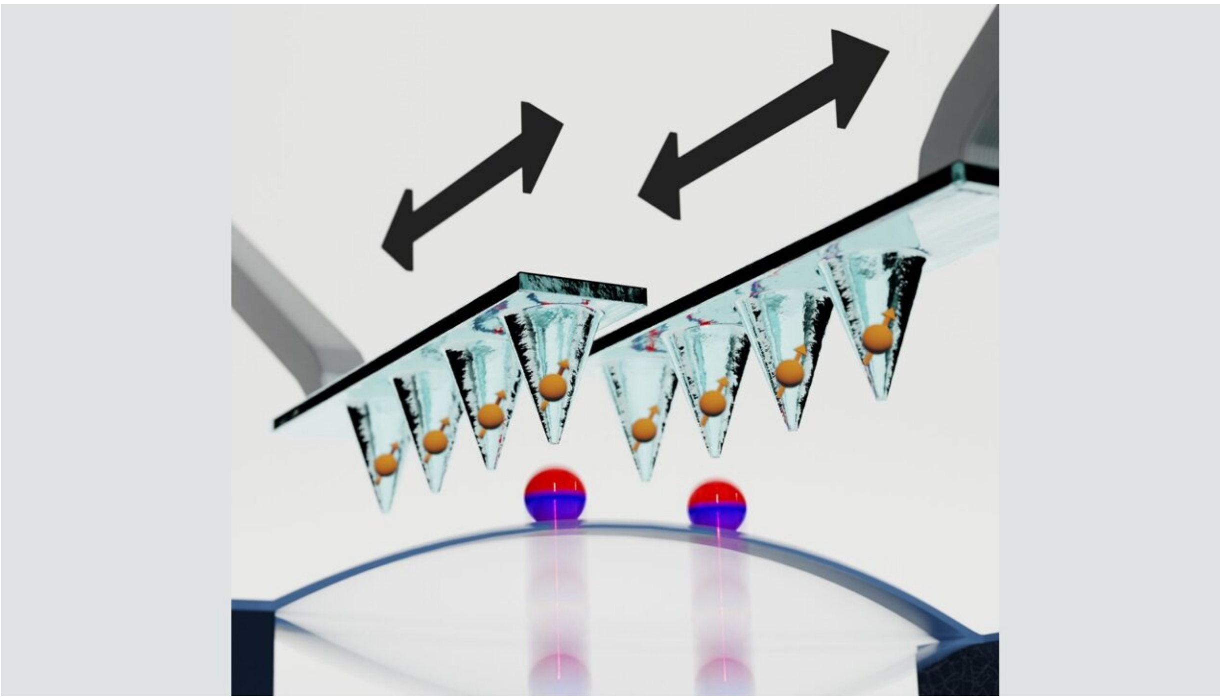
Scientists integrate solid-state spin qubits with nanomechanical resonators

July 18 2024, by Tejasri Gururaj



Spin qubits (orange) inside diamond nanopillars are moved (black arrows) over a magnetically-functionalized mechanical resonator (blue), enabling mechanically-mediated spin-spin interactions. Credit: Frankie Fung.

In a new *Physical Review Letters* study, scientists propose a new method for combining solid-state spin qubits with nanomechanical resonators for scalable and programmable quantum systems.

Quantum information processing requires qubits to have long coherence times, stability, and be scalable. Solid-state spin qubits are the candidates being pursued for these applications as they possess long-coherence times. However, they are not scalable.

The *PRL* study, led by Frankie Fung, a graduate student in Professor Mikhail Lukin's group at Harvard University, addressed this challenge while speaking to Phys.org.

He said, "While small quantum registers using solid-state spin qubits have been demonstrated, they rely on magnetic dipolar interactions, which limit the interaction range to tens of nanometers. The short interaction distance and difficulty fabricating spin qubits consistently at such close spacings make it challenging to control systems containing large arrays of qubits."

In the *PRL* study, the researchers proposed an architecture that mediates the interaction between spin qubits using a nanomechanical resonator, a mechanical oscillator.

Diamonds as qubits

The team's approach relied on nitrogen-vacancy centers in diamonds acting as qubits.

Typically, diamond structures consist of carbon atoms in a tetrahedral structure, meaning they are bonded to four other carbon atoms.

However, using methods like chemical vapor deposition, one of the carbon atoms can be substituted with a nitrogen atom. This results in a missing carbon atom adjacent to the nitrogen, creating a vacancy.

