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# SUBMICRON-RESOLUTION DOMAIN REVERSAL STUDY OF Co-BASED MULTILAYERS USING MAGNETO-OPTICAL MICROSCOPE MAGNETOMETER(MOMM)

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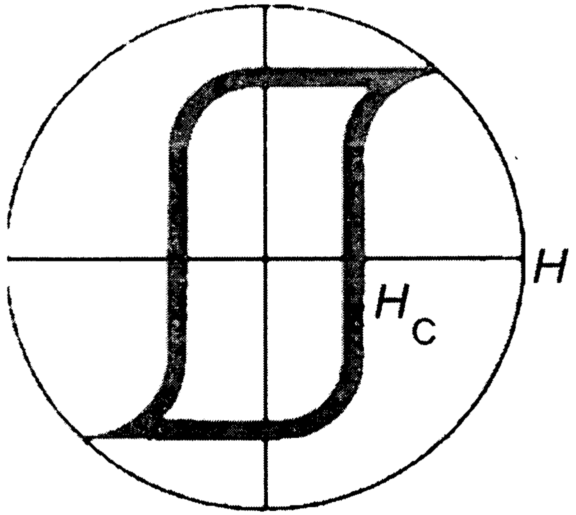
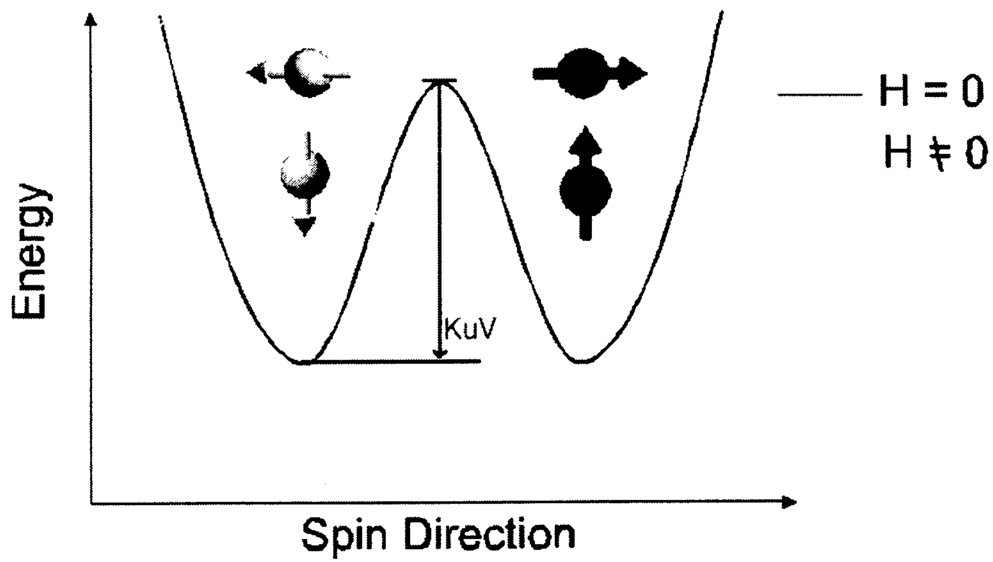
- Domain reversal dynamics study
- Capabilities of the MOMM
- New findings on domain reversal dynamics

# MAGNETIC DOMAIN REVERSAL




| | |
|---|---|
| **$H > H_c$** | **$H < H_c$** |
| **Ultrafast reversal** | **Slow reversal** |
| $\tau \leq$ **1 ns** | $\tau \leq$ **1 s** |

# MAGNETIC DOMAIN IMAGING

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Key Issues :

- High spatial resolution
- Fast data acquisition time
- Applying a magnetic field

Status of Current Available Imaging Techniques

| Magnetic Domain Imaging Techniques | Spatial Resolution | Acquisition Time | Magnetic Field |
|---|---|---|---|
| M F M | 30 - 100 nm | 30 min. | Weak |
| SEMPA | 10 - 200 nm | 10 min. | No |
| SPLEEM | ~ 10 nm | 1 sec. | No |
| Lorenz TEM | 2 - 50 nm | 1 min. | Weak |
| PEEM | 30 - 100 nm | 30 min. | Weak |
| MCXD Microscopy | 30 - 200 nm | 30 min. | Unlimited |
| MOKE Microscopy | 300 - 1000 nm. | <0.1 sec. | Unlimited |

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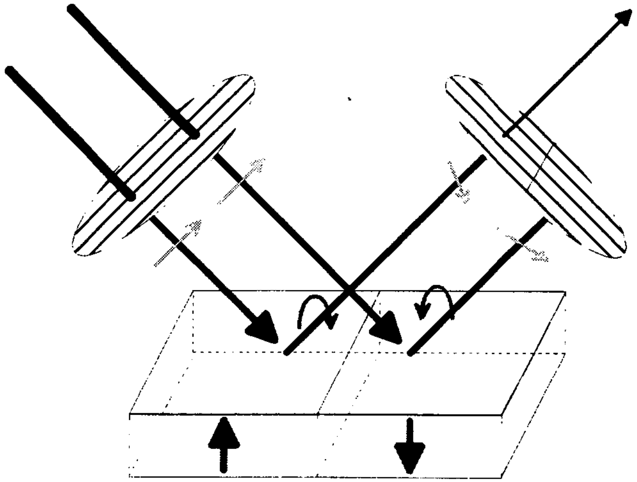
# MOKE IMAGING



Rotation of a linearly polarized incident light during reflection from a magnetized specimen.



In polar geometry

## General features of MOKE microscope

- A large field of view – no scanning
- Real-time dynamic imaging ( $\leq$ 0.1 s )
- Unlimited $B_{ext}$ Possible
- Simple and easy operation
- Relatively poor spatial resolution ( 0.3 $\mu$m ~ 1 $\mu$m )

## MAGNETOOPTICAL MICROSCOPE MAGNETOMETER (MOMM)

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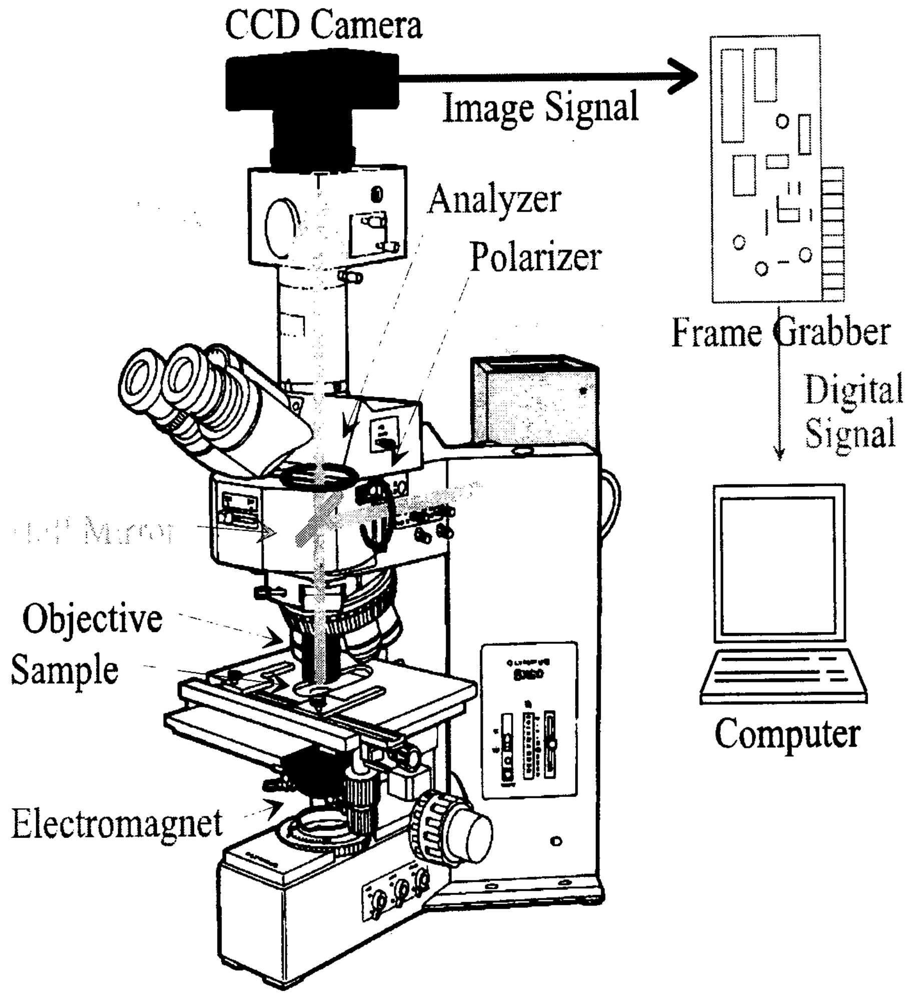
**Optical Polarizing Microscope**
- 400 nm spatial resolution
- 0.2° Kerr angle resolution

**Electromagnet**
- up to ±5 kOe external magnetic field
- interfaced to a computer

**Image Acquisition**
- 640×480 pixels
- Series of 256 images by 10 frames/s
- Image intensifying technique



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# MAGNETOOPTICAL MICROSCOPE MAGNETOMETER (MOMM)

