Study of the voltage-controlled perpendicular magnetic anisotropy (PMA) in Ta/FeB/MgO and W/FeB/MgO nanowires by the Hall effect measurements

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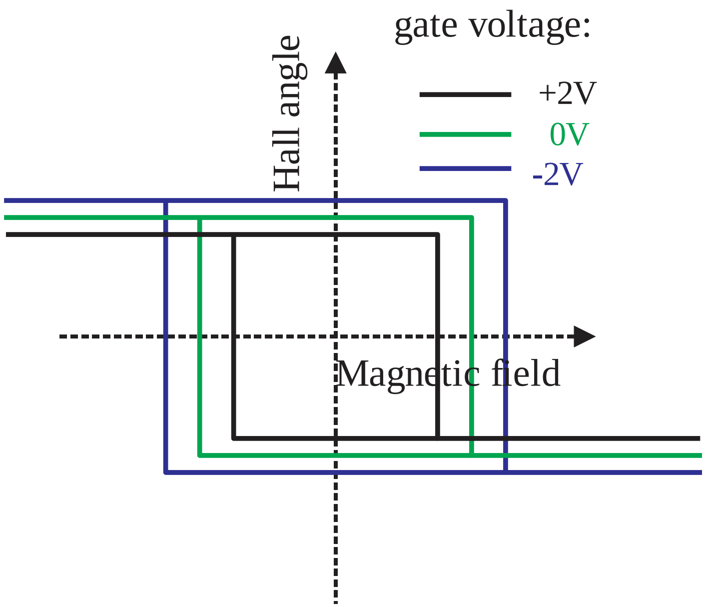

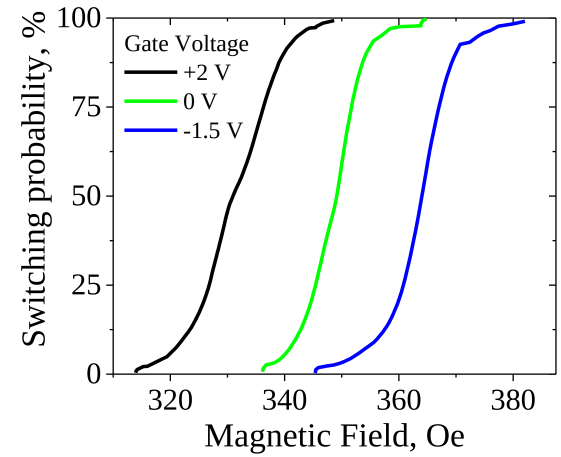

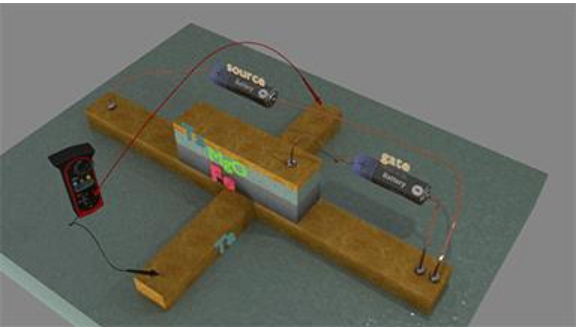

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Purpose:

1: *To clarify* ***origin*** *of the voltage-controlled PMA effect in a FeCoB thin film*

2: *Possible* ***enhancement*** *of the voltage-controlled PMA effect*

This work:

1: *Measurements of voltage-dependence of* ***coercive field, Hall angle, anisotropic field and switching time*** *in a FeB film and* $(FeB/W)_n$ *multilayer*

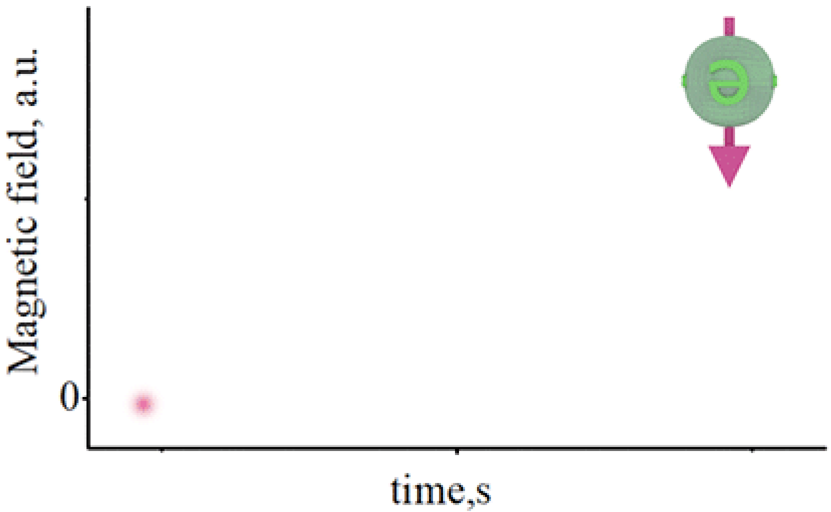
2: ***Enhancement*** *of the voltage-control PMA effect in* $(FeB/W)_n$ *multilayers*

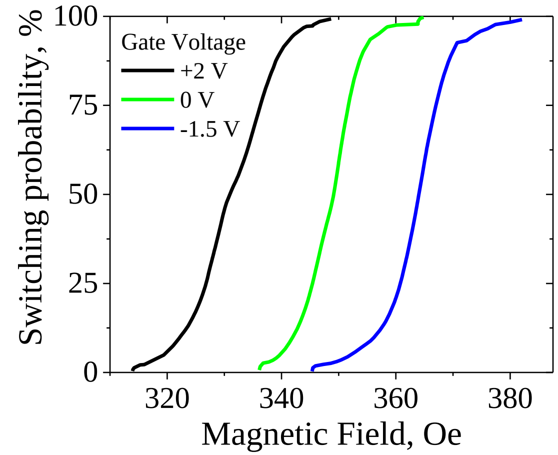
"Optimized" measurement method of coercive field

step 1: Rough measure of switching field (conventional)

