New Perspectives in Spintronics and Mesoscopic Physics

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Perpendicular magnetic anisotropy induced by Rashba spin-orbit interaction

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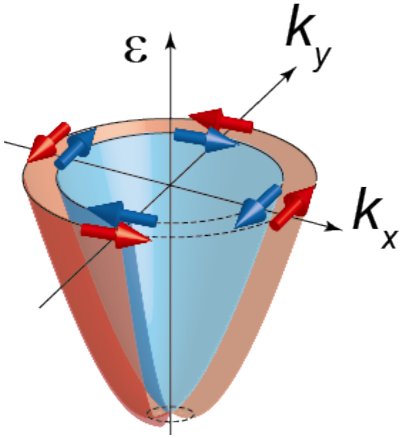

In collaboration with

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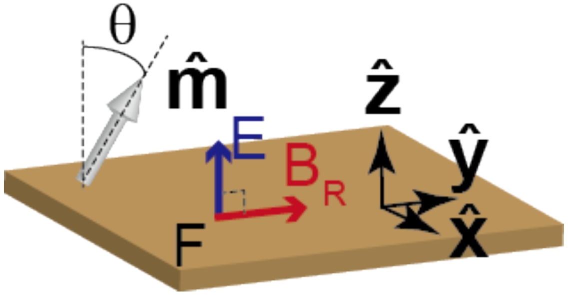


Outline

- Introduction
  - Rashba effects in Spintronics
- Model
  - Rashba mechanism of magnetic anisotropy
- Electric-Field Effect
  - Experiments and predictions
- Summary

Rashba Effect


http://news.harvard.edu/

$$H_{\mathrm{R}} = \frac{\alpha_{\mathrm{R}}}{\hbar}\mathbf{p}\cdot\left(\sigma\times\hat{\mathbf{z}}\right)$$

Inversion symmetry breaking -> E(**k**,↑) ≠ E(-**k**,↑)
Time reversal symmetry -> E(**k**,↑) ≠ E(**k**,↓)

E. I. Rashba: Fiz. Teverd. Tela (Leningrad) 2 (1960) 1224;
Y. A. Bychkov and E. I. Rashba: J. Phys., C 17 (1984) 6039.

physics of spin-orbit coupling penetrated into numerous branches of condensed matter physics

….

I guess that our paper became successful because
it was one of the first, and timely, steps of this journey.

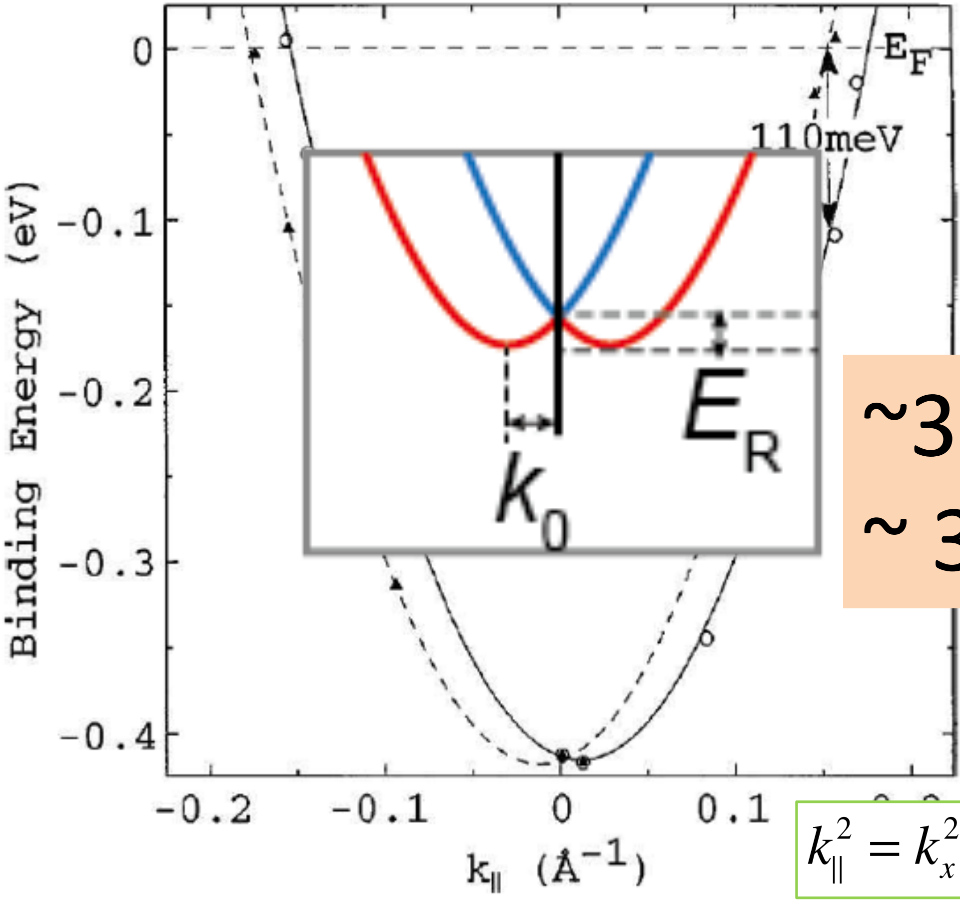
by E. I. Rashba from *the editor blog of JETP Letters*

Surface Rashba Splitting

- Au (111)

$$\varepsilon_{\vec{\mathrm{k}},\sigma} = \frac{\hbar^2 k_\parallel^2}{2m} - \sigma\alpha_\mathrm{R}\left|k_\parallel\right| = \frac{\hbar^2}{2m}\left(\left|k_\parallel\right| - \sigma k_0\right)^2 - E_\mathrm{R}$$

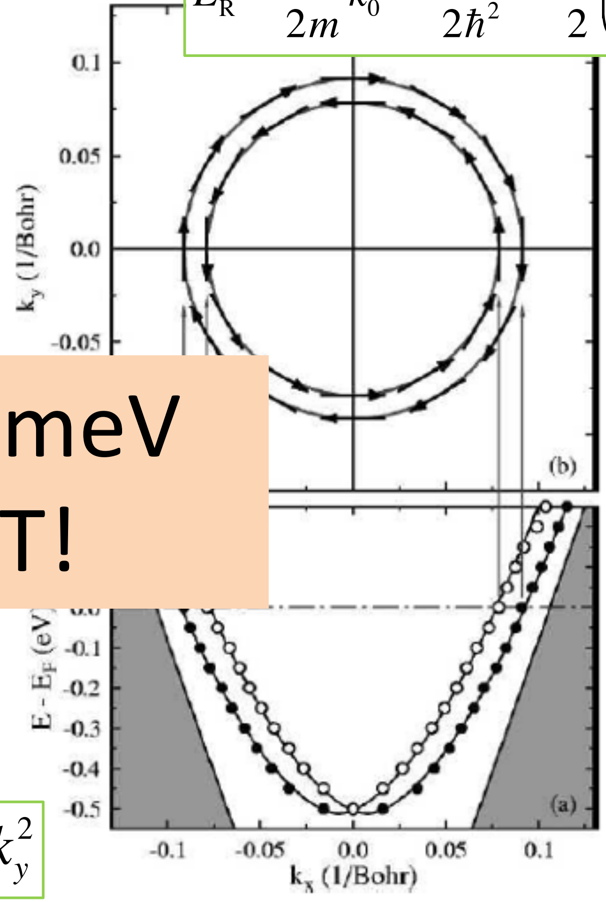
$$E_\mathrm{R} = \frac{\hbar^2}{2m}k_0^2 = \frac{m\alpha_\mathrm{R}^2}{2\hbar^2} = \frac{m}{2}\left(\frac{e\eta_\mathrm{SO}}{\hbar}\right)^2 E^2$$