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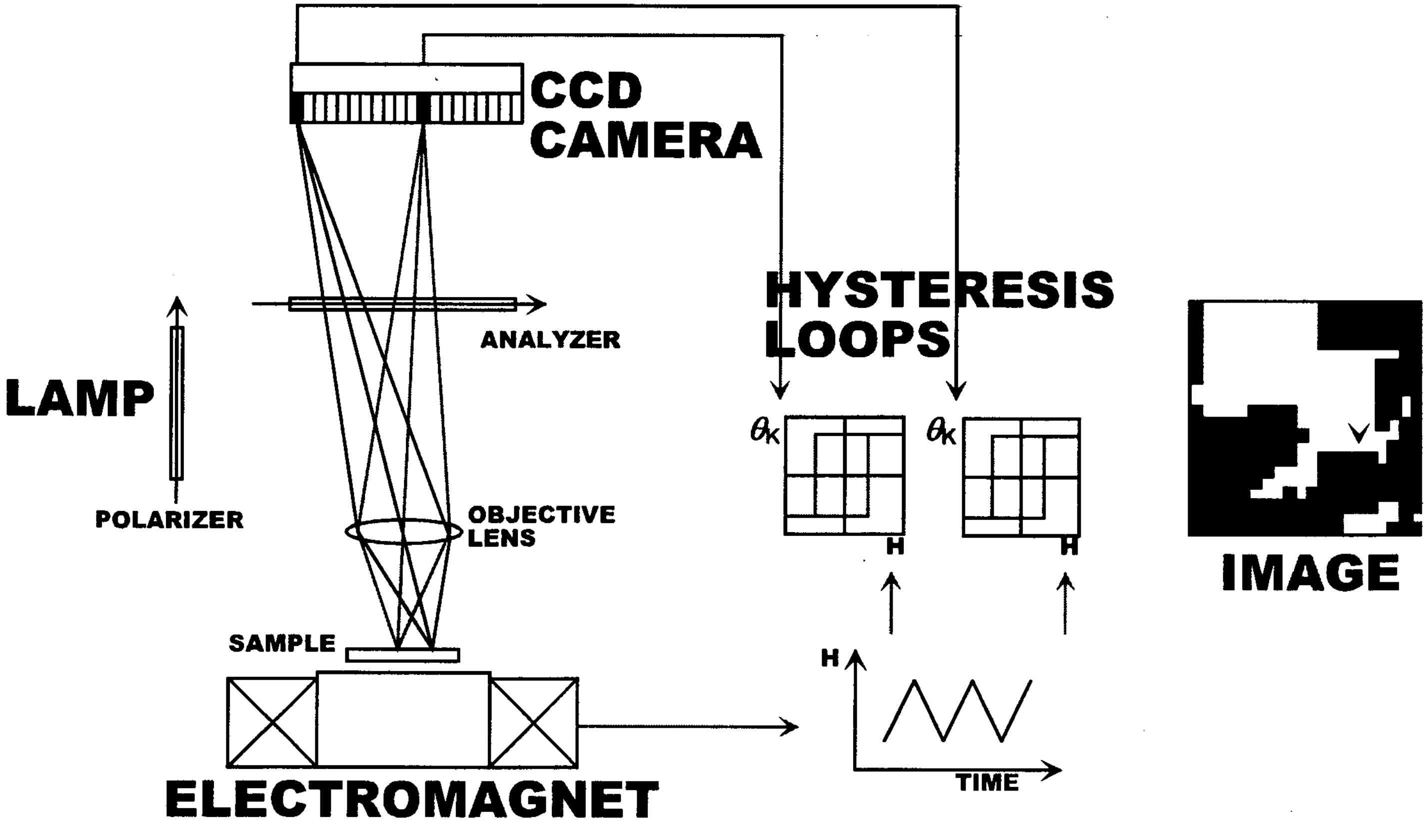
- Identify the local area with 400-nm resolution
- Simultaneous local probing



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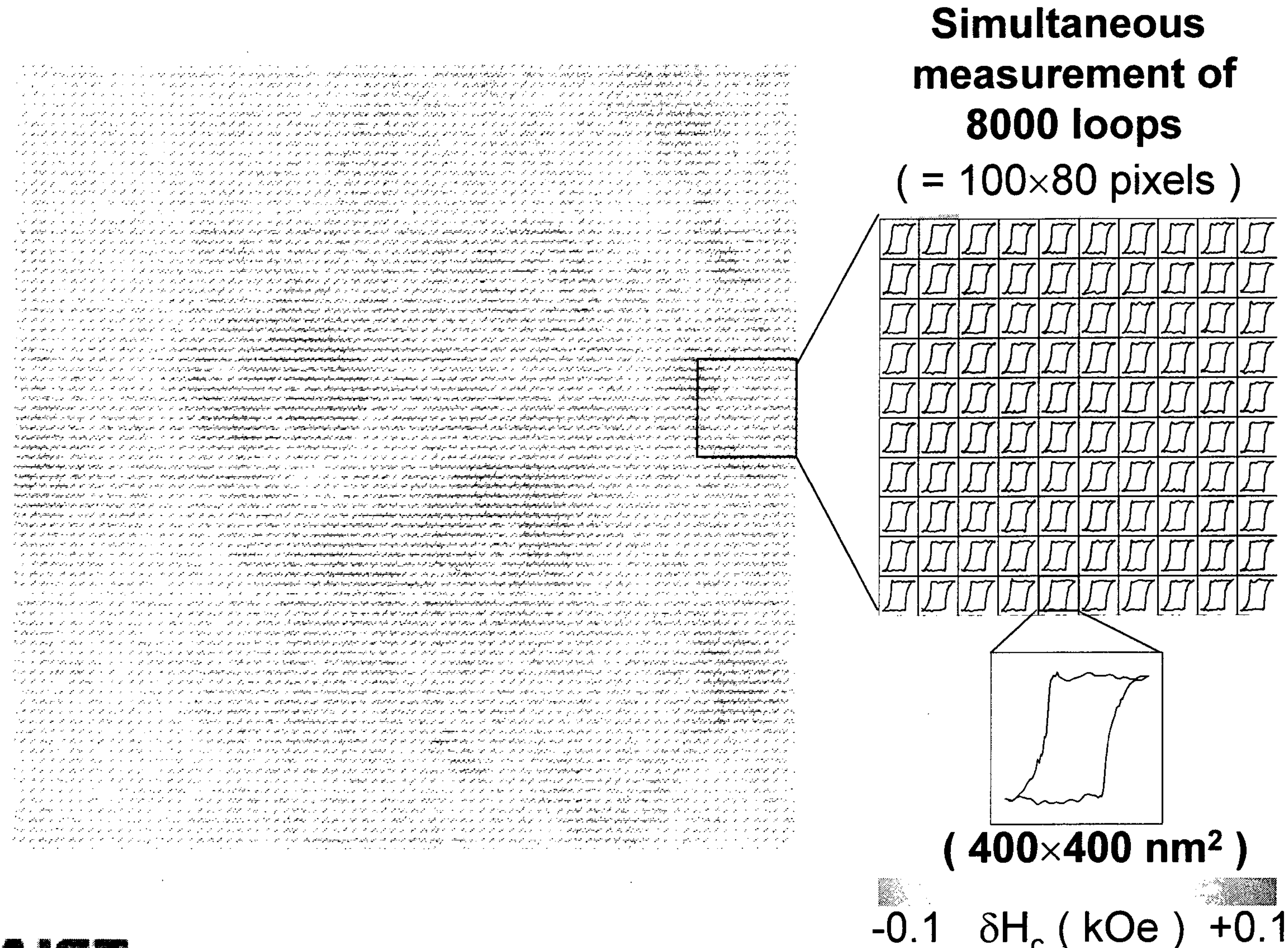
# LOCAL HYSTERESIS LOOPS AND COERCIVITY DISTRIBUTION MAPS



# Co-BASED NANOMULTILAYERS

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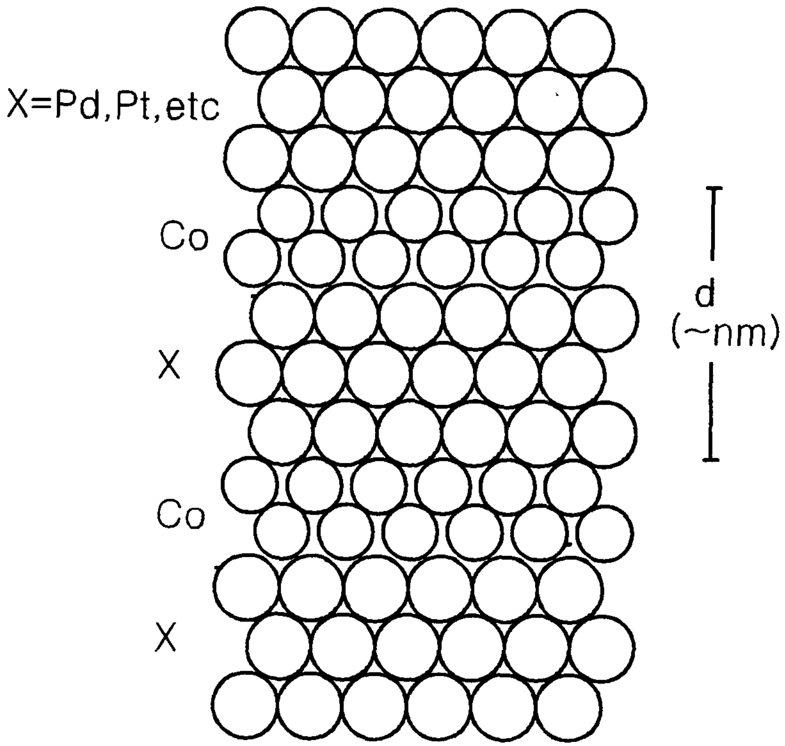


**Structural Parameters: $t_{Co}$, $t_X$, $n$**

## Why Interesting?

**Novel Phenomena:**

- Interface Anisotropy & Magnetism
- Strong Perpendicular Magnetic Anisotropy (~$10^7$ erg/cc)
- RKKY Interaction
- Giant Magnetoresistance

