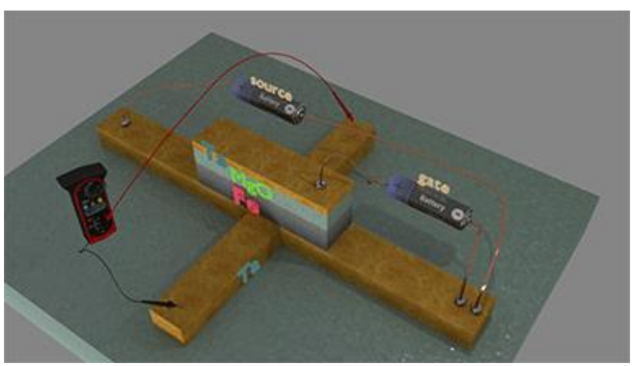
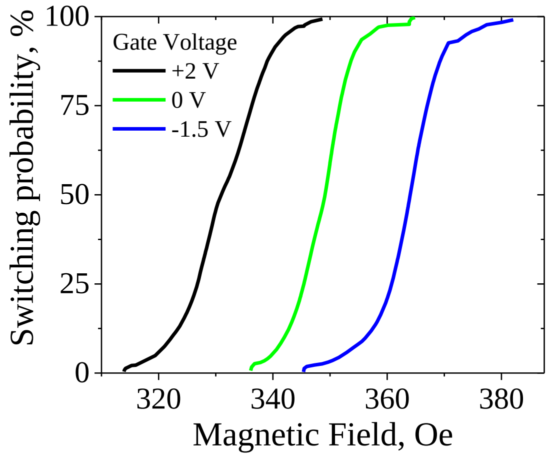
Study of voltage-controlled magnetic anisotropy (VCMA) in a FeB thin film and a FeB/W multilayer by the Anomalous Hall effect

