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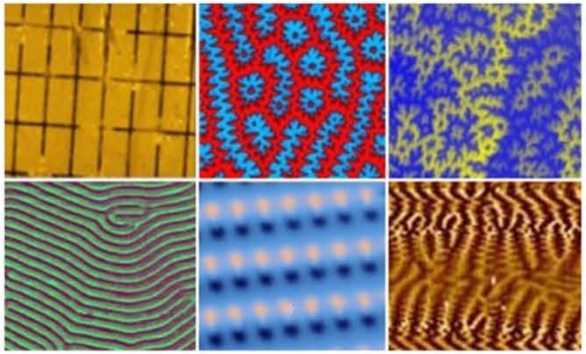
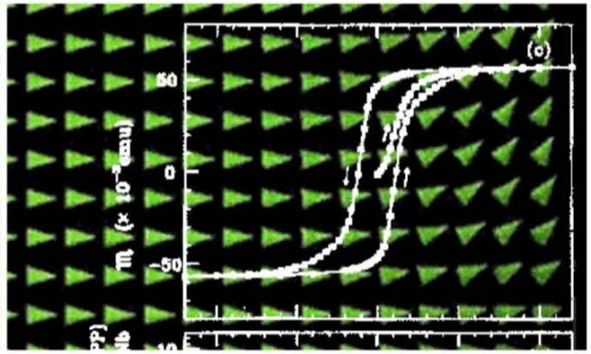




The IEEE Magnetics Society is proud to present

2011 Distinguished Lecture series

Growth-control and microstructure characterization of magnetic thin films,

application to high density perpendicular magnetic recording media

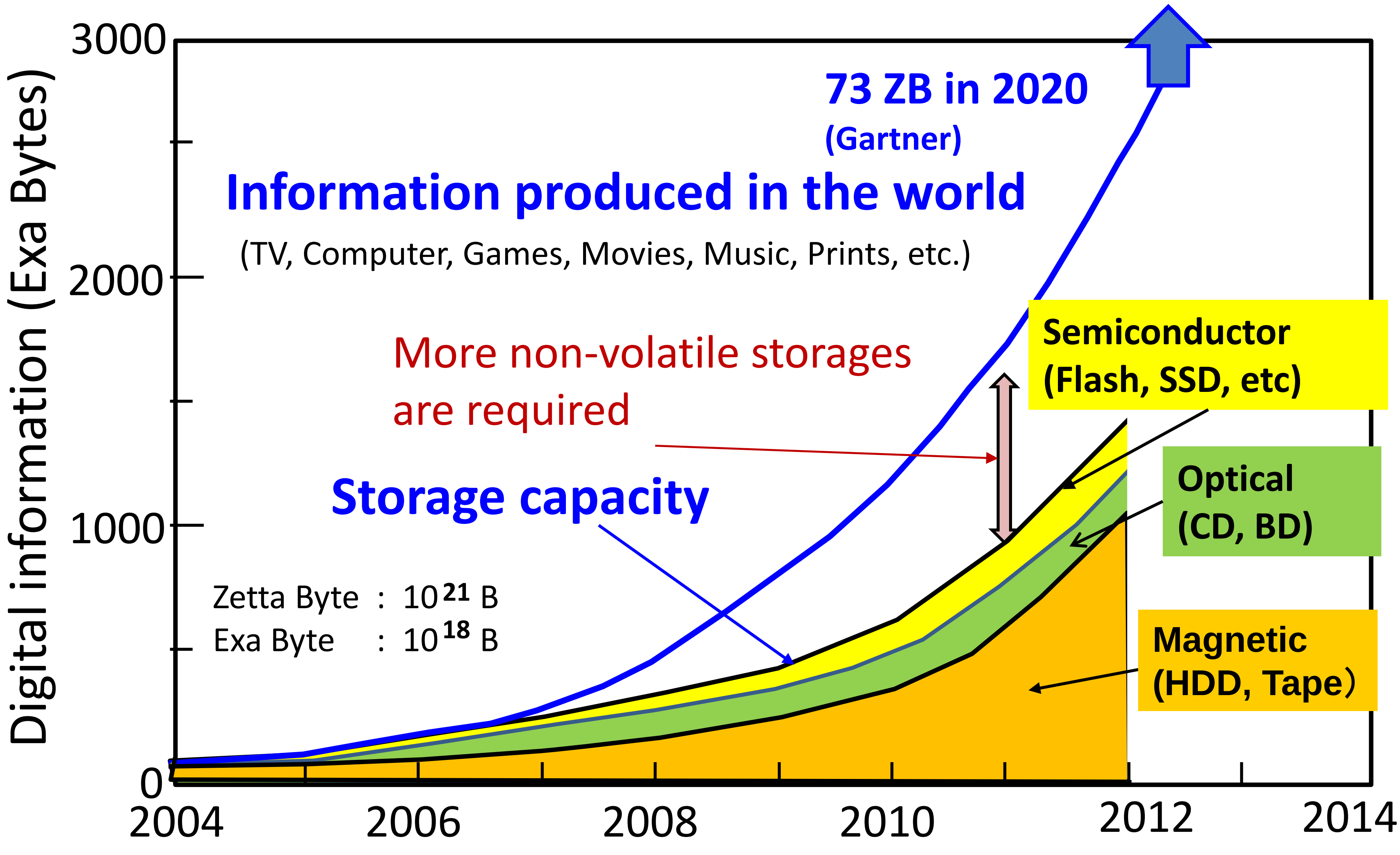
Masaaki Futamoto

Chuo University, Tokyo

Chuo University

Contents

Digital information in the world



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Technology Developments

1900 — 1950 — 2000

First Magnetic Recording System
(V. Poulsen) 1898

Wire recording | Tape recording | Video Tape Recorder

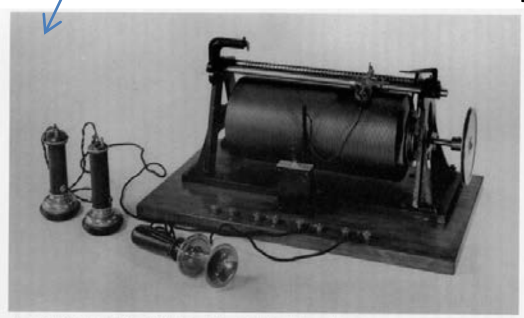

Figure 3. Cylinder telegraphone from 1898 (Courtesy: Denmark's Technical Museum, Elsinore).

