

# Remote Capacitive Sensing in Two-Dimensional Quantum-Dot Arrays

Jingyu Duan,\* Michael A. Fogarty,\* James Williams, Louis Hutin, Maud Vinet, and John J. L. Morton



Cite This: *Nano Lett.* 2020, 20, 7123–7128



Read Online

ACCESS |

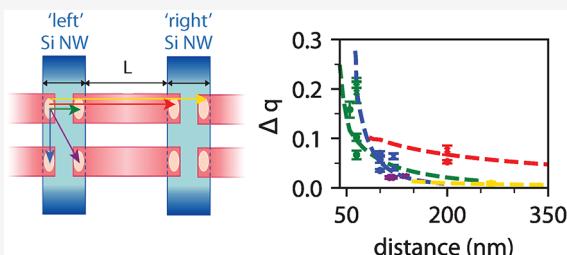
Metrics & More

Article Recommendations

Supporting Information

**ABSTRACT:** We investigate gate-induced quantum dots in silicon nanowire field-effect transistors fabricated using a foundry-compatible fully depleted silicon-on-insulator (FD-SOI) process. A series of split gates wrapped over the silicon nanowire naturally produces a  $2 \times n$  bilinear array of quantum dots along a single nanowire. We begin by studying the capacitive coupling of quantum dots within such a  $2 \times 2$  array and then show how such couplings can be extended across two parallel silicon nanowires coupled together by shared, electrically isolated, “floating” electrodes. With one quantum dot operating as a single-electron-box sensor, the floating gate serves to enhance the charge sensitivity range, enabling it to detect charge state transitions in a separate silicon nanowire. By comparing measurements from multiple devices, we illustrate the impact of the floating gate by quantifying both the charge sensitivity decay as a function of dot-sensor separation and configuration within the dual-nanowire structure.

**KEYWORDS:** Quantum dots, Reflectometry, floating gate coupler, electrostatic coupling



Spin qubits in silicon demonstrate the fundamental properties required for scaled quantum computation with state-of-the-art one- and two-qubit operations demonstrating control fidelities approaching the requirements for fault-tolerant quantum error correction.<sup>1–4</sup> While all control elements have been integrated into single devices with scalable readout mechanisms,<sup>5</sup> much effort is now being focused into developing these devices from simple laboratory prototype structures into scaled arrays of qubits capable of eventually yielding a quantum advantage.<sup>6,7</sup> The promise of a highly developed material system and mature fabrication industry, together with the success of laboratory and industry-grade prototype silicon–metal-oxide-semiconductor (SiMOS) quantum-dot-based devices,<sup>8</sup> has led to the proposition of several approaches to foundry-compatible scaling into grid-based architectures of quantum dot arrays. These approaches range from densely packed qubits with next-nearest-neighbor couplings,<sup>9</sup> dot arrays partially populated with qubits,<sup>10</sup> and arrays with qubit sites linked via mediating structures for remote qubit–qubit coupling.<sup>11</sup>

SiMOS devices, which form quantum dots in the corners of silicon nanowires, naturally produce bilinear dot arrays,<sup>12</sup> which allow for proximal sensor integration for both charge<sup>13–16</sup> and spin states<sup>17</sup> through dispersive measurements using gate-based reflectometry. The advantages of these integrated sensors can be extended by mechanisms for off-wire coupling to sense the state of dots located in remote locations within the quantum dot array. In order to enhance the capacitive coupling between spatially separated quantum dots, studies in planar GaAs/AlGaAs and Ge/Si hetero-

structures and carbon nanotubes have exploited a floating gate,<sup>18–20</sup> a metallic electrode which is galvanically isolated from but capacitively coupled to its immediate environment.

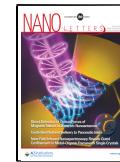
Here, utilizing a single quantum dot sensor we demonstrate a system capable of performing both proximal and remote capacitive charge sensing within a  $2 \times 4$  array of quantum dots distributed across two parallel nanowires. We compare these results with geometrically identical single-wire variants, serving as an isolated  $2 \times 2$  array. Each  $2 \times 2$  array is formed on a single silicon nanowire (SiNW), and all devices described here are located in the same die, fabricated from a fully depleted silicon-on-insulator (FD-SOI) process.<sup>21</sup> Our approach uses floating gate electrodes to capacitively couple a sensor dot to quantum dots on remote nanowires, while maintaining sensitivity to adjacent dots within the local nanowire. We quantify the sensitivity to charge movement within these two schemes by experimentally benchmarking the device capacitance matrix, supported by cryo-SiMOS simulations.