V Zayets , A. Fukushima, T. Nozaki , H.Saito, and S.Yuasa

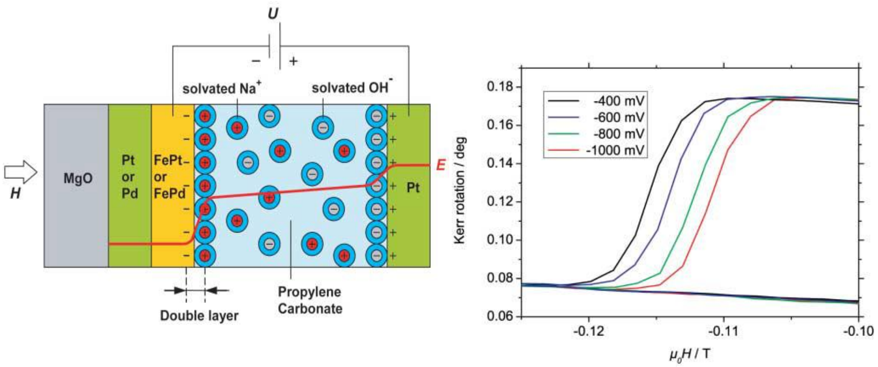




Spintronics Research Center, AIST, Tsukuba, Japan

Voltage-controlled magnetic anisotropy. VCMA effect

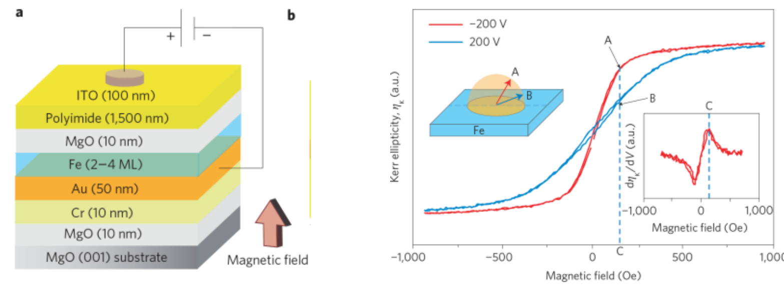
2007. 1st demonstration



M. Weisheit *et al*, Science (2007)

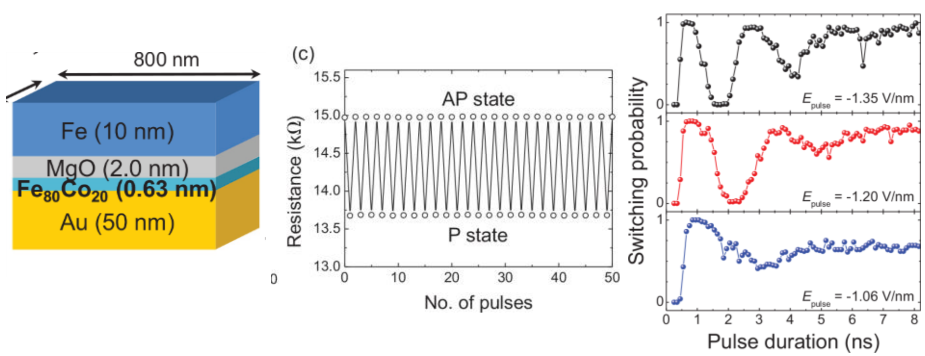
2009. 1st solid-state device

practical device



T. Maruyama *et al*, Nature Nanotech. (2009)

2012. 1st high-speed voltage-induced magnetization reversal



Y. Shiota *et al*, APL(2012)

High-speed, low-power consumption MRAM

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*

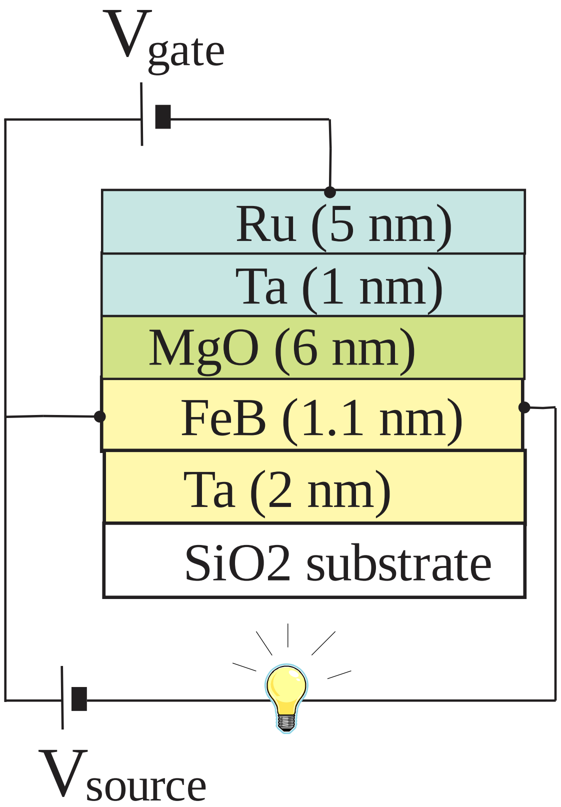
This work:

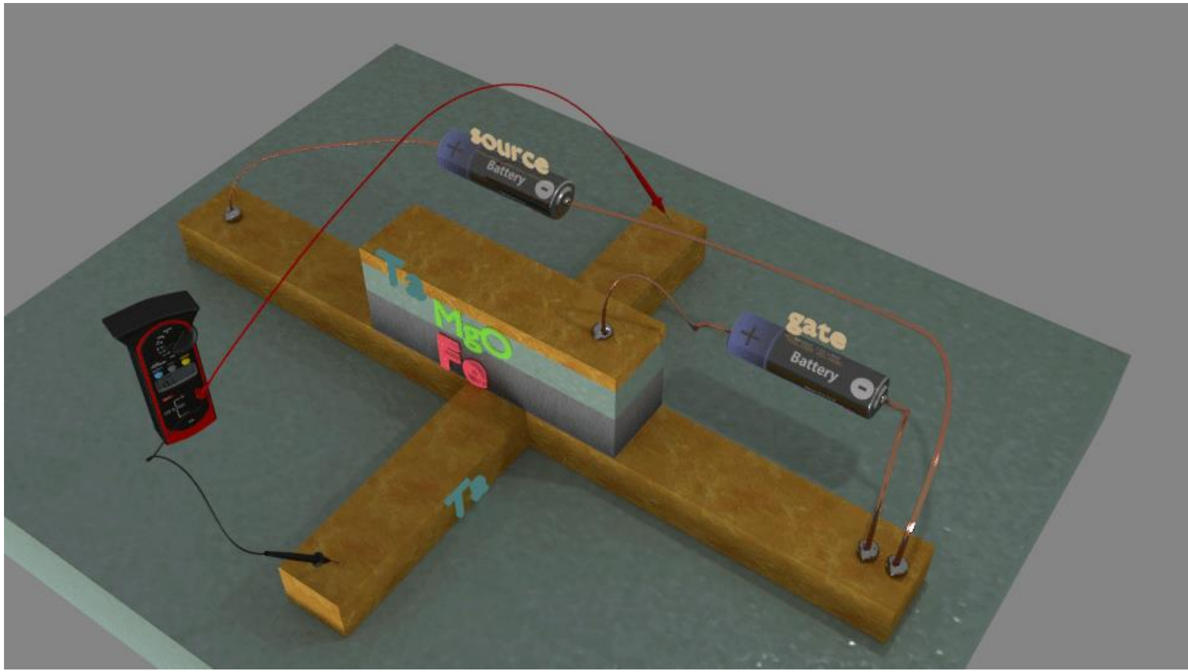
1: *Measurements of voltage-dependence of **coercive field, Hall angle, anisotropic field and switching time** in a FeB film and* $(FeB/W)_n$ *multilayer*

High-reliability, high-precision

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

Samples

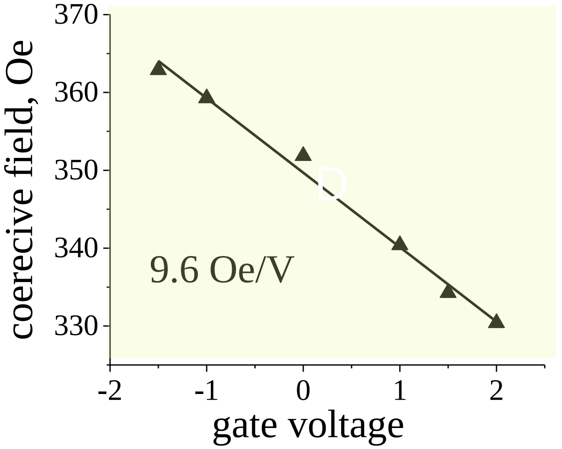

V_{gate}
Ru (5 nm)
Ta (1 nm)
MgO (6 nm)
FeB (1.1 nm)
Ta (2 nm)
SiO2 substrate
V_{source}


