Hybrid sensors based on color centers in diamond and piezoactive layers

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European Research Council

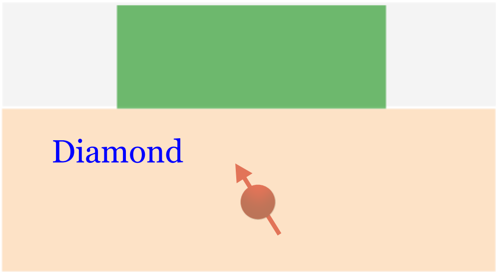
Deutsche Forschungsgemeinschaft

Alexander von Humboldt Stiftung/Foundation

MARIE CURIE ACTIONS

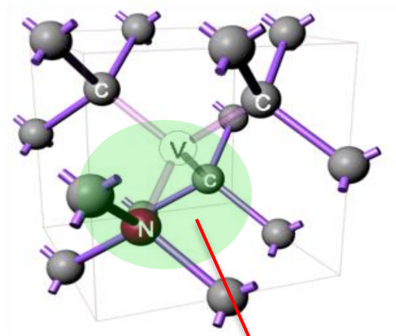
Outline

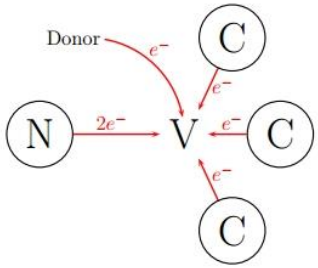
- Introduction to color centers in diamond
- Hybrid nanoscale diamond quantum sensor
  1. Design & Working principle
  2. Sensitivity analysis
  3. Potential applications
- Summary

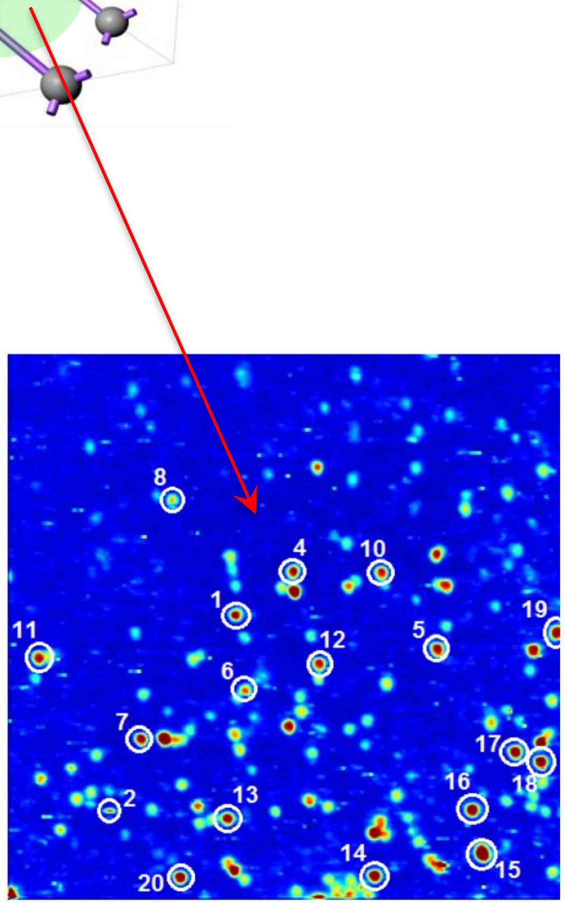


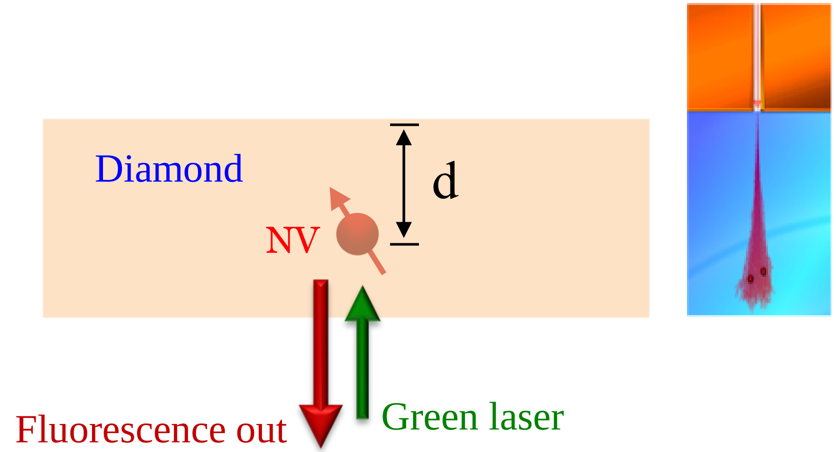
Nitrogen-Vacancy Centers in Diamond

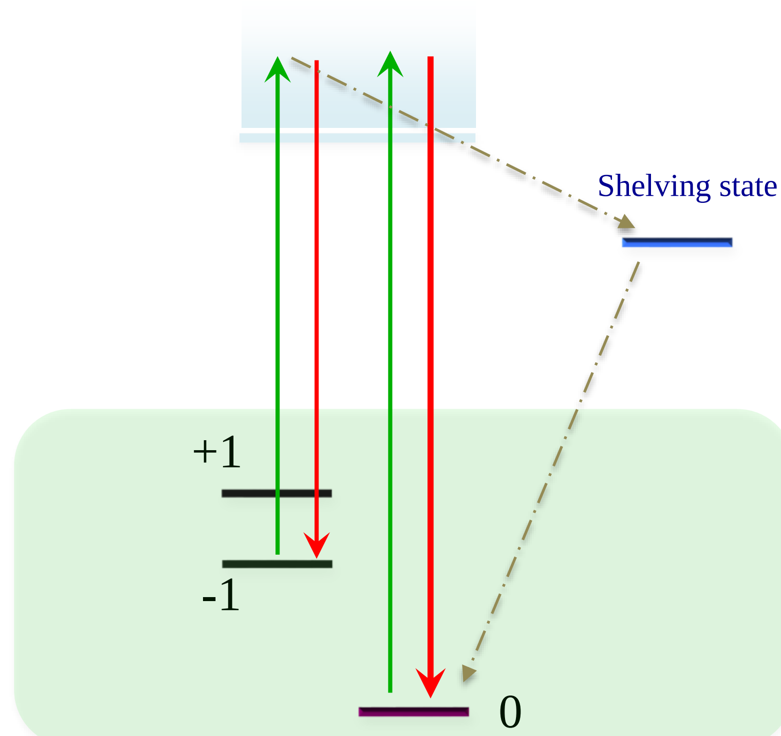
Ground triplet: Spin-1











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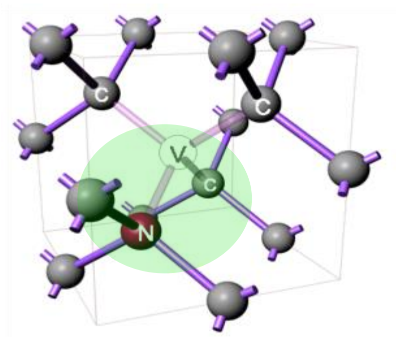