**Technological Applications:**

- Magnetic Recording Media
- Magneto-Optical Recording Media
- Magnetoresistive Heads
- Magnetoresistive Random Access Memories

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# DOMAIN REVERSAL PATTERNS: $(t_{Co}/11\text{-}Å\ Pd)_n$

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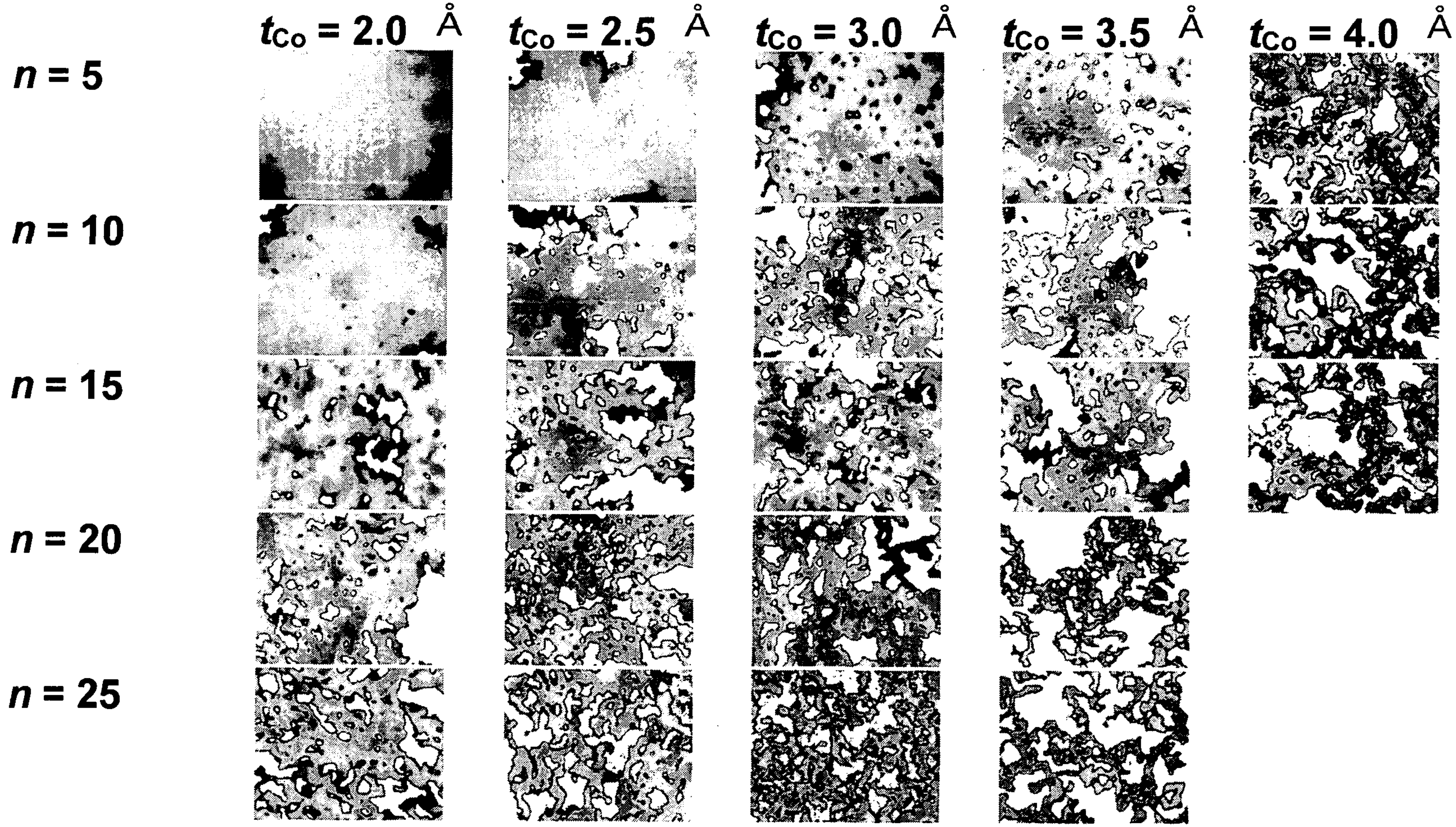


# DETERMINATION OF DYNAMICS PARAMETERS

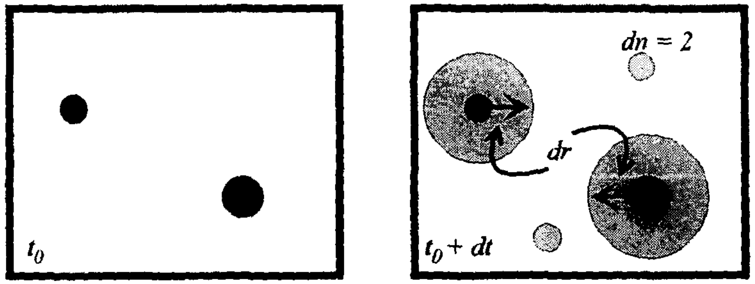
[S.-B. Choe and S.-C. Shin, Appl. Phys. Lett. 70, 3612 (1997)]

☞ Expansion of the circular domain *dr*

$$dr = Vdt$$

☞ Number of nucleation *dn*

$$dn = R(s-a)dt$$



(a) (b)

where *V* ≡ wall-motion speed, *R* ≡ nucleation rate,

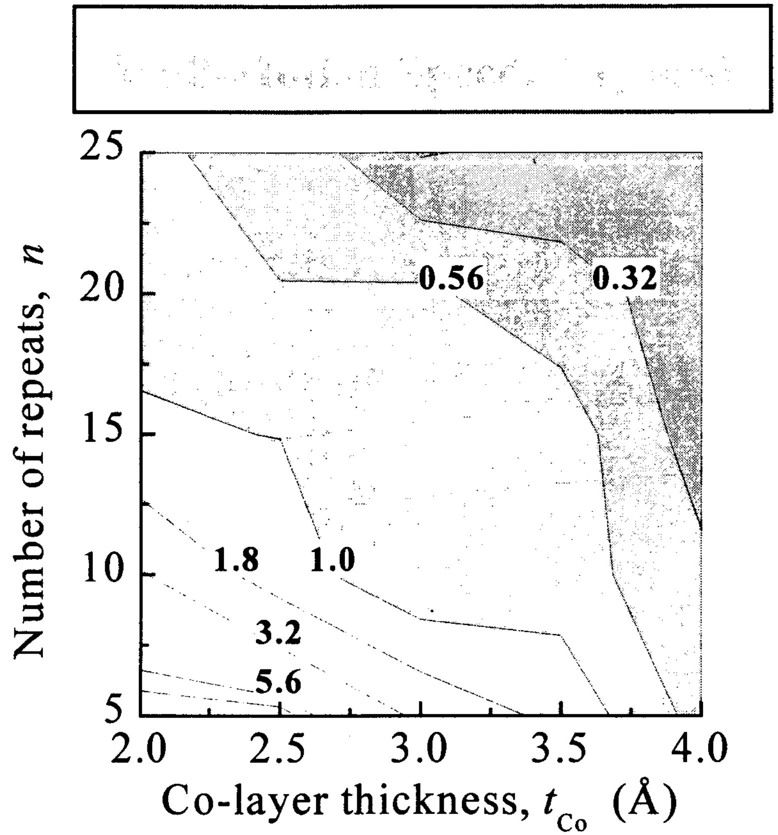
*s* ≡ total area under examination, *a* ≡ reversed domain area,

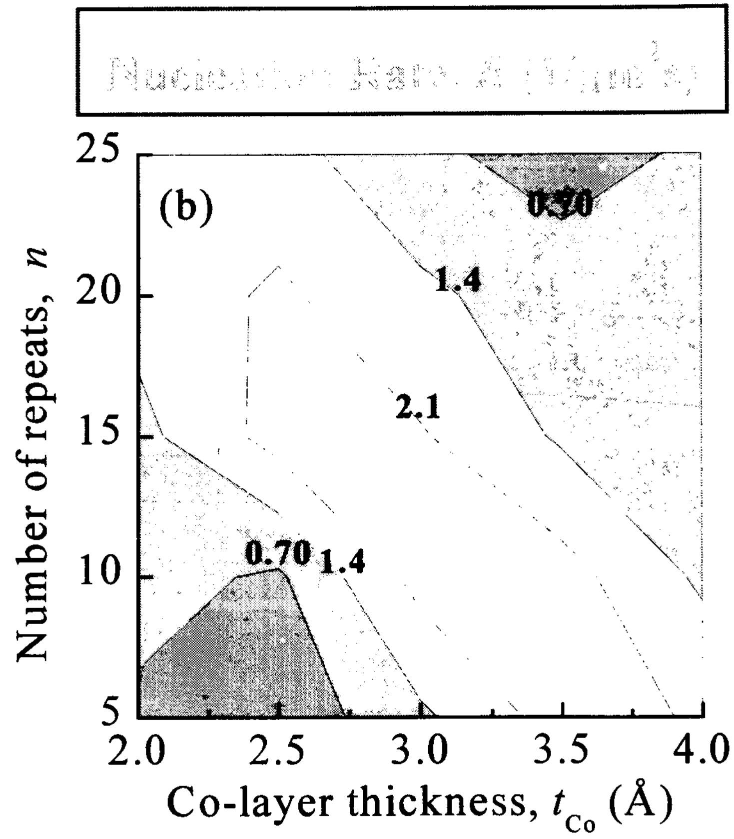
☞ Rearranged in the explicit form of *V* and *R*

$$V = (a' - r_0 l' / 2) / (l - \pi r_0)$$
$$R = (ll' / 2\pi - a') / (l - \pi r_0) r_0 (s - a)$$

where *a(t)* ≡ reversed domain area, *l(t)* ≡ domain boundary length.

