Toward optimizing multi-qubit device design and operation

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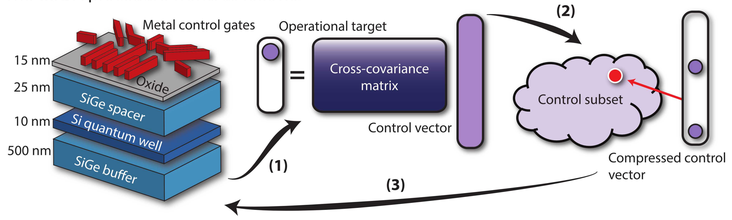
COMPRESSED OPTIMIZATION OF DEVICE ARCHITECTURES (CODA)

MOTIVATIONS AND PROCEDURE

- Designing devices which can be simply controlled may become infeasible as device complexity grows[1].
- A "simple" operation involves a small number of electrodes located near to the quantity of interest.
- Using ideas from compressed sensing[2,3], we can find the "simplest" operation associated with a desired outcome.

The CODA procedure works as follows:



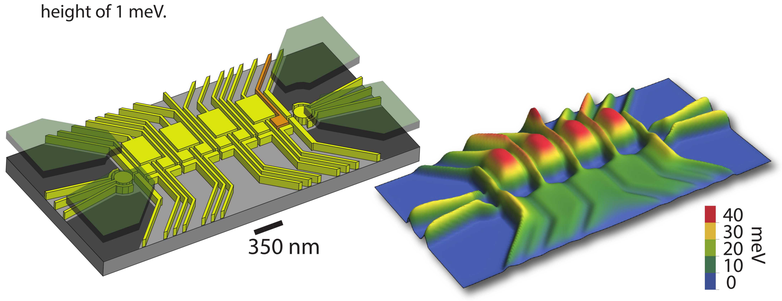
(1) Starting at a working point, use device simulation to find a linearized model (S) relating electrode voltages (control vector) to dot occupations / tunnel barriers (operational target)

(2) For a given operational target $\mathbf{t}_0$, find all control vectors $\mathbf{c}$ which satisfy $S(\mathbf{c}) = \mathbf{t}_0$. Of these, find the vector with the minimal L_1 norm (the compressed control vector).

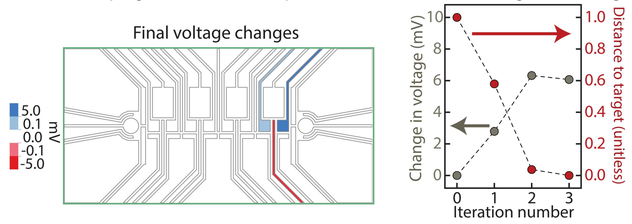
(3) This compressed control vector can be fed into the device simulations.

AUTOMATIC TUNING

Using COMSOL Multiphysics, we simulate a realistic 8-dot device, tuned such that one electron is in each quantum dot has one electron, and the inter-dot tunnel barrier has a maximum height of 1 meV.



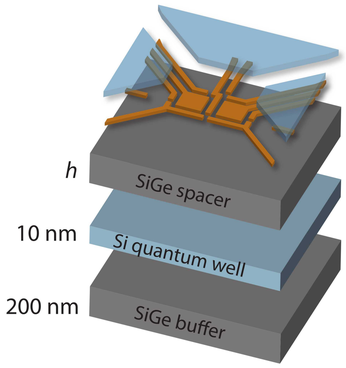
By applying the CODA procedure iteratively, we increase the occupation of the right-most dot by one electron, keeping all other dot occupations and tunnel barrier heights unchanged.

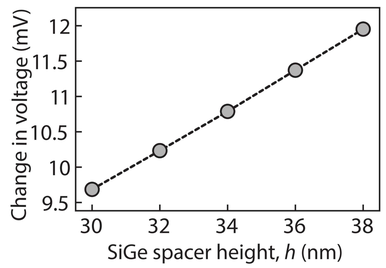


DEVICE OPTIMIZATION

Here we simulate five devices, each with identical electrode design and heterostructure, save for the layer of $Si_{0.7}Ge_{0.3}$ referred to as the "SiGe spacer." The height of the spacers range from 30 nm to 38 nm.