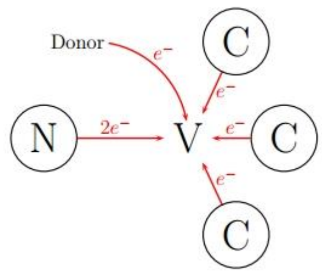

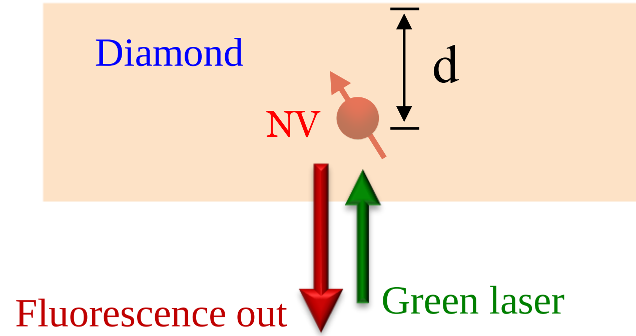

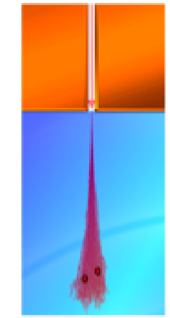

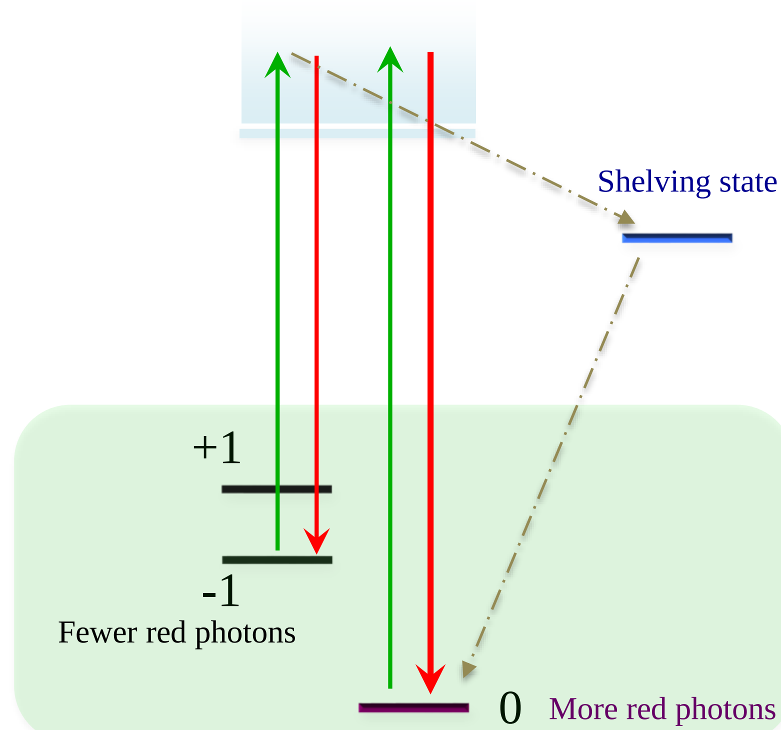

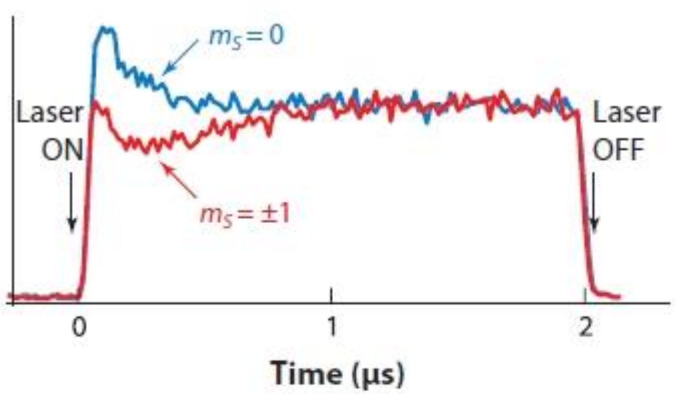

R. Schirhagl, K. Chang, M. Loretz, C. L. Degen, Annu. Rev. Phys. Chem. 2014. 65:83–105

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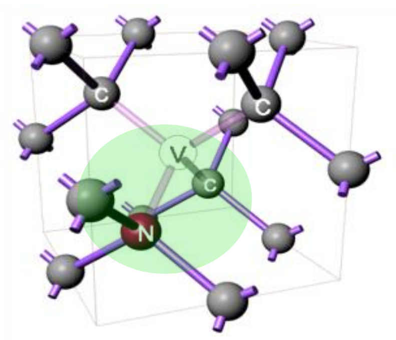
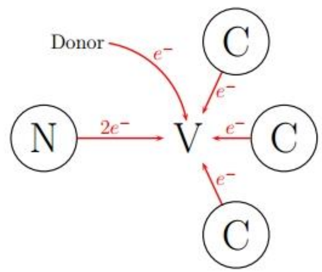
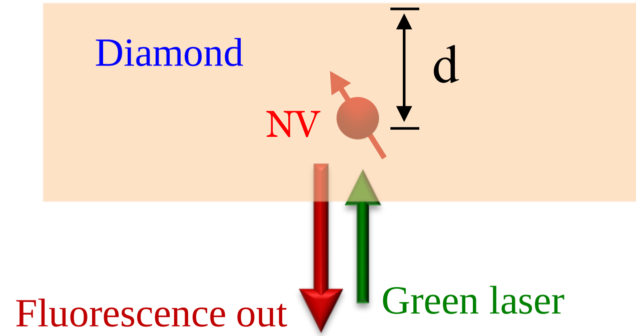
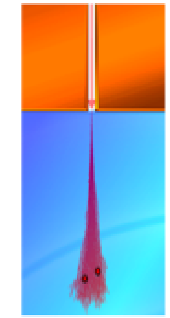
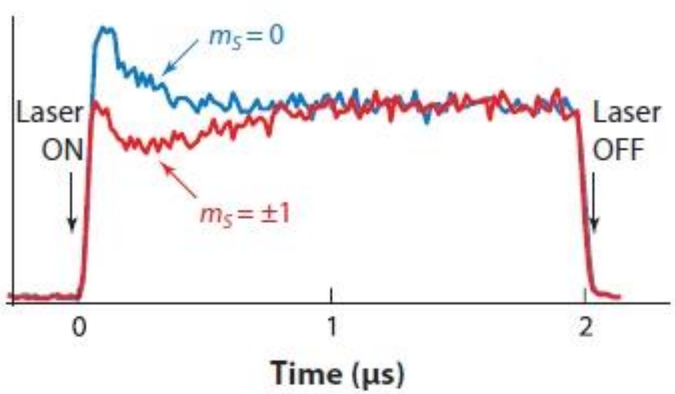


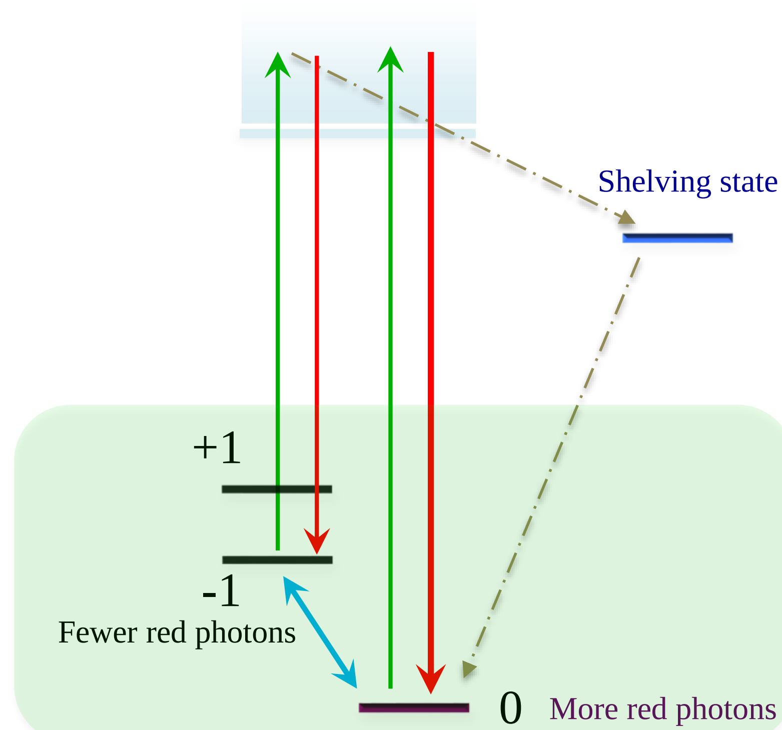






- Superior coherence property at room temperature
- Nano quantum system





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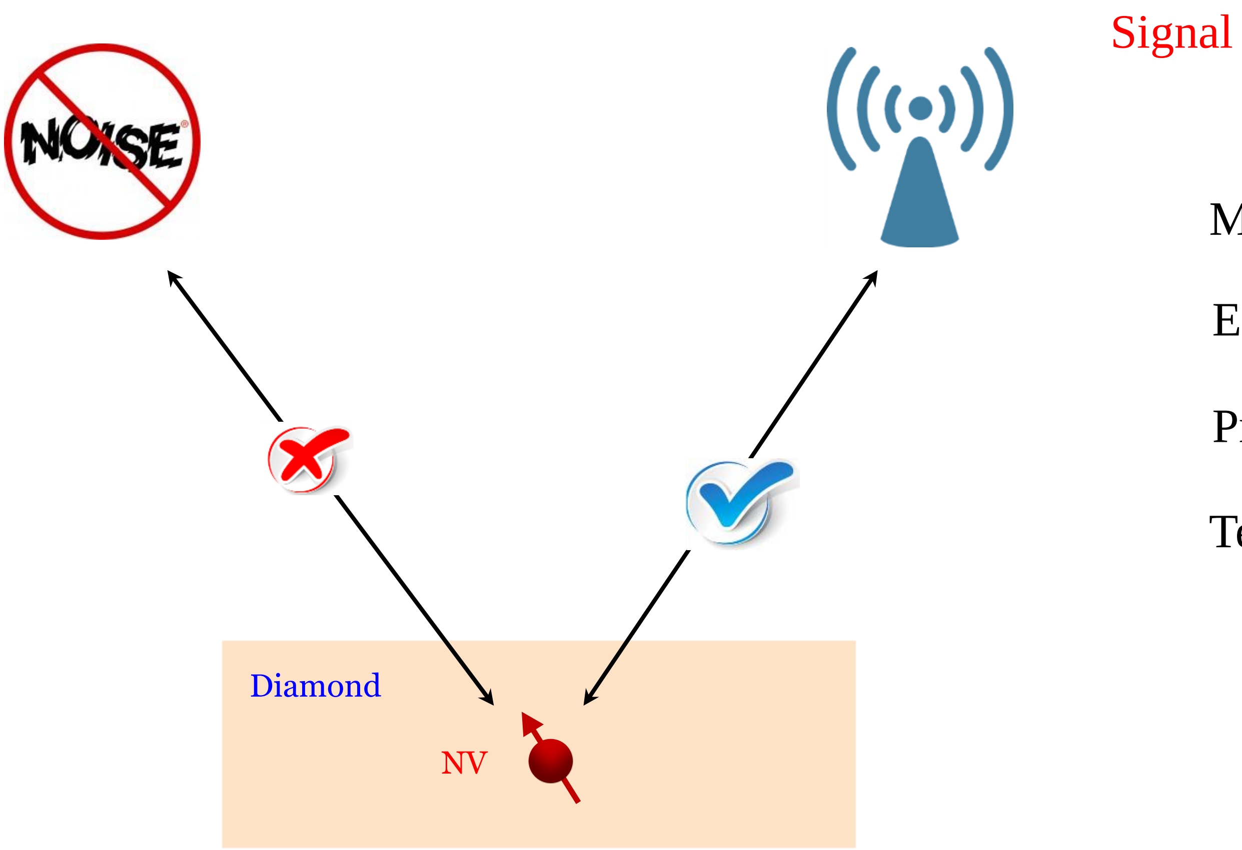
Nano-scale Diamond-based Quantum Sensing



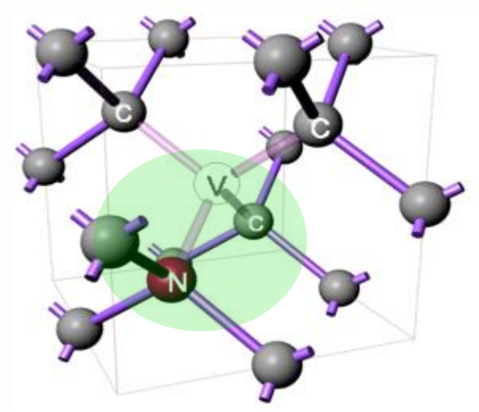
Magnetic field

Electric field

Pressure

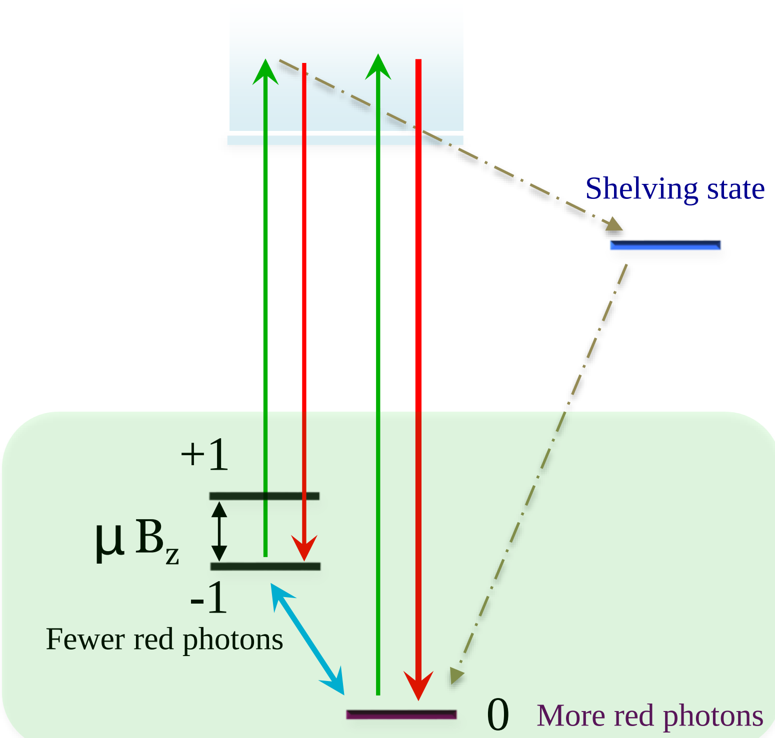
Temperature

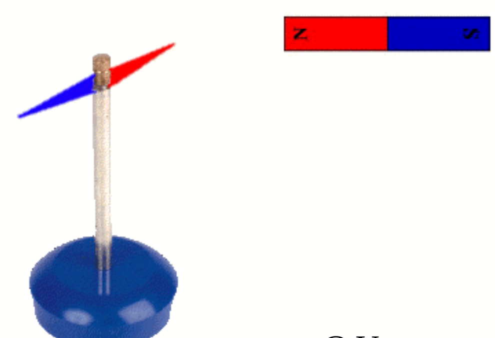
Hybrid nanoscale diamond quantum sensor



Magnetic field: 2.8 MHz per Gauss

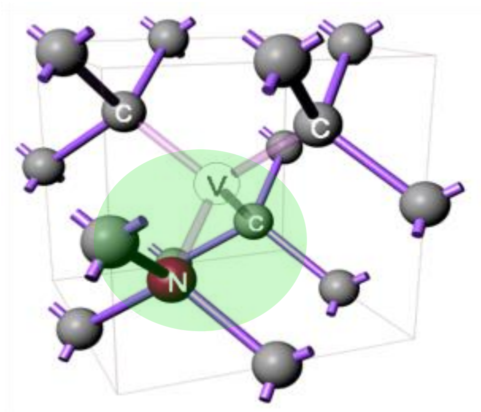
$$\hat{V}_{gs} = \mu_B g_{gs}^{\parallel} \hat{S}_z B_z + \mu_B g_{gs}^{\perp} \left(\hat{S}_x B_x + \hat{S}_y B_y\right) + \mu_N g_N \vec{I} \cdot \vec{B}$$
$$+ d_{gs}^{\parallel}(E_z + \delta_z)\left[\hat{S}_z^2 - S(S+1)/3\right] + d_{gs}^{\perp}(E_x + \delta_x)\left(\hat{S}_y^2 - \hat{S}_x^2\right)$$
$$+ d_{gs}^{\perp}(E_y + \delta_y)\left(\hat{S}_x \hat{S}_y + \hat{S}_y \hat{S}_x\right)$$