source
Battery
gate
Battery
Ta
MgO
Fe
Ta

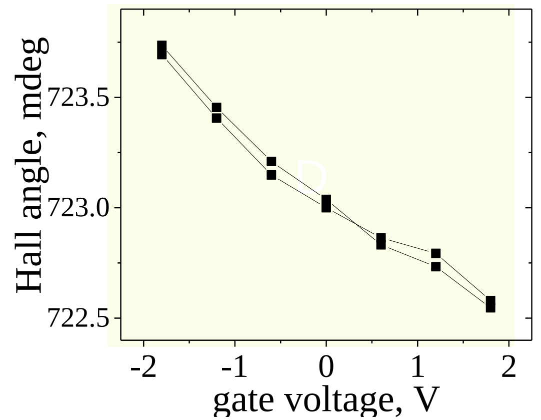
Measurement of voltage-controlled PMA effect

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

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



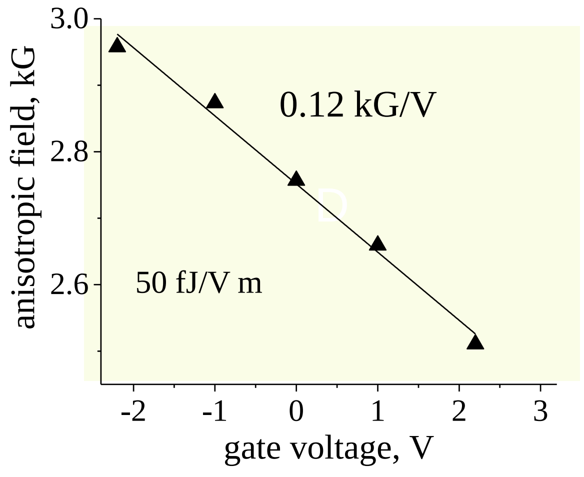
2) gate-voltage dependence of ***Hall angle***



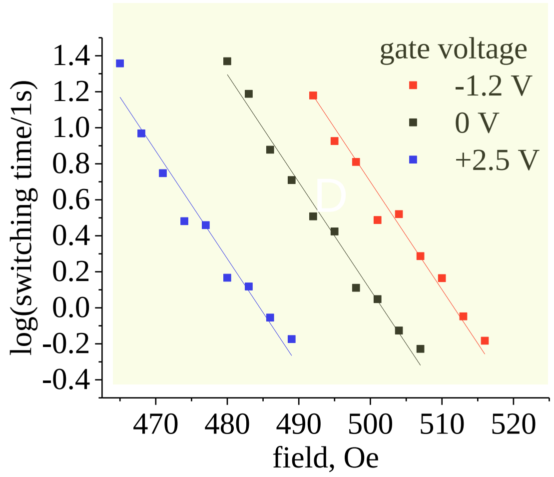
range: *0.01-13 mdeg/V*

Same tendency!
Negative polarity!

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

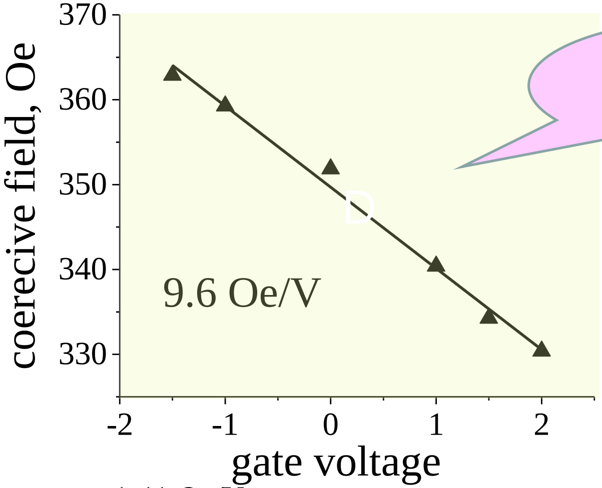


4) gate voltage dependence of ***retention time, Δ, PMA energy and magnetization***



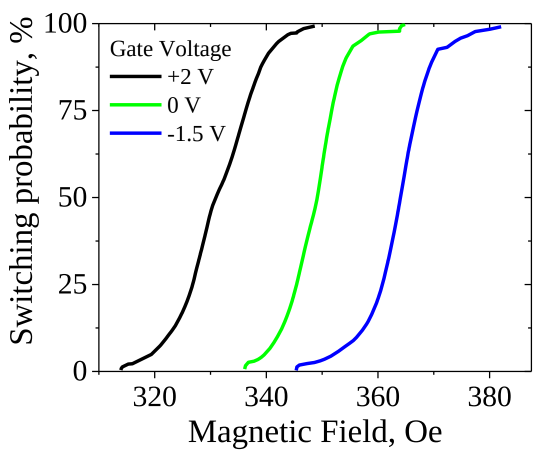
Measurement **1:**

Voltage-controlled coercive field



High reliability
High-confidence

range: *1-11 Oe/V*



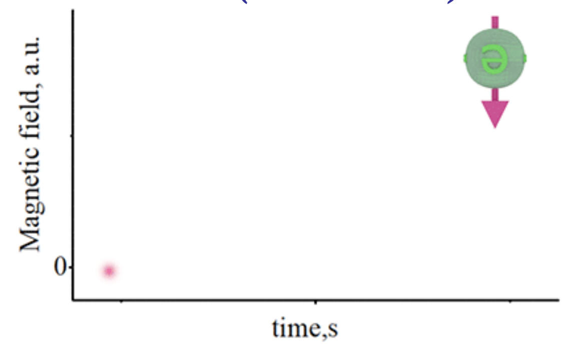
High precision measurements of coercive field ΔH_c < 0.1-1 Oe