Hard Disk Drive
IBM, 1956

Floppy disk

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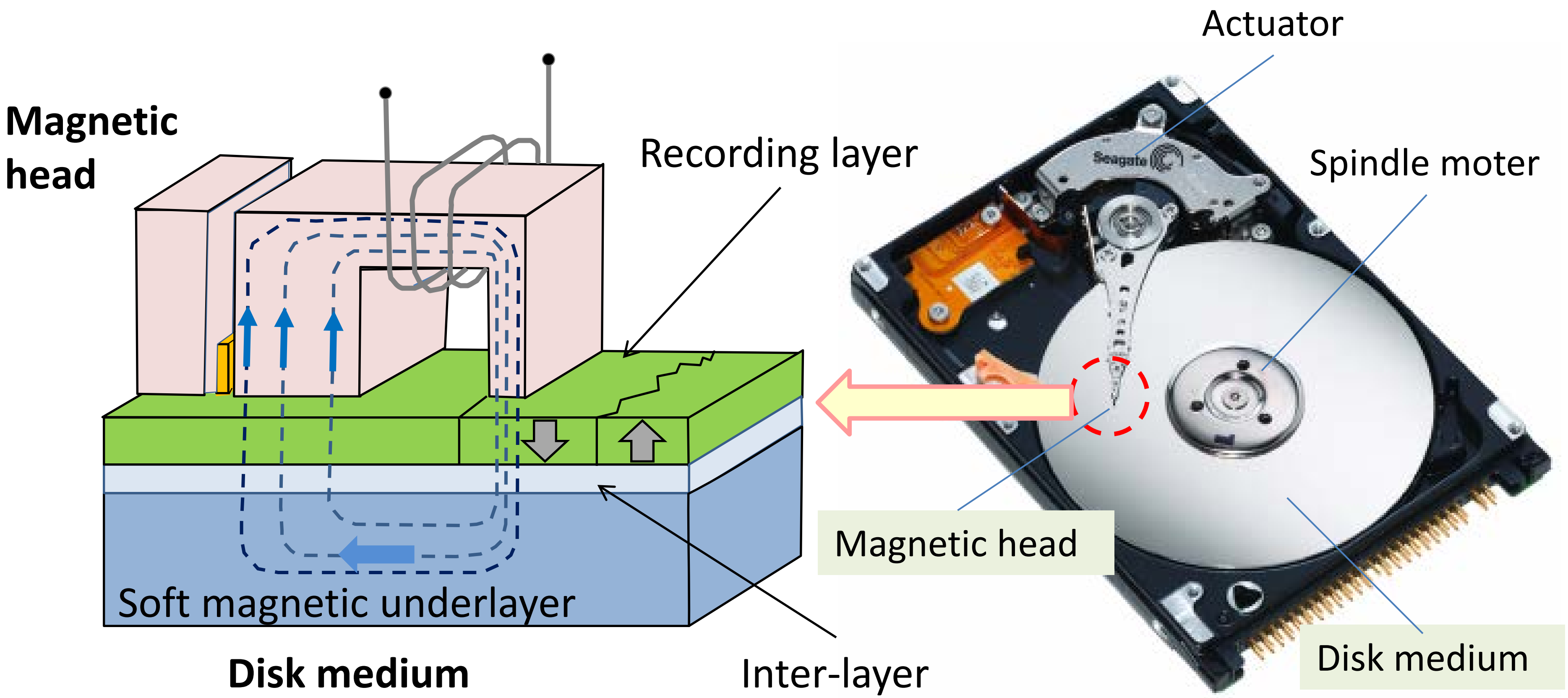
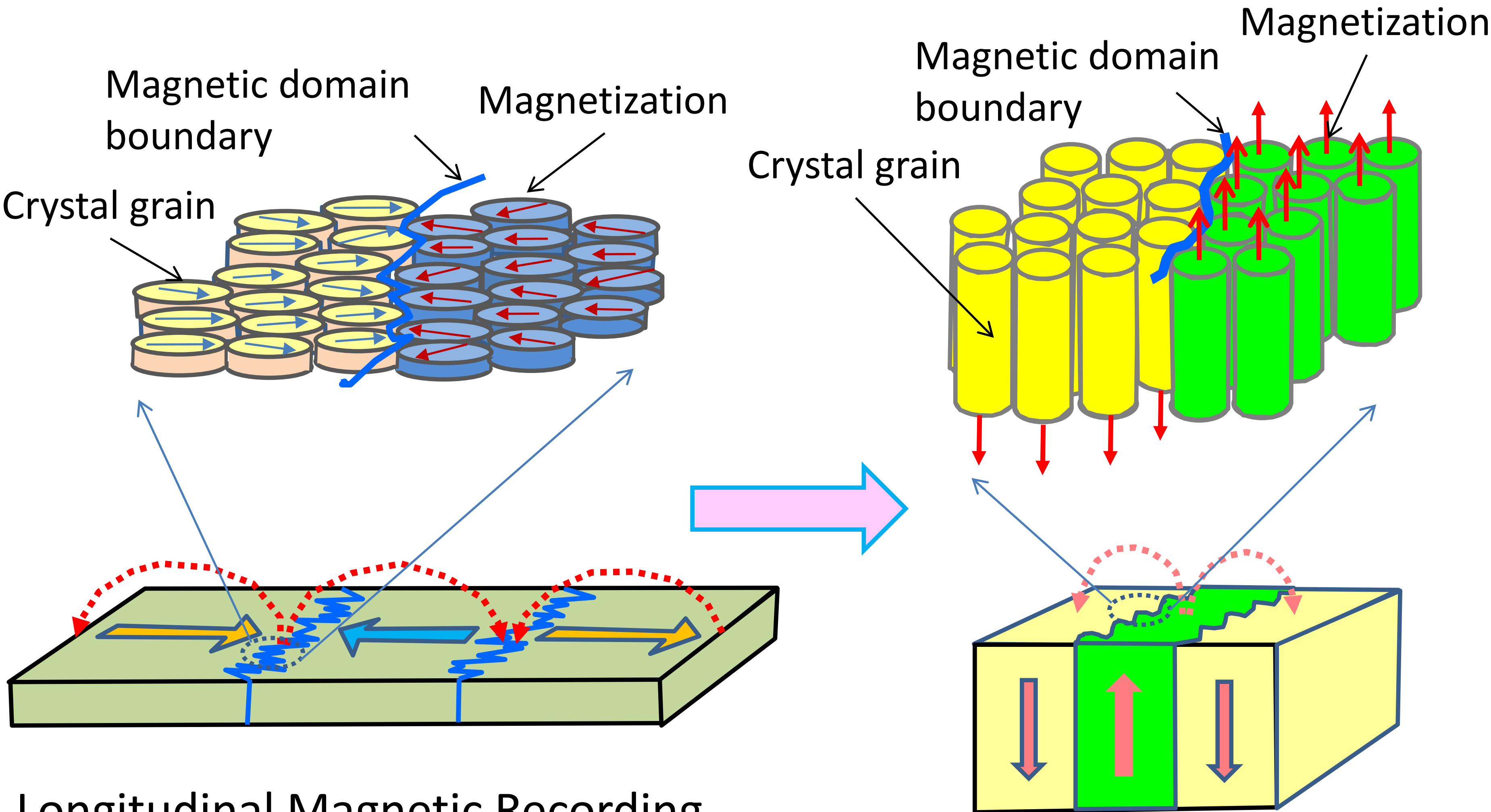
Structure of Recent Hard Disk Drive



