

Co based multilayer systems for controllable domain wall positioning

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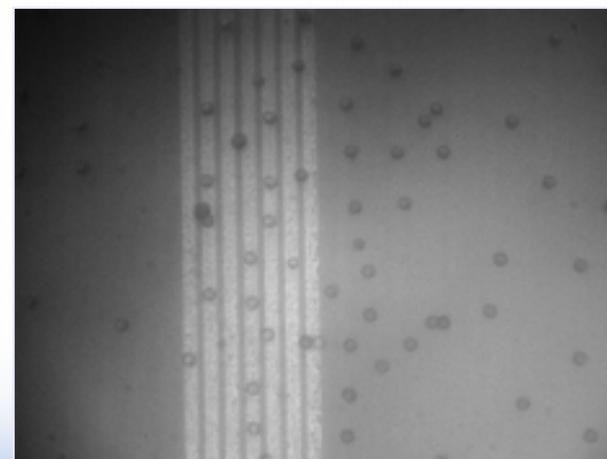
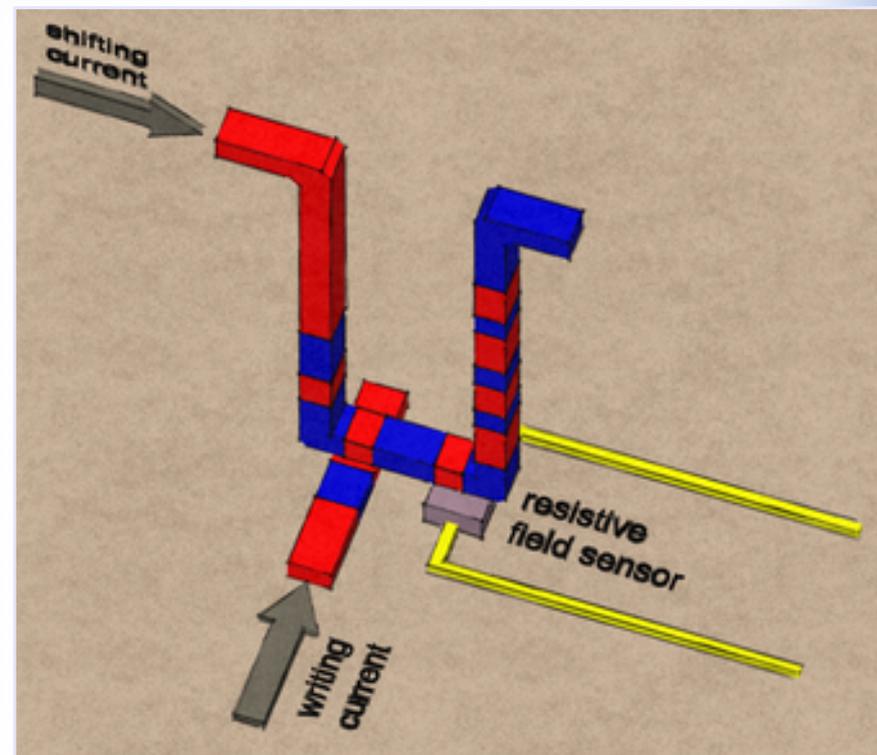
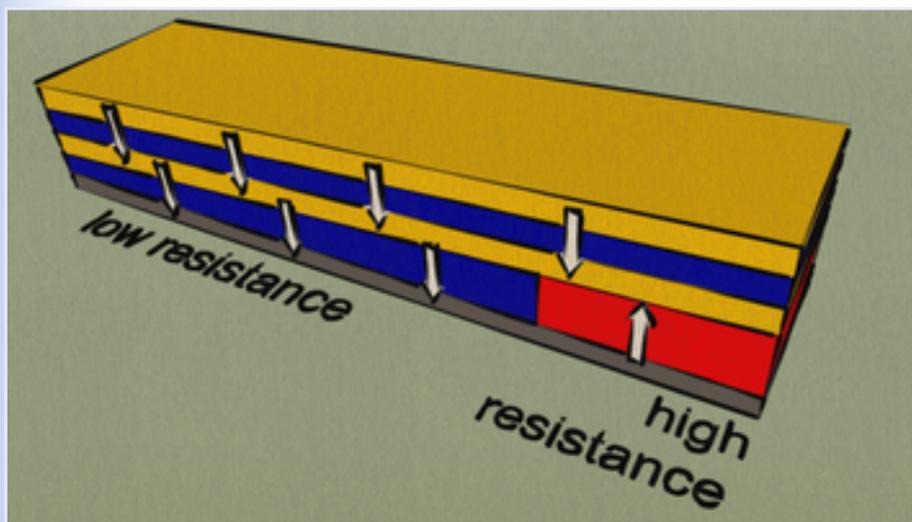
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KASSEL

Co based multilayer systems for controllable domain wall positioning

OUTLINE

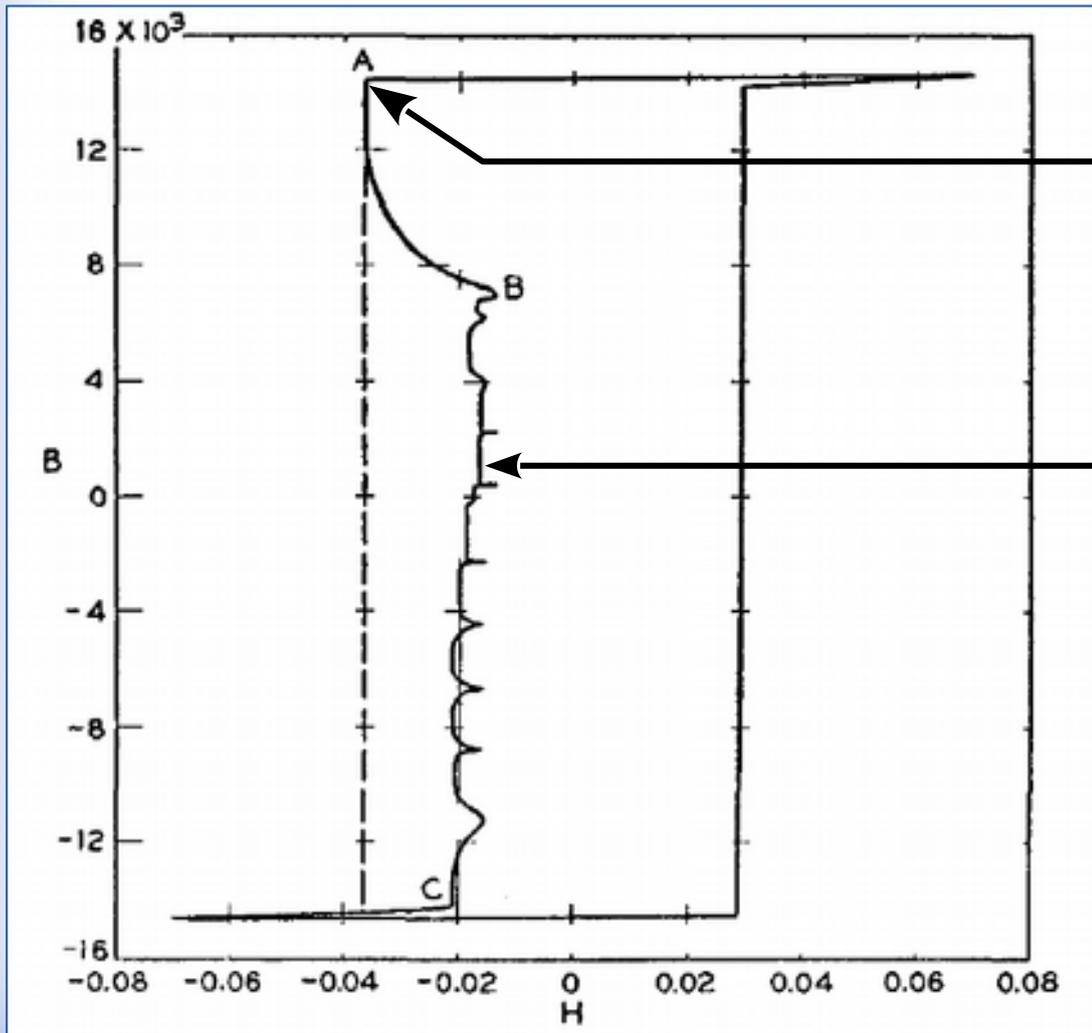
- Introduction
- Perpendicular magnetic anisotropy in Co based multilayers
- Properties modification by ion bombardment
- Domain wall control with anisotropy gradient
- Domain wall control with coupling gradient

- magnetic memories – race track memory, S.S.P. Parkin, IBM
- magnetic field sensors with memory – resistance depends on domain wall position, IFM PAN



- magnetophoresis of magnetic beads: lab-on-chip devices using functionalized beads

- the nucleation of walls often requires much higher fields than those required to sustain the domain wall motion
- if one measures the hysteresis keeping the rate of change of magnetization very slow the so called **reentrant loop** can be obtained [1,3]



domain walls start to move

weaker field is sufficient to sustain wall motion

Hysteresis loop of Perminvar after magnetic anneal. **A -Starting field**; A -B-rapid decrease of applied field; **B-C-traced under equilibrium conditions**. Dotted line indicates path described if field had not been reduced to critical field.

Perminvar (Ni 45%, Fe 30%, Co 25%)

- after switching the external field off the system moves to the nearest energy minimum
- in bulk samples the position of minimum is not controllable
- in patterned structures the position corresponding to the minimum can be set with the geometry

Since **automotive DW motion always occurs toward the narrowest part of ring, ...**

Py, 30nm

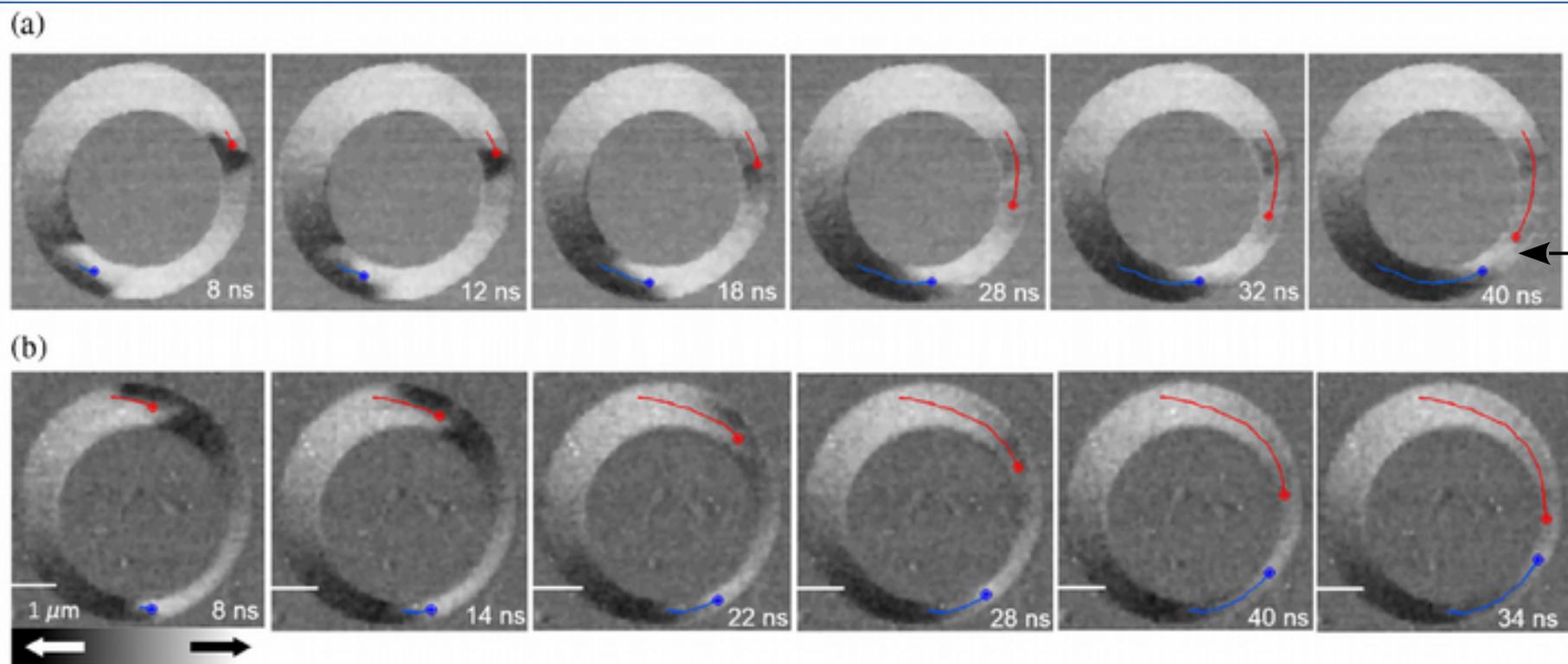


FIG. 3. Time-resolved STXM XMCD snapshots of automotive DWs' motion during the switching process from the onion to the vortex state in the ferromagnetic rings for the case of equal (a) and opposite (b) vortex wall chirality. These snapshots represent part of the XMCD videos used to extract the DW velocities plotted in Fig. 2. Red and blue lines illustrate the averaged trajectory of the vortex core of both vortex walls head to head and tail to tail, respectively.

the tendency of the domain walls to minimize its length – the neck acts as a pinning center

NiFe(20 nm)/Cu(10 nm)/NiFe(5 nm)

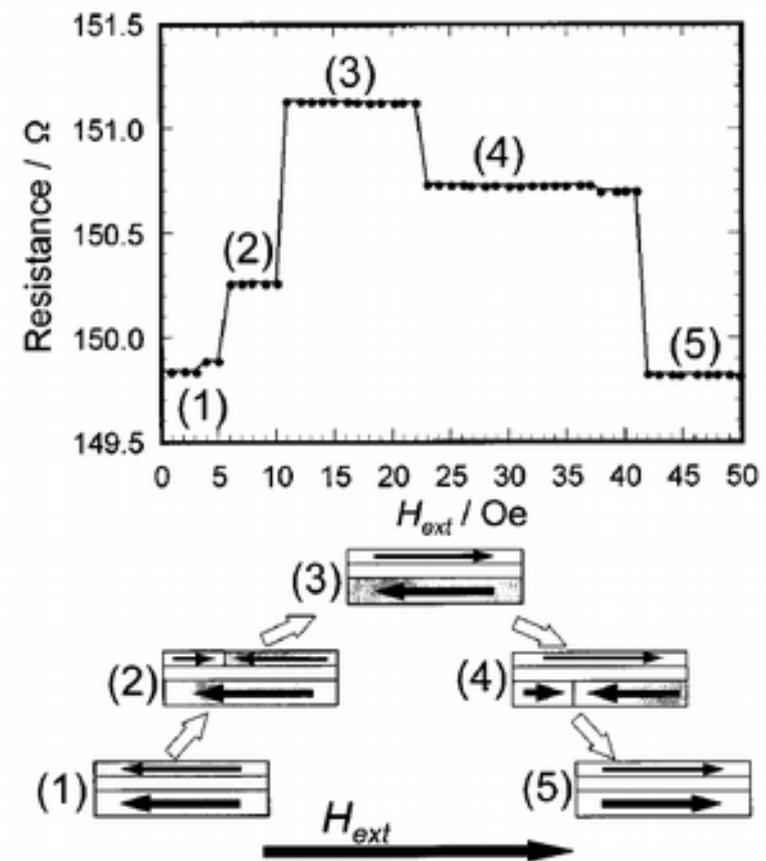
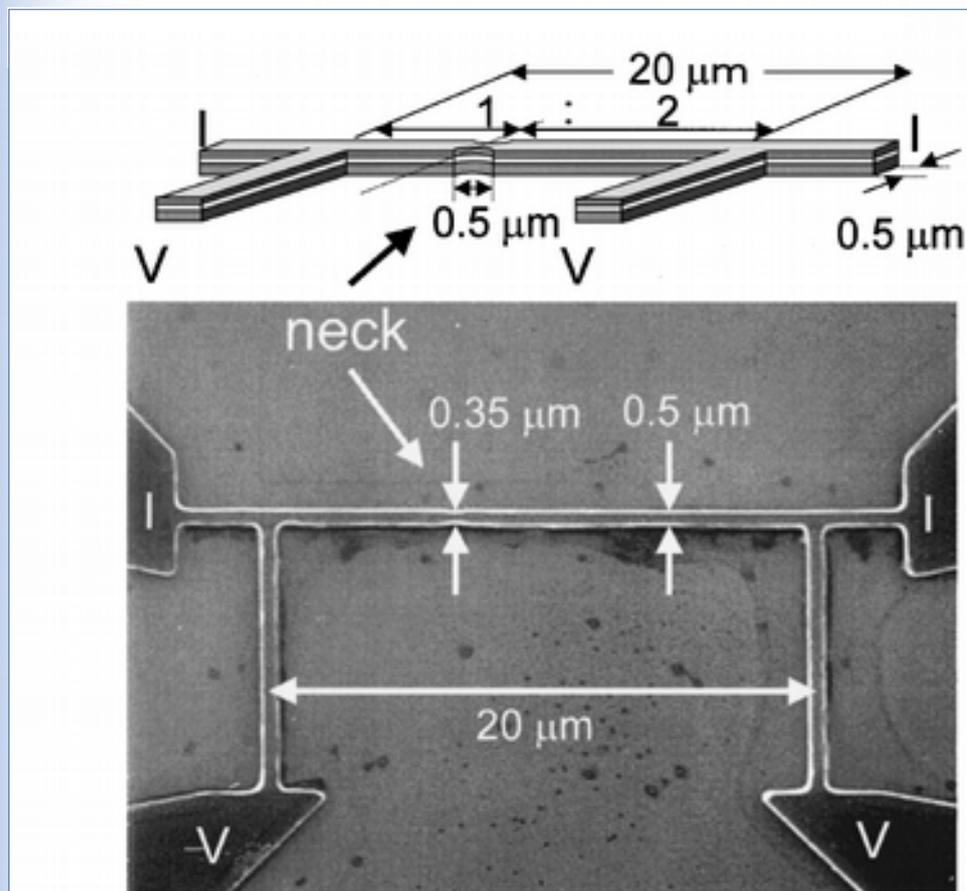


FIG. 2. Resistance as a function of the external magnetic field at 300 K determined by the four-point dc technique as illustrated in Fig. 1. The magnetic domain structures inferred from the resistance measurement and the direction of the external field are schematically shown.

FIG. 1. SEM image and schematic illustration of the sample. The sample consists of a NiFe(200 Å)/Cu(100 Å)/NiFe(50 Å) trilayer.

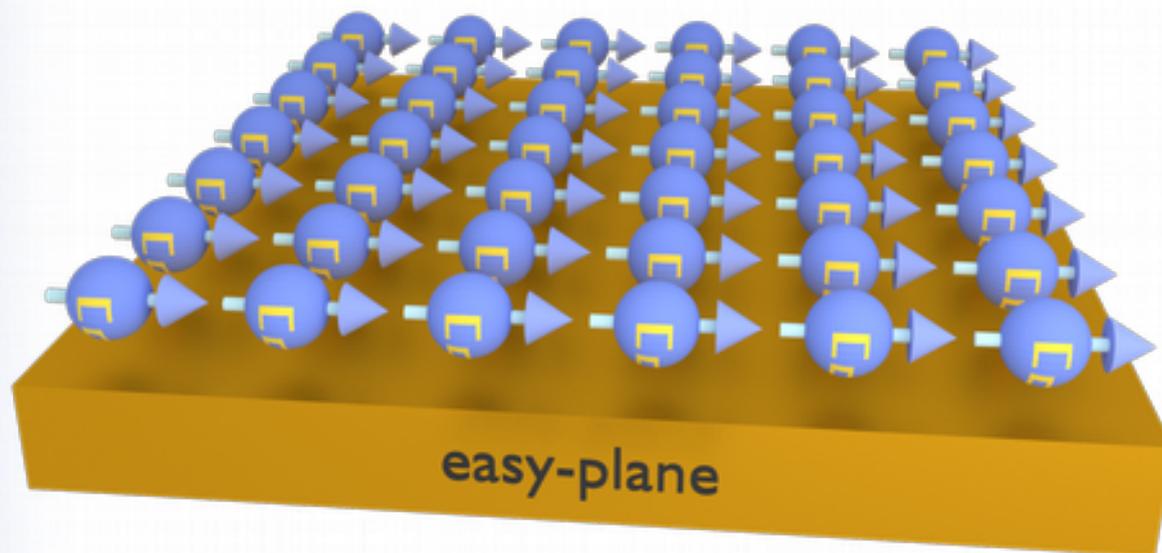
Some ways to control the position of a domain wall:

- move your sample :)
- use geometrical constraints
- use gradient of properties to change switching fields:
 - temperature gradient
 - stress gradient
 - thickness gradient
 - anisotropy gradient
 - coupling gradient

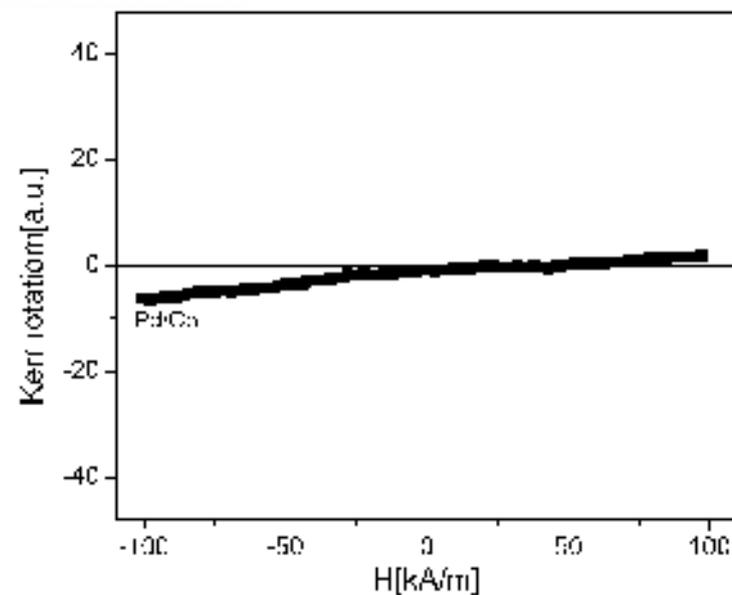
Some ways to control the position of a domain wall:

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 - thickness gradient
 - **anisotropy gradient**
 - **coupling gradient**

