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Research Briefing

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DOI
10.1038/s41565-023-01511-2

Publication date
2023

Document Version
Final published version

Published in
Nature Nanotechnology

Citation (APA)
Borsoi, F., & Veldhorst, M. (2023). A tunable two-dimensional crossbar array comprising 16 quantum dots: Research Briefing. *Nature Nanotechnology*, *19*(1), 7-8. https://doi.org/10.1038/s41565-023-01511-2

A tunable two-dimensional crossbar array comprising 16 quantum dots

Drawing inspiration from classical semiconductor technology, a strategy to address many quantum dots through a small number of control lines is presented. The two-dimensional array consisting of 16 germanium quantum dots can be tuned in the few-hole regime with odd charge fillings and individually addressable tunnel couplings.

The problem

Building fault-tolerant quantum computers requires the ability to manage millions of interacting qubits[1]. Although classical semiconductor technology has advanced to control billions of transistors using only thousands of control lines, this streamlined approach has not yet been applied in quantum technology. Leading solid-state quantum computing platforms, such as those based on superconducting and semiconducting qubits, still rely on a one-to-one connection between control lines and qubits – a brute-force method that is straightforward, but unfeasible for large-scale quantum computation[2].

Semiconductor qubits are compatible with semiconductor manufacturing[3], and proposals to efficiently scale the number of qubits take inspiration from integrated circuits[4]. But challenges in material uniformity and device quality pose major challenges. Hence, so far, experimental work has focused primarily on small and linear arrays, and it is an open question how to scale to larger systems.

The solution

In this research, we established a strategy for the sustainable control of semiconductor quantum dots. We have introduced an elegant gate layout based on a crossbar architecture to efficiently operate a two-dimensional quantum dot system. In our design, we exploit two barrier layers for the selective control of the interdot tunnel couplings, and a layer of plunger lines to collectively vary the on-site quantum dot energies (Fig. 1a). In contrast to brute-force implementations, a single shared plunger gate is used to control up to four quantum dots, and an individual shared barrier gate is used to control the coupling between quantum dots for up to six pairs (Fig. 1b).

Owing to the uniformity of our material system – a planar germanium quantum well in a silicon–germanium heterostructure – we were able to control the most (to the best of our knowledge) extensive two-dimensional quantum dot array so far constructed. We used charge-sensing methods and statistical tools to identify each quantum dot from complex charge-stability diagrams, and then defined a routine through which we were able to prepare the array in the few-hole regime and confine an unpaired spin in each site.

Our final step was to establish a random-access method for addressing the inter-dot tunnel coupling, achieving remarkable consistency between vertically and horizontally coupled pairs. These two demonstrations – tunability into an odd charge state with an unpaired spin, and selective control of the inter-dot tunnel coupling – satisfy the basic requirements for the development of quantum logic in shared-control architectures.

Future directions

Our work is relevant for the definition of a semiconductor-qubit unit cell that is compact and scalable. We envisage that our crossbar array will find application in dense semiconductor quantum processors, or be used as a register coupled via long-range quantum links for networked computing[5].

Although the shared-control approach is beneficial in terms of hardware scalability and interconnectivity, it might introduce crosstalk challenges in qubit control. Therefore, future research should focus on the implementation of high-fidelity quantum gates in such crossbar devices and on the integration of quantum buses for linking multiple registers. Furthermore, as manual tuning operations become a bottleneck, it might be necessary to adopt autonomous operations based on machine-learning algorithms to achieve more rapid and reproducible control over charge and spin.

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This is a summary of:
Borsoi, F. et al. Shared control of a 16 semiconductor quantum dot crossbar array. *Nat. Nanotechnol*. https://doi.org/10.1038/s41565-023-01491-3 (2023).

EXPERT OPINION

"The authors have targeted a critical challenge in scaling up qubits in general, and especially semiconductor qubits — namely that of shared control. The experimental achievement reported is at the impressive scale of a 4 × 4 quantum-dot array and based around a crossbar architecture, which has been discussed in various theoretical proposals for spin qubits, but to my knowledge this the first serious experimental effort aimed at realizing these ideas." **John Morton, University College London, London, UK.**

FIGURE

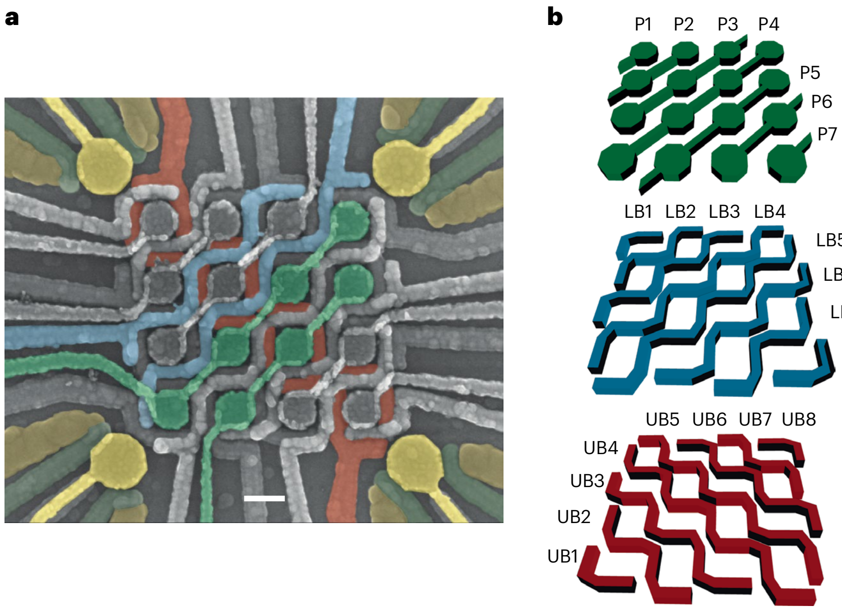

Fig. 1 | The crossbar array of 16 quantum dots. a, Scanning electron microscope image of the crossbar array device. The gate stack consists of two staircase barrier gate layers (two lines of each layer are shown in red and blue), and one plunger gate layer (two lines of which are shown in green). The 16 quantum dots are defined under the plunger gates, and four charge sensors are located at the corners. Scale bar, 100 nm. **b**, Illustration of the stack of the shared-control elements: from the bottom of the gate stack, these comprise two layers of barrier gates (UB and LB) and seven plunger gates (P). © 2023, Borsoi, F. et al., CC BY 4.0.

BEHIND THE PAPER

The field of semiconductor qubit technology has seen remarkable advances in the past few years. The focus has been on small systems, mostly arranged in one-dimensional geometries, and operated using 'brute force' approaches. So trying to realize a 4 x 4 quantum dot using shared control was certainly daunting — a step forward that required advances on several fronts. However, as the days went by in the laboratory, it became evident that each of the 16 quantum dots could indeed be tuned. Utilizing a video-mode technique, millions of charge-stability diagrams appeared at a rate of more than one per second, and, through meticulous adjustments of the gate voltages, the desired charge configuration was achieved. After a few weeks of hands-on tuning, the full array was finally operational. Although this had always been the goal of our experiment, we were still surprised by the pace of this development. **F.B. & M.V.**

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FROM THE EDITOR

"This work introduces a quantum-dot device geometry that includes shared control gates and a double-barrier design to allow, in principle, selective tunnel-coupling tunability within the array — key features towards scalability. The experimental achievement reported is at the impressive scale of a 4 × 4 quantum-dot array. They realize the co-existence of common barrier gates to selectively control the individual inter-dot couplings." **Jiajun Zhu, Senior Editor, *Nature Nanotechnology*.**