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Forefront of Silicon Quantum Computing

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***Abstract*—Forefront of the silicon quantum computer development is described.**

Keywords—quantum computing, silicon

I. Contents

A. *Why quantum computing*

Quantum computing will complement a number of advanced tasks that will be performed by the extension of today's computing frameworks. Its application is expected to span many fields such as optimization, machine learning, security, data search, etc. Here, as examples, the current states of quantum computer algorithm and software developments in the area of finance [1] and chemical engineering [2] sectors are introduced.

B. *Why silicon (See Ref. 3 for an excellent review on silicon quantum computing)*

A quantum computer is going to operate in collaboration with silicon CMOS electronics and silicon AI chips. Therefore, integration of the classical and quantum circuits together in one silicon chip is strongly preferred. Use of the state-of-the-art silicon processing technology will allow to shrink the size of silicon quantum bits (qubits), interconnects, electrodes, etc. for larger and more reproducible integration. Moreover, it has been shown recently that the silicon spin qubits can operate at "high-enough temperature" of ~5K [4-6] at which classical CMOS can also function together. The temperature of more than 4K can be achieved easily by mechanical cooling, allowing to have a very large sample space for hosting necessary electronics. Such high temperature operation possibility is a sharp contrast to the case of superconducting qubits that can only work at temperatures much less than 0.1 K requiring dilution refrigerators, whose sample space is severely limited for scaling.

C. *Variations in silicon qubits)*

Silicon qubit forefronts are categorized into the following five groups.

i) Gate-defined MOS spin qubit [7, 8]
One electron spin captured under a positively biased Si MOS gate is employed as a qubit. The two levels, spin up and down states, of the single electron are used to represent qubit states.

ii) Gate-defined Si/SiGe spin qubit [9, 10]
One electron spin captured in the layer of strained Si grown on the lattice mismatched SiGe virtual substrate in the region under a positively biased MOS gate is utilized as a qubit.

iii) Gate-defined Si/SiGe singlet-triplet qubit [11-13]
Multiple electrons confined in a pair of gate-defined Si/SiGe quantum dots form a single qubit state.

iv) MOSFET structure converted to spin qubit [4, 14, 15]
A MOSFET structure is employed to confine a single electron in a certain position of the channel to form a qubit.

v) Donor qubit [16-18]
A phosphorus donor electron spin qubit is placed in silicon by ion-implantation or scanning tunneling microscope lithography.

D. *Substrates [See Ref. 19 for a review on the isotope engineering of Si for quantum information processing]*

Naturally available silicon ($_{nat}$Si) is composed of $_{28}$Si, $_{29}$Si, and $_{30}$Si stable isotopes with the fixed compositions of 92.2%, 4.7%, and 3.1%, respectively. Among them, only $_{29}$Si has nuclear spin 1/2 and the magnetic field fluctuation arising from the $_{29}$Si nuclear spins turn out to be the major source of qubit decoherence. For this reason, isotopically enriched $_{28}$Si epilayers grown on the standard 300 mm Si wafers [20, 21] and isotopically purified $_{28}$Si strain layers grown on SiGe virtual substates [10, 14, 22] are being developed.

E. *Interconnects*

Transfer of quantum information between two distant qubits is a challenging task. It is possible to perform sequential nearest-neighbor information swapping to move quantum information from one qubit to another within a small number (~20) of quantum bit array. However, a longer distance quantum information transfer requires conversion of the electron spin qubit information to a different kind of a mobile qubit such a microwave photon [23, 24]. The microwave photon qubit can travel through a waveguide to connect two distance qubits.

F. *Architecture and integration with classical CMOS circuits*

There have been many proposals on integration of silicon quantum and classical computers [1, 25-27]. The circuit layout design including essential elements (qubits, readout devices, microwave waveguides, microwave antennas, interconnects, etc.) plays a key role.

G. *Conclusion and outlook*

Advancements are accelerating towards realization of silicon quantum computers. Based on the current state-of-the-art, outlook will be given.

Acknowledgment

This work was supported by Spintronics Research Network in Japan.

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