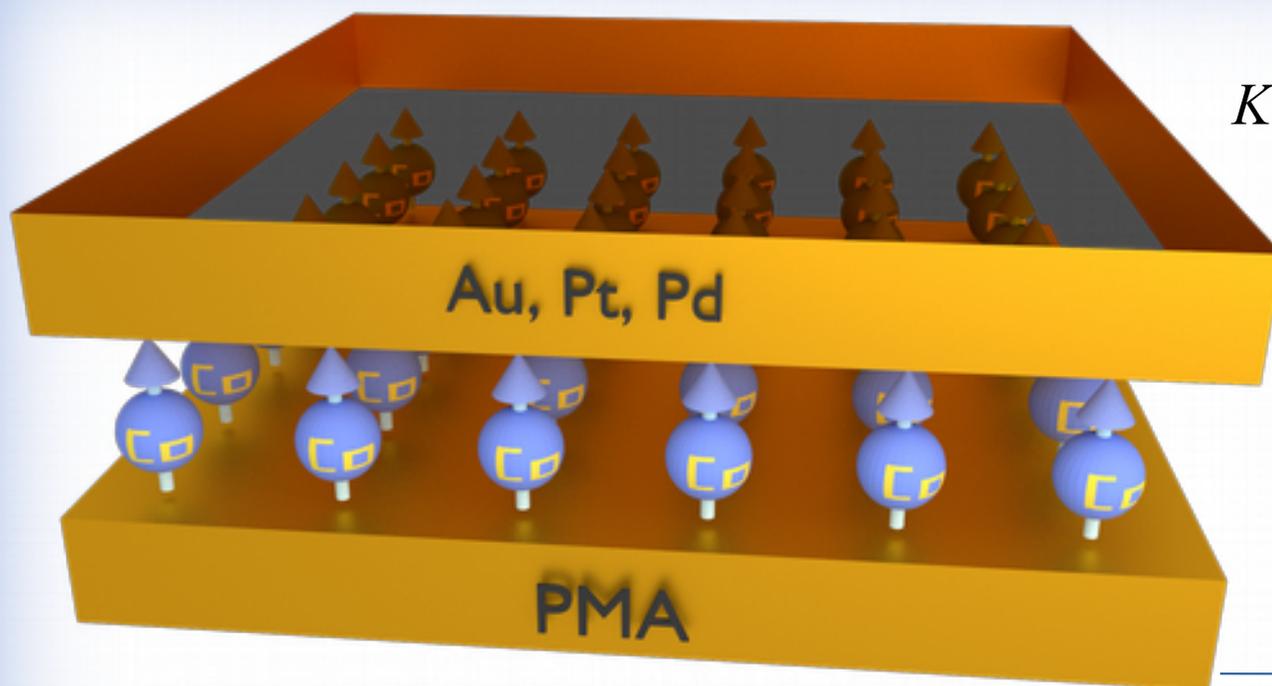
Perpendicular magnetic anisotropy in Co based multilayers



Due to the shape anisotropy thin ferromagnetic layer possess usually the anisotropy which favors in-plane orientation of magnetic moments

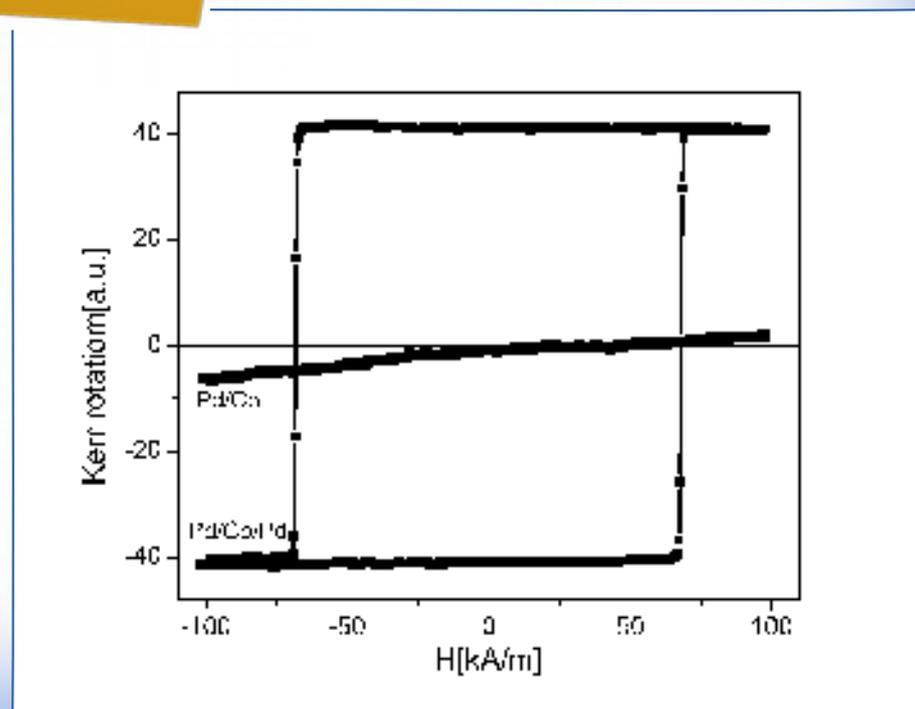


Perpendicular magnetic anisotropy in Co based multilayers



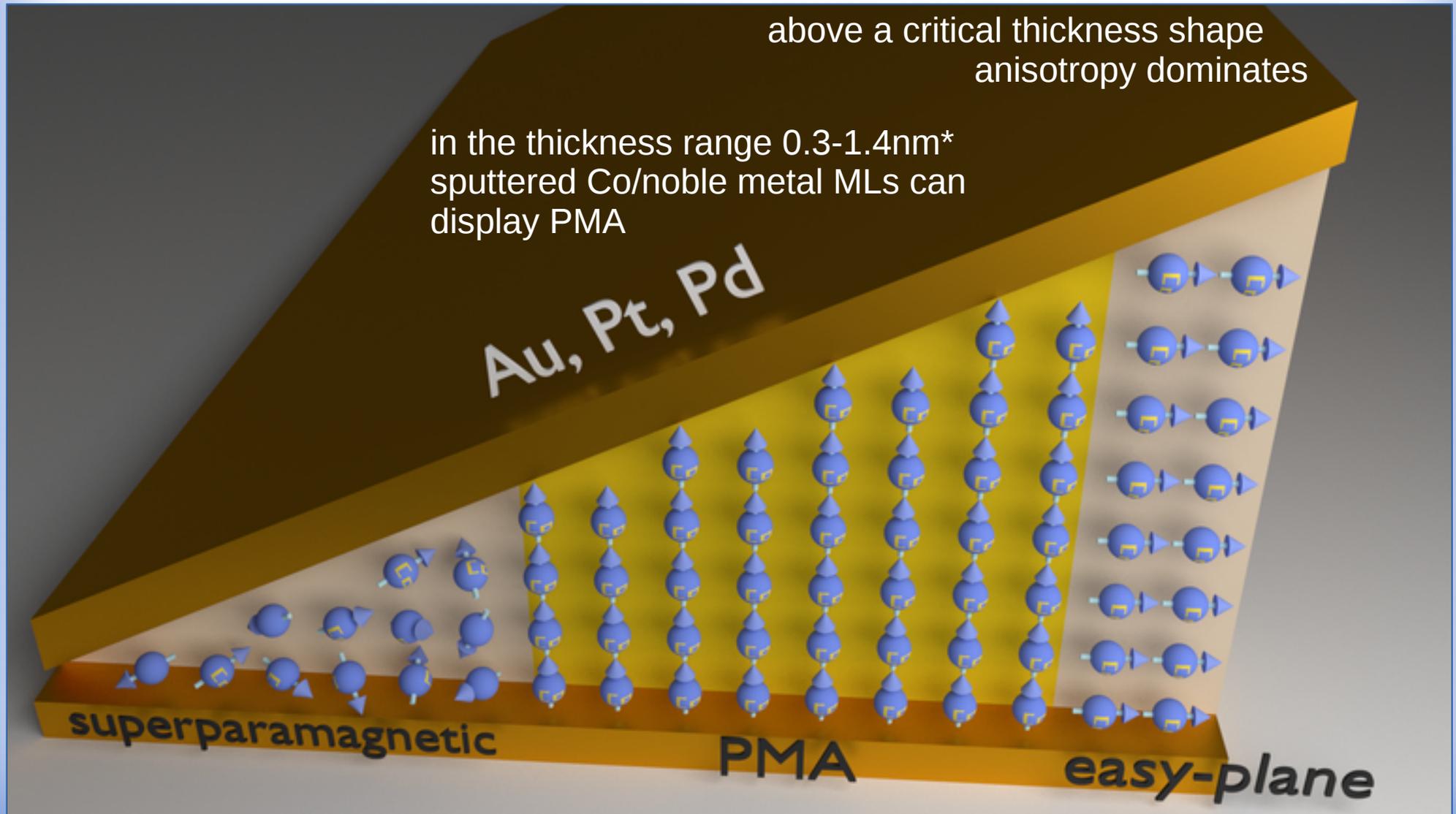
$$K_{eff} = \frac{2 K_{1s}}{t_{Co}} + K_{1v} - \frac{1}{2} \mu_0 (M_S^{Co})^2$$

Co based multilayers in which magnetic layer is sandwiched between noble metal spacer possess perpendicular magnetic anisotropy (PMA) in limited thickness range – this is due to **surface anisotropy** of the interfaces

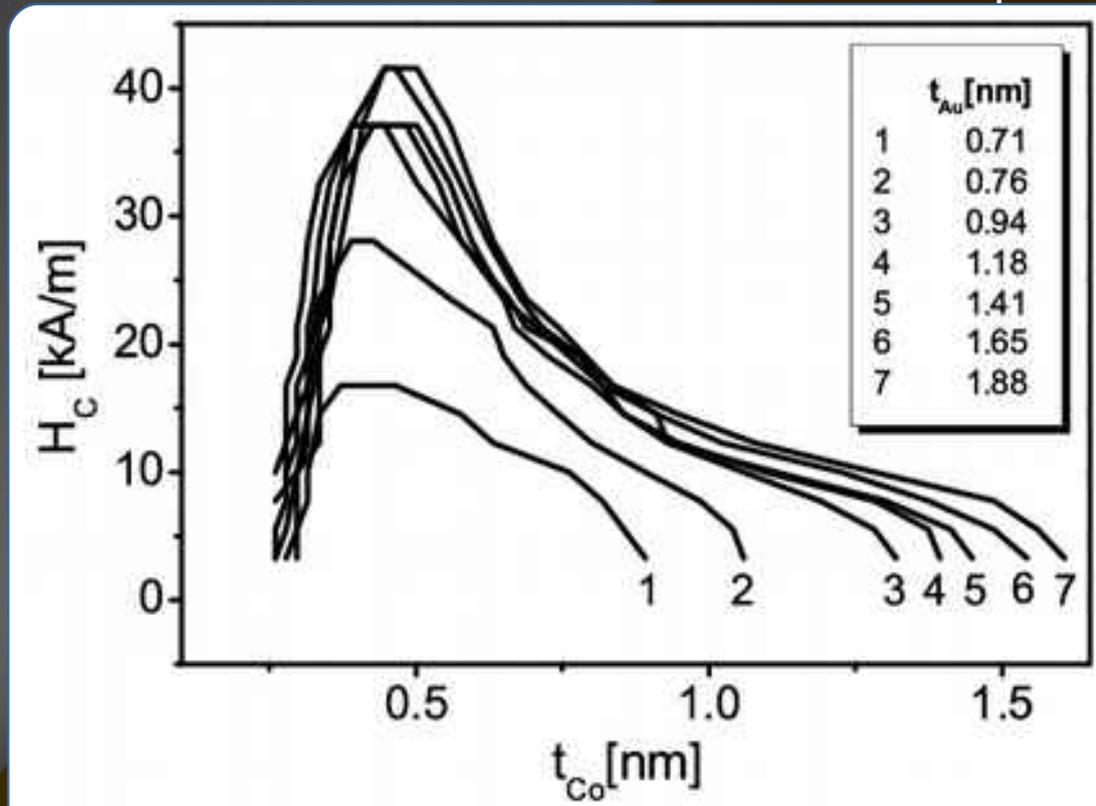


Perpendicular magnetic anisotropy in Co based multilayers

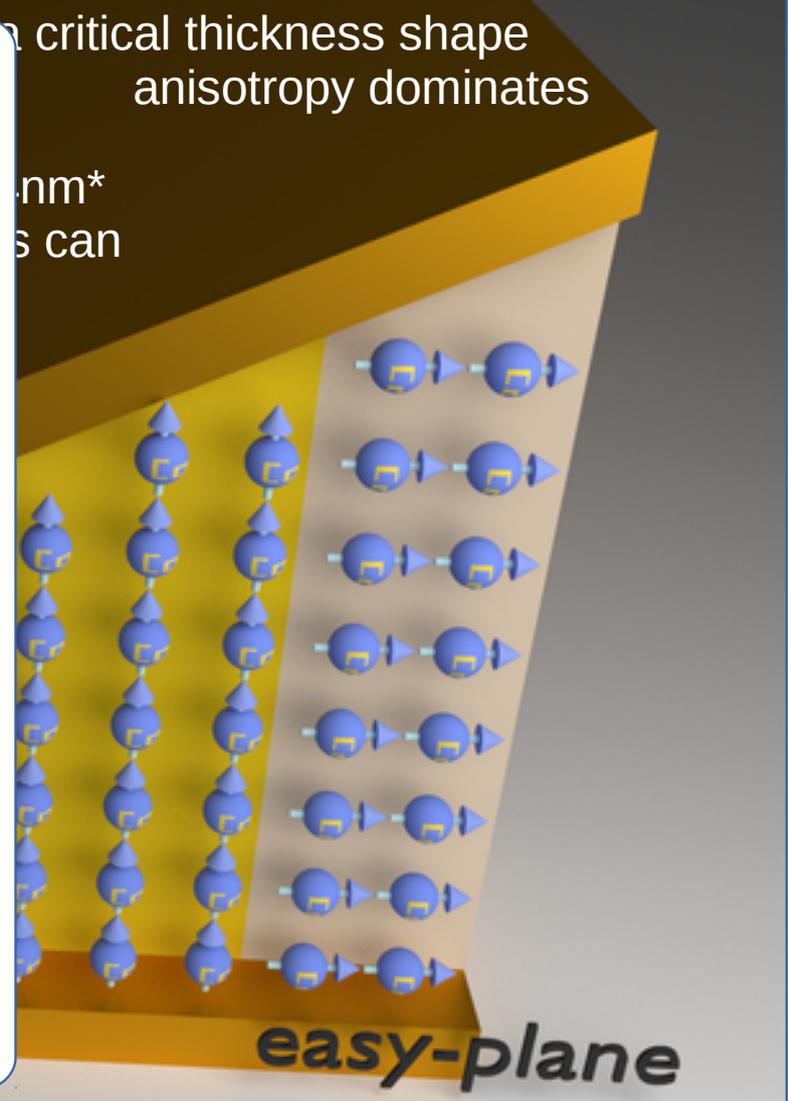
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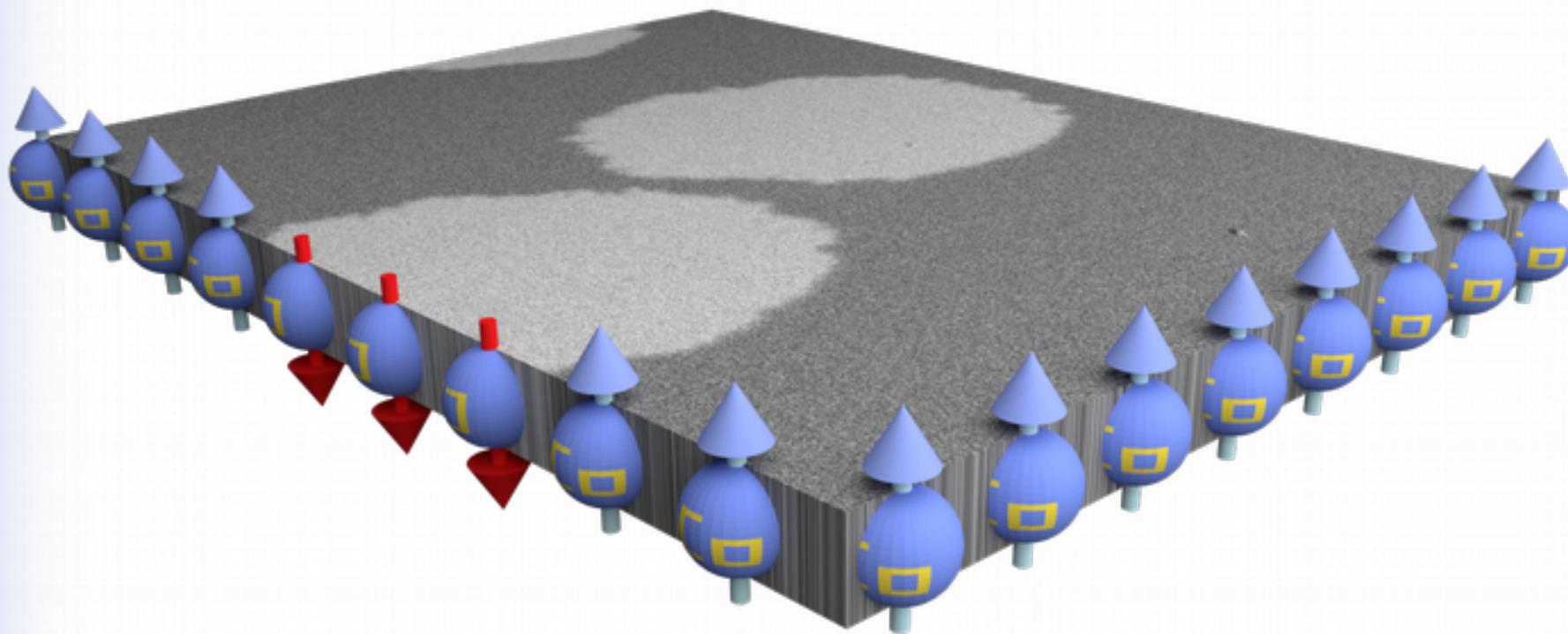
Coercive field values H_c of Co layers, as a function of Co and Au layers thicknesses, obtained from magneto-optic Kerr effect measurements
 Si(100)/[NiFe(2nm)/Au(3nm)]₁₀NiFe(2nm)/Au(0-2nm)/Co(0-2.4nm)/Au(3nm)



*for Co/Au MLs the PMA range is approximately 0.5-1.2nm

Perpendicular magnetic anisotropy in Co based multilayers

- as-deposited Si(100)/Au/[Co(0.8nm)/Au(1nm)]₂
- perpendicular magnetic anisotropy
- remanence Kerr microscopy **difference images**

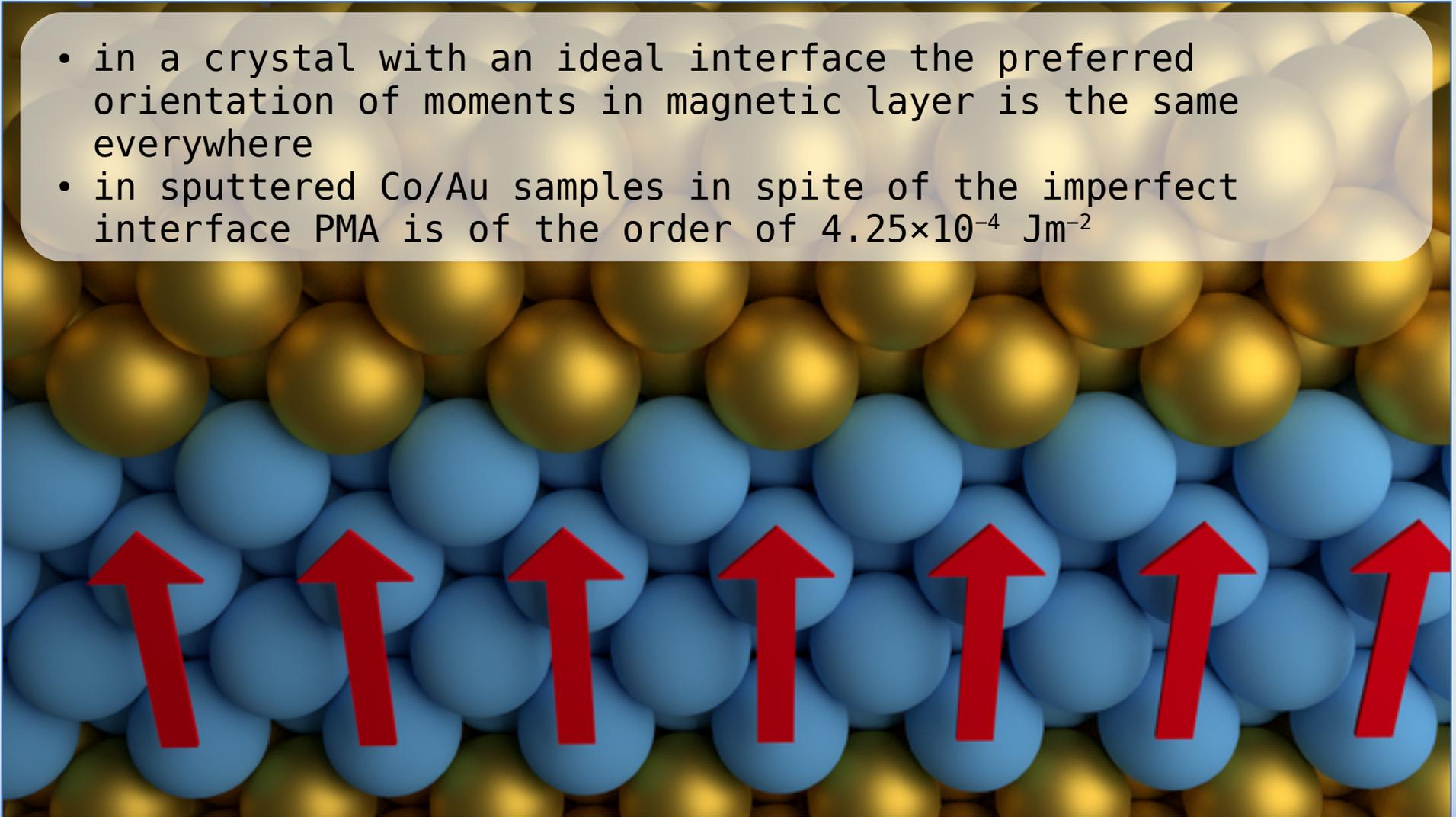


small number of repetitions – no stripe domains

Perpendicular magnetic anisotropy in Co based multilayers

Co based multilayers in which magnetic layer is sandwiched between noble metal spacer possess perpendicular magnetic anisotropy (PMA) in limited thickness range – this is due to **surface anisotropy** of the interfaces