@ Varner

Hybrid nanoscale diamond quantum sensor



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$$
\begin{aligned}
\hat{V}_{gs} \;=\;& \underline{\mu_B g_{gs}^{\parallel} \hat{S}_z B_z + \mu_B g_{gs}^{\perp}\left(\hat{S}_x B_x + \hat{S}_y B_y\right)} + \mu_N g_N \vec{I}\cdot\vec{B} \\
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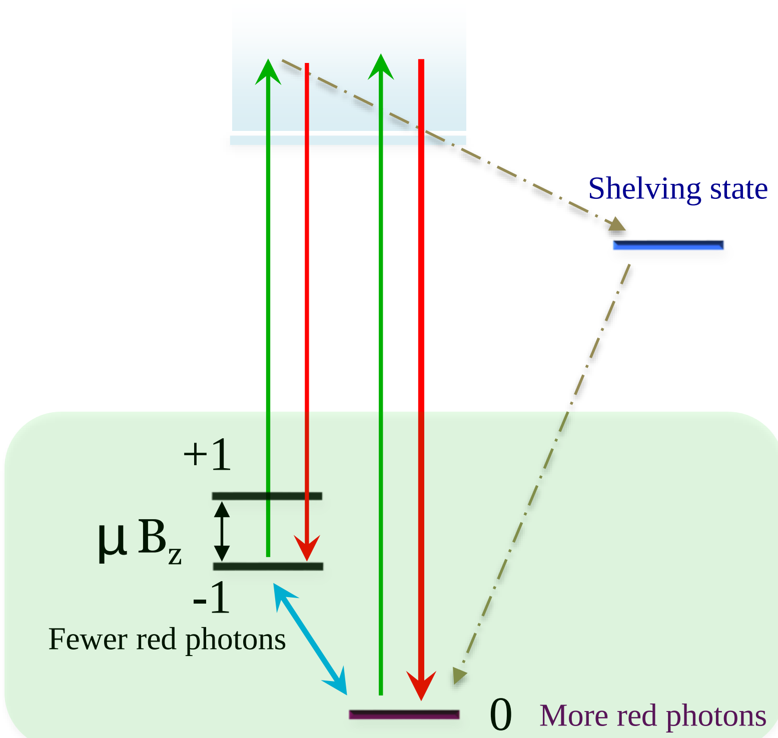
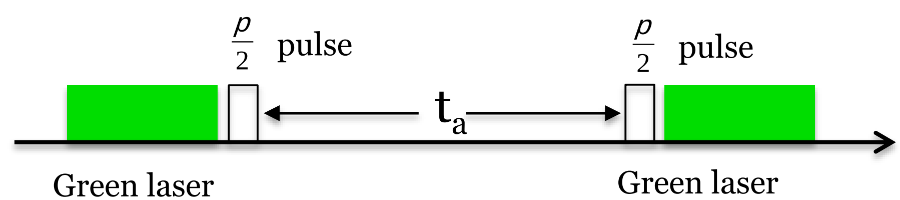
$$



Basic working principle

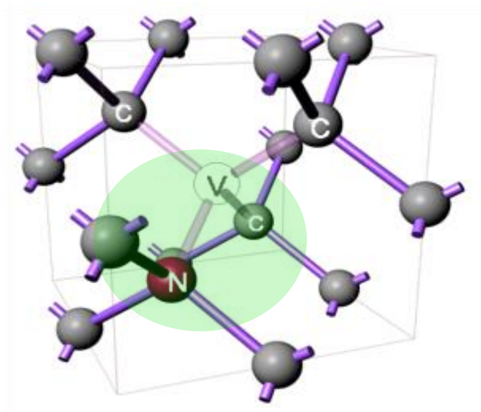


$$
\frac{1}{\sqrt{2}}\left(|-1\rangle + |+1\rangle\right) \longrightarrow \frac{1}{\sqrt{2}}\left(|-1\rangle + e^{i\theta}|+1\rangle\right)
$$

J. R. Maze, et al. Nature **455**, 644 (2008).

G. Balasubramanian, et al. Nature **455**, 648 (2008).

Hybrid nanoscale diamond quantum sensor



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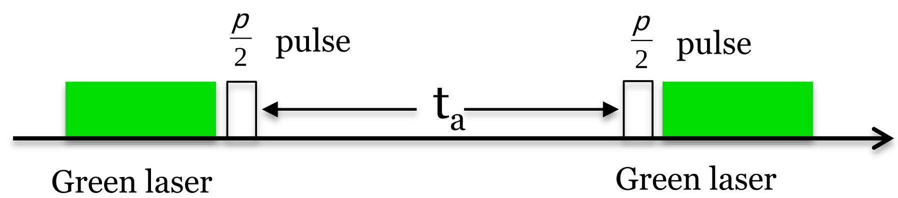

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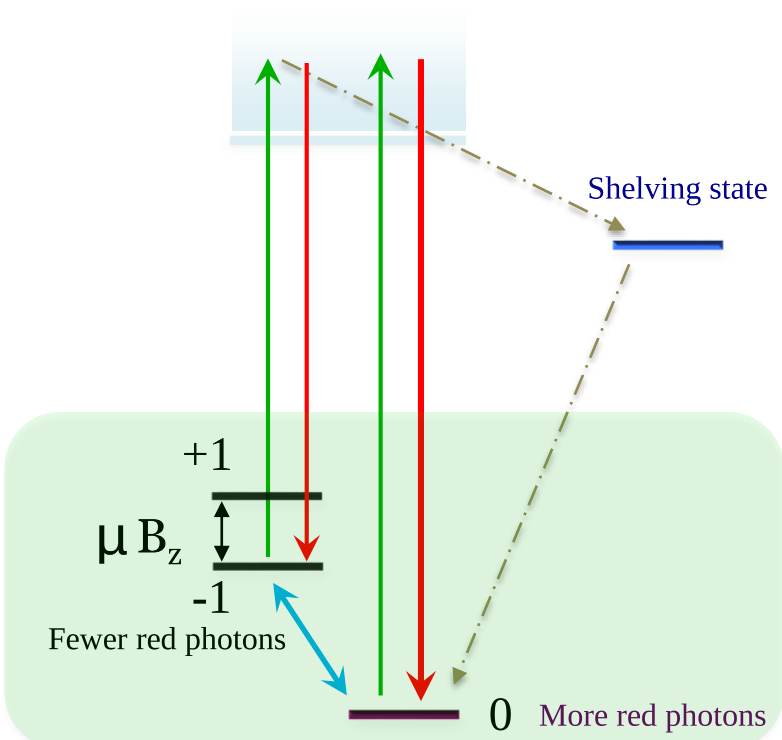

Magnetic field: 2.8 MHz per Gauss

Pressure : 15 kHz per MPa

Electric field/Strain: 0.35 - 17 Hz per (V/cm)

Temperature: 74kHz per K

E. van Oort, M. Glasbeek, Chem. Phys. Lett 168, 529 (1990)
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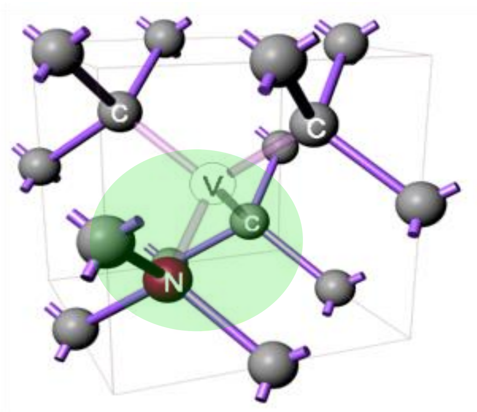

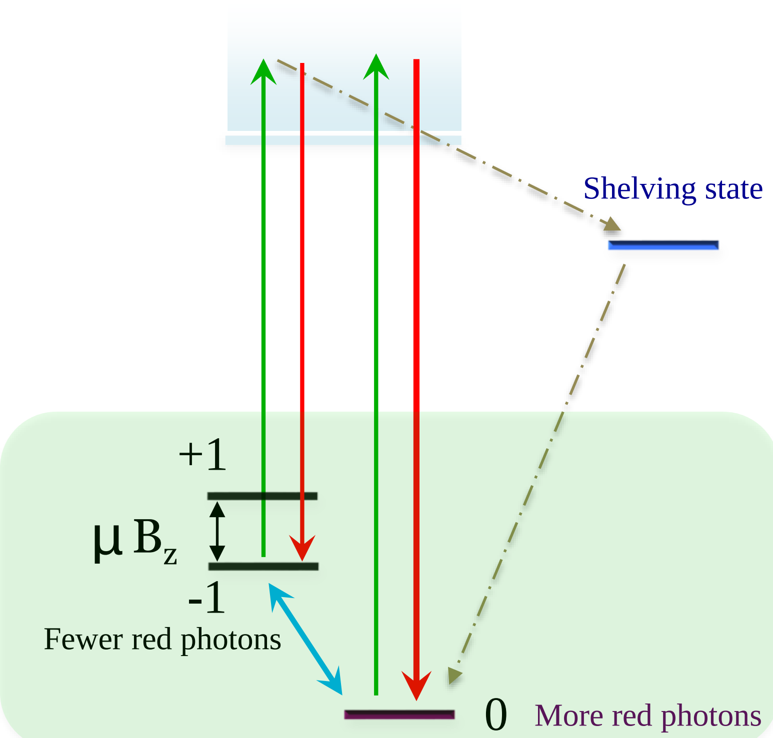

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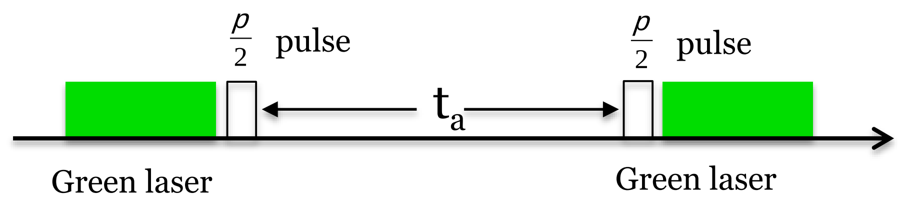

