SWISS CONTRIBUTION

AGH

FMR and standing spin waves in multifferroics

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Polish-Swiss Research Programme

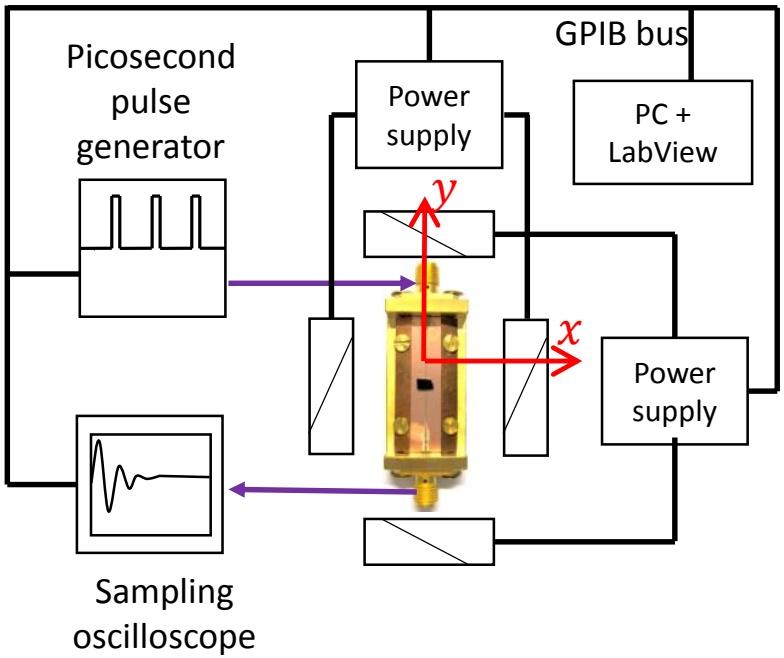
NANOSPIN

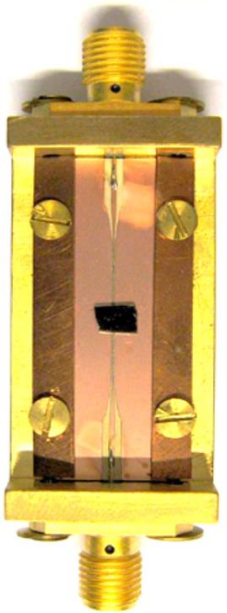
Outline

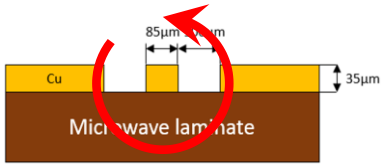
- Magnetization dynamics in ferromagnetic thin film and patterned nanostructures
  - Pulse Inductive Microwave Magnetometry (PIMM)
  - Vector/Scalar Networ Analyser (VNA)
  - Electrical rectification in microstrpis - spin diode effect (SD)
    - Ferromagnetic Resonance (FMR)
    - Standing Spin Waves (SSW)

- Voltage control of magnetic anisotorpy and magnetization dynamics in PMN-PT/NiFe multiferroic heteostructures
  - Voltage control of magnetic anisotropy in PMN-PT/NiFe thin film
  - Voltage control of FMR and SSW in PMN-PT/NiFe microstrips

Pulse Inductive Microwave Magnetometry







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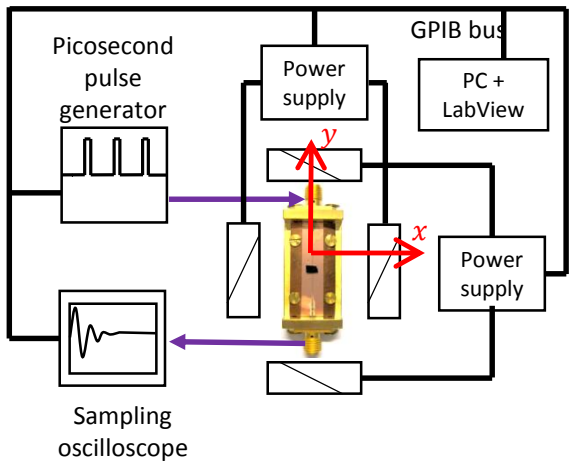
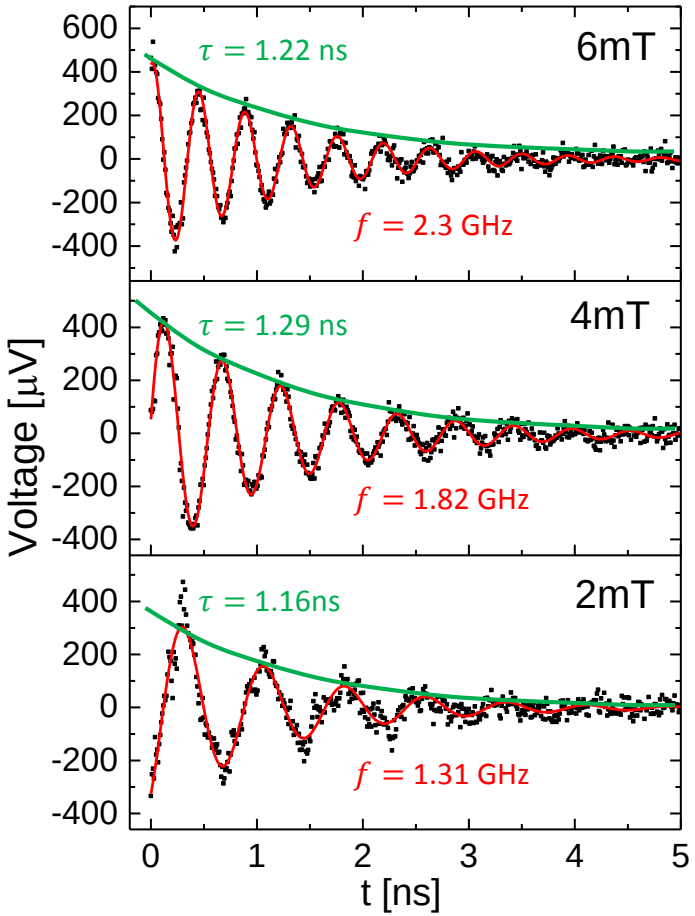
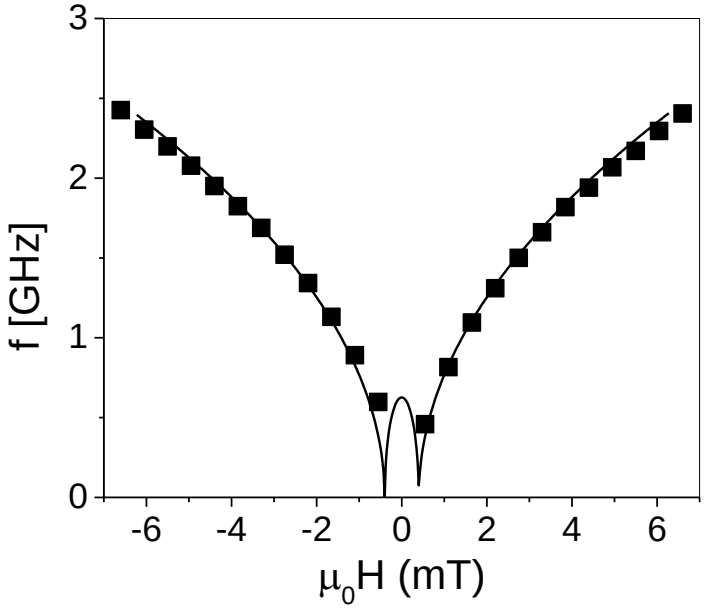
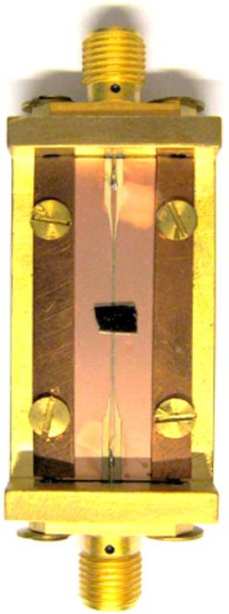


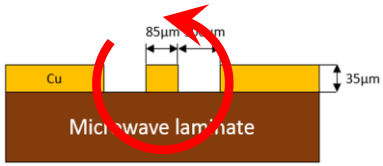
$$\alpha = \frac{2}{\gamma \tau_0 \mu_0 M_S}$$



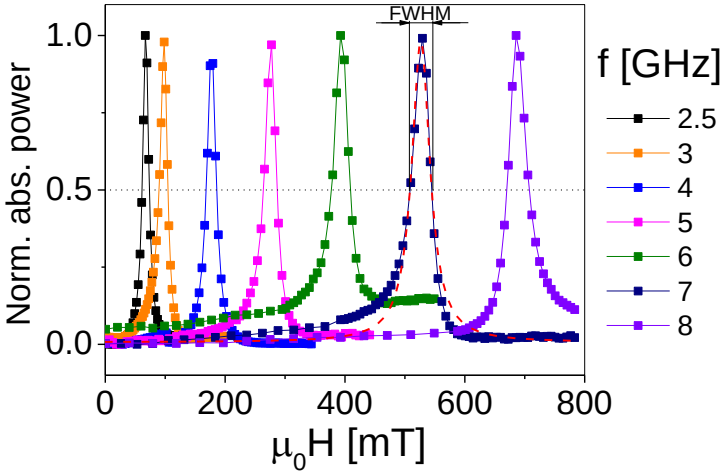


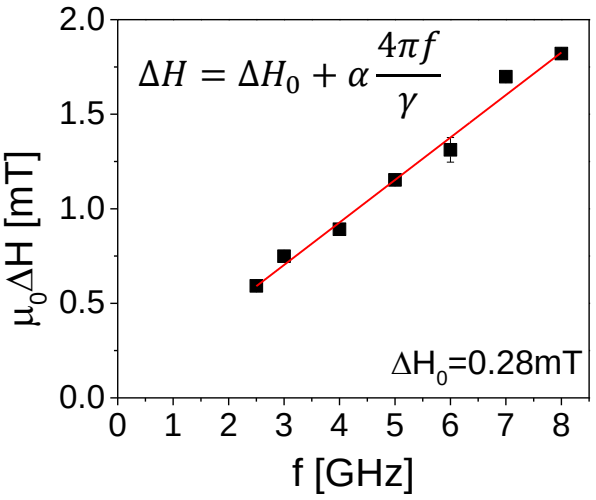
$$U(t) = U_0 + A \exp\left(\frac{-t}{\tau_0}\right) \sin(\omega t + \varphi)$$