(Perpendicular magnetic recording) Hard Disk Drive (HDD)

Shift from LMR to PMR



Longitudinal Magnetic Recording (LMR)

Perpendicular Magnetic Recording (PMR)

R&D History of Perpendicular Recording Media

Year

‘75 ‘80 ‘85 ‘90 ‘95 ‘00 ‘05 ‘10

5 Mb/in^2 10 Mb/in^2 100 Mb/in^2 1 Gb/in^2 10 Gb/in^2 100 Gb/in^2

- **CoCr-alloy media (’78)** Tohoku U.
- **Underlayer effect (’84-85)** Hitachi
- **SUL noise observation** (’84-85)
- **Cross-sectional TEM (’84-85) by ion-thinning**
- **Magnetization structure observation E-holography (’86 – ’87),** Hitachi
- **MFM (’92-’93)**
- **SUL noise reduction** (’96) **JVC**
- **Improved underlayers (96-’97)** Hitachi
- **Media noise reduction,** Hitachi **High Hc, High Mr/Ms media (’97-’98)**
- **Compositional segregation by EELS & EDX TEM (’96-’97),** Hitachi
- **Co-alloy basic properties, Ku, α (’96-’97),** Hitachi, Tohoku U.
- **CoCrPtO high Mr/Ms media** (’00-‘01) Toshiba
- **Improved SUL (’00-’02)** Hitachi & Many companies
- **52.5Gb/in2 demonstration with PMR (’00) ,** Hitachi

Invention of PMR by Prof. Iwasaki (’76) Tohoku U.

Key technologies: Media

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Cross-sectional Structure of CoCr-alloy Thin Film

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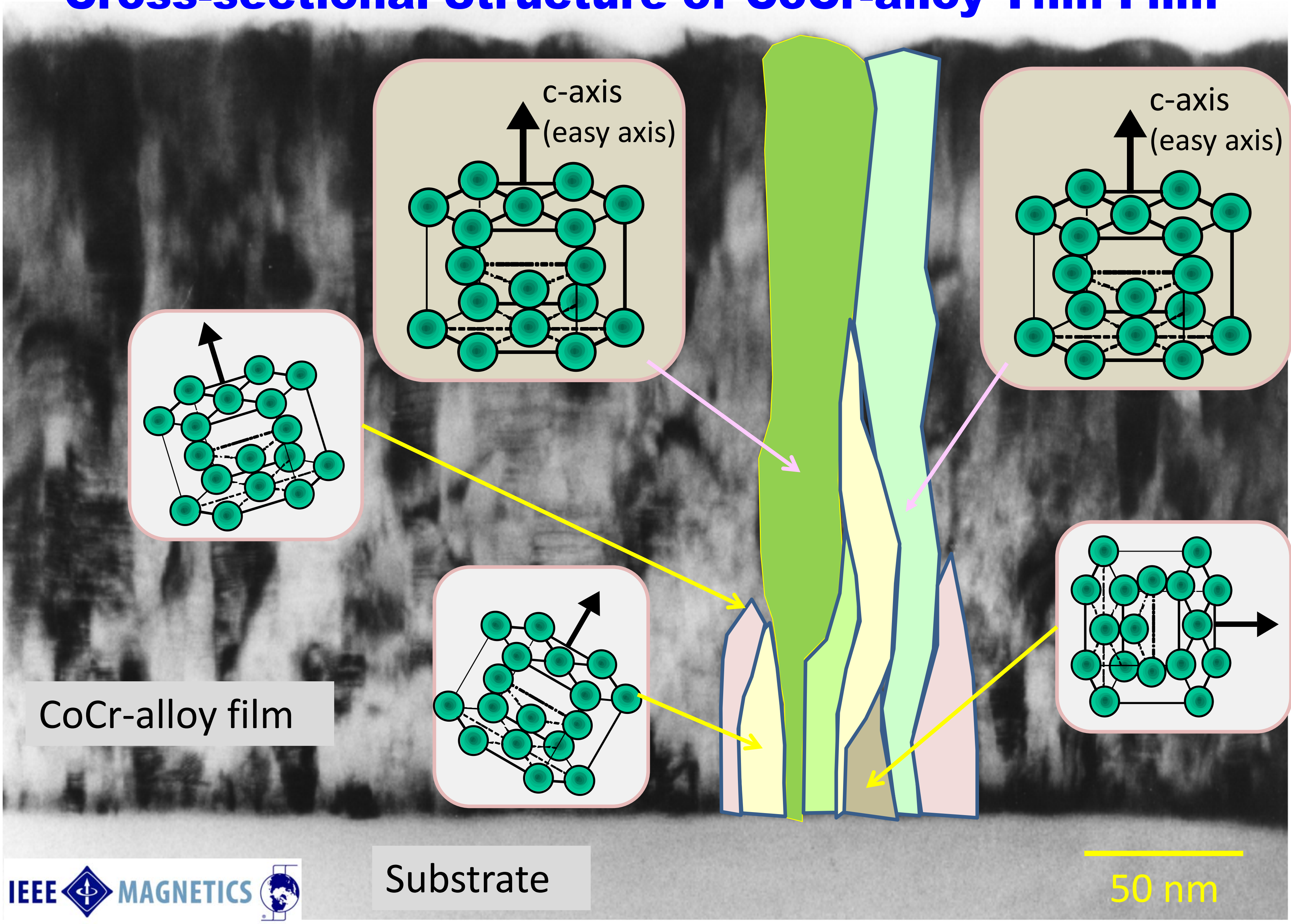
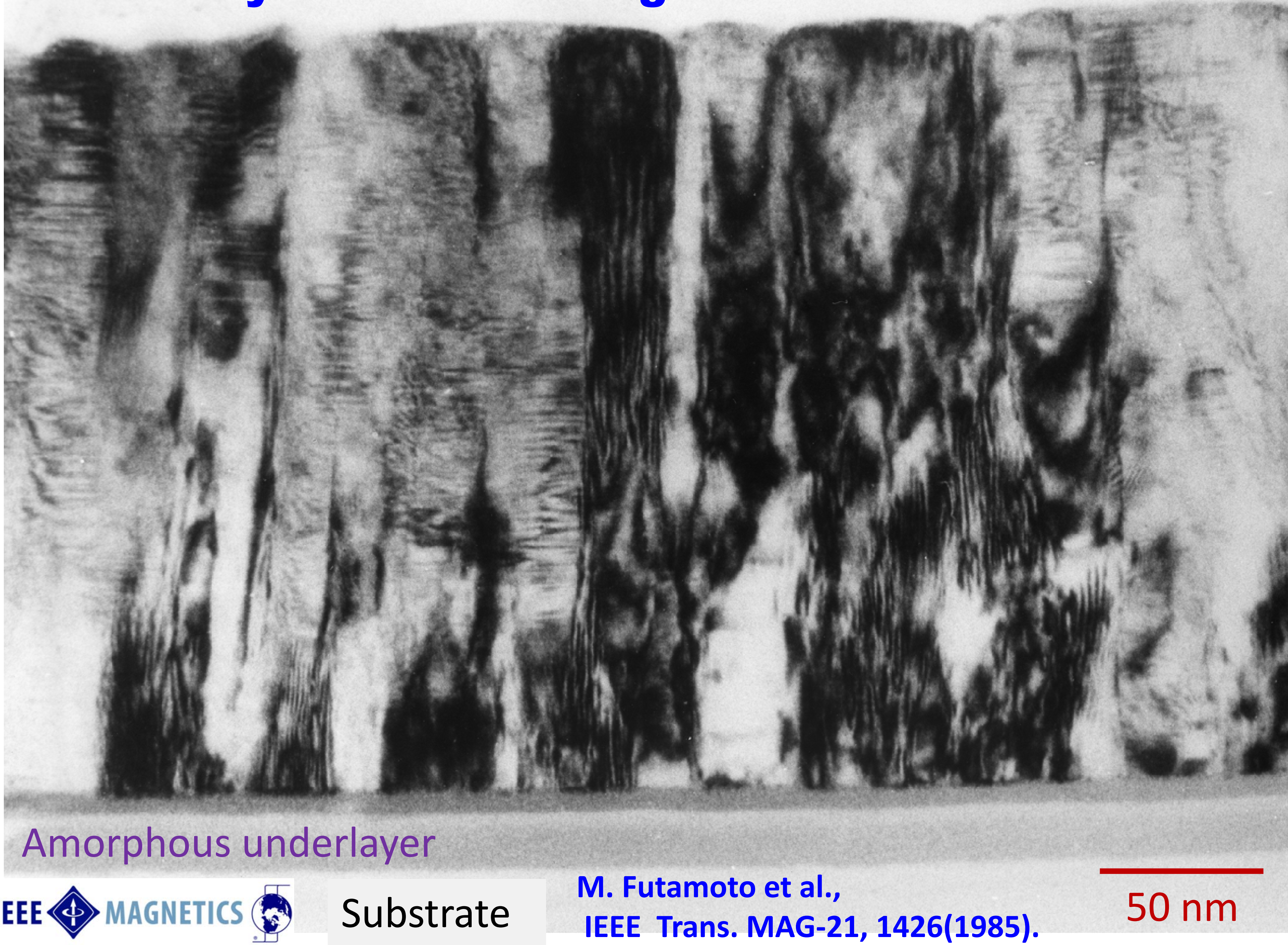
M. Futamoto et al., Japan. J. Appl. Phys., 24, L460(1985).