~3.5meV

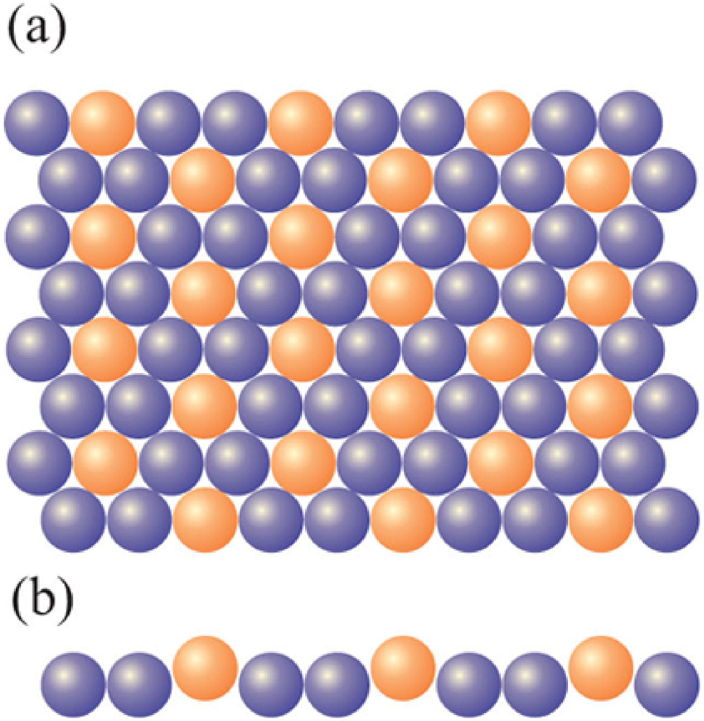
~ 35T!

$$k_\parallel^2 = k_x^2 + k_y^2$$

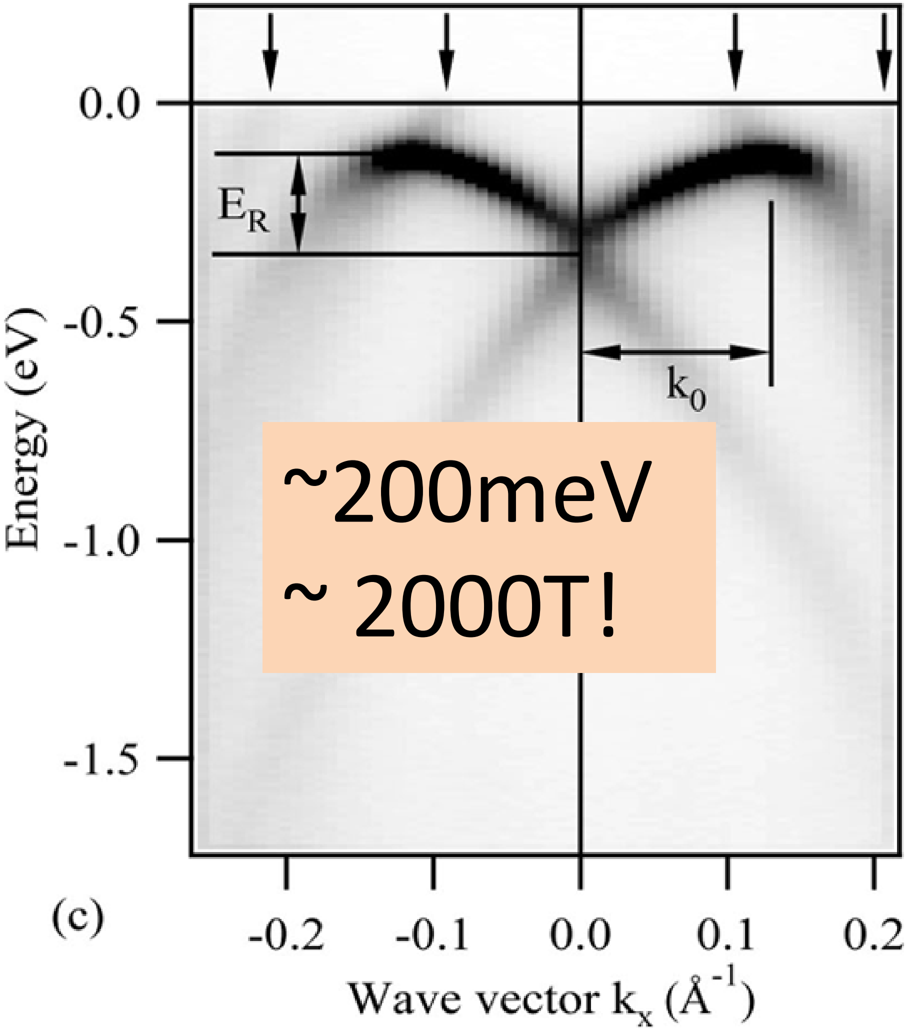


Huge “Magnetic Field”

- Bi on Ag (111)



Ast et al. PRL (2007).



~200meV

~ 2000T!