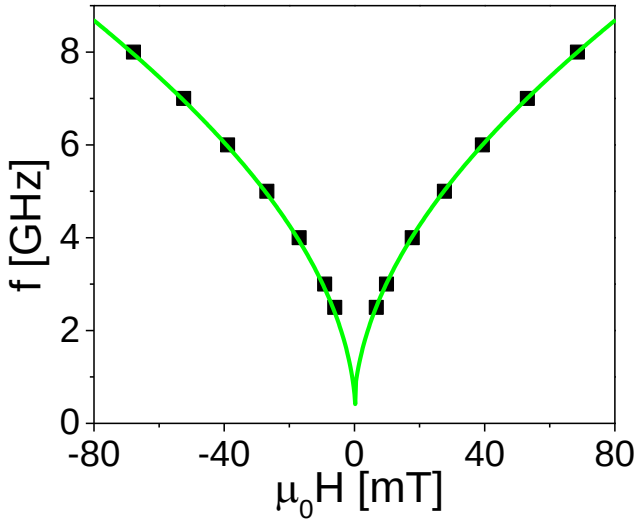


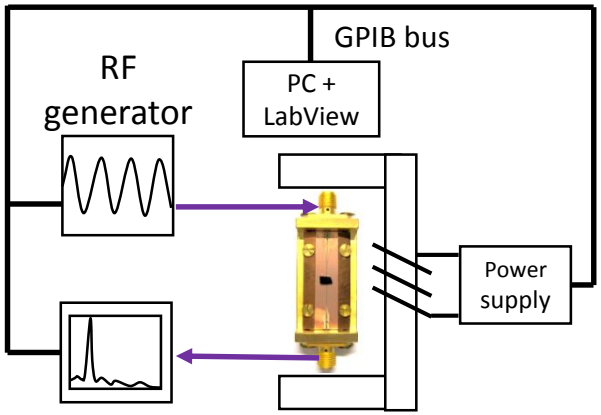


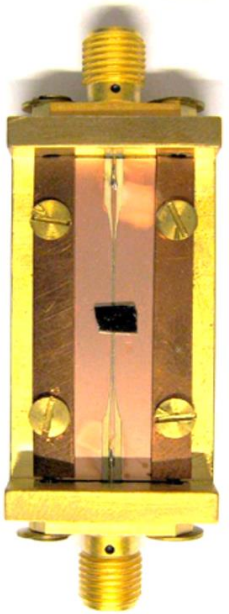
Vector/Scalar Networ Analyser

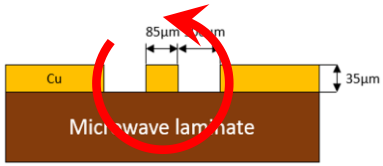




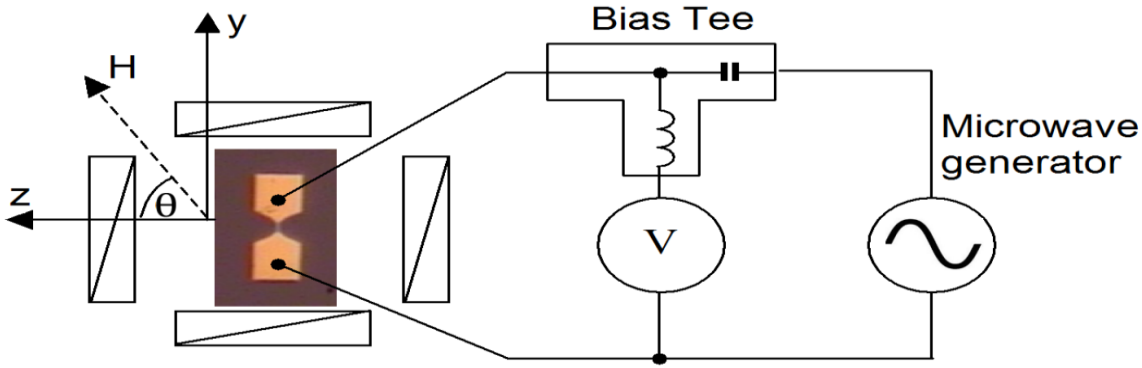








Oersted Field induced spin diode effect in NiFe micro-strips



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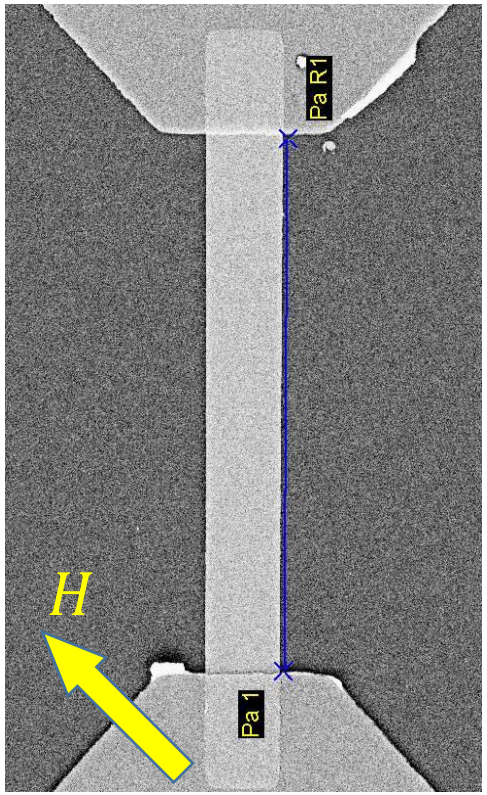
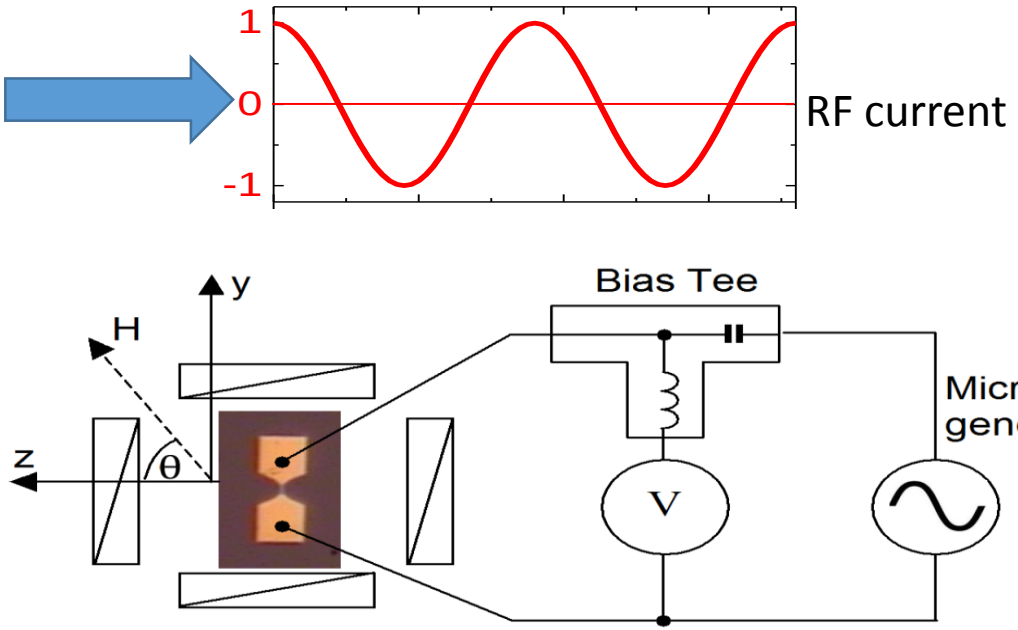
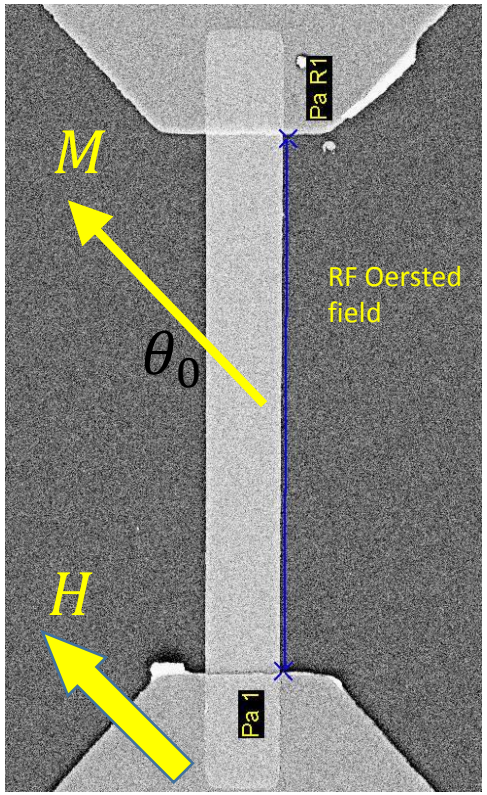
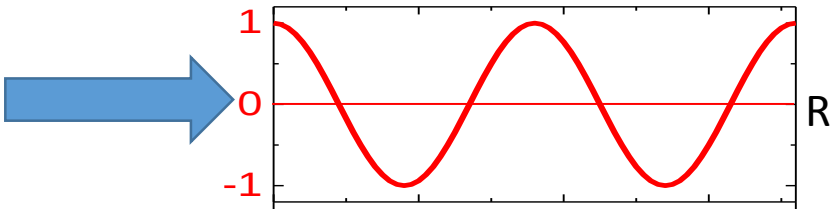


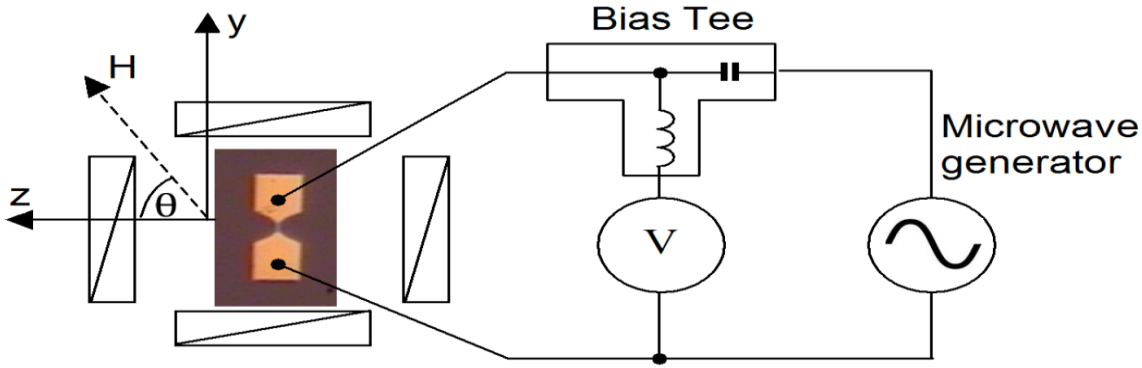


Oersted Field induced spin diode effect in NiFe micro-strips

Magnetization oscillation due to Oersted field







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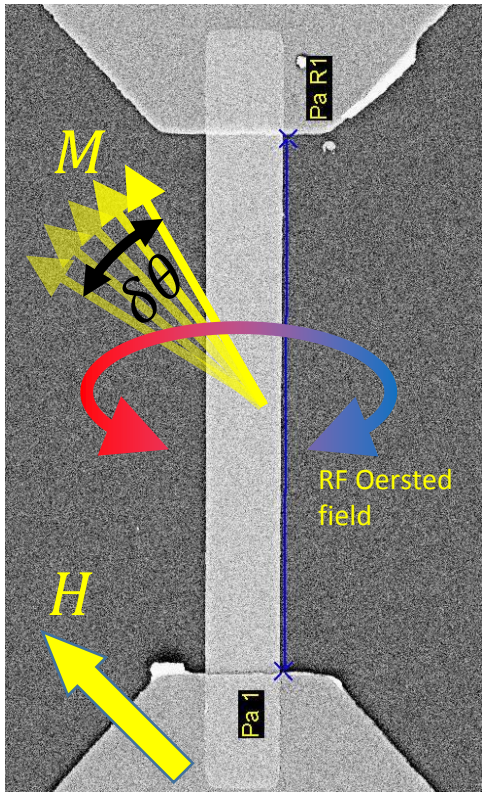

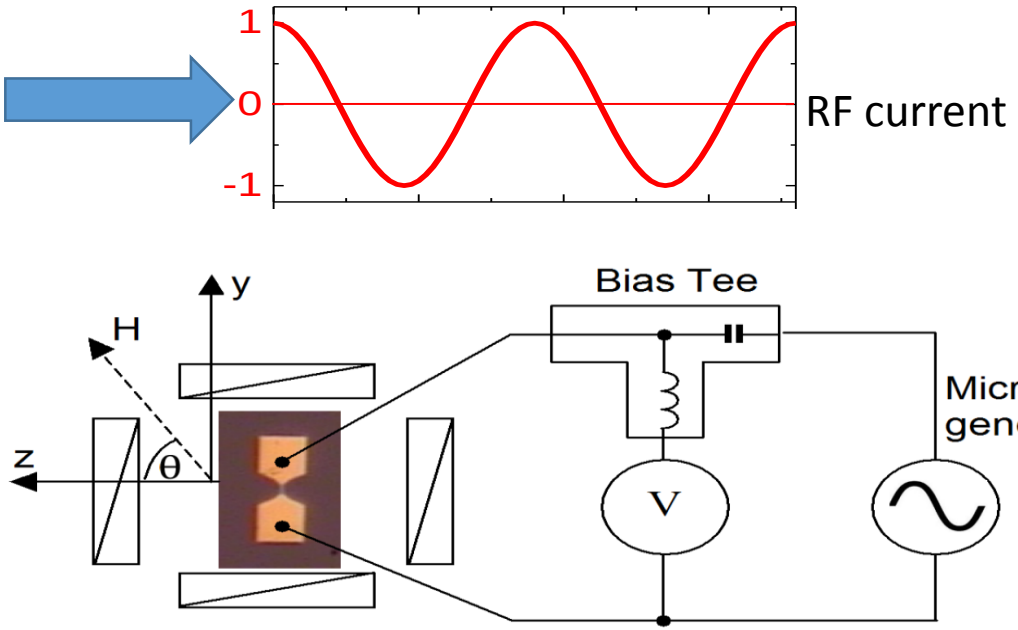

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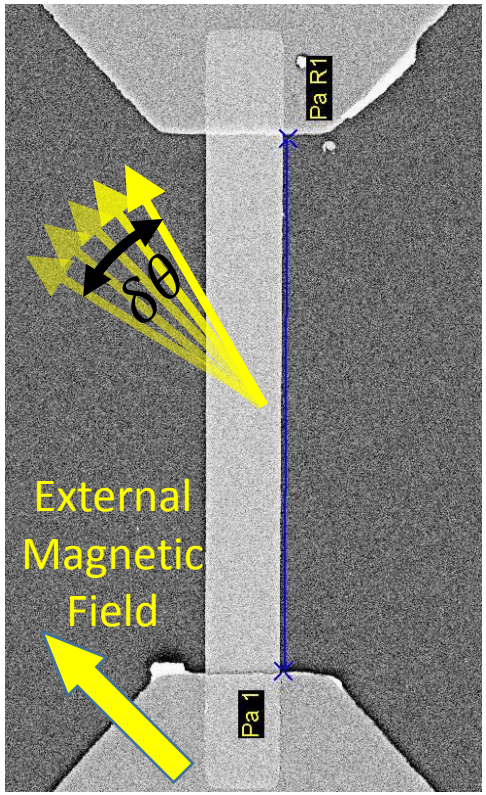

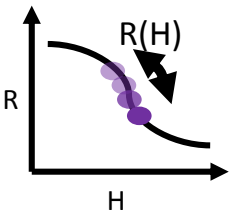

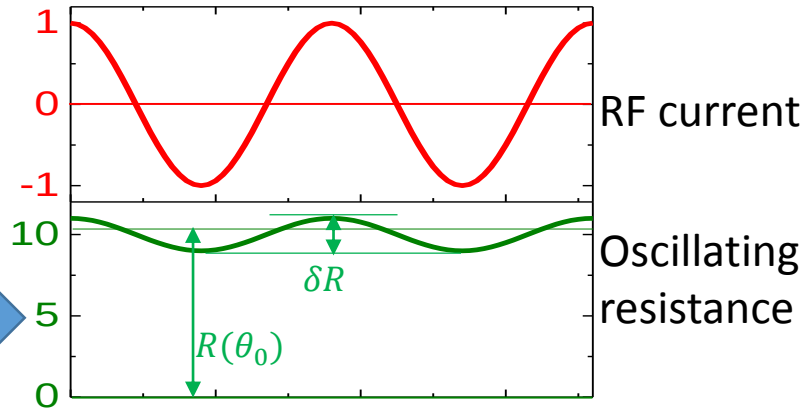

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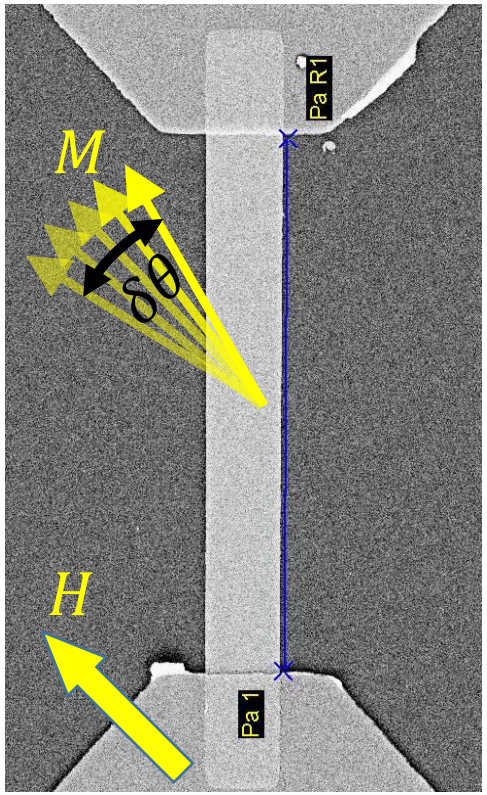
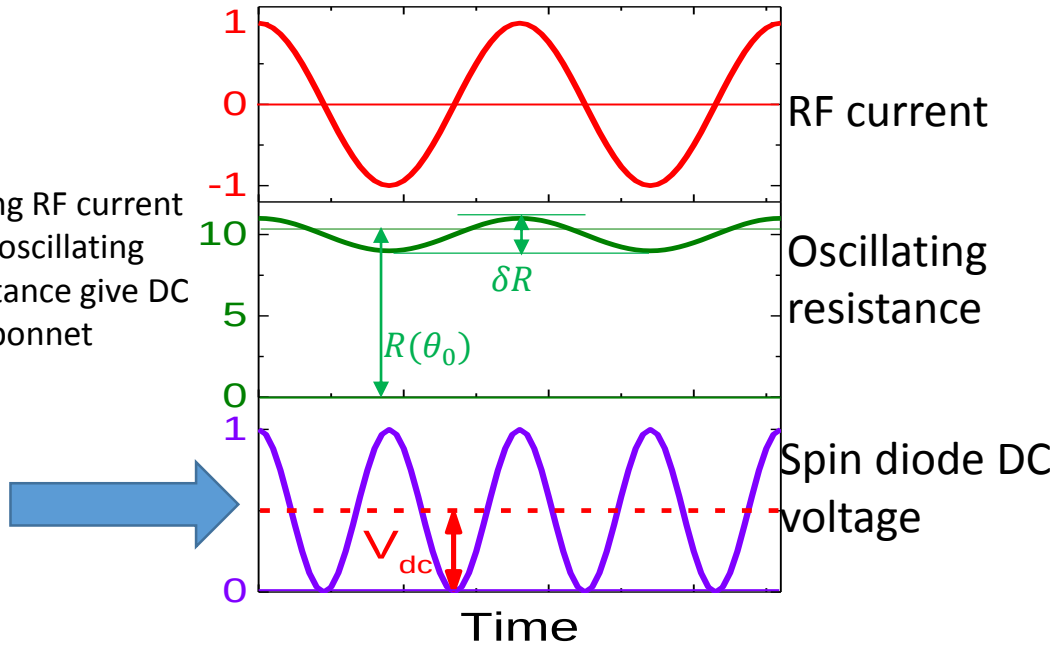