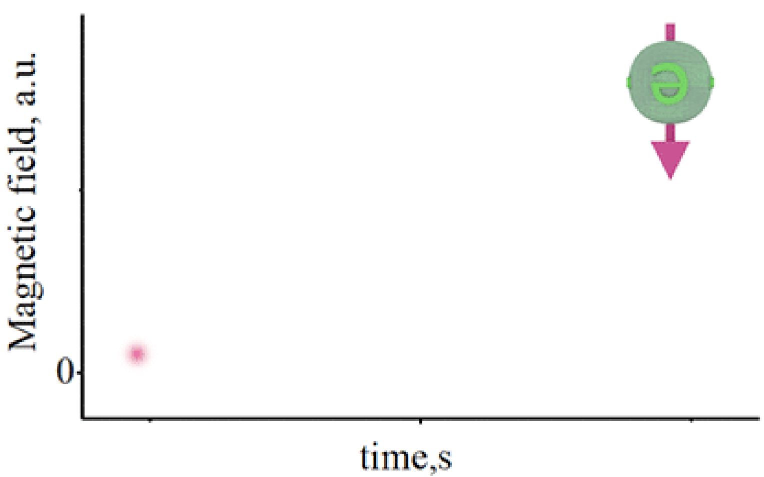
Zhang *et.al*. Phys. APL (2015)

Jinnai *et.al*. Phys. APL (2017)





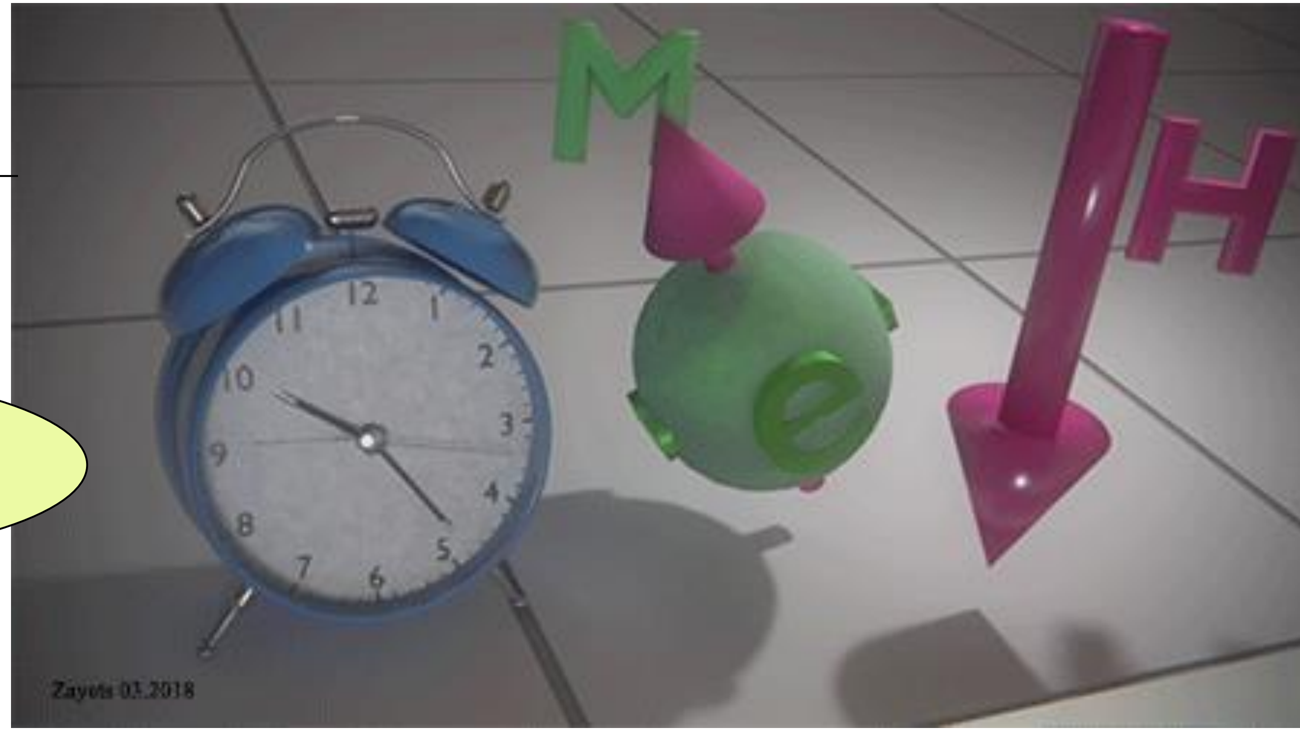
step 2: Measure of switching time



two methods are combined!!!

To get the required precision within a shorter time

Measurement of switching time



Neel-Brown relaxation time

Néel-Arrhenius equation

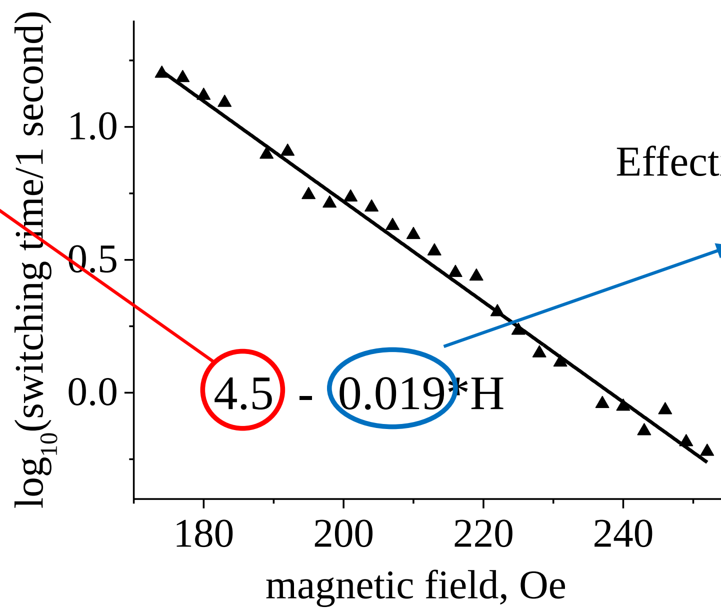
$$\text{switching time} \sim e^{-\frac{E_{PMA} - \vec{H}\cdot\vec{M}}{kT}}$$

