Nanoscale sensing with single spins in diamond

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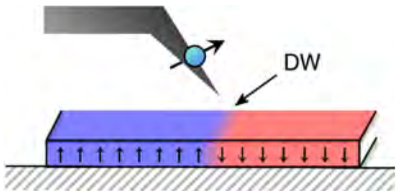
Collaborators: David Hunger (KIT), Olivier Arcizet, (CNRS, Grenoble)

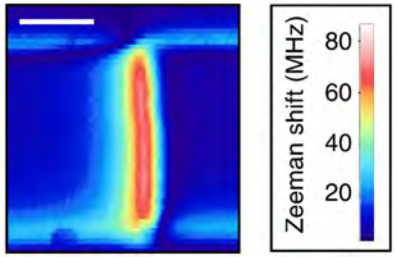
SPICE Workshop: Mainz, 10.12.2019

Nanoscale metrology

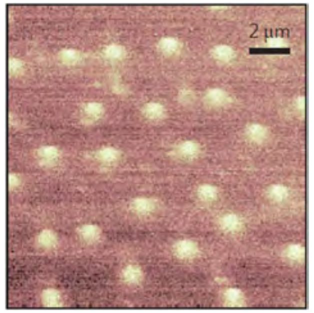
Magnetometry

Domain wall imaging

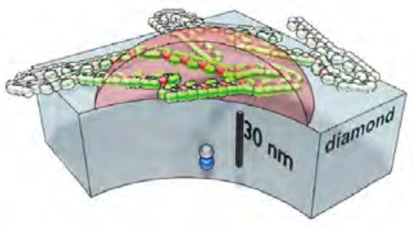


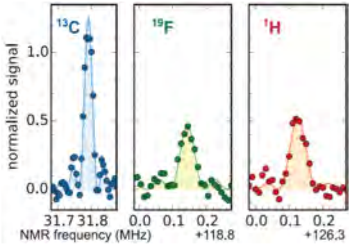


Supercond. vortices



NMR with shallow NVs





L. Thiel *et al.*,Nature Nano. **11**, 677 (2016)
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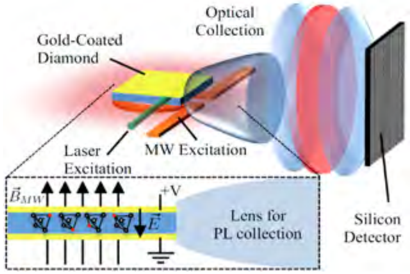
Electrometry



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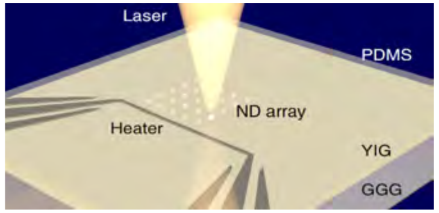
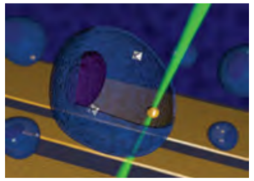
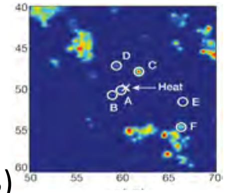
Bulk sensing



NV in living cell





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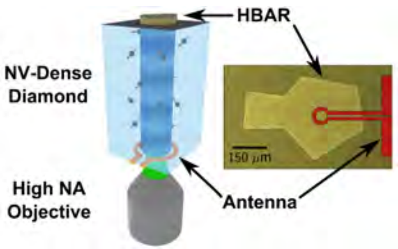
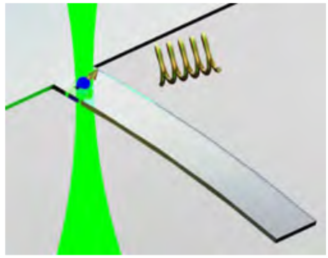
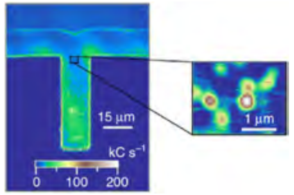
Strain & Spin hybrid

Bulk acoustic resonator

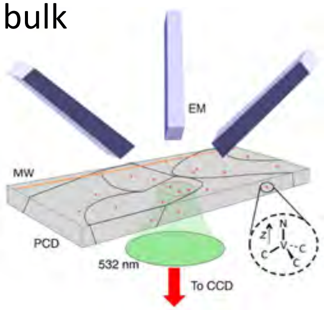


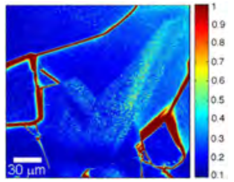
Cantilever QHS



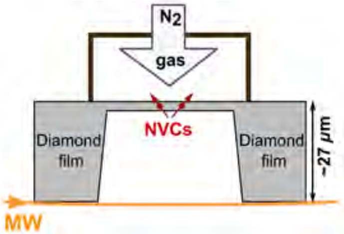


PC bulk





Membrane



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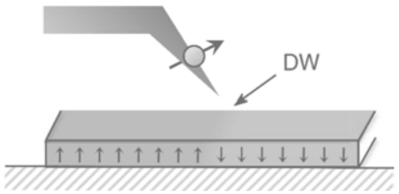

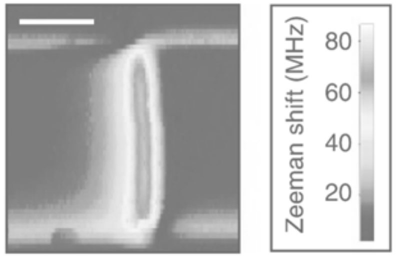

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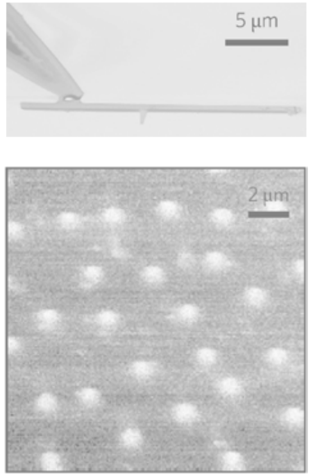

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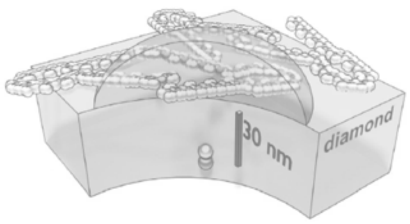

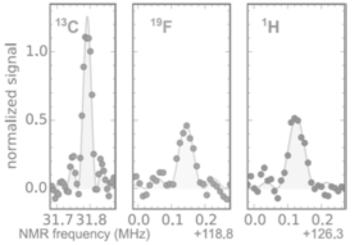

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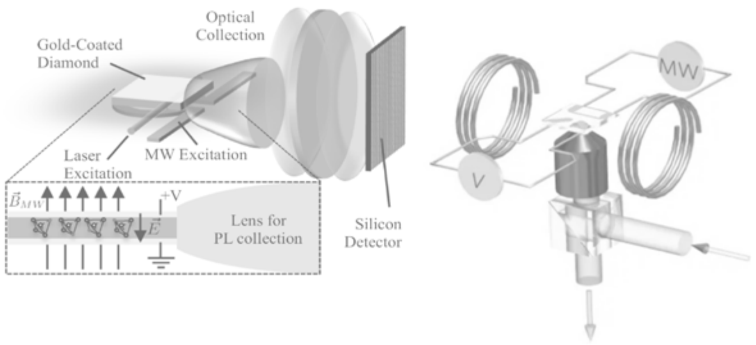

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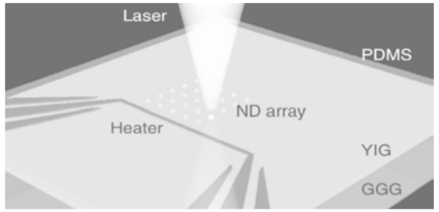

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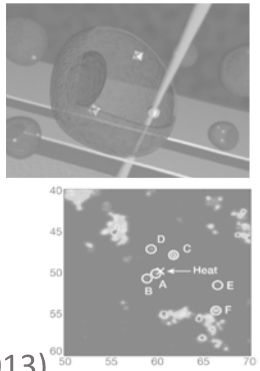

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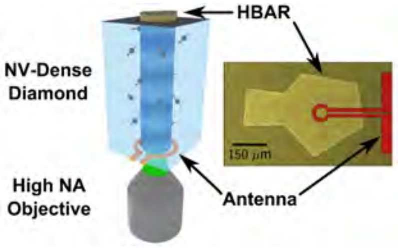

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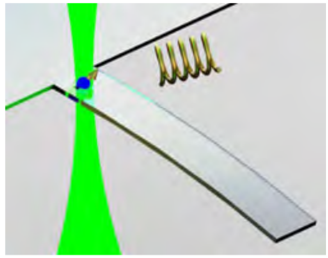

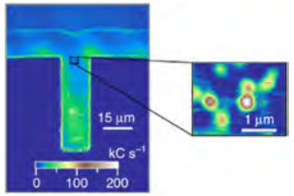

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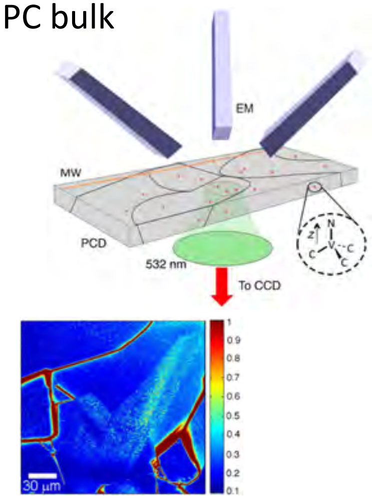

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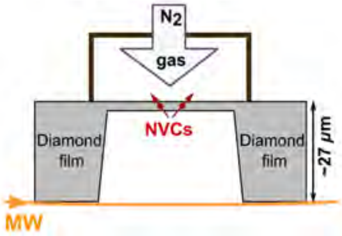