Mixing RF current with oscillating resistance give DC componnet

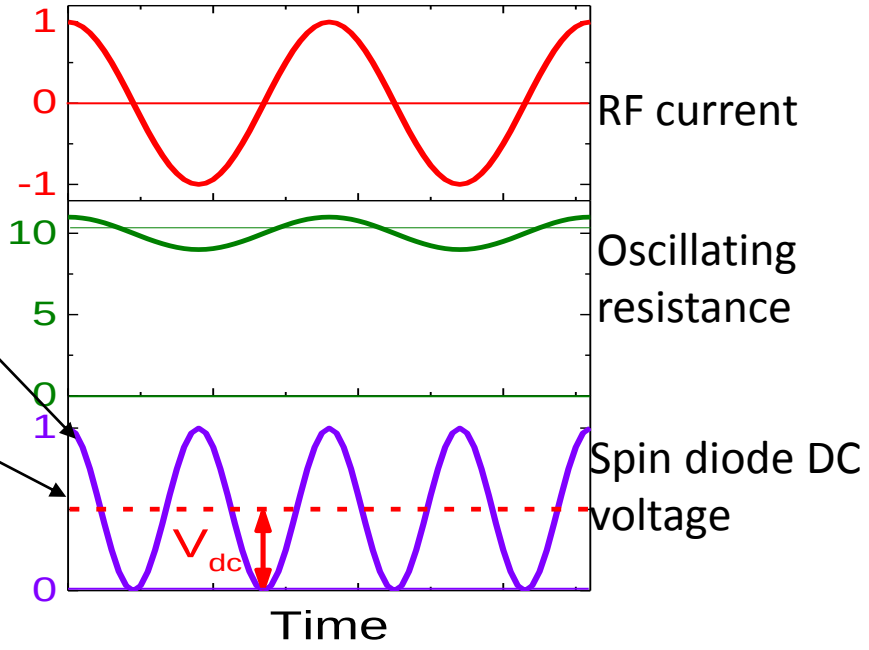


Spin diode effect theory

$$V_{out} = V_{dc} + V_{ac} = \delta R cos(\omega t + \beta) \times \frac{V}{R(\theta_0)} \cos(\omega t)$$
$$= \frac{V \delta R}{2R(\theta_0)} (cos\beta + \cos(2\omega t + \beta))$$

time undependent (SPIN DIODE VOLTAGE)

time dependent



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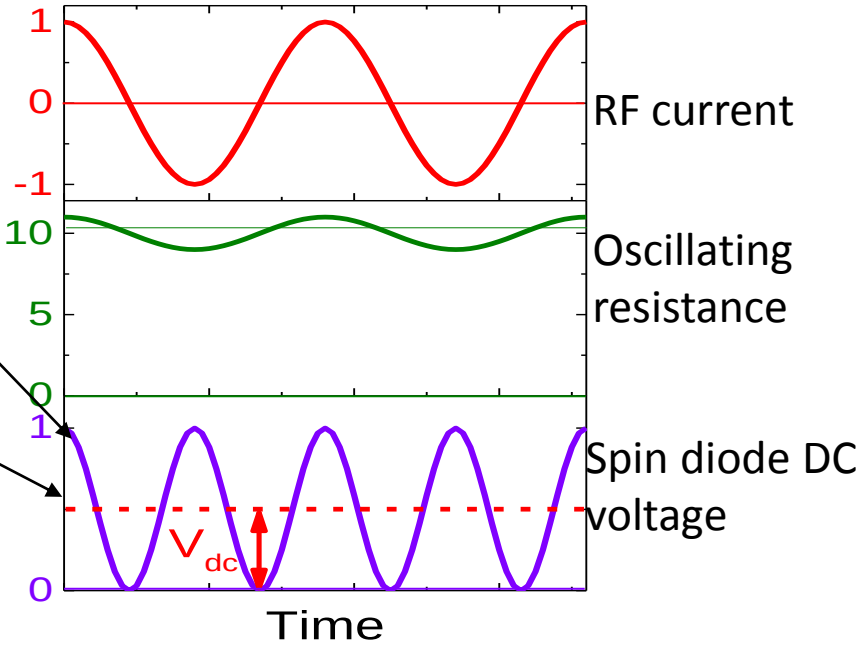

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AMR angular dependence

$$R(\theta) = \boldsymbol{R_\perp + \Delta R \cos^2}$$

Stationary point specified by total magnetic energy

$U = -K_{[100]} \sin^2\theta \sin^2\phi$ } **Uniaxial anisotropy (perpendicular to the long axis)**

$-\vec{M} \cdot \vec{H}$ } **Zeeman energy**

$-\vec{M} \cdot \overrightarrow{H_d}$ } **Shape anisotropy**

$-\frac{3}{2}\lambda\left(\sigma_{[01-1]}(\mathrm{E})\cos^2\theta + \sigma_{[100]}(E)\sin^2\theta \sin^2\phi\right)$ } **magnetoelastic anisotropy**

$-\vec{M} \cdot \vec{H}_{oe[100,011]}$ } **Oersted Field component**

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Resistance changes in around the stationary point

$$\delta R = -2\Delta R \sin(\theta_0) \cos(\theta_0) \delta\theta$$

To calculate $\delta\theta$ we use the LLG equation

$$\frac{\partial \vec{m}(\vec{r})}{\partial t} - \alpha\, \vec{m}(\vec{r}) \times \frac{\partial \vec{m}(\vec{r})}{\partial t} = \vec{\Gamma}$$

$$\vec{\Gamma}(\vec{r}) = -\vec{m}(\vec{r}) \times \nabla U(\vec{r})$$

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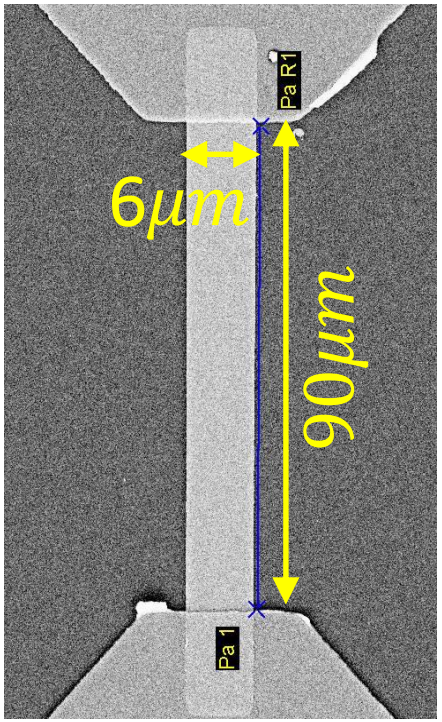
Final expression for spin diode voltage

$$V_{DC} \sim \frac{[a(\omega^2 - \omega_0^2) + b\sigma\omega^2]\cdot cos(\psi) + [b\omega(\omega^2 - \omega_0^2) - a\,\sigma\omega]\cdot sin(\psi)}{(\omega^2 - \omega_0^2)^2 + \sigma^2\omega^2}$$

Spin diode detection of FMR and SSW in NiFe strips



20nm of NiFe on Si/SiOx substrate

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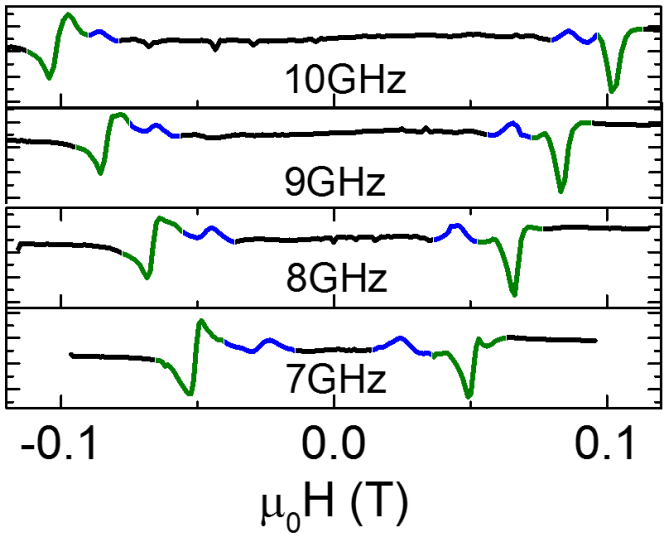

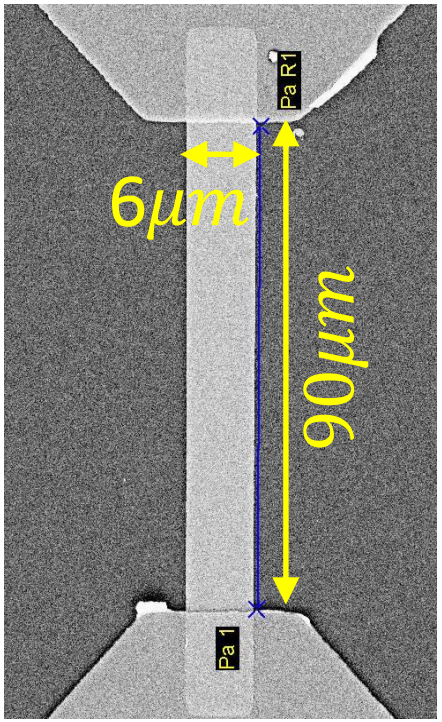

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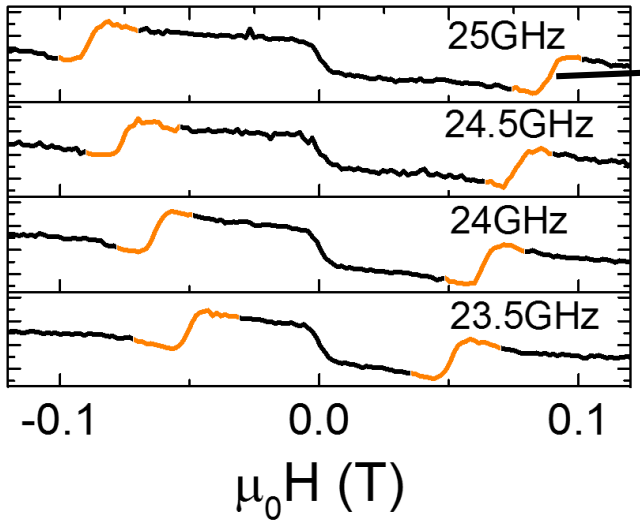
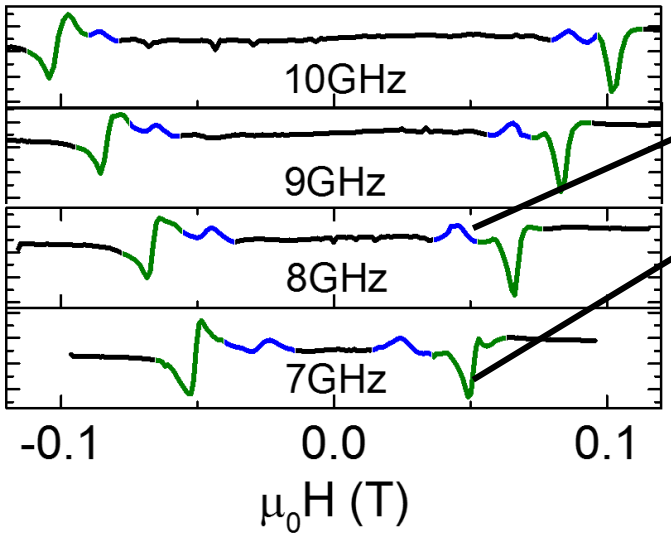
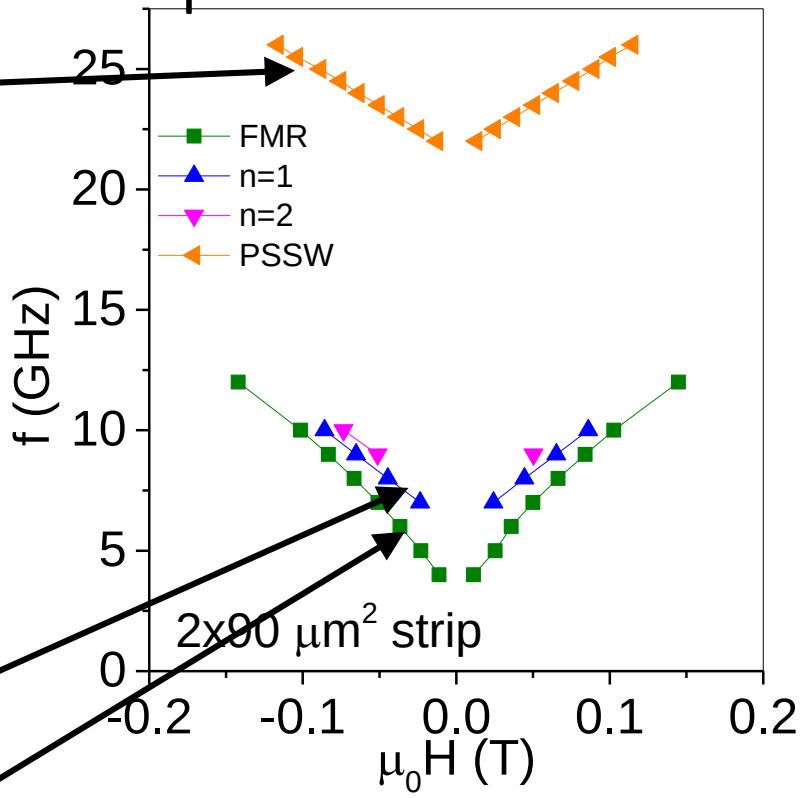
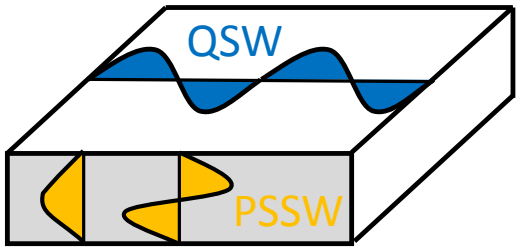
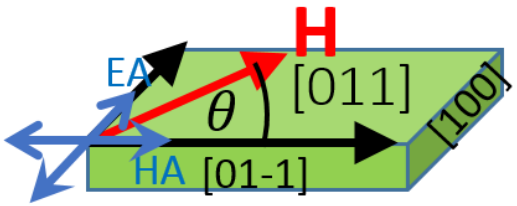