Rashba Splitting

Rashba splitting band:

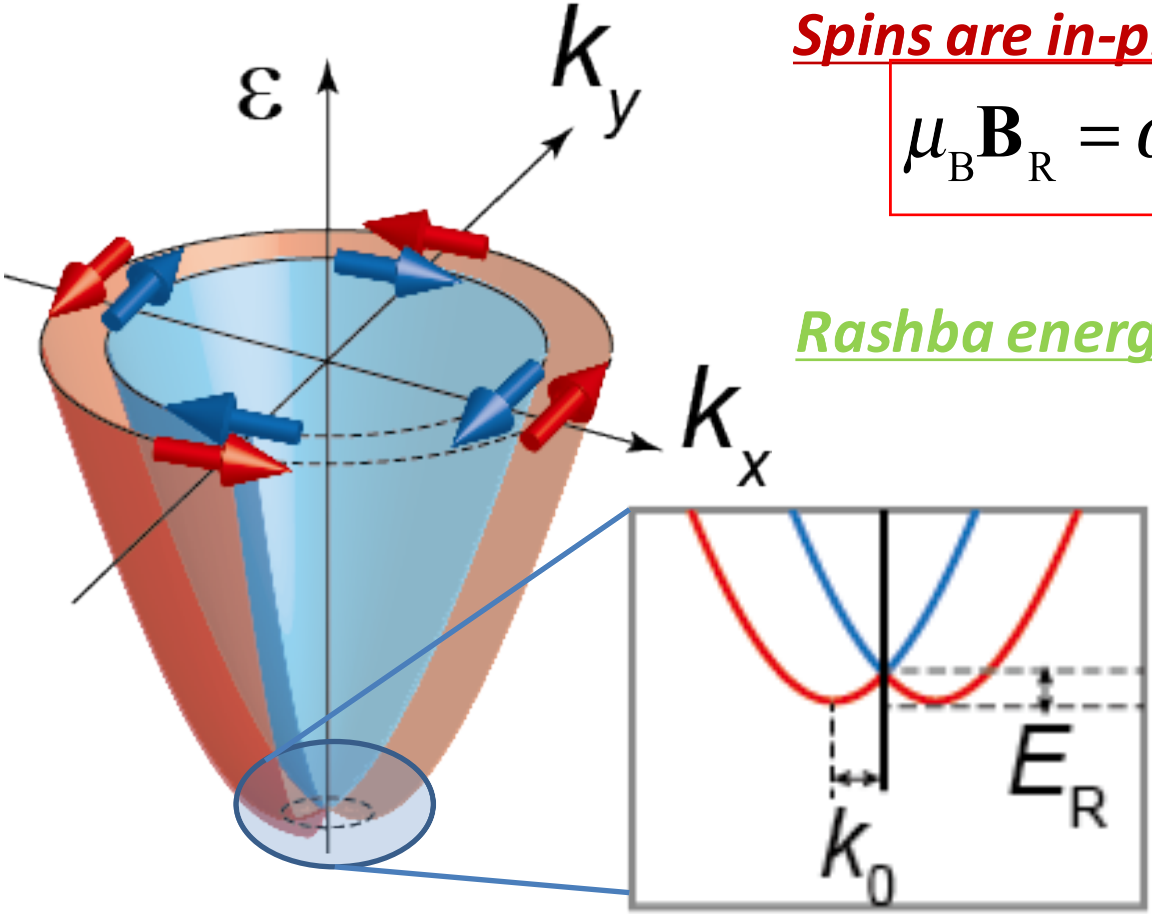
$$\varepsilon_{\vec{k},\sigma} = \frac{\hbar^2}{2m}\left(\left|k_{\parallel}\right| - \sigma k_0\right)^2 - E_{\mathrm{R}}$$

Spins are in-plane

$$\mu_{\mathrm{B}}\mathbf{B}_{\mathrm{R}} = \alpha_{\mathrm{R}}\left(-k_y, k_x, 0\right)$$

Rashba energy:

$$E_{\mathrm{R}} = \frac{m\alpha_{\mathrm{R}}^2}{2\hbar^2}$$



Energy gain

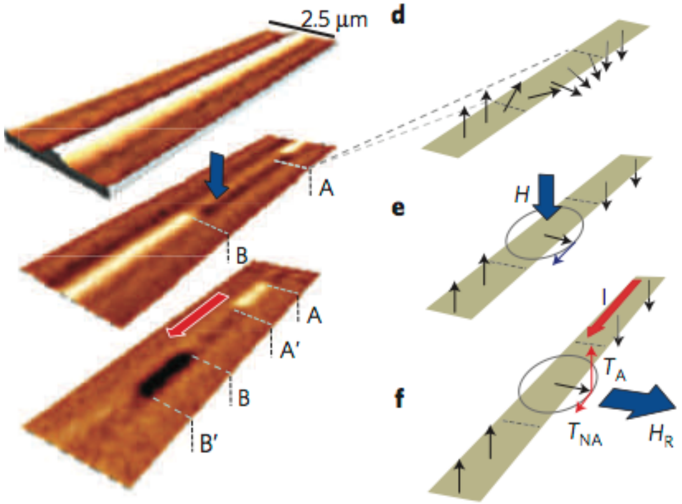
~ 3.5meV

for Au(111)

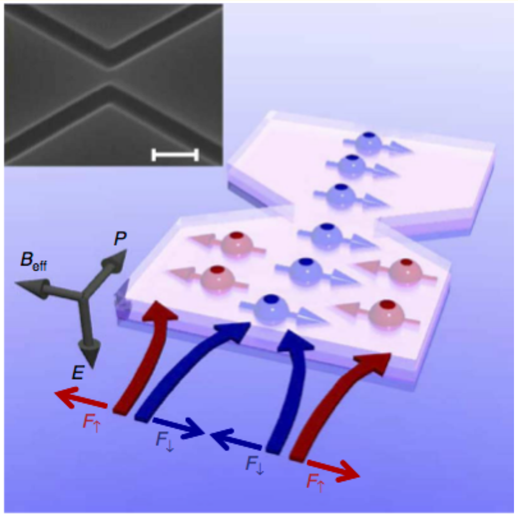
~ 35T!

Rashba in Spintronics

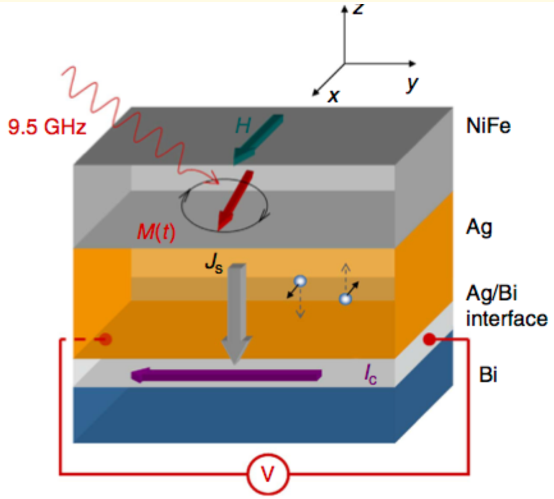
Domain wall motion
[Miron: Nat. Mat. (2011)]



Spin filtering
[Kohda: Nat. Com. (2012)]



Spin-charge conversion
[J. Sanchez: Nat. Com. (2013)]