# DEPENDENCES OF V AND R



# DEPENDENCES OF REVERSAL RATIO V/R

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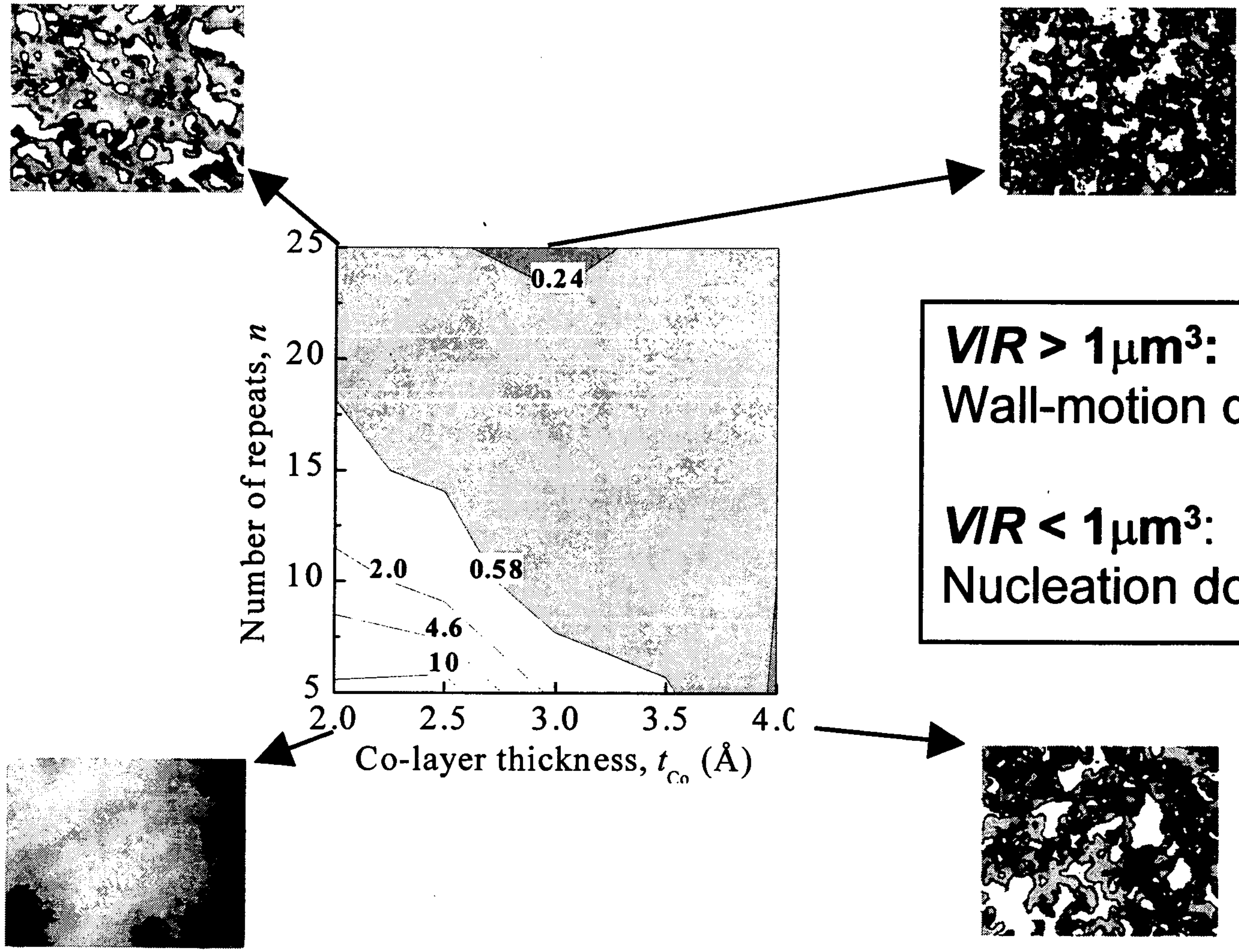


***V/R* > 1μm³:**
Wall-motion dominant

***V/R* < 1μm³:**
Nucleation dominant


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# DOMAIN REVERSAL IN Co/Pt MULTILAYERS

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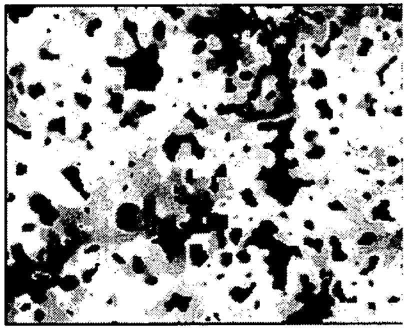
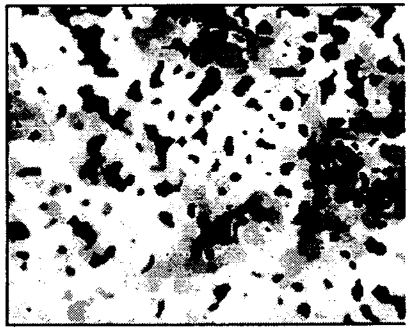


200-Å Pt/(2-Å Co/11-Å Pt)$_{10}$



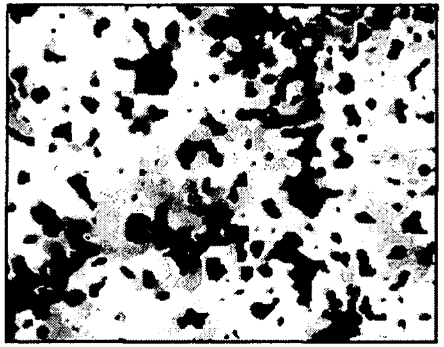
250-Å Pt/(2-Å Co/11-Å Pt)$_{10}$

at Ar pressure of 6 mTorr

| | V/R |
|---|---|
| 200- Å Pt/(2-Å Co/11-Å Pt)$_{10}$ | 0.27±0.11 |
| 250- Å Pt/(2-Å Co/11-Å Pt)$_{10}$ | 0.31±0.13 |

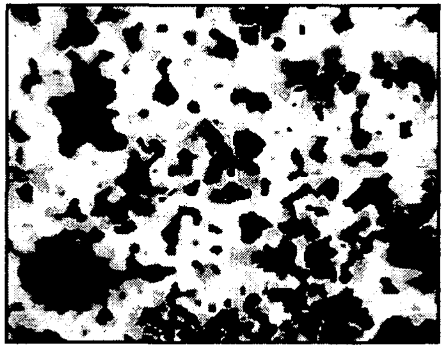
# *DOMAIN REVERSAL IN Co/Pt MULTILAYERS*