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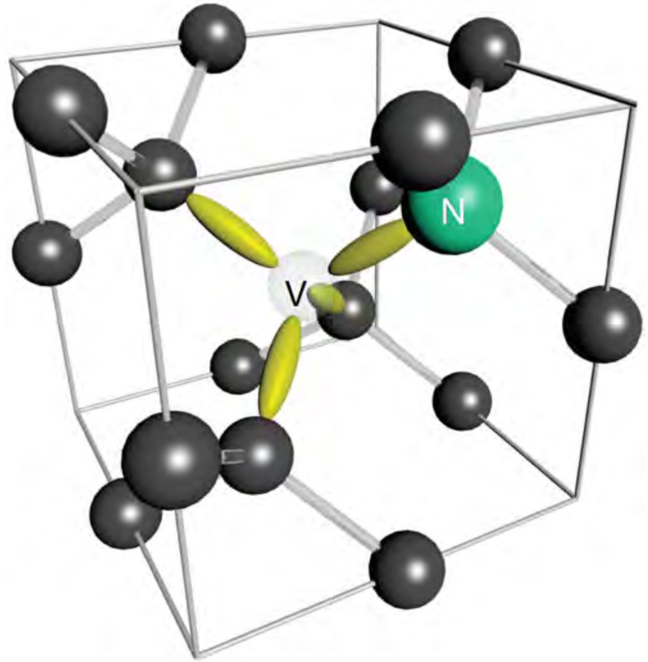
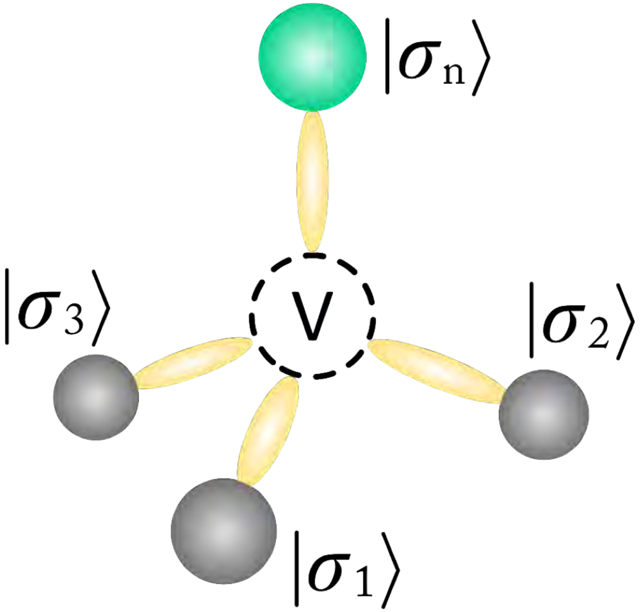
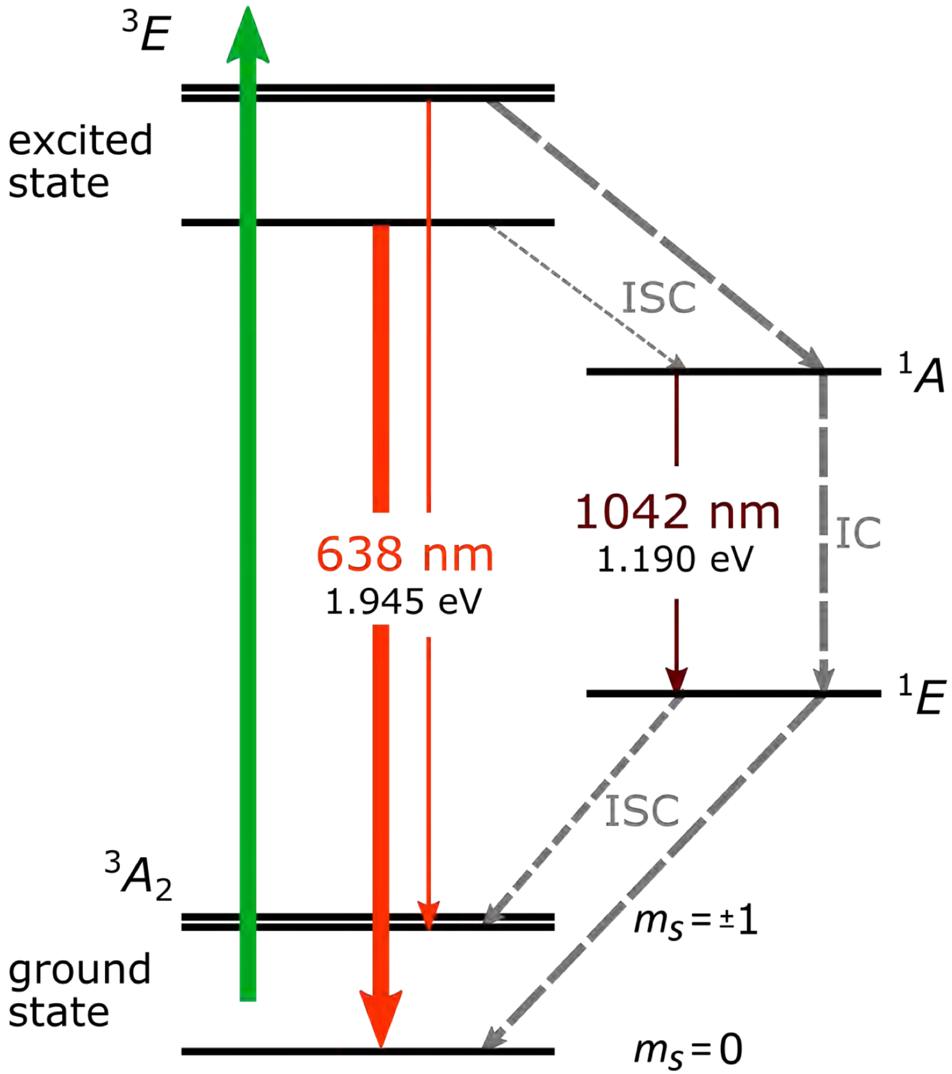
Nitrogen-Vacancy center in diamond







- NV$^-$: 6 electrons, $S = 1$, C_{3v} point group
- Spin preserving optical transitions
- Spin selective intersystem crossings (ISC)

zero field spin triplet: $\mathcal{H} = D\left[S_z^2 - \frac{1}{3}S(S+1)\right]$

Qubit control

Qubit: electron spin levels in GS or ES:

$\{m_s, m_s\}$: {0, ±1} {-1, +1}

Spin polarization:

- Initialization to $^3A_2$ $\boldsymbol{m_s = 0}$, yield ≥ 85%

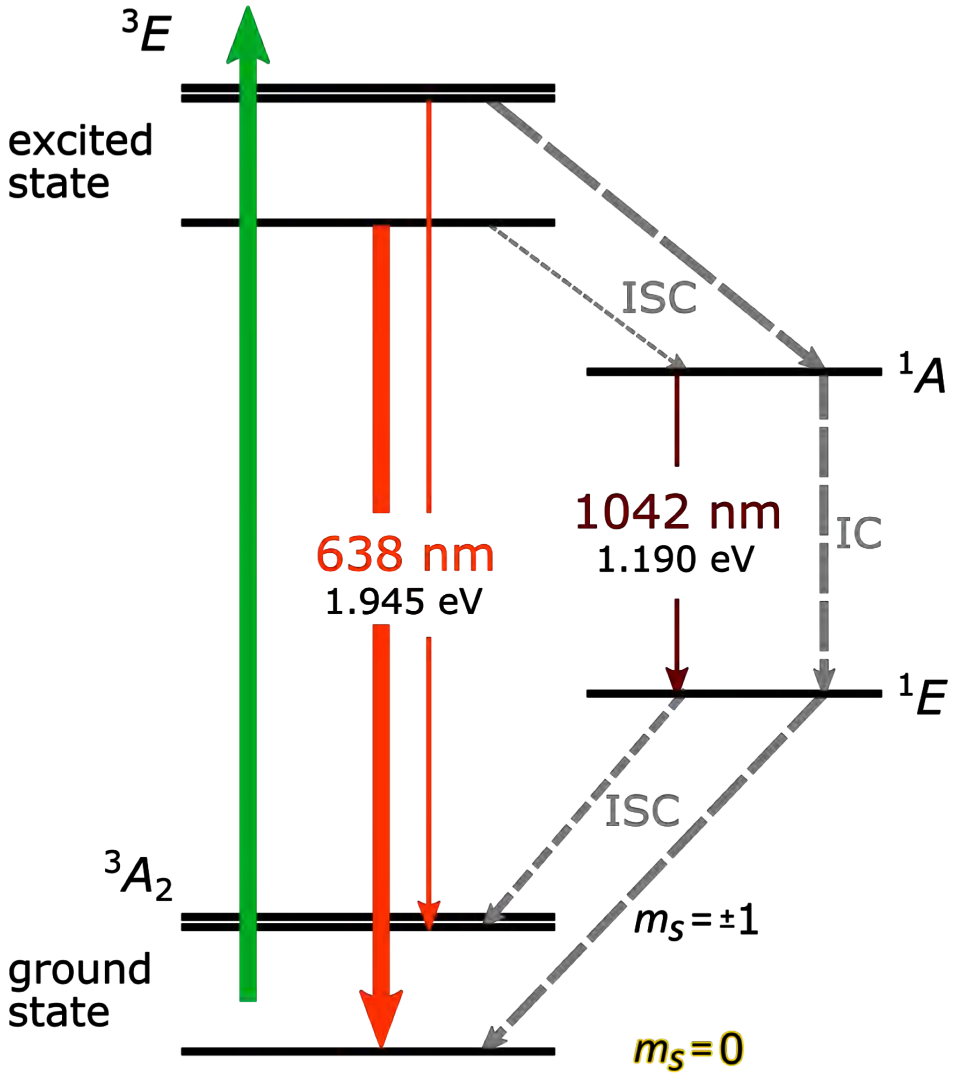
Spin readout:

- Spin detection via fluorescence intensity

$m_s = 0$ → **bright**

$m_s = \pm 1$ → **dark**

- Contrast up to 20 % for GS



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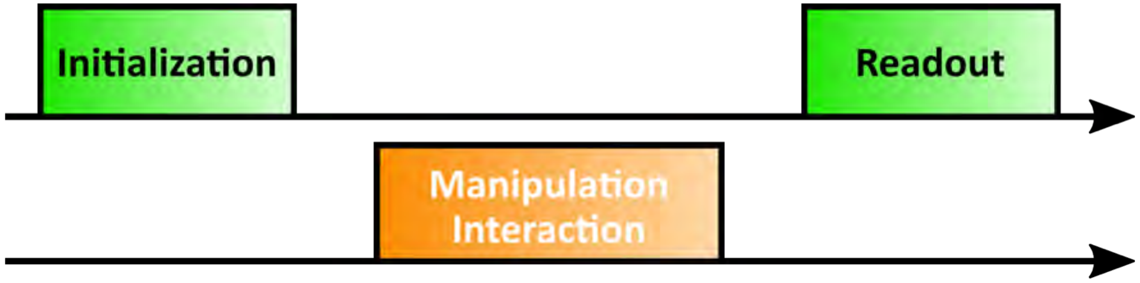

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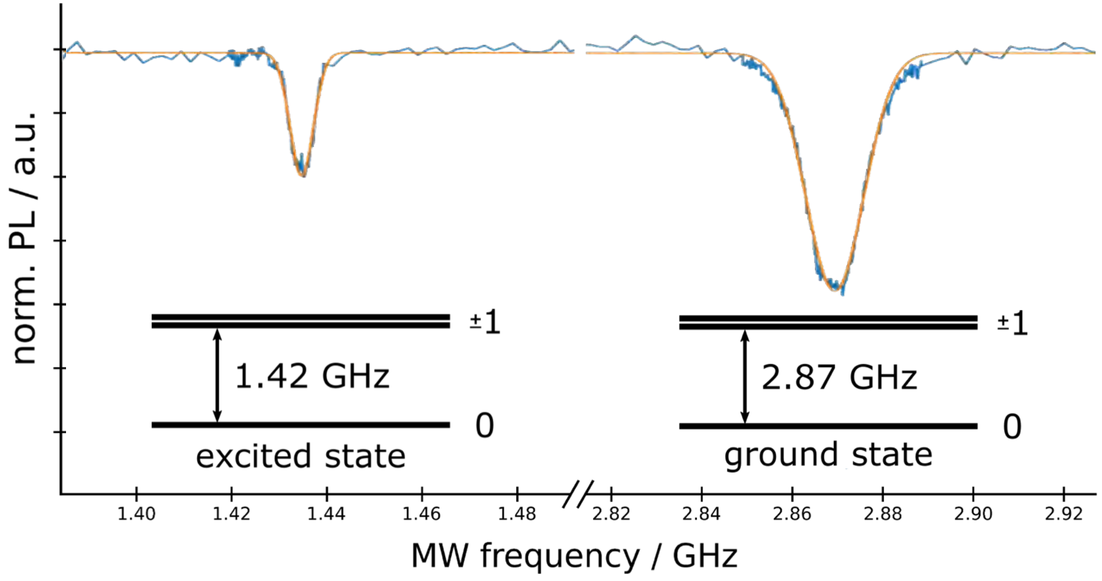
Optically detected magnetic resonance (**ODMR**)