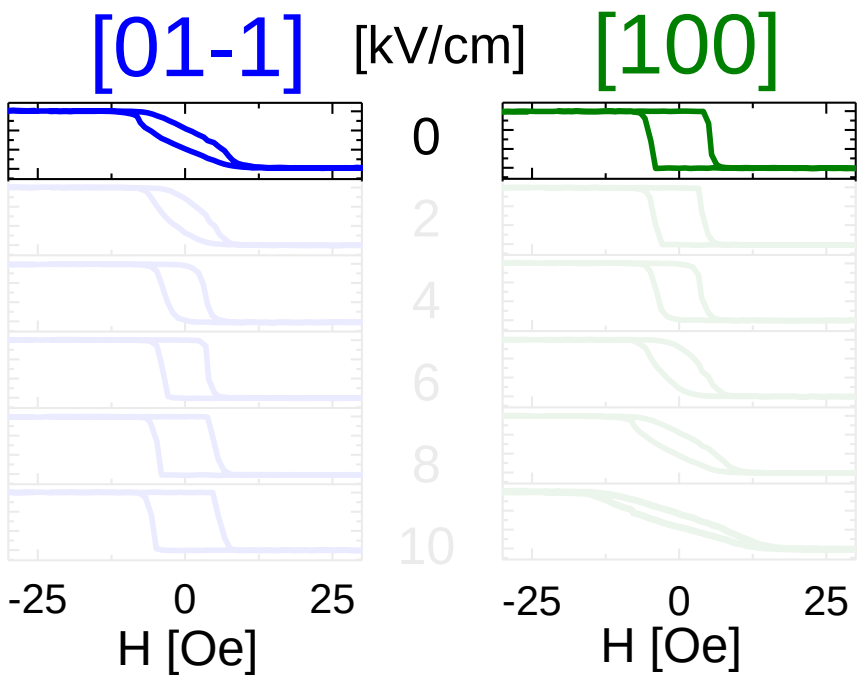


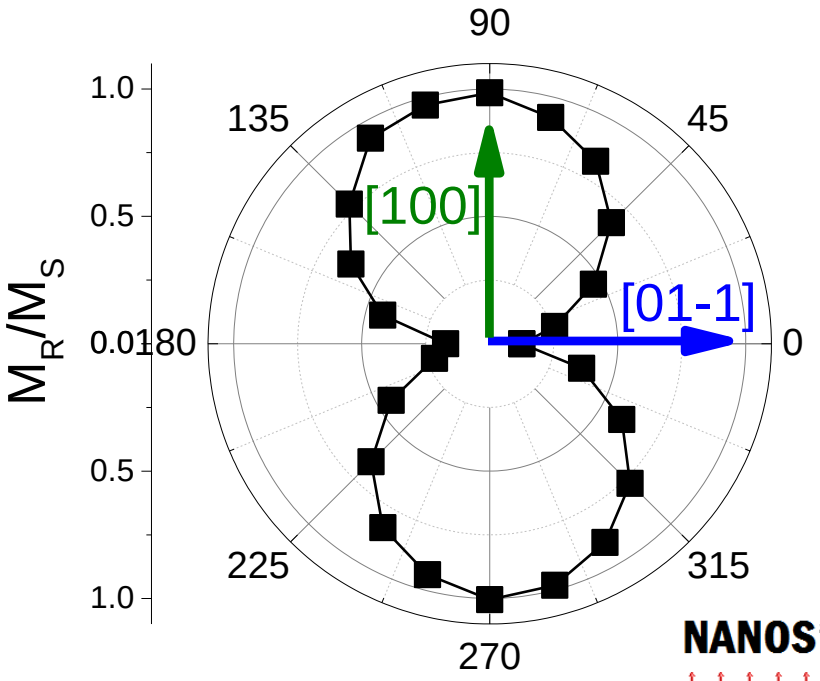


Electric field influence on magnetic anisotorpy in PMN-PT/NiFe film

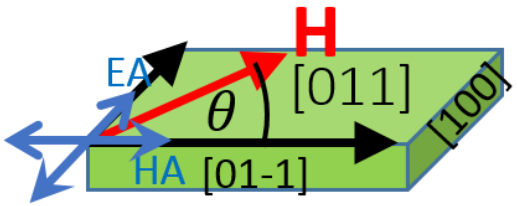


E-field

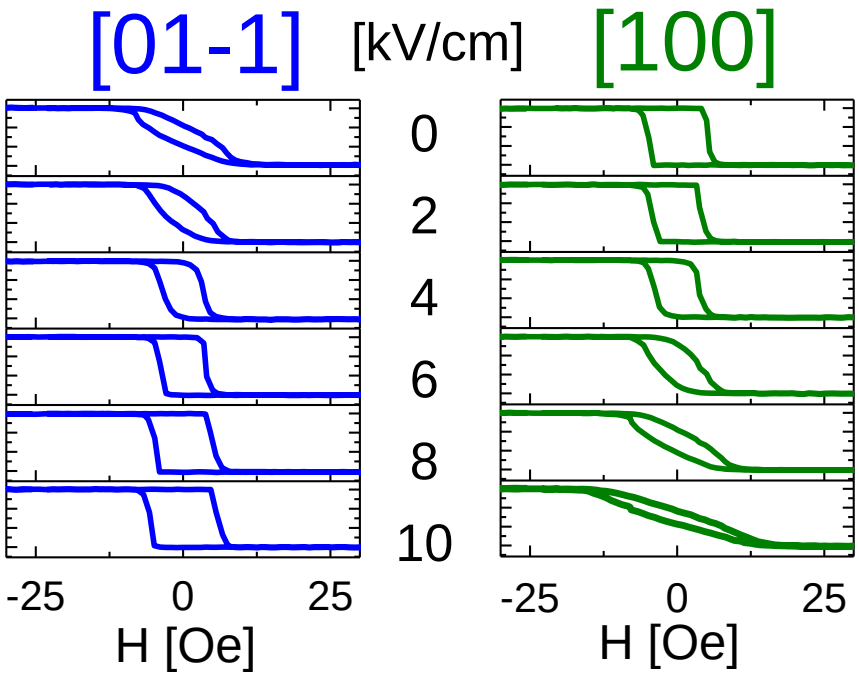


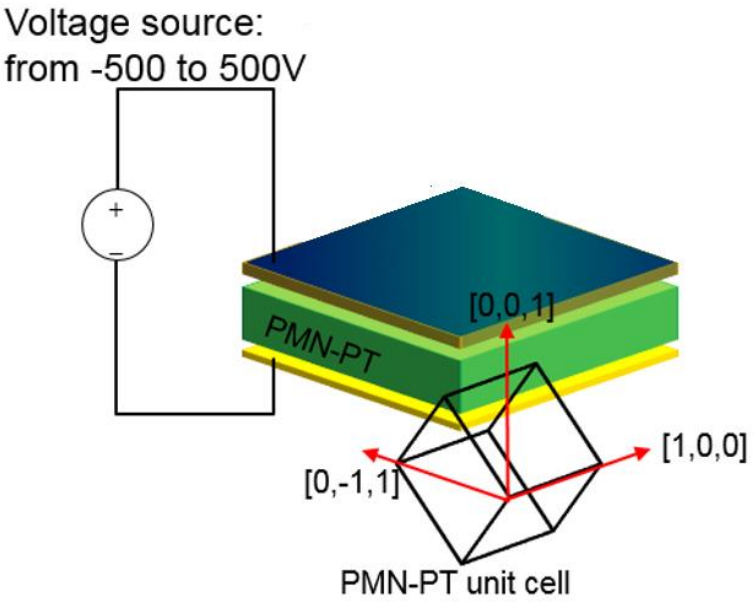


Electric field influence on magnetic anisotorpy in PMN-PT/NiFe film

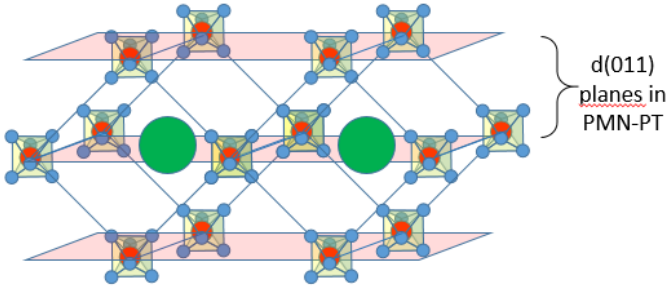


E-field



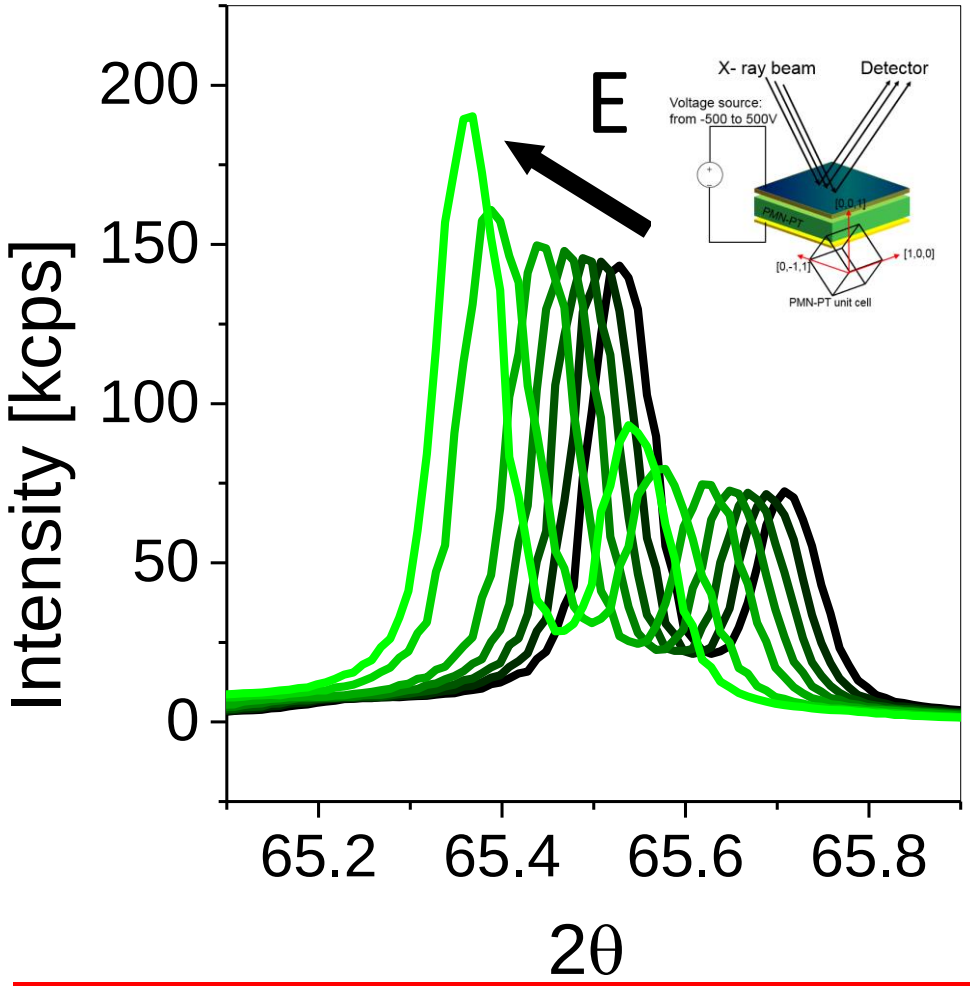


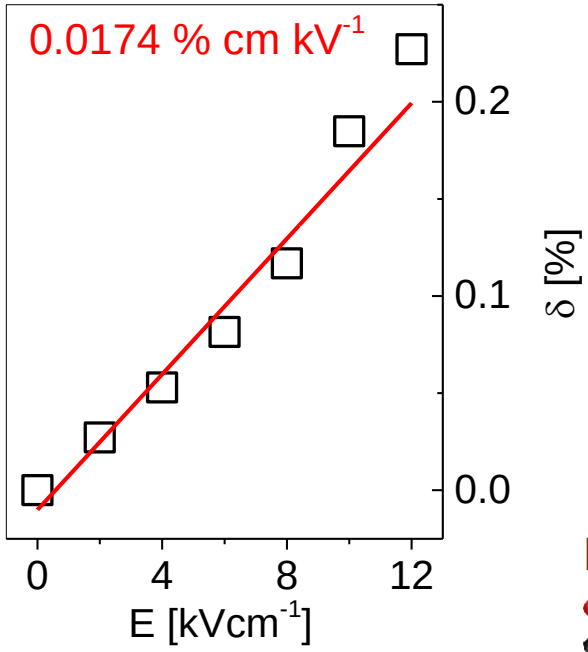
$\theta - 2\theta$ scans of PMN-PT (011) vs. E-field.