Cross-sectional Structure of CoCr-alloy Thin Film



Underlayer for Controling Nucleation & Growth



M. Futamoto et al.,
IEEE Trans. MAG-21, 1426(1985).

2^{nd} Underlayer for Controling Grain Diameter

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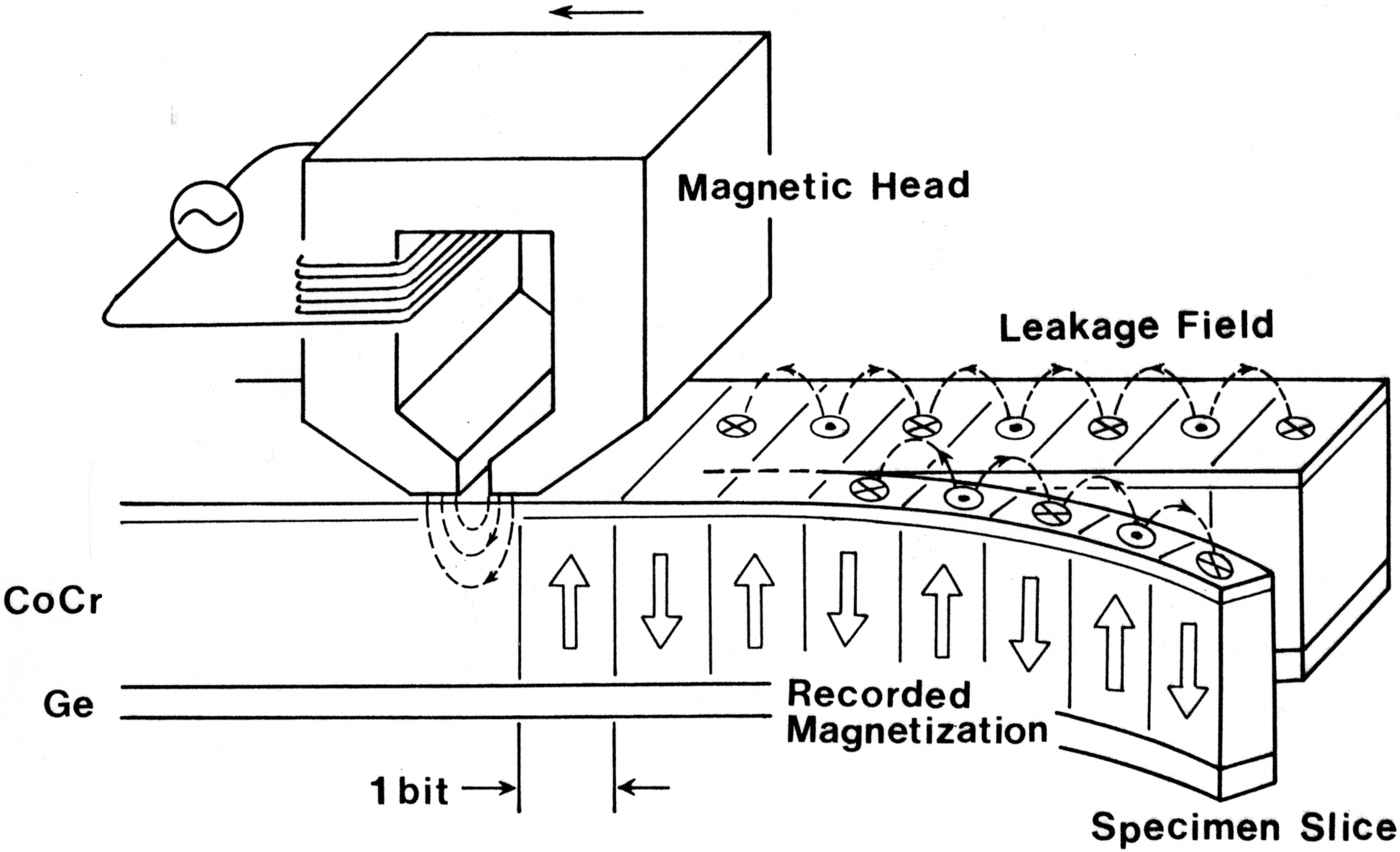
Sample Preparation for Electron Holography