Measurements of a small VCMA of ~1 Oe/V

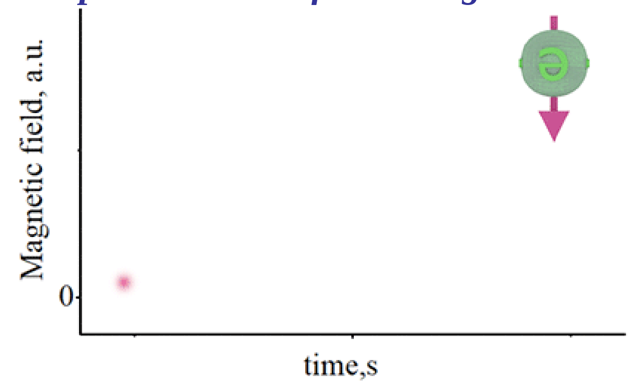
OK!

1-month repeated measurement -> **ΔH_c < 1 Oe**

step 1: Measure of switching field (conventional)



step 2: Measure of switching time



step 3: Simultaneous fitting

V.B. Naik *et al*, APL (2014)

H.Meng et al, APL (2014)

J.Huang, JMMM (2016)

W.G.Wang, Nat. Mat. (2012)

VCMA polarity

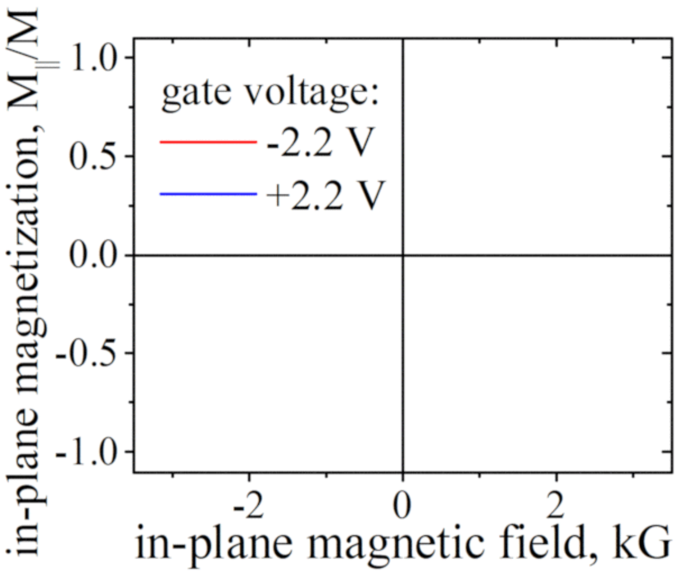
negative

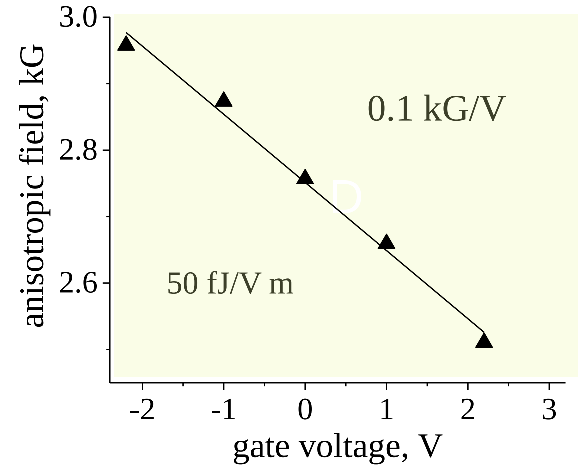
positive

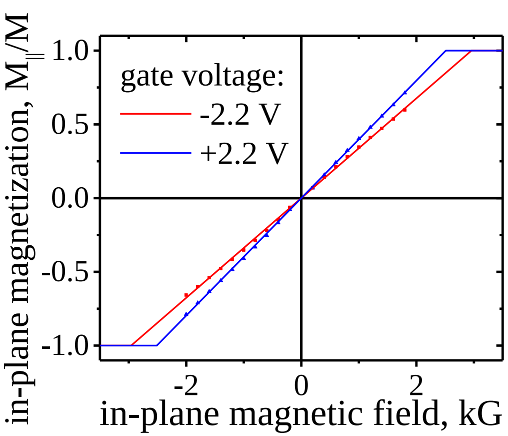
negative + positive

negative

Measurement 2: Voltage-controlled anisotropic field





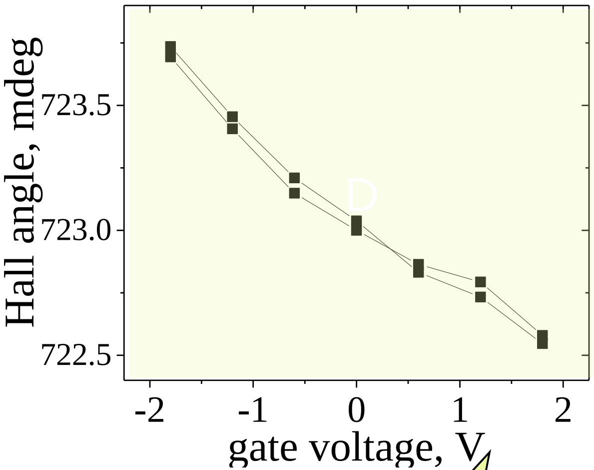


$$E_{PMA} = \frac{1}{2} M \cdot H_{anisotropy}$$