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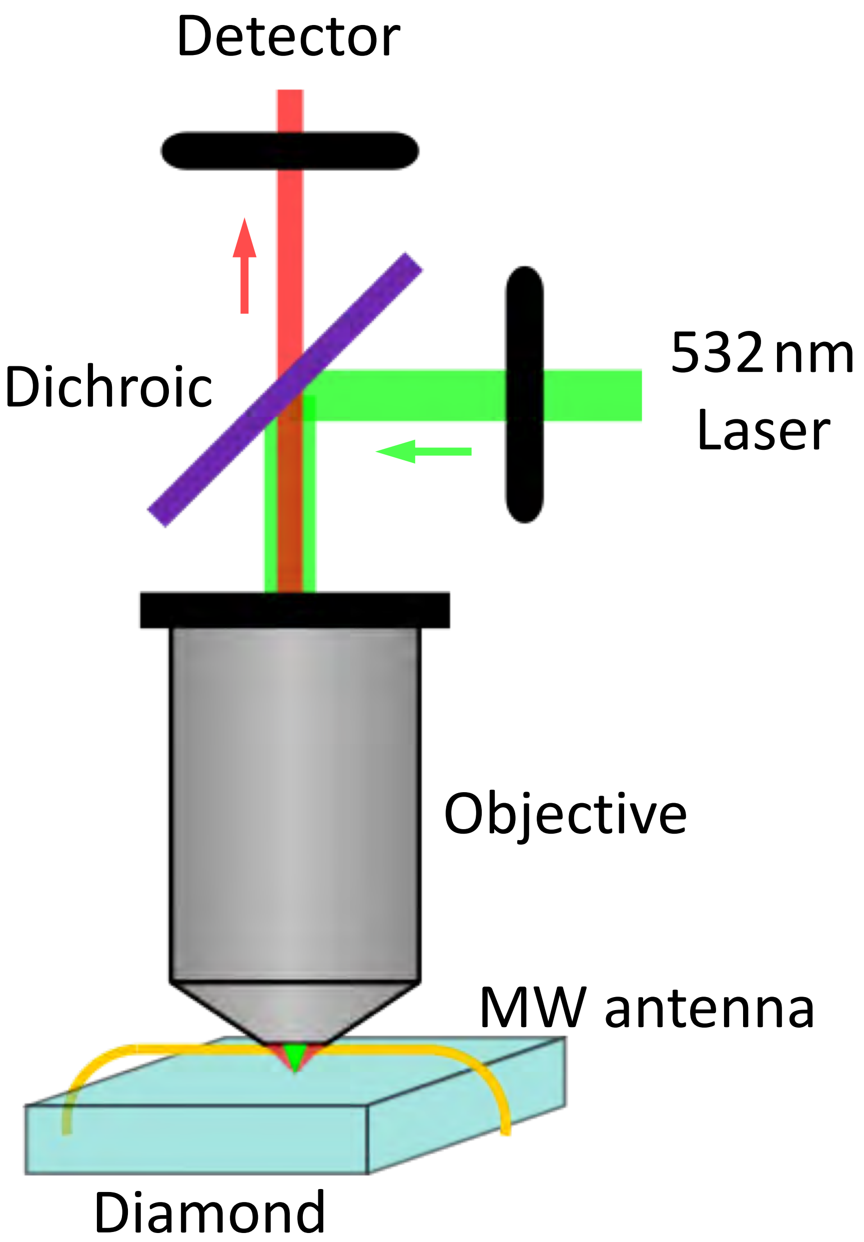
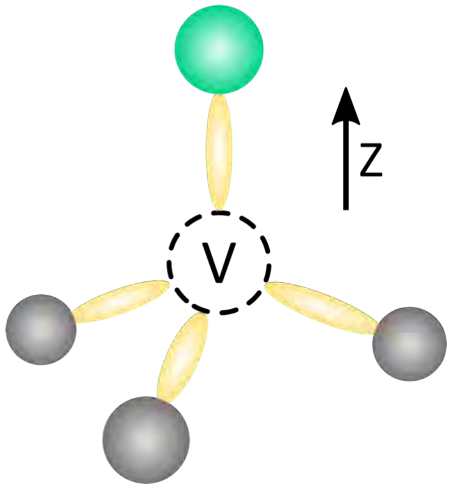


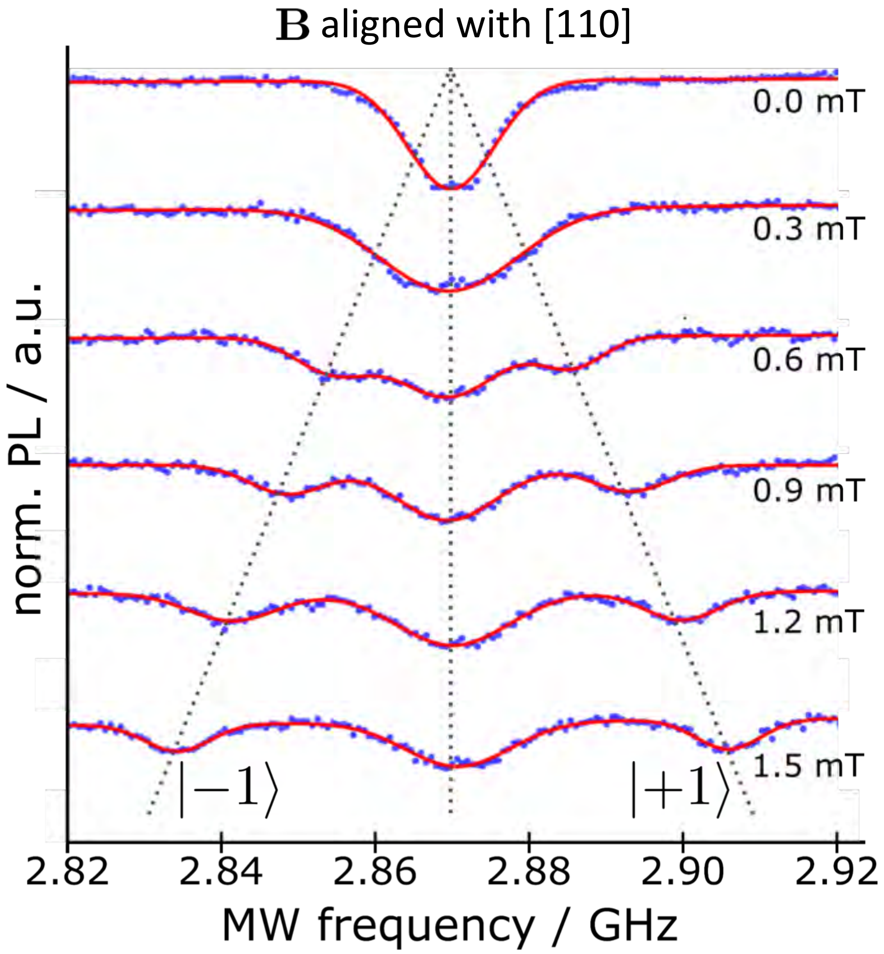
NV center under perturbation

Ground state Hamiltonian:

$$\mathcal{H} = D_{\mathrm{GS}} S_z^2 + \underbrace{\gamma_{\mathrm{NV}} \mathbf{S} \cdot \mathbf{B}}_{\text{Zeeman}} + \underbrace{\varepsilon_z S_z^2}_{\text{axial strain}} - \underbrace{\varepsilon_x (S_x^2 - S_y^2) + \varepsilon_y (S_x S_y - S_y S_x)}_{\text{non-axial strain}}$$

with $D_{\mathrm{GS}} = 2.87\,\mathrm{GHz}$
$\gamma_{\mathrm{NV}} = g\mu_{\mathrm{B}} = 2.8\,\mathrm{MHz G^{-1}}$





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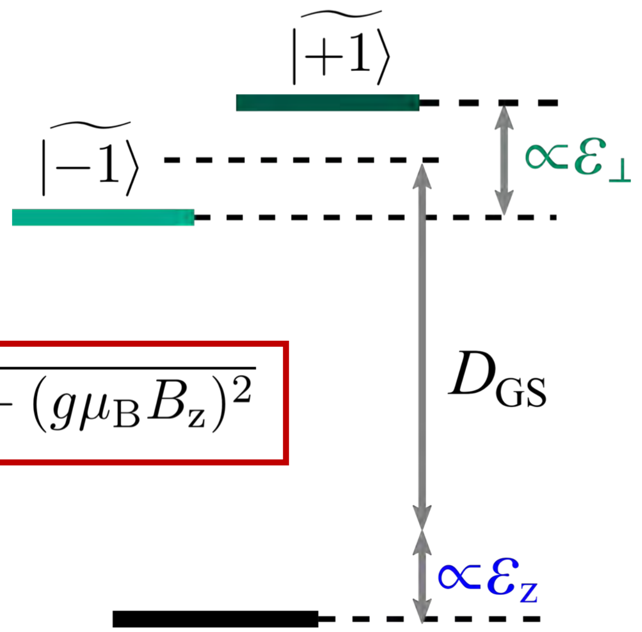
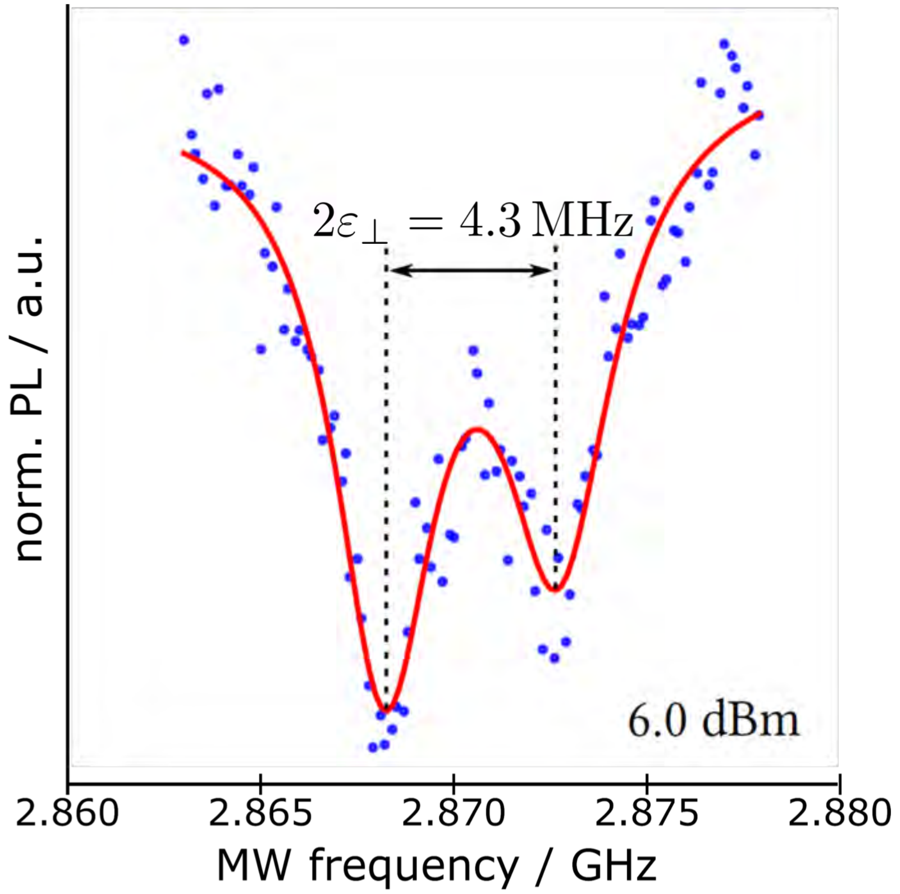
for $B_\perp = \sqrt{B_x^2 + B_y^2} \ll D_{\mathrm{GS}}$

$$\hbar\omega_\pm = D_{\mathrm{GS}} + \varepsilon_z \pm \sqrt{\varepsilon_\perp^2 + (g\mu_B B_z)^2}$$