Y. Honda et al.,
J. de Phys., Coloq. C8, 1969(1988).

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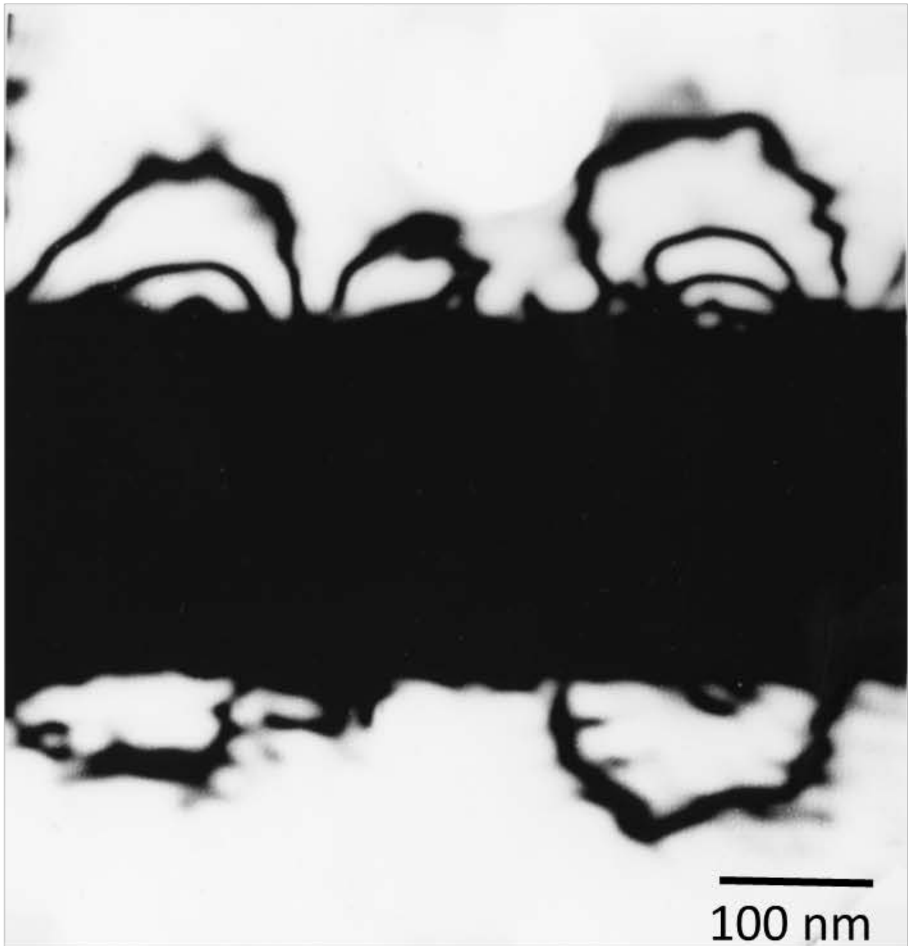
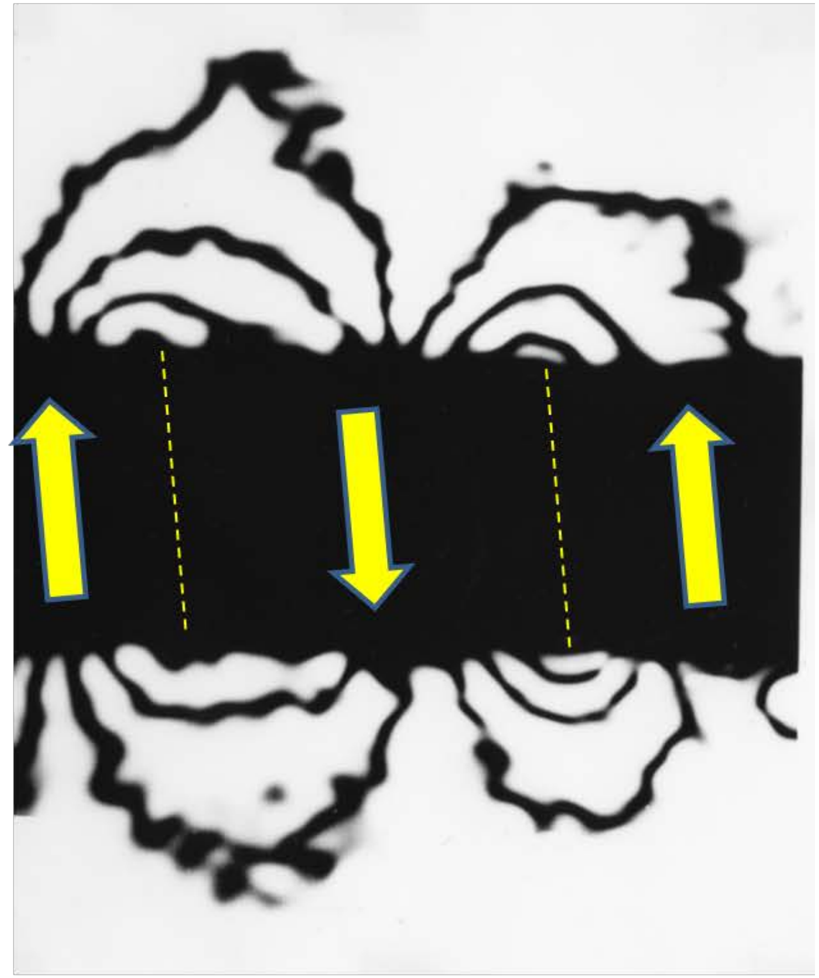
Effect of Film Orientation on Interference Micrograph of Leakage Magnetic Flux from Top and Rear Surfaces