W.F.Brown, PR (1963)

Li and Zhang, PRB (2004)

R.H.Koch, PRL (2000)

retention time=$10^{4.5}$ seconds

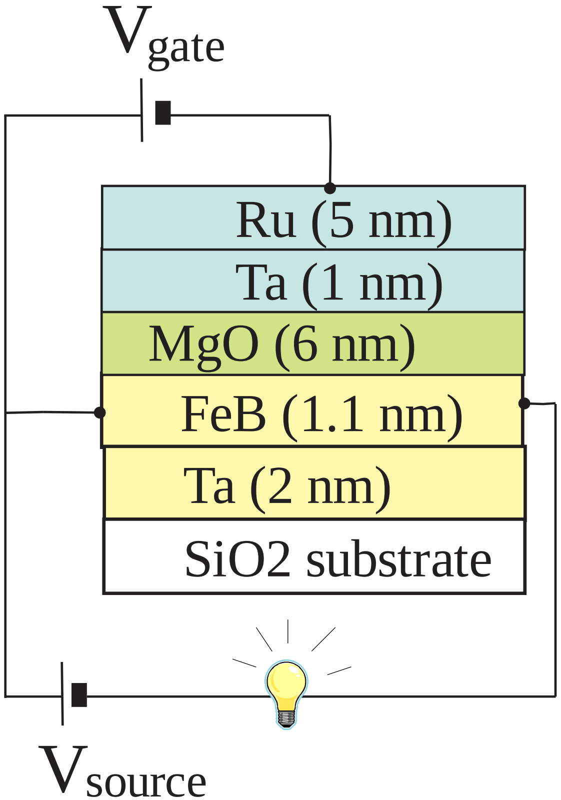


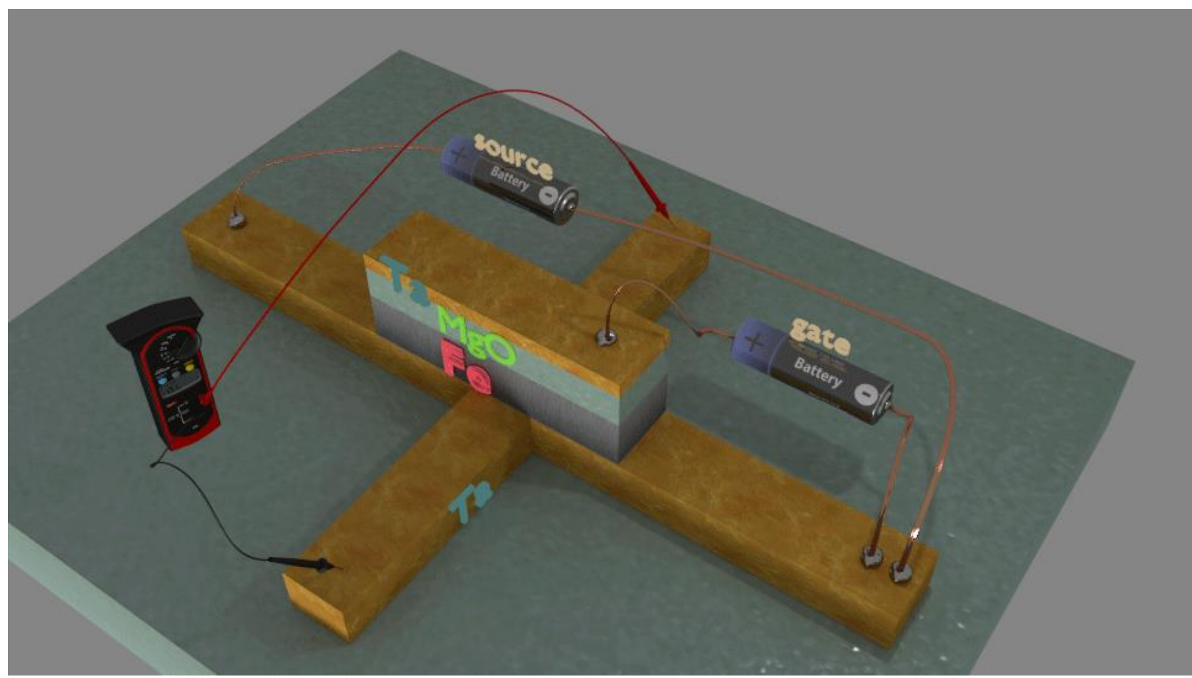
Effective magnetization

wire width: 400 nm
gate length: 10 µm

Ta(2): FeB(1.1)/ MgO(7)/Ta(1)/Ru(5)

Samples





Similar setup:

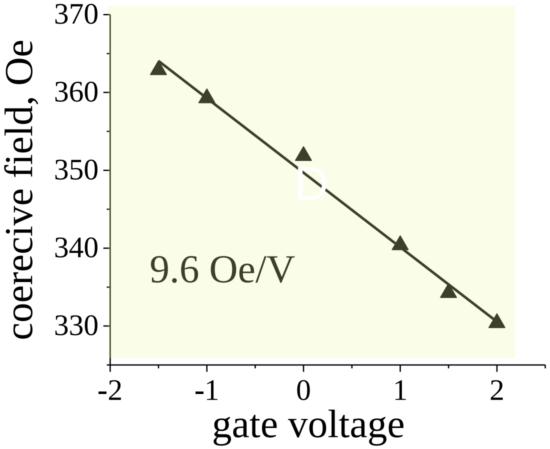
M. Endo *et al*, APL (2010)

