Superconducting Qubits and High Resistivity Silicon Substrates

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Qubit experiments at UC Santa Barbara in the mid 2000's showed excess dissipation in resonators made on low-resistivity wafers of about 1 Ω-cm; low loss was then observed after changing to high-resistivity wafers 100 Ω-cm. Here an explanation is suggested based on tunneling between dopant sites at a high dopant density.

It is important to build models for every decoherence mechanism in superconducting qubits in order to know all the systems engineering constraints for a quantum computer. Explained here is a constraint on the resistivity of silicon substrates, which are often used for superconducting qubits.

In the mid 2000's, qubit experiments at UC Santa Barbara showed excess dissipation when resonators were built on low resistivity wafers, about 1 Ω-cm at room temperature. When switching to high-resistivity wafers 100 Ω-cm, the dissipation was removed. This result was surprising since the electrical carriers of the low resistivity wafer should have frozen out at dilution refrigerator temperatures, since the dopant density was much smaller than needed for degenerate (metallic) doping.

I explain here that even though the temperature was low enough so that there would not be any thermally generated motion of the dopant carriers (electrons or holes), motion from quantum tunneling is still expected at these dopant levels. This can be semi-quantitatively understood by the data of Fig. 1 from the silicon qubit literature. Here tunneling rate predictions and measurements show an exponential decrease with increasing distance between two donor sites. Table I gives distances for a range of tunneling rates, the last of which is where the effects of tunneling should be turned off. From this distance an average doping density can be calculated, along with an approximate resistance of the silicon substrate from the literature. It is clear that the tunneling rates are exponentially suppressed at a doping level with resistivity greater than 1 Ω-cm.

This rough model only computes the average tunneling rate. There is a random distribution of distances between dopants, so individual tunneling rates will be higher and lower given here. In addition, one should consider that tunneling between donor sites is more complex than this simple estimate because they are typically already occupied with an electron or hole. However, since tunneling can occur to a doubly occupied site, analogous to the H^+ ion, then charge transfer can still occur. Since the doping density is high and the resonator loss experiments were sensitive to modest changes in dissipation, then rare tunneling events are like to still be important.

Table I shows at resistivities of 100 Ω-cm, the tunneling rate is vanishing small. Thus this substrate, which is readily commercially available, has been a safe choice.

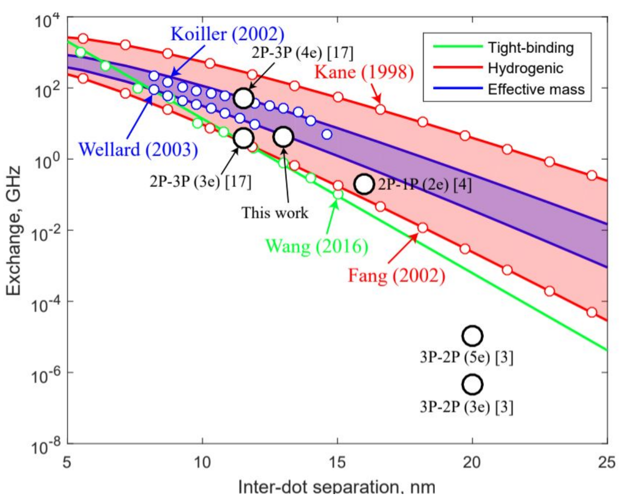

Figure 1. a) Plot of donor-donor tunnel rates for Phosphorous donors, with both theoretical calculations and experimental data for silicon qubits. From supplement of Ref. [1]. This data shows characteristic tunneling rates that become exponentially small at large distance, at around a distance 50-100 nm.

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[1] Y. He1, S. K. Gorman, D. Keith, L. Kranz, J. G. Keizer, M. Y. Simmons, A two-qubit gate between phosphorus donor electrons in silicon, Nature **571**, 371 (2019).

tunnel rate (Hz)	distance (nm)	density ($1/cm^3$)	resistivity (Ω-cm)
1 M	30	3.7e16	0.6
1 k	40	1.5e16	1.2
1	50	8e15	2
1 m	60	5e15	3
1e-45	200	1.4e14	100

Table I. Tunneling rates for various distance between donors. Their density and approximated resistivity is also given for Boron doping. This data shows donor-donor tunneling rapidly turns off at a wafer resistivity of about 1 Ω-cm.