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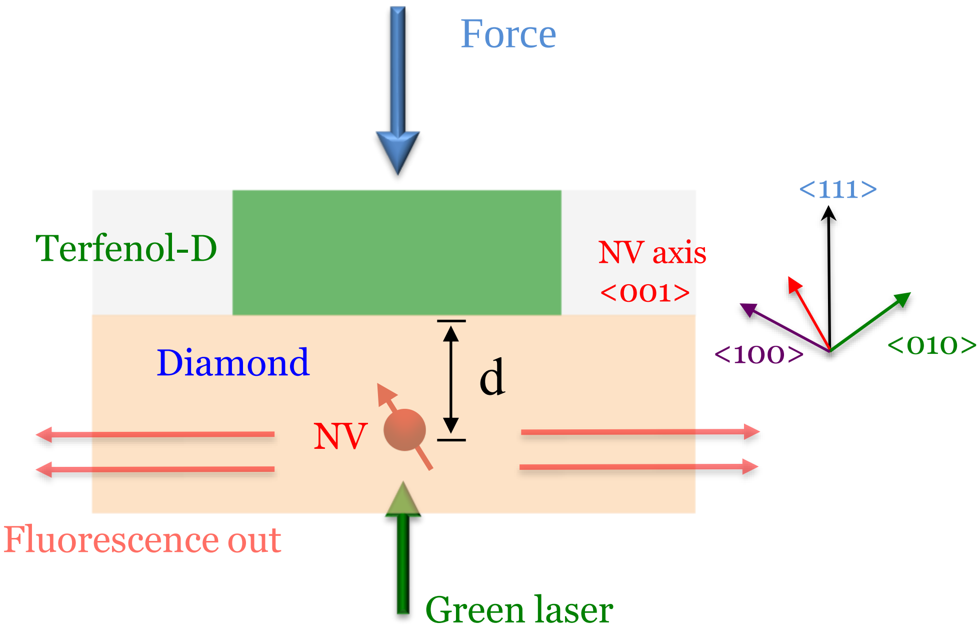
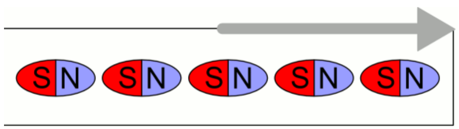


Magnetostriction

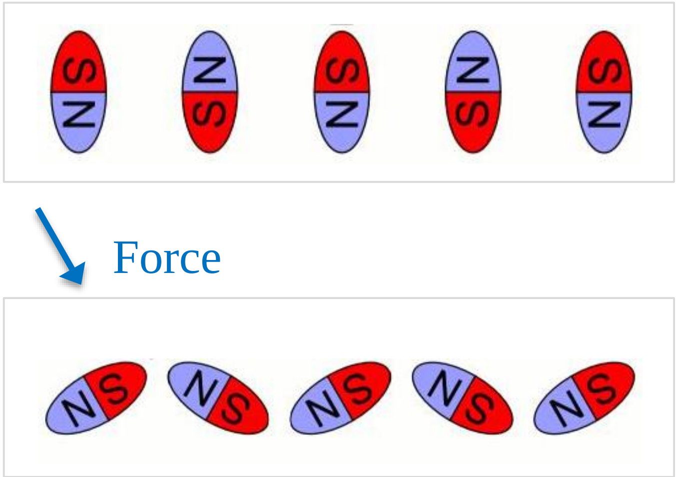


James Joule 1842

"Hard" + "Soft"

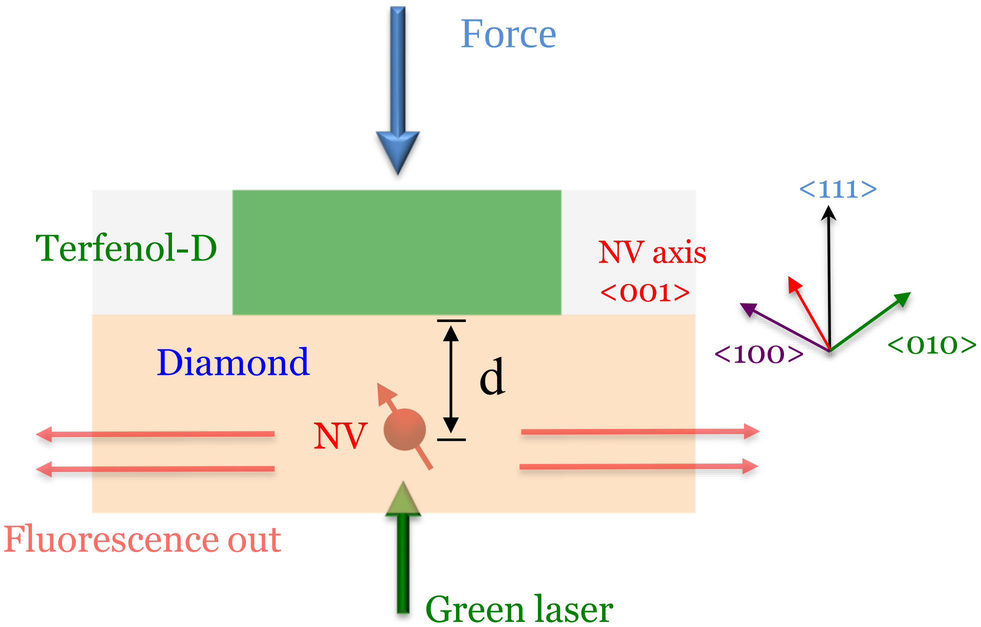
✓ Force induced deformation (magnetization)

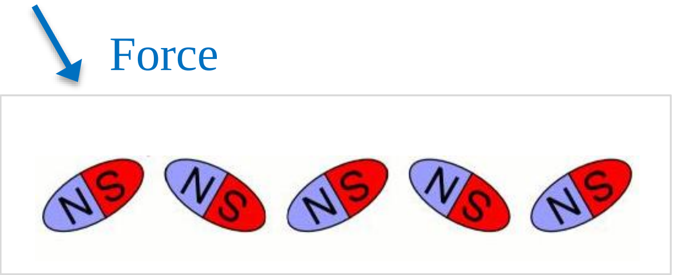
Inverse magnetostrictive effect



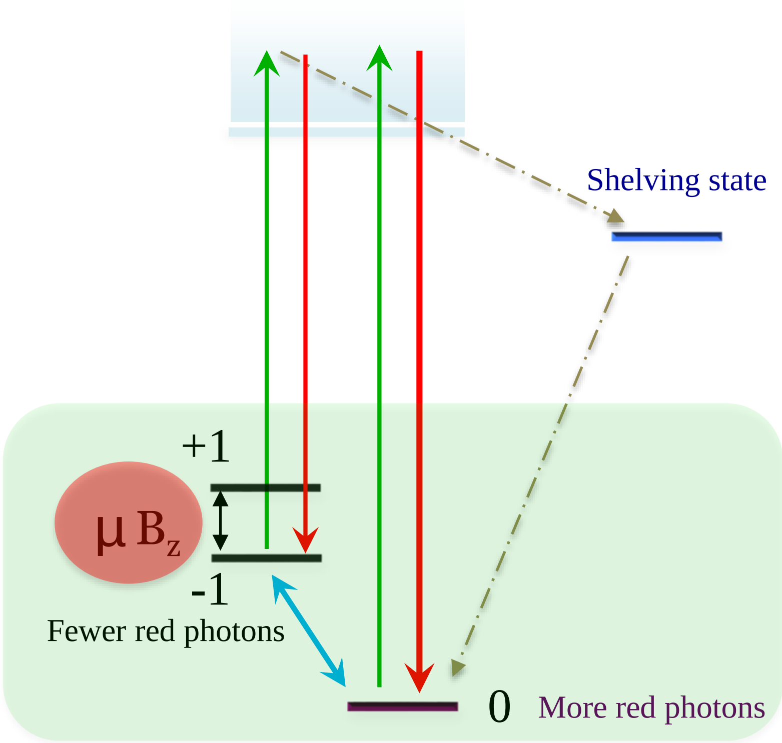
J.-M. Cai, F. Jelezko, M. Plenio, Nat. Comm. 5, 4065 (2014)

Hybrid nanoscale diamond quantum sensor





“Hard” + “Soft”



- ✓ Force induced deformation (magnetization)
- ✓ Stray magnetic field detected by the NV spin sensor

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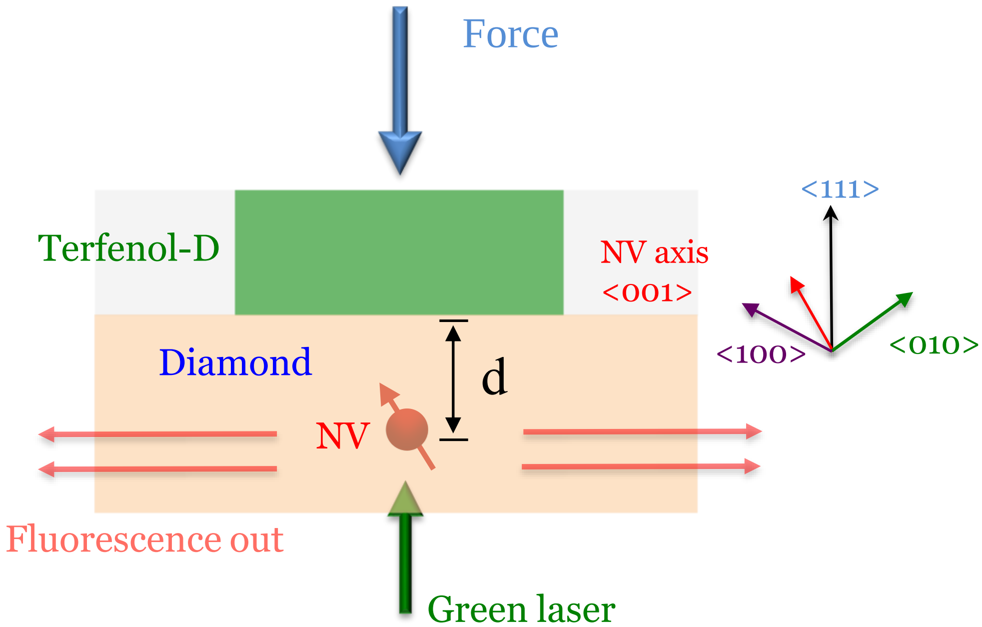
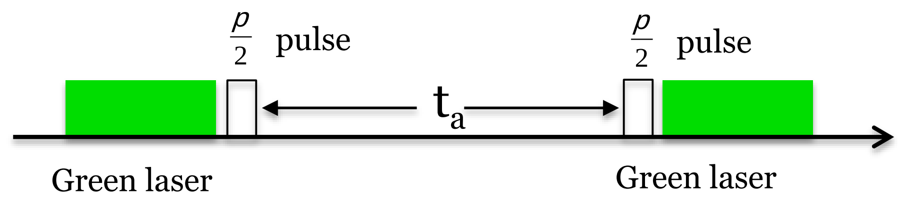
Hybrid nanoscale diamond quantum sensor