**(2.0- Å Co/11-Å Pt)$_{10}$**



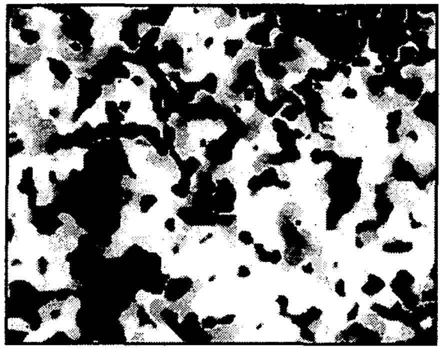
$V/R = 0.27$

**(3.0- Å Co/11-Å Pt)$_{10}$**



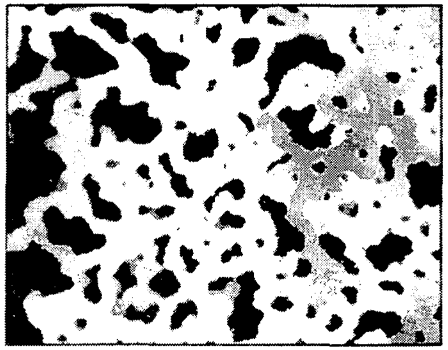
$V/R = 0.35$

**(3.5- Å Co/11-Å Pt)$_{10}$**



$V/R = 0.33$

**(4.0- Å Co/11-Å Pt)$_{10}$**



$V/R = 0.46$

# FIELD DEPENDENCE OF V AND R

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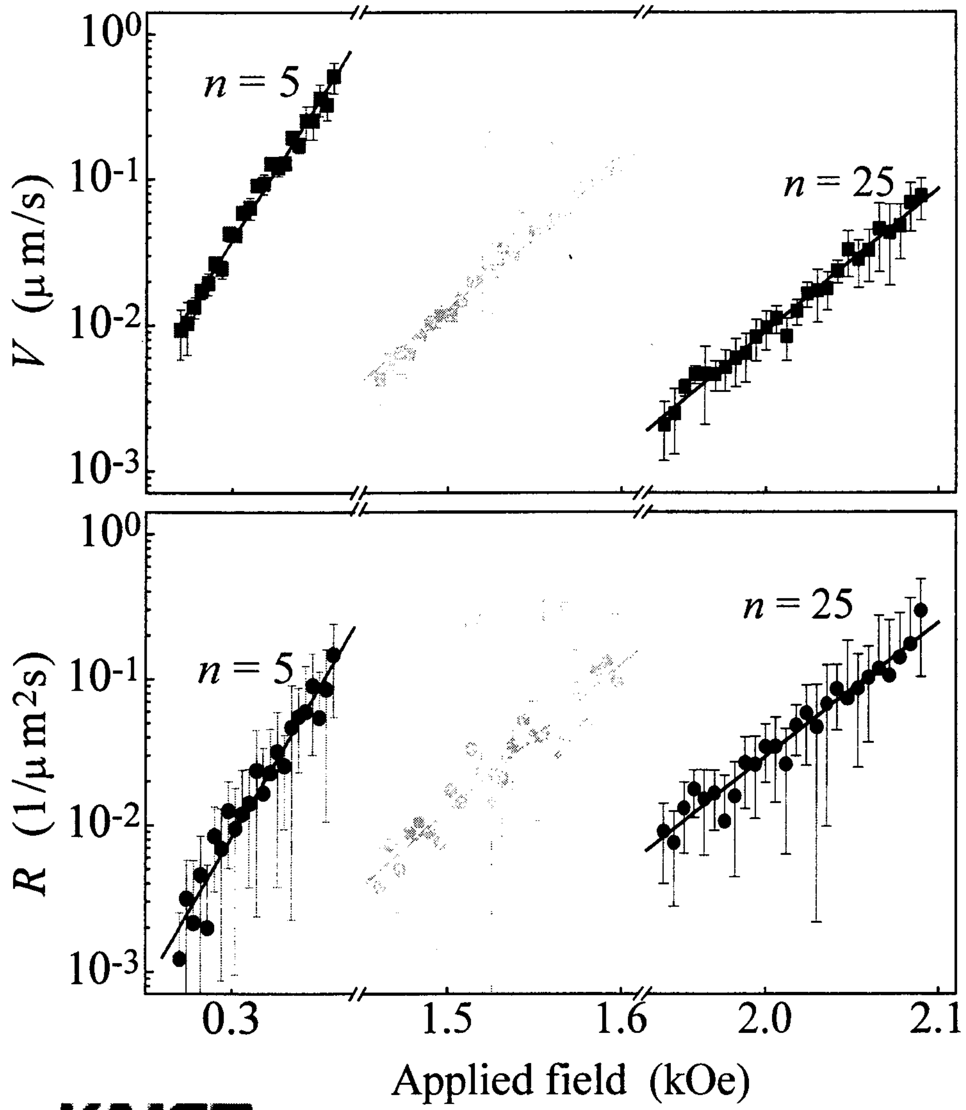


$$\log V(H) = \alpha_W + \beta_W H$$

$$\log R(H) = \alpha_N + \beta_N H$$

**Thermally Activated Process**

$$\beta_W = V_W M_S / k_B T$$

$$\beta_N = V_N M_S / k_B T$$

**[ Raquet *et al.* PRB 54, 4128 (1996). ]**

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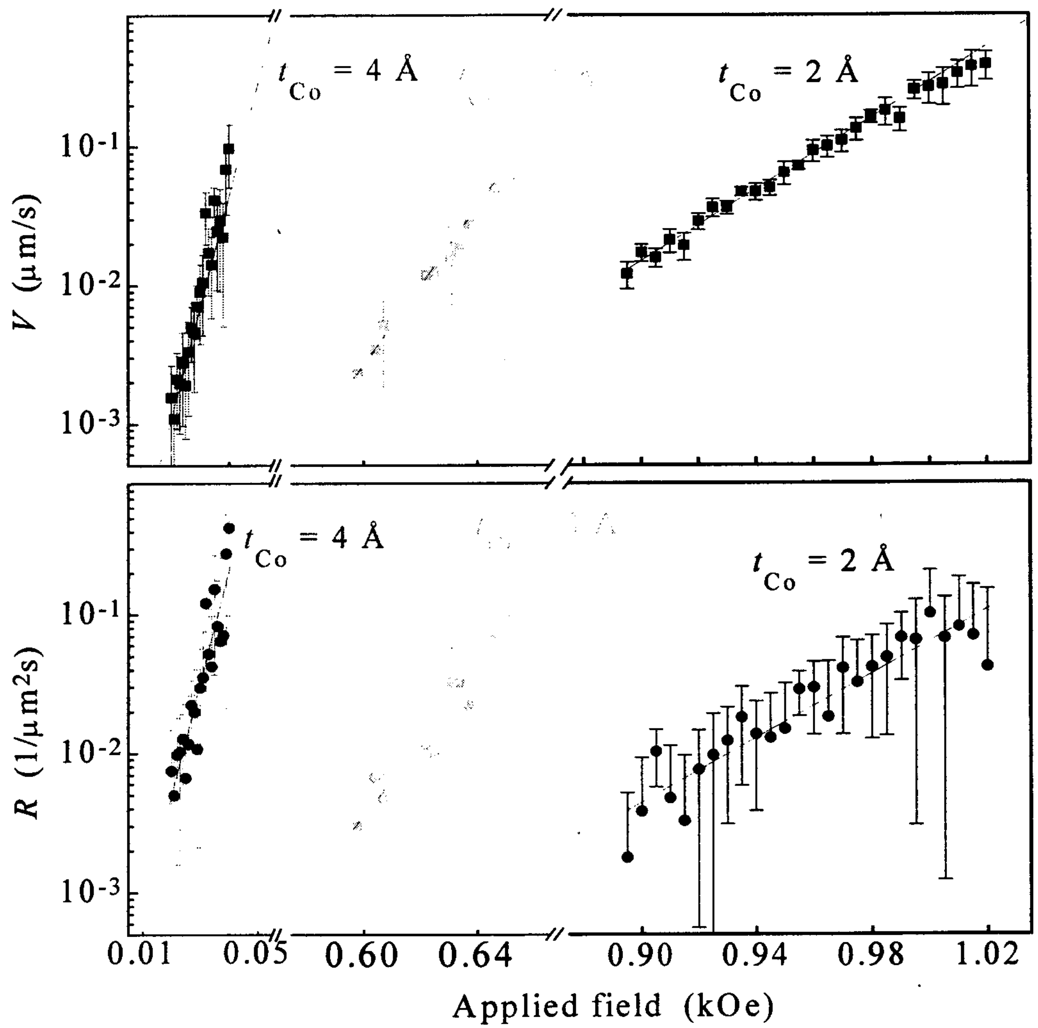
# FIELD DEPENDENCE OF V AND R





# ACTIVATION VOLUMES OF $V_W$ AND $V_N$

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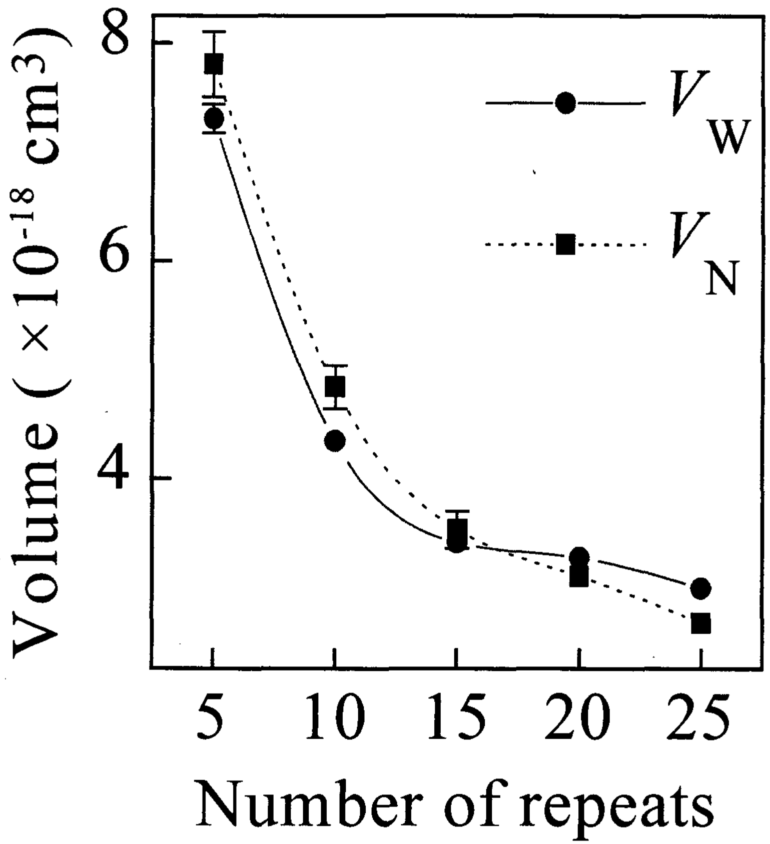