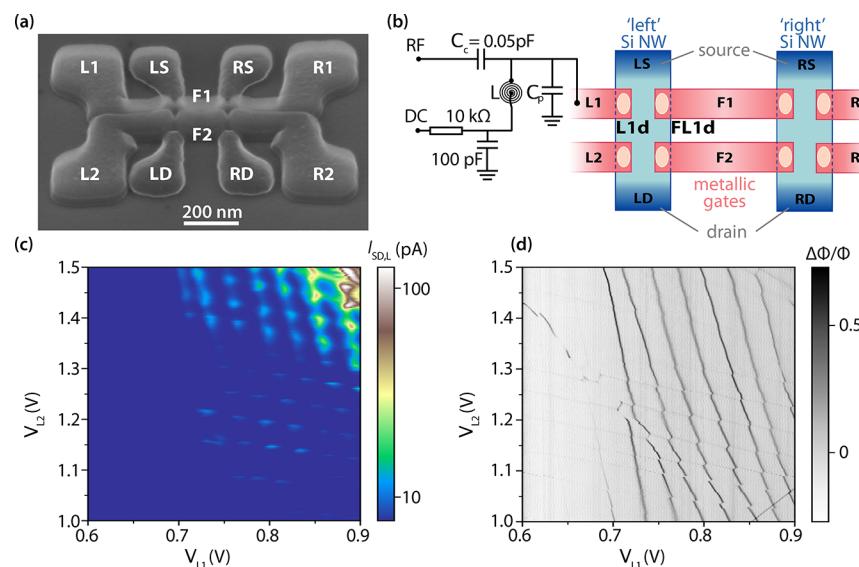
The scanning electron micrograph (SEM) image in Figure 1a shows a device of the type used in these remote sensing experiments. Two parallel nanowires with center-to-center spacing of 200 nm are fabricated with two central floating gates

**Received:** June 9, 2020

**Revised:** September 18, 2020

**Published:** September 18, 2020





**Figure 1.** Device, measurement, and configuration. (a) Oblique-angle scanning electron micrograph illustrating the gate structure of the double-nanowire device coupled by two floating gates. (b) Cartoon of the gate structure and reflectometry circuit diagram. Charge transitions in a variety of quantum dots are detected by the “single electron box” sensor under L1, including those in dots within the same (left, L) nanowire or located remotely in an adjacent (right, R) nanowire, and detected capacitively through coupling facilitated by the floating gate. (c) Double-dot signatures within the left nanowire through a transport current map of gate L1 versus L2 voltage-space with a source-drain bias 4 mV. (d) A concurrent zero-biased reflectometry measurement illustrates dot-lead charge transitions of the L1 sensor dot and capacitive shifts due to addition of electrons to a local quantum dot defined under gate L2.

F1 and F2 wrapping the interior edges of both, spanning the gap between the two silicon structures. Gates F1 and F2 are capacitively coupled to the surrounding gates by proximity but are otherwise electrically isolated. All gate structures are separated by a SiN spacer which increases cross capacitance. The device is further encapsulated by 300 nm of silicon oxide, above which an additional top gate T is deposited utilizing a back-end metallization layer (not shown). Full geometric details for the family of devices compared in this work can be found in Supporting Information (SI) Section I. The charge sensor for these experiments consists of a two-terminal structure in which a charge island is connected to single reservoir, known as a single electron box (SEB).<sup>13–17</sup> The sensor is configured under a single gate, L1, utilizing the dot L1d, which is coupled to an electron reservoir and measured using the reflectometry circuit depicted in Figure 1b. With this configuration, the addition of electrons to the dots within the left nanowire can be inferred from either the transport current  $I_{SD,L}$  through the device with source-drain bias  $V_{SD} = 4$  mV, seen in Figure 1c, or the  $S_{11}$  reflectometry signal  $\Delta\Phi/\Phi$  (measured at  $V_{SD} = 0$  V) seen in Figure 1d, which maps the same gate voltage space. Both measurements contain a structure attributed to multiple dots within the  $2 \times 2$  array of the left nanowire. Because of the low transport current through the device, discerning the occupancy of the dots via transport is a significant challenge, while the capacitive shifts due to the addition of an electron are readily detected in reflectometry, which can probe all proximal quantum dots down to the last electron transition (SI Section I). The SEB dot-lead transitions at lower SEB electron numbers are less visible due to the reduction in tunneling rates below the RF frequency of the reflectometry measurement.<sup>22</sup>

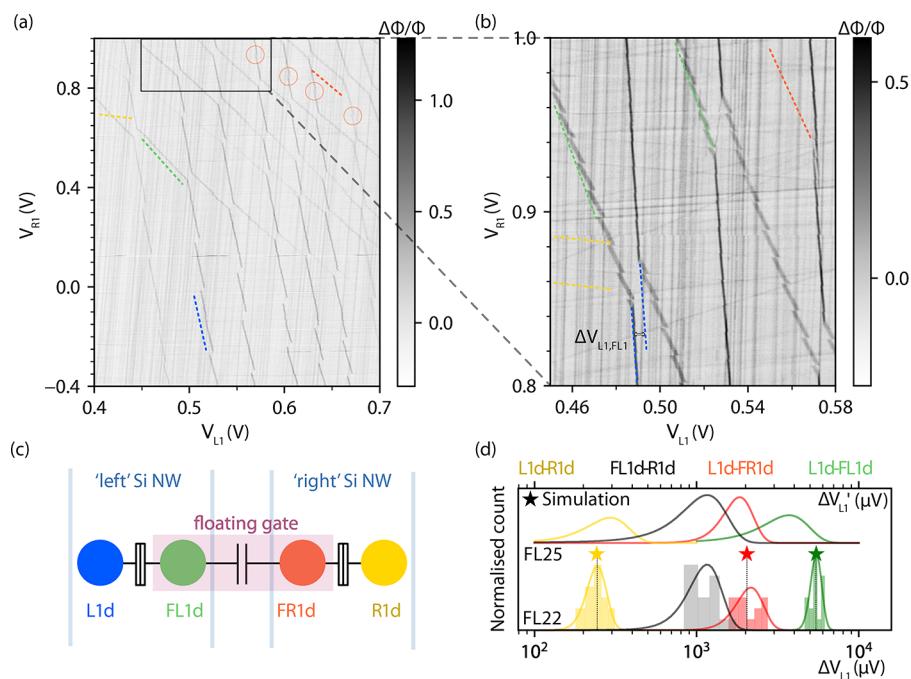
As the floating gates are galvanically isolated, we use the top metal gate T to assist in the accumulation of quantum dots under floating gates, primarily via the mutual capacitance between gates F1, F2, and T (see SI Section V).