- ***Non-equilibrium state: current, magnetization dynamics…***

Aim

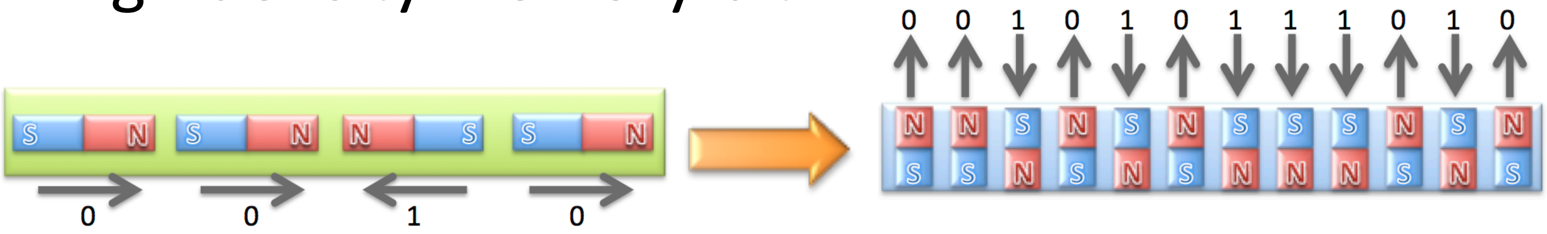
- Perpendicular Magnetic Anisotropy (PMA)

  ➔ *Indispensable properties for MRAM*

  – Simple bit structure for efficient magnetization flips

  – High thermal stability (vs. superparamagnetism)

  – High density memory bit



- Gate control of PMA

  ➔ *Electric control of magnetism*

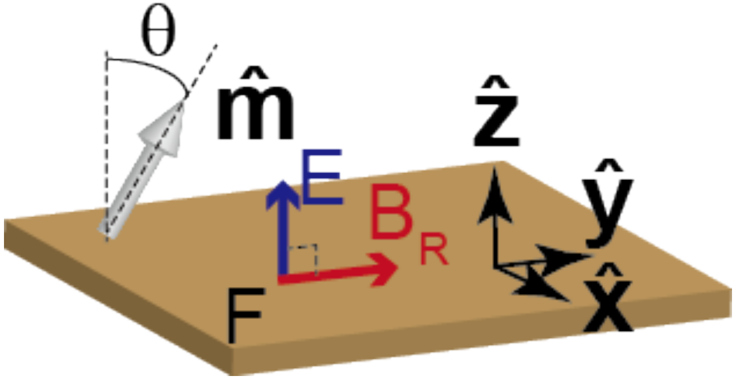
We propose Rashba-induced PMA.

Question

How does the ***in-plane*** Rashba field lead to ***PMA***?

Answer

Cooperation with the exchange interaction.

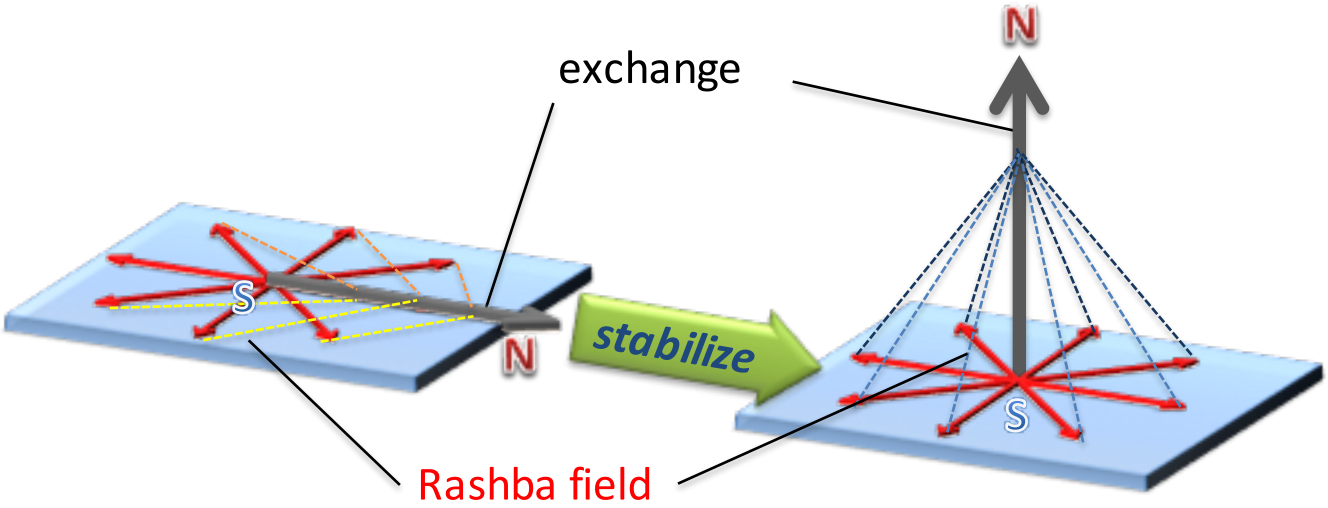


Ultrathin ferromagnetic film

Rashba Field: $\mathbf{B}_\mathrm{R}$

$$\boxed{{}_{\mathrm{B}}\mathbf{B}_{\mathrm{R}} \qquad {}_{\mathrm{R}} \qquad k_y, k_x, 0}$$

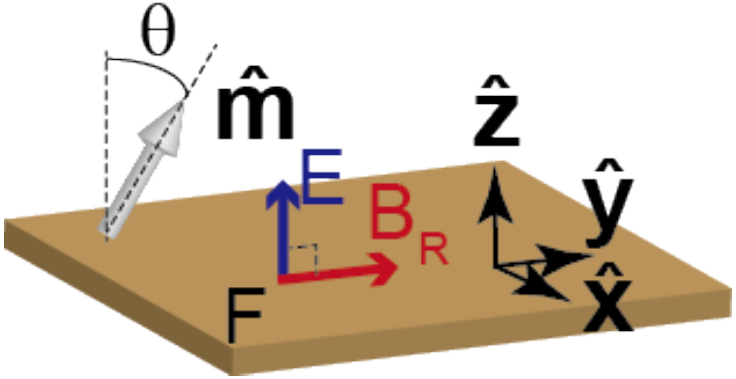
Reinforcement



Model

- Ferromagnet with Rashba SOI:

$$H = \frac{\hbar^2}{2m}\left(k_x^2 + k_y^2\right) - J_0 S\hat{\mathbf{m}}\cdot\boldsymbol{\sigma} + \alpha_{\mathrm{R}}\left(k_y\sigma_x - k_x\sigma_y\right)$$