with $\varepsilon_\perp = \sqrt{\varepsilon_x^2 + \varepsilon_y^2}$



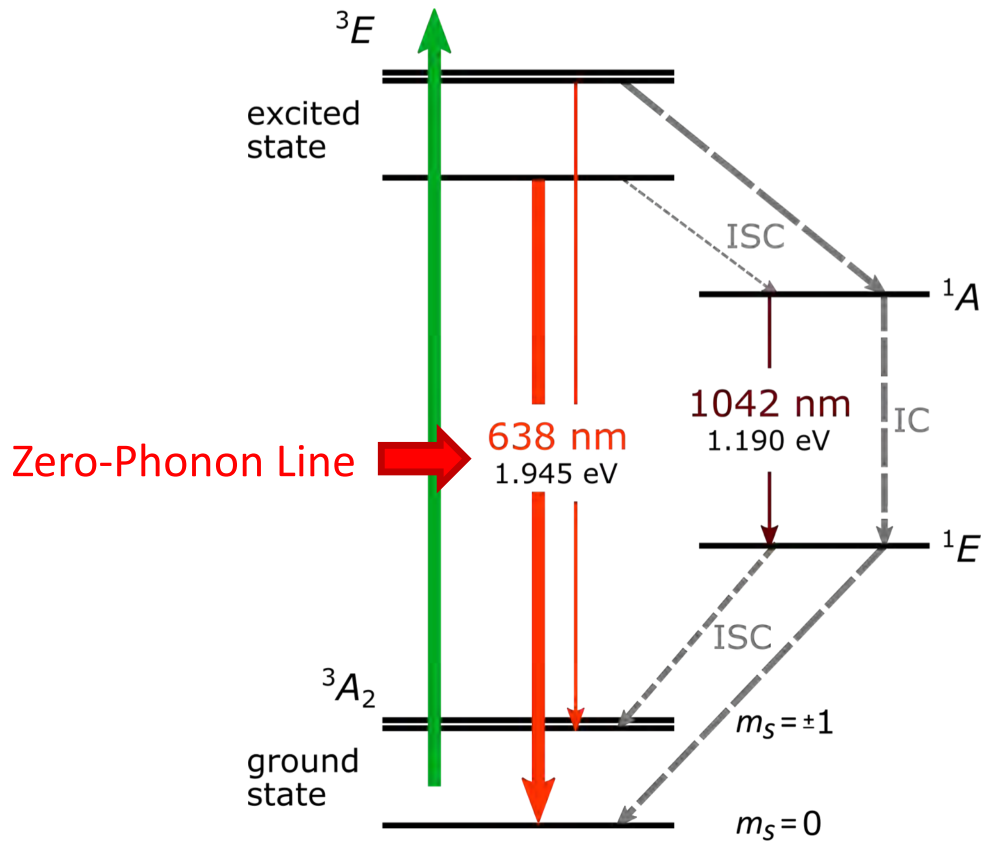
intrinsic non-axial strain $\varepsilon_\perp$

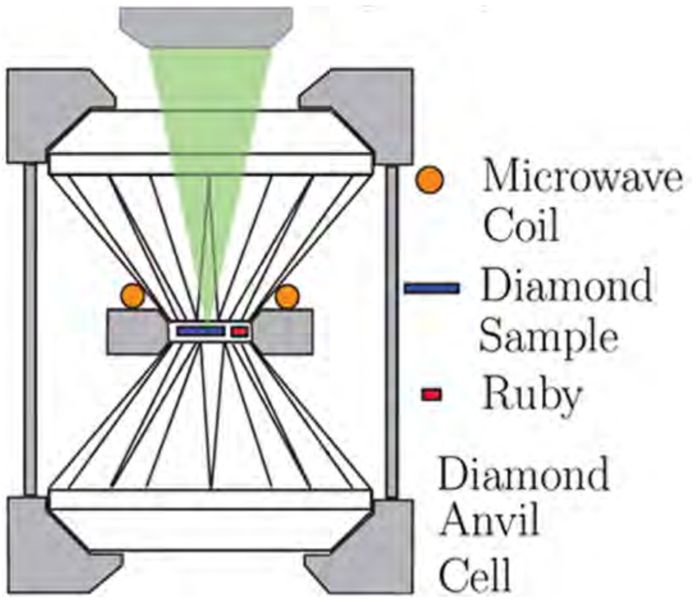


Sensing strain with NV

High stress regime

axial strain <
- ground state ODMR shift to higher frequencies
- ZPL shift to higher energies





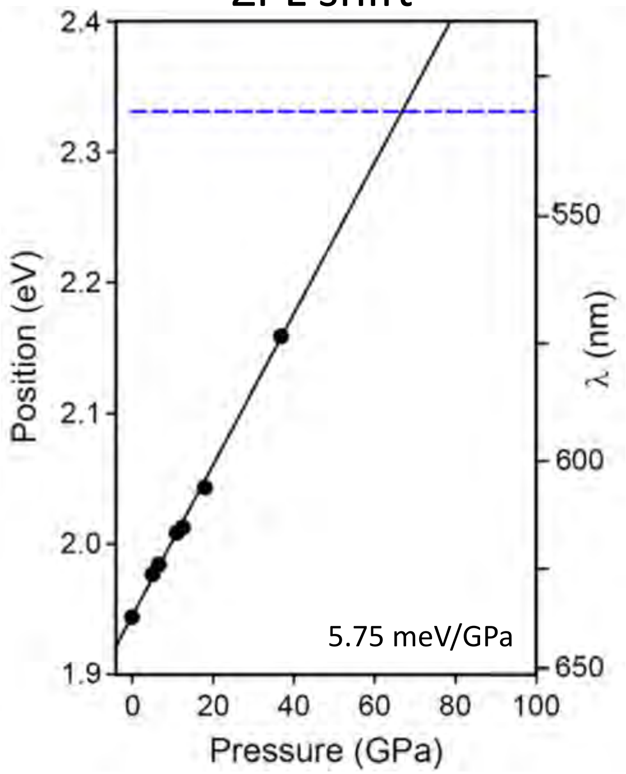
M. Doherty *et al.*, *PRL* ***112***, 047601 (2014)

Sensing strain with NV

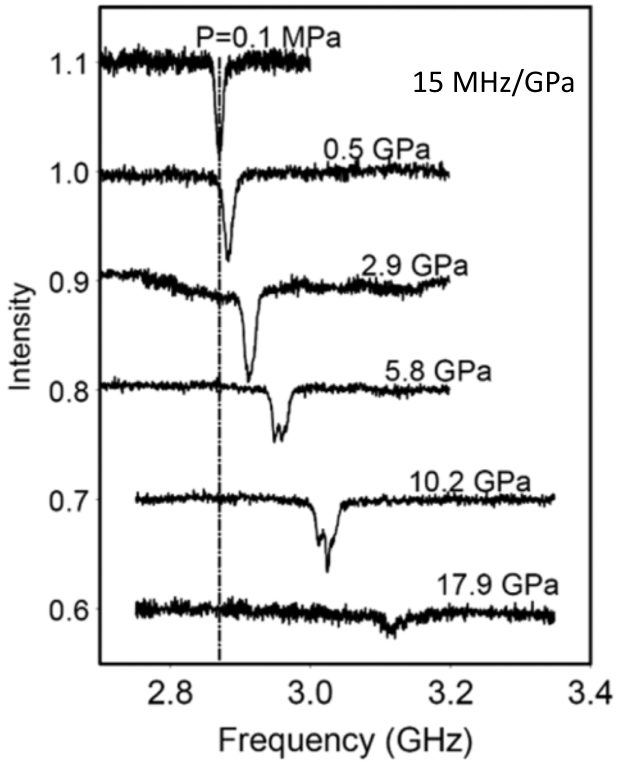
High stress regime

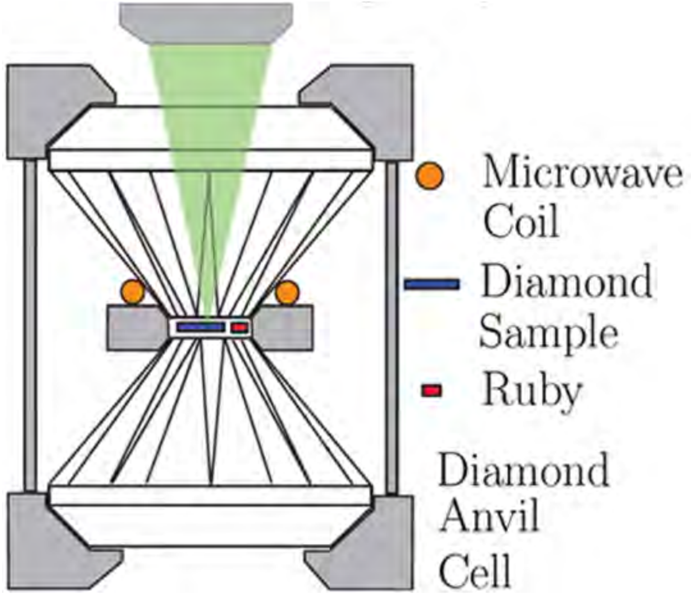
axial strain < ground state ODMR shift to higher frequencies / ZPL shift to higher energies

ZPL shift



GS ODMR shift





Sensitivity $\eta_{\mathrm{GS}} = \left[\frac{\Delta D}{\Delta P} \cdot C \cdot \sqrt{T_2^* \cdot t}\right]^{-1}$

C : optical setup parameter
t : averaging time

ODMR shift: $\eta_{\mathrm{GS}} \sim 0.6\,\mathrm{MPa}/\sqrt{\mathrm{Hz}}$

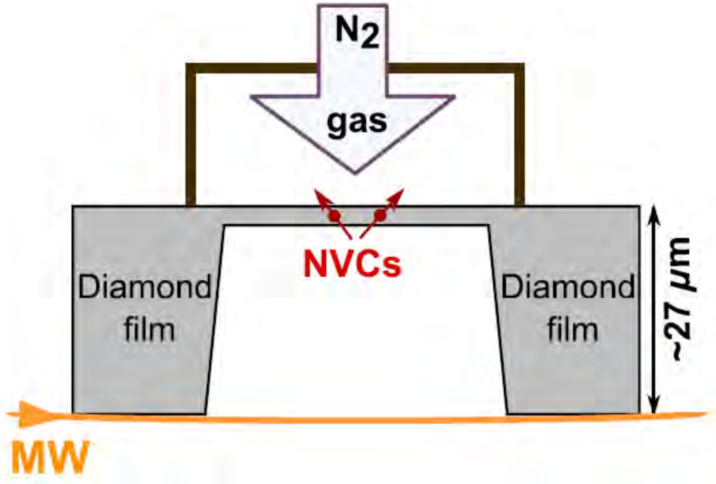
ZPL (at T = 10 K): $\eta_{\mathrm{GS}} < 100\,\mathrm{Pa}/\sqrt{\mathrm{Hz}}$