D. Chiba *et al*, Nature Mat. (2011)

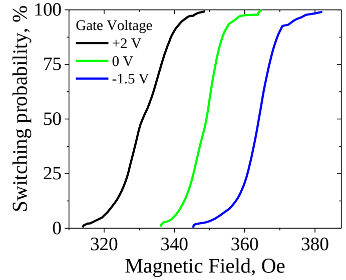
Measurement of voltage-controlled PMA effect

4 independent measurements. All data are from ***Hall measurements***

1) gate-voltage dependence of ***coercive field***

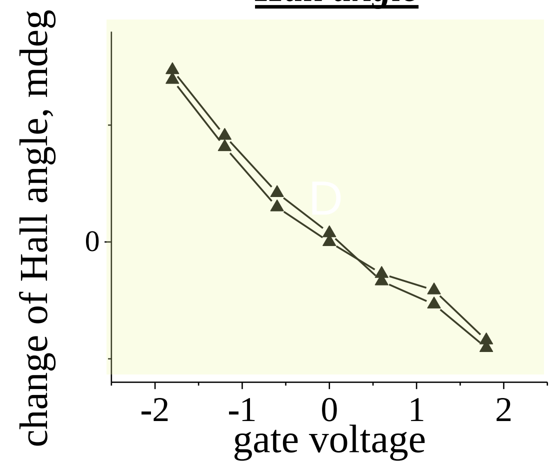


range: *1-11 Oe/V*



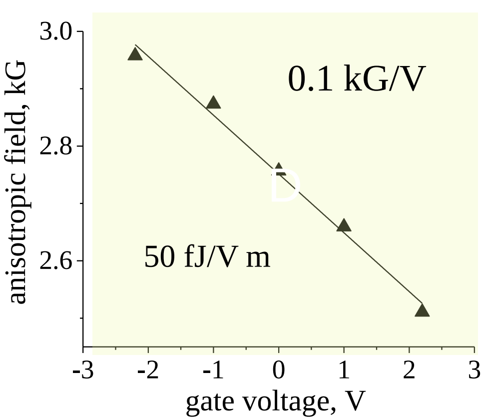
	symmetry	slope
M. Endo *et al*, APL (2010)	***A***	***N***
V.B. Naik *et al*, APL (2014)	***A***	***N***
H.Meng et al, APL (2014)	***A***	***P***
J.Huang, JMMM (2016)	***A***	***N +P***
W.G.Wang, Nat. Mat. (2012)	***A***	***N***

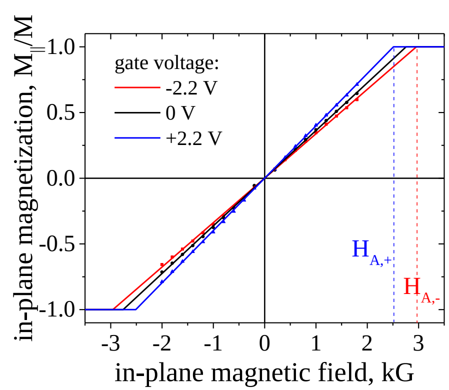
2) gate-voltage dependence of ***Hall angle***



range: *0.01-13 mdeg/V*

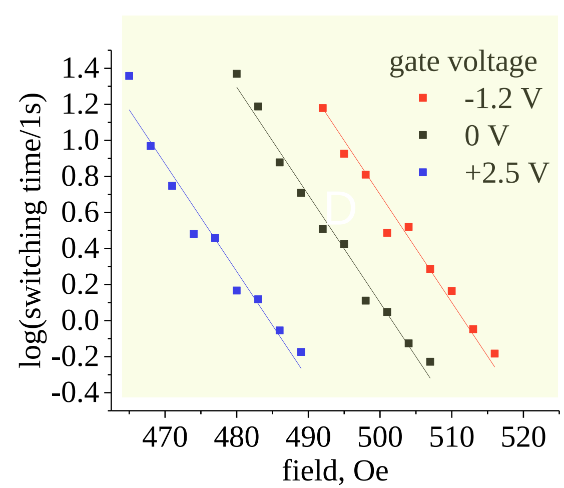
3) gate voltage dependence of ***anisotropy field***





MTJ	symmetry	slope
T. Nozaki, PR Appl. (2016)	***A***	***N***

4) gate voltage dependence of ***retention time, Δ, PMA energy and magnetization***