In each device, we start with one electron in each dot, and an inter-dot tunnel barrier height of 1 meV, and apply the iterative CODA procedure, adding one electron to the right dot.





Comparing the L_1 norms of the voltages determined via the iterative CODA procedure, we find that the L_1 norm increases with SiGe spacer height. As the L1 norm is the metric for the "simplicity" of an operation, this implies that in the absence of charge noise and interfacial roughness, a smaller SiGe spacer yields a device which is "simpler" to control.

METHODS

We perform semi-classical Thomas-Fermi calculations using the COMSOL Multiphysics software package to solve a nonlinear Poisson equation in three dimensions. The L1 regularized optimizations are performed using the CVXPY package[4] to transform our convex optimization problem into an equivalent conic problem, which can then be efficiently solved using a matrix-free cone solver. Unless otherwise stated, the heterostructure used in simulated devices is: 200 nm of $Si_{0.7}Ge_{0.3}$ (with dielectric constant $\varepsilon = 13.19$), a 10 nm Si quantum well ($\varepsilon = 11.7$), 30 nm of $Si_{0.7}Ge_{0.3}$, 10 nm of Al_2O_3 ($\varepsilon = 9.0$), a 10 nm layer of metallic electrodes, 80 nm of Al2O3, and a second 10 nm layer of metallic electrodes. For more information, see:

http://arxiv.org/abs/1409.3846.

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[1] J. R. Koza, F. H. Bennett, D. Andre, M. A. Keane, and F. Dunlap, IEEE Transactions on Evolutionary Computation **1**, 109 (1997).

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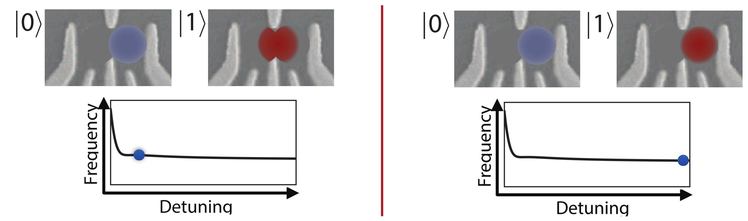
TWO-QUBIT OPERATIONS IN THREE-ELECTRON DOUBLE QUANTUM DOTS

MOTIVATIONS

- The semiconductor hybrid qubit has been shown[1] to be capable of fast single-qubit operations at reasonably high fidelities.
- Strong capacitive coupling has been observed[2] between pairs of double quantum dots similar to those used as hybrid qubits.
- We discuss how this capacitive coupling can be used to produce two-qubit gates, and propose a path towards increasing the fidelity of these gates.

MODULATING EFFECTIVE COUPLING

Changing the relative energy between quantum dots (the detuning) in a semiconductor hybrid qubit changes the charge signiture of the logical states, as shown in the cartoon below.



Using the Schrieffer-Wolff transformation[3] to determine the effective coupling between the qubits, we find that the qubit-qubit coupling can be modulated, despite the fact that the strength of the capacitive coupling between the double-dot systems remains constant.

PATH TOWARD INCREASING FIDELITY

When the detuning of both qubits is decreased, the qubit-qubit coupling becomes non-negligible, and entangling gates may be performed. One of the main contributors to the high fidelity observed in single-qubit gates in the semiconductor hybrid qubit comes from the use of the sweet spot[1], where the derivative of the frequency with respect to the detuning is close to zero: $\frac{\partial \omega}{\partial \epsilon} \approx 0$

In a two-qubit system, there are three frequencies and two detunings, meaning that the "two-qubit sweet spot" consists of six constraints:

$$\frac{\partial \omega_i}{\partial \epsilon_j} \approx 0, \quad i=1,2,3; \quad j=1,2$$

Analytical techniques such as the Schrieffer-Wolff transformation[3] and numerical techniques such as the Nelder-Mead method[4] will indicate the set of physical parameters which best meet these criteria, and therefore minimize the effect of charge noise on the proposed two-qubit gate.

METHODS AND REFERENCES

We perform fourth order Schrieffer-Wolff transformations[3] using the Mathematica software package to reduce the nine-dimensional Hilbert space of the coupled system down to an effective four-dimensional Hilbert space.

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