M. Doherty *et al.*, *PRL* ***112***, 047601 (2014)

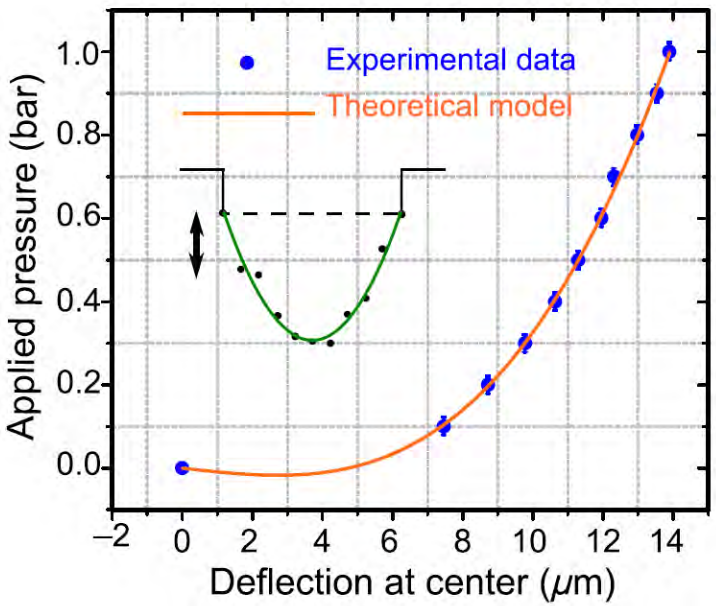
Sensing strain with NV

Low stress regime

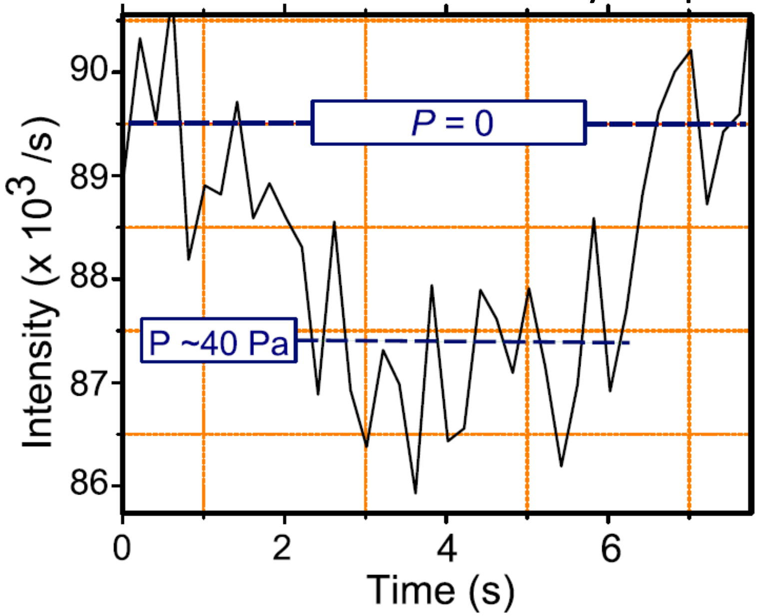
- deflection *d* of membrane depending on pressure *P* ($d \propto P$)
- Sensitivity: $\eta_{\mathrm{deflect.}} < 6\,\mathrm{Pa}/\sqrt{\mathrm{Hz}}$ vs. $\eta_{\mathrm{ODMR}} \sim 100\,\mathrm{Pa}/\sqrt{\mathrm{Hz}}$
- Pressure range $\Delta P \sim 10^4\,\mathrm{Pa}$



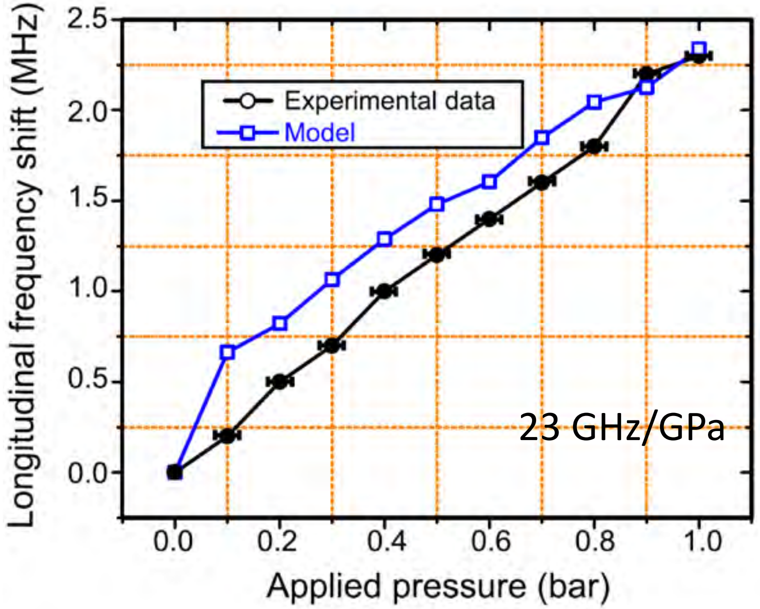
Membrane deflection



Fluorescence intensity drop



GS ODMR shift



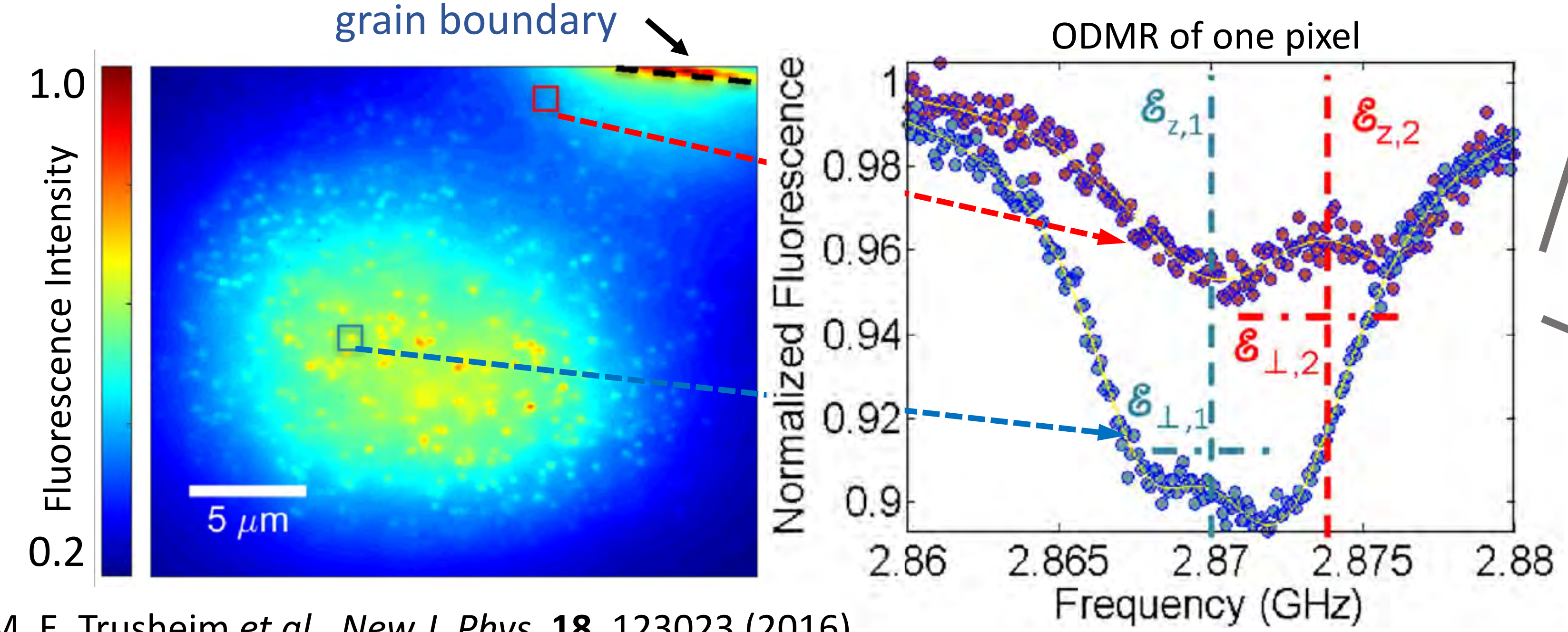
S. Ali Momenzadeh *et al.*, *Phys. Rev. Applied* **6**, 024026 (2016)

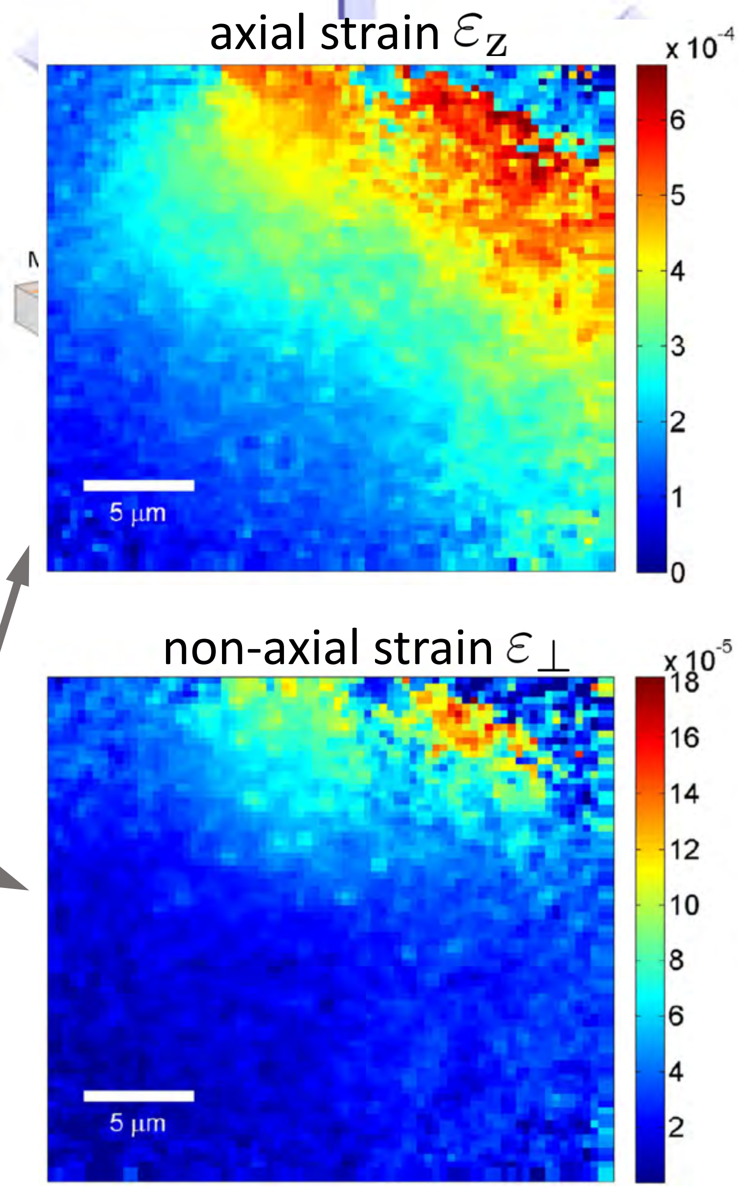
Sensing strain with NV

Wide field imaging

- PCD type IIa sample
  - NV density: 0.1 to 1 NV/µm²
  - regional preferential orientation of NVs
- Sensitivity:

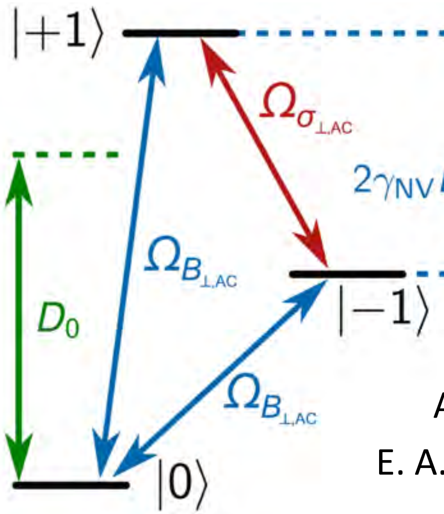
$$\eta_{\text{axial}} = 1.02 \cdot 10^{-4}\,\text{strain} / \sqrt{\text{Hz}}$$
$$\eta_{\text{non-axial}} = 4.7 \cdot 10^{-5}\,\text{strain} / \sqrt{\text{Hz}}$$