$$\Delta H_{anisotropy} \sim \text{40-100 Oe/V}$$

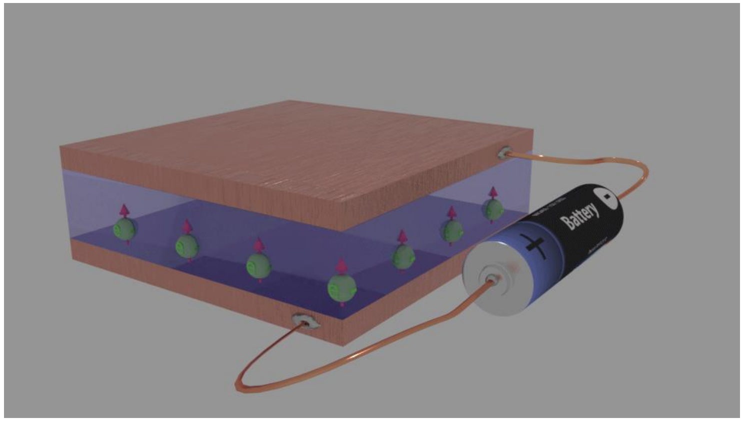
	VCMA polarity
T. Nozaki, PR Appl. (2016)	*negative*
Y. Shiota *et al*, APL (2013)	*negative + positive*
J. Alzte *et al*, APL (2013)	*negative*

Measurement 3: Voltage-controlled Hall rotation angle

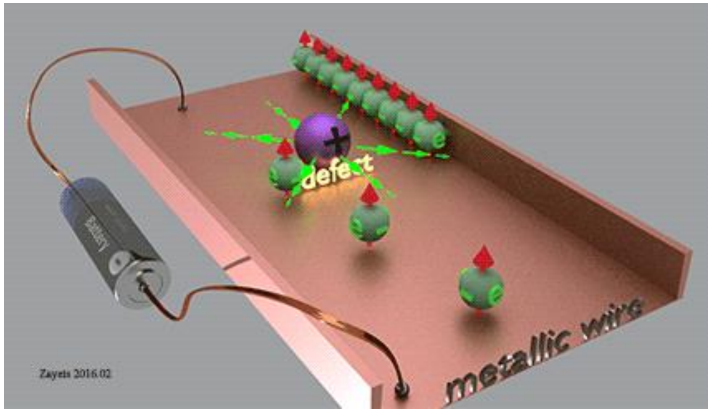


magnetization change

or orbital reconstruction ?



Anomalous Hall effect

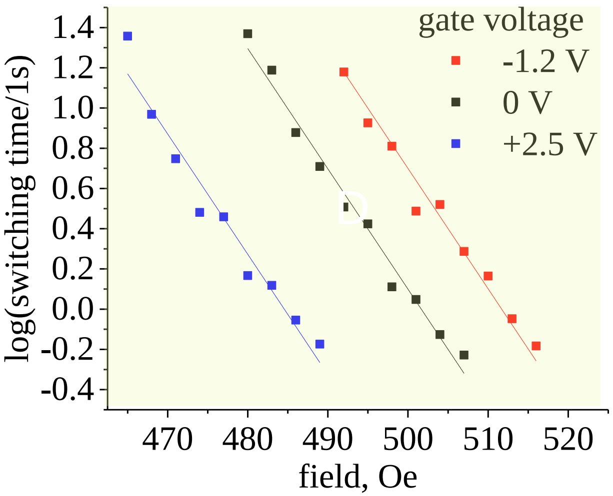


Hall angle depends on:

(1) Spin polarization of conduction electrons
(2) Strength of spin-orbit interaction
(2a) Magnetization
(2b) orbital reconstruction

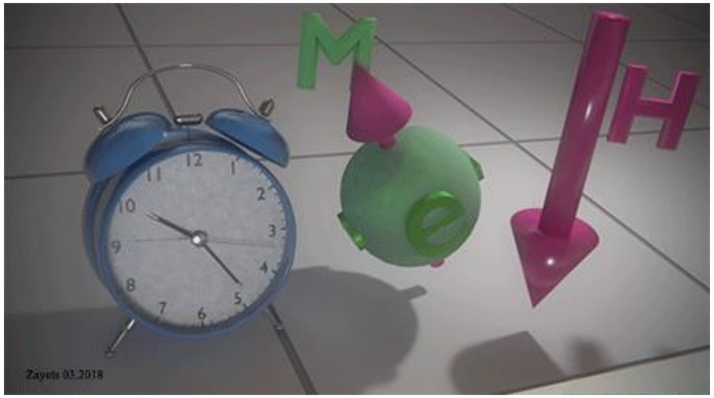
C.M. Hurd, The Hall Effect in Metals and Alloys, Plenum Press, 1972.