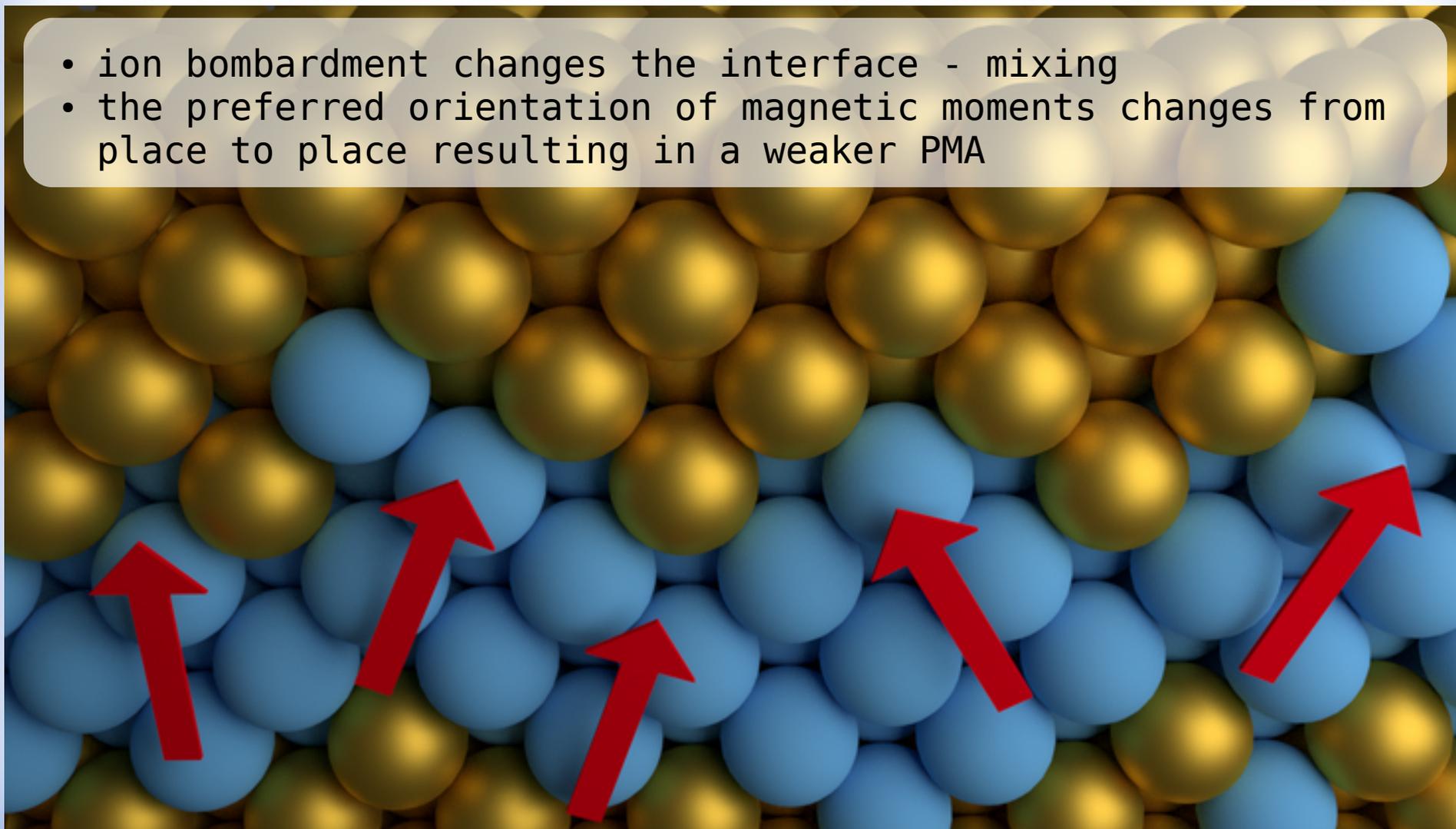
- in a crystal with an ideal interface the preferred orientation of moments in magnetic layer is the same everywhere
- in sputtered Co/Au samples in spite of the imperfect interface PMA is of the order of $4.25 \times 10^{-4} \text{ Jm}^{-2}$



Perpendicular magnetic anisotropy in Co based multilayers

Co based multilayers in which magnetic layer is sandwiched between noble metal spacer possess perpendicular magnetic anisotropy (PMA) in limited thickness range – this is due to **surface anisotropy** of the interfaces

- ion bombardment changes the interface - mixing
- the preferred orientation of magnetic moments changes from place to place resulting in a weaker PMA



Perpendicular magnetic anisotropy in Co based multilayers

The influence of the ion bombardment:

- moderate fluences can be used to modify the switching fields
- higher fluences, depending on the Co layer thickness, lead either to a change to an easy-plane anisotropy or destroy ferromagnetic order

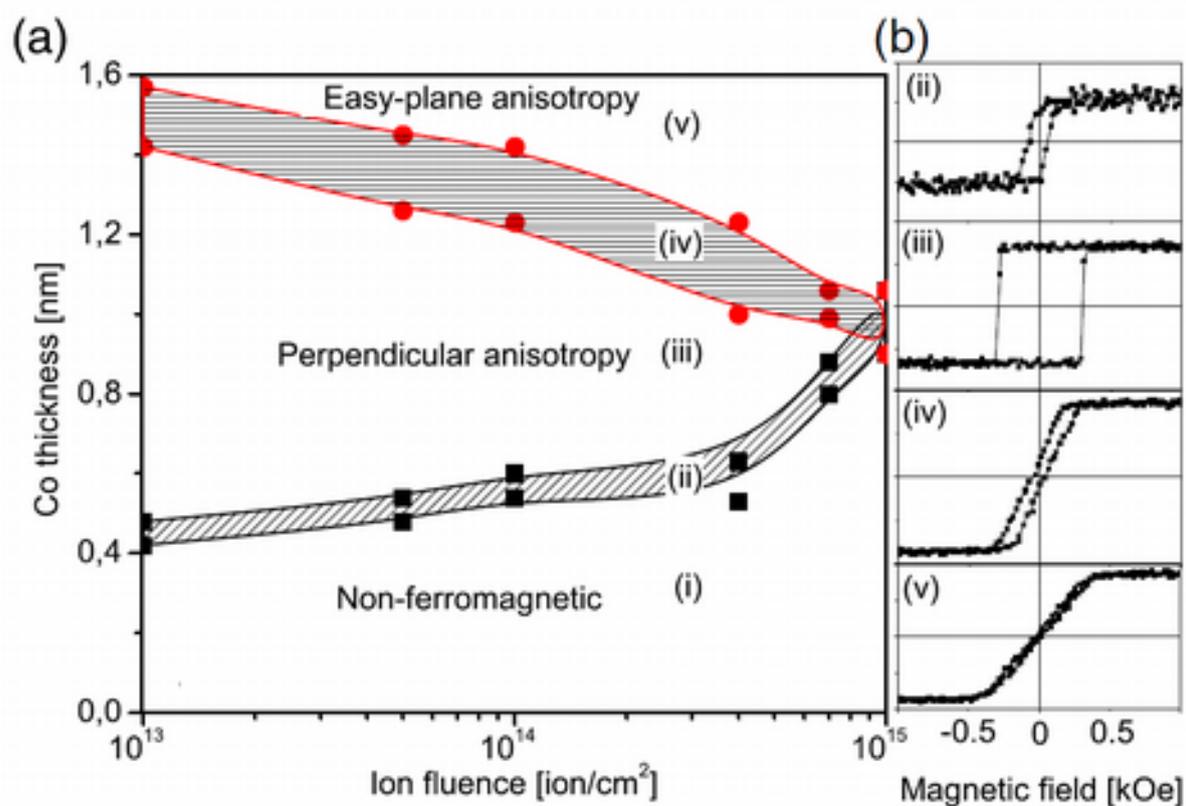
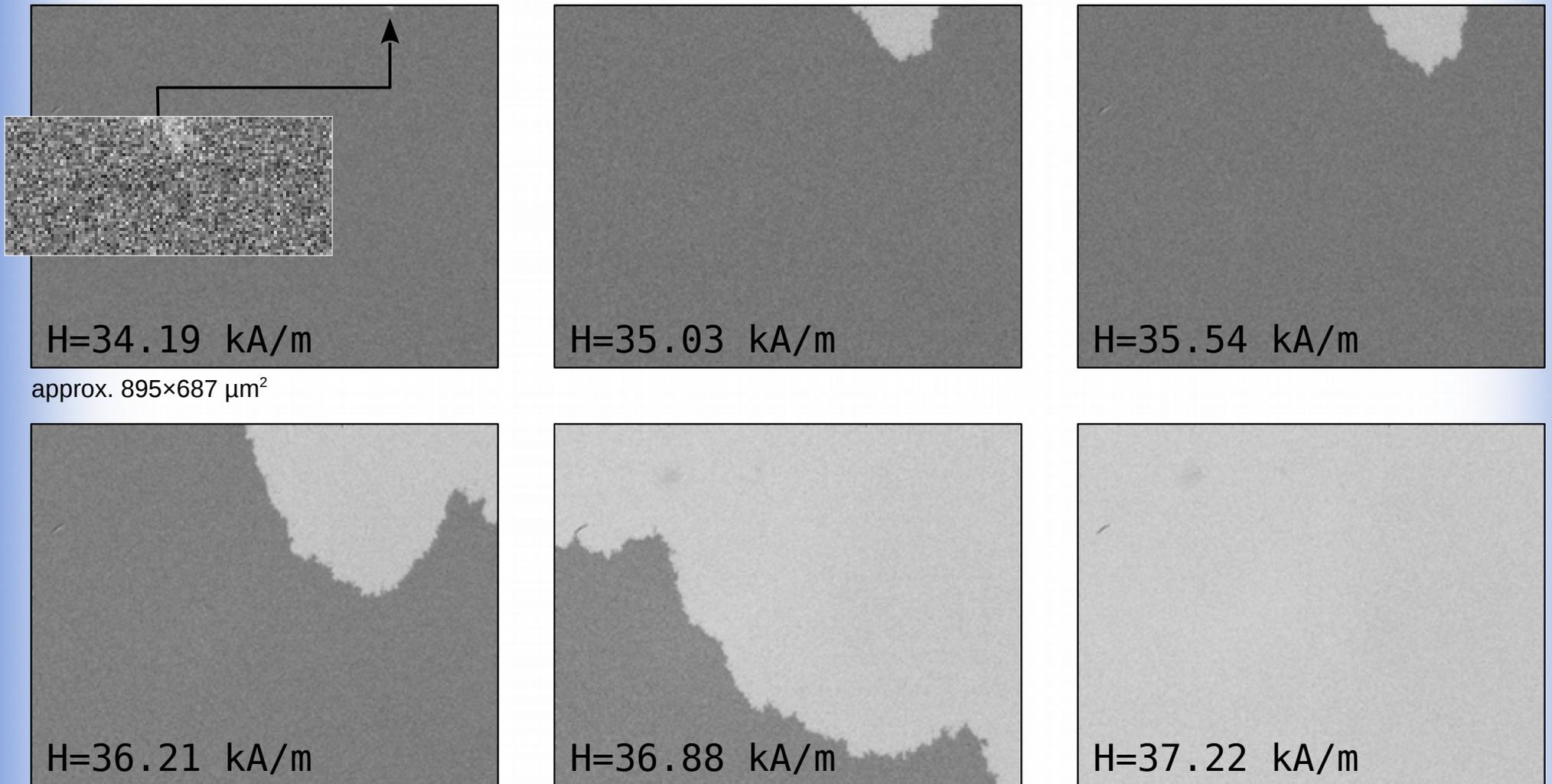


Figure 3. Magnetic phase changes of the Co layer as a function of Co layer thickness caused by bombardment with 10 keV He⁺ ions. (a) Variation of the Co thickness intervals (i)–(v) as a function of He⁺ ion fluence. (b) Hysteresis loops corresponding to thickness intervals (ii)–(v). Dashed areas (ii) and (iv) are guides to the eye for the transition regimes.

Nucleation centers

Domain wall propagation driven reversal in $(\text{Co/Au})_2$ films

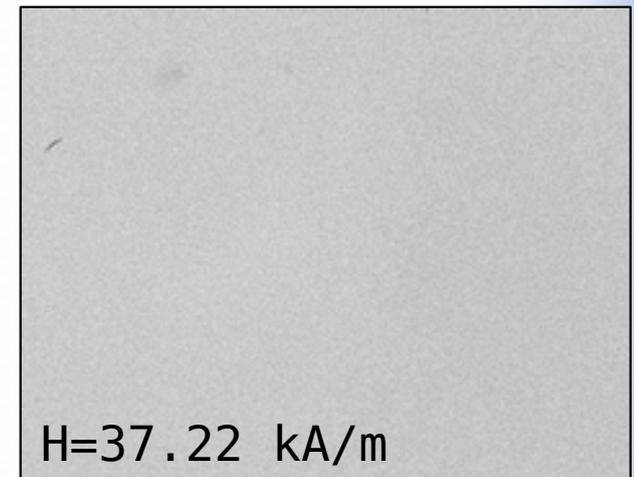
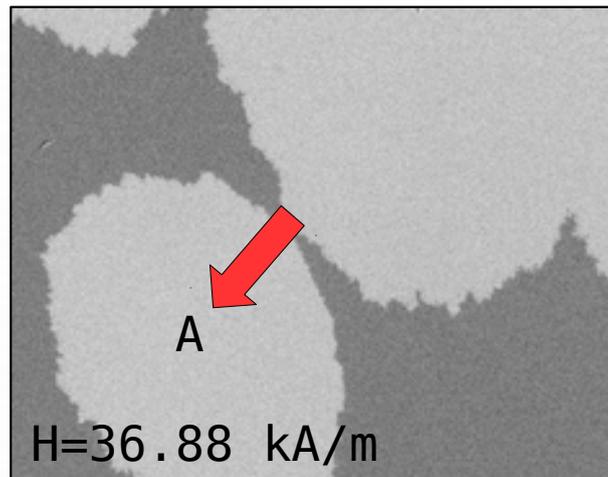
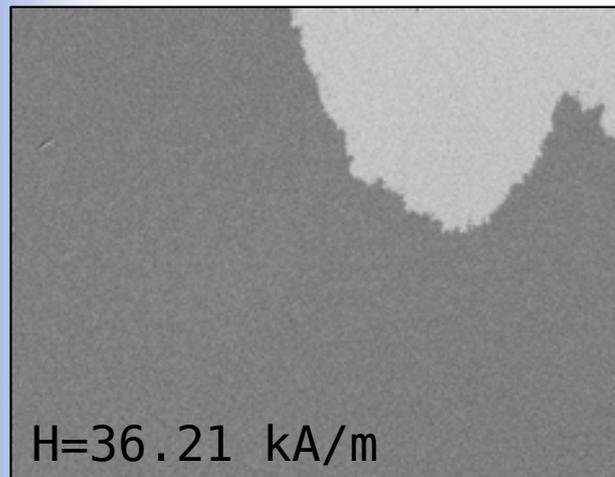


In films deposited by sputtering the density of nucleation centers can be very low. For the series of images shown above there seems to be no nucleation center within the image (approx. $0.9 \times 0.7 \text{ mm}^2$)

Nucleation centers

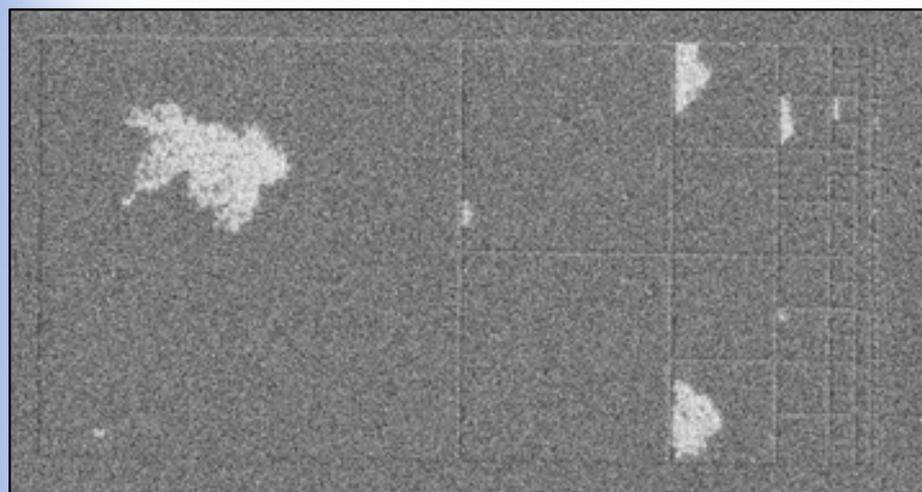
Domain wall propagation driven reversal in $(\text{Co/Au})_2$ films

- **randomly distributed nucleation centers**
- **no control over the nucleation**

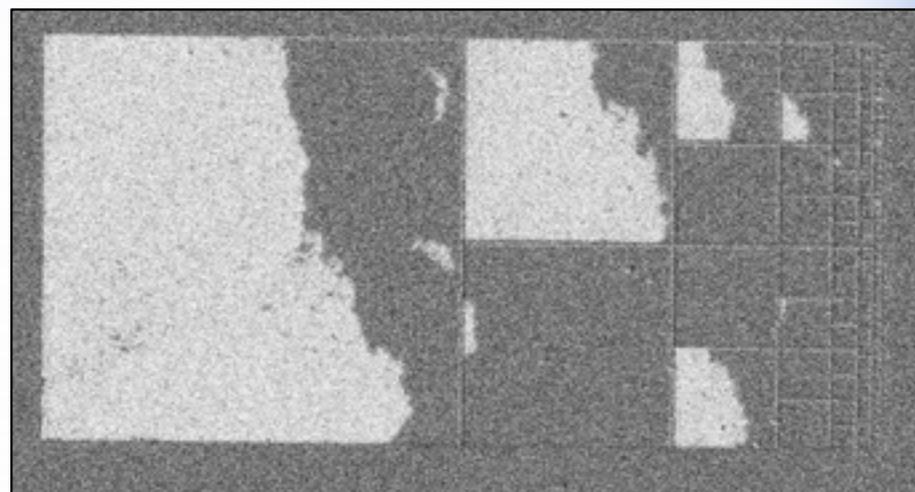


The exact evolution of the domains is not reproducible as evidenced by a domain expanding from the probable nucleation center near the point A.

Nucleation centers



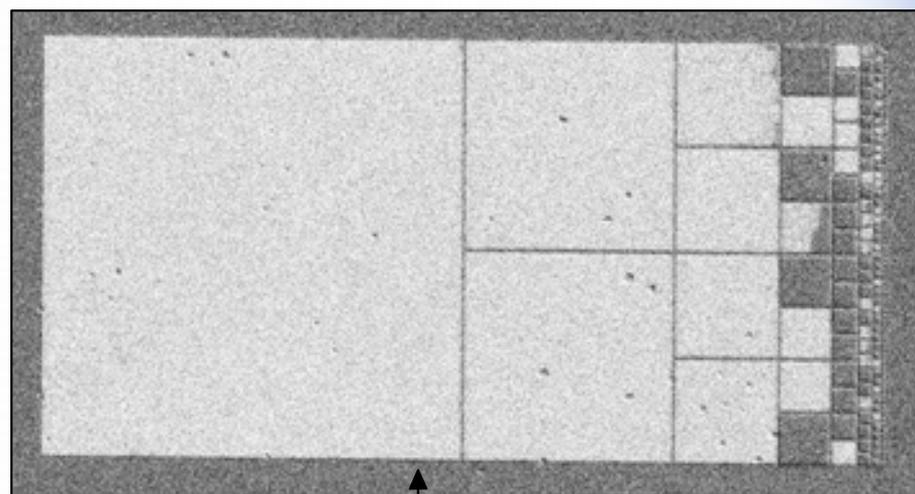
H=34.7 kA/m



H=36.38 kA/m



H=37.22 kA/m



H=37.89 kA/m

256 x 256 μm^2

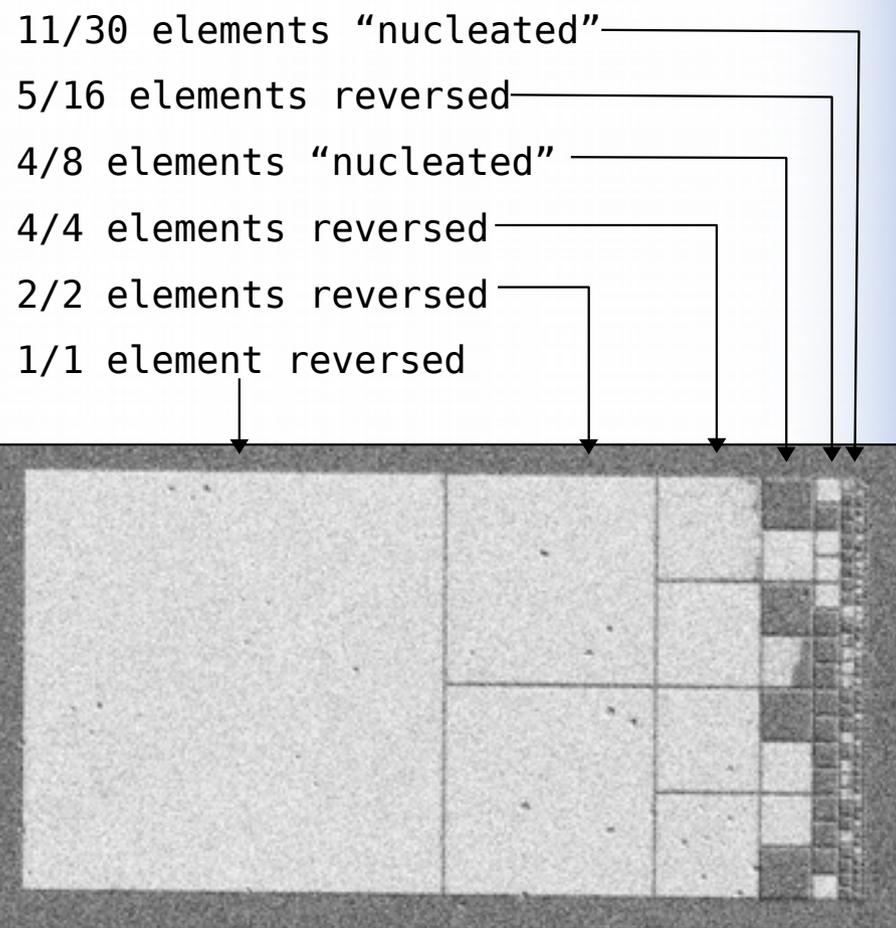
Nucleation centers

The probability of activating the nucleation center is roughly proportional to element area.

If nucleation centers areal density is low the large elements may reverse while the small ones do not.