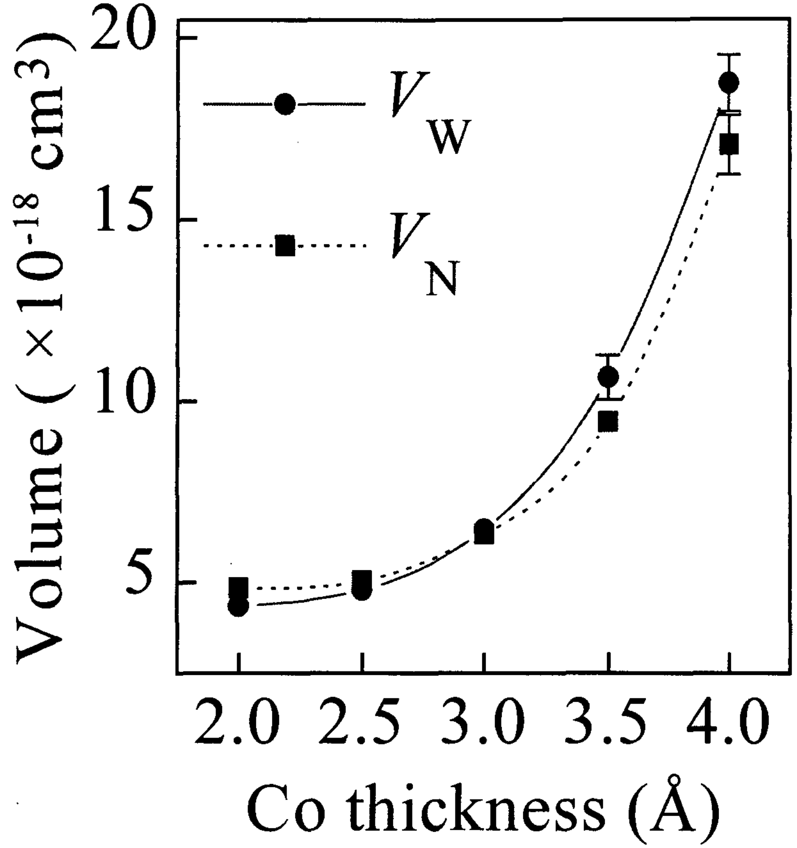


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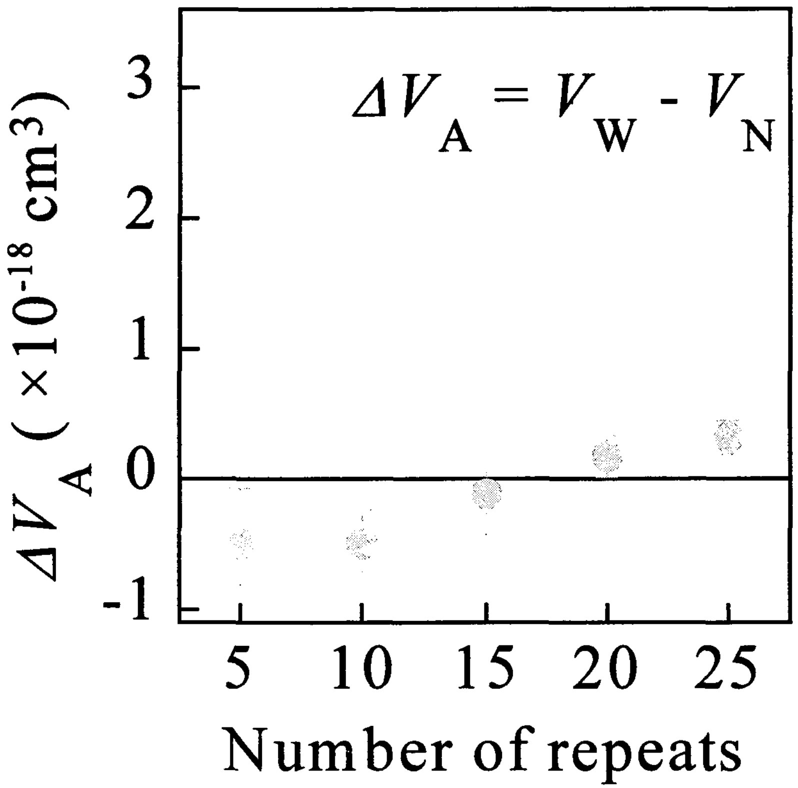
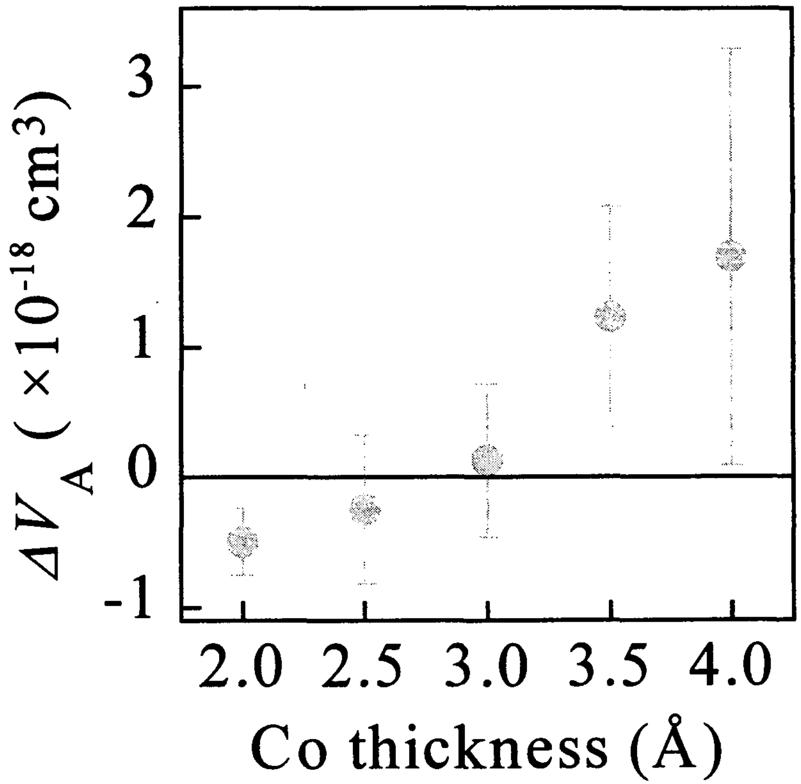
# UNEQUAL ACTIVATION VOLUMES

스핀정보물질연구단

[S.-B. Choe and S.-C. Shin, PRL. Submitted (2000)]



# V/R vs. $V_W - V_N$

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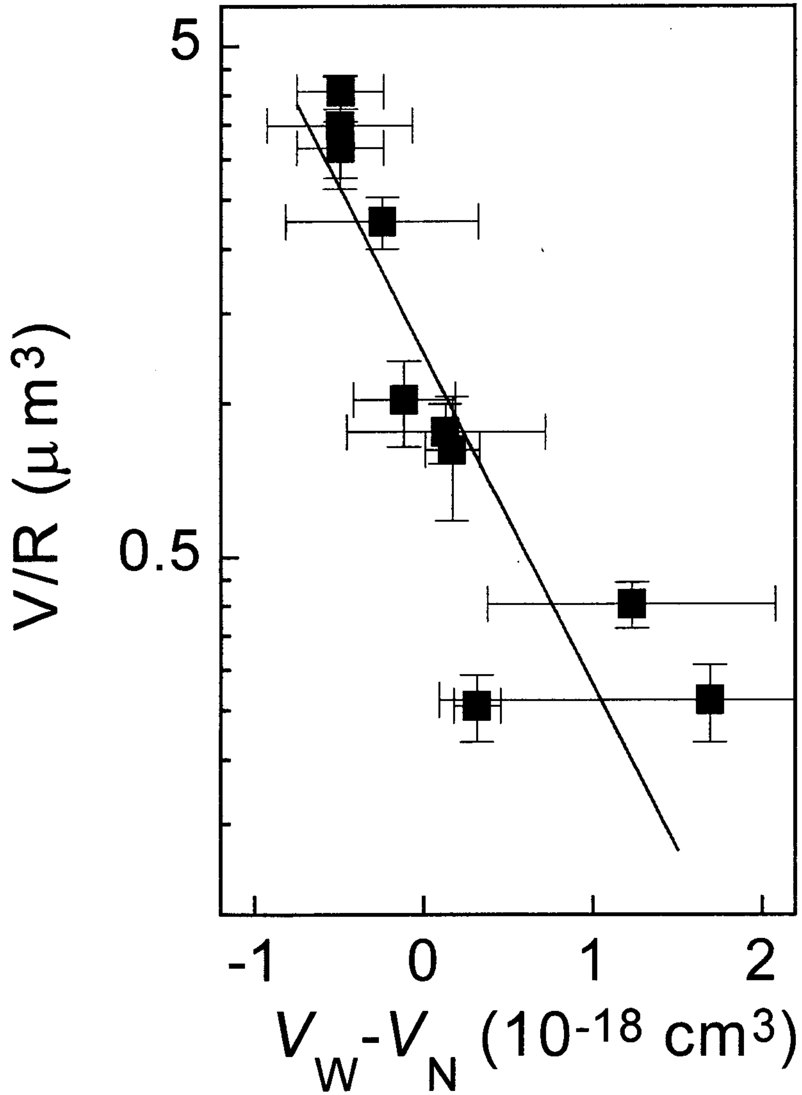


$$V = v_0 \exp\left[-\left(K_U V_W - HM_S V_W\right)/k_B T\right]$$

$$R = r_0 \exp\left[-\left(K_U V_N - HM_S V_W\right)/k_B T\right]$$

$$\frac{V}{R} = \ln\frac{v_0}{r_0} - (V_W - V_N)\frac{(K_U - HM_S)}{k_B T}$$

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## MONTE CARLO SIMULATION FOR DOMAIN REVERSAL

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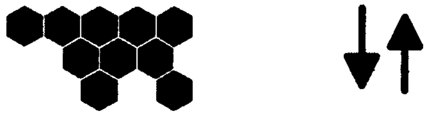
[S.-B. Choe and S.-C. Shin, Phys. Rev. B 57, 1085 (1998)]

### DESCRIPTION OF ALGORITHM



Uniform film with nano-sized cells based on a exagonal lattices ($V_c$=2.92×10$^{-18}$ cc)

Calculation of energy barrier:

$$E_j = K_u V \sin^2\theta_j - M_s V(H - NM_z)\cos\theta_j + \frac{1}{6}(3 - \frac{1}{2}S_j\cos\theta_j)E_w$$

$$E_j^B = K_u V_c[1 + m_j\{\frac{M_s V_c(H_z + H_j^D) + S_j E_w/12}{2K_u V_c}\}]^2$$