Voltage-controlled Hall switching time & retention time

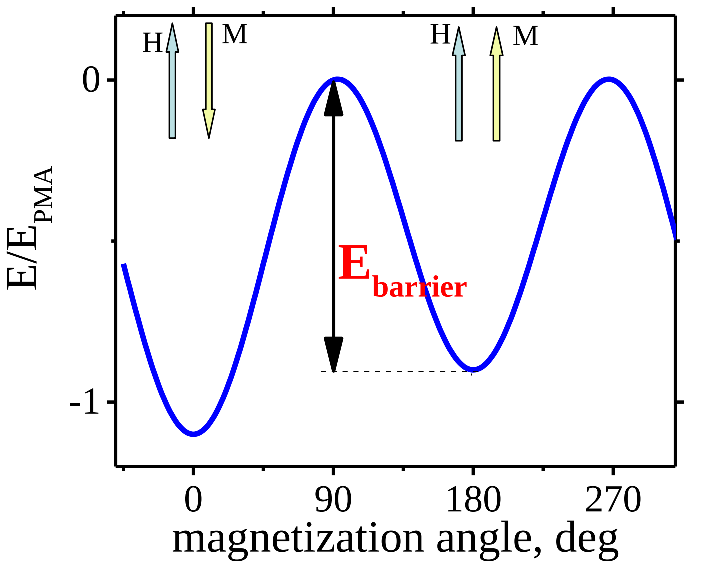


$$\log\left(\tau_{switching}\right) = \log\left(\tau_{retention}\right) + \frac{M}{kT} \cdot H$$

from fit



Energy vs magnetization angle



Néel model

L. Néel, Adv. Phys., 1955

Energy of a thermo fluctuation > $E_{barrier}$

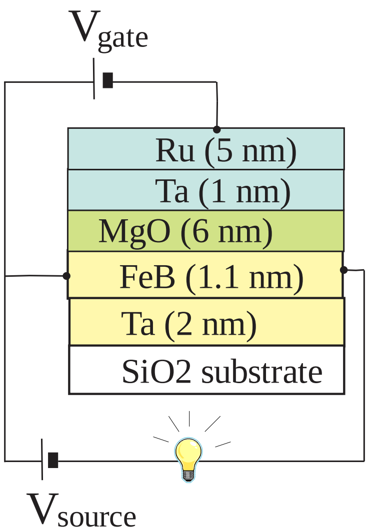
$$\tau_{switching} \sim e^{\frac{E_{barrier}}{kT}} = \tau_{retention} \cdot e^{\frac{H \cdot M}{kT}}$$

$$E_{barrier} = E_{PMA}\left(1 - \frac{H}{H_{anis}}\right)^2 \approx E_{PMA}\left(1 - 2\frac{H}{H_{anis}}\right) = M \cdot H$$

