Mechanical Spin Control of Nitrogen-Vacancy Centers in Diamond

E. R. MacQuarrie, T. A. Gosavi, N. R. Jungwirth, S. A. Bhave, and G. D. Fuchs*

Cornell University, Ithaca, New York 14853, USA

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We demonstrate direct coupling between phonons and diamond nitrogen-vacancy (NV) center spins by driving spin transitions with mechanically generated harmonic strain at room temperature. The amplitude of the mechanically driven spin signal varies with the spatial periodicity of the stress standing wave within the diamond substrate, verifying that we drive NV center spins mechanically. These spin-phonon interactions could offer a route to quantum spin control of magnetically forbidden transitions, which would enhance NV-based quantum metrology, grant access to direct transitions between all of the spin-1 quantum states of the NV center, and provide a platform to study spin-phonon interactions at the level of a few interacting spins.

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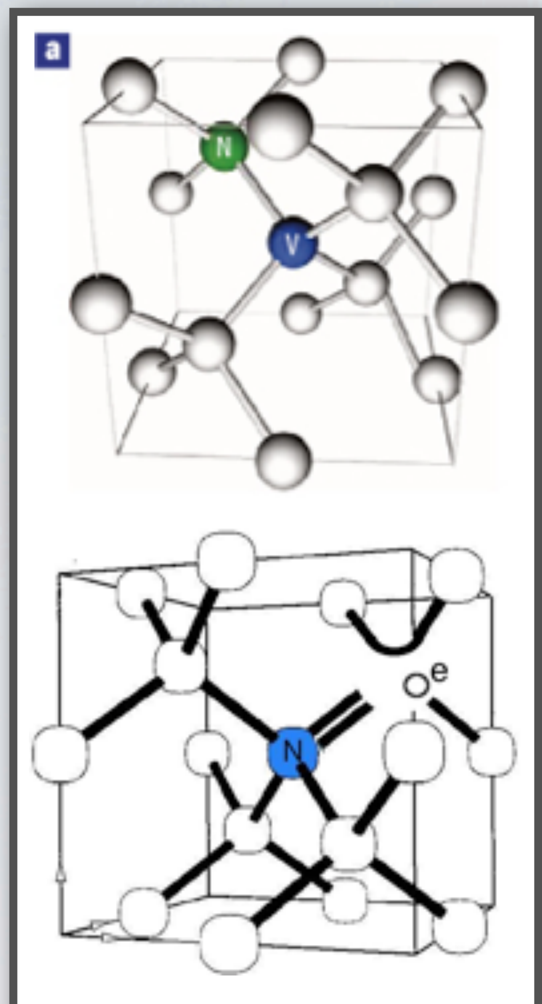
Department of Physics, University of Basel

N-V CENTERS IN DIAMOND



Figures
T. Gäbel *et al.*, Nat. Physics **2**, 408 (2006) (top)
wikipedia (bottom)

Point defect in diamond lattice.
Consists of neighboring Nitrogen atom and vacancy

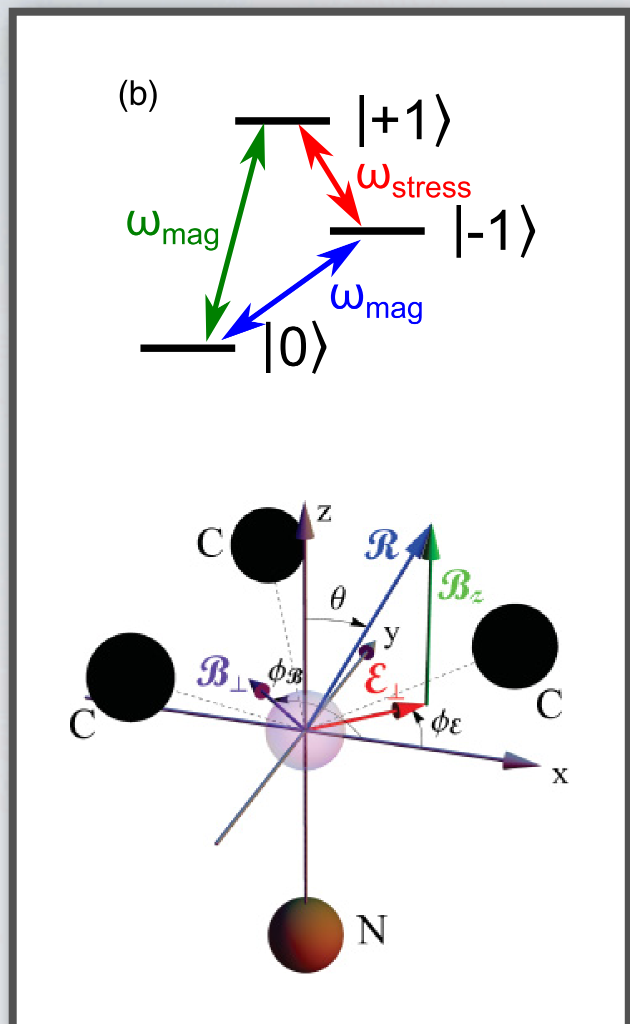
Two types exist: neutral $N\text{-}V^0$ and charged $N\text{-}V^{-1}$ **(spin 1)**