Simultaneously, both  $V_{L2}$  and  $V_{R2}$  are set to a depletion mode to avoid formation of quantum dots under gates L2, R2 and F2, to effectively “shut-off” the lower half of the device by electron depletion. With the voltage sweep of  $V_{L1}$  and  $V_{R1}$  shown in Figure 2a and noting the influence of the floating gate F1 which is capacitively coupled to both active gates, we can load electrons into dots L1d and R1d, as well as dots FL1d and FR1d, from their neighboring reservoirs. Charge detection of these four distinct quantum dots is shown in the stability diagram measured in the reflectometry phase signal Figure 2a and includes the remote sensing of dots FR1d and R1d, located in the “right” SiNW, detected by the sensor dot L1d, located in the “left” SiNW. The sensor dot L1d is estimated to hold  $\sim 10$  electrons in this voltage range, where dot-reservoir charge transitions can be observed directly as a phase peak. We can then identify the remaining three different quantum dots capacitively coupled to the sensor through two complementary approaches

(1) Through the ratio of cross capacitance between the two active gate voltages  $V_{L1}$  and  $V_{R1}$  and the dot.

(2) Through direct charge detection by the sensor dot, assessing the magnitude of the capacitive shift upon the sensor.

For the voltage map between  $V_{L1}$  and  $V_{R1}$  shown in Figure 2a, each of the four dots capacitively couple to the L1 and R1 electrodes with differing strength, and we illustrate the four quantum dots present with reference to the color code shown in the capacitance connectivity diagram of Figure 2c. In Figure 2a,b, the blue dashed line indicates dot-lead charge transition of the SEB, L1d, which naturally has the highest lever arm to  $V_{L1}$ . The other three colored dashed lines highlight each remaining variety of dot-lead charge transition. The floating-gate-induced quantum dot in the left SiNW FL1d (green) is more strongly coupled to the sensor gate L1 due to its proximity, whereas in the SiNW on the right the other floating-gate-induced quantum dot FR1d (red) and gate-induced quantum dot R1d (yellow) are more strongly coupled to gate



**Figure 2.** Remote sensing of quantum dot charge transitions in different silicon nanowires using the floating gate. (a) Charge stability map in the L1 and L2 gate-space ( $V_T = 4$  V;  $V_{L2}$  and  $V_{R2} = -1$  V). (b) Zoom-in of (a) illustrating the different capacitive shifts of the sensor dot-lead transition due to loading electrons into different quantum dots along the floating gate direction. (c) Schematic of the remote sensing showing quantum dots as a network of charge nodes and capacitors. Dot-lead transition in stability diagram are indicated by dashed line with corresponding quantum dot color. (d) Histogram of capacitive shifts induced on the sensor dot by a charge transition in another quantum dot measured at various anticrossings, following the color-coding in (c), normalized as a dot L1 Coulomb peak shift  $\Delta V$ . The colored solid-line is the normalized fit to a Gaussian probability density function of the histogram which attributes to the same quantum dot. Stars (★) show calculated values from a COMSOL finite element simulation. Gray curves and histogram represent capacitive shifts from transitions in dot R1d measured using FL1d dot-lead transition. All data described above are from device “FL22”, a normalized fit of the  $\Delta V$  histogram from a similar device “FL25” is shown vertically offset above.

R1. When quantum dot FL1d is sufficiently occupied, the increase in tunnel rates allows for FL1d dot-lead transitions to also be directly detected in the reflectometry phase shift signal. This signal allows us to trace back the number of electrons in sensor dot L1d (see SI Section I). This approach can be further quantified by comparing the cross-capacitance ratios  $\alpha_{(i,j)}$  calculated as the degree to which gate L1 influences the other dot-lead transitions in voltage space. Assuming  $\alpha_{(L1,L1)} = 1$ , this method yields  $\alpha_{(FL1, L1)} = 0.173$ ,  $\alpha_{(FR1, L1)} = 0.124$ ,  $\alpha_{(R1, L1)} = 0.005$ . A significant drop in the cross-capacitance ratio is therefore apparent for groups of dots under spatially separated gates.

