Charge Sensing in Silicon Metal-Oxide-Semiconductor Quantum Dots

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Motivation—In recent years, semiconductor lateral quantum dots have emerged as an appealing approach to quantum computing. The demonstration of electrically controlled spin qubits in GaAs/AlGaAs heterostructures and spin blockade within Si systems are recent advances toward that goal. Silicon offers the potential for very long spin decoherence lifetimes in both donors and quantum dots. The Si metal-oxide-semiconductor (MOS) system features highly tunable carrier densities and the possibility of very small dot sizes, as well as providing further opportunities to couple single donors to gated quantum dots

Accomplishment—Silicon MOS nanostructure devices are fabricated using a version of the CINT Electrical Transport Discovery Platform. In the Microelectronics Development Lab, silicon wafers are fabricated (Figure 1a,b) with a stack that included ohmic contacts, a high quality thermal oxide, a doped poly-silicon layer and a region for additional nanolithography (Figure 1c). In order to operate sub-100 nm structures, the poly-silicon gate is patterned using electron beam lithography and subsequent dry etching. A negative voltage expels electrons from the depletion gate regime and defines the nanostructure. Field-effect based devices also require a positive gate voltage to induce electrons at the silicon-silicon oxide interface, and this is implemented using a separate overall Al top gate (Figure 1d). The top gate and depletion gates are electrically isolated with atomic layer deposition of aluminum oxide.

The device shown in Figure 2a is designed as a double quantum dot (gates B-F,H) with narrow constrictions to the left and right of the double dot regime (gates A-B and F-G). In future experiments we plan to use the full double dot structure, but for the charge sensing demonstration we use the gates highlighted in red to form a single quantum dot (D-F and H) with an integrated charge sensor (F-G). The quantum dot has approximately 100 electrons, and a negative bias on the plunger gate, E, reduces the electron number of the dot by a single electron every 43 mV. The electron addition can be observed directly by monitoring the transport through the dot (Figure 2c, red line). Each time an electron energy level aligns with the reservoirs, the current increases and when the levels are not aligned the dot conductance is blocked. The point contact constriction can be used as a remote sensor for the changes in electron number (Figure 2c, black line). For a fixed bias, the current changes by approximately 3% every time the electron number in the dot changes. The charge sensor can effectively measure changes in electron occupation even when the direct conductance through the dot is too small to observed Coulomb blockade (V_E<-1 volt)

Significance—Spin quantum computing in semiconductors requires working with single electrons in quantum dots. In this regime it is important that no current flow through the dot. The successful demonstration of a point contact electrometer in a silicon MOS nanostructure is a critical element to both reducing the electron number to one, and eventually for measuring the spin using a spin-to-charge transduction technique. This approach is also compatible with sub-microsecond single electron measurements using an rf-SET approach.

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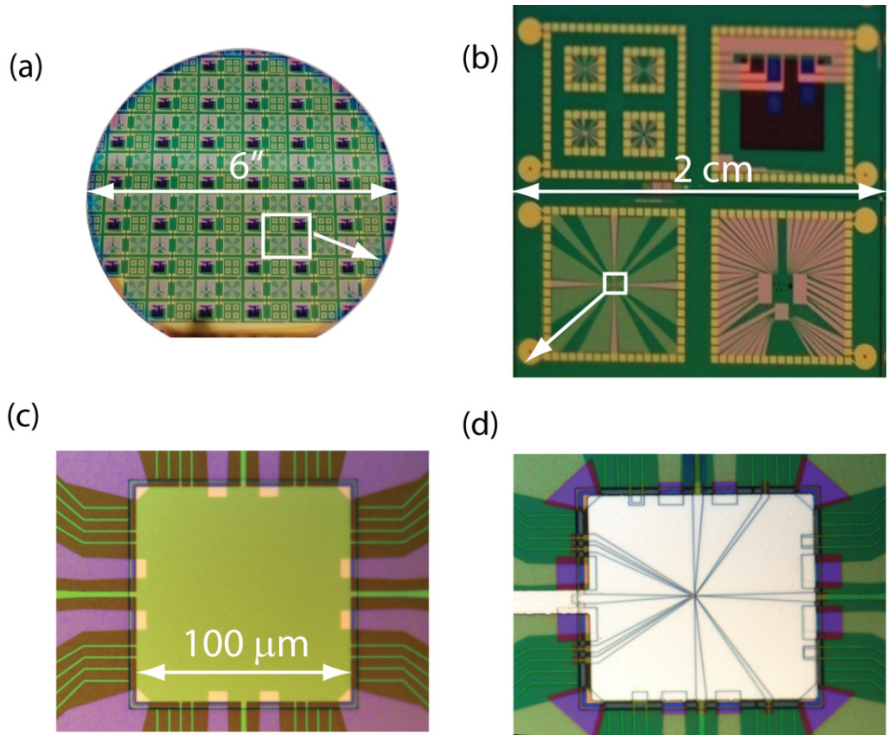

Figure 1. (a) Front-end 6 inch silicon wafer with many MOSFET structures. (b) 2 cm die with 4 quadrants for back-end nanolithography. (c) 100 micron poly gate (green) ready for depletion gate patterning. Ohmic contact to the 2D electrons are purple. (d) Same region after electron beam lithography, Al2O3 and top Al gate.

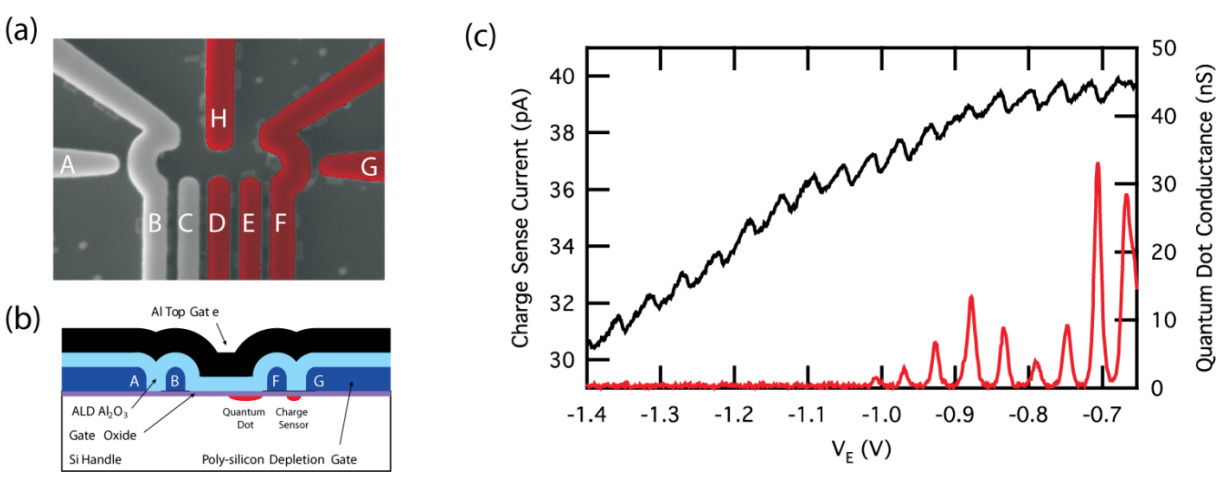

Figure 2. a) Double quantum dot is defined by depletion gates (B-F and H); integrated electrometers are the point contacts defined by A-B and F-G. (b) Cross section of double gated MOSFET layers with the dot and point contacts represented schematically. (c) Coulomb blockade peaks in a many-electron single dot (defined by H,D,E and F). The compensated charge sensor current shows a step each time another electron is added to the dot.