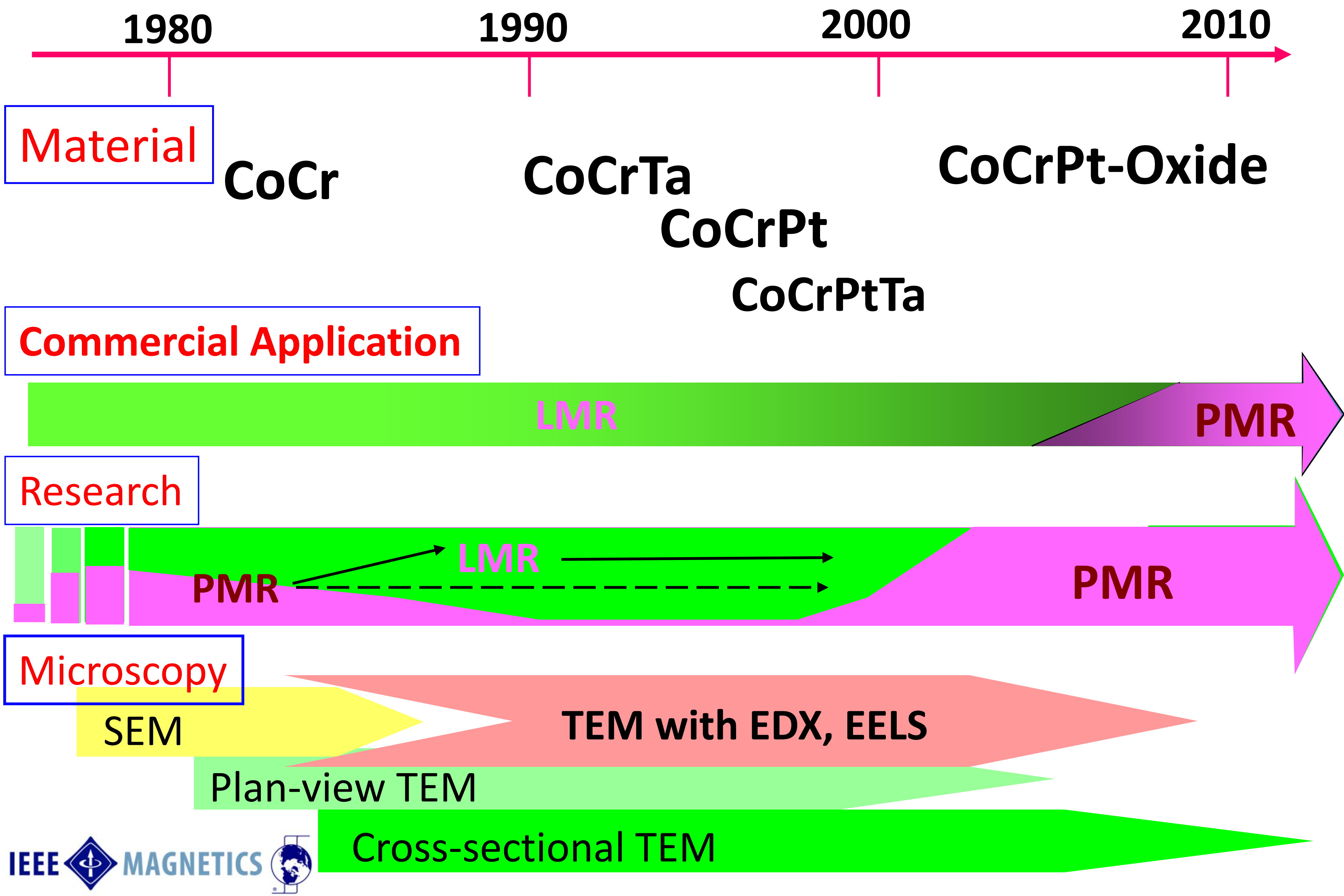


Poorly c-axis oriented
(CoCr with no underlayer)