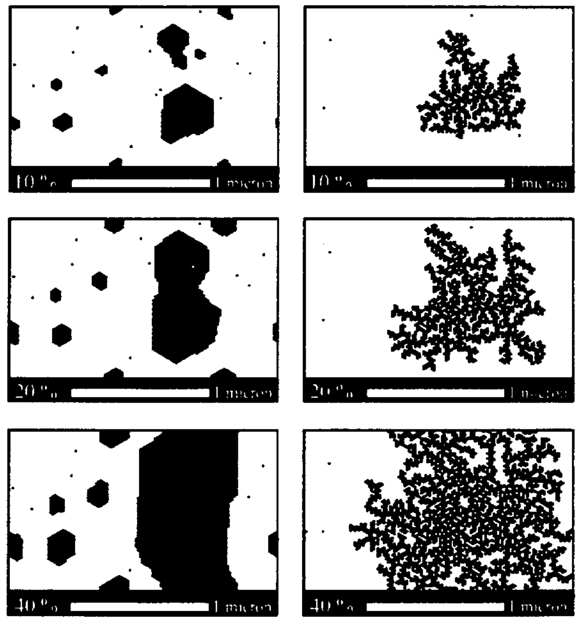
Probability of reversal by thermal energy that cell j reverses its magnetization in time $\Delta t$: .

$$P_j = R\ \exp(-E_j^B / k_B T)\Delta t$$

Simulation with uniform macroscopic magnetic properties $M_s$, $K_u$, $E_w$ (measured values)

### SIMULATION RESULTS

(2-Å Co/11-Å Pd)$_{10}$ (4-Å Co/11-Å Pd)$_{10}$



(a) (b)

$M_S$ = 230 280 emu/cc

Well explanation of contrasting reversal phenomena only with uniform macroscopic magnetic properties

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# UNDERSTANDING REVERSAL BEHAVIOR WITH *n*

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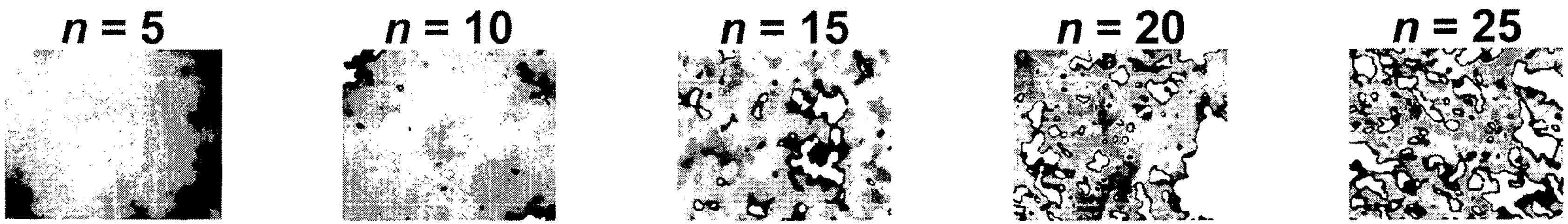
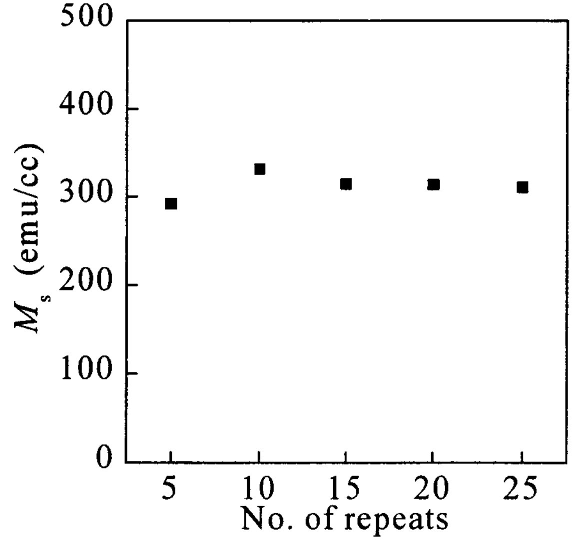
(2-Å Co/11-Å Pd)$_n$ nanomultilayers




**Saturation Magnetization (per total volume)**

**Constant irrespective of the number of repeats**

# LOCAL COERCIVITY AND REVERSAL-TIME DISTRIBUTION MAPS

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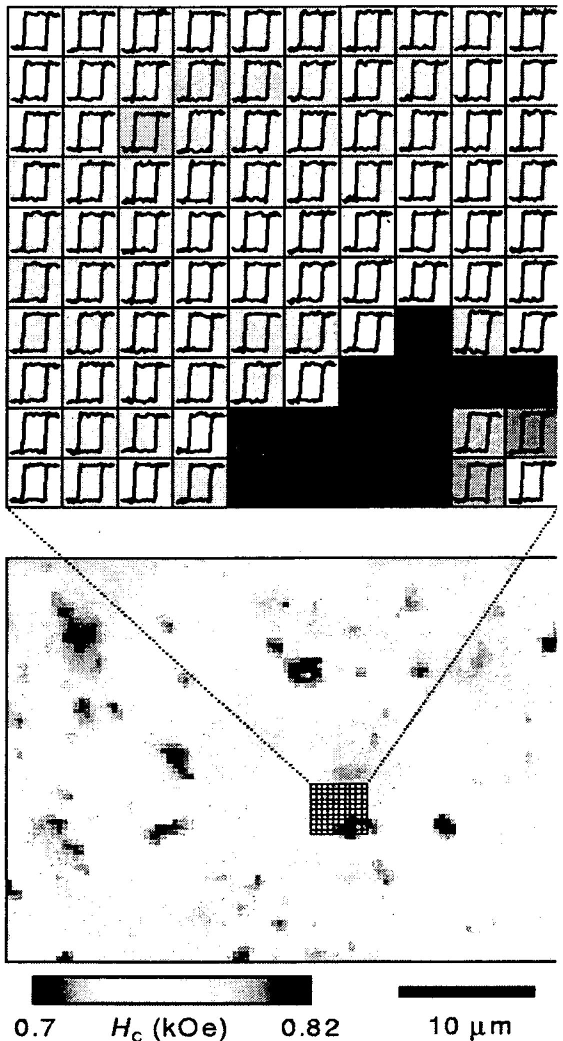
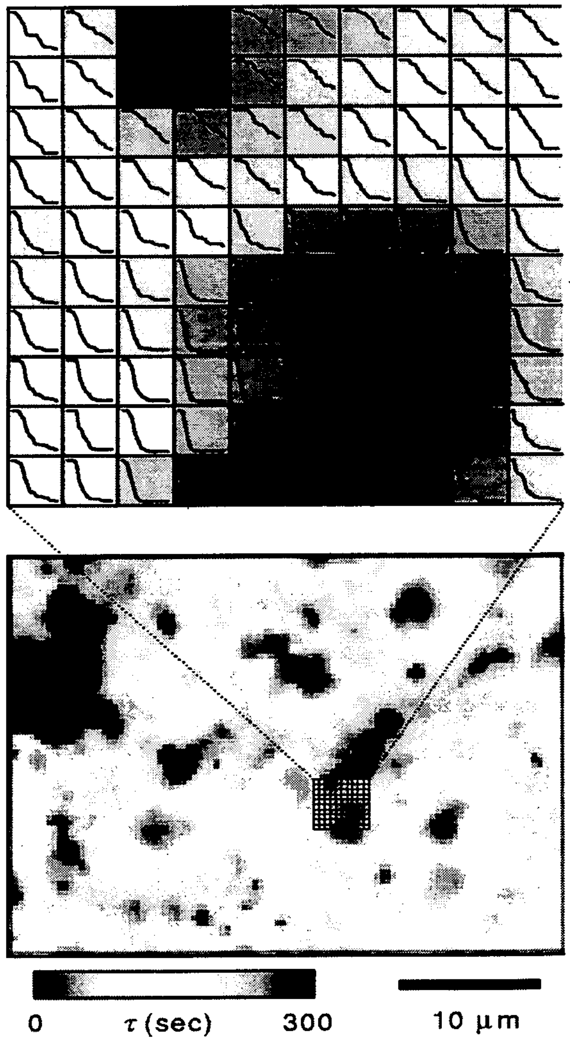
## Coercivity Distribution




## Reversal-Time Distribution

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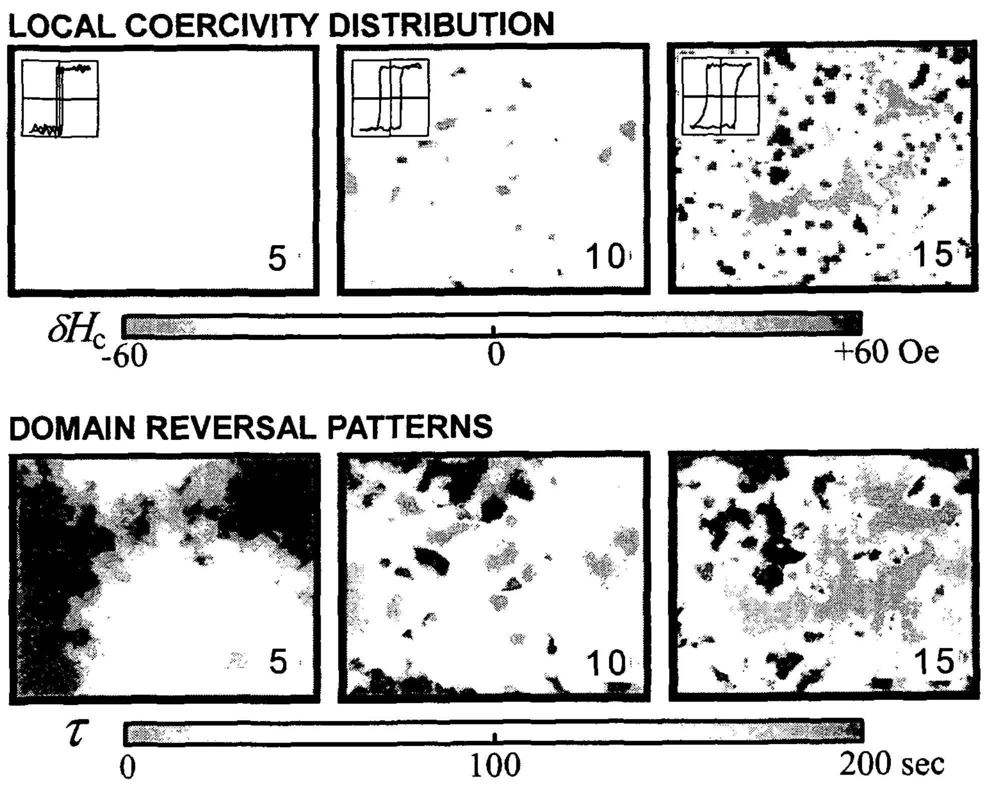
*DOMAIN REVERSAL BEHAVIOR UNDER LOCAL COERCIVITY VARIATION*