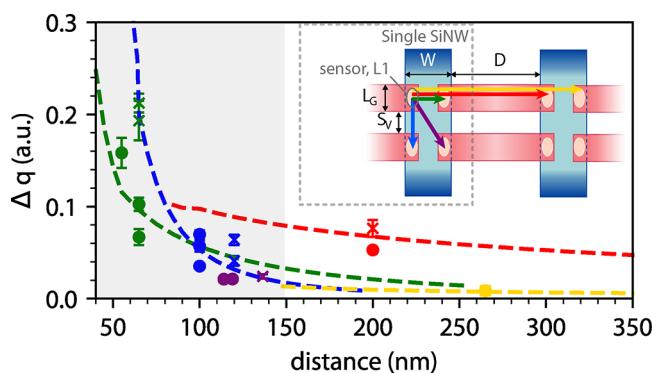
A second quantitative approach to distinguish the different quantum dots coupled to the sensor is to analyze the strength of the capacitive coupling between the sensor dot L1d and each of the remaining dots. In Figure 2d, we plot a histogram of the shifts  $\Delta V_{(L1,i)}$ , expressed in terms of the gate L1 voltage  $V_{L1}$ , arising from the capacitive shift in the sensor dot L1d due to the addition of an electron to some other dot  $i$ .<sup>23</sup> We use a peak-finding algorithm near a capacitive shift of interest in Figure 2b and take the difference between the shifted dot-lead reflectometry peaks, extrapolated to the same value of  $V_{R1}$ . The capacitive shifts extracted in this way group naturally into three distinct sets, each corresponding to the transitions in another quantum dot indicated following the color code in Figure 2c). Being located in the same nanowire, FL1d (green) is the most strongly coupled to the sensor dot, while the other floating-gate-induced quantum dot FR1d (red), located in the remote nanowire, shows a slightly weaker coupling. The R1 gate-

induced quantum dot R1d (yellow) in the remote nanowire shows the weakest coupling but can still be detected. A normalized fit of the probability density function of each group provides the mean capacitive shift referenced against the sensor dot gate voltage:  $\bar{\Delta V}_{(L1,FL1d)} = 5.47$  mV,  $\bar{\Delta V}_{(L1,FR1d)} = 2.16$  mV,  $\bar{\Delta V}_{(L1,R1d)} = 0.243$  mV. These values show good agreement to simulations of the capacitance matrix for this device structure (see SI Section III).

As certain charge transitions FL1d are directly visible in the phase response, we can also extract a corresponding capacitive shift between dots FL1d and R1d which is the symmetric analogue to the sensor dot coupling through the floating gate to FR2d. Data corresponding to such  $\Delta V_{(L1d,FR1d)}$  shifts are shown in gray in Figure 2d and indeed fall within a similar range to  $\Delta V_{(L1,FR1d)}$ . This asymmetry is not captured in our simulations and is most likely due to finite lithographic misalignment between the patterns of the nanowire and the split between the gates. On the basis of automated overlay controls and tools specifications we estimate that the cuts, although centered on the nanowires by design, are probably shifted by 5–10 nm on a typical device. In our case, this asymmetry translates into stronger lever-arm parameters for the dots defined along the right edges of the nanowires and is systematically observed in other devices.<sup>17,24</sup> Finally, to show the consistency of these values across different devices that are fabricated on the same die, we performed the same set of measurements on a second device and plot the extracted Gaussian fits to  $\Delta V_{(i,j)}$  for each pair of dots on the same axis in Figure 2d.

To demonstrate the enhancement of capacitive coupling arising from the floating gates, we compare results from floating gate devices with those from devices with similar dimensions containing only single, isolated silicon nanowires (see SI Section I). In order to facilitate the comparison of results from different devices, sensor dots, and lever arms, we adopt a measure of the SEB sensitivity to the charge transitions in nearby quantum dots based on normalizing the voltage-referenced capacitive coupling by the addition voltage required to add an electron to the SEB:  $\Delta q = \Delta V_{(L1,i)}/V_{CL1d}$ , where  $\Delta V_{(L1,i)}$  is the detected voltage shift in  $V_{L1}$  arising from coupling to dot  $i$ , and  $V_{CL1d}$  is the change in  $V_{L1}$  required to add an electron to the sensor dot L1d.

We first study the normalized SEB charge sensitivity within a  $2 \times 2$  quantum dot array located in a single silicon nanowire. Here, we can compare the capacitive coupling between dots formed on opposite edges of the nanowire between adjacent dots formed along a common SiNW edge and also between diagonally coupled, next-nearest neighbor quantum dots. These configurations are shown in the inset of Figure 3,



**Figure 3.** Normalized capacitive coupling as a function of distance. Voltage shifts in the sensor dot arising from capacitive coupling to other quantum dots are normalized against the addition voltage of the individual SEB to compare measurements from two floating gate devices and three single-nanowire devices ( $\times$ ,  $L_g = 60$  nm;  $\bullet$ ,  $L_g = 50$  nm). Arrows in the inset illustrate the type of sensing: green, blue, and purple data points relating to sensing within a single-nanowire and are obtained from both type of devices. Red and yellow data points required floating gate devices. COMSOL simulations are used to obtain parameter sweeps relating to each class of dot being sensed; following the coloring in the inset, a single normalization is applied to all simulated curves. Error bars in the data include the uncertainties in both the capacitive voltage shifts and addition voltages.

which also illustrates configurations for sensing dots in a neighboring SiNW, with coupling facilitated through the floating gate. The data in Figure 3 compare three single-nanowire devices, each consisting a  $2 \times 2$  quantum dot array, as well as the corresponding single-nanowire arrays within two floating-gate devices. The intrawire normalized sensitivities  $\Delta q$  fall off quickly with increasing separation between the quantum dots though a single power law cannot be used to describe the overall trend with distance for all couplings, due to the difference in mutual capacitance for dots located on the same or opposite edges of the nanowire.