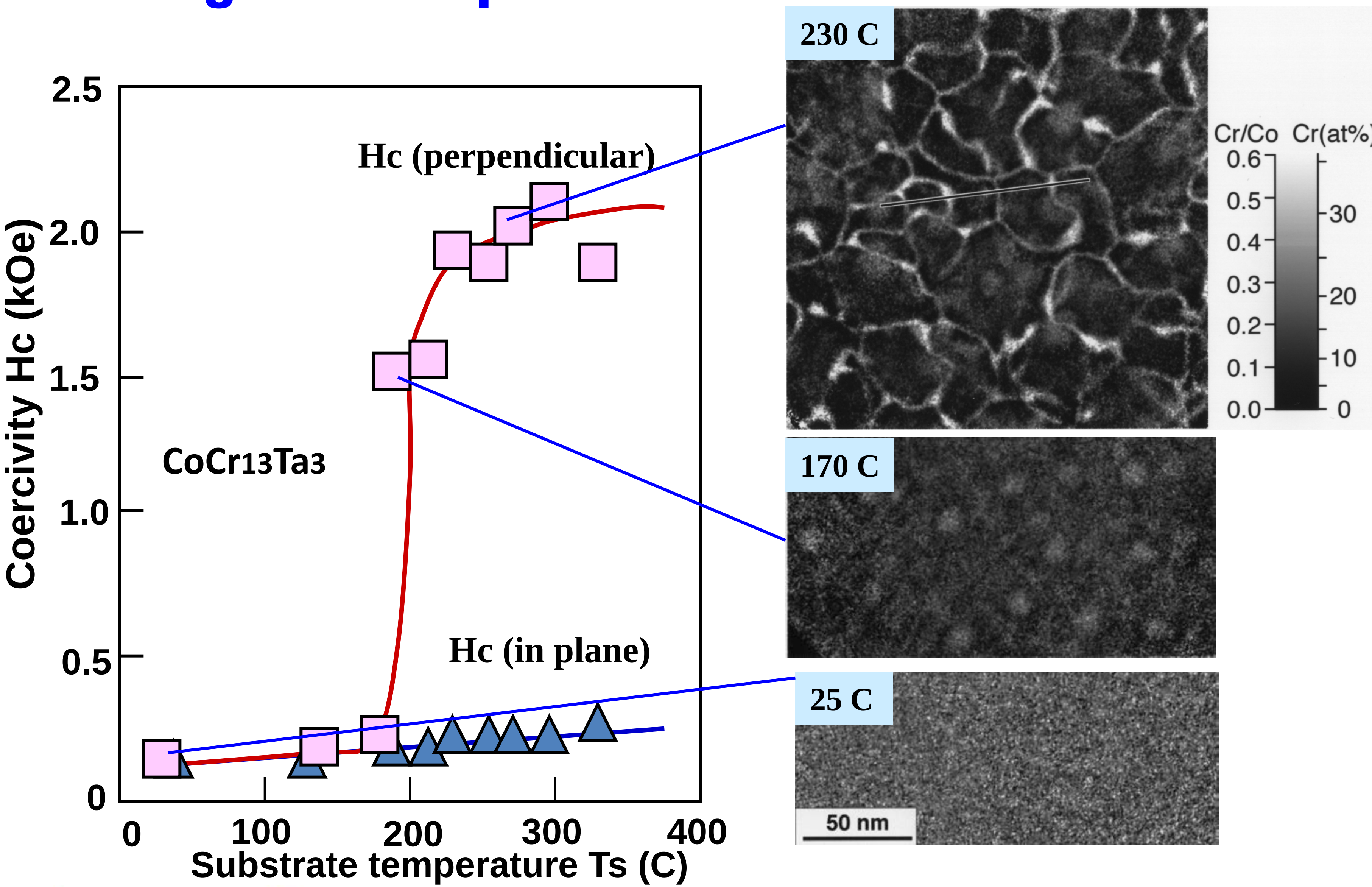


Highly c-axis oriented
(CoCr with Ge underlayer)

PMR Media Technology Development

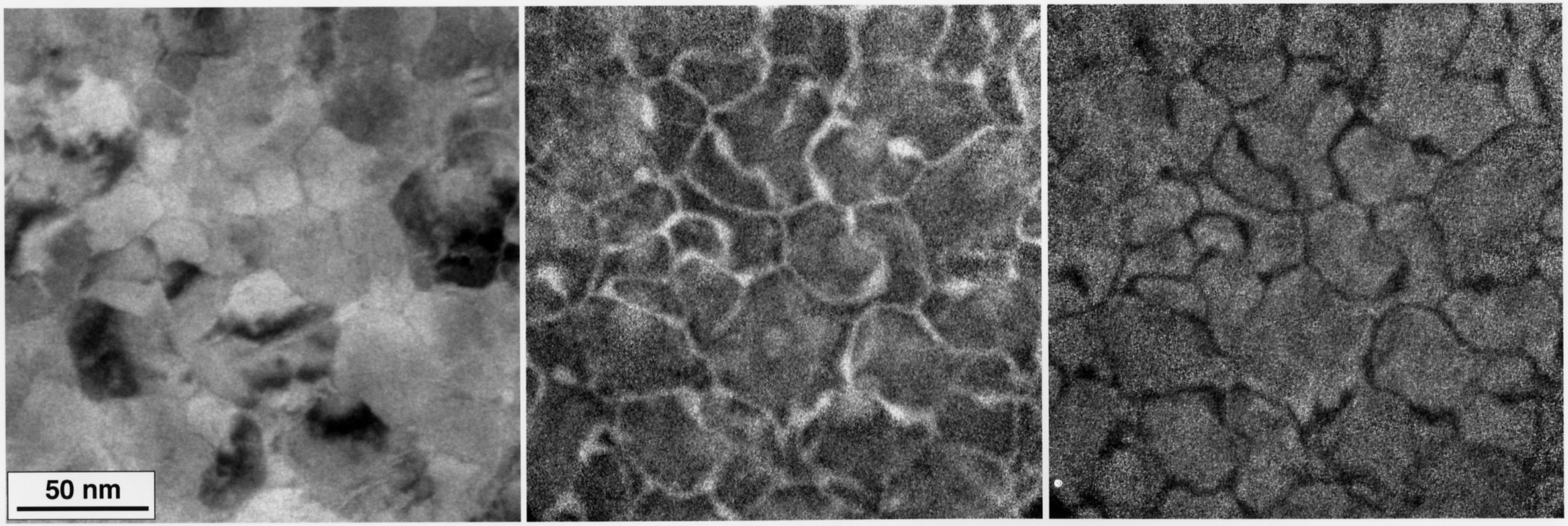


Cr Segregation at Grain Boundaries and Magnetic Properties



K. Kimoto, Y. Hirayama, M. Futamoto, J. Mag. Mag. Mater. 159(1996)401.

Plan-view TEM and Elemental Distribution Maps of CoCrTa PMR Medium



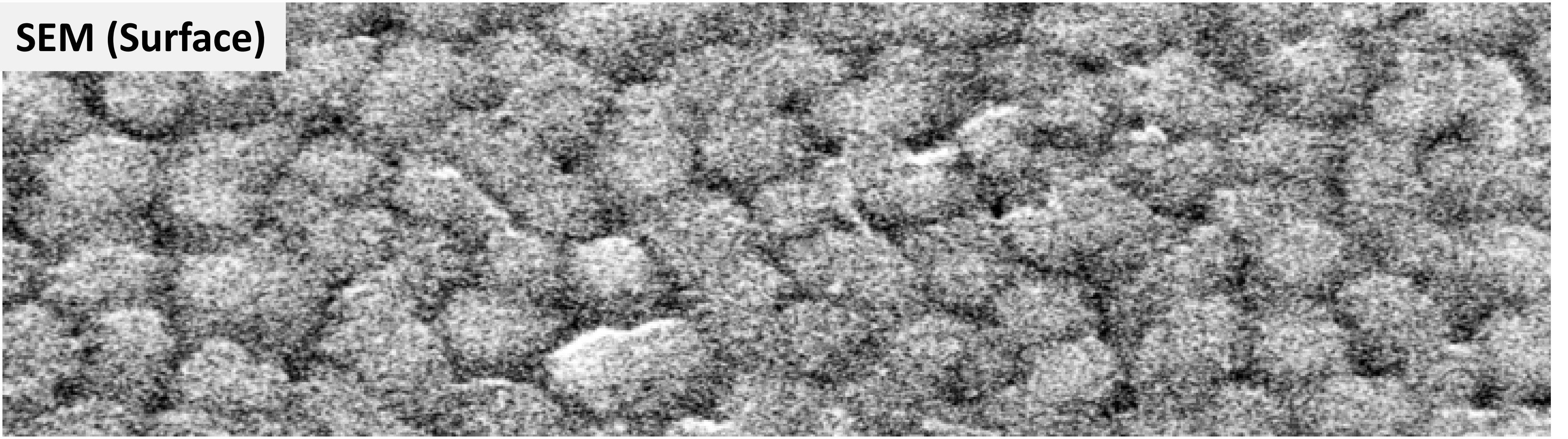
Zero loss image Cr ratio map Co ratio map

