a negligible crosstalk in a compact overall system.

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