Ultrathin ferromagnetic film

Magnetization (Order parameter)

$$\hat{\mathbf{m}} \quad \sin \quad \cos \quad , \sin \quad \sin \quad , \cos$$

Rashba Field: **B**$_{\mathrm{R}}$

$$_{\mathrm{B}}\mathbf{B}_{\mathrm{R}} \qquad _{\mathrm{R}} \qquad k_y, k_x, 0$$

Rashba parameter: α_{R}

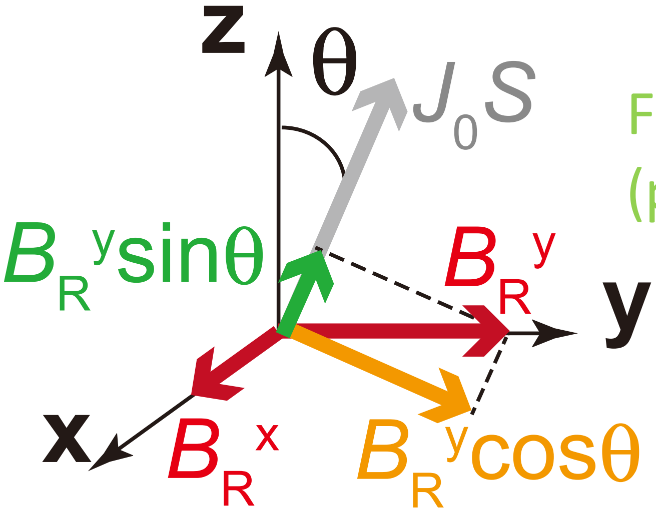
$$_{\mathrm{R}} \qquad _{\mathrm{SO}}E_z$$

α_R & α_R^2 terms

- "Total" field ($J_0\mathbf{S}$ in the *y*-*z* plane).

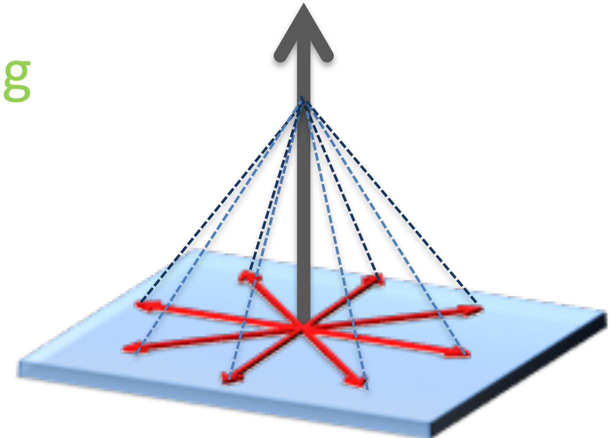
$$\mu_\mathrm{B}\left|\mathbf{B}_\mathrm{tot}\right| = \left[\left(J_0 S+\mu_\mathrm{B} B_\mathrm{R}^y\sin\theta\right)^2+\left(\mu_\mathrm{B} B_\mathrm{R}^y\cos\theta\right)^2+\left(\mu_\mathrm{B} B_\mathrm{R}^x\right)^2\right]^{1/2}$$

$$\simeq J_0 S+\boxed{\alpha_\mathrm{R} k_x\sin\theta}+\boxed{\frac{1}{2}\frac{\alpha_\mathrm{R}^2}{J_0 S}\left(k_x^2\cos^2\theta+k_y^2\right).}$$