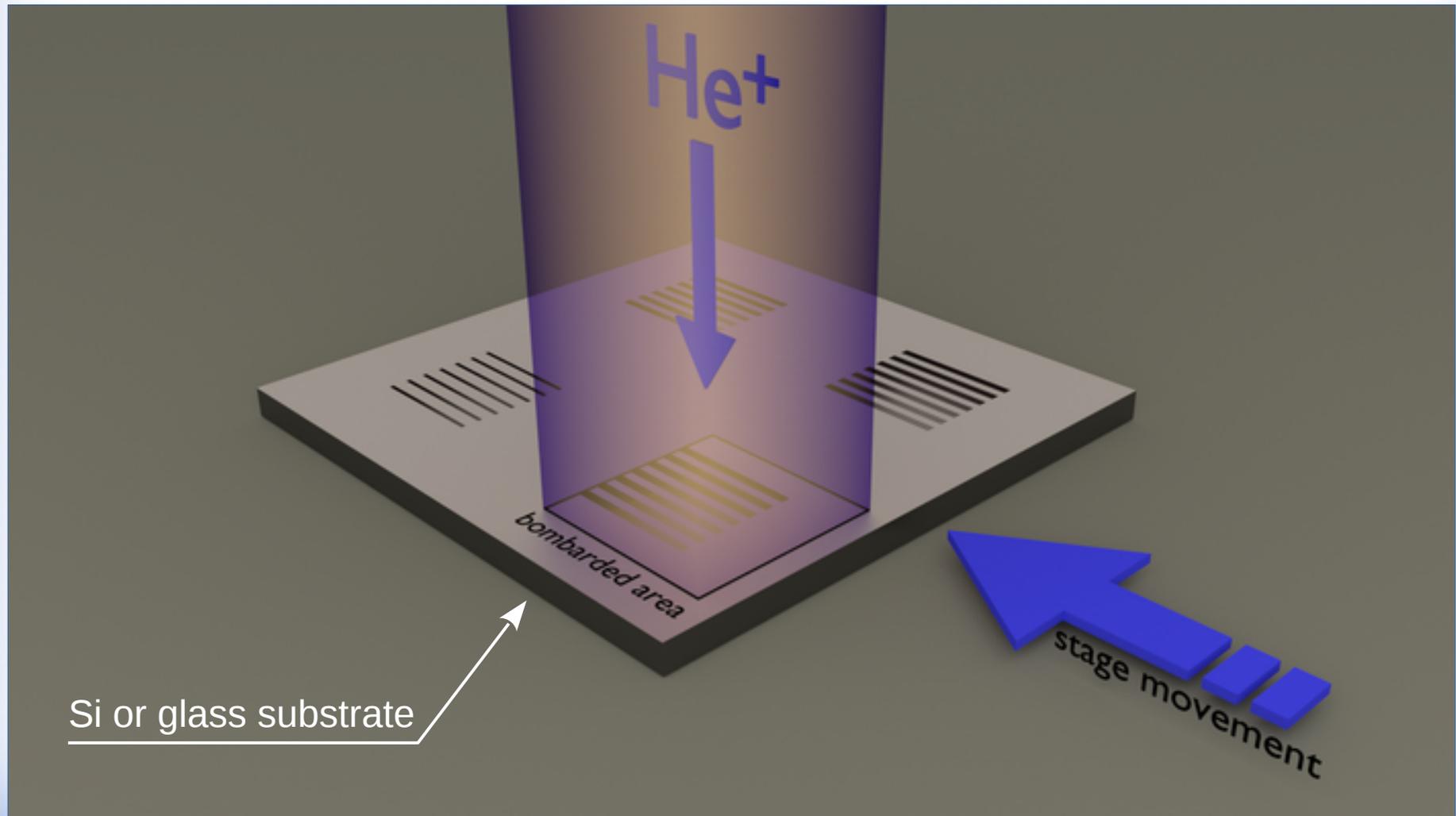
H=37.22 kA/m



H=37.89 kA/m

Ion bombardment

- Sample holder moves along the longer edges of the stripes and ion fluence gradient is created along the stripes
- He^+ ion fluences are up to 10^{15} ion/cm²
- The fluence changes linearly from approx. 0 to 10^{15} ion/cm² over the length of the stripes (990 μm)
- The 10^{15} ion/cm² fluence corresponds to approx. **one He^+ ion for seven Co atoms**

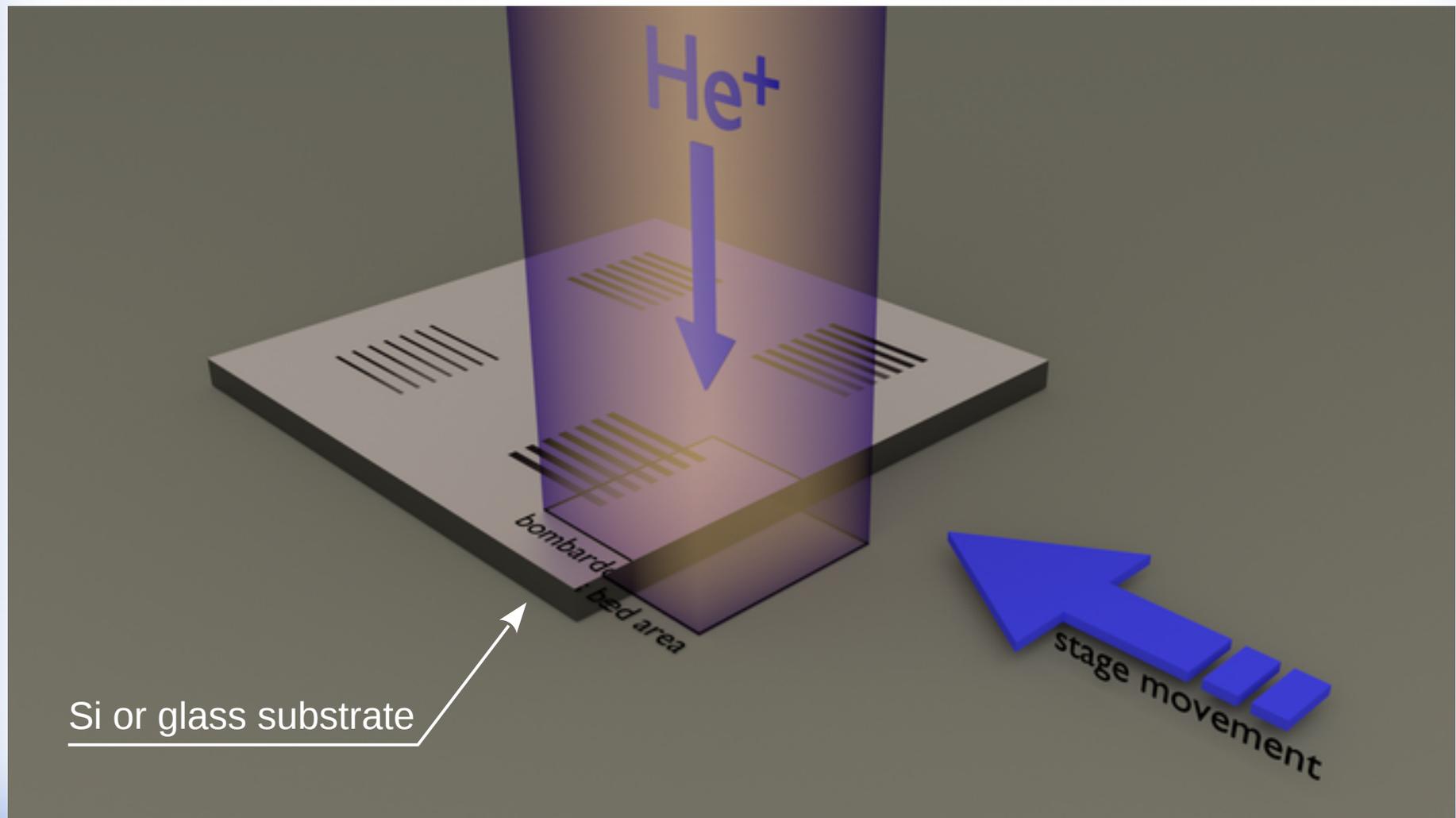


Si or glass substrate

stage movement

Ion bombardment

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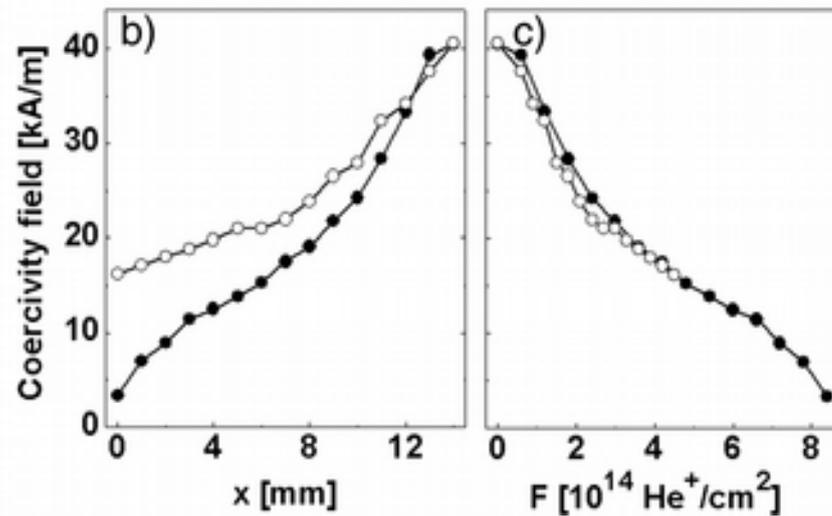
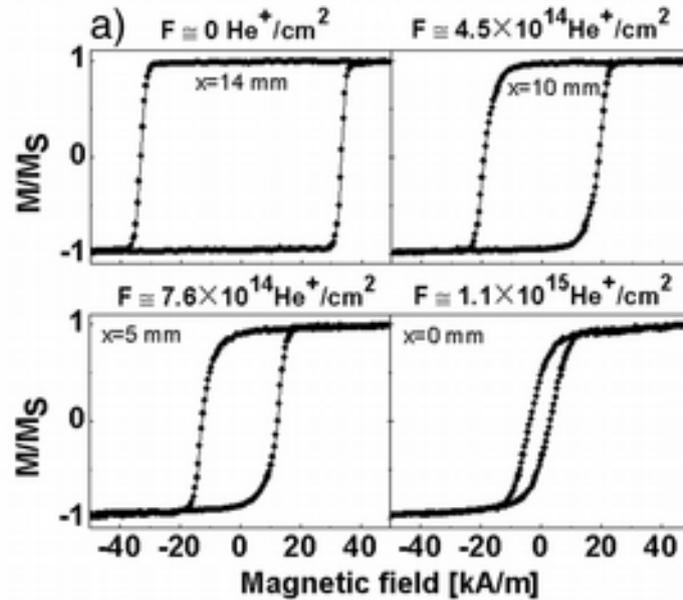
Si or glass substrate

stage movement

Ion bombardment

The influence of fluence on coercive field

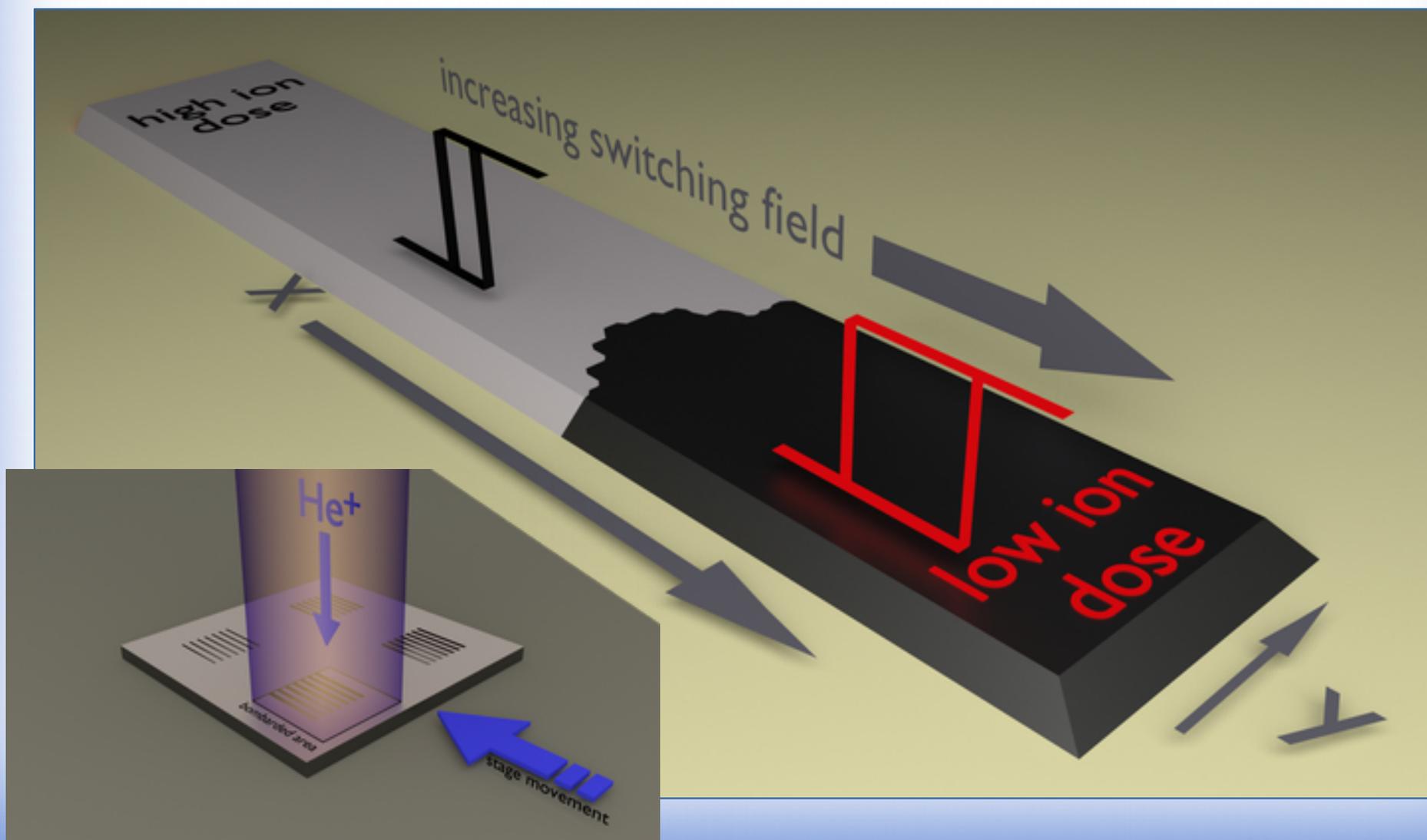
Si(100)/Ti(4nm)/Au(60nm)/
[Co(0.8nm)/Au(1nm)]₂



10 keV He⁺

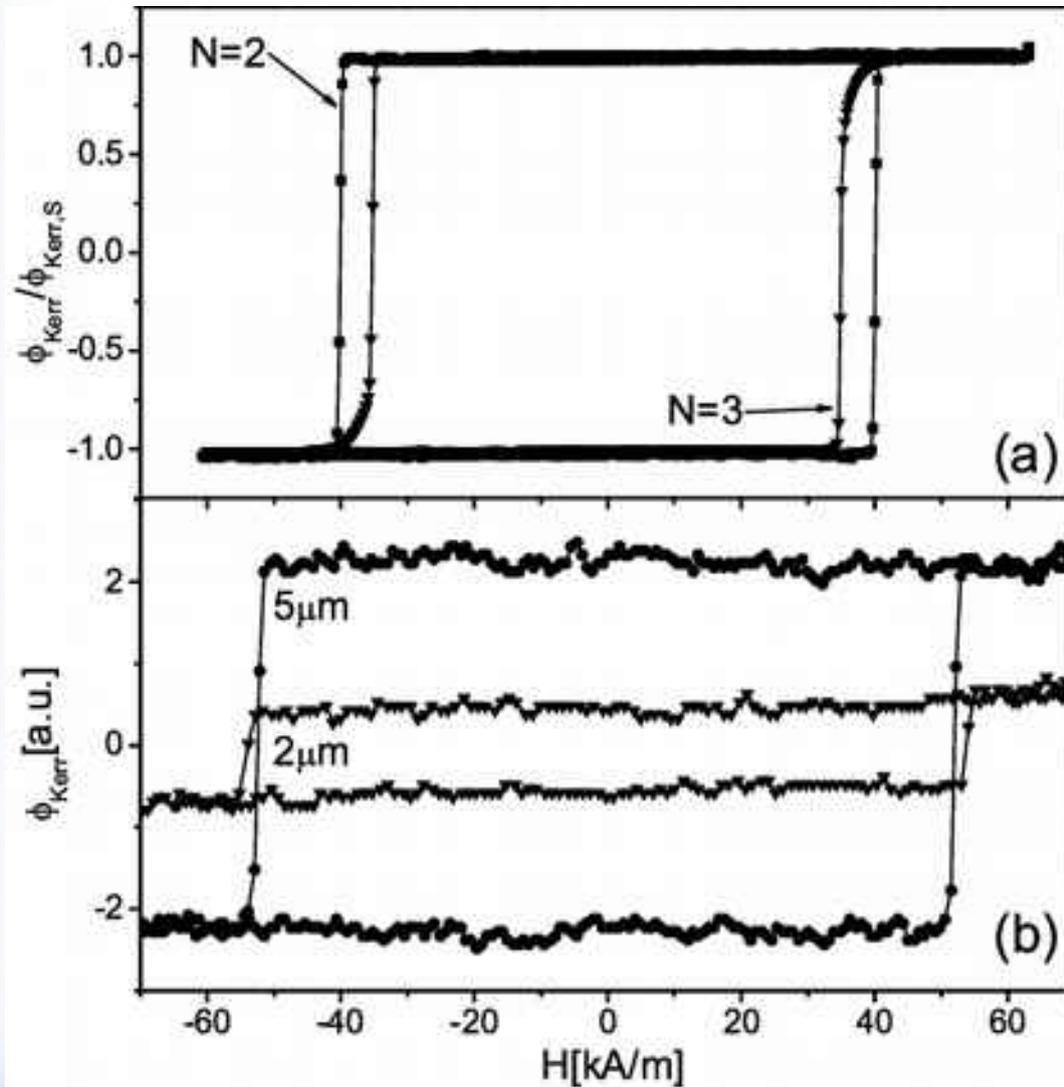
Ion bombardment

- Sample holder moves along the longer edges of the stripes and **ion fluence gradient is created along the stripes**
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- The 10^{15} ion/cm² fluence corresponds to approx. one He^+ ion for seven Co atoms



Patterning

- patterning (EBL) into the stripes increases the coercivity
- possible mechanism: lower number of nucleation centers in small area samples and/or pinning centers introduced during patterning



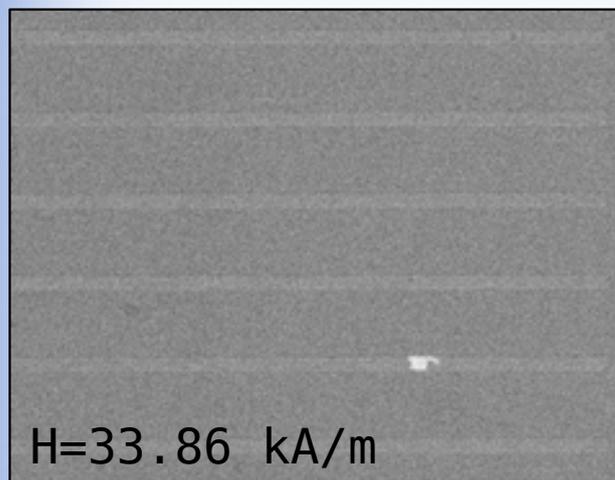
continuous

patterned

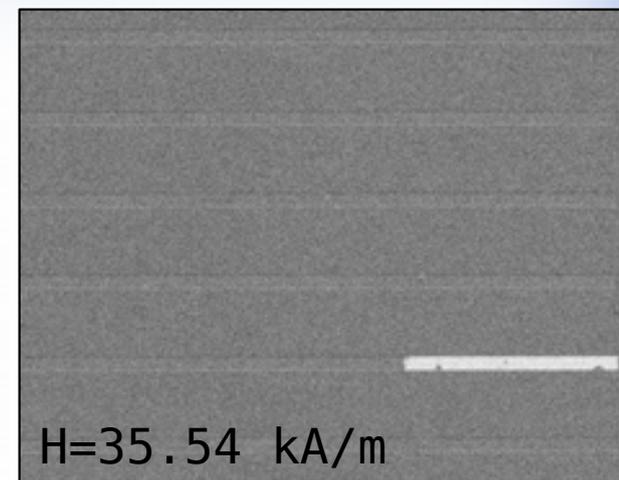
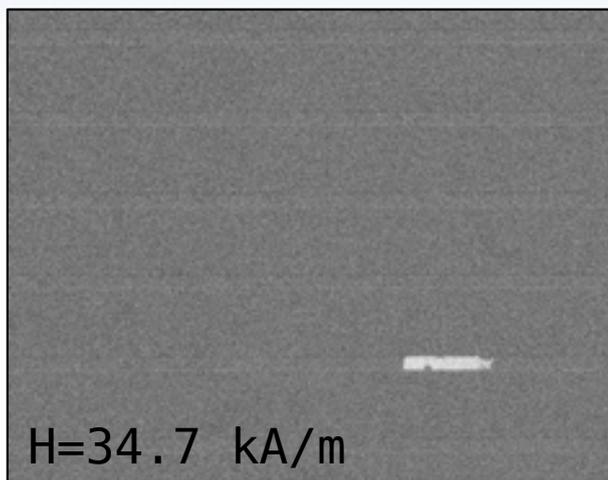
(a) Characteristic P-MOKE hysteresis loops of continuous [Co(0.8 nm)/Au(1 nm)]_N MLs.

(b) The analogous loops for the [Co(0.8 nm)/Au(1 nm)]₂ layer patterned into 5 and 2 μm wide stripes.

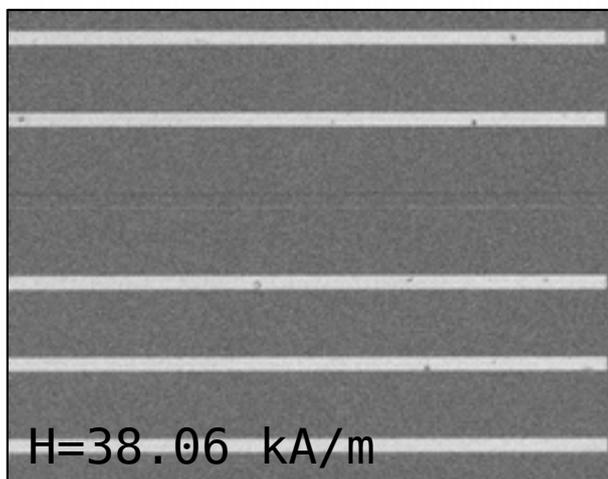
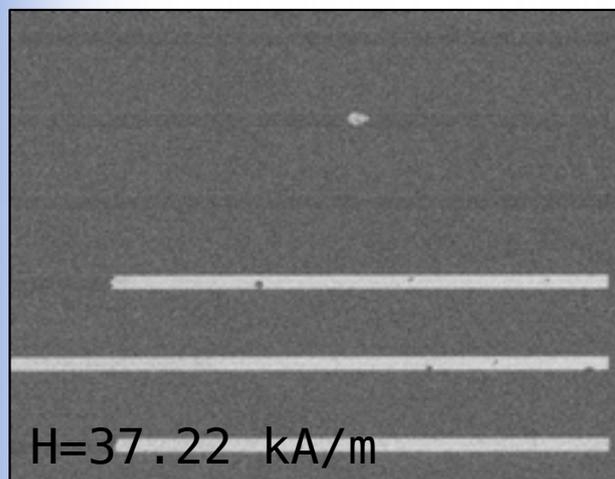
Nucleation in as-deposited Co PMA stripes