Long history, first studied in the 70s

Remarkable properties:
Long coherence times at room temperature Balasybramanian *et al.*, Nat . Mat. 8, 383 (2007)
Well-controlled (creation, control spin state, read-out)

Current interests: metrology and quantum computation
Magnetometry: P. Maletinsky et al., Nat. Nano 7, 320 (2007)
Electrometer: F. Dolde et al., Nat. Phys. 7, 459 (2011)
Review quantum computation: V.V. Dobrovitski et al., Annu. Rev. Condens. Matter Phys. **4**, 23 (2013)

SPIN-STRESS COUPLING



Figures
E. R. MacQuarrie *et al.*, PRL **111**, 227602 (2013) (top)
M. W. Doherty *et al.*, PRB **85**, 205203 (2012) (bottom)

$$\epsilon_\perp = 0.03 \text{ MHz/MPa}$$
$$D_0 = 2.873 \text{ GHz}$$

What's done in the experiment?

magnetic spin transition. Here, we use a MEMS transducer to directly drive electronic spin transitions in NV centers using gigahertz-frequency mechanical (stress) waves. This work demonstrates direct spin-phonon interactions at room temperature as a means to drive magnetically forbidden spin transitions.

$$\hat{H}_e = \sum_i \hat{T}_i + \hat{V}_{Ne}(\vec{r}_i, \vec{R}_0) + \hat{V}_{so}(\mathbf{x}_i, \vec{R}_0) + \hat{V}_{hf}(\mathbf{x}_i, \mathbf{X}_0) + \sum_{i>j} \hat{V}_{ee}(\mathbf{x}_i, \mathbf{x}_j) + \hat{V}_{ss}(\mathbf{x}_i, \mathbf{x}_j),$$

Defining $\vec{E}$ to be the applied electric field that is assumed to be approximately constant over the dimensions of the NV$^-$ center, the interaction of the center's electrons with the electric field is described by the potential[59]

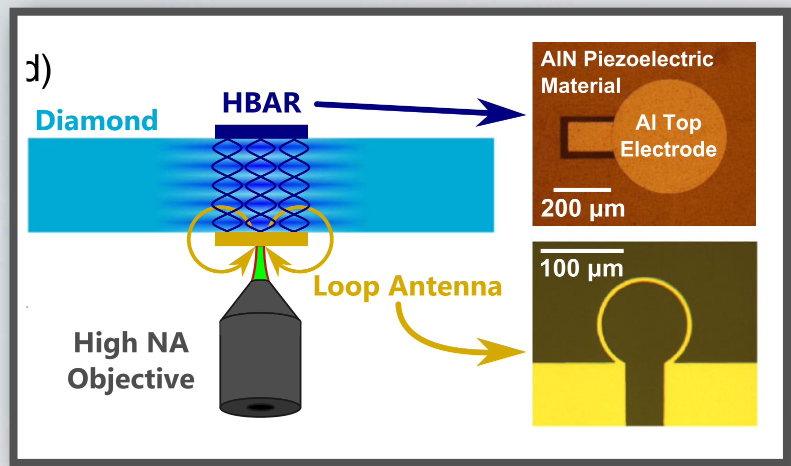
$$\hat{V}_{\rm el} = \sum_i \vec{d}_i \cdot \vec{E},$$

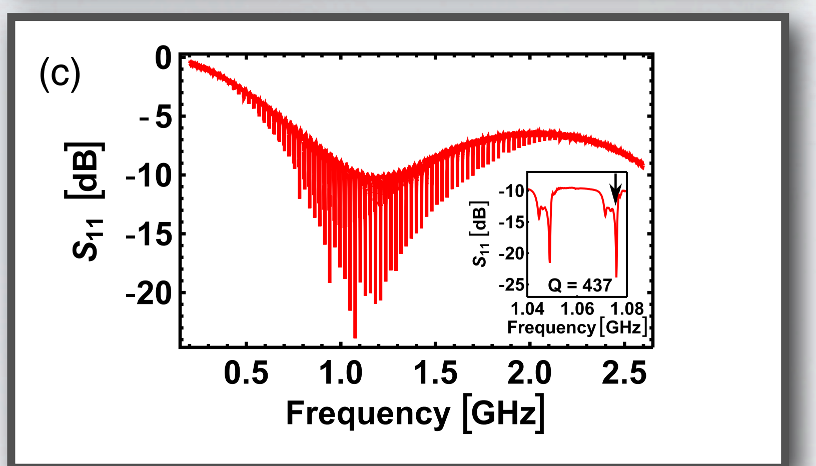
The interaction of the center's electrons with a crystal strain field can be approximately described by performing a Taylor series expansion of the electronic Hamiltonian $\hat{H}_e$ in terms of the displacements of the nuclear coordinates $\vec{R}$ from their ground-state equilibrium coordinates $\vec{R}_0$ induced by the strain field and retaining only the linear terms of the expansion.