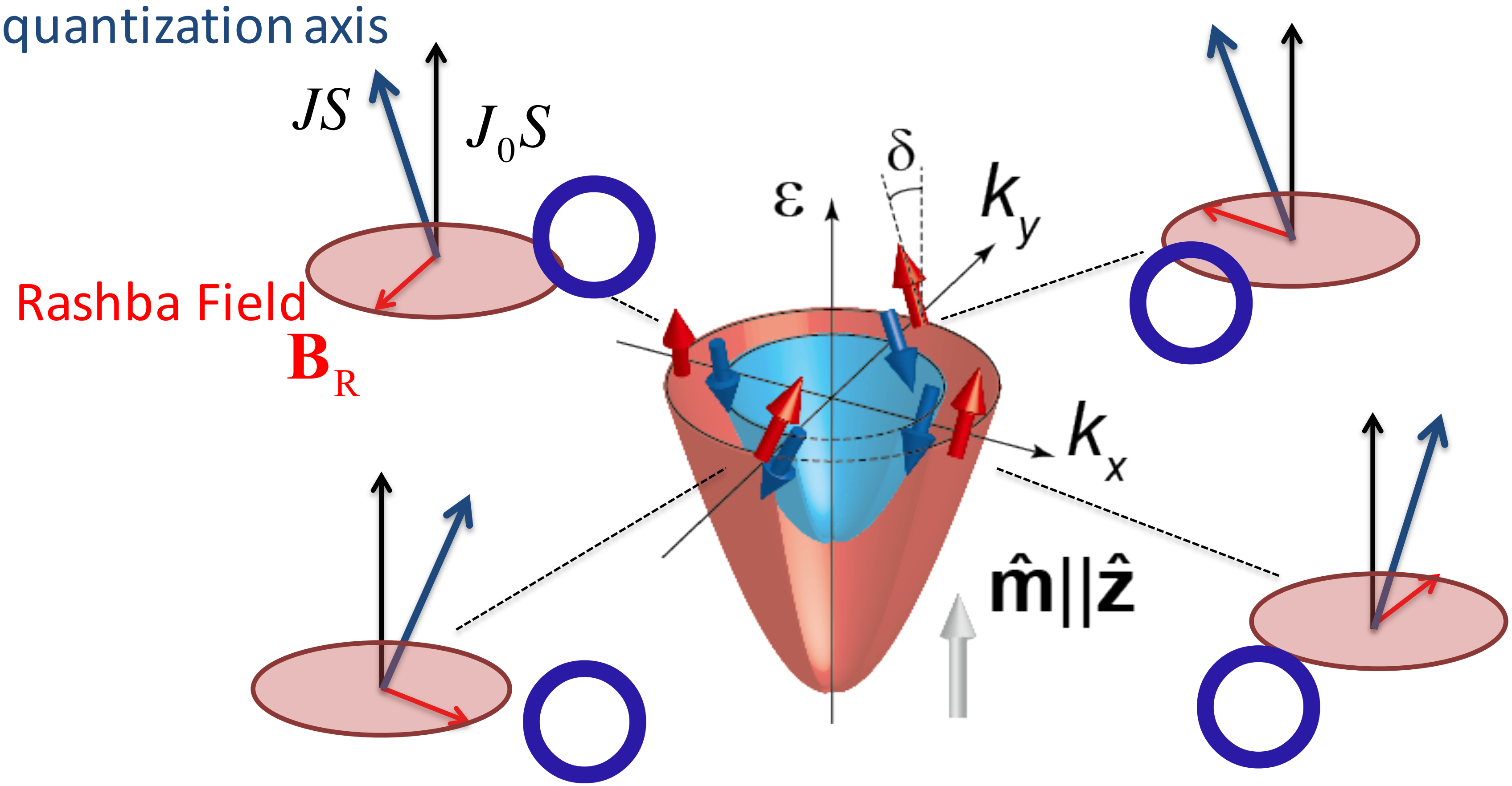


Fermi sea shift &
(partial) Rashba splitting

exchange reinforcement

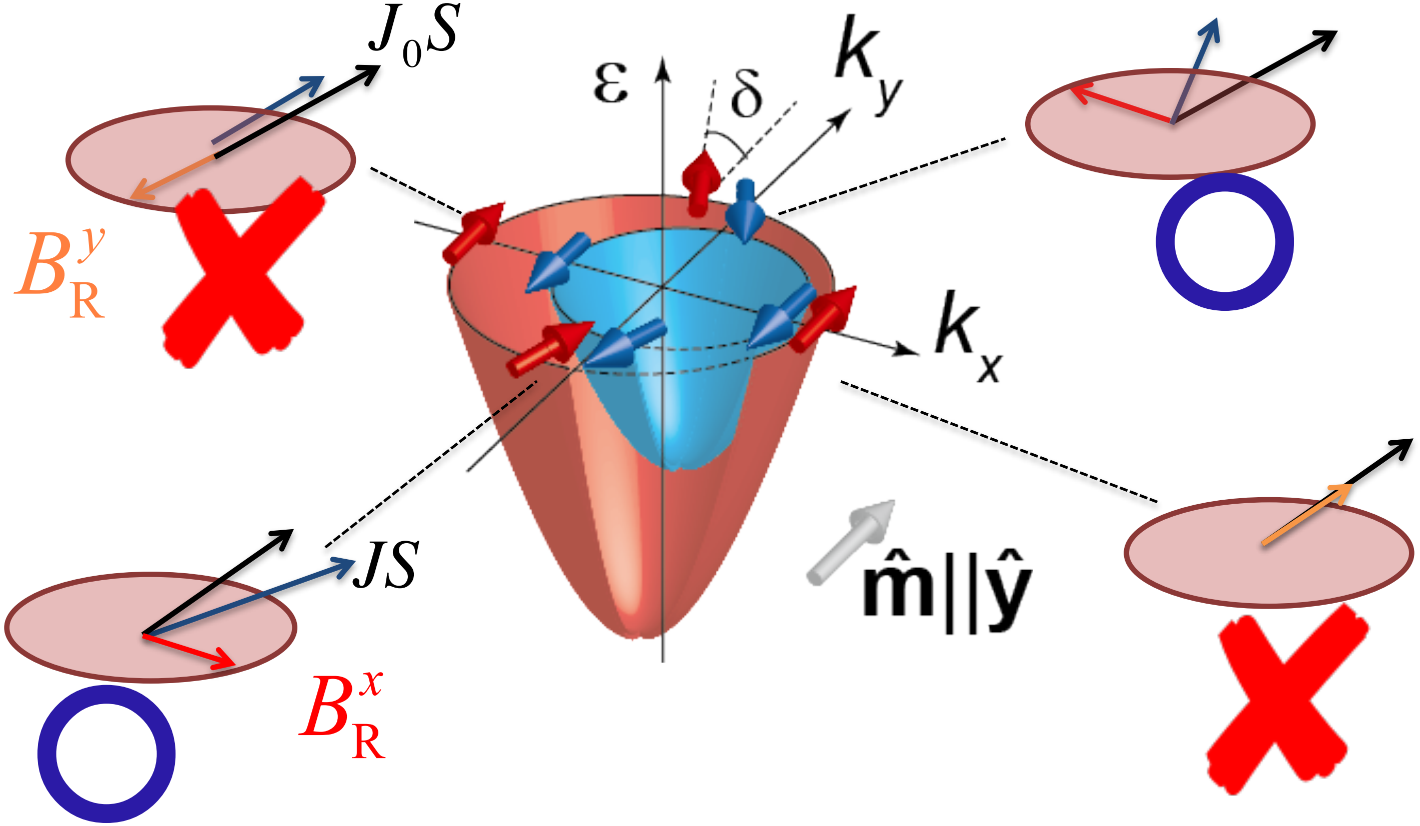


Out-of-plane configuration



Energy gain due to reinforced exchange splitting
(no energy gain from Rashba splitting)

In-plane configuration



Rashba fields go into exchange (B_R^x) and Rashba (B_R^y) splittings.

Rashba-PMA

$$\varepsilon_{\vec{\mathrm{k}},\sigma} = \frac{\hbar^2}{2m}\left[\left(k_x - \sigma k_0 \sin\theta\right)^2 + k_y^2\right] \boxed{- E_{\mathrm{R}} \sin^2\theta}$$

$$-\sigma\left[\left(J_0 S\right)^2 + \boxed{\alpha_{\mathrm{R}}^2\left(k_x^2 \cos^2\theta\right.} + \left.k_y^2\right)\Big]^{1/2}$$

Rashba splitting gain
→ in-plane MA

exchange splitting gain
→ PMA

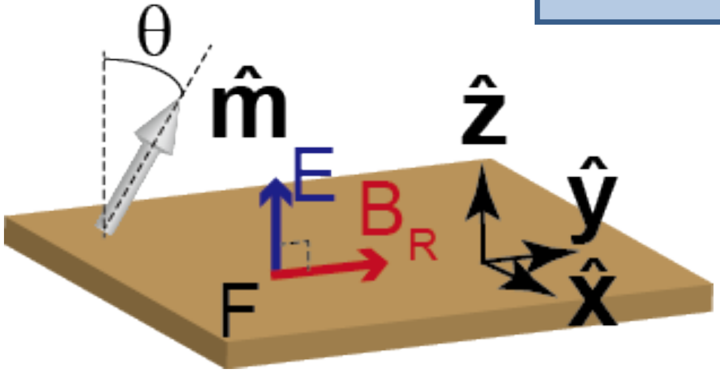
Averaging over occupied states...

