Quantum computing

https://doi.org/10.1038/s41928-023-00968-2

A solid-state quantum microscope

Dohun Kim

Check for updates

A technique based on a scanning tunnelling microscope can provide simultaneous control, visualization and spectroscopic characterization of quantum states with atomic resolution.

Being able to directly address the details of a quantum state as a function of device operating conditions is of use in the exploration of exotic phases in correlated systems and the development of integrated quantum systems that coherently control and measure individual qubits[1,2]. In atomic molecular optics – where devices typically consist of arrangements of spatially trapped atoms – an optical quantum microscope[3] is used to position arrays of atoms, as well as to address, manipulate and measure the occupation of individual sites with spatially resolved probes. These microscopes can facilitate the scale-up of arrays to hundreds of atoms.

Making a version of such a probe in a solid-state-based quantum device platform is desirable. However, only spatially integrated – not local – information can so far be obtained because local control is provided by the electrostatic gates, and quantum-state measurements are usually performed through a fixed charge sensor. Writing in *Nature Electronics*, Benoit Voisin and colleagues now report a solid-state quantum microscope that enables simultaneous control, visualization and spectroscopy of quantum states in a nanodevice with atomic resolution[4].

Several techniques have previously been used to obtain spatially resolved information in solid-state devices, including scanning gate microscopy, atomic force microscopy and scanning single-electron quantum dot microscopy[5]. Although these techniques provide local information on some material properties, such as topography or variations of the electrostatic potential, they all rely on capacitive coupling between the scanning probe and the device, and cannot perform direct measurement of the quantum states. They are microscopy techniques on quantum devices, but the probe itself cannot serve as a quantum microscope.

Scanning tunnelling microscopy (STM), which relies on tunnel coupling between the device and the probe, does provide a local measurement of a quantum state in the solid state since the measured tunnelling current directly represents energy-resolved quantities, such as the local density of states or energy splittings of the qubit devices, with atomic resolution. However, STM is limited to conductive substrates[6] and, despite some progress to increase controllability[7], it remains difficult to achieve local electrostatic control that is compatible with conventional nanoelectronic devices. Therefore, even with STM, the quantum states are still measured through the underlying device, for example, via conductance through a nanowire or a charge sensor built into the device[8].

To overcome this, Voisin and colleagues – who are based at UNSW Sydney, the University of British Columbia, the University of Melbourne and RMIT University – developed light-assisted STM measurement techniques, which they demonstrate in quantum-dot-based devices made of phosphorus atoms in silicon (Fig. 1). For topographic measurements, the sample is made conductive by illuminating the sample with red light (that is, a wavelength above the silicon bandgap), enabling normal STM measurement and stabilization of the probe tip. For quantum-state mapping, local gating and spectroscopy measurements, the illumination is removed, which turns the sample to a highly insulating state (more than 9 GΩ).

The combination of local gating and spatial mapping enables dynamic control of the quantum state-to-probe coupling, minimizing the decoherence of quantum states that occurs due to probing[9]. In addition, the STM-based solid-state quantum microscope can

