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James Badham

Using mechanical inputs to enhance quantum states in sensors

Most people think of diamonds as high-end adornments. Not Ania Bleszynski Jayich. The UC Santa Barbara physicist sees diamonds, which she grows in the UC Quantum Foundry, as a potentially powerful foundation for quantum sensors.

Sensors are currently much farther along in their development than other potential quantum applications. Diamond sensors are particularly promising because diamonds require relatively few quantum bits (qubits) to operate, whereas a quantum computer, for instance, requires more than 100,000, perhaps as many as a million, qubits to handle error correction, one of the main hurdles for quantum computing.

A paper about the latest advance from the Bleszynski Jayich lab,“Spin-embedded diamond optomechanical resonator with a mechanical quality factor exceeding one million,” has been published in the journal Optica.

Getting it to resonate

Mechanical resonators are among the simplest technologies. “You tap a tuning fork, and it rings,” said Bleszynski Jayich, a professor and director of the UC Quantum Foundry. “That’s mechanical resonance.”

Resonance in the quantum realm is created by phonons, which refer to a coordinated mechanical excitation of many atoms, such as those vibrating in a tuning fork. A mechanical resonator is an element that resonates at a specific frequency. The basic requirement of a high-performing oscillator is that it oscillates for a long time before the energy — and the oscillation amplitude — decays. In the photonic regime, the simplest optical resonator involves two mirrors that face each other, such that light can bounce back and forth between them many times.

Researchers in Bleszynski Jayich’s lab use a mechanically oscillating beam, called a diamond optomechanical crystal*,* which is a very thin beam approximately one micrometer wide, or one-hundredth the diameter of a human hair. A telecom frequency optical resonator is co-located with the mechanical resonator to aid in driving and reading out the mechanical degree of freedom.

The quality of any mechanical oscillator is quantified largely by its quality (Q) factor, which refers to how many times it oscillates before the energy dissipates away. A Q factor of 1 million is very high, but by using 10-gigahertz-scale frequencies, researchers in Blesyinski Jayich’s lab made an oscillator that cycles its signal *10* billion times per second.

“We’re focused on implementing mechanical resonators into quantum technologies, and for that, we need a high frequency,” she said.

The diamond deal: tuning the sensor

“If you could see the tines of a vibrating tuning fork, you’d see them moving back and forth at some amplitude before the energy left the tuning fork and the sound died down. Our diamond resonator oscillates about 1 million times before the energy leaks out into the environment,” Bleszynski Jayich said. “That's why it’s important to have very high-Q mechanical resonators, because they can store quantum information for a relatively long time. To do quantum computing or quantum sensing or quantum anything with mechanics requires that information can be stored in this mechanical degree of freedom for as long as possible, for use as a memory or as a transducer for instance.”

An important feature of her long-lived diamond resonators, she explained, is the fact that they host engineered defects that make excellent quantum sensors.

“Suppose you have a piece of diamond with billions of carbon atoms in it,” Bleszynski Jayich posited. “Every once in a while, there's a nitrogen atom — found often in diamond — that has a vacancy next to it, called a nitrogen vacancy (NV) center. These NV centers, which are physically housed inside the diamond and fluoresce when excited by light, constitute long-lived quantum bits that can sense tiny magnetic, electric, strain or thermal fields.

“Advanced quantum sensors and other eventual applications require those bits not only to exist, but also to interact,” she continued. “Our lab can easily make hundreds of such qubits at a time, but one of our long-term goals is to get them to ‘talk’ to each other and work together to solve some computation, or to sense with sensitivity beyond what is classically possible.

“The coordinated motion of atoms in the lattice provides one interesting pathway by which the embedded defects can talk to each other. And the high Q factor allows for stronger mediation and, as a result, more control over that interaction. Eventually, if I can put N sensors together and engineer the right type of interactions, mediated by mechanical motion of the lattice in which they are embedded, I can build a better sensor than I can with N classically interacting sensors. The quantum advantage can lead to improved precision.”

Diamond vs. silicon

“Nearly everyone who explores mechanical systems for quantum technologies starts with a substrate of silicon or a silicon-nitride, because they are well-established materials,” Bleszynski Jayich noted.

“Diamond has exciting prospects, as it not only hosts highly coherent qubits, but also has the highest thermal conductivity of any material, a wide band gap, and phenomenal optical and mechanical properties. But it does have the drawback of being difficult to fabricate. However, in our lab, during roughly the past fifteen years, we have overcome many of the fabrication hurdles.”

To date, silicon has been shown to have a higher mechanical Q than diamond, but, said Bleszynski Jayich, the differences in Q have a lot to do with how it is measured, since the Q of any material is highly sensitive to the measuring technique. Researchers in her lab did their measurements by constantly shining light on the system, a technique called continuous optical probing. That, however, causes significant, problematic heating due to absorption of the light “So, if you're out to prove you have the highest Q, you would not measure under continuous optical illumination,” she said.

“A better method is pulsed optical probing, in which light is turned on and off, and the measurement is made when it’s off,” explained Bleszynski Jayich. “Looking forward, we aim to use a pulsed technique to see how good our resonators are when we’re not shining light on them. We expect to see significantly improved Q, comparable to or even better than silicon.”

Ultimately, the researchers hope to leverage even higher mechanical Q’s to realize mechanically mediated NV-NV qubit interactions to realize a many-body, metrologically useful entangled state.

“That work is still ahead,” Bleszynski Jayich said. “At the moment we are motivated by theoretical proposals.”

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Media Contact
Shelly Leachman
Editorial Director
(805) 893-2191
sleachman@ucsb.edu

About UC Santa Barbara