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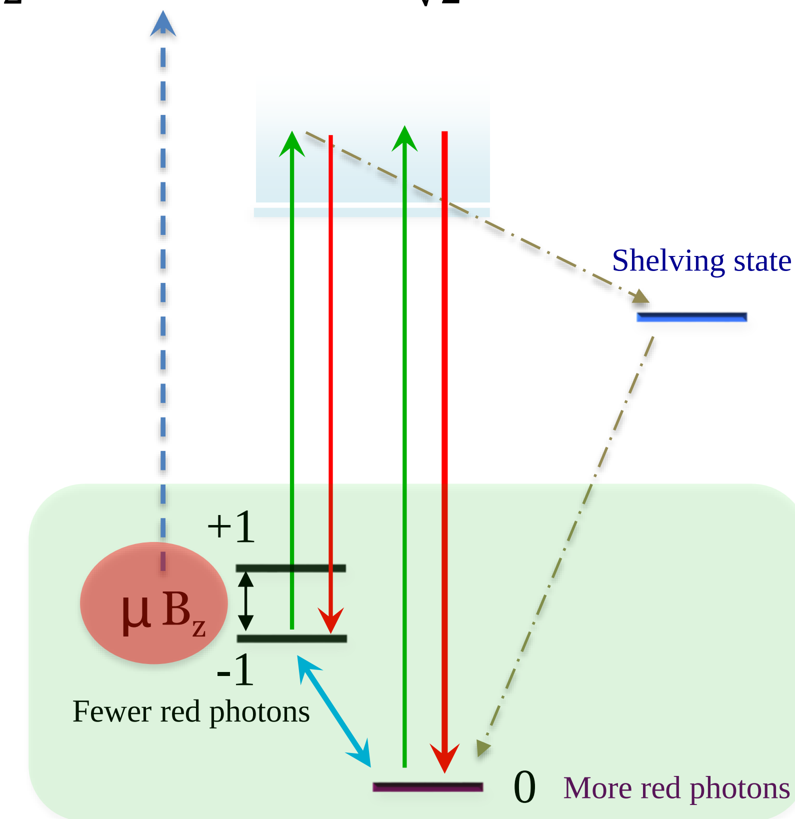

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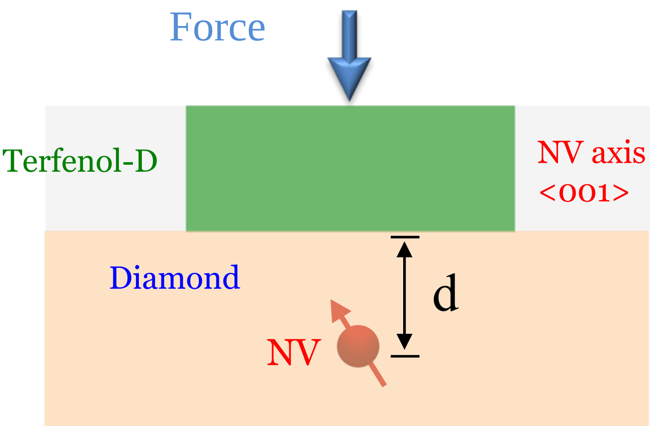
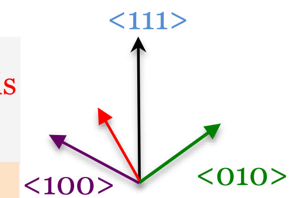
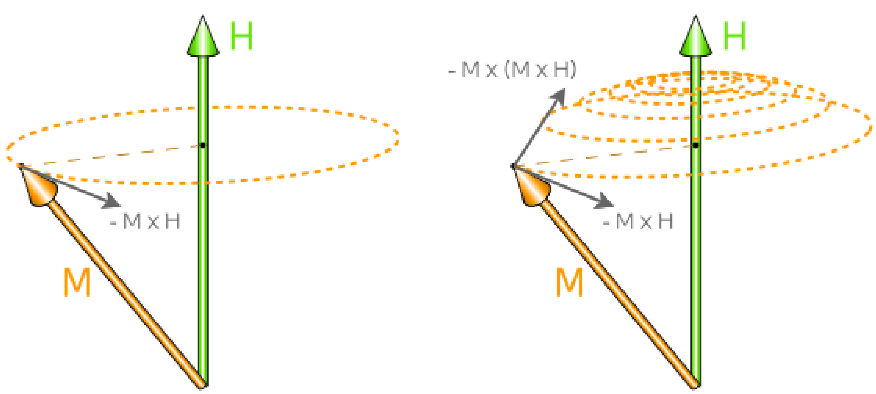
Hybrid nanoscale diamond quantum sensor





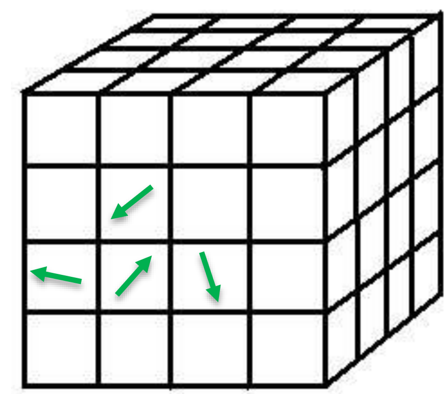
Damped procession & fluctuation



Micromagnetic simulation

Landau-Lifshitz-Gilbert (LLG) equation

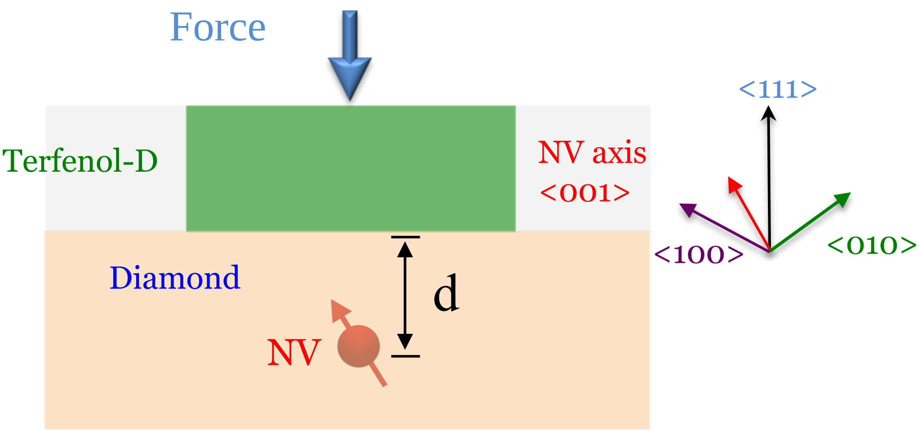
$$\frac{d\mathbf{M}_k}{d\tau} = -\gamma \mathbf{M}_k \times \mathbf{H}_k - \frac{\gamma \alpha_d}{M_S} \mathbf{M}_k \times (\mathbf{M}_k \times \mathbf{H}_k)$$



- Effective magnetic field

$$\mathbf{H}_k = -\frac{1}{\mu_0} \frac{\partial \mathbf{E}}{\partial \mathbf{M}_k}$$

Hybrid nanoscale diamond quantum sensor



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- Effective magnetic field

$$\mathbf{H}_k = -\frac{1}{\mu_0} \frac{\partial \mathbf{E}}{\partial \mathbf{M}_k}$$

- Free energy

  Magnetoelastic energy

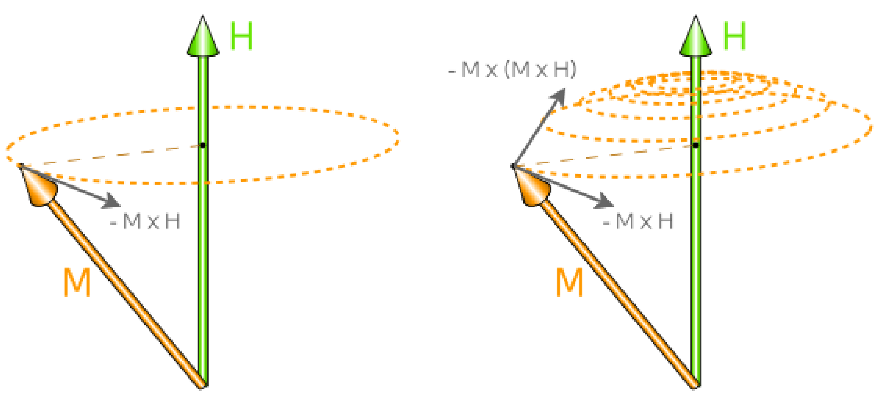
  Exchange energy

  Magnetocrystalline anisotropy energy

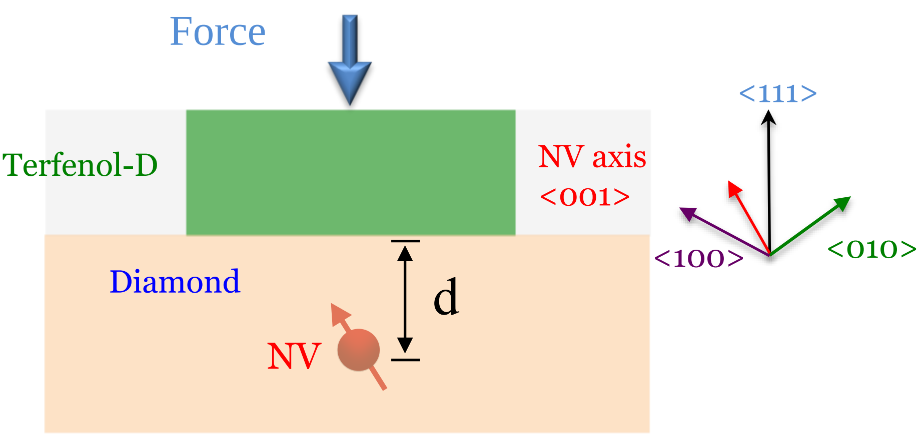
  Magnetostatic energy

  Zeeman energy

Damped procession



Hybrid nanoscale diamond quantum sensor



Magnetoelastic energy

$$\mathbf{E}_{me} = \sigma \int \{ -\frac{3}{2}\lambda_{100} \sum_{i=1}^{3} \beta_i^2 \theta_i^2 - \frac{3}{2}\lambda_{111} \sum_{i,j=1; i\neq j}^{3} \beta_i \beta_j \theta_i \theta_j \} d^3 r$$

Stress (σ)

Domain magnetization (β_i)

Stress direction (θ_i)