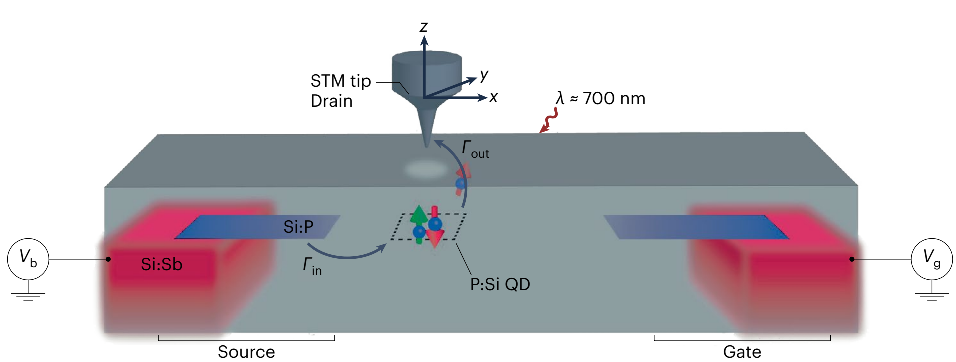

Fig. 1 | An STM-based solid-state quantum microscope. The light-assisted STM enables topographic and spectroscopic characterization of the central atomic quantum dot (QD) device (single phosphorus (P) atoms in silicon (Si)). Source and gate electrodes are defined by antimony (Sb) implantation, and the STM tip acts as the drain electrode. Red light (wavelength $\lambda \approx 700$ nm) is used to make the silicon substrate temporarily conductive for aligning and stabilizing the STM tip. During measurement, a bias voltage (V_b) at the source electrode injects electrons though a tunnel barrier (Γ_{in}) into the QD and from the QD to the STM tip (Γ_{out}). Local gating (gate voltage V_g) provides quantum control of the chemical potential difference between the quantum device and probe. Figure reproduced with permission from ref. 4, Springer Nature Ltd.

measure the local spectral function in active atomic devices; the corresponding measurement is challenging to achieve in optical quantum microscopes[3].

A key step in achieving this is to reverse the device fabrication routine compared with conventional dopant-based qubit devices in silicon. Typically, the macroscopic parts of the electrodes are formed using cleanroom equipment after dopant incorporation[10]. Here, the electrodes are formed before incorporation of the phosphorus atoms. Subsurface implantation of antimony defines the electrodes, before in situ flash annealing is used to ensure a high level of surface cleanliness for the STM lithography and so that good electrical contacts with atomic precision can be achieved. With this solid-state quantum microscope, the researchers are able to show spatially resolved quantum-state measurements of a dopant-based quantum dot fabricated using atomically precise lithography.

Realizing the full capabilities of this solid-state quantum microscope will require further developments — such as scaling the number of sites and gates, and operation at sub-kelvin temperatures[11] — with the ultimate goal being in situ quantum manipulation and exploration of exotic quantum regimes with engineered coupling interactions in large atomic arrays[6]. Nevertheless, the current system creates opportunities for experiments that provide a link between device performance and geometry, instead of relying on indirect transport or occupation measurements where details of the charge distribution are unknown. These capabilities are essential when, for example, mapping the ground state of complex states of matter away from half-filling. Moreover, using the STM tip as an active element of the device (its drain electrode) enables the parallel fabrication and measurement of several devices on the same sample, providing a route for the high-throughput characterization of quantum devices at cryogenic conditions.

Dohun Kim
Department of Physics and Astronomy, and Institute of Applied Physics, Seoul National University, Seoul, Republic of Korea.
e-mail: dohunkim@snu.ac.kr

Published online: 26 June 2023

References

1. Kiczynski, M. et al. *Nature* **606**, 694–699 (2022).
2. Usman, M., Wong, Y. Z., Hill, C. D. & Hollenberg, L. C. L. *npj Comput. Mater.* **6**, 19 (2020).
3. Gross, C. & Bakr, W. S. *Nat. Phys.* **17**, 1316–1323 (2021).
4. Voisin, B. et al. *Nat. Electon.* https://doi.org/10.1038/s41928-023-00979-z (2023).
5. Martin, J. et al. *Nat. Phys.* **4**, 144–148 (2008).
6. Kempkes, S. N. *Nat. Mater.* **18**, 1292–1297 (2019).
7. Tsai, H. Z. et al. *Nat. Electron.* **3**, 598–603 (2020).
8. Shapir, I. et al. *Science* **364**, 870–875 (2019).
9. Yang, K. et al. *Science* **366**, 509–512 (2019).
10. He, Y. et al. *Nature* **571**, 371–375 (2019).
11. Paul, W. et al. *Nat. Phys.* **13**, 403–407 (2017).

Competing interests

The author declares no competing interests.