approx. 895×687 μm²



2929

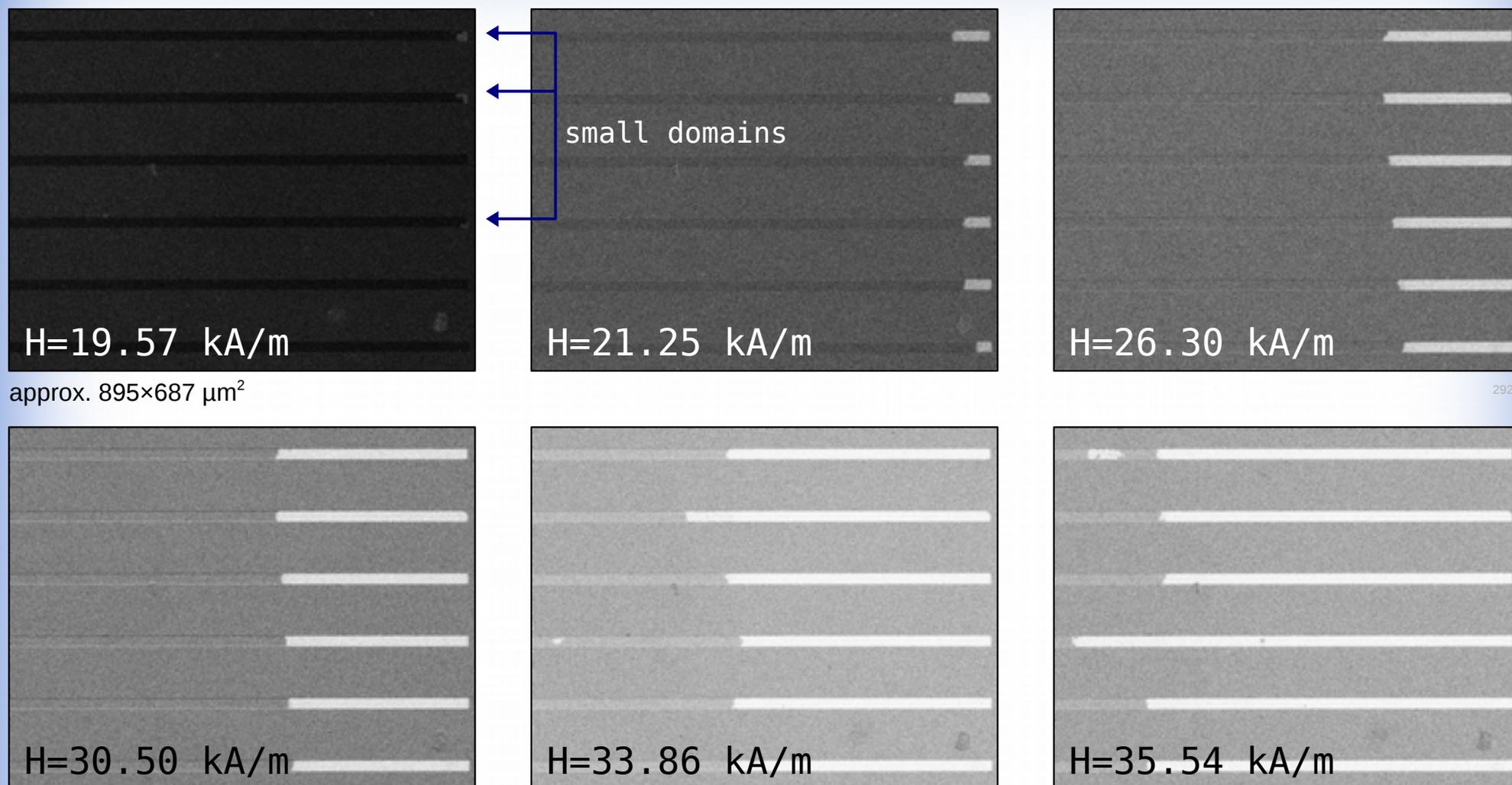


no "active"
nucleation center
up to 38.06kA/m

[Co(0.8nm)/Au(1nm)]₃

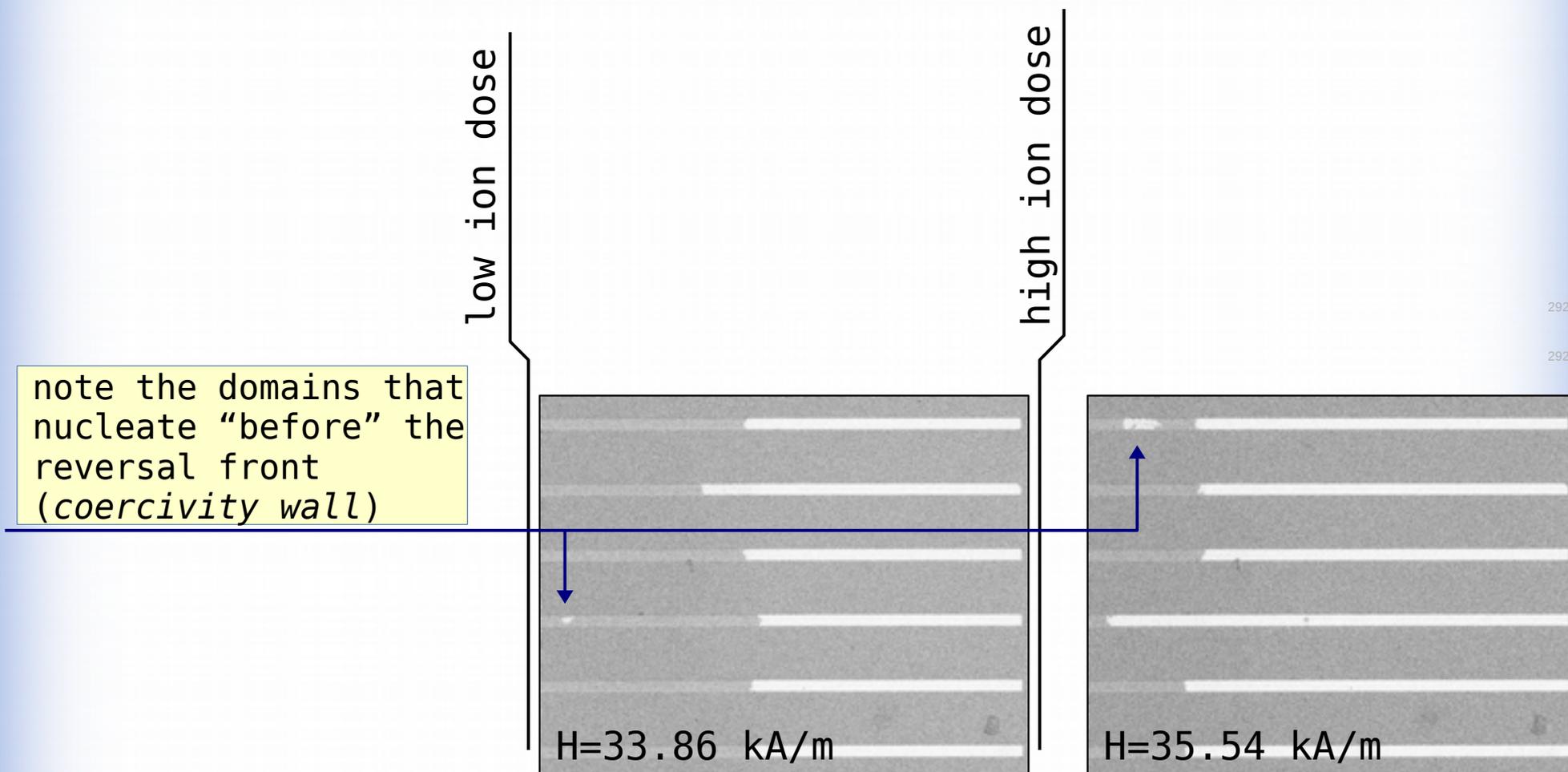
- no visible preference for nucleation of domains in any specific area
- a possible preference for the direction of domain propagation may be a result of thickness gradient which is possible in thin films deposition
- note the strong coupling between Co sublayers – single gray level of domain

Magnetization reversal in bombarded $[\text{Co}(0.8\text{nm})/\text{Au}(1\text{nm})]_3$ stripes



- reversed domains expand from right to left
- note much wider field range (approx. 16 kA/m), as compared to the stripes that were not bombarded (approx. 4 kA/m, previous slide), in which the stripes are not in "single domain" state

Magnetization reversal in bombarded [Co(0.8nm)/Au(1nm)]₃ stripes



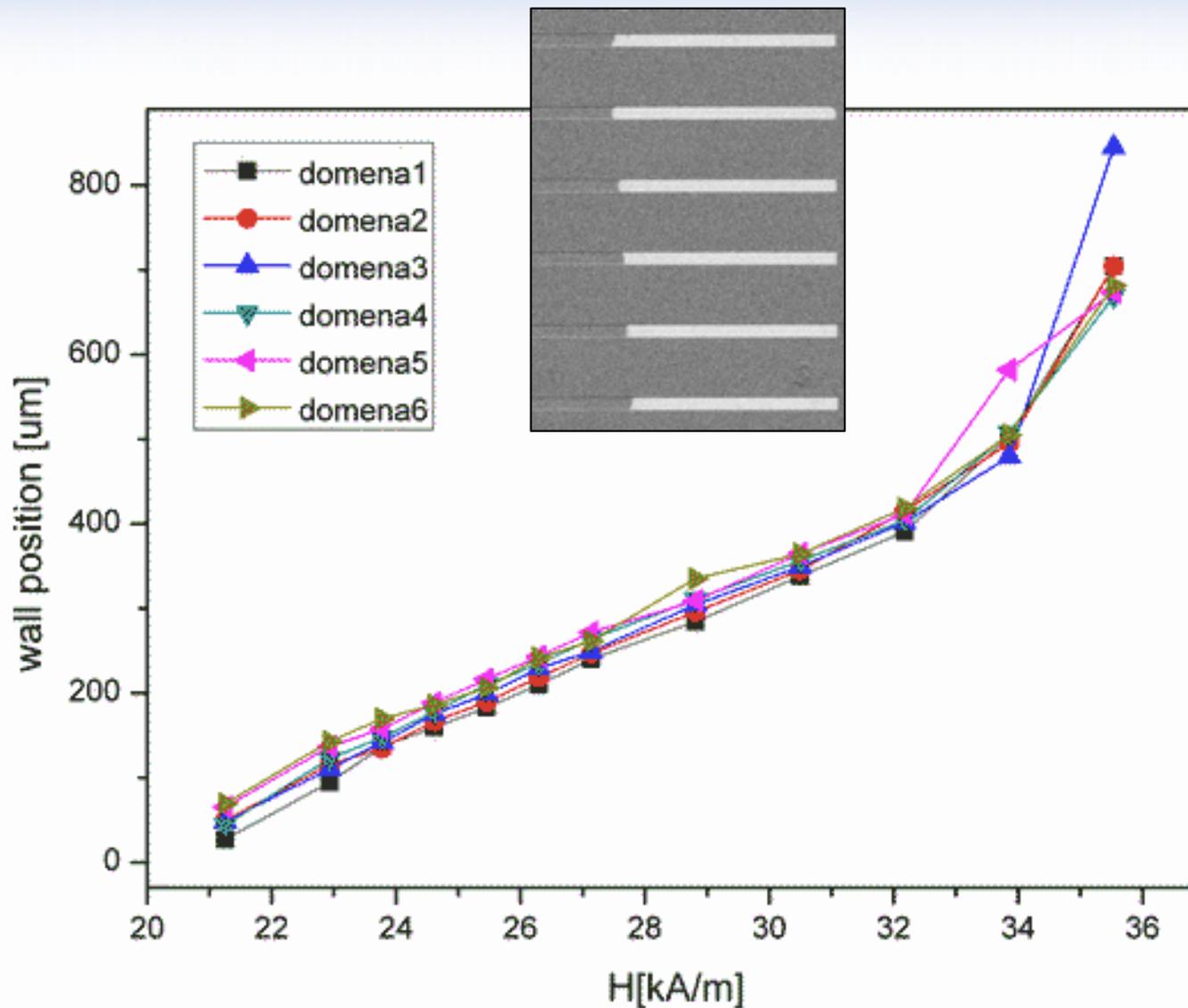
2929

2929

- reversed domains expand from right to left (**high dose -> low dose**)
- note much wider field range (approx. 16 kA/m), as compared to the stripes that were not bombarded (approx. 4 kA/m, previous slide), in which the stripes are not in "single domain" state

Magnetization reversal in bombarded $[\text{Co}(0.8\text{nm})/\text{Au}(1\text{nm})]_3$ stripes

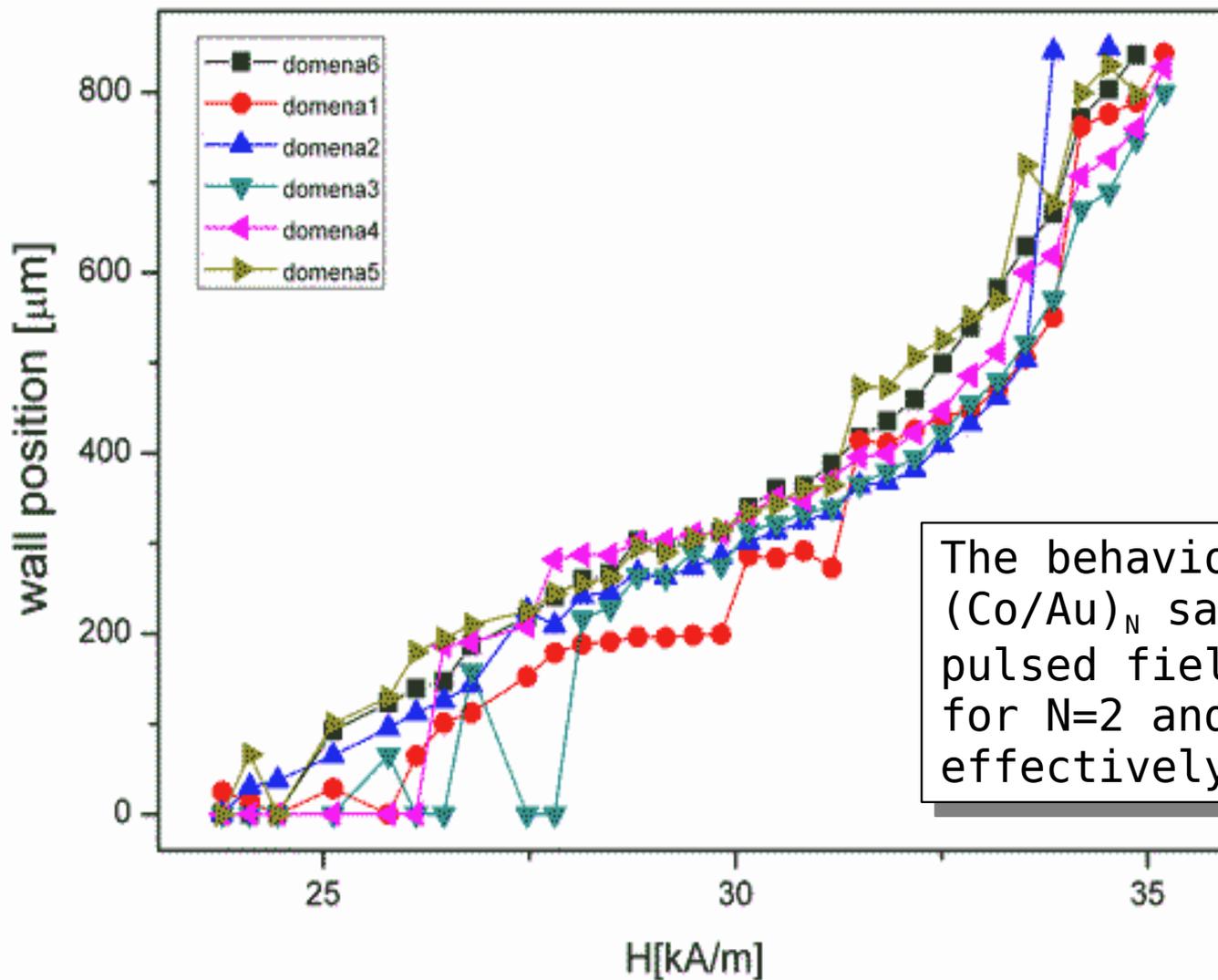
$N=2$
 $w=20\mu\text{m}$



- in all stripes the domain wall position is approximately linear function of the magnetic field pulse strength H_p (for $H_p \ll H_c$)
- global H_c of the extended reference sample is approx. 35 kA/m and H_s is over 40 kA/m.

Magnetization reversal in bombarded $[\text{Co}(0.8\text{nm})/\text{Au}(1\text{nm})]_2$ stripes

$N=3$
 $w=20\mu\text{m}$

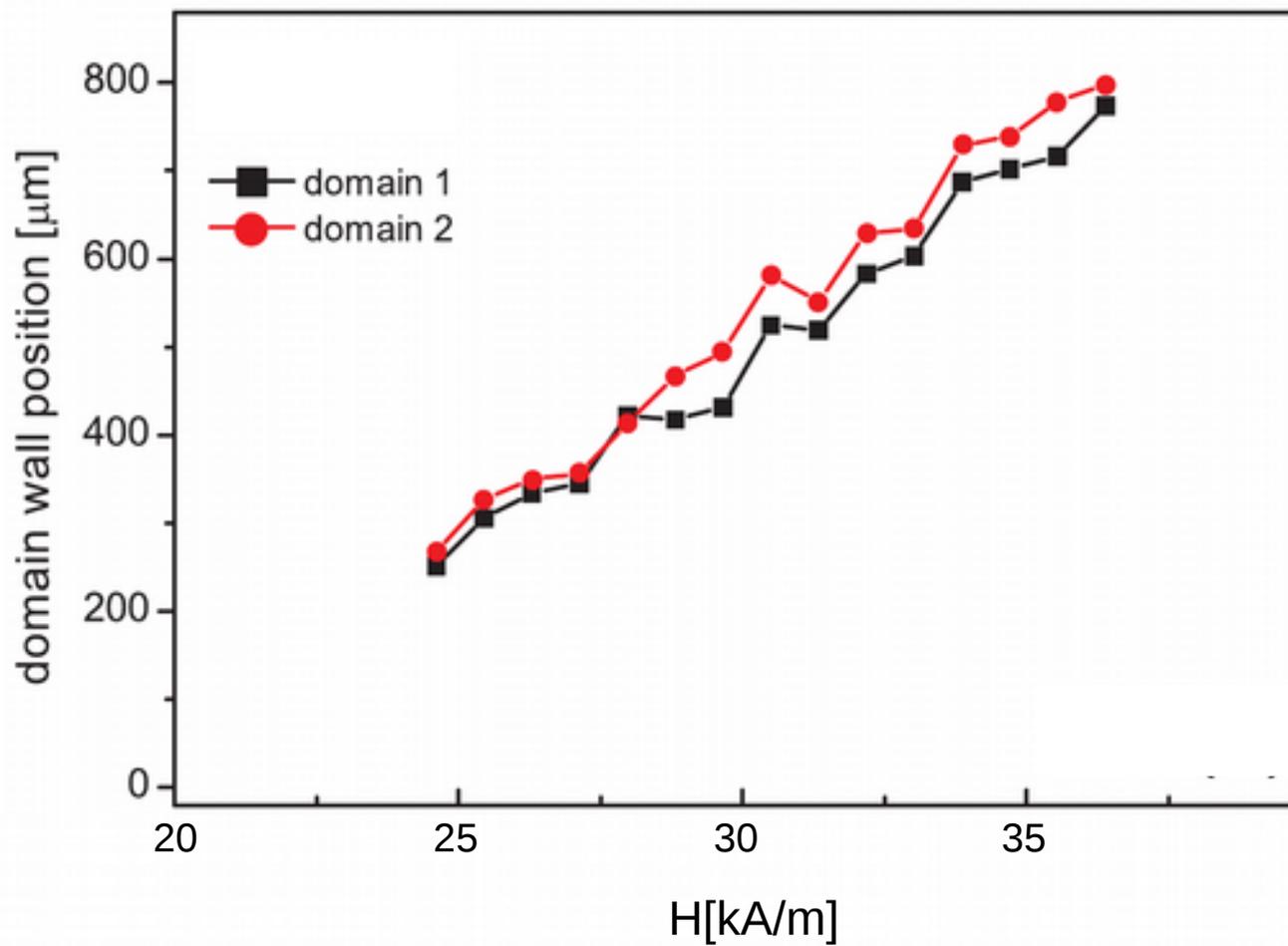


The behavior of the $(\text{Co}/\text{Au})_N$ samples in pulsed fields for $N=2$ and $N=3$ is effectively the same.

- in all stripes the domain wall position is approximately linear function of the magnetic field pulse strength H_p (for $H_p \ll H_c$)
- global H_c and H_s of the extended reference sample are approx. 40 kA/m (square loop)

Magnetization reversal in bombarded $[\text{Co}(0.8\text{nm})/\text{Au}(1\text{nm})]_2$ stripes

$N=3$
 $w=2\mu\text{m}$



- the behavior of stripes with $2\mu\text{m}$ is similar (DW position was determined using other procedure than for wider stripes)
- for $1\mu\text{m}$ the behavior seems to be the same but limited resolution of Kerr microscope did not allow us to quantify this

Magnetization reversal in bombarded stripes – phenomenological model

- assume that H_c is a measure of H_n
- we know the dependence of H_c on ion fluence and the fluence on position along the stripe

$$H_n(x) = H_0 \exp(-x/0.13 \text{ mm})$$

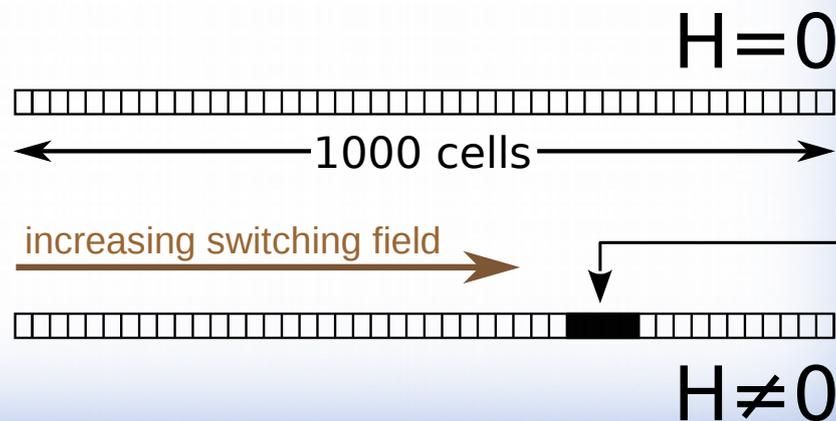
- field dependence of the **barrier height** to nucleation is given by*:

$$\Delta E_n(x) = E_n \left(1 - \frac{H}{H_n(x)} \right)^{1.5}$$

- the magnetization reversal can be activated thermally and its rate, r , or frequency may be described by an **Arrhenius type law**

$$r(x, T) = r_0 \exp\left(\frac{-\Delta E_n(x)}{k_B T}\right)$$

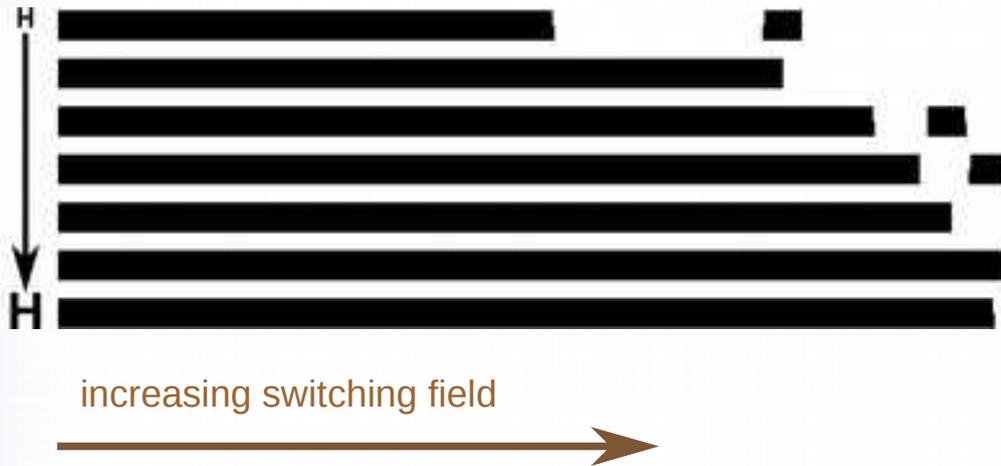
- we divide the stripe, along its length, into 1000 pieces/cells and for each of them calculate reversal rate
- for each cell, using random numbers and the reversal rate, we decide whether it becomes a nucleation center
- each domain is allowed to grow by 20 cells in both directions during the application of the field



*J. Vogel, J. Moritz, and O. Fruchart, C.R. Phys. 7, 977 (2006)

Magnetization reversal in bombarded stripes – phenomenological model

- like in the experiment the domains grow with increasing H
- for some values of H domains nucleate to the right of the reversal front
- in some cases the length of the domain is less for higher H , as is observed experimentally