M. E. Trusheim *et al., New J. Phys.* **18**, 123023 (2016)

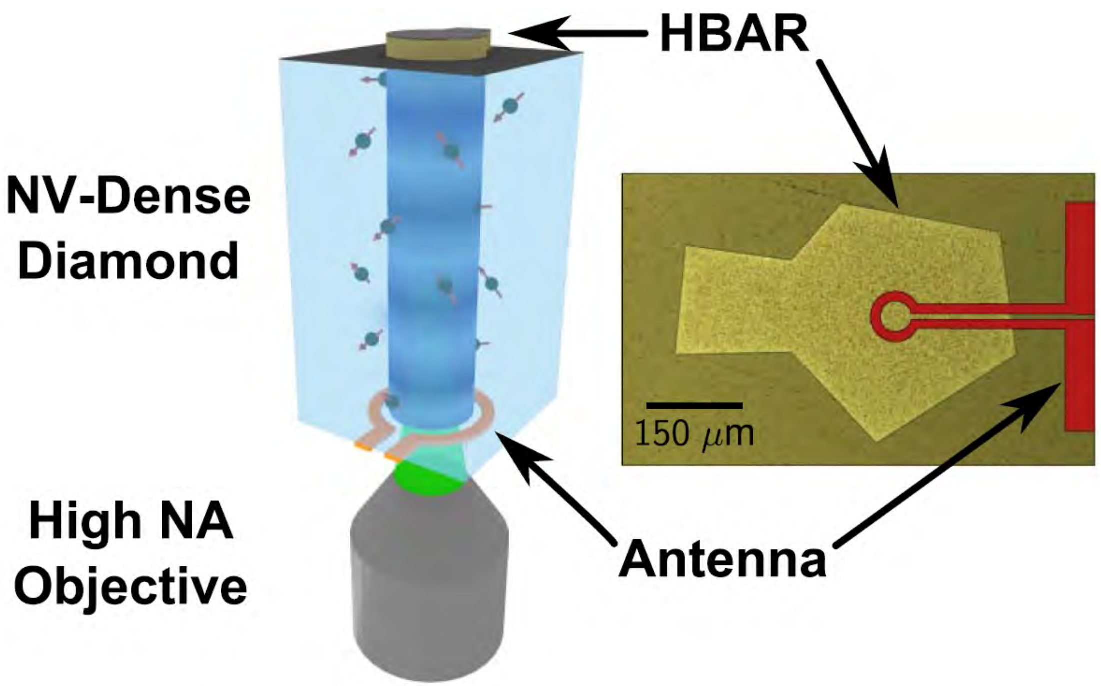
Enhanced NV spin state control



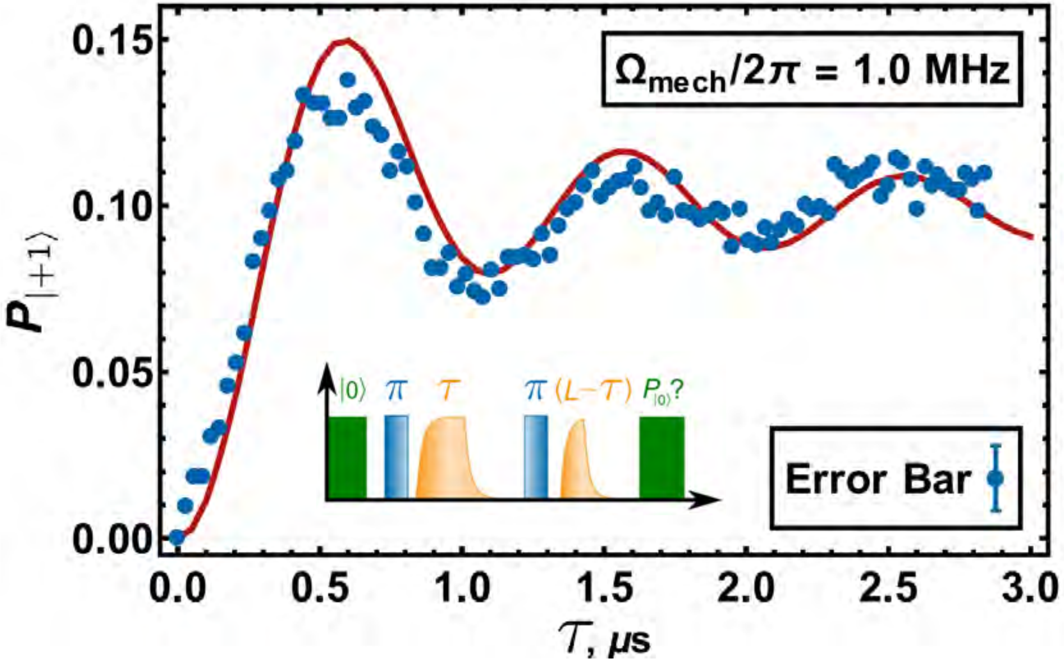
E. A. MacQuarrie *et al., Optica* **2**, 3 (2015)
A. Barfuss *et al., Nature Phys* **11**, *820* (2015)
E. A. MacQuarrie *et al., PRL* **111**, 227602 (2013)

The {-1, +1} qubit

- Transition $|-1\rangle \leftrightarrow |+1\rangle$ magnetically forbidden
  → transversal ac stress couples both states



mech. driven Rabi oscillations



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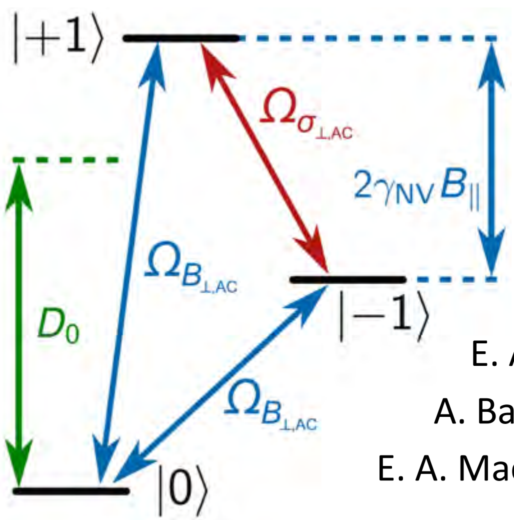

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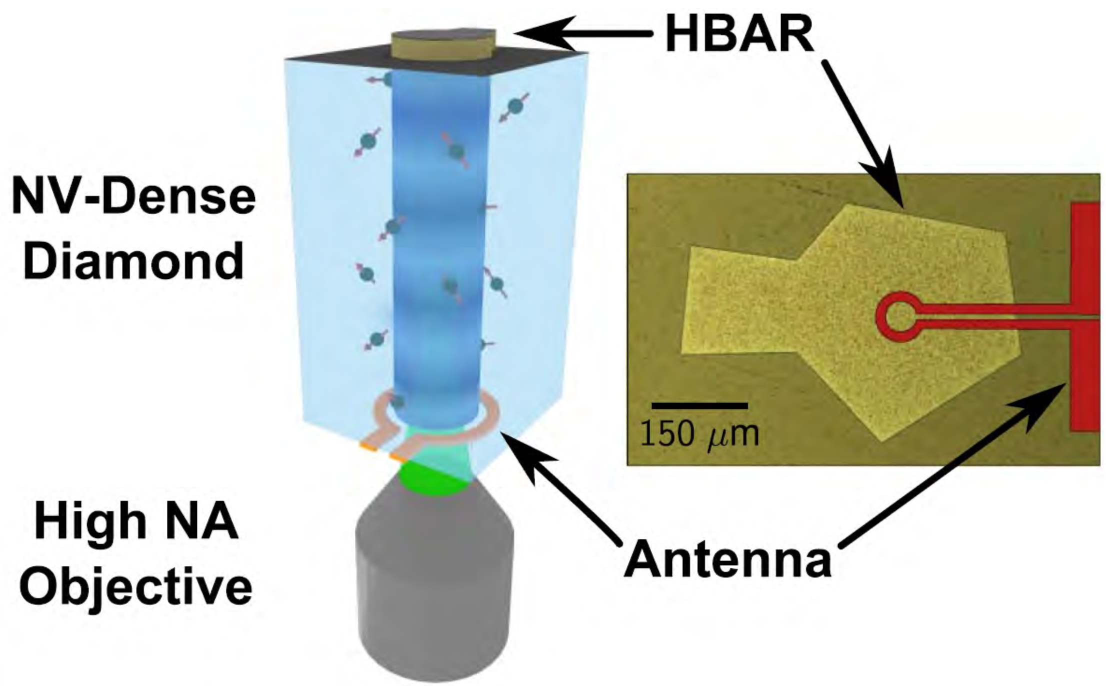
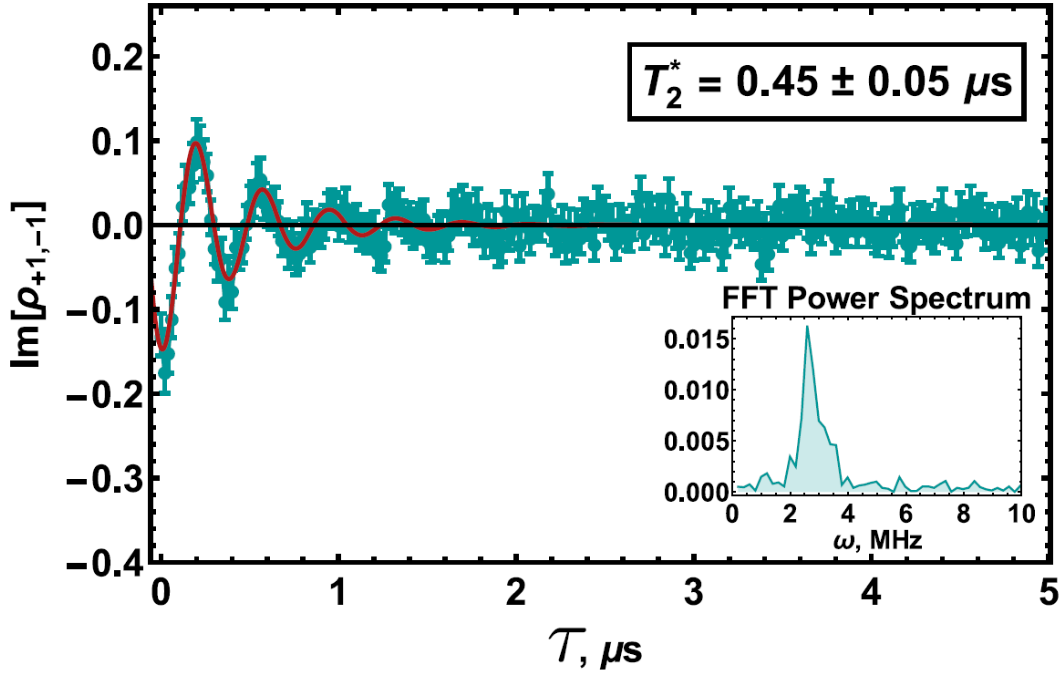
A. Barfuss *et al.*, *Nature Phys* **11**, *820* (2015)
E. A. MacQuarrie *et al.*, *PRL* **111**, 227602 (2013)



