Transient Analysis of Local Heating on Current-Addressing Qubit Selection in Silicon Quantum Computing Systems

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Silicon quantum devices are promising for large-scale integrated quantum computers due to the highly sophisticated microfabrication technology. Recently the hybrid architecture of controller and qubit array [1,2] and current-addressing qubit selection [3,4,5] have been proposed for the scalability of the quantum computers. When controlling the spin of a quantum bit, a selection operation is performed using local field modulation generated by applying a current to the gate electrode. There is a risk of local heating caused by the addressing currents. Hence the feasibility study on the quantum computing systems in terms of heat budget is one of the key issues because cryogenic sub-Kelvin environment is essential for Si spin qubits to keep long coherence time and high fidelity in operation & readout.

There are several challenges to establish such kinds of thermal analyses scheme: (i) Thermal conductivity and specific heat at sub-Kelvin drastically decrease depending on temperature. (ii) Thermal diffusion highly depends ton fine structures around qubits. (iii) Temperature distribution and its transient behavior inside Si chip is governed by operation state. (iv) Cooling power of cryo-fridge also depends on temperature.

Here, we tackled thermal modeling of quantum devices and cryo-fridge environments using the current-addressing qubit selection [3,5] as an example. The thermophysical properties of the silicon materials were modeled as Log-Log interpolated function of temperatures based on their public data at several Kelvins or over. The transient thermal analysis on actual fine structures of Si chip and cryo-fridge was adopted in coupled form with Ohm's law, heat transfer equation, and Ampere's law. We employed COMSOL Multiphysics® for this purpose.

In parallel with our analytical approach, we measured electron temperatures of qubits using well-known technique Coulomb blockage thermometry (CBT) [6]. By devising the data sampling of CBT and parametrizing the distance between heat sources and quantum dots, we characterized the thermal conductance and specific heat of the real silicon device. The verification & validation for the modeling scheme will be discussed.

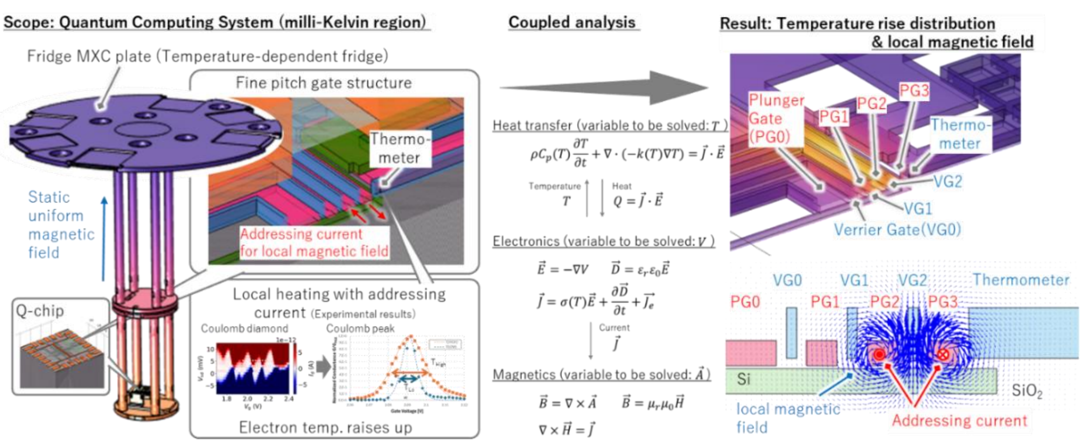

Fig.1. Thermal modeling scheme of cryo-fridge environment.

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