Micromagnetic simulation

Landau-Lifshitz-Gilbert (LLG) equation

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- Effective magnetic field

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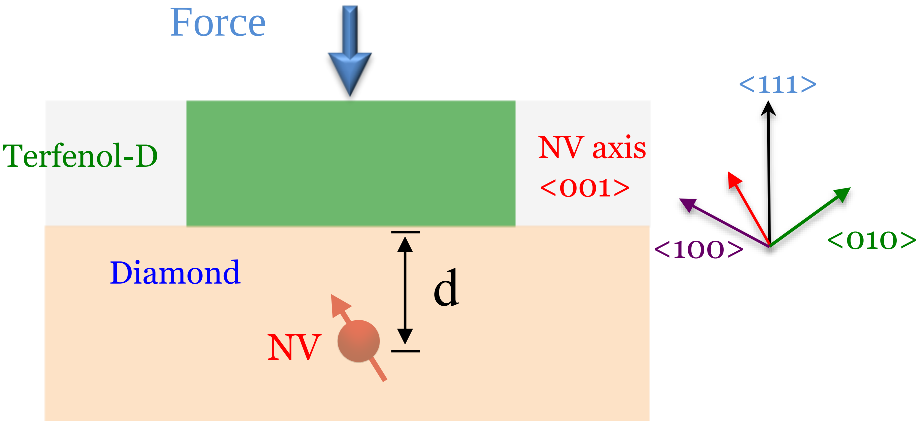
Hybrid nanoscale diamond quantum sensor



Micromagnetic simulation

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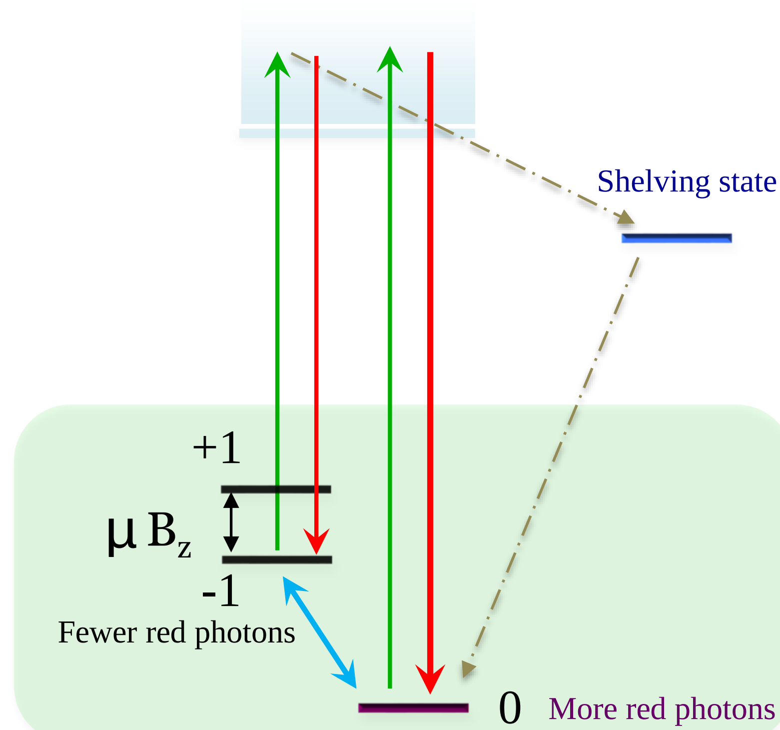
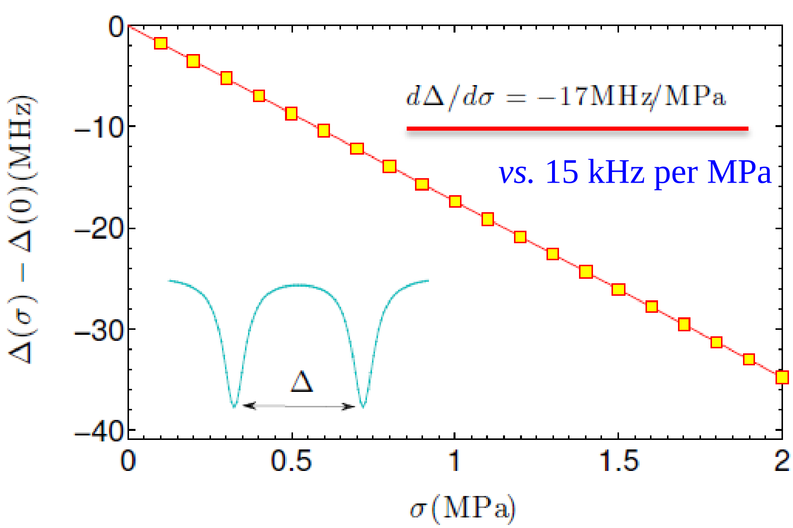
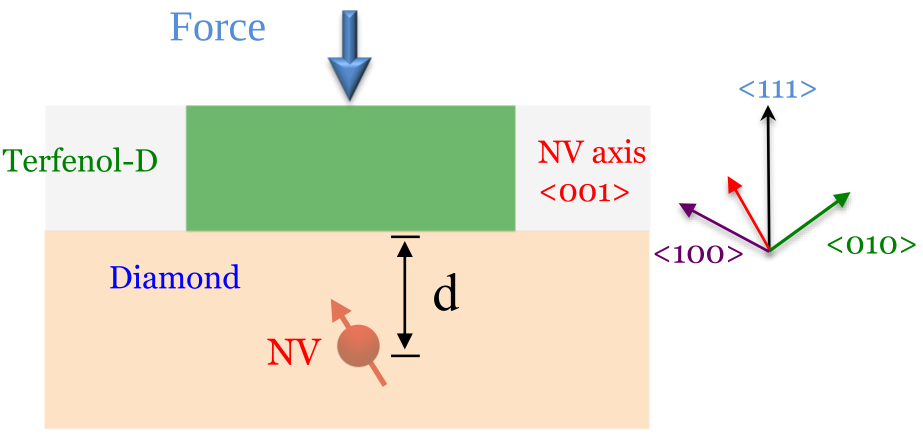


Frequency shift



Hybrid nanoscale diamond quantum sensor



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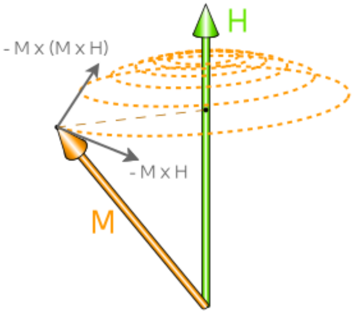
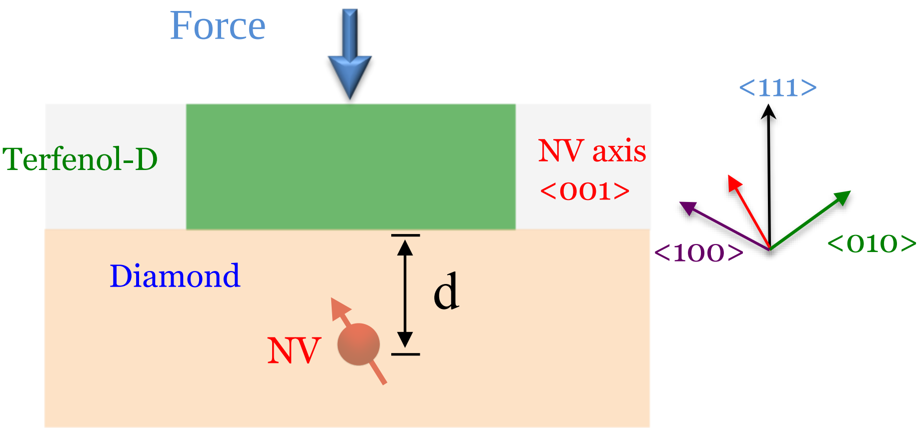
Thermal fluctuation

$$\mathbf{H}_{th}^{m,i}(t) = \underline{\kappa^{m,i}(t)} \left(\frac{2\alpha_d k_B T_m}{\gamma \mu_0 M_S \Delta x^3 \Delta t} \right)^{1/2}$$

Gaussian random noise

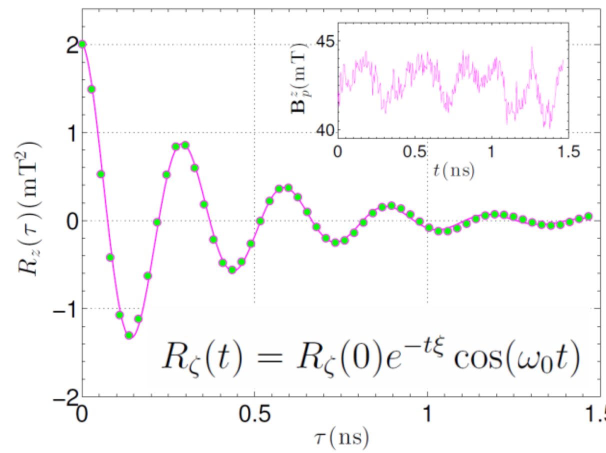


Hybrid nanoscale diamond quantum sensor



Magnetic noise autocorrelation

$$R_\zeta(t) = \langle B_\zeta(t) B_\zeta(0)\rangle - \langle B_\zeta(t)\rangle\langle B_\zeta(0)\rangle$$



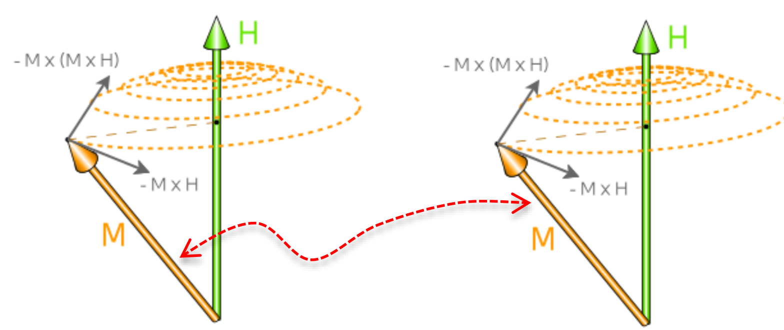
Landau-Lifshitz-Gilbert (LLG) equation

$$\frac{d\mathbf{M}_k}{d\tau} = -\gamma \mathbf{M}_k \times \mathbf{H}_k - \frac{\gamma \alpha_d}{M_S} \mathbf{M}_k \times (\mathbf{M}_k \times \mathbf{H}_k)$$

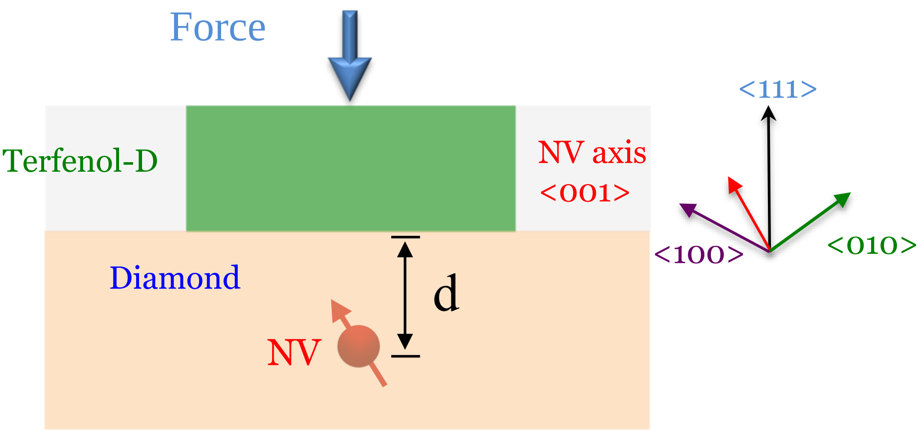
Thermal fluctuation

$$\mathbf{H}_{th}^{m,i}(t) = \underline{\kappa^{m,i}(t)} \left(\frac{2\alpha_d k_B T_m}{\gamma \mu_0 M_S \Delta x^3 \Delta t} \right)^{1/2}$$