mech. Ramsey sequence



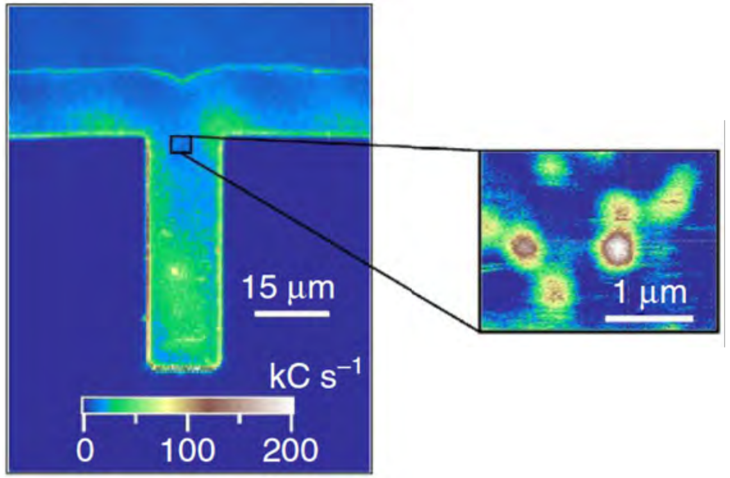
Coherent strain-mediated coupling

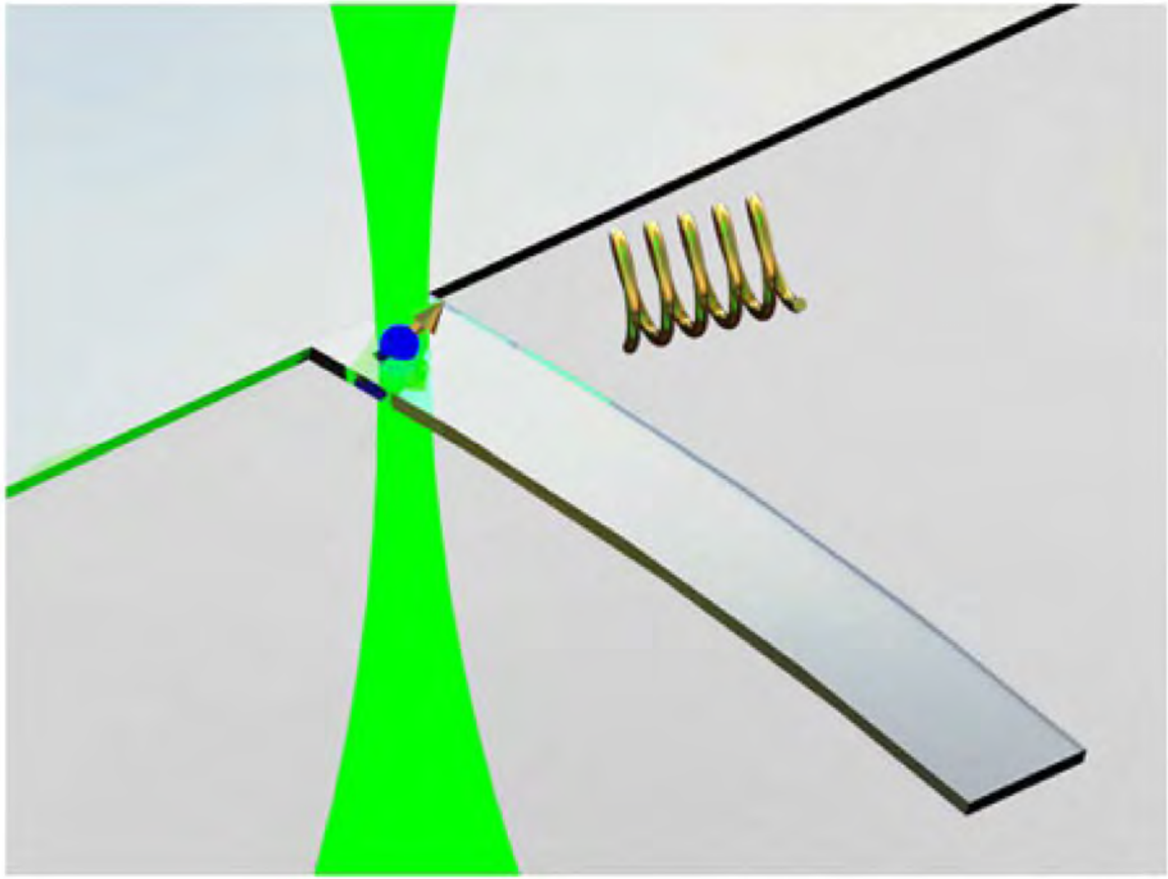
NV in mechanical resonators

i. high Q-facor: $Q > 10^6$

ii. long coherence: $T_2 > 1\,\mathrm{ms}$

iii. large strain at base





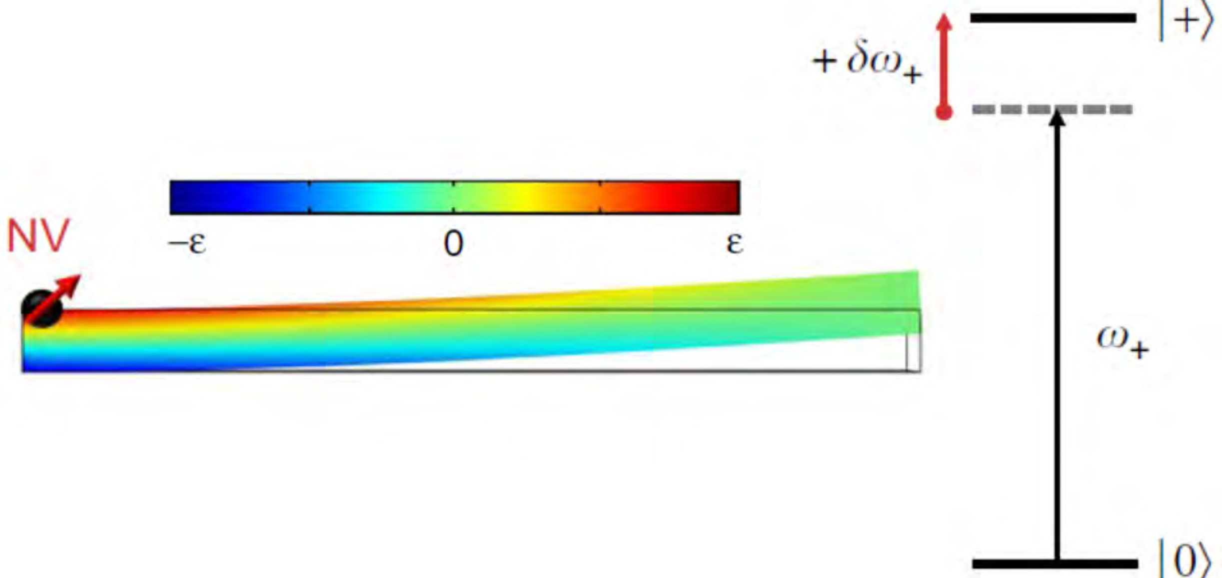
P. Ovartchaiyapong *et al., Nature Comm.* **5**, 4429 (2014)

Coherent strain-mediated coupling

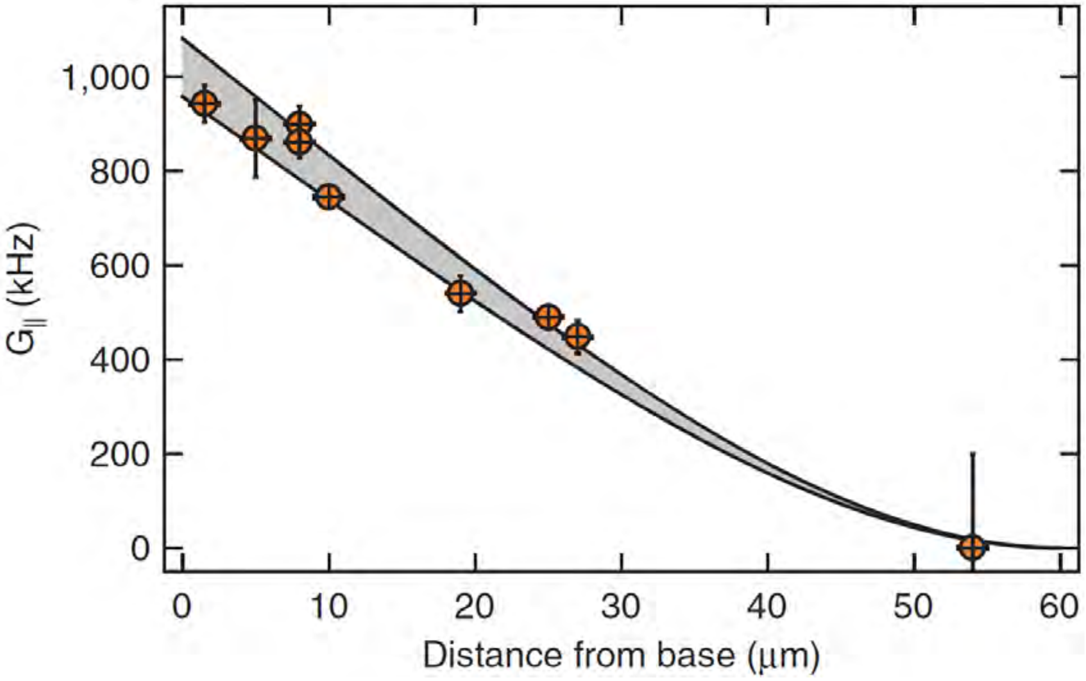
NV in cantilever mech. resonator

- NV depth $d \approx 50\,\mathrm{nm}$
- Geometry: $l = 60\,\mu\mathrm{m}, \quad w = 15\,\mu\mathrm{m}, \quad t \approx 1\,\mu\mathrm{m}$
- Sensitivity: $\eta_{\mathrm{axial}} = 3 \cdot 10^{-6}\,\mathrm{strain} / \sqrt{\mathrm{Hz}}$

$$\hbar\omega_{\pm} = D_{\mathrm{GS}} + \varepsilon_{\mathrm{z}} \pm \sqrt{\varepsilon_{\perp}^{2} + (g\mu_{\mathrm{B}}B_{\mathrm{z}})^{2}}$$



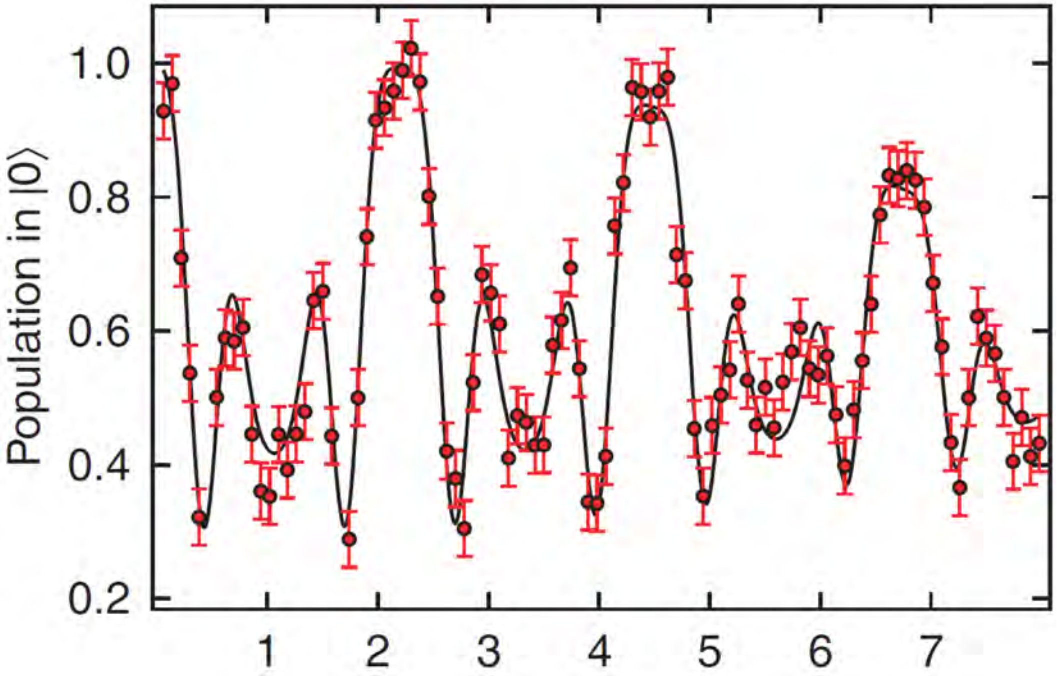
Varying NV distance from cantilever base