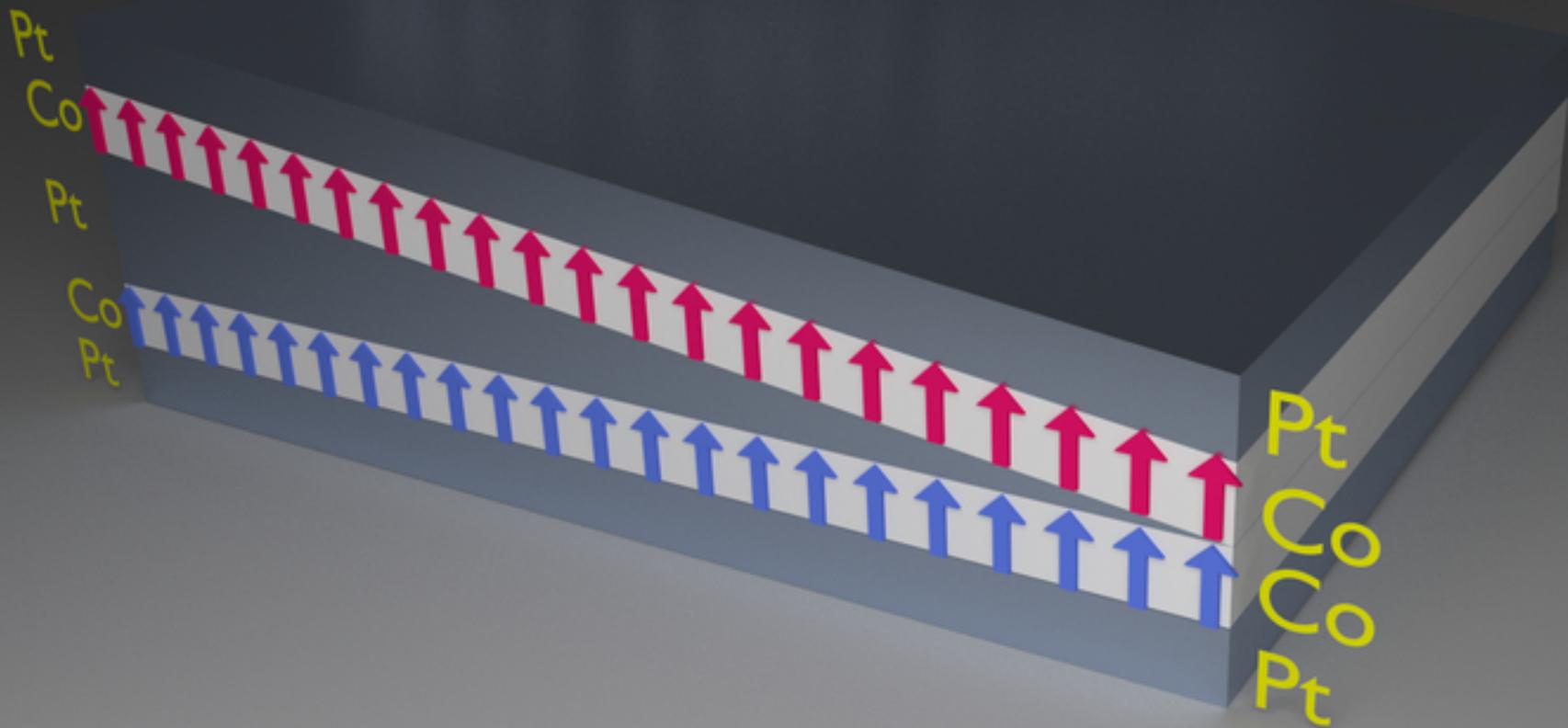


Exemplary simulated magnetic configuration obtained from the phenomenological model. The field pulse strength increases from the top to bottom stripe ($H = 0.01, 0.05, 0.10, 0.15, 0.2, 0.25, 0.3$ [a.u.]). The parameters used in the model are: $H_0 = 1, E_n = 1, r_0 = 1, k_B = 1$, and $T = 0.1$.

Co/Pt multilayers with coupling gradient

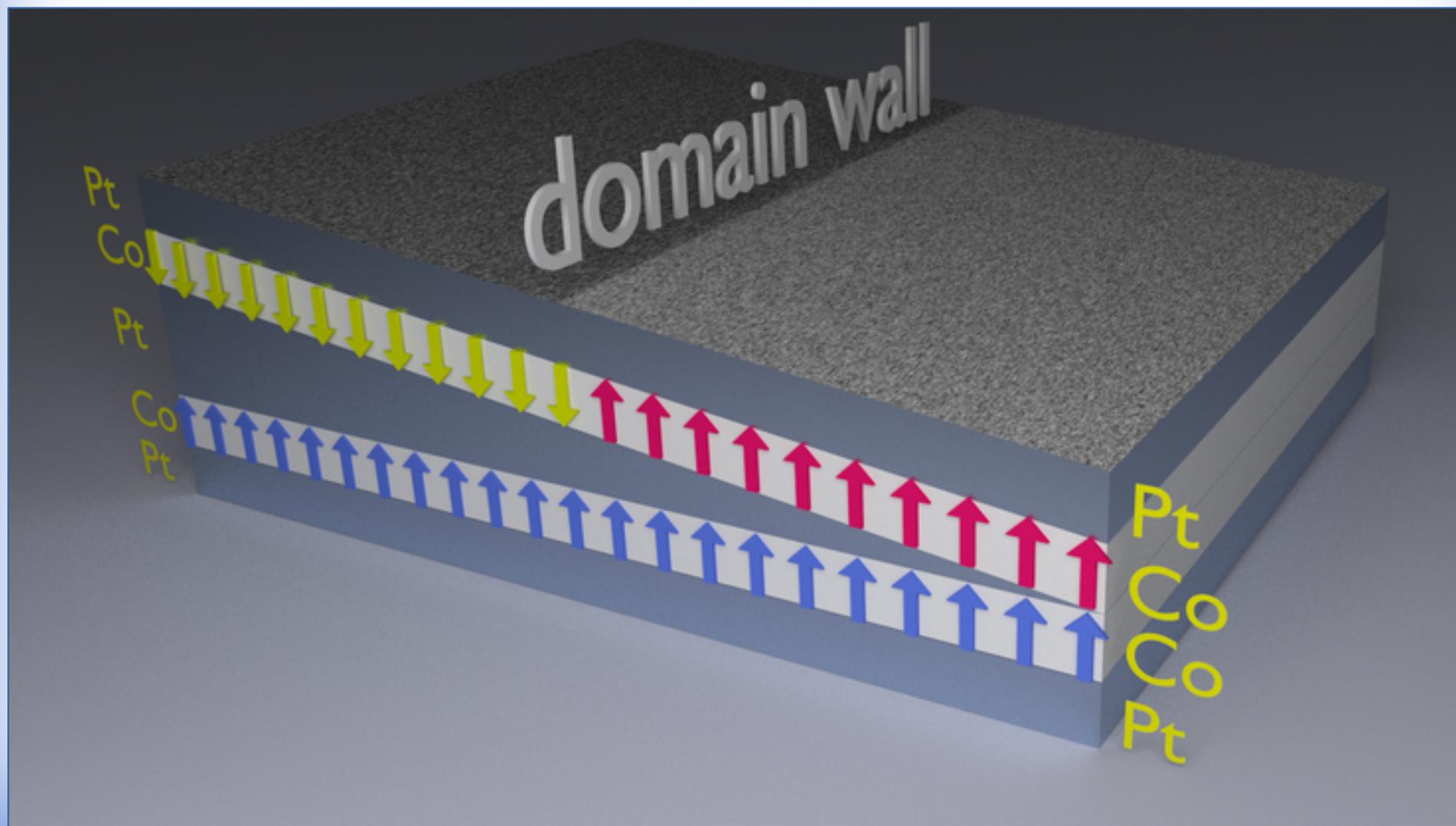
- sputtered
- two Co layers with different coercivity which is determined by the thickness of the layers
- coupling changes with position along the platinum wedge

Si(100)/Pt(15 nm)/Co(0.8 nm)/Pt wedge (0-7 nm)/Co(0.6 nm)/Pt (2 nm)



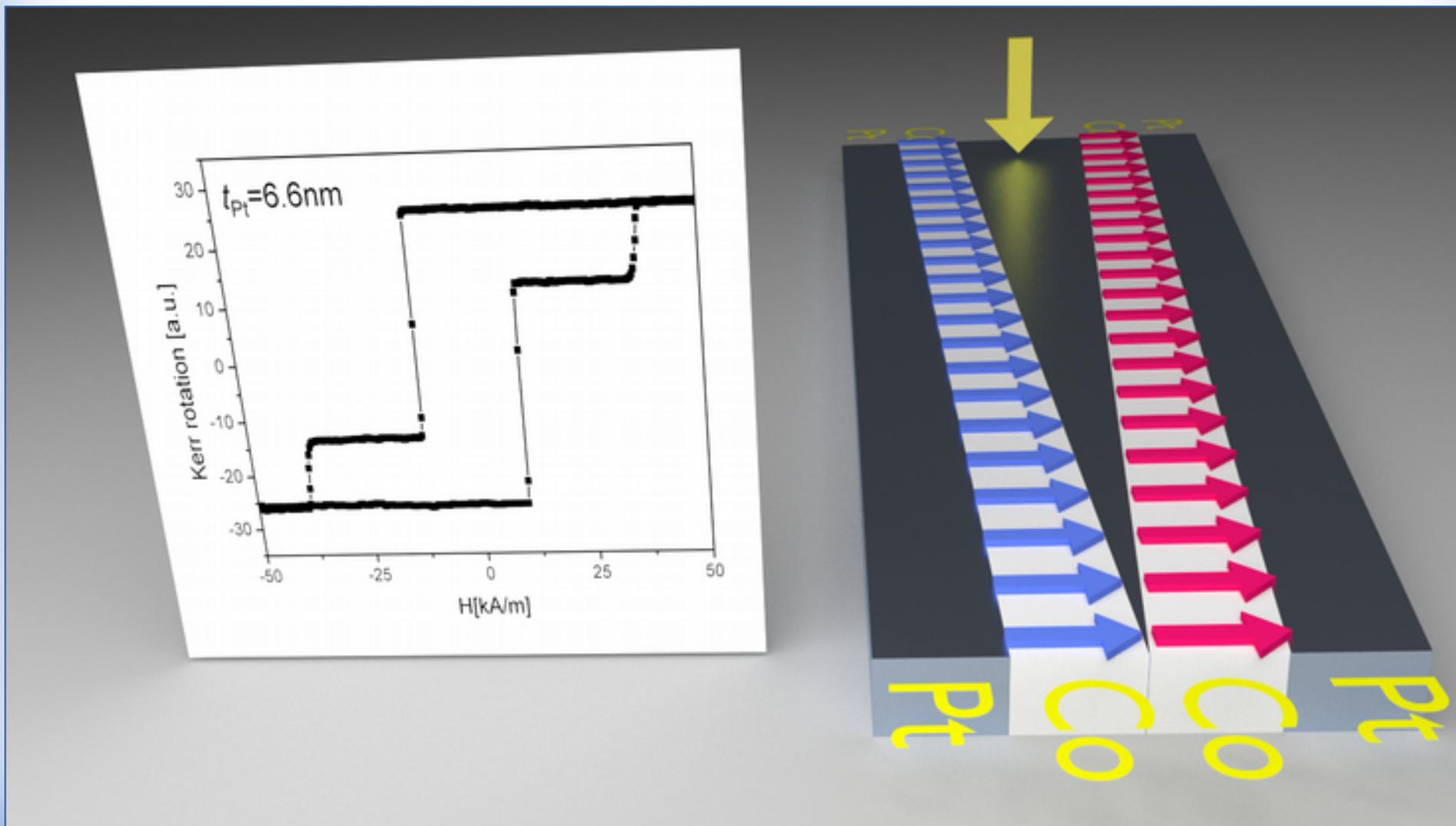
Co/Pt multilayers with coupling gradient

How to influence the position of the domain wall?



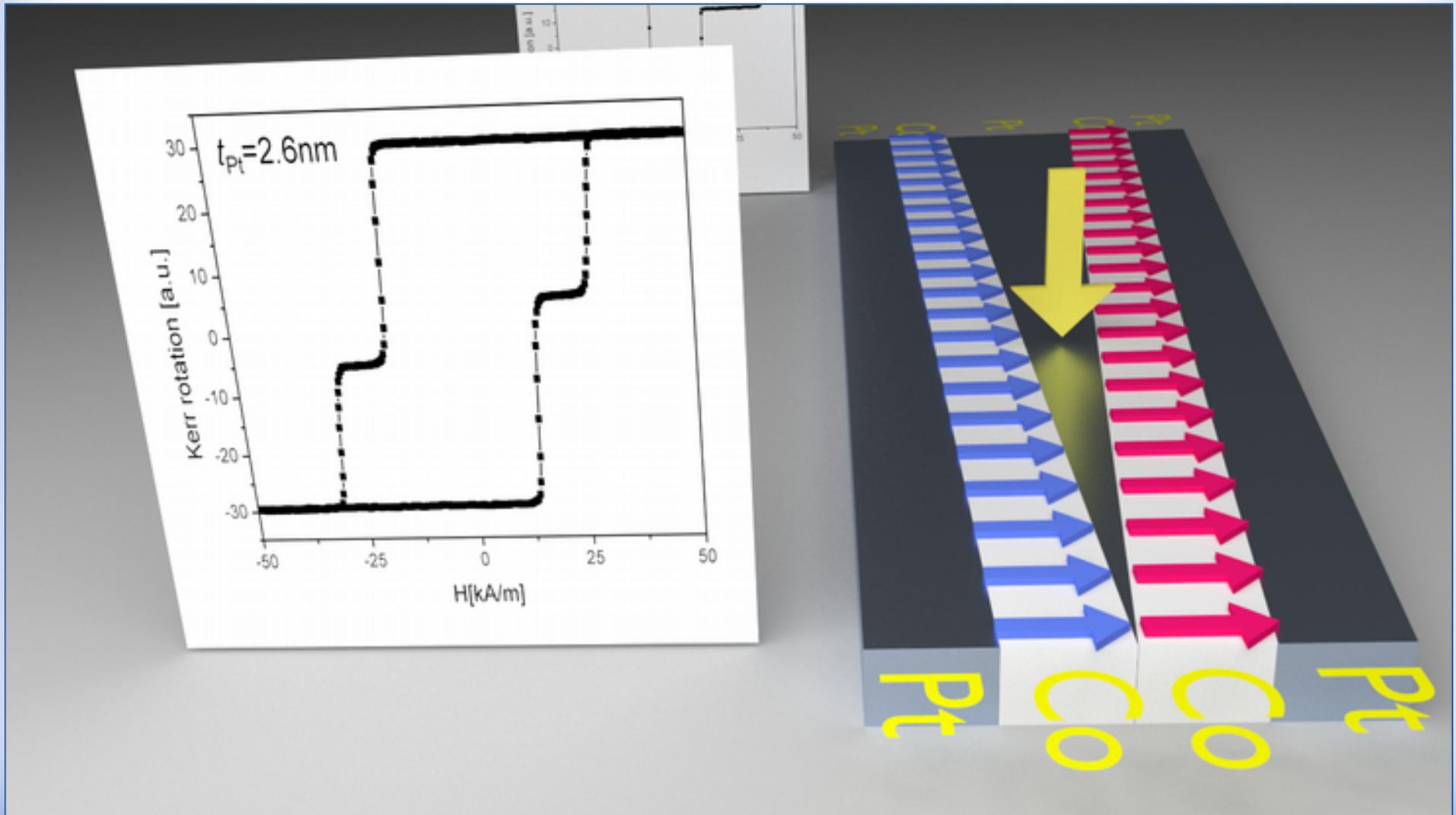
Co/Pt multilayers with coupling gradient

- the local hysteresis loop depends on the strength of the coupling between Co layers parted by platinum spacer
- thick Pt spacer – both layers reverse independently



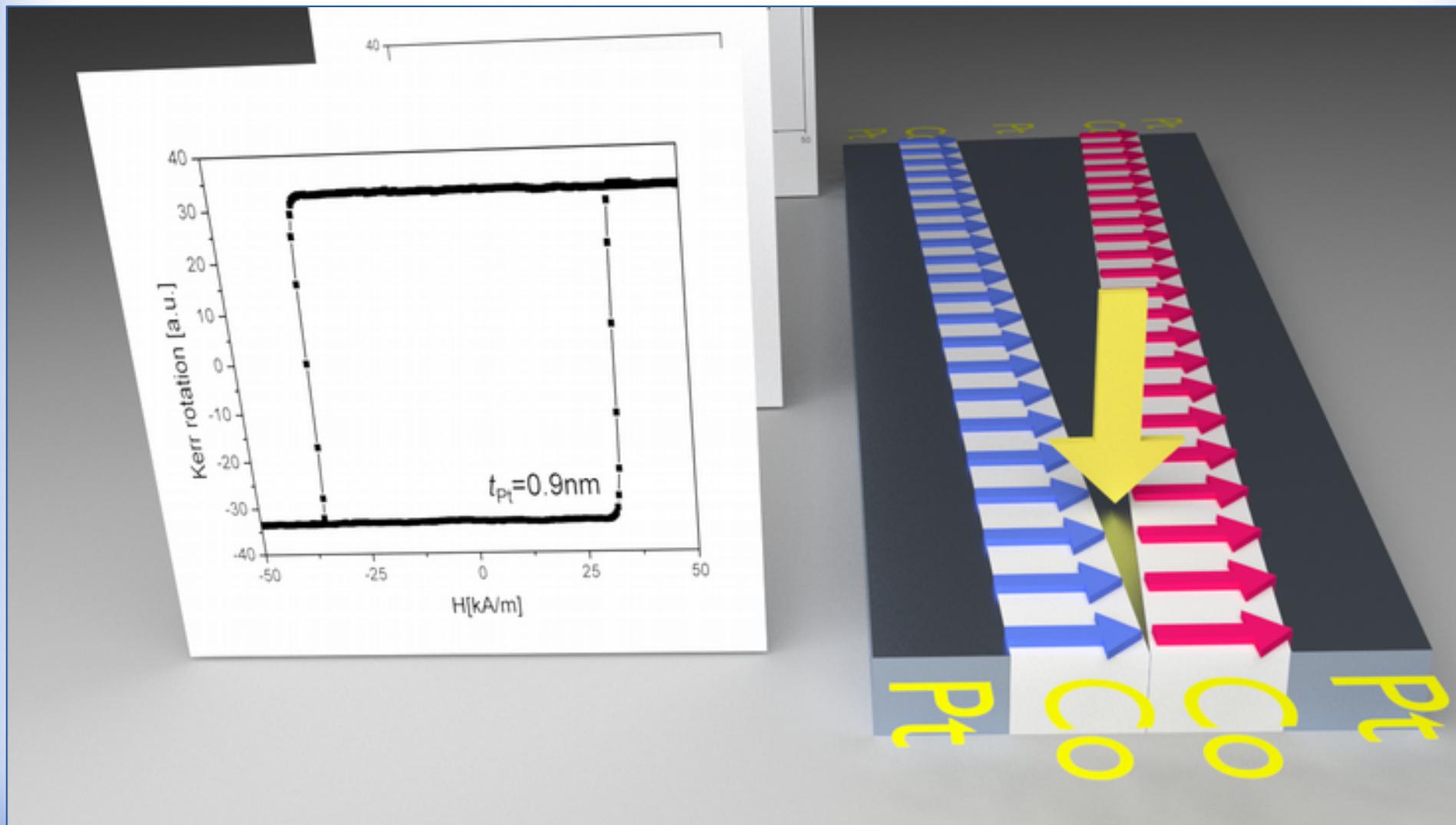
Co/Pt multilayers with coupling gradient

- the local hysteresis loop depends on the strength of the coupling between Co layers parted by platinum spacer
- intermediate Pt thickness – the switching fields of both Co layers are position dependent

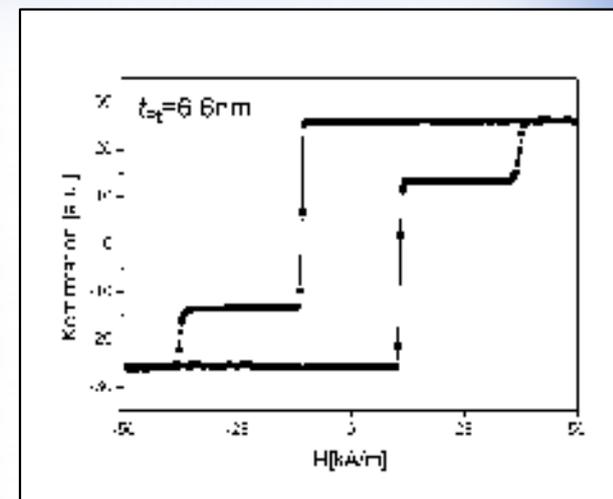
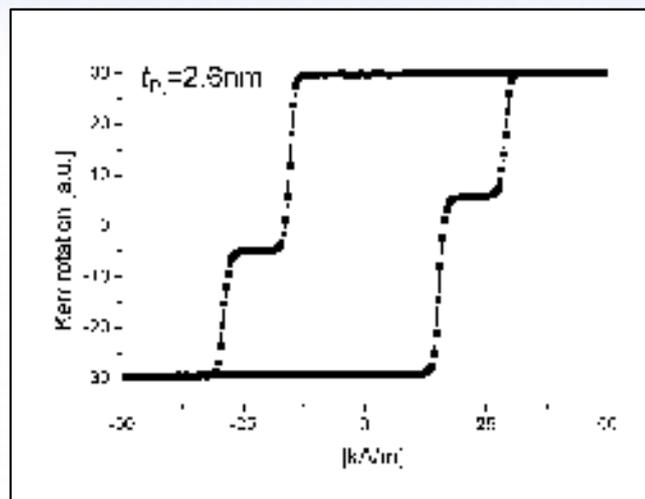
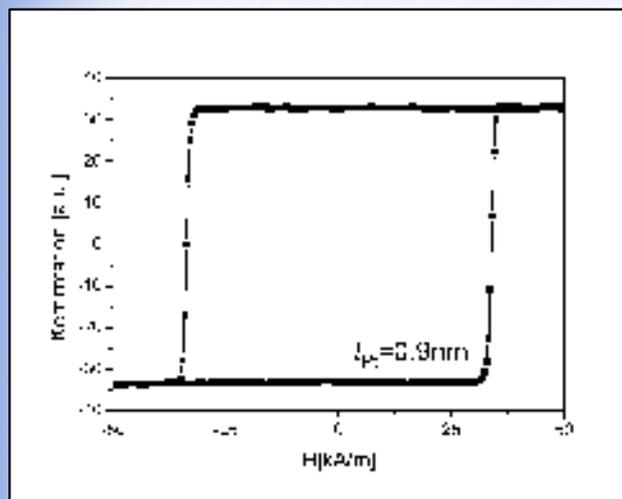


Co/Pt multilayers with coupling gradient

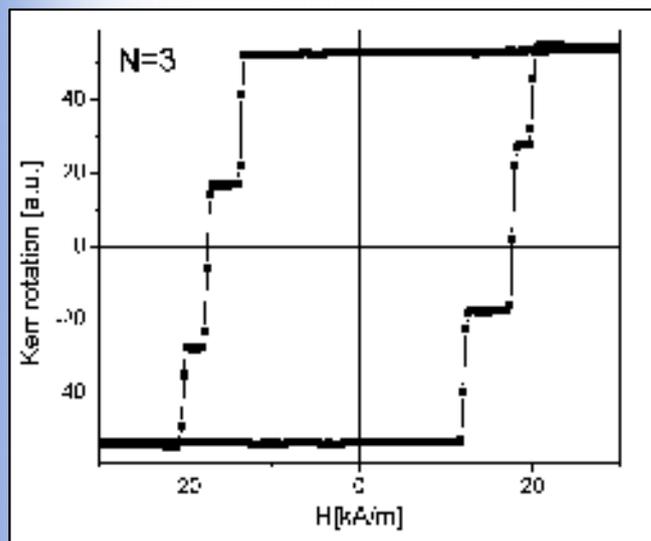
- the local hysteresis loop depends on the strength of the coupling between Co layers parted by platinum spacer
- thin Pt spacer – cooperative switching of both Co layers