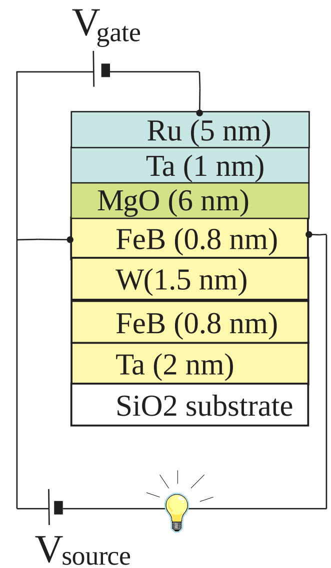
when $\frac{H}{H_{anis}} << 1$

FeB/W multilayer

***without** tungsten*

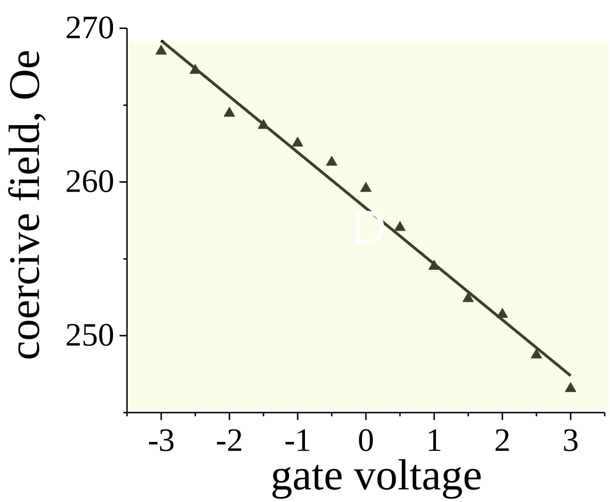


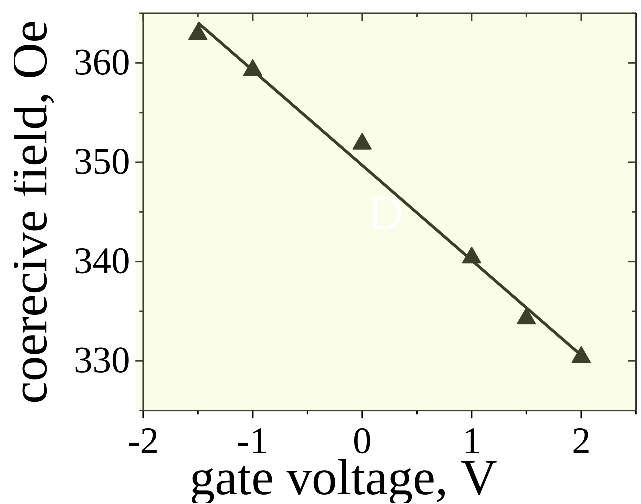
***with** tungstem*



3.7 Oe/V

9.6 Oe/V





$$E_{PMA} = \frac{1}{2} M \cdot H_{anisotropy}$$

Fitting to existing models

Possible origins

of the effect of voltage-controlled PMA

group 1: *Modulation of Fermi level*

Estimate: 4.5 meV per 1 V

origin 1: ***Modulation of magnetization***

M.Endo *et al*, , APL(2010) K. Yamada *et al*, Appl. Phys. Exp. (2013)

origin 2: ***Modulation of orbit symmetry*** *due to band intermixing*

C.G. Duan *et al*, PRB (2008)

group 2: *Not related to modulation of Fermi level*

origin 3: ***Magnetostriction effect***

P. V. Ong *et al*, , PRB (2017)

origin 4: ***Orbital reconstruction by electrical field***

K. Nakamura *et al*, PRB (2009) F. Ibrahim *et al*, PRB. (2016)

group 3:

origin 5: ***Oxygen electro-diffusion***

response time ~30 sec

undesirable

GdO_x

U. Bauer *et al*, PRL. (2014)

C.Bi *et al*, PRL. (2014)