Magnetic Anisotropy Energy:

$$\boxed{E_{\mathrm{MA}} \quad E_{\mathrm{R}} \quad 1 \quad \frac{2T}{J_0 S} \quad \cos^2}$$

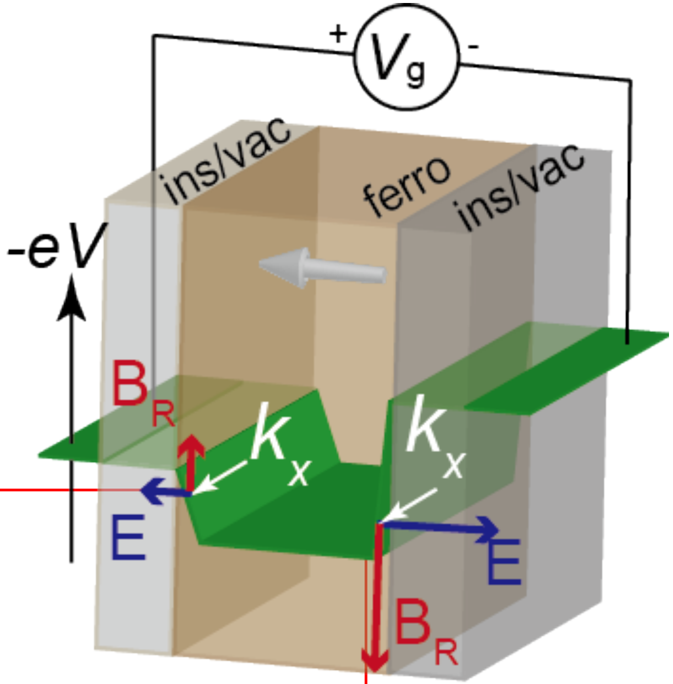
$$E_{\mathrm{R}} = \frac{m\alpha_{\mathrm{R}}^2}{2\hbar^2} \sim 35\mathrm{T}\ (\mathrm{Au})$$

$$T = \frac{\hbar^2}{2m}\left(\left\langle k_x^2\right\rangle_{\uparrow} - \left\langle k_x^2\right\rangle_{\downarrow}\right)$$



Two interfaces interaction

- I/F/I tri-layer with gating



Magnetic Anisotropy Energy:

$$E_{\mathrm{MA}} = \boxed{E_{\mathrm{R}}} \left(1 - \frac{2T}{J_0 S} \right) \cos^2 \theta$$

$$E_{\mathrm{R}} = \frac{m\left(\alpha_{\mathrm{R}}^{\mathrm{top}} + \alpha_{\mathrm{R}}^{\mathrm{bottom}}\right)^2}{2\hbar^2}$$

$$= \frac{me^2}{2\hbar^2}\left[\eta_{\mathrm{SO}}^{\mathrm{top}}\left(E_0^{\mathrm{top}} + E_{bias}\right) + \eta_{\mathrm{SO}}^{\mathrm{bottom}}\left(-E_0^{\mathrm{bottom}} + E_{bias}\right)\right]^2$$

$$\sim \frac{2me^2\eta_{\mathrm{SO}}^2}{\hbar^2}\left(E_{bias}\right)^2$$

MgO/FeB/MgO

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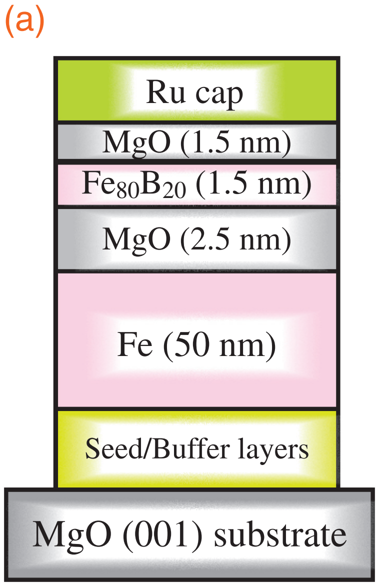
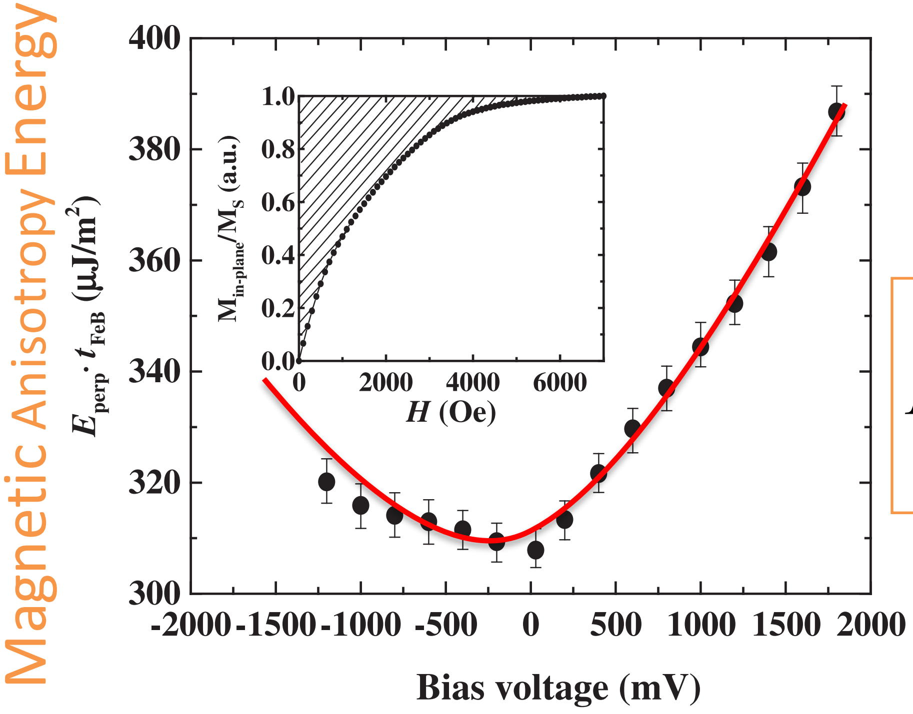
http://dx.doi.org/**10.7567/APEX.6.073005**

Voltage-Induced Magnetic Anisotropy Changes in an Ultrathin FeB Layer Sandwiched between Two MgO Layers

Takayuki Nozaki[1,2*], Kay Yakushiji[1,2], Shingo Tamaru[1], Masaki Sekine[1], Rie Matsumoto[1,2], Makoto Konoto[1,2], Hitoshi Kubota[1,2], Akio Fukushima[1,2], and Shinji Yuasa[1,2]

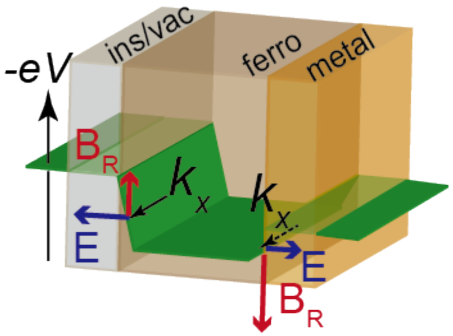




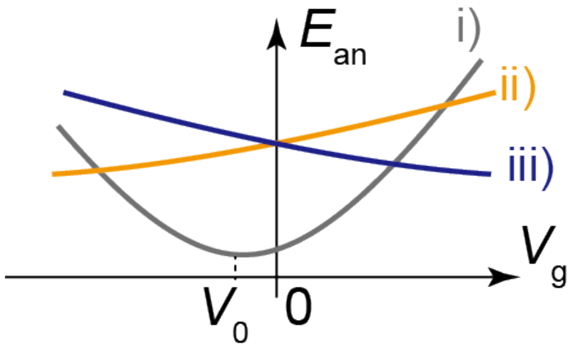
$$E_{\mathrm{MA}} \quad \frac{2me^{2} \quad {}^{2}_{\mathrm{SO}}}{\mathrm{h}^{2}} \quad E_{bias} \; {}^{2} \quad 1 \quad \frac{2T}{J_{0}S}$$