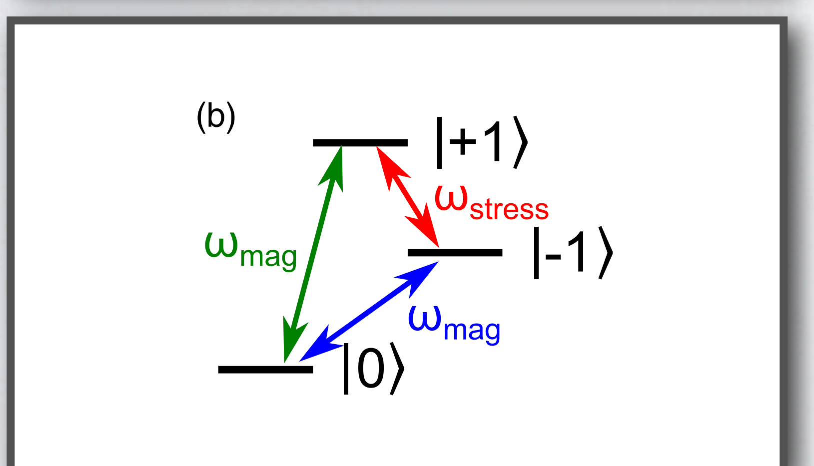
$$H_{\rm NV} = (D_0 + \epsilon_\parallel \sigma_\parallel) S_z^2 + \gamma_{\rm NV} B_\parallel S_z + \gamma_{\rm NV} B_\perp S_x - \epsilon_\perp \sigma_x (S_x^2 - S_y^2) + \epsilon_\perp \sigma_y (S_x S_y + S_y S_x),$$

Relativistic (SOI) effect

EXPERIMENTAL SETUP







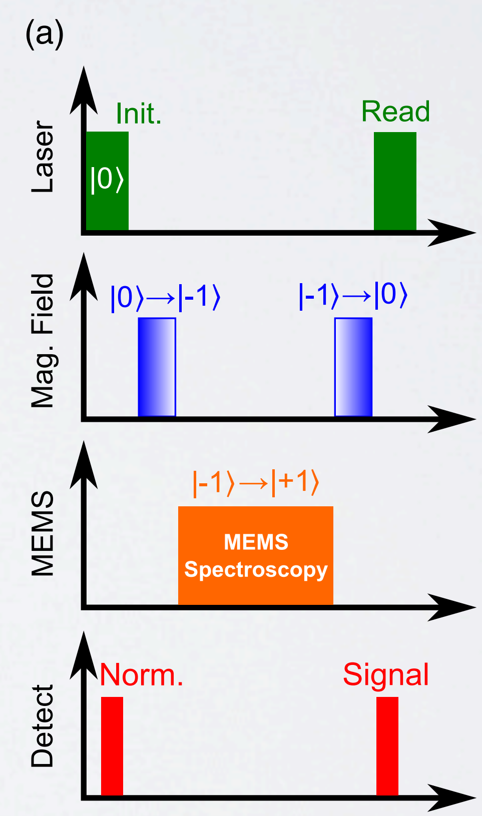
Top: experimental setup
Middle: reflection signal
Bottom: Level structure

Apply GHz-frequency voltage to piezoelectric aluminum nitride

Gives rise to 'stress wave' into the diamond

Diamond acts as Fabry-Perot cavity for these waves

Standing stress waves, 7 MPa (~200 KHz)