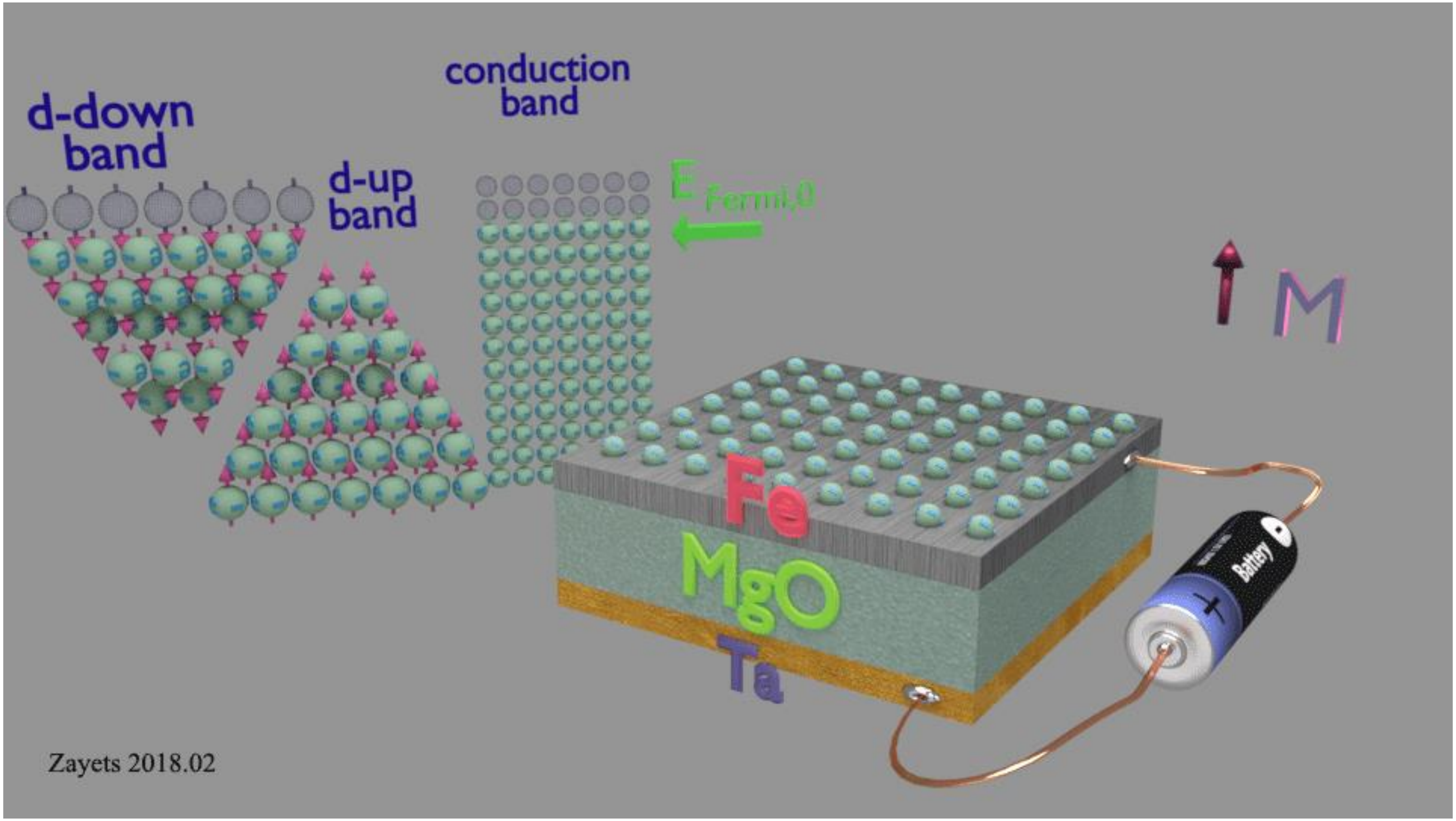
AlO_x

gate oxide with defects

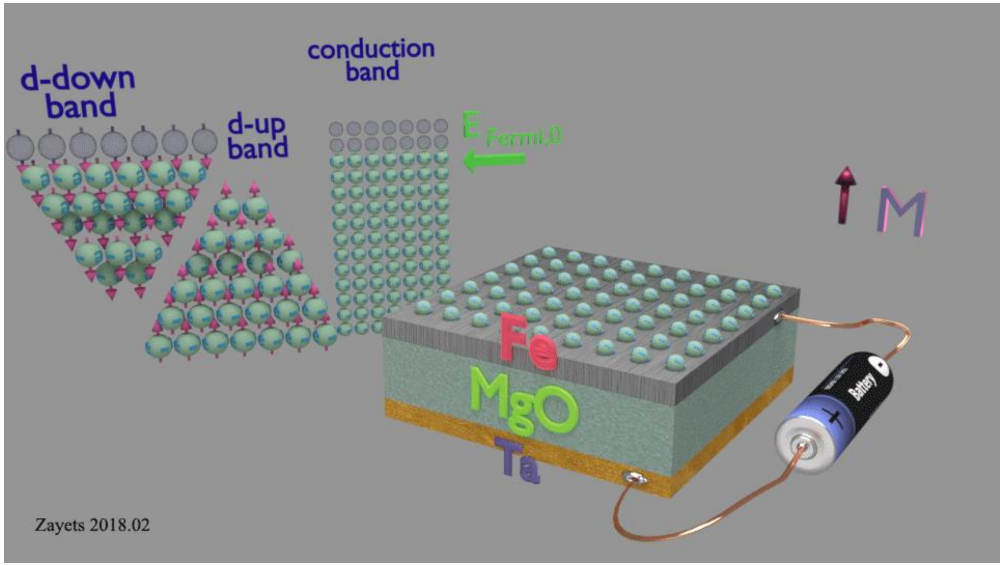
can be suppressed

S. Baek *et al*, Nat. Elect (2018)

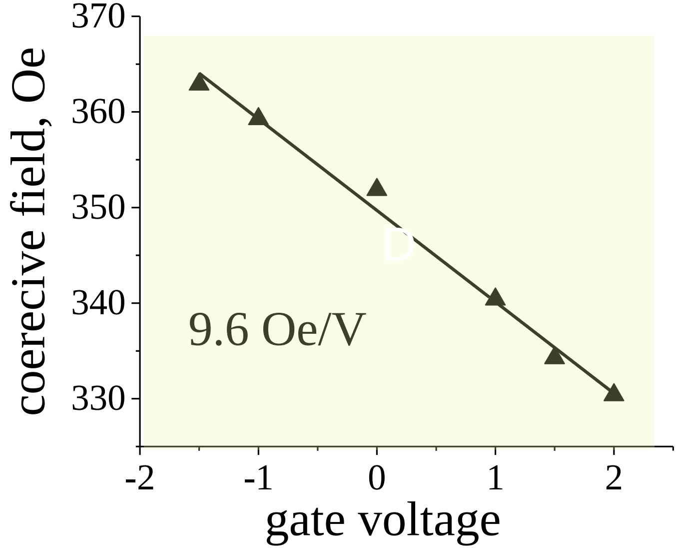
Charge accumulation/depletion or the effect of a capacitor

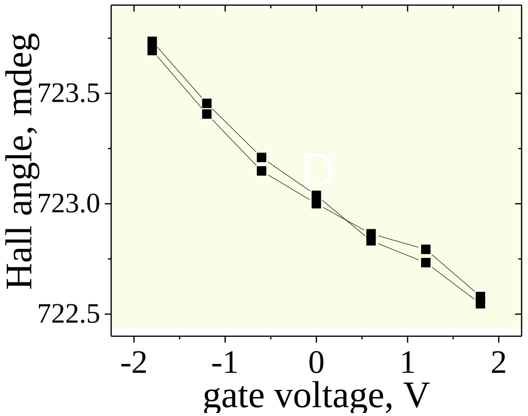


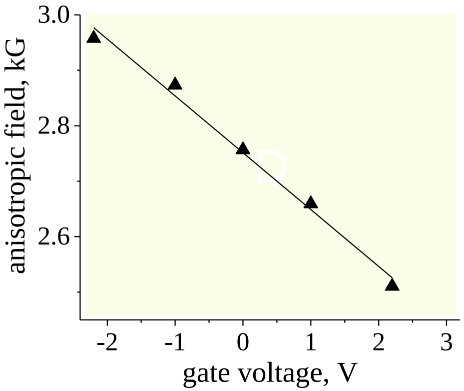
Charge accumulation/depletion or the effect of a capacitor



all asymmetric
+
negative slope







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