스핀정보물질연구단

**[S.-B. Choe and S.-C. Shin, PRB. Accepted (2000)]**




**Simultaneous measurement of**
**8000 loops**
**with 400 nm resolution**
**on 40 μm× 32 μm area**

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# CORRELATION BETWEEN LOCAL COERCIVITY AND LOCAL REVERSAL TIME

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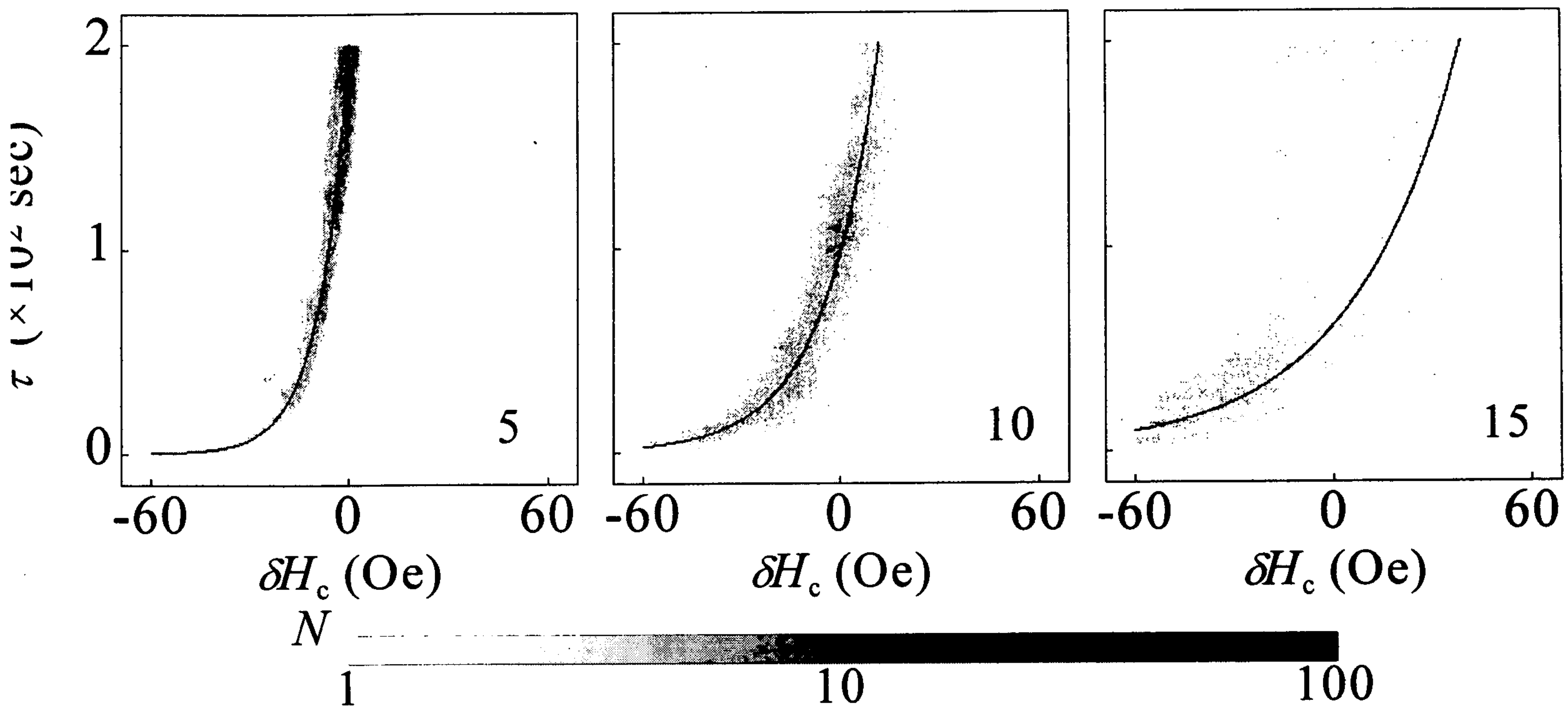


**Fitting curve:** $\log\tau = \alpha + \beta \cdot \delta H_C$

**Local reversal time with coercivity variation:** $\tau(x,y) = \tau_0 \exp\left(\frac{V_A M_S}{k_B T}\left(H_C(x,y) - H\right)\right)$

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## *MONTE CARLO SIMULATION WITH THE LOCAL COERCIVITY VARIAION*

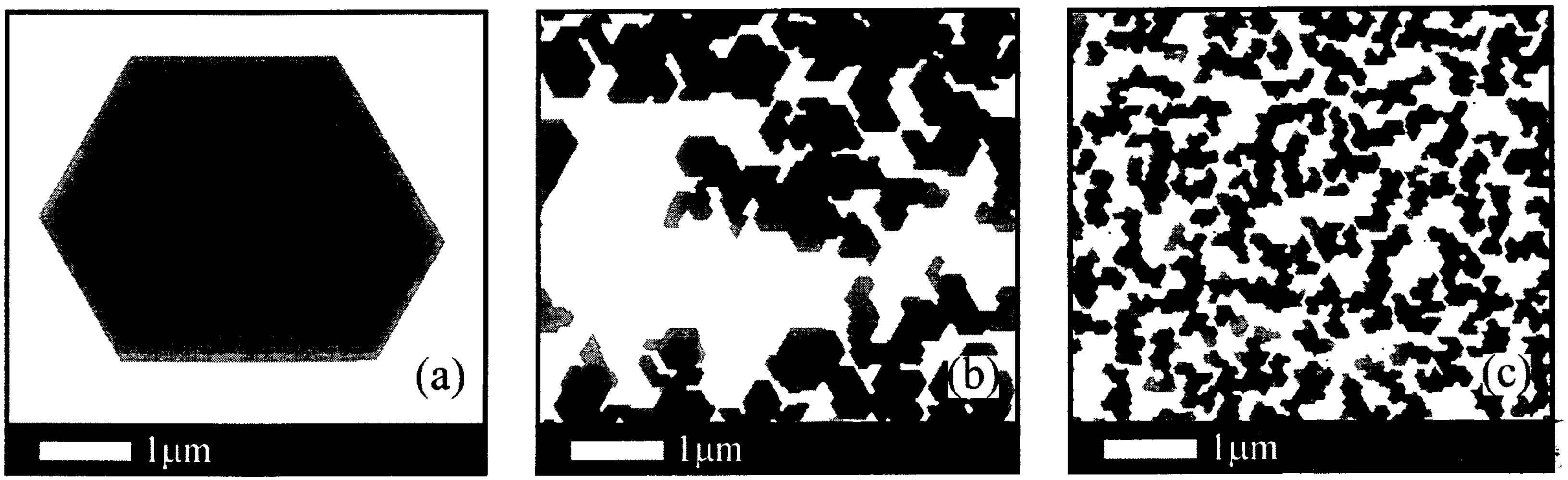
**Coercivity Variation ⇔ Anisotropy Fluctuation:** $H_C(x,y) = 2K_U(x,y)/M_S - H_{\text{int}}$

**Assumption:** $\delta K_U(x,y) = \overline{K}_U \cdot \left(\delta H_C(x,y)/\overline{H}_C\right)$

**Energy barrier equation:** $E_j^B = K_u V_c [1 + m_j \{\frac{M_s V_c (H_z + H_j^D) + S_j E_w / 12}{2K_u V_c}\}]^2$

**Thermal activation probability:.** $P_j = R \ \exp(-E_j^B / k_B T)\Delta t$

**Uniform film without $K_u$ variation** | **Irregular film With 2 % $K_u$ variation** | **Irregular film without 4 % $K_u$ variation**



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## SUMMARY

- A novel system of magneto-optical microscope magnetometer (MOMM), capable of simultaneous local problems of magnetic properties as well as real-time magnetic domain evolution imaging of ferromagnetic thin films with 400-nm spatial resolution
- New findings in domain reversal dynamics of Co-based multilayers:
  - The reversal ratio of V/R is a governing physical parameter.
  - The activation volumes of wall-motion and nucleation processes are generally unequal.
  - Submicron-scale local coercivity variation determines domain reversal dynamics.
  - A thermally activated relaxation process during domain reversal is existed on the submicron-scale in realistic films.
  - Local variation of magnetic properties should be considered for a realistic simulation.

*The fantastic capabilities of the MOMM can open many possibilities to broaden and deepen our understanding of domain reversal phenomena in ferromagnetic thin films.*