Modeling the quantum dot as conducting ellipsoids we calculate the Maxwell capacitance matrix for varying center-to-center dot separation  $d$ , along with other nanowire design parameters (full details of the simulation method and relation to device dimensions are given in SI Sections I–V). Each of

the parametric sweeps from the simulations (dashed lines in Figure 3) settles to a power law attributed to each sensor-dot configuration: nearest-neighbor couplings along the edge of the nanowire (L1d-L2d) or across the nanowire (L1d-FL1d) have couplings which decay approximately as  $\Delta q \propto d^{-2.8}$  or  $d^{-2.5}$  respectively, over the range of distances studied here. Data for a next-nearest neighbor configuration L1d-FL2d, where the dots are positioned diagonally across the wire, are shown for completeness but are not modeled. For the “remote sensing” configuration where charge transitions are detected through the floating gate, the normalized capacitive coupling is sustained over a much greater distance, as reflected in the experimental data and simulations. By sweeping the floating gate length (approximated to be the SiNW separation,  $D$ ), simulations show that the two dots under each corner of the floating gate have a coupling which is dominated by the second-order capacitive coupling via the floating gate at these distances and decays only as  $\propto D^{-0.4}$  (see SI Section VI). Combined with the additional spacing of the nanowire width local to the SEB, this results in an coupling decay for the dot L1d-FL1d configuration which can be approximated as  $\Delta q \propto d^{-0.6}$  in the range studied here. As a result, the mutual capacitive shift for dot L1d-FL1d remains relatively high even at distances exceeding 300 nm, as shown in Figure 3.

Coupling the sensor to dot R1d now involves three degrees of separation from the sensor with a corresponding drop in sensitivity for short separations. However, the action of the floating gate leads to a much more gradual decay in sensitivity with distance that goes as  $\Delta q \propto d^{-0.7}$  in our simulations. As a result, for distances above  $d \approx 220$  nm the floating gate mediated coupling between dots arranged on opposite edges of different nanowires exceeds that from two dots on opposite edges of the same silicon nanowire (see SI Section VI). Furthermore, the charge distribution due to floating gate geometry could be optimized to yield a stronger absolute coupling, while maintaining the much more gradual decay with distance.<sup>25</sup>

Our experimental measurements and simulations indicate decays in capacitive coupling strength which fall off more slowly than  $\propto d^{-3}$ , as previously observed within arrays of Si/SiGe planar quantum dots.<sup>26,27</sup> However, such measurements were made within planar quantum dot devices with a high density of metallic gate electrodes, expected to screen mutual capacitive coupling. Indeed, considering only the first-order approximations to capacitive couplings, our simulations also show decays that approach  $d^{-3}$  (see SI Section VI). In contrast, the devices studied here contained a relatively low density of metallic gate electrodes, and the fabrication of the split-gates involved etching of metal that was replaced by SiN. The result is a reduced decay rate in sensitivity as a function of dot–dot separation, most strikingly when facilitated by the capacitively coupled floating gate. Instead of screening charge movement, the floating gate propagates the effect of charge movement over a distance to be chosen as a design parameter, coupling charge between two otherwise separate silicon structures. While the simulations are able to capture well the trends in the different classes of coupling, the residual spread in experimental values across the measurements may be due to the asymmetry in realistic devices not captured by the simulations, which can influence not only the dot to dot geometrical distance but also the device lever arms.

The capacitive shifts we measured between QDs, both locally and on distinct nanowires, are well above the full width

at half-maximum (fwhm) of the SEB dot-lead charge transition (see SI Section II). Assuming a Lorentzian line shape for the measured SEB charge transition, any capacitive shift greater than twice the fwhm gives at least 94% of the maximum sensor contrast (e.g., for spin-dependent tunneling readout). On the basis of our simulations and the intrinsic fwhm of the sensor transition of 0.24 mV, dot L1d-FR1d type couplings mediated by the floating gate could be used to achieve spin readout for distances up to 500 nm without a reduction in readout contrast.

In addition to applications for sensing, capacitive coupling has been used to realize local multiqubit interactions in a variety of systems, including singlet–triplet qubits<sup>28</sup> and charge qubits.<sup>29,30</sup> Meanwhile, several approaches to scaling quantum dot arrays pursue long-range coupling between qubits to facilitate the integration and fan-out of control electronics and suppress charge leakage;<sup>6,11</sup> solutions to realizing such two-qubit gates include exploiting a RKKY mediating exchange interaction<sup>11,31</sup> or coupling via a superconducting resonator.<sup>32</sup> Multiqubit operations utilizing capacitive coupling via floating gates, coupling two singly occupied planar dot structures, have been proposed to produce a spin–spin coupling Hamiltonian  $H_{S-S} \approx J_{12}(\sigma_x^1\sigma_x^2 + \sigma_y^1\sigma_y^2)$  when the Zeeman energy  $E_z \gg J_{12}$  and where  $\sigma_{x,y,z}$  are the Pauli matrices in the relevant qubit basis,<sup>25</sup> which can be used to implement the iSWAP operation.<sup>33</sup> Combining the assumptions within ref 25 with the parameters of the devices studied here and spin–orbit coupling strength for silicon,<sup>34</sup> we estimate a coupling of  $H_{S-S} \approx 10^3$  Hz under realistic device operating conditions between FL1d and FR1d with nanowire separation  $\sim 200$  nm, which is too weak for practical applications. However, utilizing the floating gate to couple two singlet–triplet qubits via  $H_{ST-ST} \approx J_{12}/2((\sigma_z - I) \otimes (\sigma_z - I))$ ,<sup>28</sup> where  $I$  is the identity matrix, exploits the much stronger electric-dipole coupling to achieve the CZ operation. For the nanowire geometry presented here (i.e., with singlet–triplet qubits arranged on each nanowire and the nearest dots of each pair separated by  $\sim 200$  nm), we estimate  $H_{ST-ST} \approx 10^{12}$  Hz via the model in ref 25, made more favorable in this geometry due to reduced oxide thickness. In SiGe devices, coupling between charge qubits  $H_{C-C} \approx g/4((I - \sigma_z) \otimes (I - \sigma_z))$  mediated by the mutual capacitance term<sup>29,30</sup> has been demonstrated with a strength of  $\sim 15$  GHz over dot separations of 130 nm,<sup>30</sup> while for the device geometry studied here our results predict  $H_{C-C} \approx 10^{11}$  Hz for dots separated by 200 nm on different nanowires.