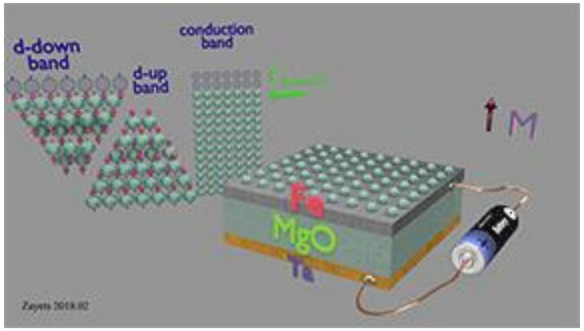


Fitting to existing models

Comparison for <u>symmetries</u> and <u>polarities</u>

Possible origins

of the effect of voltage-controlled PMA

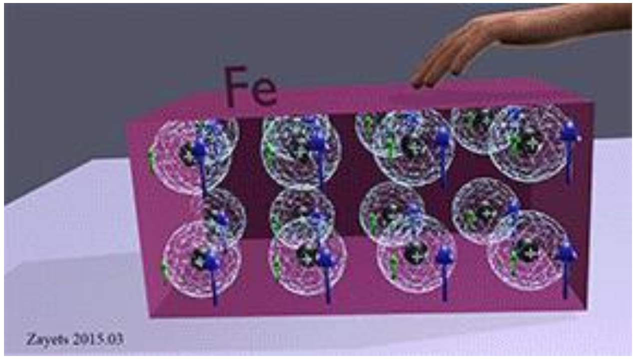


origin 1: dominant

Charge accumulation/depletion, modulation of Fermi level

asymmetrical vs voltage

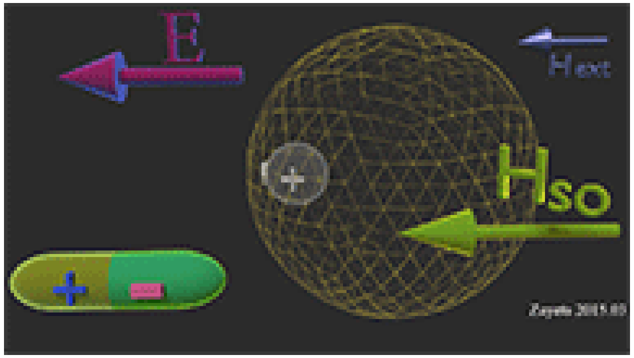
- H.Ohno *et al*, Nat. (2000)
- J. Zhang *et al*, PRB (2017)
- M. Endo *et al*, APL (2010)
- M. Tsujikawa,T. Oda, PRL. (2009)
- K. Nakamura *et al*, PRB (2009)
- D. Chiba *et al*. Nature (2008))



origin 2: ***magnetostriction effect***

symmetrical vs voltage

- C. Song, X.Zhou, Prog. Mat. Sci. (2017)



origin 3: ***Orbital reconstruction***

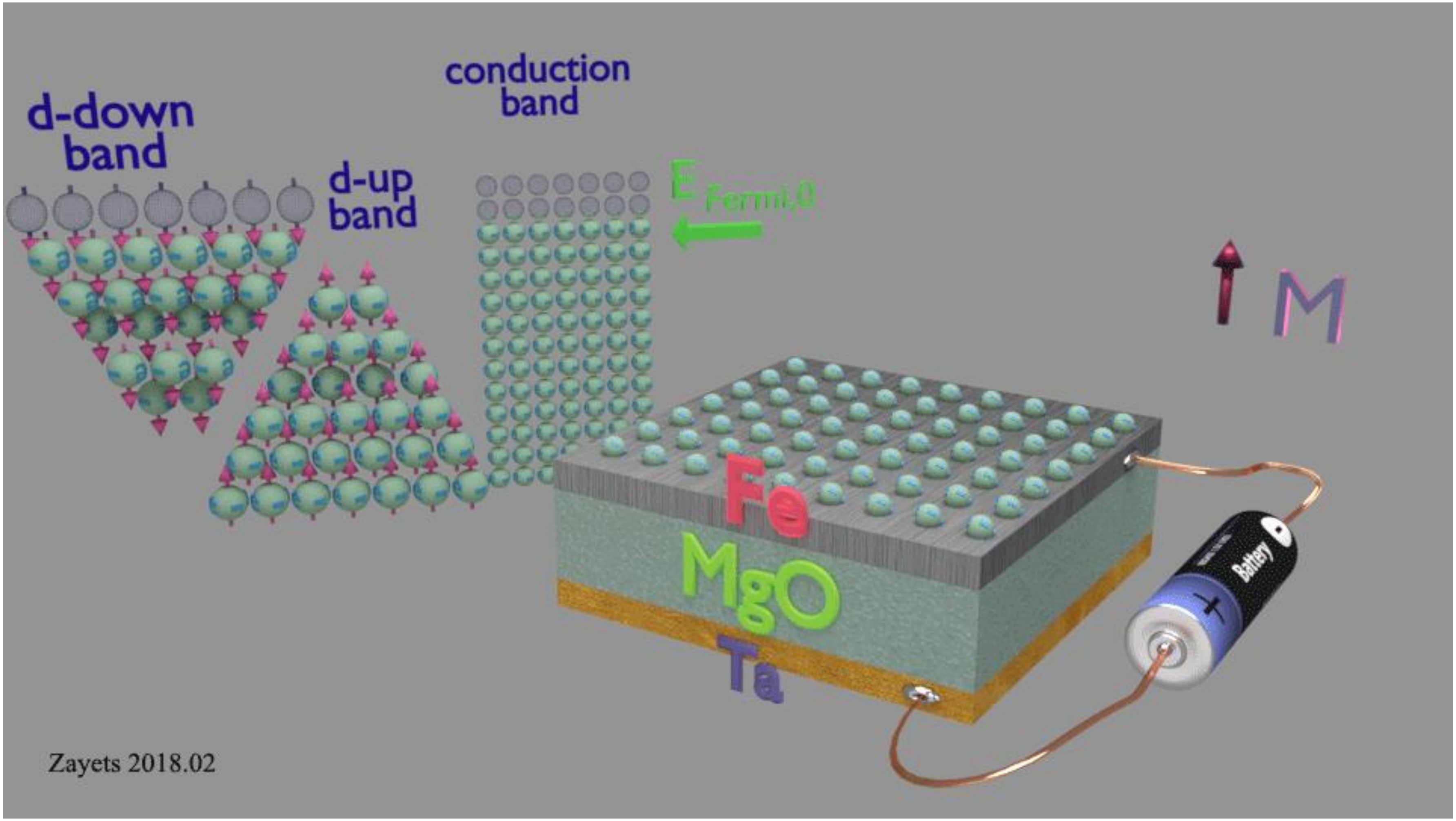
symmetrical + **asymmetrical** vs voltage

- S.Miwa *et al*, Nat. Comm. (2017)
- F. Maruyama *et al*, Nat. Nanotech. (2009)