P. Ovartchaiyapong *et al., Nature Comm.* **5**, 4429 (2014)

Coherent strain-mediated coupling

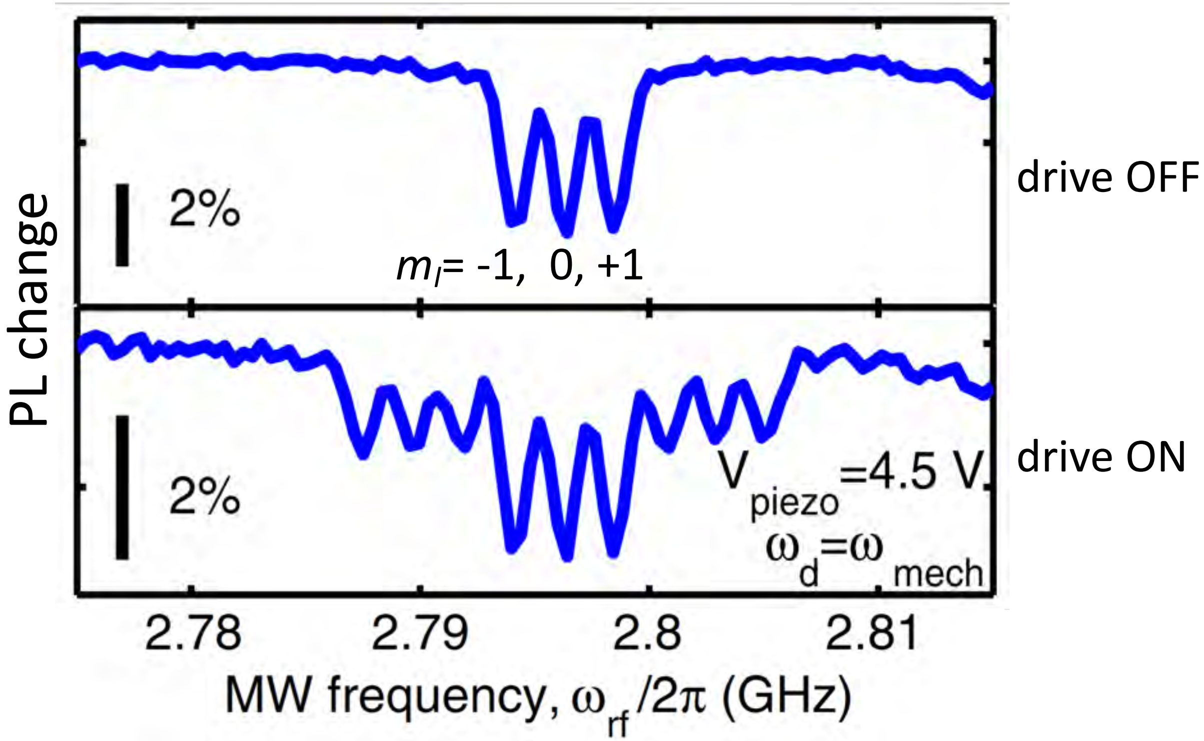
axial strain: Hahn echo sequence



- Hahn echo: $\omega_{\mathrm{mech}}/2\pi = 882.0 \pm 2.0\,\mathrm{kHz}$
- Driving: $\omega_{\mathrm{d}}/2\pi = 884.583\,\mathrm{kHz}$

P. Ovartchaiyapong *et al., Nature Comm.* **5**, 4429 (2014)

^{14}N (I = 1) hyperfine splitting

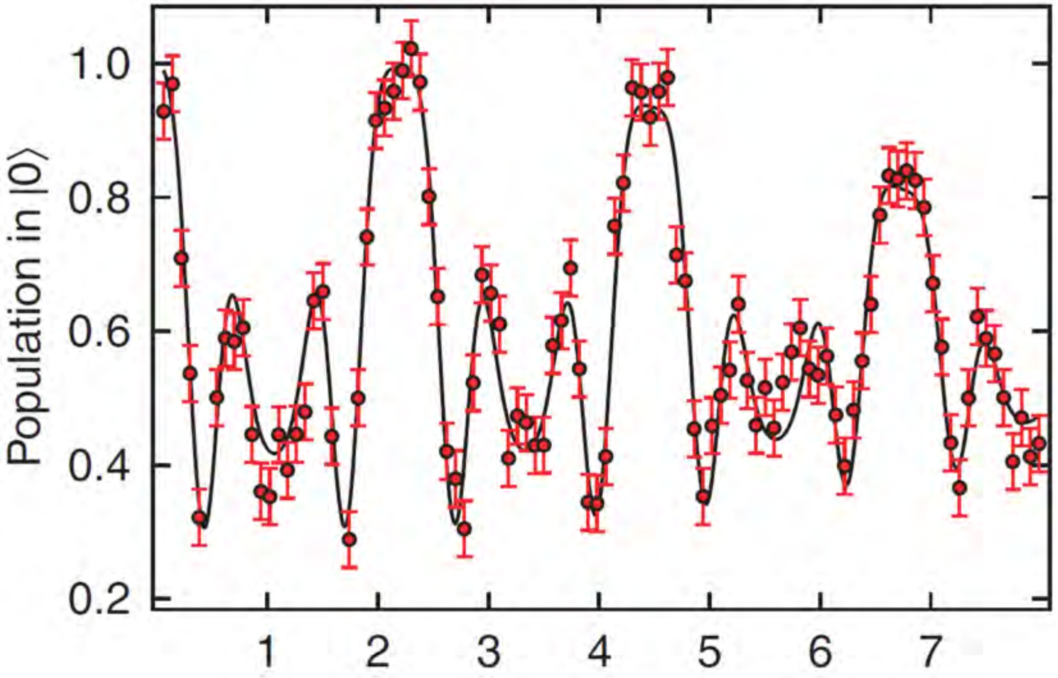


- ^{14}N axial hyperfine parameter $A_{\mathrm{GS}}^{\parallel} = -2.16\,\mathrm{MHz}$

J. Teissier *et al., PRL* ***113***, 020503 (2014)

Coherent strain-mediated coupling

axial strain: Hahn echo sequence



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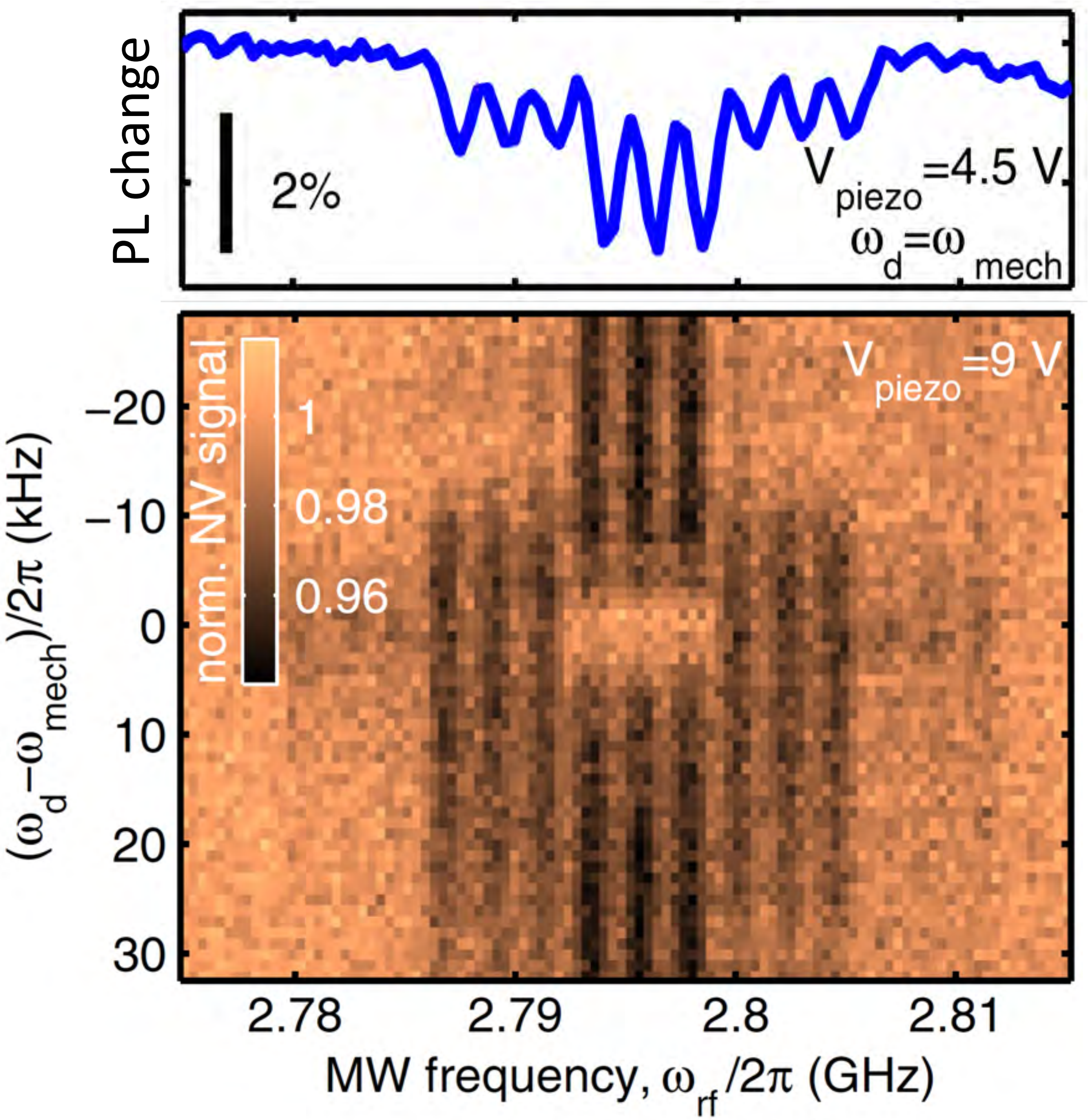
P. Ovartchaiyapong *et al., Nature Comm.* **5**, 4429 (2014)

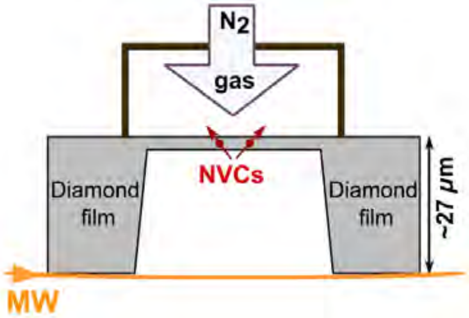
^{14}N (I = 1) hyperfine splitting



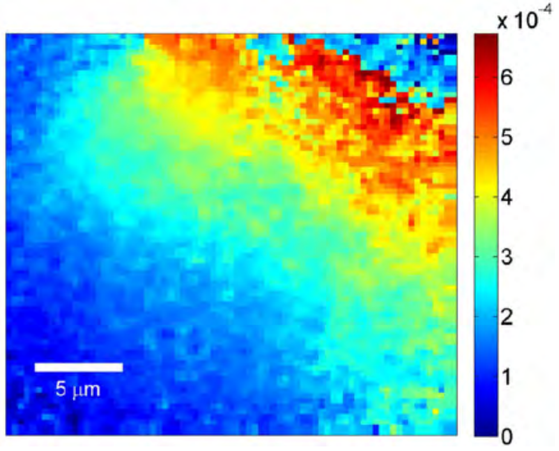
J. Teissier *et al., PRL* ***113***, 020503 (2014)

Summary

- Nanoscale metrology of *B*, *E*, *T*, and *ε* with NV centers in diamond



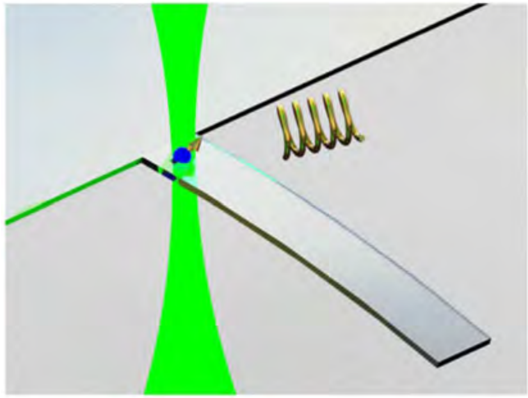
- Shot noise limited strain sensing with NV center



- Different diamond geometries allow sensing of strain fields

Outlook: metallic films deposited on ultrathin diamond with shallow NV centers

- Enhanced NV spin control by {-1, +1} sublevel qubit



- Coherent strain-mediated coupling of NV spin state

Thank you