We have demonstrated through experiments and simulation the effect of integrating floating gate electrodes to extend the sensitivity range of a single capacitive sensor, highlighting in particular the potential to couple quantum dots located on distinct silicon nanowires. Our measurements made the use of a single electron box charge sensor, while we note that a parallel study on similar devices illustrates an alternative mode for charge detection in such structures with one nanowire acting as a single electron transistor that remotely senses the charge occupancy of dots on the other nanowire.<sup>35</sup> In future devices with overlapping gate architecture,<sup>3</sup> a second layer of gate electrodes could be used to independently tune the quantum dots confined under the floating gates and achieve remote interactions. Given the substantial promise of spin qubits formed along quasi-1D arrays along the edges of silicon nanowires,<sup>17</sup> the enhanced capacitive couplings we measure using floating gates provide a potential route to couple qubits

distributed across separate nanowires and thus for scaling in a second dimension.

## ■ ASSOCIATED CONTENT

### SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.nanolett.0c02393>.

Further information on the device, charge stability diagram of SiNW dot arrays, details of simulation, and extraction of capacitance matrix ([PDF](#))

## ■ AUTHOR INFORMATION

### Corresponding Authors

Jingyu Duan — London Centre for Nanotechnology, University College London, London WC1H 0AH, United Kingdom; Quantum Motion Technologies, Nexus, Leeds LS2 3AA, United Kingdom; [orcid.org/0000-0001-5648-8779](https://orcid.org/0000-0001-5648-8779); Email: [j.duan.17@ucl.ac.uk](mailto:j.duan.17@ucl.ac.uk)

Michael A. Fogarty — London Centre for Nanotechnology, University College London, London WC1H 0AH, United Kingdom; Quantum Motion Technologies, Nexus, Leeds LS2 3AA, United Kingdom; Email: [m.fogarty@ucl.ac.uk](mailto:m.fogarty@ucl.ac.uk)

### Authors

James Williams — London Centre for Nanotechnology, University College London, London WC1H 0AH, United Kingdom

Louis Hutin — CEA, LETI, F-38054 Grenoble, France

Maud Vinet — CEA, LETI, F-38054 Grenoble, France

John J. L. Morton — London Centre for Nanotechnology and Department of Electronic and Electrical Engineering, University College London, London WC1H 0AH, United Kingdom; Quantum Motion Technologies, Nexus, Leeds LS2 3AA, United Kingdom

Complete contact information is available at:

<https://pubs.acs.org/10.1021/acs.nanolett.0c02393>

### Notes

The authors declare no competing financial interest.

## ■ ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support from the European Union's Horizon 2020 research and innovation programme under Grant Agreement 688539 (<http://mosquito.eu>), as well as the Engineering and Physical Sciences Research Council (EPSRC) through the Centre for Doctoral Training in Delivering Quantum Technologies (EP/L015242/1), QUES<sup>2</sup>T (EP/N015118/1), and the Hub in Quantum Computing and Simulation (EP/T001062/1).

## ■ REFERENCES

- (1) Yoneda, J.; Takeda, K.; Otsuka, T.; Nakajima, T.; Delbecq, M. R.; Allison, G.; Honda, T.; Kodera, T.; Oda, S.; Hoshi, Y.; Usami, N.; Itoh, K. M.; Tarucha, S. A quantum-dot spin qubit with coherence limited by charge noise and fidelity higher than 99.9%. *Nat. Nanotechnol.* **2018**, *13*, 102–106.
- (2) Xue, X.; Watson, T. F.; Helsen, J.; Ward, D. R.; Savage, D. E.; Lagally, M. G.; Coppersmith, S. N.; Eriksson, M. A.; Wehner, S.; Vandersypen, L. M. K. Benchmarking Gate Fidelities in a Si/SiGe Two-Qubit Device. *Phys. Rev. X* **2019**, *9*, 021011.
- (3) Zajac, D. M.; Sigillito, A. J.; Russ, M.; Borjans, F.; Taylor, J. M.; Burkard, G.; Petta, J. R. Resonantly driven CNOT gate for electron spins. *Science* **2018**, *359*, 439–442.