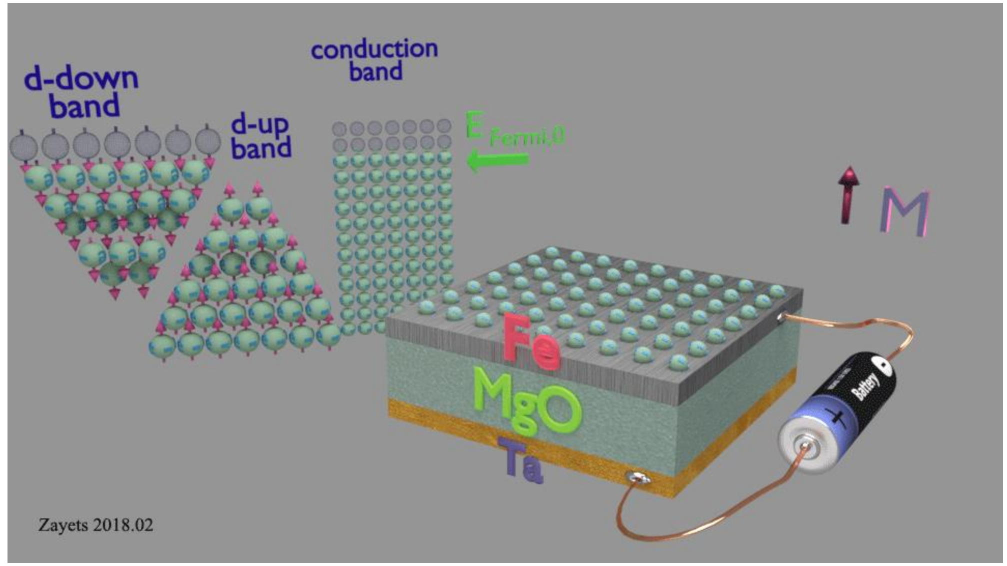
origin 4: ***Ion electro-diffusion & position reconstruction***

- J.Carcia-Barriocanal *et al*, Nat. Comm. (2010)
- C.Bi *et al*, PRL. (2014)

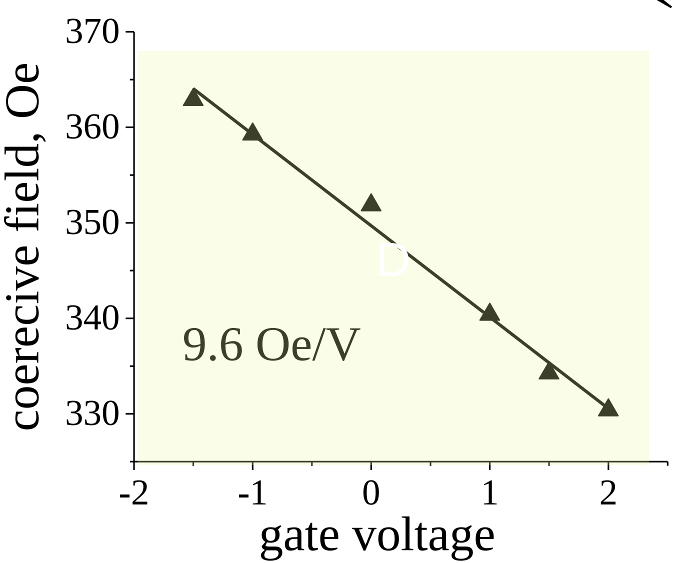
Charge accumulation/depletion or the effect of a capacitor

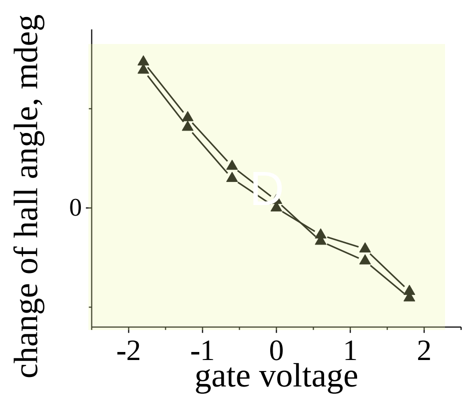


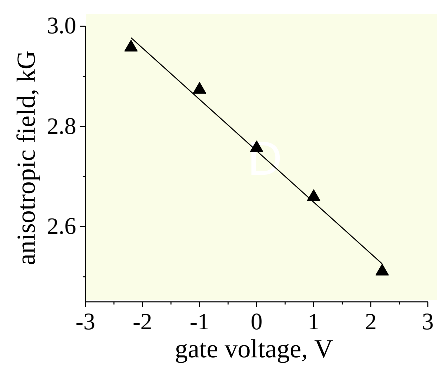
Charge accumulation/depletion or the effect of a capacitor



all asymmetric
+
negative slope







FeB/W multilayer

merit 1: ***well-matched*** BCC structure

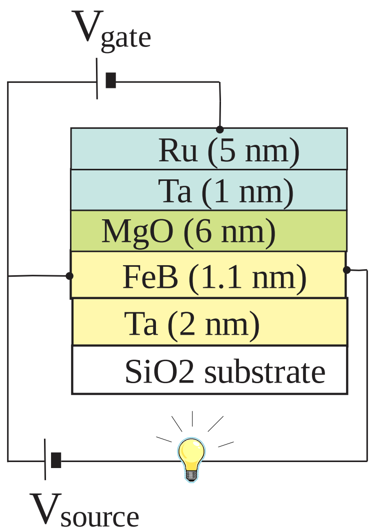
merit 2: **substantial PMA** at FeB/W interface

- J. Chatterjee *et al*, APL (2017)
- D. C. Worledge,*et al*, JAP (2014)
- W. Skowronski *at al*, JAP (2015)

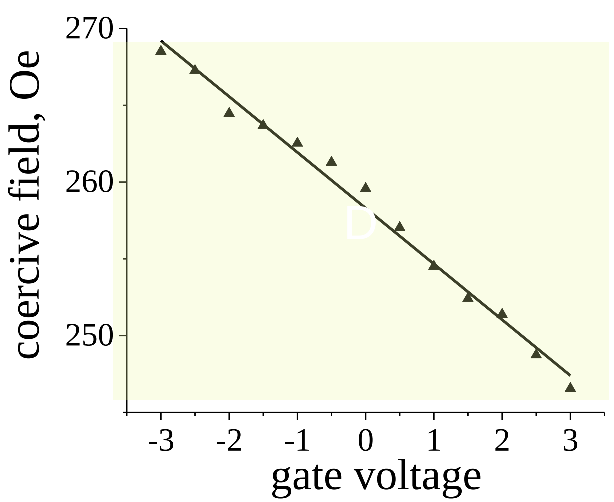
merit 3: a **thick film** with a substantial PMA and VCMA

