Diamond-Based Hybrid Quantum Mechanical Systems

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Primary CNF Tools Used: GCA 5x stepper, Heidelberg mask writer DWL2000, AJA sputtering deposition system, YES Asher, P10 profilometer, Westbond 7400A ultrasonic wire bonder

Abstract:

Nitrogen vacancy (NV) centers are atom-like quantum emitters in diamond, with narrow orbital transition linewidth and a long-lived spin coherence that persists to room temperature. Diamond-based microelectromechanical systems (MEMS) devices integrate these quantum defects with classical mechanics, providing direct coupling between diamond NV center spin/orbital states and phonons in a mechanical resonator. We demonstrate orbital state manipulation of a single NV center with a GHz diamond high-overtone bulk acoustic resonator (HBAR). Furthermore, we are developing a new diamond MEMS device that is designed to realize the control of mechanical quantum states using diamond spins, which is potentially useful for quantum-enhanced metrology and quantum information processing.

Summary of Research:

Diamond-based hybrid quantum spin-mechanical systems marry the two fields of microelectromechanical systems (MEMS) and quantum information science with the goal of realizing coherent mechanical control of diamond nitrogen-vacancy (NV) centers [1] and quantum enhanced mechanical sensing [2]. Following the recent demonstration of coherent mechanical control of spin state of NV centers [3,4], we recently demonstrated orbital state manipulation of a single NV center using a diamond MEMS device [5].

The device adopts the design of a high-overtone bulk acoustic resonator (HBAR) device fabricated from a diamond substrate using a zinc oxide (ZnO) piezoelectric mechanical transducer. We study the resonant optical orbital transition of a single NV center under the influence of coherent phonon driving from a mechanical resonator (Figure 1). We demonstrated coherent Raman sidebands out to the ninth order and orbital-phonon interactions that mix the two excited-state orbital branches. These interactions are spectroscopically revealed through a multi-phonon Rabi splitting of the orbital branches, which scales as a function of resonator driving amplitude.

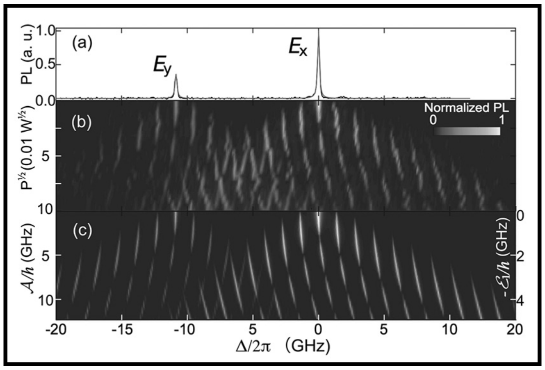

Figure 1: (a) Photoluminescence (PLE) spectrum of a NV center with orbital E*-state splitting of 10.6 GHz in the absence of mechanical driving. (b) Phonon-dressed state PLE measurement with mechanical driving at 1.3844 GHz. The mechanical driving amplitude is proportional to square root of the power applied to the transducer,* $P^{1/2}$*. Sideband transitions and level repulsion are evident in between* E *states.*
(c) Reconstruction of experimental data through quantum master equation simulation.

We show that the application of mechanical driving to engineering NV center orbital states can potentially stabilize NV center optical transition by reducing its sensitivity to fluctuating parasitic electric fields.

For quantum-enhanced mechanical sensing, the physical interaction, NV center electron spin-phonon coupling is rather weak in the current device design, which limits their application to quantum acoustodynamics (QAD) [6]. Engineering new generation of diamond MEMS device with higher quality factors, smaller mode volumes and higher NV-center density can help increase the coupling rate, and potentially enable sensing and control of resonator mechanical state using NV centers. We are in the process of developing the next generation device (Figure 2), a parabolic diamond HBAR. The device consists a 10 μm thick diamond membrane as the substrate, fabricated through deep reactive ion etching from a 100 μm thick diamond chip. On the etched surface, we mill a parabolic solid immersion lens (SIL) using focused ion beam (Figure 3). The parabolic SIL serves two purposes: 1) create a stable plano-convex acoustic cavity to confine the active phonon mode; 2) improve light collection efficiency from NV centers in the SIL by eliminating surface refraction.

Finally, we fabricate a piezoelectric transducer (Figure 4) using photolithography and DC sputtering, whose size mode-matches with the confined acoustic beam. The device is proposed to have frequency and quality-factor product fQ > 10^{13}, enabling defect-assisted quantum mechanical sensing.

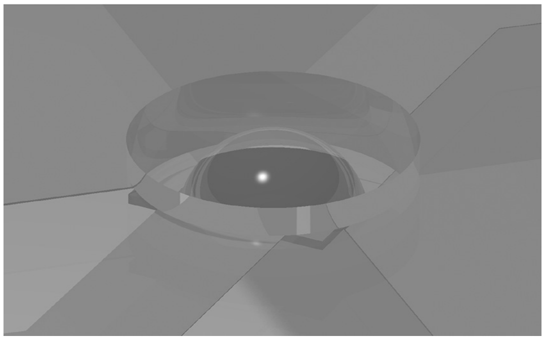

Figure 2: 3D illustration of the next generation device, with integrated plano-convex diamond acoustic cavity and mechanical transducer.

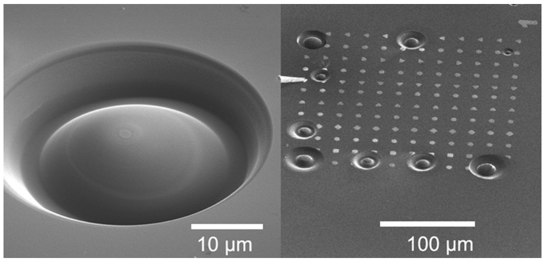

Figure 3: SEM images of solid immersion lenses on diamond milled through focused ion beam.

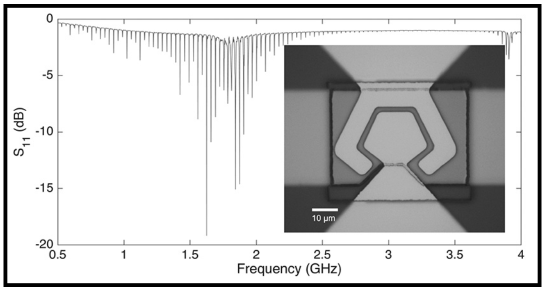

Figure 4: Electromechanical response of a HBAR sample measured by vector network analyzer. The inset shows an optical image of a device.

References:

[1] Lee, D., et al. Topical Review: Spins and mechanics in diamond. J. Opt. 19 033001 (2017).

[2] Barson, M. S.J., et al. Nanomechanical Sensing Using Spins in Diamond. Nano Lett. 17 (3), 1496-1503 (2017).

[3] MacQuarrie, E. R., et al. Mechanical Spin Control of Nitrogen-Vacancy Centers in Diamond. Phys. Rev. Lett. 111, 227602 (2013).

[4] Barfuss, A., et al. Strong mechanical driving of a single electron spin. Nat. Phys. 11, 820-824 (2015).

[5] Chen, H. Y., et al. Orbital state manipulation of a diamond nitrogen-vacancy center using a mechanical resonator. Phys. Rev. Lett. 120,167401 (2018).

[6] Chu, Y. W., et al. Quantum acoustics with superconducting qubits. Science, 358, 6360, 199-202 (2017).