- (4) Huang, W.; Yang, C. H.; Chan, K. W.; Tanttu, T.; Hensen, B.; Leon, R. C. C.; Fogarty, M. A.; Hwang, J. C. C.; Hudson, F. E.; Itoh, K. M.; Morello, A.; Laucht, A.; Dzurak, A. S. Fidelity benchmarks for two-qubit gates in silicon. *Nature* **2019**, *569*, 532–536.
- (5) Fogarty, M. A.; Chan, K. W.; Hensen, B.; Huang, W.; Tanttu, T.; Yang, C. H.; Laucht, A.; Veldhorst, M.; Hudson, F. E.; Itoh, K. M.; Culcer, D.; Ladd, T. D.; Morello, A.; Dzurak, A. S. Integrated silicon qubit platform with single-spin addressability, exchange control and single-shot singlet-triplet readout. *Nat. Commun.* **2018**, *9*, 4370.
- (6) Vandersypen, L. M. K.; Bluhm, H.; Clarke, J. S.; Dzurak, A. S.; Ishihara, R.; Morello, A.; Reilly, D. J.; Schreiber, L. R.; Veldhorst, M. Interfacing spin qubits in quantum dots and donors—hot, dense, and coherent. *npj Quantum Inf* **2017**, *3*, 34.
- (7) Jones, C.; Fogarty, M. A.; Morello, A.; Gyure, M. F.; Dzurak, A. S.; Ladd, T. D. Logical qubit in a linear array of semiconductor quantum dots. *Phys. Rev. X* **2018**, *8*, 021058.
- (8) Maurand, R.; Jehl, X.; Kotekar-Patil, D.; Corna, A.; Bohuslavskyi, H.; Laviéville, R.; Hutin, L.; Barraud, S.; Vinet, M.; Sanquer, M.; De Franceschi, S. A CMOS silicon spin qubit. *Nat. Commun.* **2016**, *7*, 13575.
- (9) Veldhorst, M.; Eenink, H. G.; Yang, C. H.; Dzurak, A. S. Silicon CMOS architecture for a spin-based quantum computer. *Nat. Commun.* **2017**, *8*, 1766.
- (10) Li, R.; Petit, L.; Franke, D. P.; Dehollain, J. P.; Helsen, J.; Steudtner, M.; Thomas, N. K.; Yoscovits, Z. R.; Singh, K. J.; Wehner, S.; Vandersypen, L. M. K.; Clarke, J. S.; Veldhorst, M. A crossbar network for silicon quantum dot qubits. *Sci. Adv.* **2018**, *4*, No. eaar3960.
- (11) Cai, Z.; Fogarty, M. A.; Schaal, S.; Patomäki, S.; Benjamin, S. C.; Morton, J. J. L. A Silicon Surface Code Architecture Resilient Against Leakage Errors. *Quantum* **2019**, *3*, 212.
- (12) Voisin, B.; Nguyen, V.-H.; Renard, J.; Jehl, X.; Barraud, S.; Triozon, F.; Vinet, M.; Duchemin, I.; Niquet, Y.-M.; de Franceschi, S.; Sanquer, M. Few-Electron Edge-State Quantum Dots in a Silicon Nanowire Field-Effect Transistor. *Nano Lett.* **2014**, *14*, 2094–2098.
- (13) Urdampilleta, M.; et al. Gate-based high fidelity spin readout in a CMOS device. *Nat. Nanotechnol.* **2019**, *14*, 737–741.
- (14) House, M. G.; Bartlett, I.; Pakkiam, P.; Koch, M.; Peretz, E.; Van Der Heijden, J.; Kobayashi, T.; Rogge, S.; Simmons, M. Y. High-Sensitivity Charge Detection with a Single-Lead Quantum Dot for Scalable Quantum Computation. *Phys. Rev. Appl.* **2016**, *6*, 044016.
- (15) Chanion, E. et al. Charge detection in an array of CMOS quantum dots. 2020, arXiv:2004.01009. arXiv.org e-Print archive. <http://arxiv.org/abs/2004.01009> (accessed September 4,2020).
- (16) Ansaloni, F.; Chatterjee, A.; Bohuslavskyi, H.; Bertrand, B.; Hutin, L.; Vinet, M.; Kuemmeth, F. Single-electron control in a foundry-fabricated two-dimensional qubit array. 2020, arXiv:2004.00894. arXiv.org e-Print archive. <http://arxiv.org/abs/2004.00894> (accessed September 4,2020).
- (17) Ciriano-Tejel, V. N.; Fogarty, M. A.; Schaal, S.; Hutin, L.; Bertrand, B.; Gonzalez-Zalba, M. F.; Li, J.; Niquet, Y. M.; Vinet, M.; Morton, J. J. L. Spin readout of a CMOS quantum dot by gate reflectometry and spin-dependent tunnelling. 2020, arXiv:2005.07764. arXiv.org e-Print archive. <http://arxiv.org/abs/2005.07764> (accessed September 4,2020).
- (18) Chan, I. H.; Westervelt, R. M.; Maranowski, K. D.; Gossard, A. C. Strongly capacitively coupled quantum dots. *Appl. Phys. Lett.* **2002**, *80*, 1818–1820.
- (19) Churchill, H. O. H.; Bestwick, A. J.; Harlow, J. W.; Kuemmeth, F.; Marcos, D.; Stwertka, C. H.; Watson, S. K.; Marcus, C. M. Electron–nuclear interaction in <sup>13</sup>C nanotube double quantum dots. *Nat. Phys.* **2009**, *5*, 321–326.