Gaussian random noise



Hybrid nanoscale diamond quantum sensor



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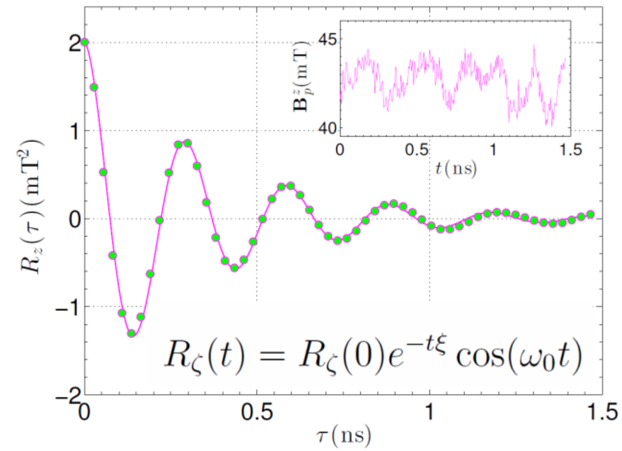
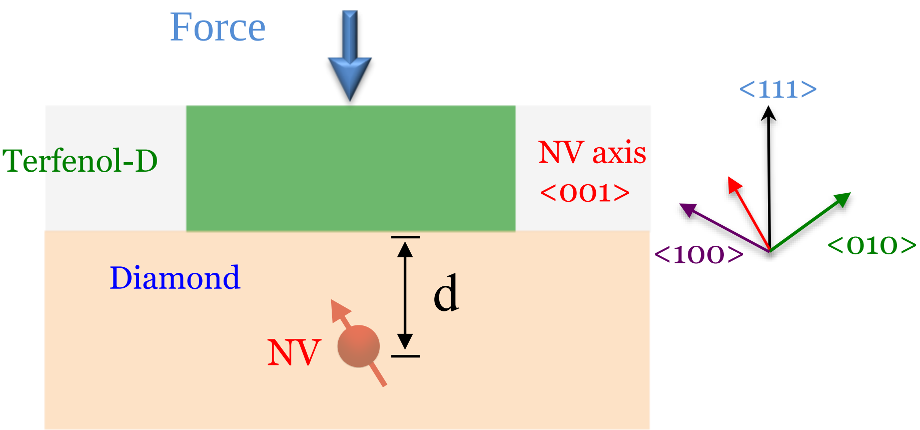


Noise power spectrum

$$\mathcal{S}_\zeta(\omega) = \frac{R_\zeta(0)}{2} \left[\frac{\xi}{\xi^2 + (\omega - \omega_0)^2} + \frac{\xi}{\xi^2 + (\omega + \omega_0)^2} \right]$$

Hybrid nanoscale diamond quantum sensor



Influence of surface defects

Defect

$$H_{NV-dm} = \sum_k \sum_{\alpha,\beta=x,y,z} a_k^{\alpha\beta} \mathbf{S}_\alpha \mathbf{s}_\beta^k$$

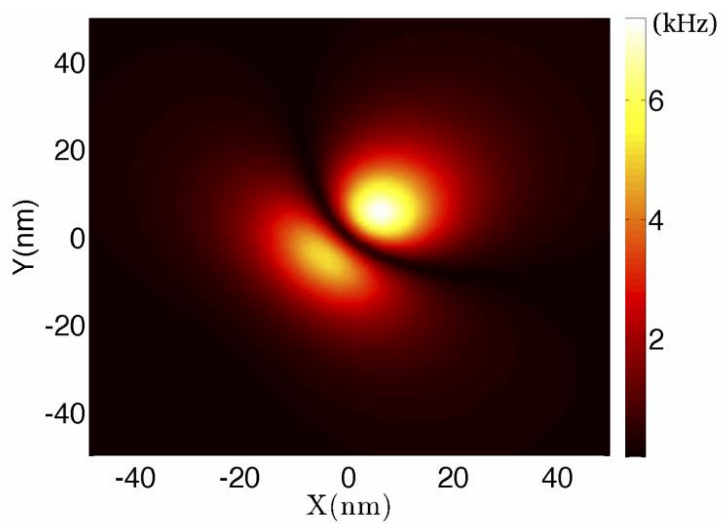
NV spin

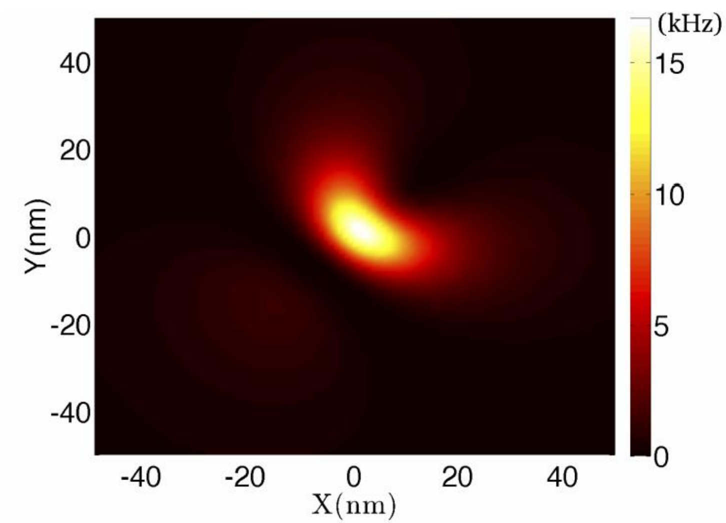
Defect densitiy

$$\rho_d = 10^{13}\mathrm{cm}^{-2}$$

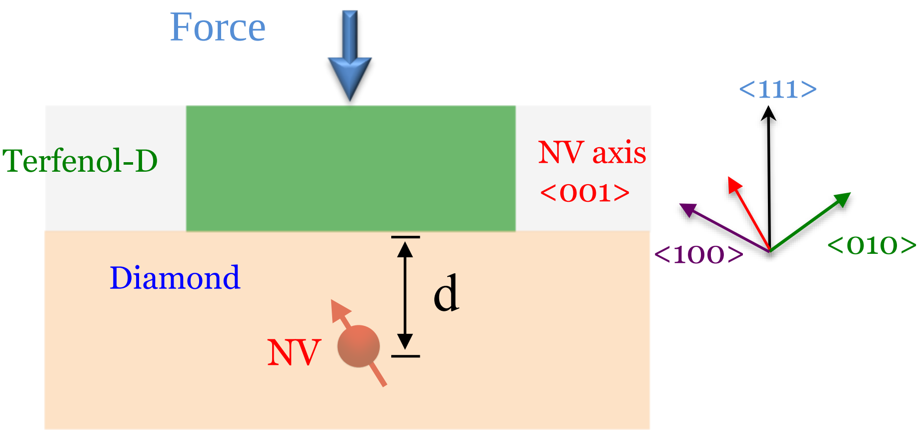
$$\Delta \mathbf{B}_z = \langle \delta \mathbf{B}_z^2 \rangle^{1/2} = \left[\sum_k \left(\frac{\mu_0 \mu_d}{8\pi r_k^3} \right)^2 \left(3\cos^2\theta_k - 1\right)^2 \right]^{1/2}$$

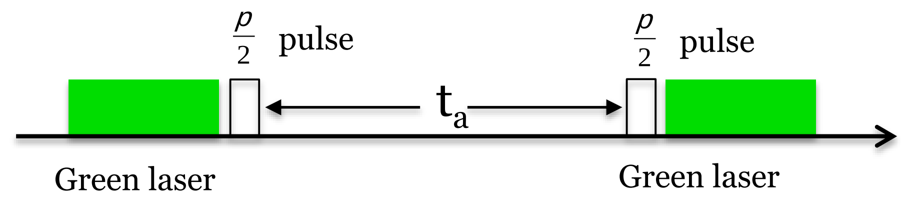
$$\Delta \mathbf{B}_\perp = \langle \delta \mathbf{B}_\perp^2 \rangle^{1/2} = \left[\sum_k 9 \left(\frac{\mu_0 \mu_d}{8\pi r_k^3} \right)^2 \cos^2\theta_k \left(1 - \cos^2\theta_k\right) \right]^{1/2}$$





Hybrid nanoscale diamond quantum sensor





$$\frac{1}{\sqrt{2}}(|-1\rangle + |+1\rangle) \rightarrow \frac{1}{\sqrt{2}}(|-1\rangle + e^{i\theta}|+1\rangle)$$

Open system dynamics of the spin sensor:

$$\frac{d\rho}{dt} = -i[H,\rho] + \mathcal{S}_z(0)\mathcal{L}^\rho(s_z) + \sum_{\kappa=\pm1} \mathcal{S}_\perp(\omega_\kappa)\mathcal{L}^\rho(s_{0\kappa})$$

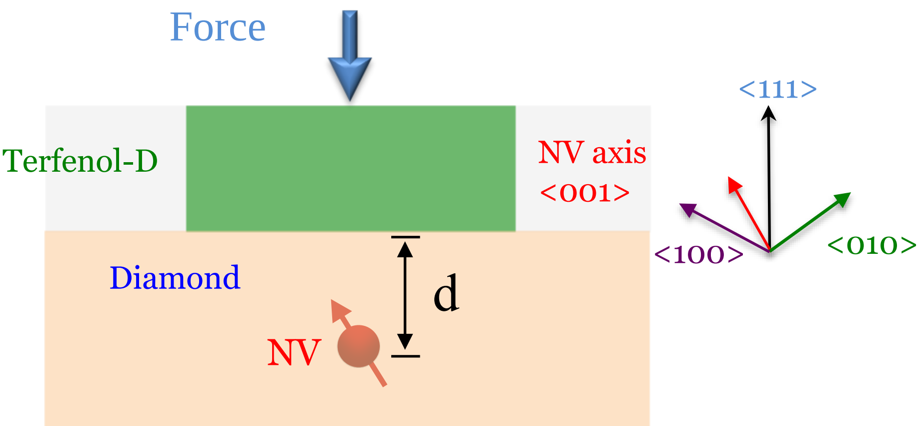
Signal: solution

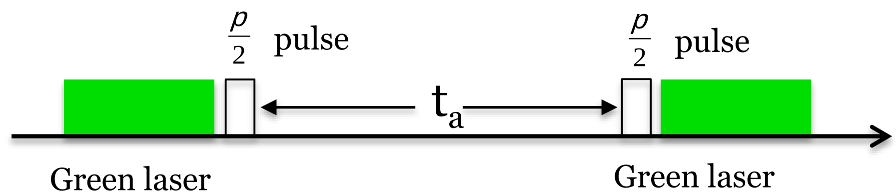
$$P(\sigma, t_a) = \frac{1}{8}\left[3 + \underline{\chi_\perp^2(t_a)}\right] + \frac{1}{2}\cos\left[2\pi\Delta(\sigma)\,t_a\right]\underline{\chi_\perp(t_a)\chi_\parallel(t_a)}.$$