The nitrogen atom adjacent to a vacancy forms the NV center, which has an unpaired electron with spin states used as qubits.

The NV centers offer many advantages due to their unique optical properties. They have long coherence times, meaning their interaction with the environment is low, making them very stable.

Additionally, they are optically compatible, which means that it is easy to input and output information using light. Since they have unpaired electrons, they are also highly sensitive to magnetic fields.

These properties make them ideal to be used as qubits, especially when integrating them with solid-state devices.

The problem arises due to the short-range interaction between the qubits themselves. This is because solid-state spin qubits interact with each other via magnetic dipole interactions, which are short-ranged.

Interaction between qubits is necessary to create entangled states, which are a foundation for quantum information processing.

Mechanical resonators as mediators

To address the long-range interaction of qubits, the researchers propose coupling the NV centers in diamonds with mechanical resonators.

"Our research aims to use nanomechanical resonators to mediate interactions between these spin qubits. More specifically, we propose a new architecture, where spin qubits inside individual scanning probe tips can be moved over a nanomechanical resonator that mediates spin-spin interactions," explained Fung.

Nanomechanical resonators are tiny structures that can oscillate at high frequencies (typically nanoscales). They are sensitive to external fields and forces.

By coupling the qubits with a nanomechanical resonator, the researchers are creating a way for non-local qubit interactions. This potentially enables the creation of large-scale quantum processors, addressing the drawback of scalability with solid-state quantum systems.

Refining the architecture

The research team's architecture, therefore, consists of a spin qubit inside individual scanning probe tips, which are precise scanning devices that can gather information.

"The scanning probe tips can be moved over a mechanical resonator that mediates spin-spin interactions. Since we can choose which qubits to move over this mechanical resonator, we can create programmable connectivity between spin qubits," explained Fung.

The individual qubits are NV centers inside a diamond nanopillar. This structure allows the NV center to be close to a micromagnet, which creates the magnetic field used to manipulate the electron spin state.

"It also helps that the nanopillar acts as a waveguide that reduces the laser power needed to excite the NV center," added Fang. This happens because the nanopillar guides the laser to the exact location it needs to go, the NV center.

The micromagnet is located on a silicon nitride nanobeam, completing the nanomechanical resonator.

In theory, the setup works as follows. The micromagnet creates a magnetic field around the qubit and the resonator. This magnetic field changes the electron spin state of the qubit.

The change in the spin state causes the qubit to interact with the nanomechanical resonator differently than it was before, making it oscillate with a different frequency. This oscillation affects other qubits, affecting their spin state.

The architecture allows for non-local qubit interactions.

Architecture feasibility and hybrid quantum systems

To show that their architecture is achievable, the researchers demonstrated the qubit's coherence over the mechanical transport of the micromagnet.

Fung said, "As a proof-of-principle measurement, we stored some coherent information in the NV center, moved it around in a large field gradient, and showed that the information was preserved afterward."

The coherence was also demonstrated via the quality factor, indicating the efficiency of a resonant system.

For the architecture, the quality factor was around a million at low temperatures, suggesting that the nanobeam resonator can maintain highly coherent mechanical motion despite being functionalized with a micromagnet. However, the highest recorded quality factor for mechanical resonators is 10 billion.

"While this coupling is not strong enough to make this architecture a reality yet, we believe that there are several realistic improvements that could get us there," said Fung.

The researchers are working on introducing an optical cavity with a nanomechanical resonator.

Fung explained, "The cavity would allow us to not only measure the mechanical motion more precisely, but also potentially prepare the mechanical resonator in its ground state. This greatly expands the experiments we can do, such as transferring a single quanta of information from the spin to the mechanics and vice versa."

The researchers also believe nanomechanical resonators are ideal intermediaries between different qubits because they can interact with various forces, such as Coulomb repulsion and radiation pressure.

"A hybrid quantum system can leverage the advantages of different kinds of qubits while mitigating their disadvantages. Because they can be fabricated on-chip, nanomechanical resonators can be integrated with other components, such as an electrical circuit or an optical cavity, which opens up possibilities for long-range connectivity," concluded Fung.

More information: F. Fung et al, Toward Programmable Quantum Processors Based on Spin Qubits with Mechanically Mediated Interactions and Transport, *Physical Review Letters* (2024). DOI: 10.1103/PhysRevLett.132.263602. On *arXiv*: DOI: 10.48550/arxiv.2307.12193