Co/Pt multilayers with coupling gradient



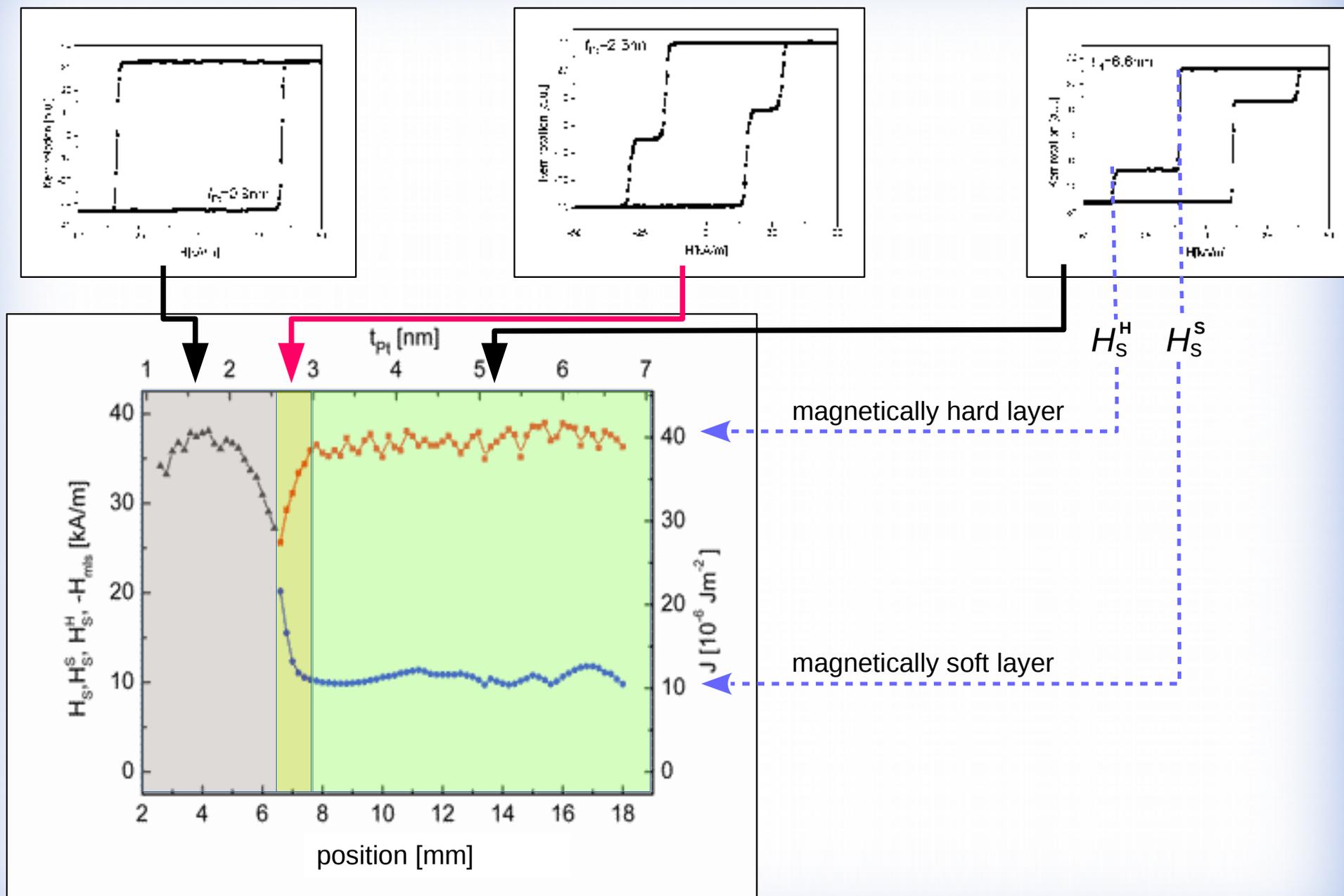
Si(100)/Pt(15 nm)/Co(0.8 nm)/Pt wedge (0-7 nm)/Co(0.6 nm)/Pt(2 nm), $N=2$



- In multilayers the switching fields of various layers are usually different due to different growth conditions, differing behavior of outer layers etc.
- Simultaneous switching may suggest the interlayer coupling

Si(100)/Ti(15 nm)/Au(40 nm)/[Au(2nm)/Co(0.5 nm)]₃ /Au(2 nm), $N=3$

Co/Pt multilayers with coupling gradient

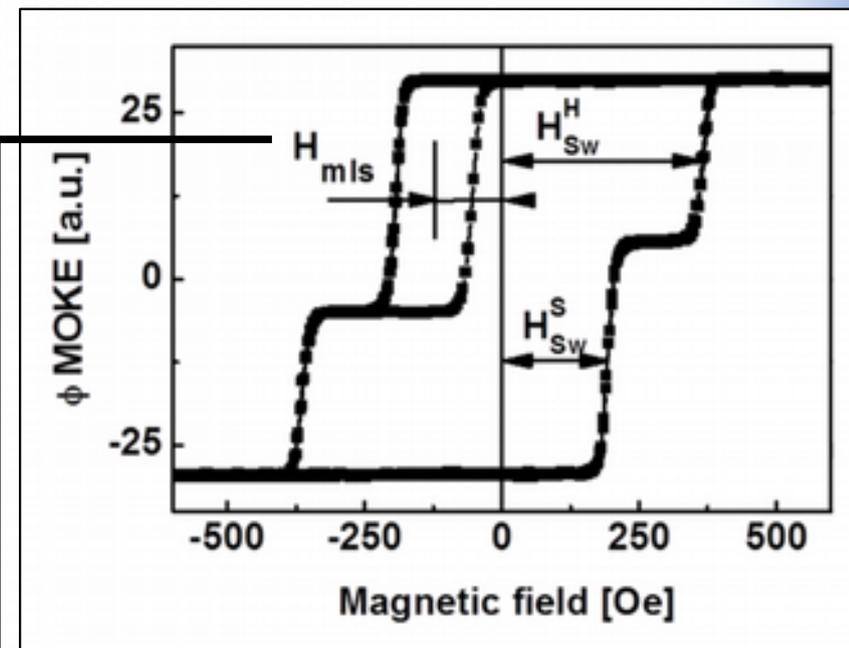
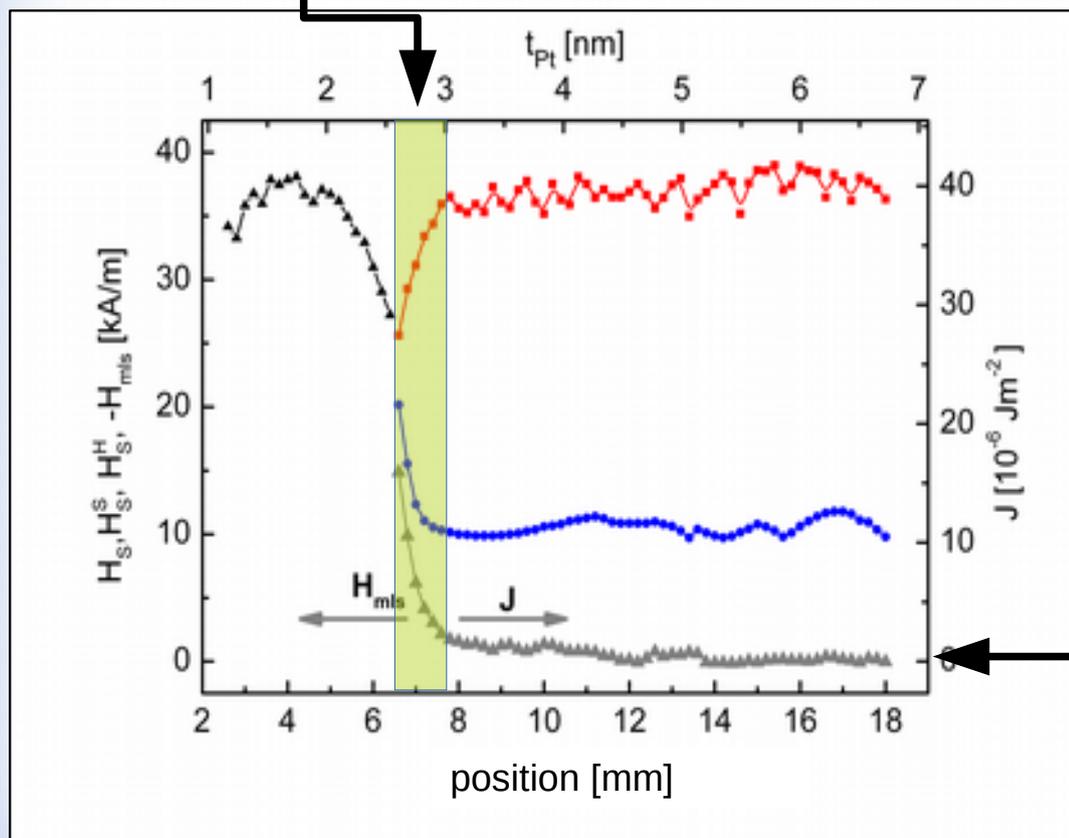


Si(100)/Pt(15 nm)/Co(0.8 nm)/Pt wedge (0-7 nm)/Co(0.6 nm)/Pt(2 nm), $N=2$

Co/Pt multilayers with coupling gradient

we investigated mainly the Pt thickness range corresponding to significant gradient of the coupling between Co layers

the shift of the minor hysteresis loop H_{mls} of the magnetically soft layer, if the magnetization of the hard layer is "up", is a measure of the coupling between Co layers



Si(100)/Pt(15 nm)/Co(0.8 nm)/Pt wedge (0-7 nm)/Co(0.6 nm)/Pt(2 nm), $N=2$

Co/Pt multilayers with coupling gradient

In the thickness range corresponding to a weak interlayer coupling the domain propagates in the “creep” regime

$$v = v_0 \exp\left[-\frac{P}{H^{1/4}}\right]$$

reference image

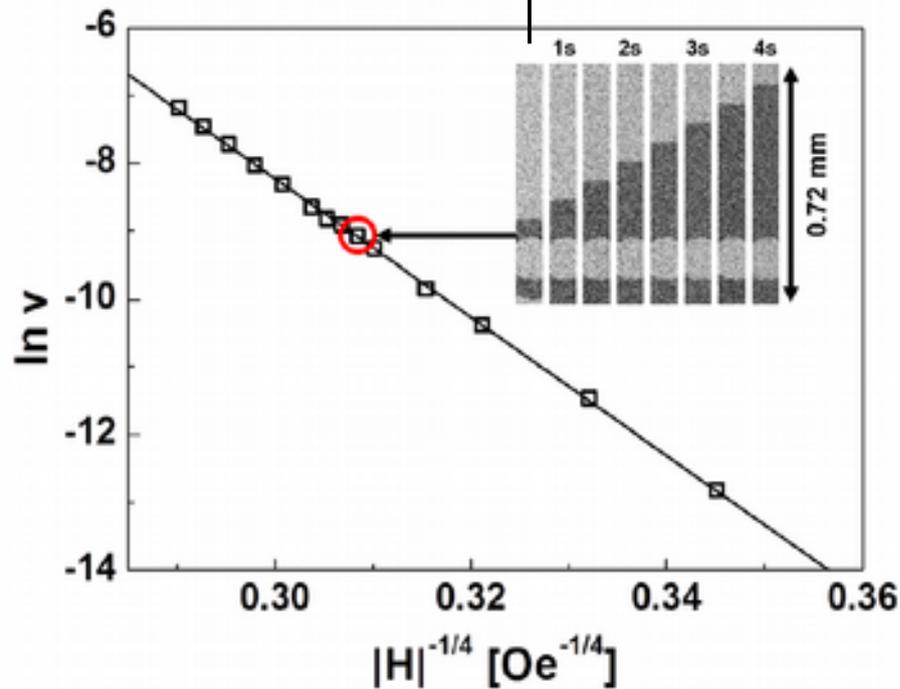
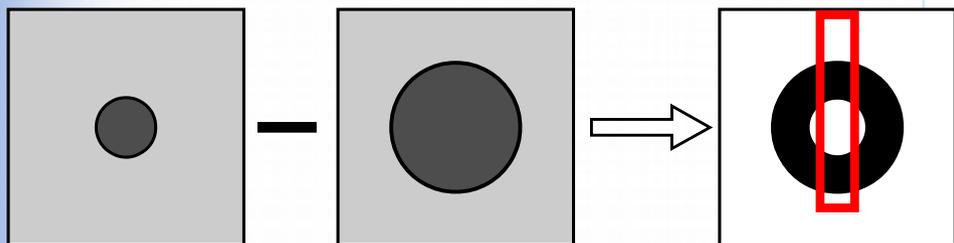
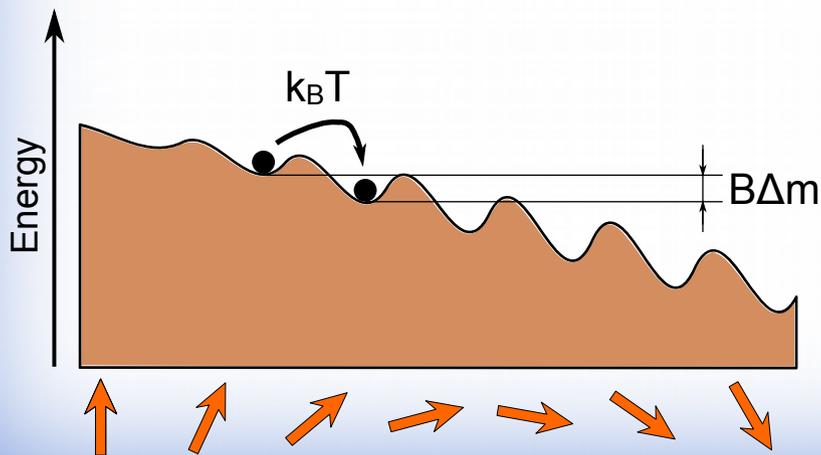
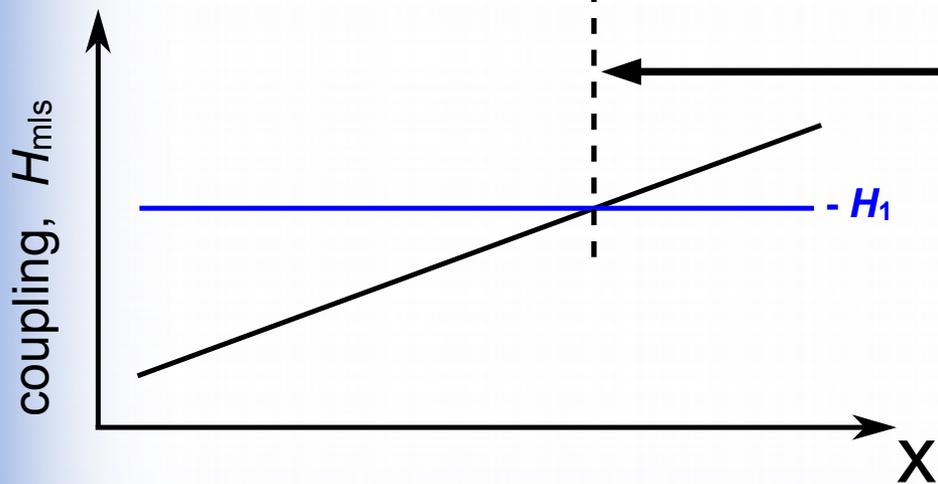
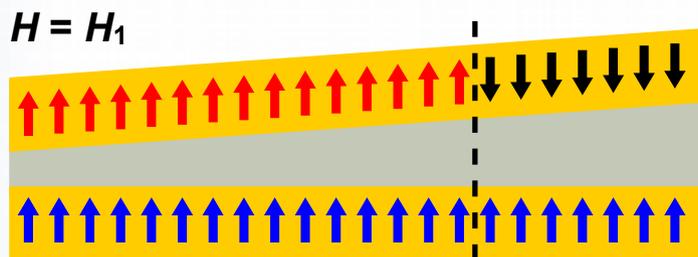
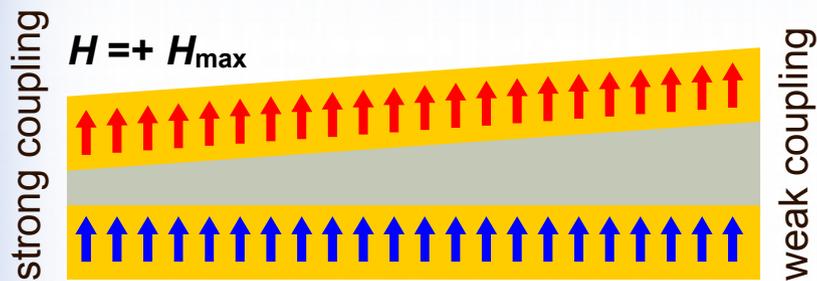


FIG. 3. Natural logarithm of the DW velocity v (expressed in m/s), in the Co^S layer versus $H^{-1/4}$ for a $\text{Co}^H/\text{Pt-wedge}/\text{Co}^S$ layered film determined for a spacer layer thickness $t_{\text{Pt}} = 6.6 \text{ nm}$ ($x = 17 \text{ nm}$), i.e., in the range corresponding to a weak interlayer coupling. The inset shows difference domain images where the upper dark area corresponds to the area reversed by the sum of consecutive field pulses.



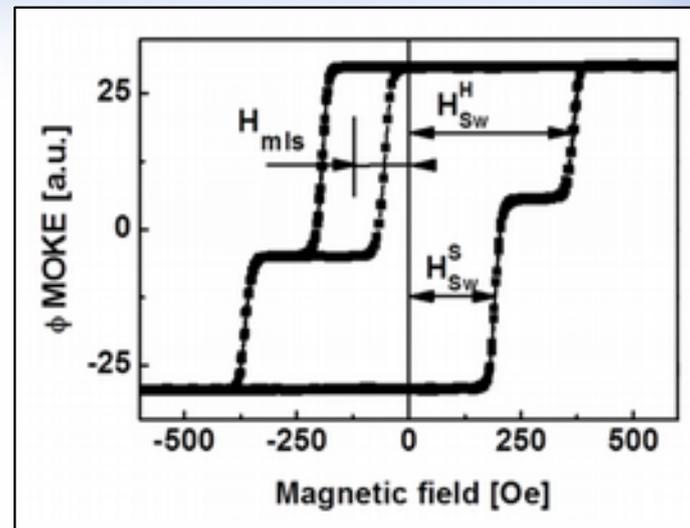
Co/Pt multilayers with coupling gradient



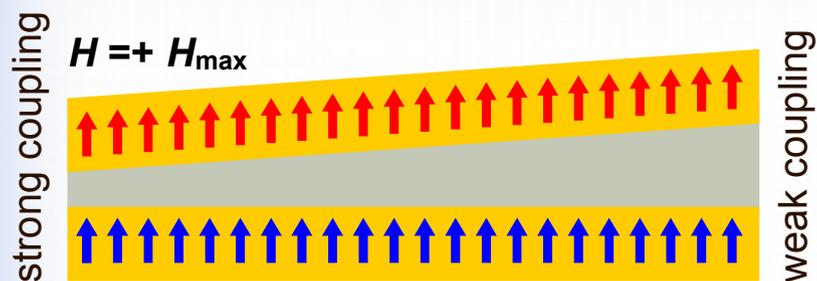
In the external field $H = -H_{mls}(x)$ the effective field acting on the spins positioned at x is zero.

- effective local field acting on the spins of the soft layer is a sum of the external field and the coupling field between Co layers
- the effective field is a function of position (x)

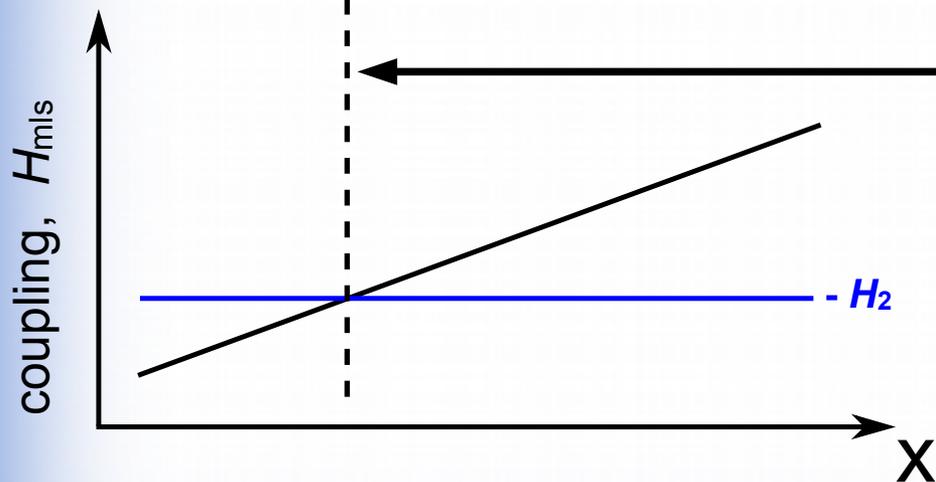
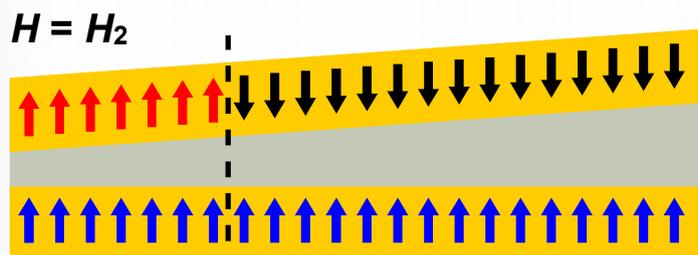
H_{mls}



Co/Pt multilayers with coupling gradient



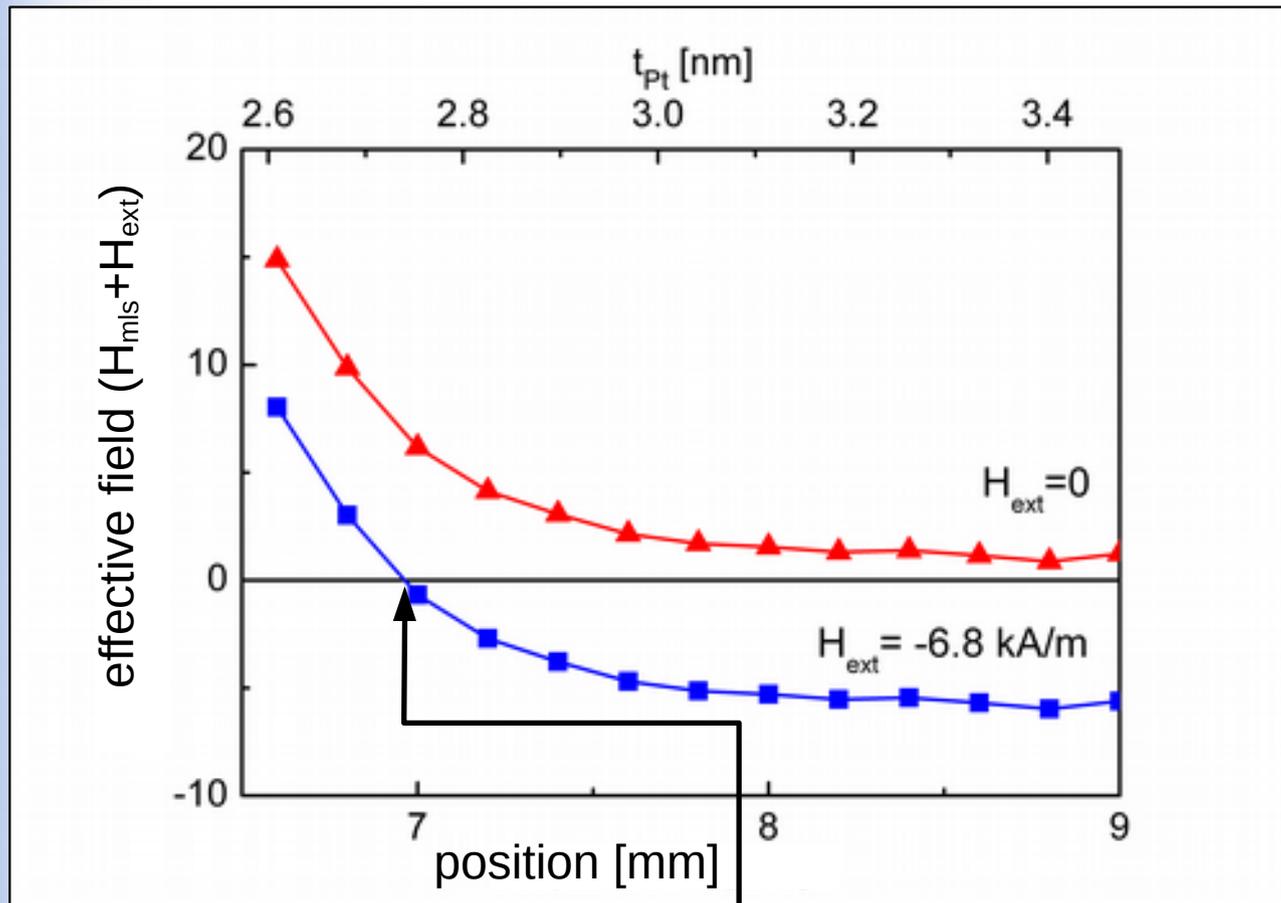
$$v = v_0 \exp \left[- \frac{P}{(|H - H_{mls}|)^{(1/4)}} \right]$$



In the external field $H = -H_{mls}(x)$ the effective field acting on the spins positioned at x is zero.