FeB/W multilayer

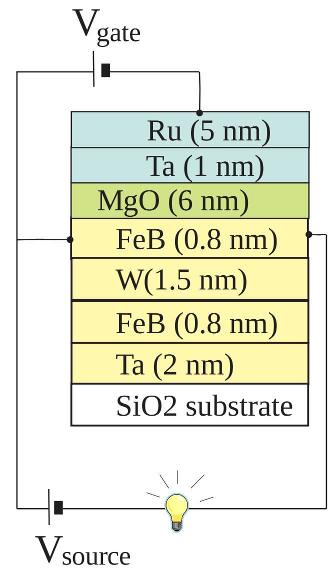
***without* tungsten**



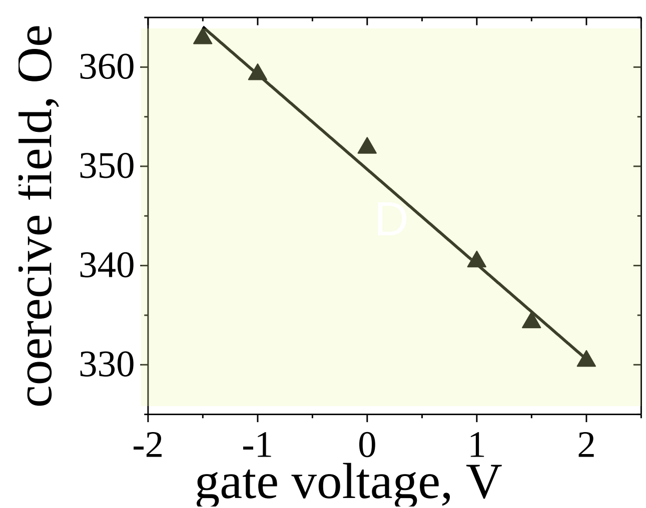
3.7 Oe/V



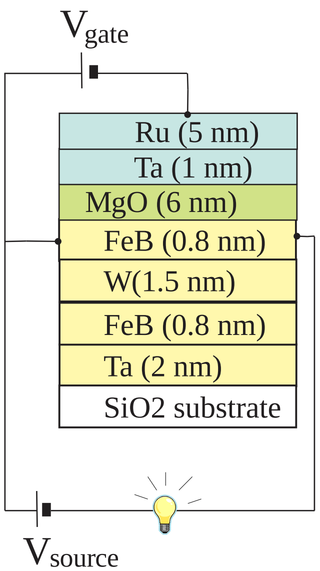
***with* tungstem**



9.6 Oe/V



FeB/W multilayer



possible <u>reason 1</u>: **<u>blocking</u>** diffusion of Ta

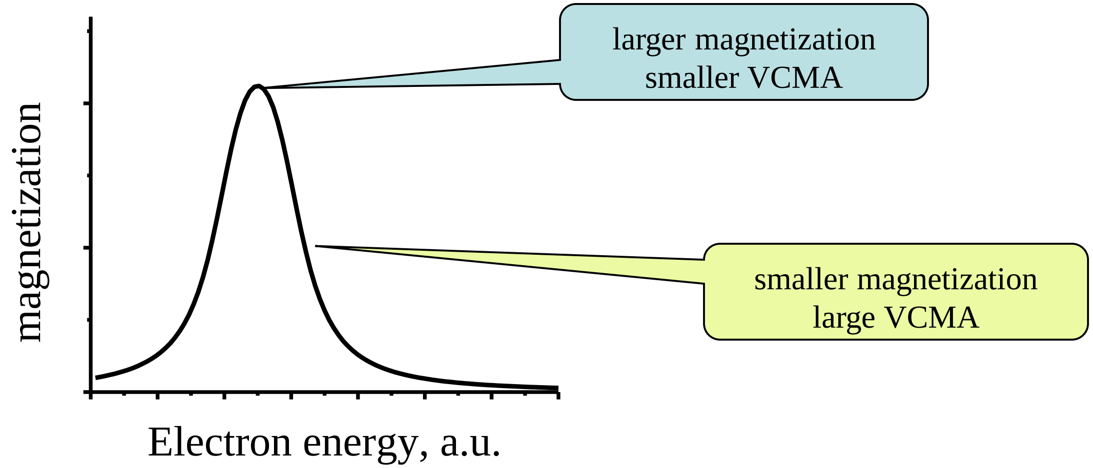
J. Chatterjee *et al*, APL (2017)

possible <u>reason 2</u>: **<u>Work-function Engineering</u>**

Work-Function
Engineering of magnetic properties

Magnetization vs Fermi level position

Oversimplified



Work-Function
Engineering of magnetic properties

Ab initio first-principal calculations

A.A. Katanin *et al*, PRB (2010)