0.7 $Pb(Mg_{0.33}Nb_{0.66})O_3$-0.3 $PbTiO_3$

(022) PMN-PT

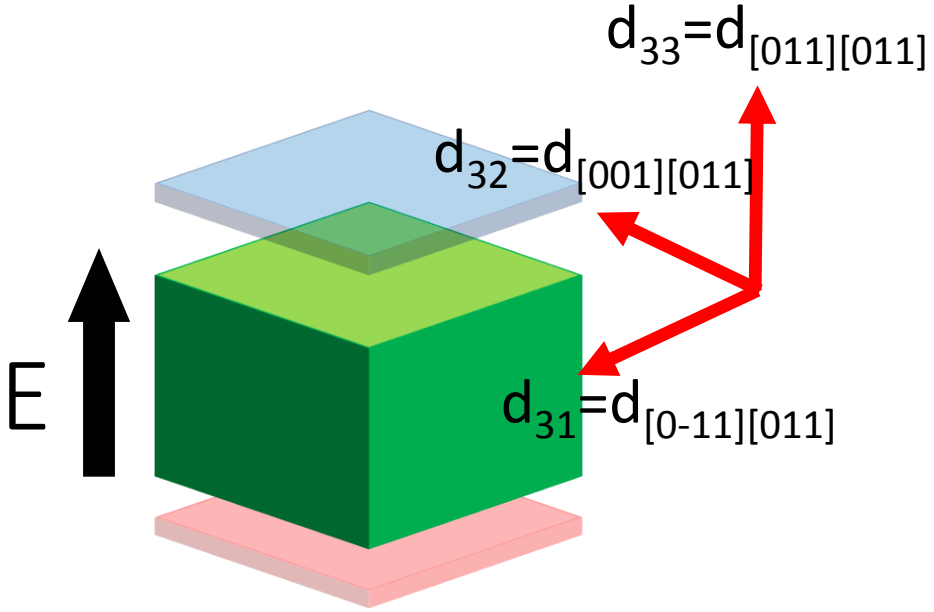


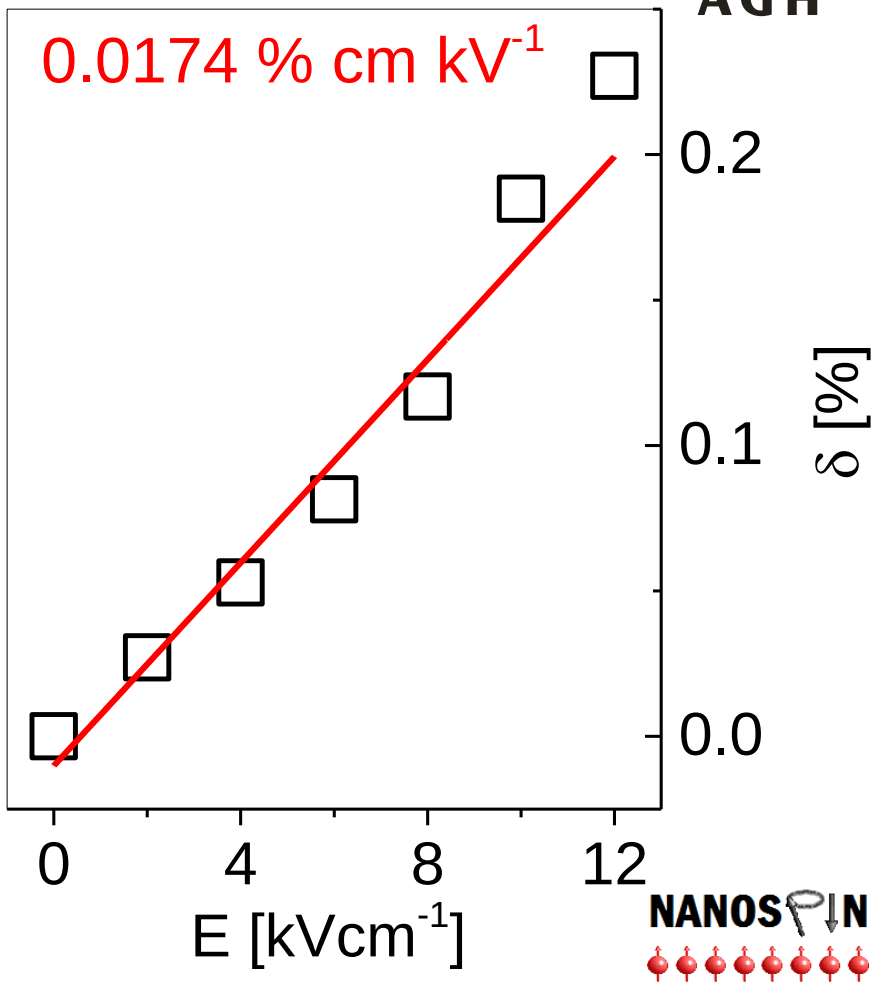


Piezoelectric parameters: d_{31}, d_{32}, d_{33}

$$\epsilon_i = d_{ki} E_k$$

$$d_{33} = 1740 \frac{pC}{N}$$





Piezoelectric parameters: d_{31}, d_{32}, d_{33}

$$\epsilon_i = d_{ki} E_k$$

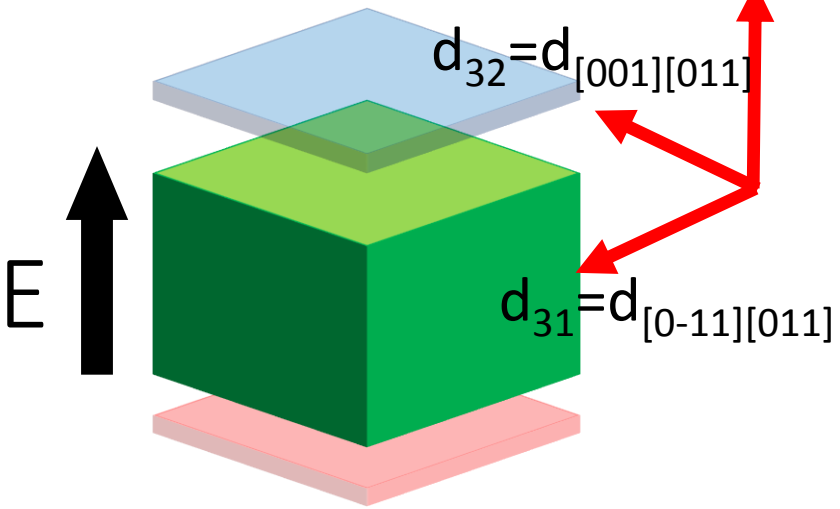
$$d_{33} = 1740 \frac{pC}{N}$$

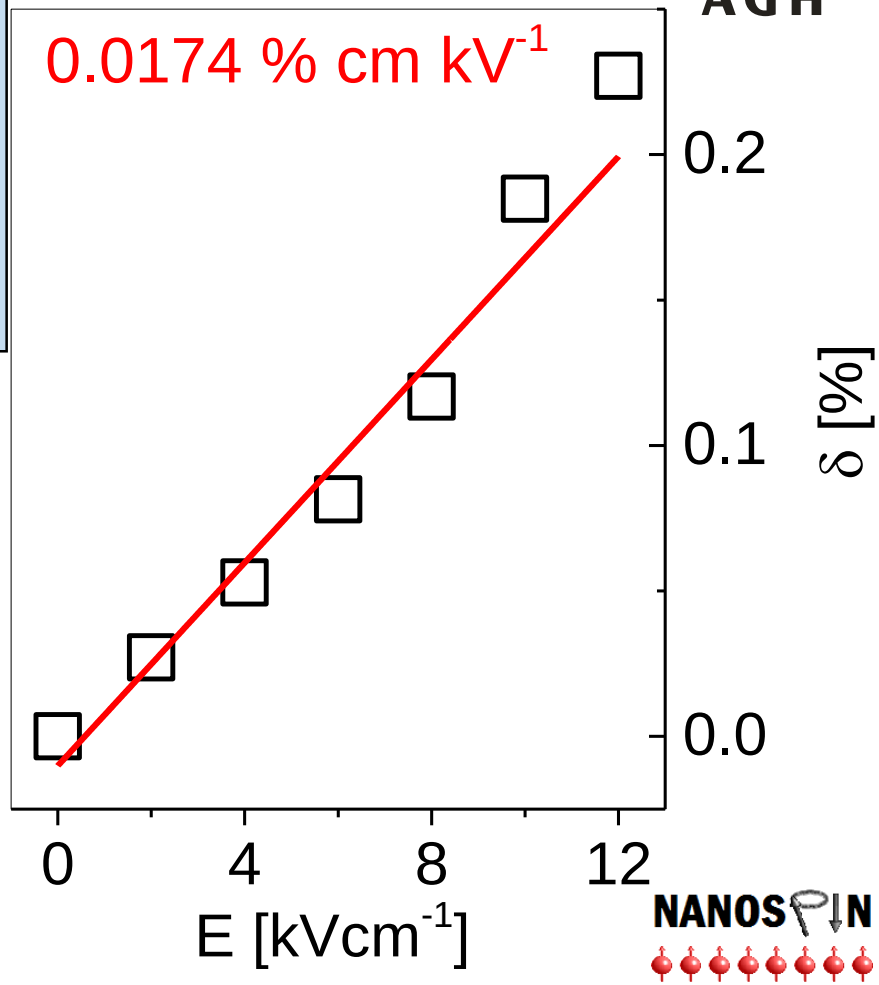
[1]

$$d_{33} = 1766 \frac{pC}{N}$$

$$d_{32} = 1761 \frac{pC}{N}$$

$$d_{31} = 723 \frac{pC}{N}$$

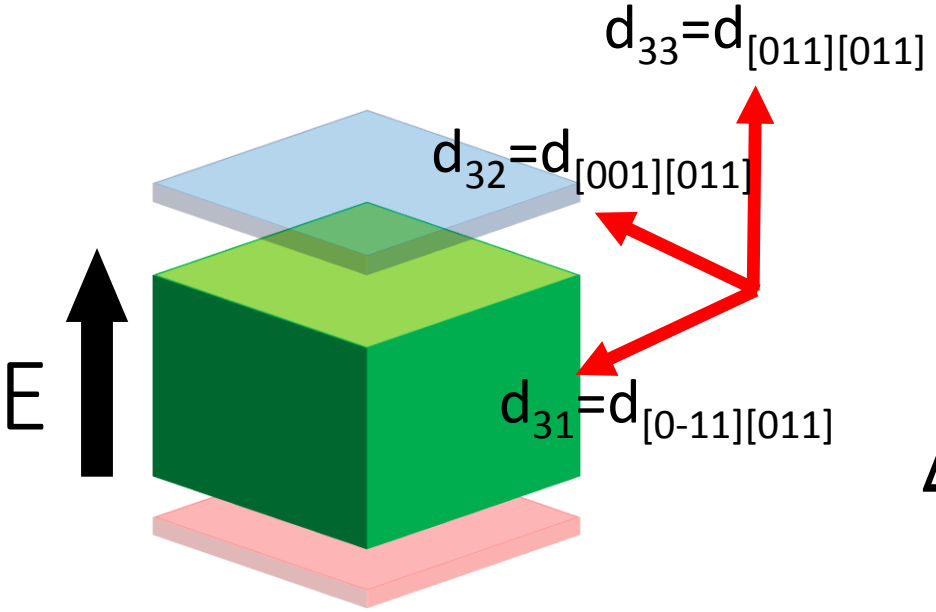




[1] M. Shanthi ae al., Appl. Phys. Lett, vol. 92, no. 14, p. 142906, 2008.

Stress in permalloy and inverse magnetostriction effect

$$\sigma_{[01-1]}(E) = \frac{Y(d_{31} + \nu d_{32})}{(1-\nu^2)} E_{[001]} \qquad \sigma_{[100]}(E) = \frac{Y(d_{32} + \nu d_{31})}{(1-\nu^2)} E_{[001]}$$

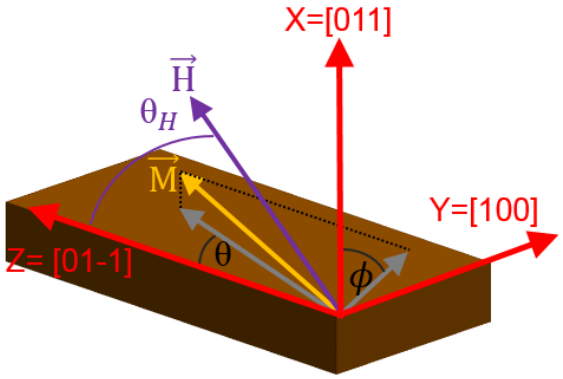


$$Y = 200GPa$$
$$\upsilon = 0.22$$

$$\Delta U_{ME}(E) = 3\lambda\sigma(E)$$

[1] M. Shanthi ae al., Appl. Phys. Lett, vol. 92, no. 14, p. 142906, 2008.

Magnetic energy and FMR in PMN-PT/NiFe heterostructure



$$\sigma_{[01-1]}(E) = \frac{Y(d_{31}+\nu d_{32})}{(1-\nu^2)} E_{[001]} \qquad \sigma_{[100]}(E) = \frac{Y(d_{32}+\nu d_{31})}{(1-\nu^2)} E_{[001]}$$

$$U = -K_{[100]} \sin^2\theta \sin^2\phi - \vec{M}\cdot\vec{H}_d - \vec{M}\cdot\vec{H} - \frac{3}{2}\lambda\sigma_{[01-1]}(E)\cos^2\theta - \frac{3}{2}\lambda\sigma_{[100]}(E)\sin^2\theta\sin^2\phi$$

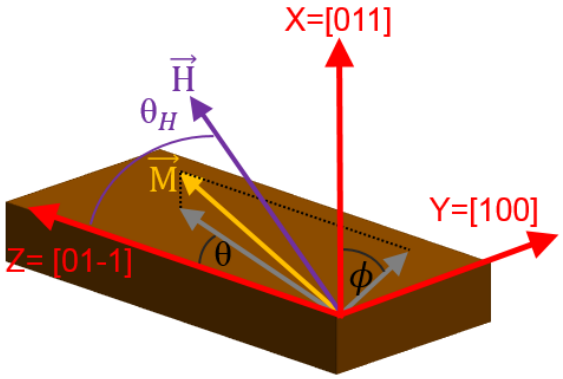
Uniaxial magnetocristalline energy

Demag. energy

Zeeman energy

Magnetostriction energy

Magnetic energy and FMR in PMN-PT/NiFe heterostructure



$$\sigma_{[01-1]}(E) = \frac{Y(d_{31}+\nu d_{32})}{(1-\nu^2)} E_{[001]} \qquad \sigma_{[100]}(E) = \frac{Y(d_{32}+\nu d_{31})}{(1-\nu^2)} E_{[001]}$$

$$U = -K_{[100]} \sin^2\theta \sin^2\phi - \vec{M}\cdot\vec{H}_d - \vec{M}\cdot\vec{H} - \frac{3}{2}\lambda\sigma_{[01-1]}(E)\cos^2\theta - \frac{3}{2}\lambda\sigma_{[100]}(E)\sin^2\theta\sin^2\phi$$

Uniaxial magnetocristalline energy

Demag. energy

Zeeman energy

Magnetostriction energy

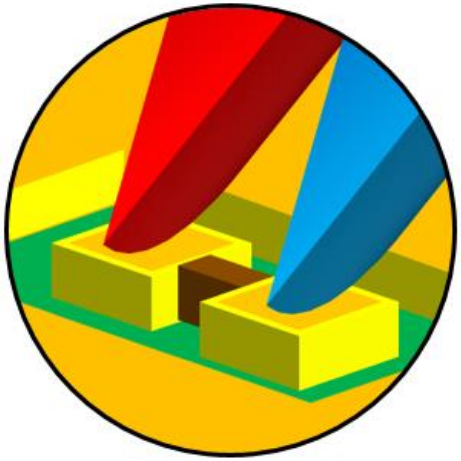
$$f \equiv \frac{\omega_0}{2\pi} = \frac{1}{2\pi}\sqrt{\begin{array}{c}\left(H + H_K + \frac{M_S}{\mu_0}\left(N_{[001]} - N_{[100]}\right) + \frac{3\lambda}{M_S}\sigma_{[100]}(E)\right) \times \\ \times \left(H\sin^{-2}\theta + H_K + \frac{M_S}{\mu_0}(N_{[01-1]} - N_{[100]}) + \frac{3\lambda}{M_S}(\sigma_{[100]}(E) - \sigma_{[01-1]}(E))\right)\sin^2\theta\end{array}}$$

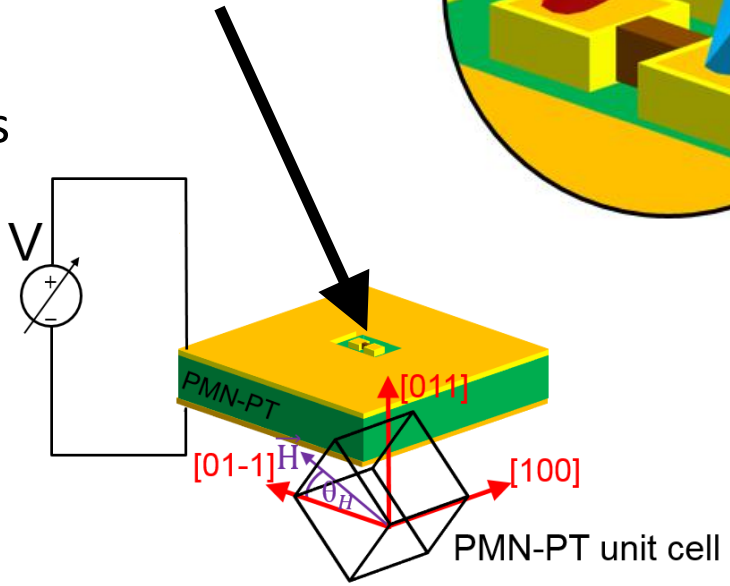
Lithography

- PMN-PT substrate
  - Orientation: [011]
  - Substrate size: 10x10x0.5mm^3
- 50nm of Au (with 5nm Ti buffer) was deposited in order to create bottom electorde

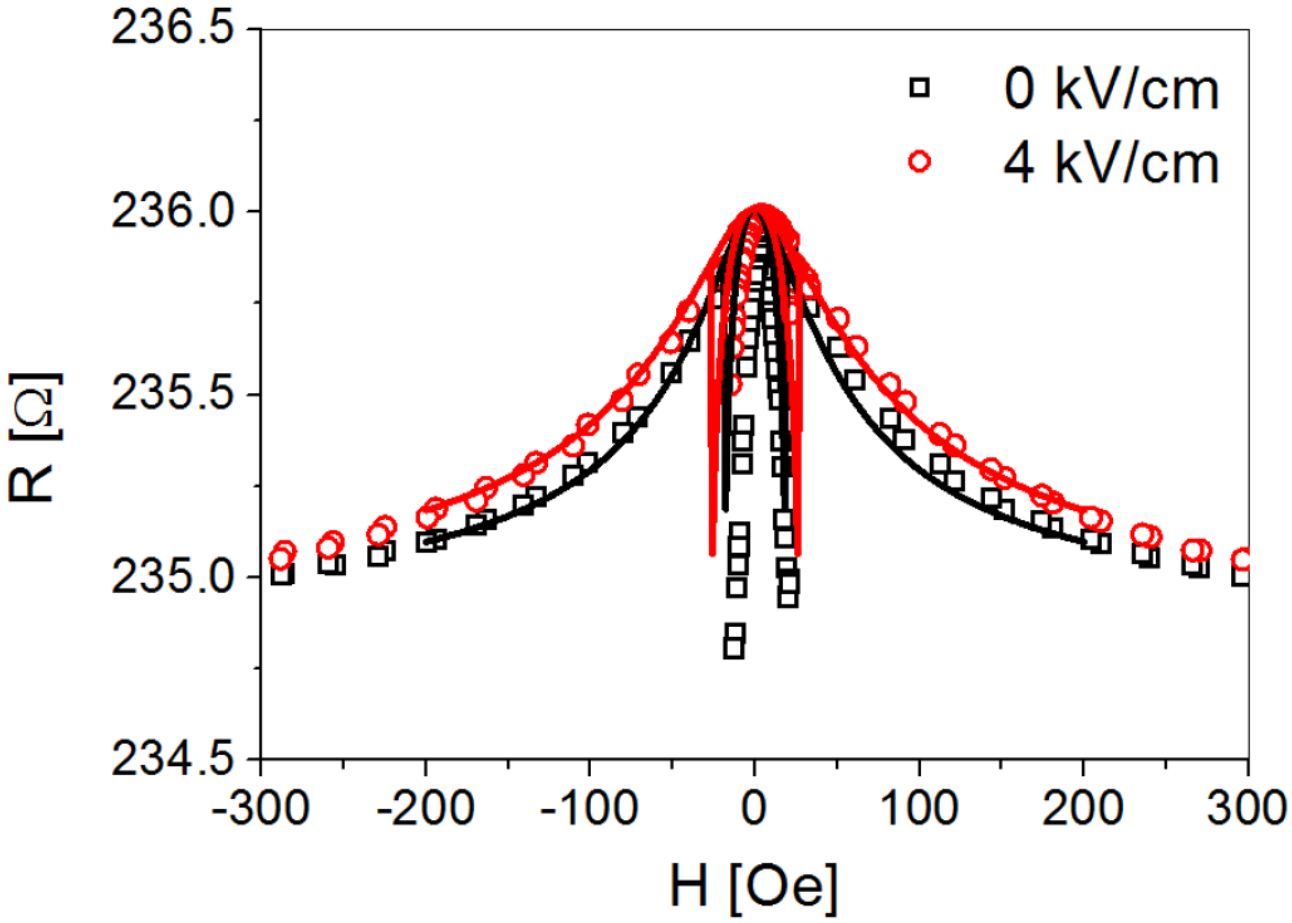
90 um long NiFe strip were fabricated with fallowing widths:

- 1.5 um
- 2.6 um
- 6.7 um





Voltage control of AMR

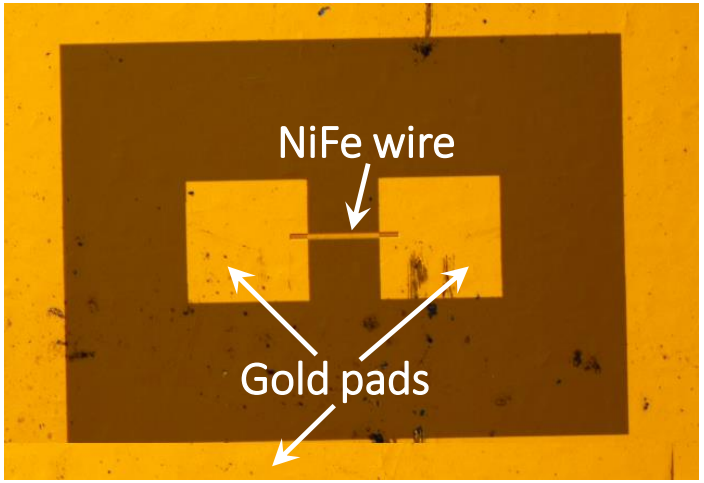


$K=785 J/m^3$

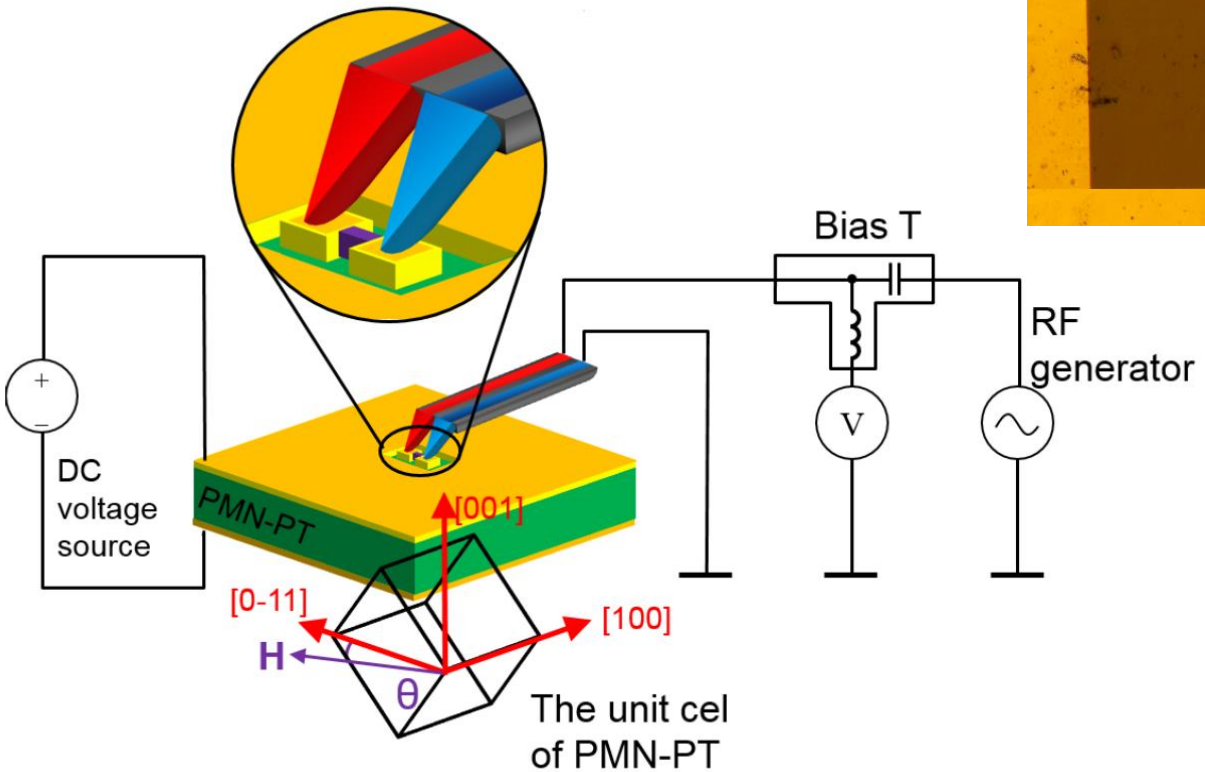
$M_S=0.97T$

$\lambda=2.5\times 10^{-6}$

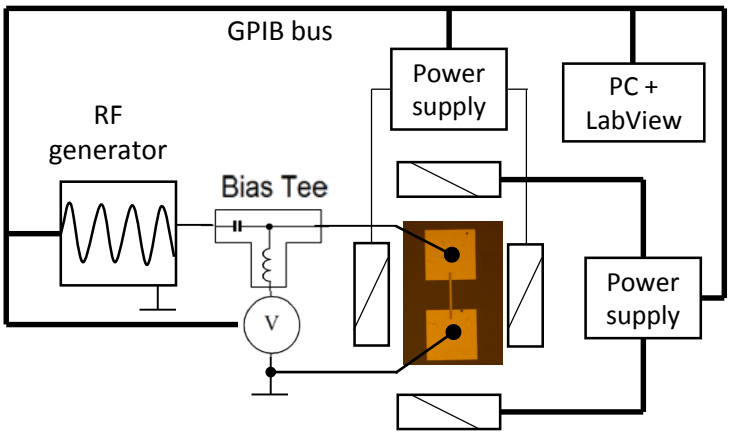
Experimental setup for SDE measurements

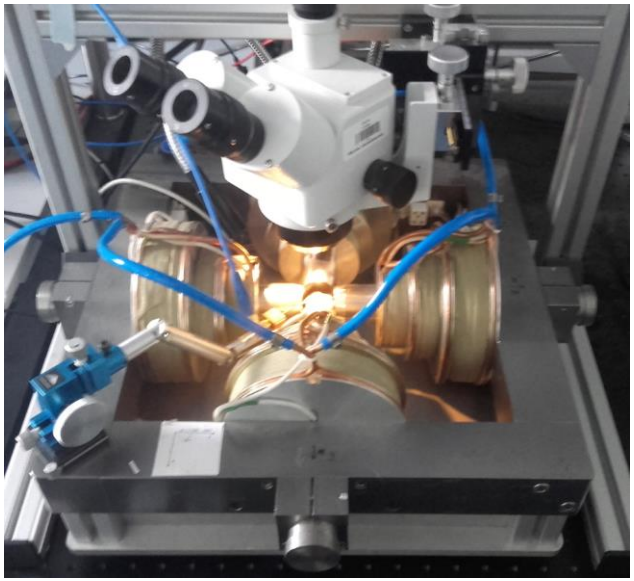


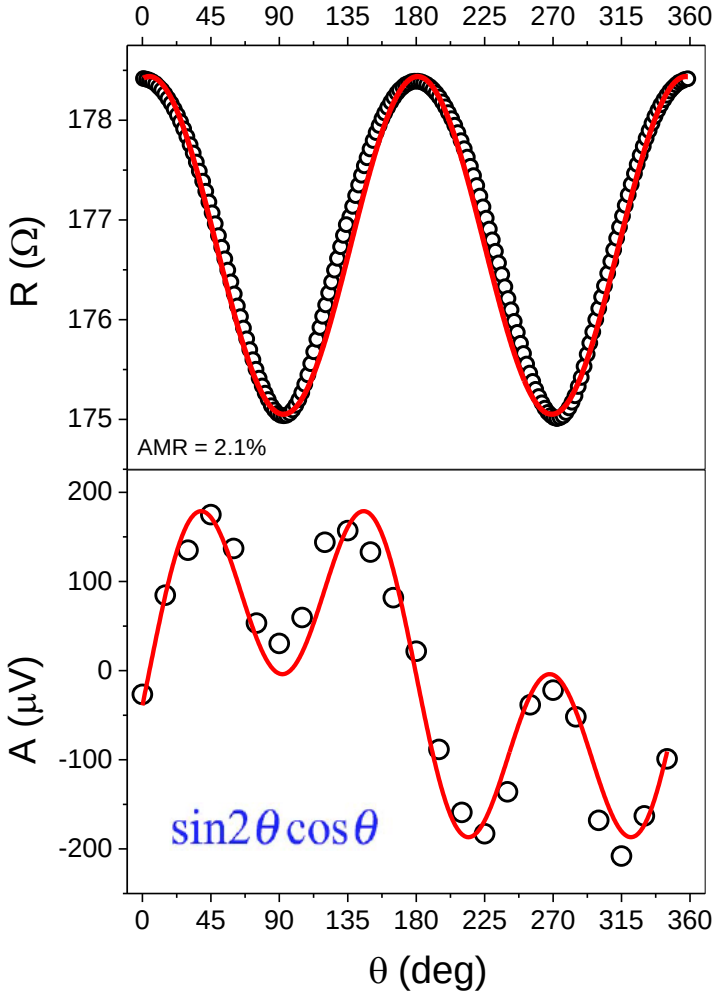
L=90 μm
W=1.5, 2.6, 6.7 μm

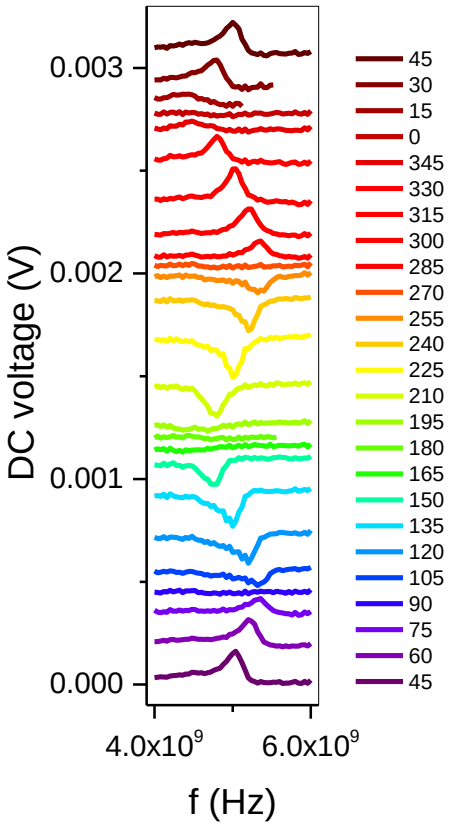


Angular depndence of spin diode FMR



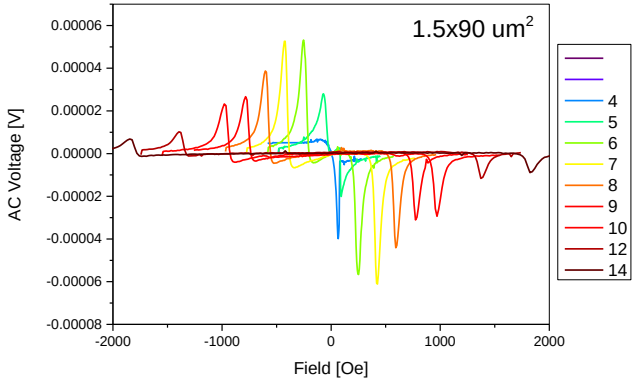


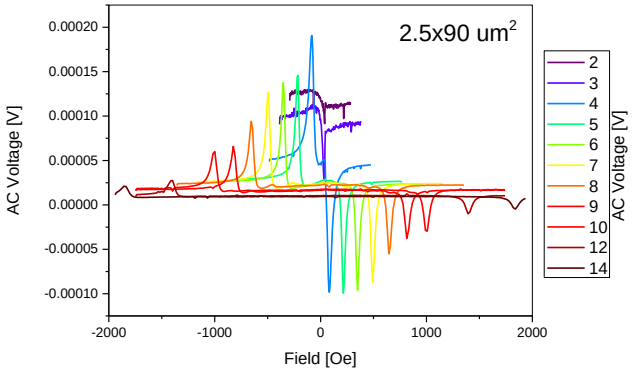


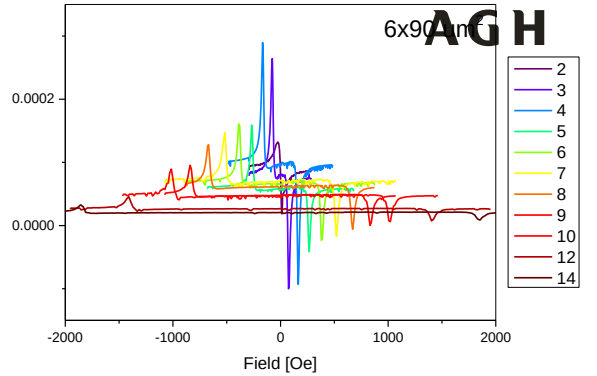


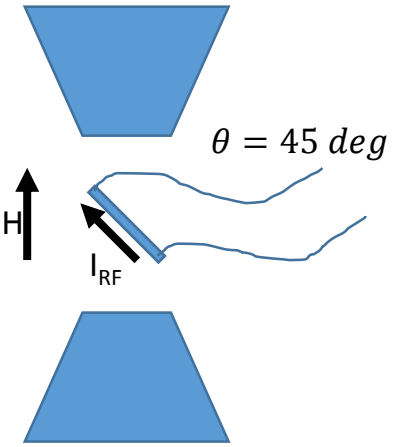
Yamaguchi, A., et al. "Rectification of radio frequency current in ferromagnetic nanowire." *Applied physics letters* 90.18 (2007): 182507.