- effective local field acting on the spins of the soft layer is a sum of the external field and the coupling field between Co layers
- the effective field is a function of position (x)

Domain wall propagation in the presence of the gradient of ferromagnetic coupling



equilibrium position (the effective field equal to zero) for $H_{\text{ext}} = -6.8 \text{ kA/m}$

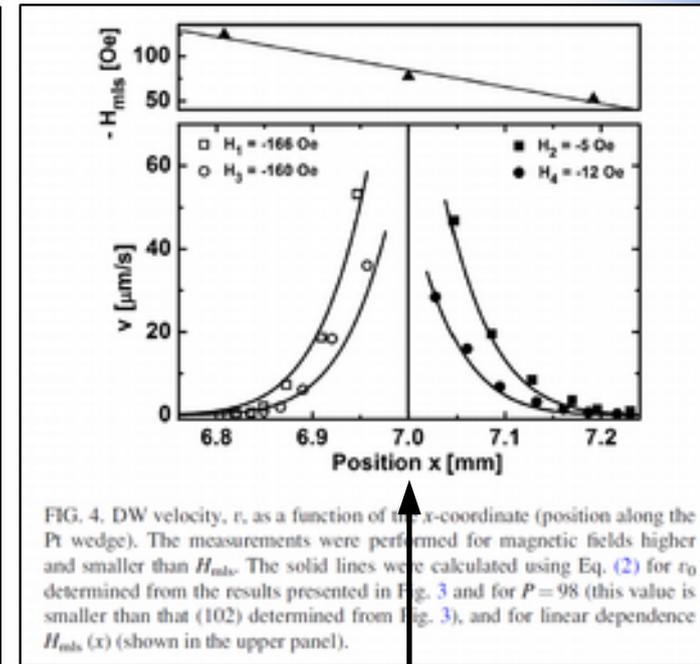
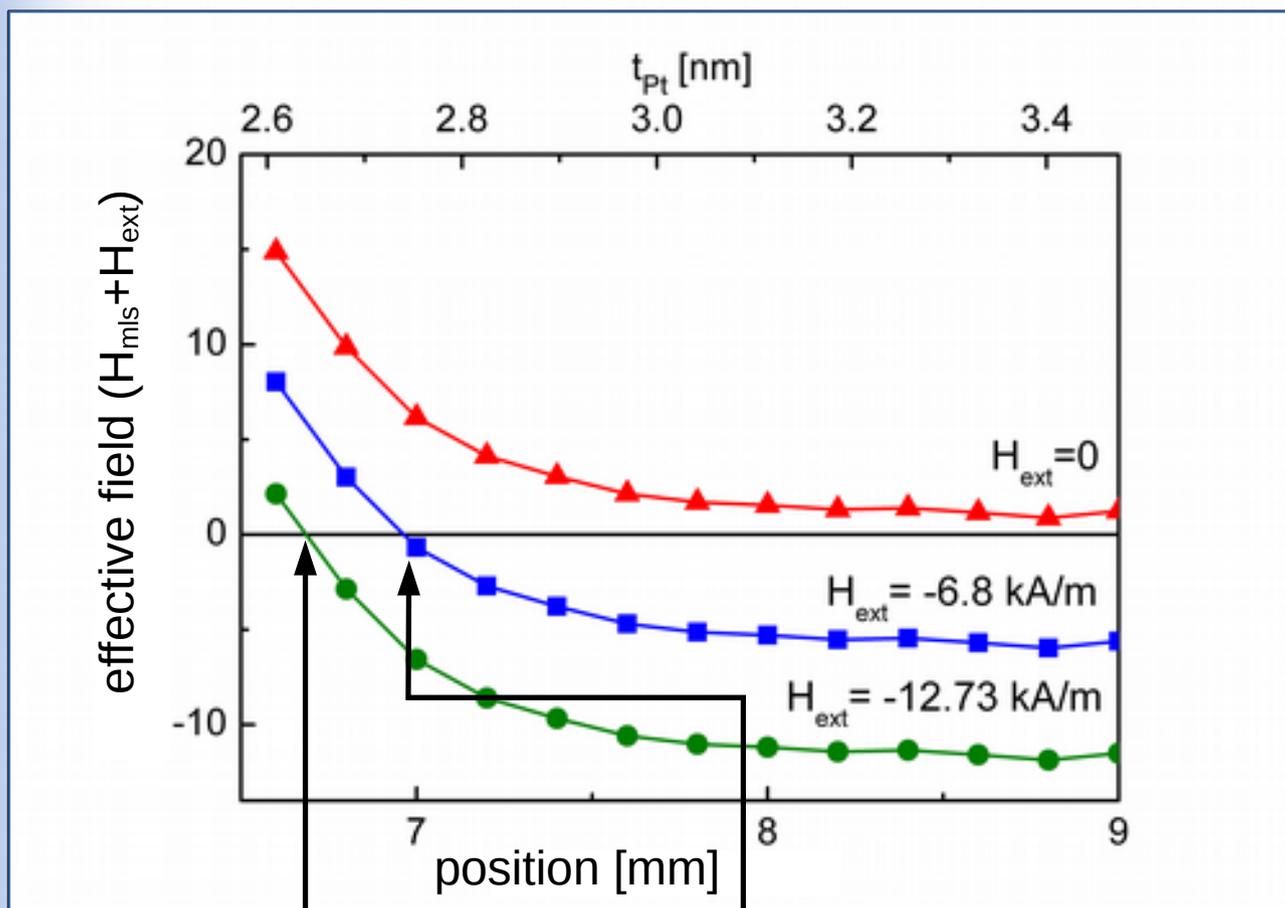


FIG. 4. DW velocity, v , as a function of the x -coordinate (position along the Pt wedge). The measurements were performed for magnetic fields higher and smaller than H_{mfs} . The solid lines were calculated using Eq. (2) for τ_0 determined from the results presented in Fig. 3 and for $P = 98$ (this value is smaller than that (102) determined from Fig. 3), and for linear dependence $H_{\text{mfs}}(x)$ (shown in the upper panel).

Domain wall propagation in the presence of the gradient of ferromagnetic coupling



equilibrium position (the effective field equal to zero) for $H_{\text{ext}} = -12.73 \text{ kA/m}$

equilibrium position (the effective field equal to zero) for $H_{\text{ext}} = -6.8 \text{ kA/m}$

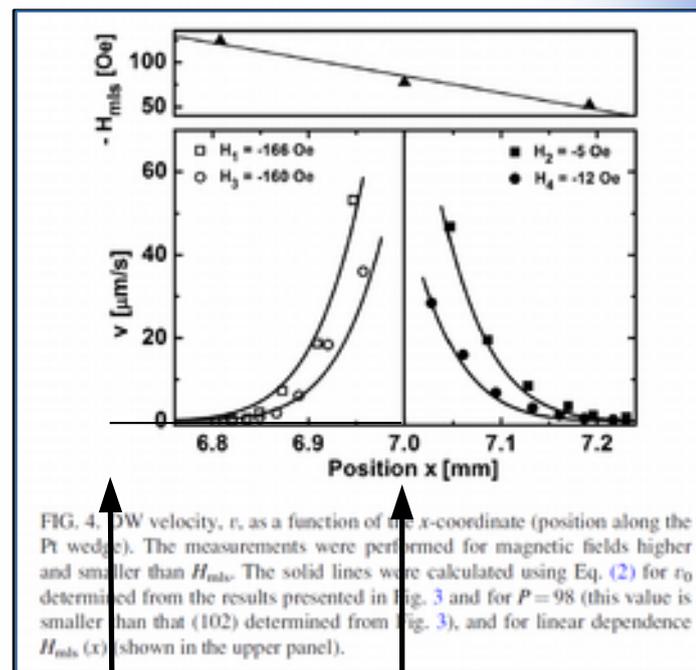


FIG. 4. DW velocity, v , as a function of the x -coordinate (position along the Pt wedge). The measurements were performed for magnetic fields higher and smaller than H_{mfs} . The solid lines were calculated using Eq. (2) for τ_0 determined from the results presented in Fig. 3 and for $P = 98$ (this value is smaller than that (102) determined from Fig. 3), and for linear dependence $H_{\text{mfs}}(x)$ (shown in the upper panel).

* -160 Oe

Domain wall propagation in the presence of the gradient of ferromagnetic coupling

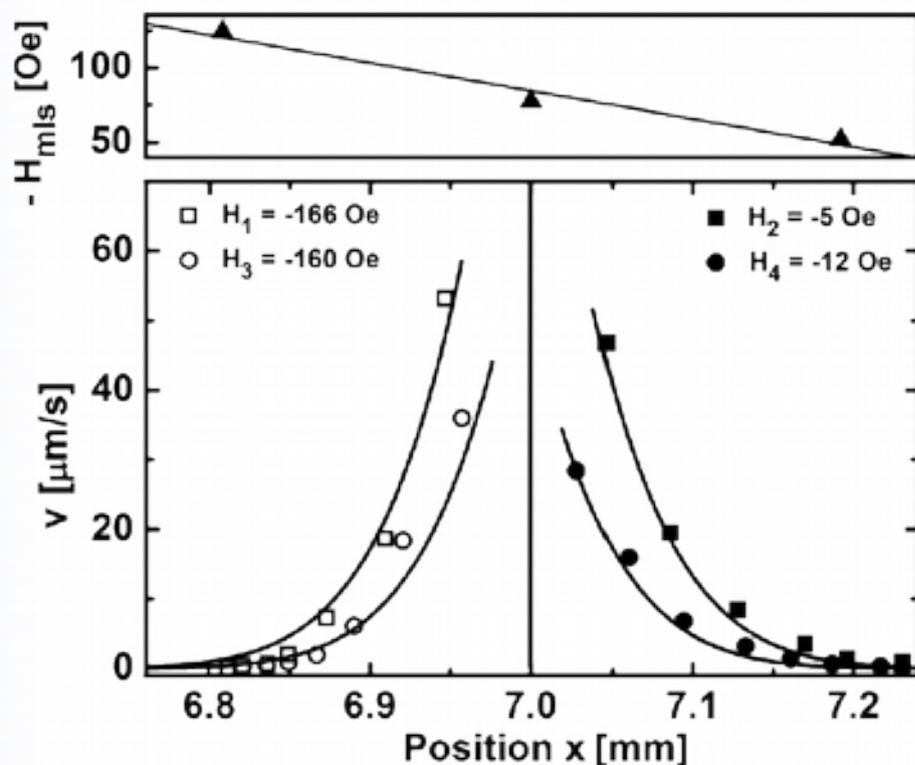


FIG. 4. DW velocity, v , as a function of the x -coordinate (position along the Pt wedge). The measurements were performed for magnetic fields higher and smaller than H_{mls} . The solid lines were calculated using Eq. (2) for v_0 determined from the results presented in Fig. 3 and for $P = 98$ (this value is smaller than that (102) determined from Fig. 3), and for linear dependence $H_{mls}(x)$ (shown in the upper panel).

The interlayer coupling between Co layers suppresses thermally activated creep in the magnetically soft layer

$$v = v_0 \exp \left[- \frac{P}{(|H - H_{mls}|)^{1/4}} \right]$$

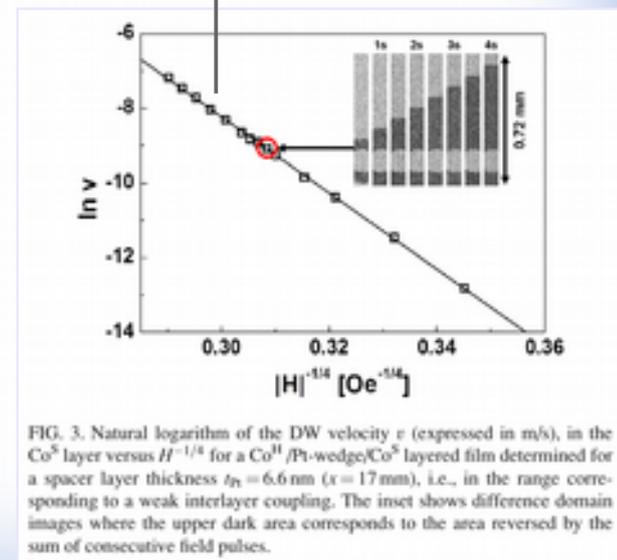


FIG. 3. Natural logarithm of the DW velocity v (expressed in m/s), in the Co^5 layer versus $H^{-1/4}$ for a $\text{Co}^{11}/\text{Pt-wedge}/\text{Co}^5$ layered film determined for a spacer layer thickness $t_{\text{Pt}} = 6.6 \text{ nm}$ ($x = 17 \text{ nm}$), i.e., in the range corresponding to a weak interlayer coupling. The inset shows difference domain images where the upper dark area corresponds to the area reversed by the sum of consecutive field pulses.

Co/Pt multilayers with coupling gradient



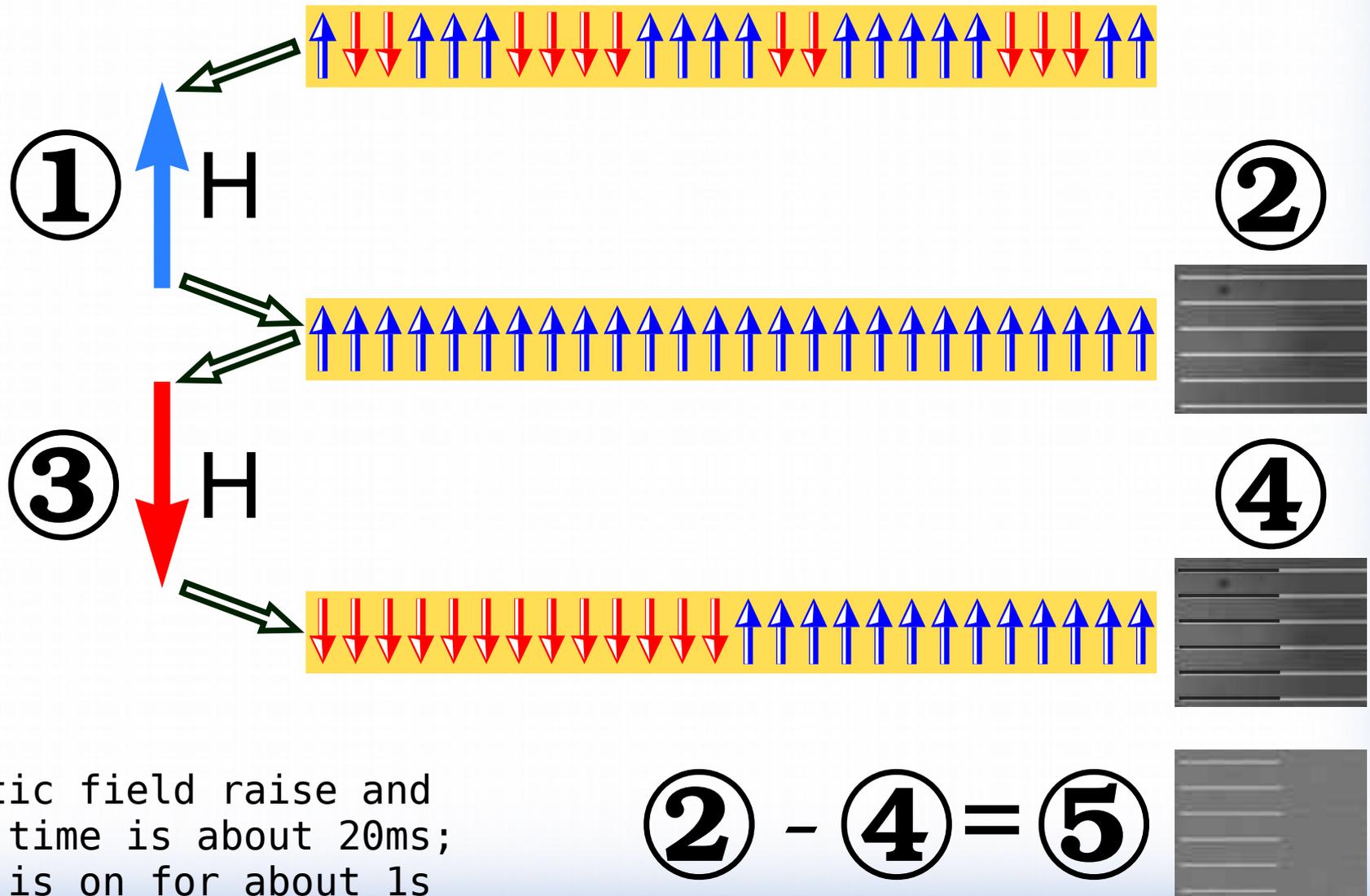
- prior to the measurements the sample was saturated in 1000 Oe
- within the area of high coupling gradients the position of the wall can be changed back and forth with the external field



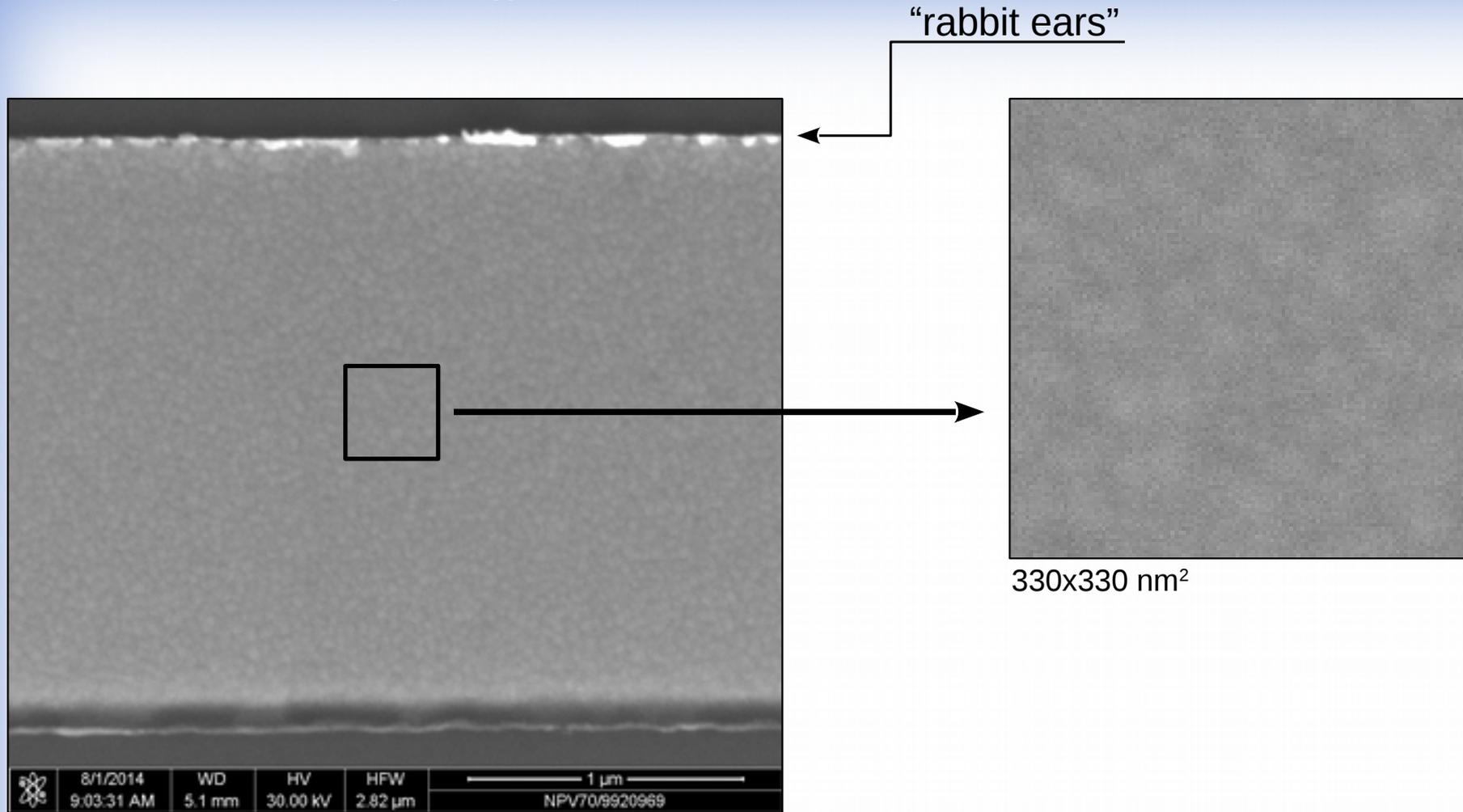
- Perpendicular magnetic anisotropy in Co based multilayers can be easily tailored with light ion bombardment
- The gradient of switching fields achieved this way can be use for domain walls positioning
- Control of domain walls position can be realized using the switching field gradients that are due to Co thickness gradients or using gradients of the interlayer coupling

Measurement procedure

- We calculate the arithmetic difference between two images of the sample recorded for different magnetization configurations



- Magnetic field raise and decay time is about 20ms; field is on for about 1s



- grainy surface due to the structure of the Au buffer – grain boundaries may act as nucleation sites
- “rabbit ears” due to fabrication technique