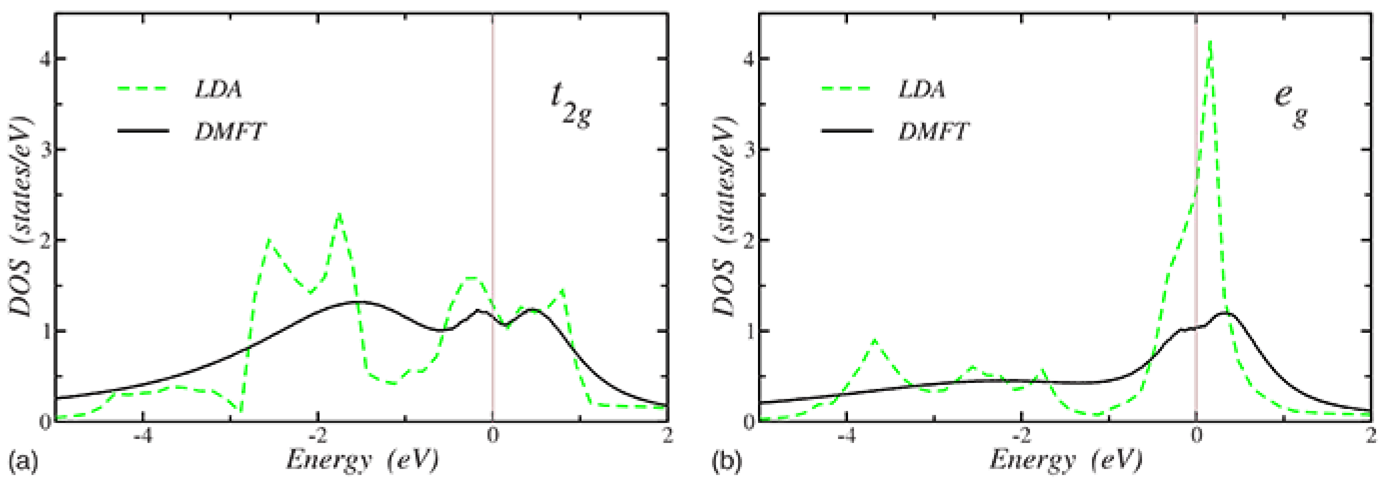


FIG. 5. (Color online) The iron t_{2g} (left panel) and e_g (right panel) partial density of states obtained within LDA+DMFT method (black solid lines) compared with LDA DOS (green dashed lines).

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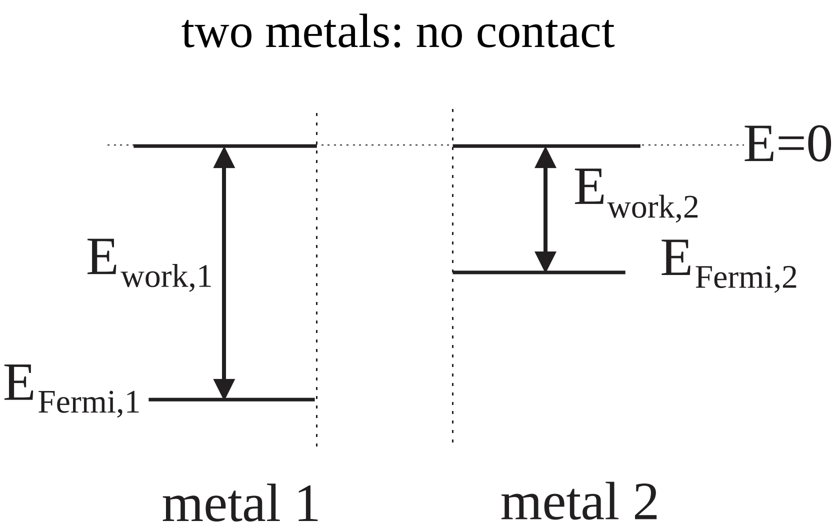
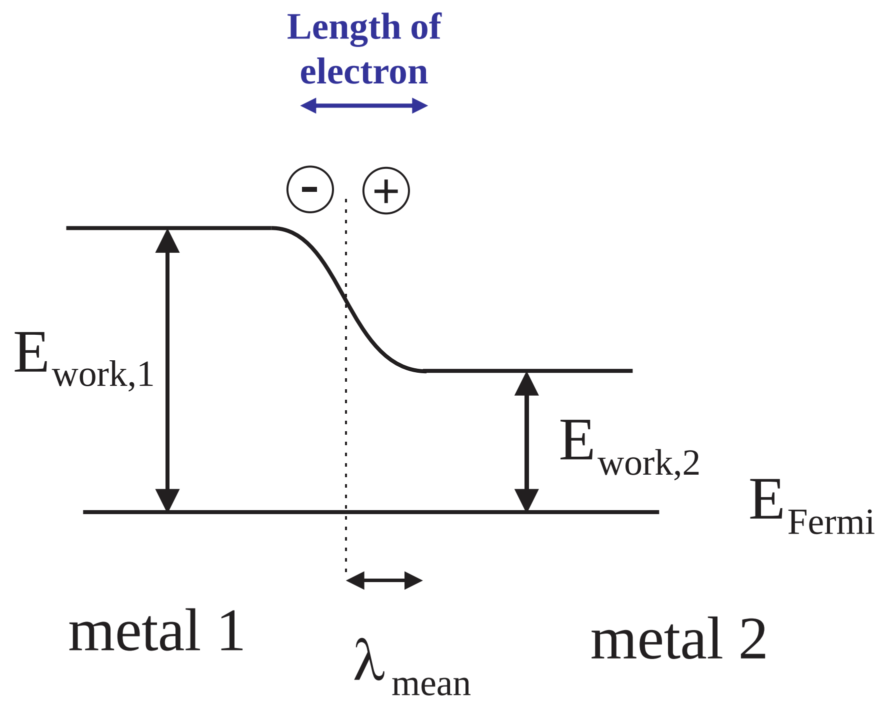
Work-Function
Engineering of magnetic properties





Conclusions

1: “***optimized” measurement method*** *of magnetic properties of a nanomagnet*

coercive field (~1 Oe), effective magnetization, Δ, retention time, anisotropic field,

2: ***Measurements*** *of the voltage-control PMA effect*

1. coercive field vs gate voltage : *2-11 Oe/V , negative slope*
2. Hall angle vs gate voltage : *0.01-20 mdeg/V , negative slope*
3. Δ vs gate voltage: *negative slope*
4. Anisotropic field vs gate voltage: *50 Oe/V, negative slope*

3: *A possible* ***Origin*** *of the voltage-control PMA effect in a FeB/MgO thin film*

Modulation of Fermi level

4: ***Enhancement*** *of the voltage-control PMA effect in a FeB/W multilayer*

4 Oe/V -> 10 Oe/V