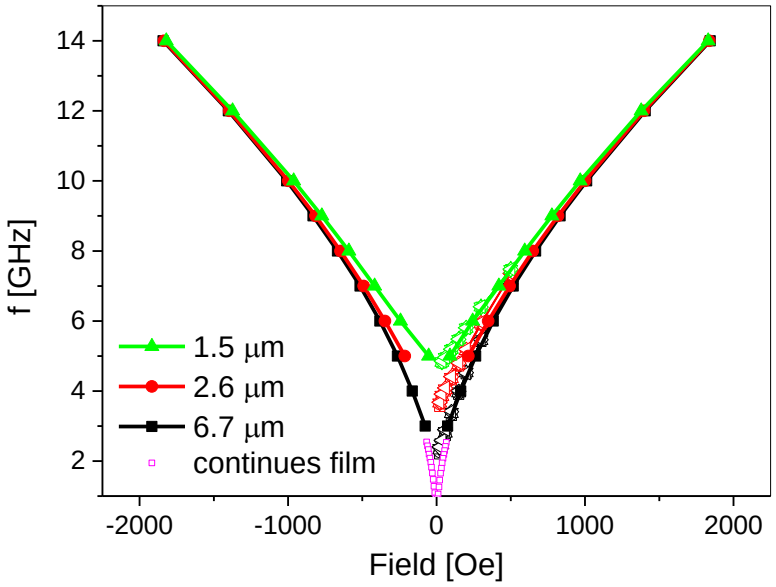
Spin diode in H-domain

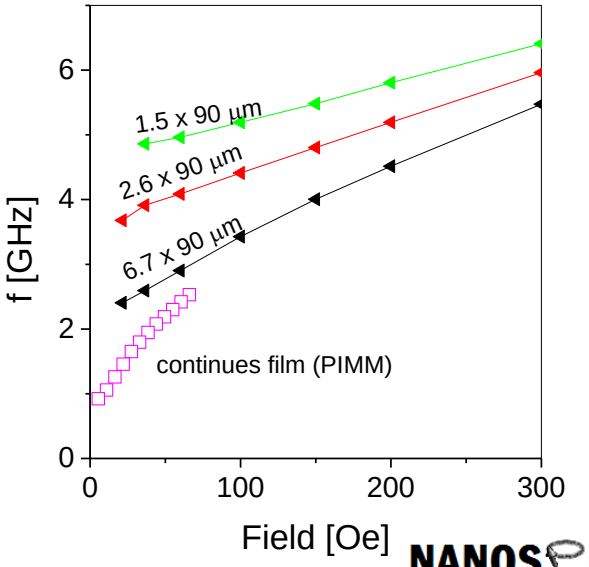






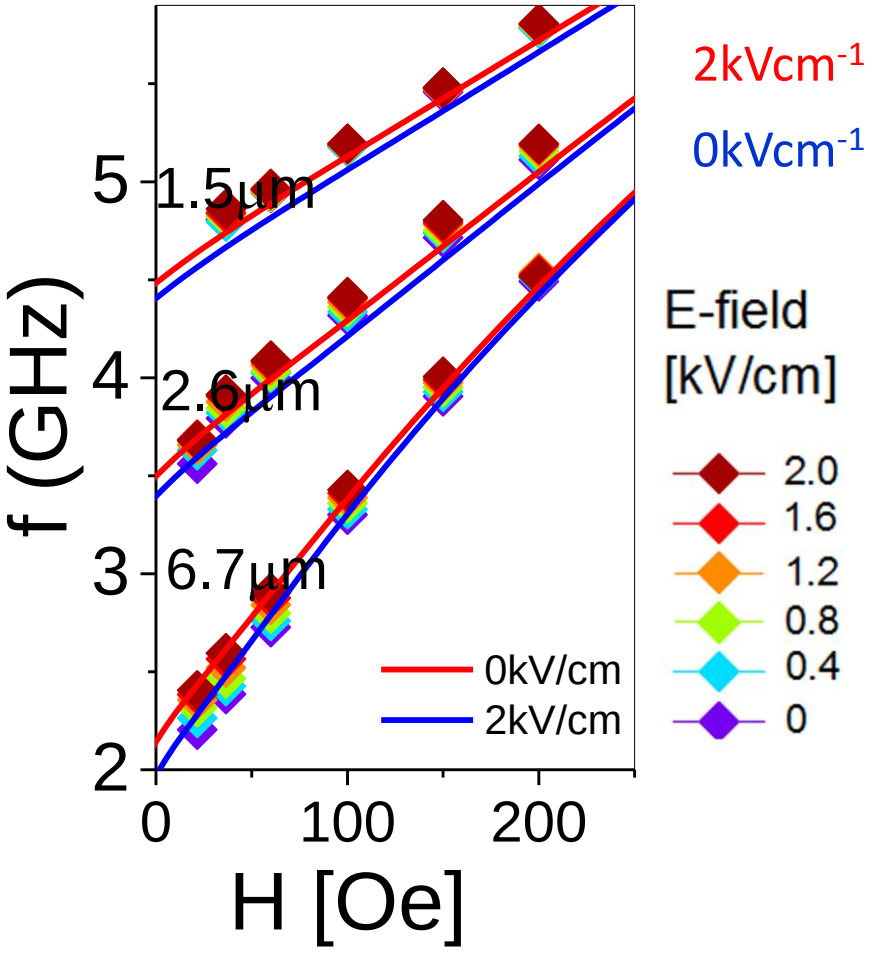






Voltage control of FMR frequency

$$f \equiv \frac{\omega_0}{2\pi} = \frac{1}{2\pi}\sqrt{\begin{array}{c}\left(H + H_K + \frac{M_S}{\mu_0}\left(N_{[001]} - N_{[100]}\right) + \frac{3\lambda}{M_S}\sigma_{[100]}(E)\right) \times \\ \times \left(H\sin^{-2}\theta + H_K + \frac{M_S}{\mu_0}(N_{[01-1]} - N_{[100]}) + \frac{3\lambda}{M_S}(\sigma_{[100]}(E) - \sigma_{[01-1]}(E))\right)\sin^2\theta\end{array}}$$

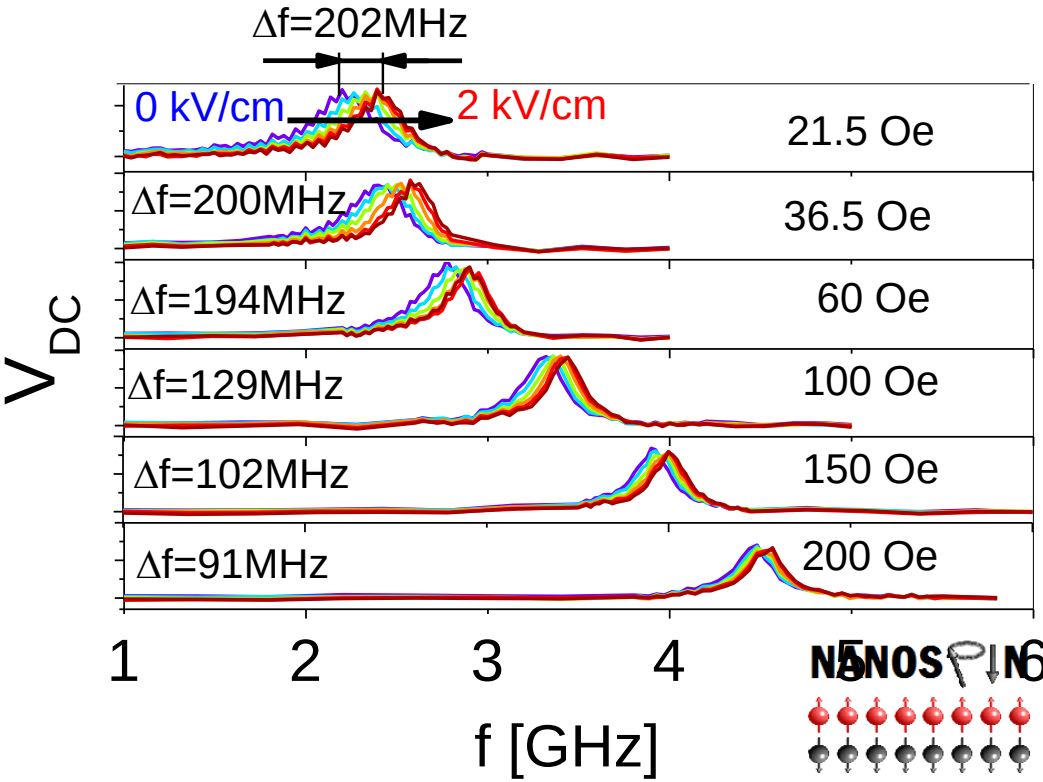


2kVcm^{-1}

0kVcm^{-1}

K=785J/m^3 λ=2.5× 10^{-6}

M_S=0.97T



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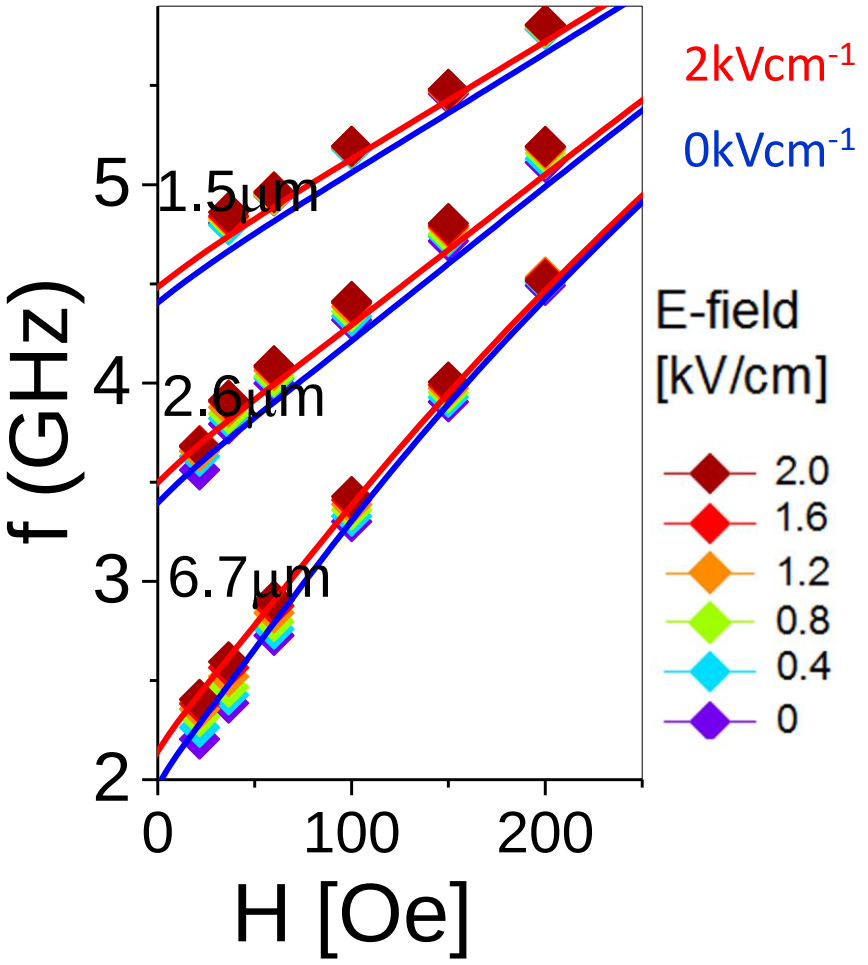

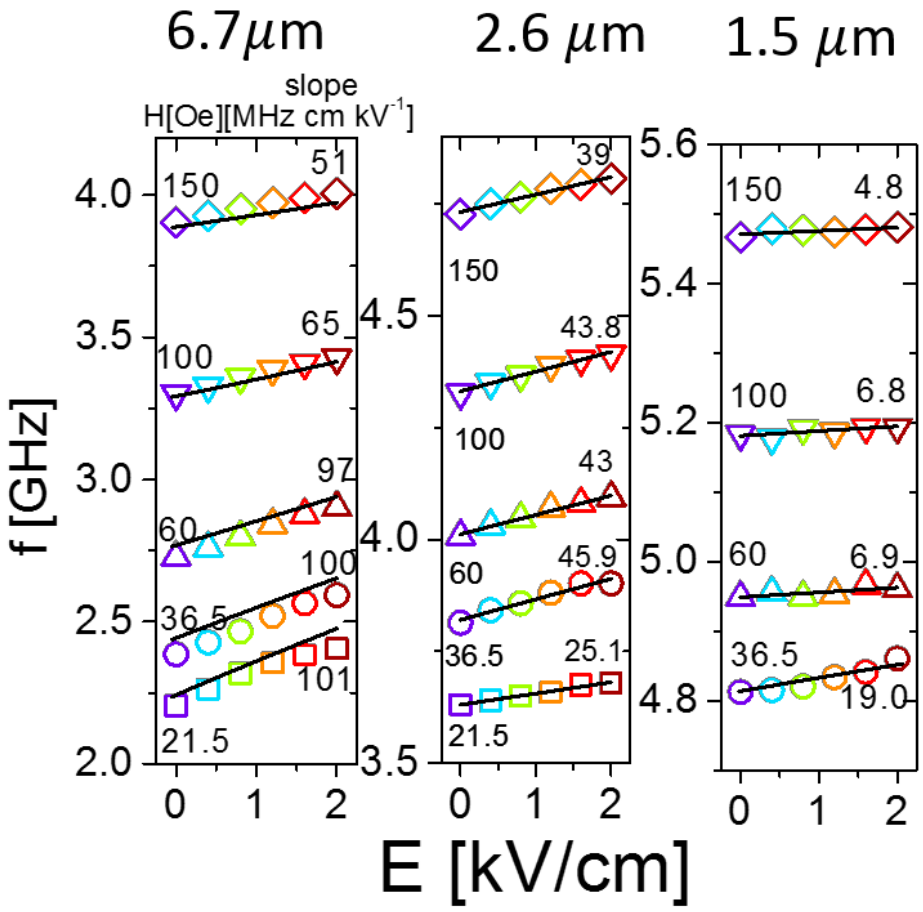

Voltage control of FMR frequency

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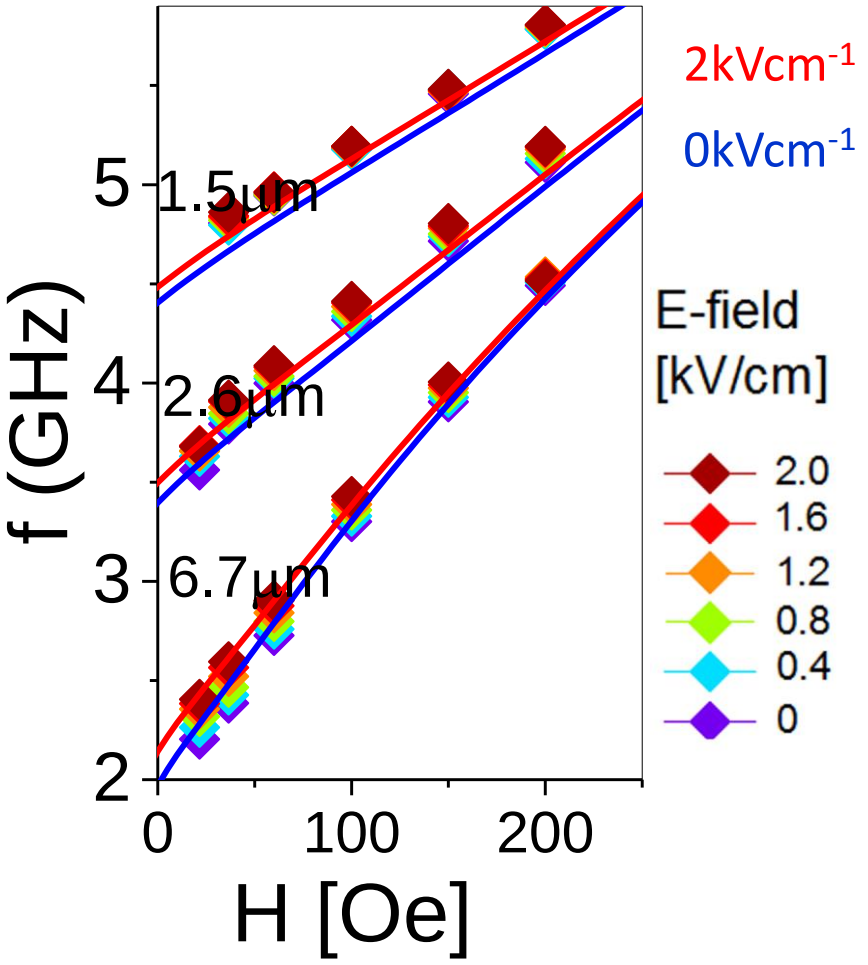
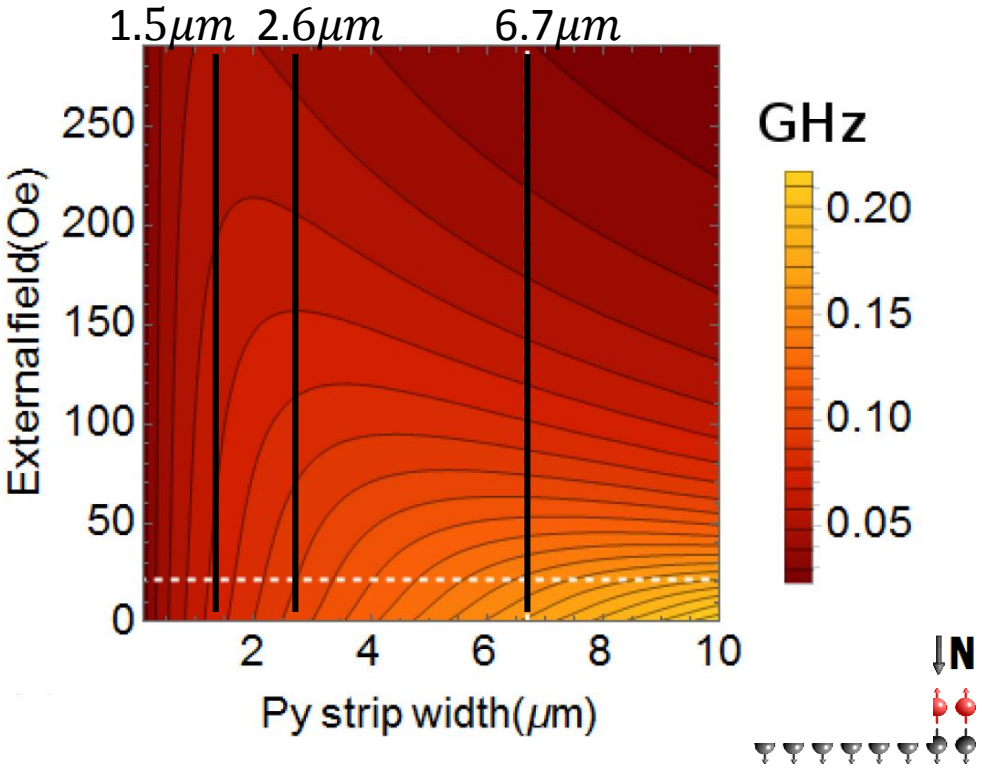
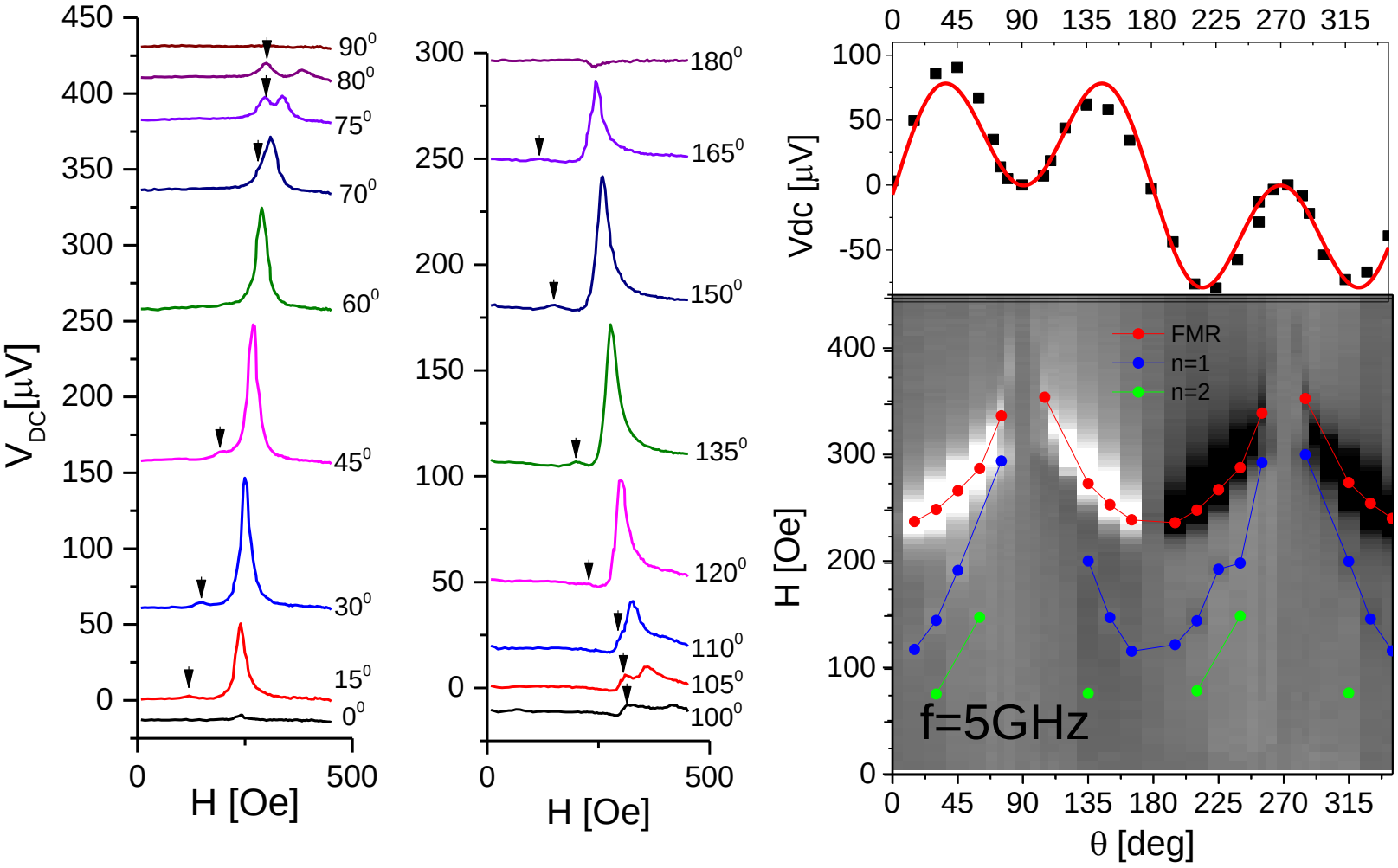