Shot-noise limited sensitivity:

$$\eta_{\sigma,t_a,\tau} = \frac{\sqrt{(3+\chi_\perp^2(t_a))(5-\chi_\perp^2(t_a))}}{8\pi\mathcal{C}\chi_\perp(t_a)\chi_\parallel(t_a)t_a\left(\frac{d\Delta}{d\sigma}\right)}\sqrt{\frac{t_a+t_p}{T}}$$

Hybrid nanoscale diamond quantum sensor





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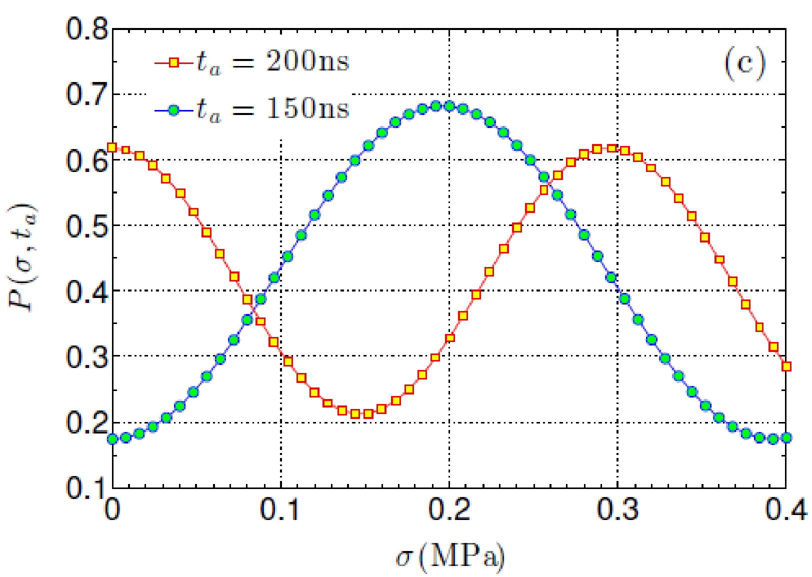
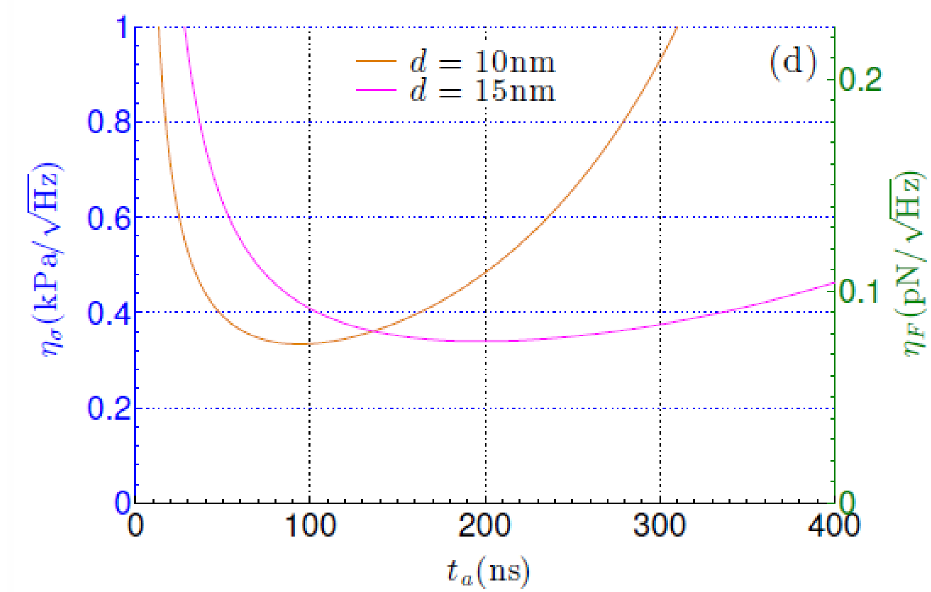
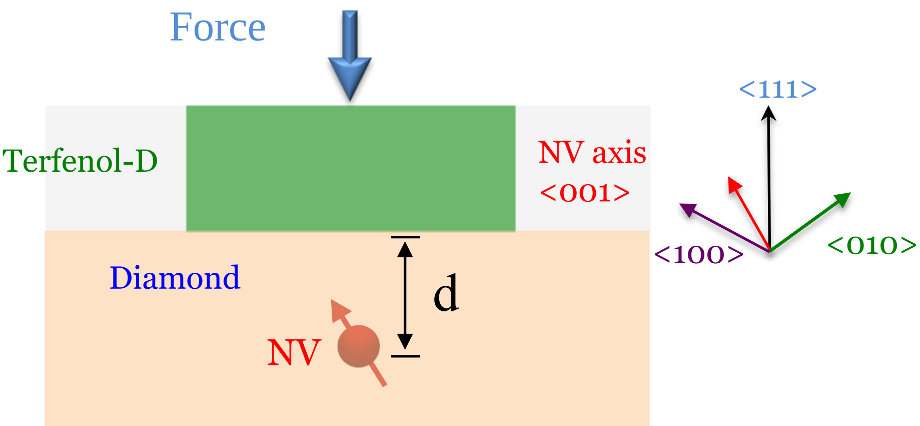
Measurement signal

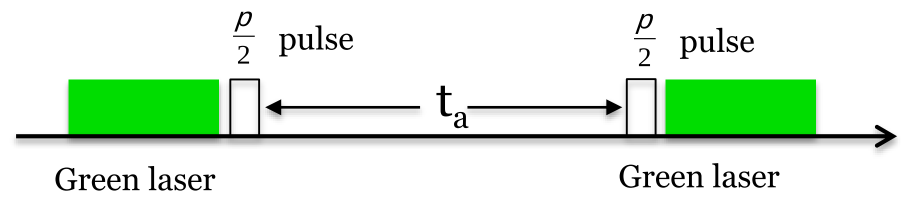


Shot-noise limited sensitivity:



Hybrid nanoscale diamond quantum sensor





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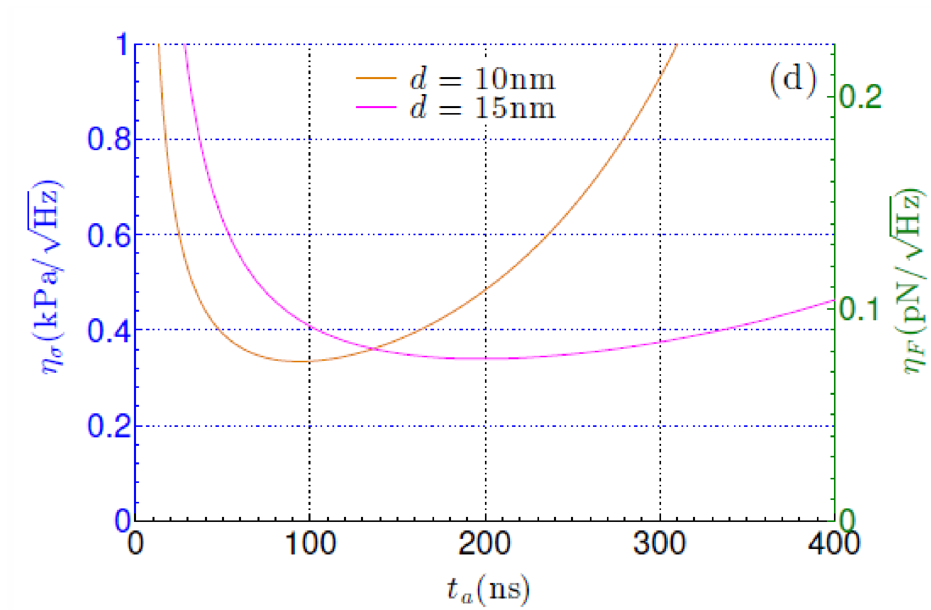
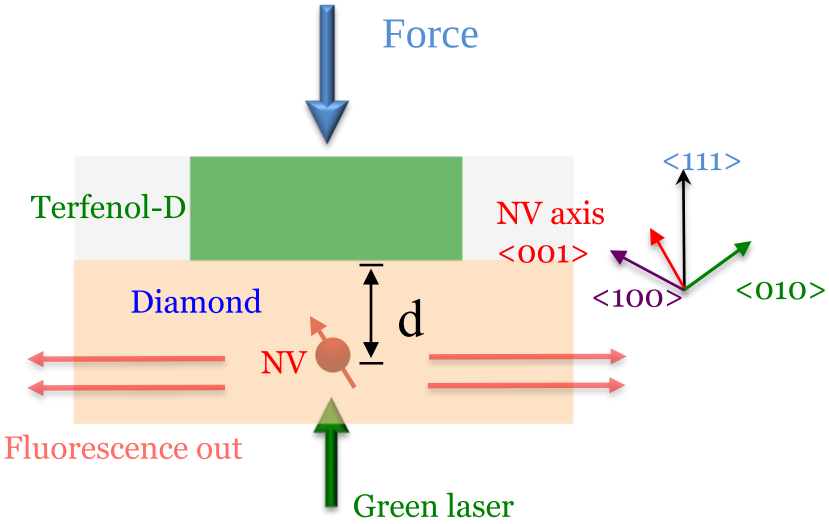


- Similar sensitivity as AFM and optical tweezers
- Scalable and portable
- Nano-scale quantum sensor
- Hybrid electric field and temperature sensor

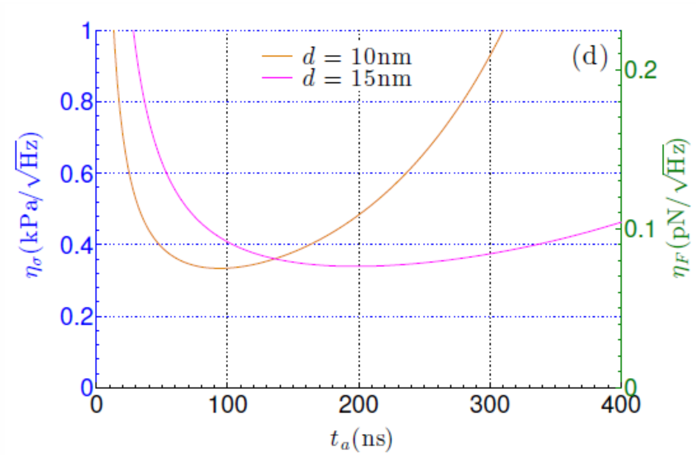
Summary

Hybrid nanoscale diamond quantum sensor

- Design & Working principle



- Sensitivity analysis



- Potential applications

J.-M. Cai, F. Jelezko, M. Plenio, Nat. Comm. 5, 4065 (2014)

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