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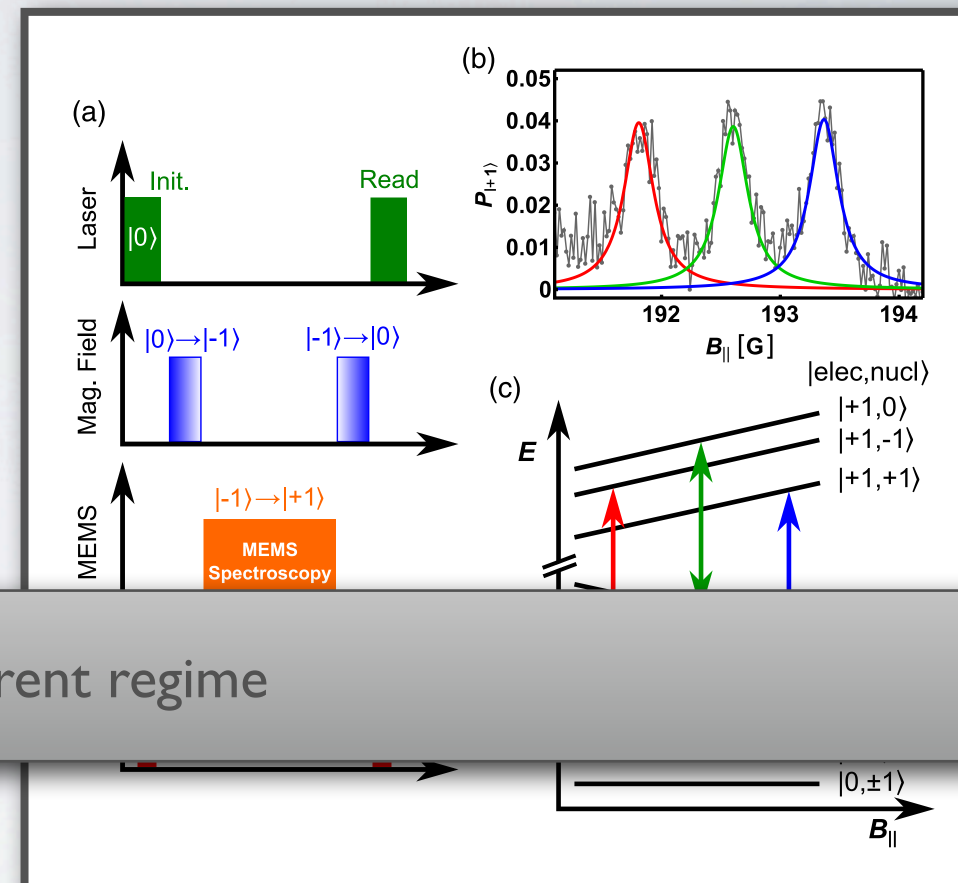
RESULTS

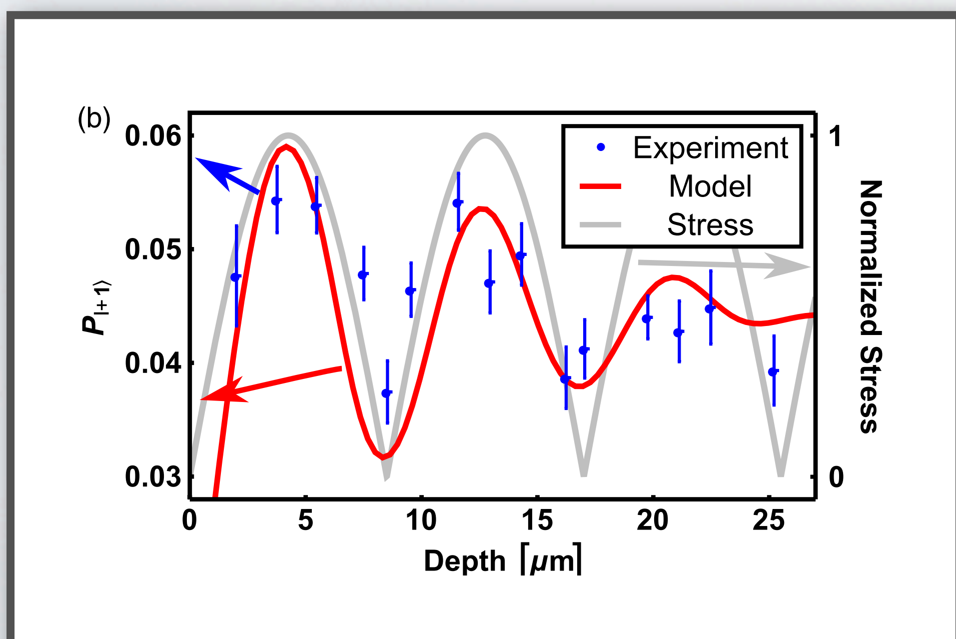
Repeat steps with varying B

If B matches ω of resonator, expect peak

3 peaks due to hyperfine splitting of N nuclear spins



Note: this is in the incoherent regime



Measure at different depths in the material

Period matches that of the standing wave

Signal decreases due to refractive abberation