K=785J/m^3 λ=2.5× 10^{-6}

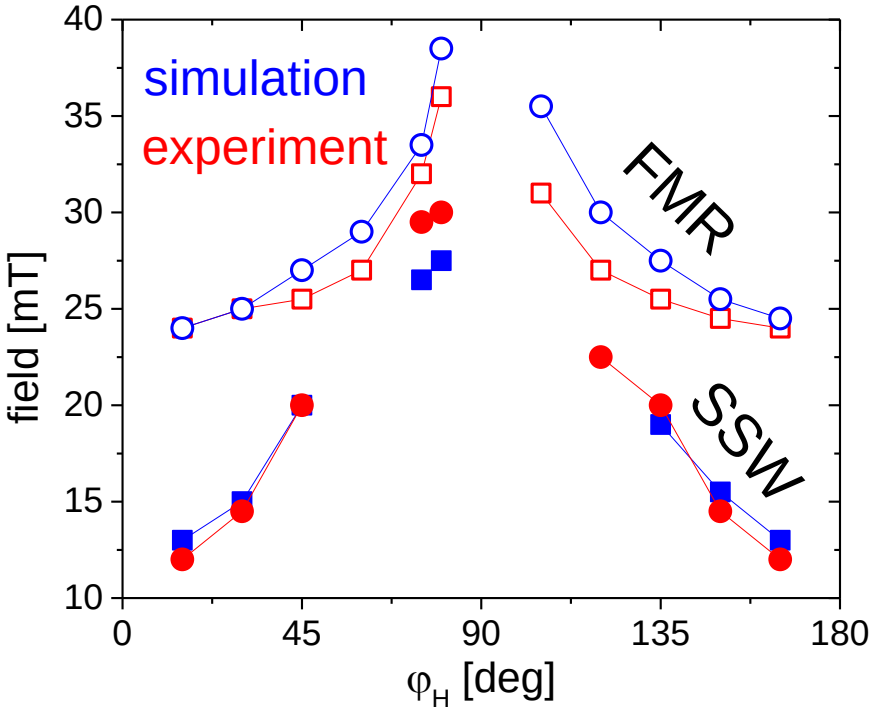
M_S=0.97T

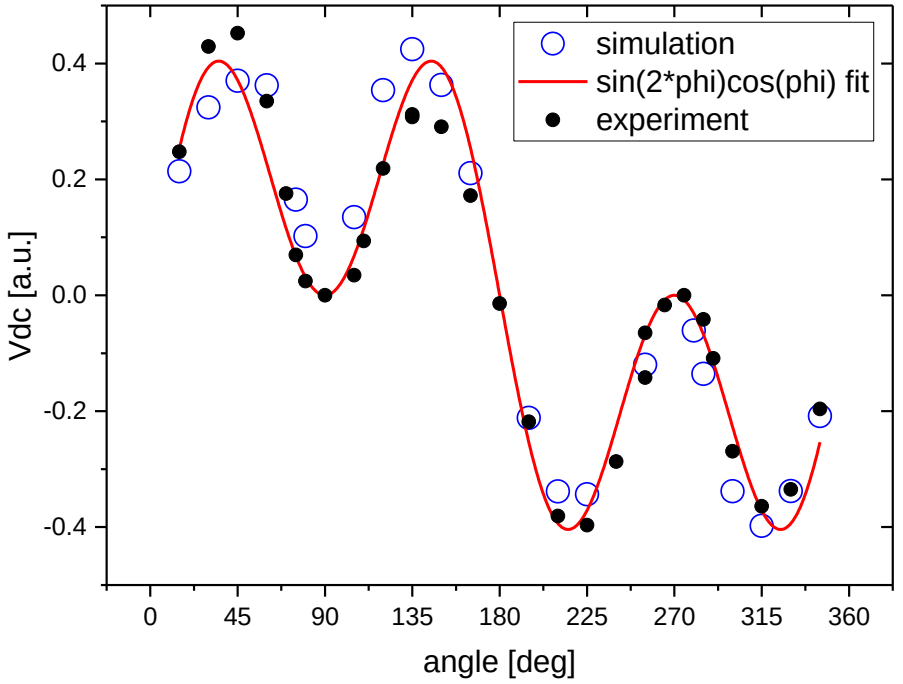


Angular depndence of spin diode SSW



Micromagnetic simulations





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Voltage control of quantized spin waves

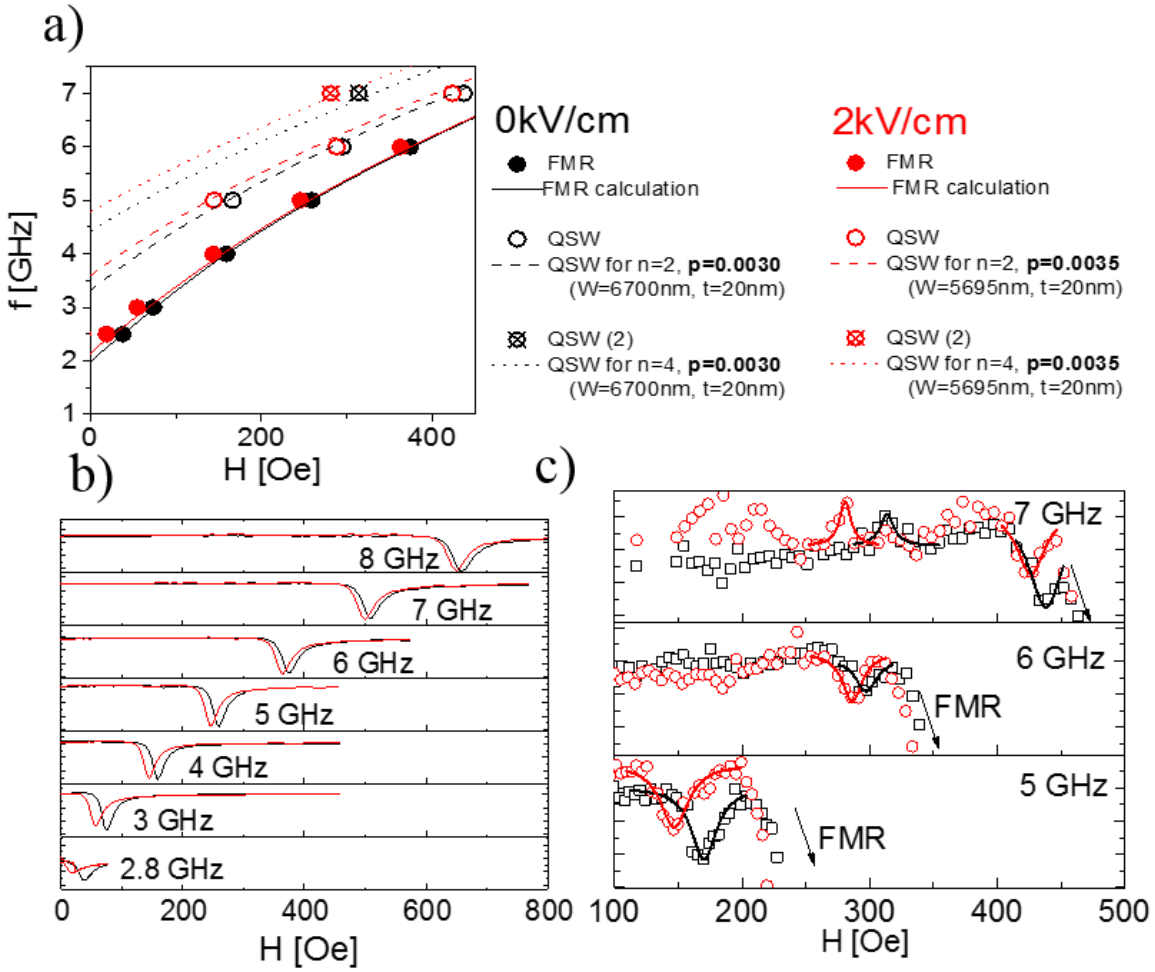
$$\left(\frac{\omega_N}{\omega_M}\right)^2 = \left(\frac{\omega_H}{\omega_M} + \frac{\lambda_n}{4\pi} + 1\right)\left(\frac{\omega_H}{\omega_M} - \frac{\lambda_n}{4\pi}\right)$$

$$\lambda_n(p) = -4\pi + \pi^2(2n+1)p, n = 0, 1, 2, \ldots$$

$$P = \frac{t}{W}$$

W = 6700nm

t = 20nm



Guslienko, K. Y., Demokritov, S. O., Hillebrands, B., & Slavin, A. N. (2002). *Phys. Rev. B*, *66*(13), 132402.

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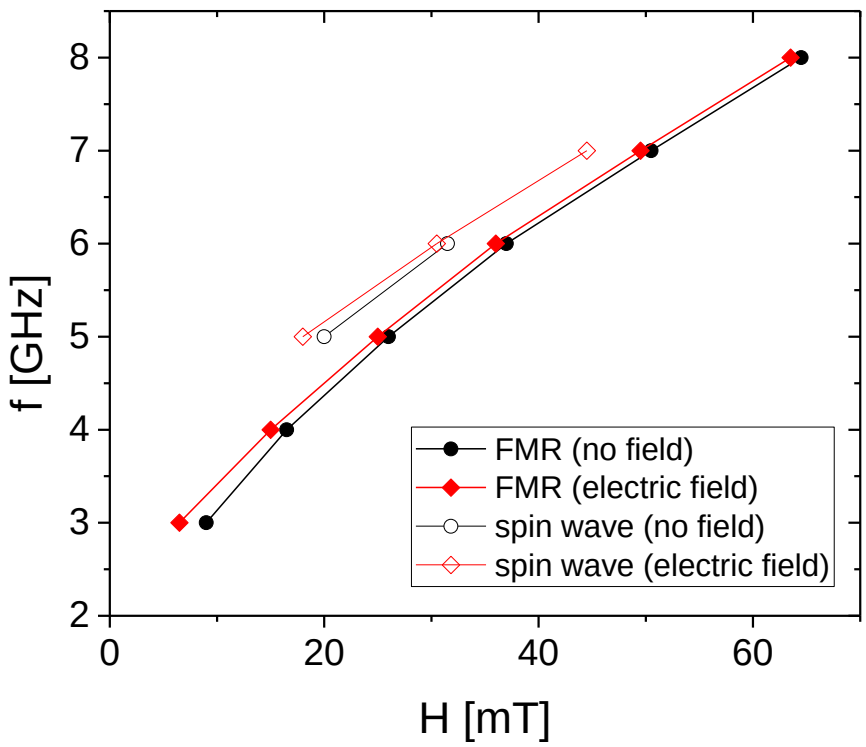
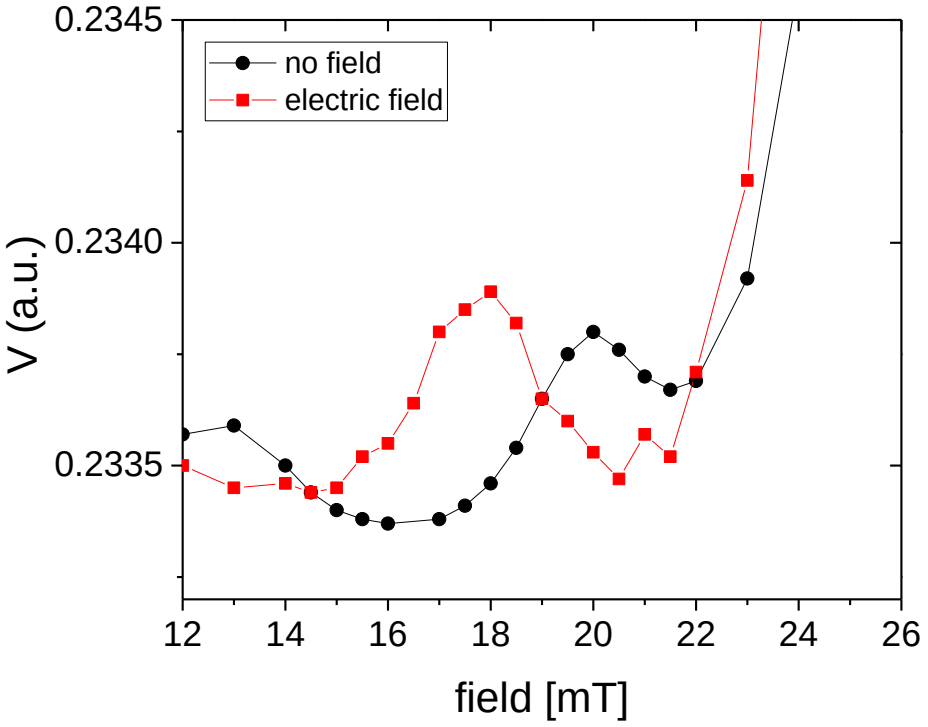
Micromagnetic simulations – electric field influence





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Thank you for your attention!

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