- (20) Hu, Y.; Churchill, H. O. H.; Reilly, D. J.; Xiang, J.; Lieber, C. M.; Marcus, C. M. A Ge/Si heterostructure nanowire-based double quantum dot with integrated charge sensor. *Nat. Nanotechnol.* **2007**, *2*, 622–625.
- (21) Hutin, L.; Maurand, R.; Kotekar-Patil, D.; Corna, A.; Bohuslavskyi, H.; Jehl, X.; Barraud, S.; De Franceschi, S.; Sanquer,
- M.; Vinet, M. Si CMOS platform for quantum information processing. 2016 *IEEE Symp. VLSI Technol.* 2016; pp 1–2.
- (22) Gonzalez-Zalba, M. F.; Barraud, S.; Ferguson, A. J.; Betz, A. C. Probing the limits of gate-based charge sensing. *Nat. Commun.* **2015**, *6*, 6084.
- (23) van der Wiel, W. G.; De Franceschi, S.; Elzerman, J. M.; Fujisawa, T.; Tarucha, S.; Kouwenhoven, L. P. Electron transport through double quantum dots. *Rev. Mod. Phys.* **2002**, *75*, 1–22.
- (24) Ibbsen, D. J.; Lundberg, T.; Haigh, J. A.; Hutin, L.; Bertrand, B.; Barraud, S.; Lee, C.-M.; Stelmashenko, N. A.; Robinson, J. W. A.; Vinet, M.; Gonzalez-Zalba, M. F.; Ibbsen, L. A. Large dispersive interaction between a CMOS double quantum dot and microwave photons. 2020, arXiv:2004.00334. arXiv.org e-Print archive. <http://arxiv.org/abs/2004.00334> (accessed September 4,2020).
- (25) Trifunovic, L.; Dial, O.; Trif, M.; Wootton, J. R.; Abebe, R.; Yacoby, A.; Loss, D. Long-Distance Spin-Spin Coupling via Floating Gates. *Phys. Rev. X* **2012**, *2*, 011006.
- (26) Zajac, D. M.; Hazard, T. M.; Mi, X.; Nielsen, E.; Petta, J. R. Scalable Gate Architecture for a One-Dimensional Array of Semiconductor Spin Qubits. *Phys. Rev. Appl.* **2016**, *6*, 054013.
- (27) Neyens, S. F.; MacQuarrie, E.; Dodson, J.; Corrigan, J.; Holman, N.; Thorgrimsson, B.; Palma, M.; McJunkin, T.; Edge, L.; Friesen, M.; Coppersmith, S.; Eriksson, M. Measurements of Capacitive Coupling Within a Quadruple-Quantum-Dot Array. *Phys. Rev. Appl.* **2019**, *12*, 064049.
- (28) Shulman, M. D.; Dial, O. E.; Harvey, S. P.; Bluhm, H.; Umansky, V.; Yacoby, A. Demonstration of Entanglement of Electrostatically Coupled Singlet-Triplet Qubits. *Science* **2012**, *336*, 202–205.
- (29) Li, H. O.; Cao, G.; Yu, G. D.; Xiao, M.; Guo, G. C.; Jiang, H. W.; Guo, G. P. Conditional rotation of two strongly coupled semiconductor charge qubits. *Nat. Commun.* **2015**, *6*, 7681.
- (30) MacQuarrie, E. R.; Neyens, S. F.; Dodson, J. P.; Corrigan, J.; Thorgrimsson, B.; Holman, N.; Palma, M.; Edge, L. F.; Friesen, M.; Coppersmith, S. N.; Eriksson, M. A. Progress Towards a Capacitively Mediated CNOT Between Two Charge Qubits in Si/SiGe. 2020, arXiv:2003.06768. arXiv.org e-Print archive. <http://arxiv.org/abs/2003.06768> (accessed September 4,2020).
- (31) Malinowski, F. K.; Martins, F.; Smith, T. B.; Bartlett, S. D.; Doherty, A. C.; Nissen, P. D.; Fallahi, S.; Gardner, G. C.; Manfra, M. J.; Marcus, C. M.; Kuemmeth, F. Fast spin exchange across a multielectron mediator. *Nat. Commun.* **2019**, *10*, 1196.
- (32) Borjans, F.; Croot, X. G.; Mi, X.; Gullans, M. J.; Petta, J. R. Resonant microwave-mediated interactions between distant electron spins. *Nature* **2020**, *577*, 195–198.
- (33) Schuch, N.; Siewert, J. Natural two-qubit gate for quantum computation using the XY interaction. *Phys. Rev. A: At., Mol., Opt. Phys.* **2003**, *67*, 032301.
- (34) Tanttu, T.; Hensen, B.; Chan, K. W.; Yang, C. H.; Huang, W. W.; Fogarty, M.; Hudson, F.; Itoh, K.; Culcer, D.; Laucht, A.; et al. Controlling spin-orbit interactions in silicon quantum dots using magnetic field direction. *Phys. Rev. X* **2019**, *9*, 021028.
- (35) Gilbert, W.; Saraiva, A.; Lim, W. H.; Yang, C. H.; Laucht, A.; Bertrand, B.; Rambal, N.; Hutin, L.; Escott, C. C.; Vinet, M.; Dzurak, A. S. Single-electron operation of a silicon-CMOS 2 × 2 quantum dot array with integrated charge sensing. 2020, arXiv:2004.11558. arXiv.org e-Print archive. <http://arxiv.org/abs/2004.11558> (accessed September 4,2020).