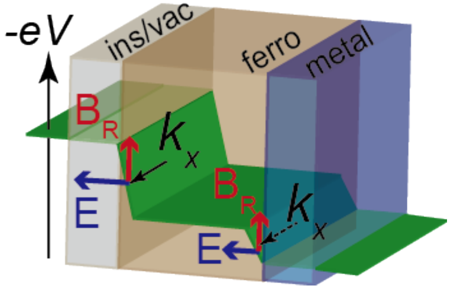
I/F/N tri-layer

- Depending on N-layer…

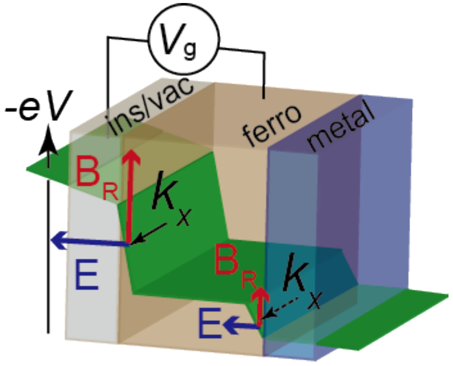


Rashba fields cancel





Rashba fields add



gating experiments distinguish the cases.

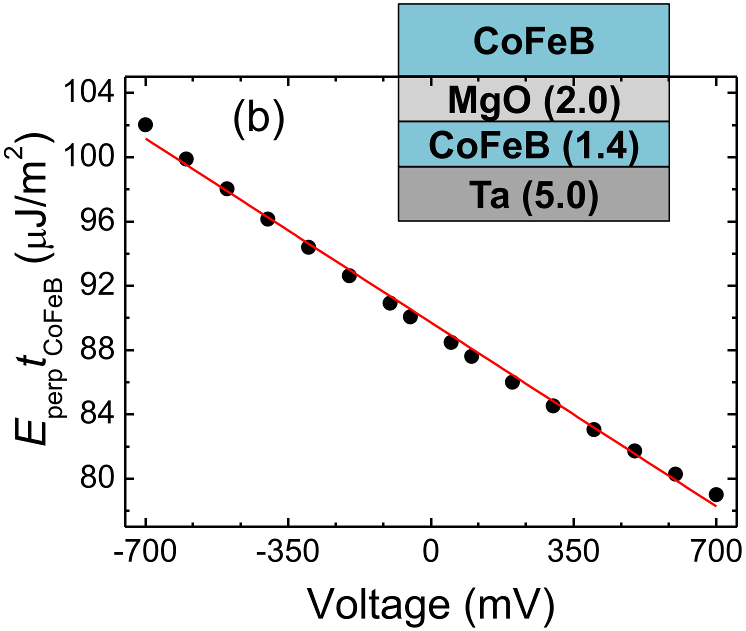
$MgO/Co_{16}Fe_{64}B_{20}/Ta(Ru)$

APPLIED PHYSICS LETTERS **103**, 082410 (2013)

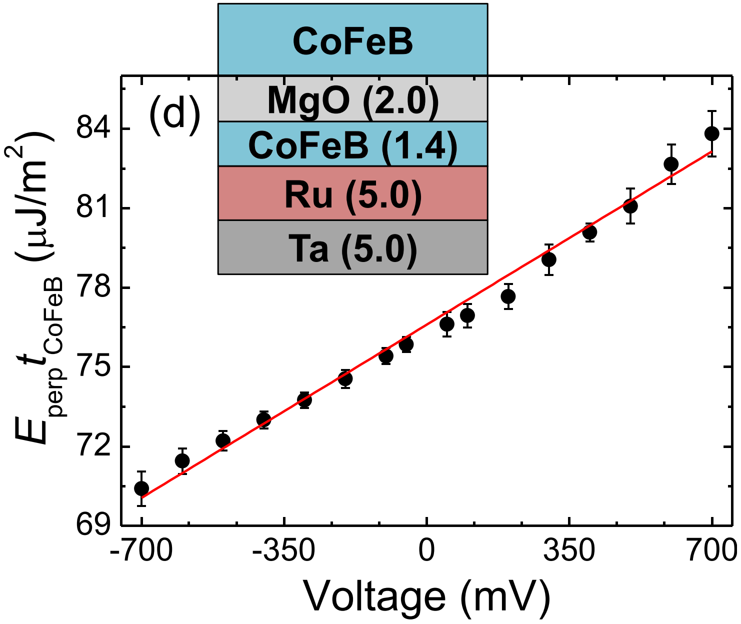
Opposite signs of voltage-induced perpendicular magnetic anisotropy change in CoFeB|MgO junctions with different underlayers

Yoichi Shiota,[1,2] Frédéric Bonell,[1,2] Shinji Miwa,[1,2] Norikazu Mizuochi,[1] Teruya Shinjo,[1]
and Yoshishige Suzuki[1,2,a)]

Ta-MTJ



Ru-MTJ

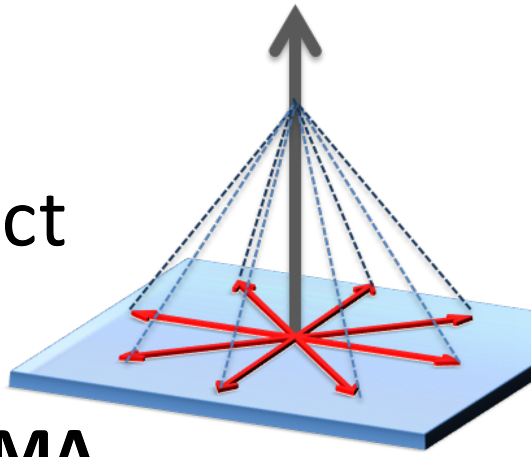


Relative work function:

$\phi^{Ta}-\phi^{Fe}=-0.25$ eV <0

$\phi^{Ru}-\phi^{Fe}=0.21$ eV >0

Summary



- **PMA** mechanism due to Rashba effect
- Two energy gain processes:
  - Reinforced exchange splitting -> **perp. MA**
  - Residual Rashba splitting -> **in-plane MA**
- Magnetic anisotropy energy scales with Rashba energy E_R and can be changed by applied field ***E***.

Ref.: Scientific Reports 4, 4105 (2014).