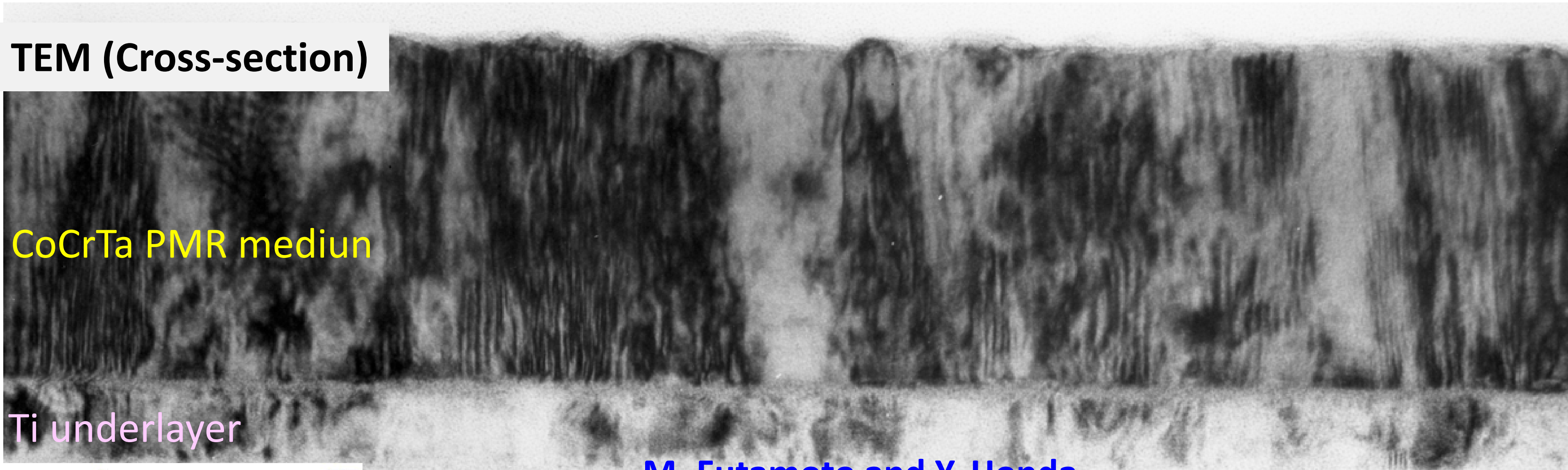
Co-13at%Cr-3at%Ta
PMR Medium

Ts=230 C

K. Kimoto, et al.
J. Mag. Mag. Mater.159, 401(1996).

Structure of CoCrTa Perpendicular Media





M. Futamoto and Y. Honda
J. Mag. Soc. Japan. 18, Suppl. S1, 485(1994).

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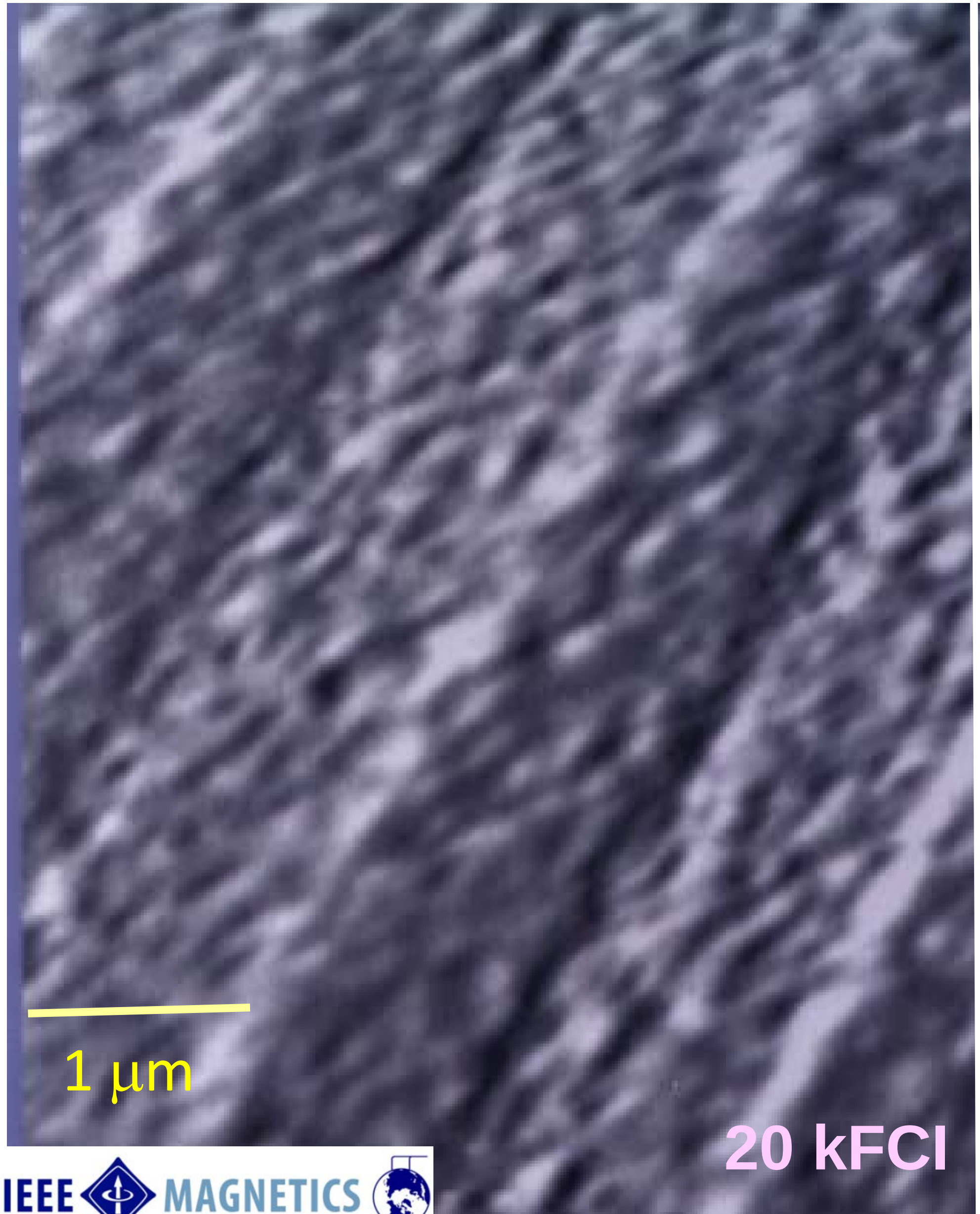
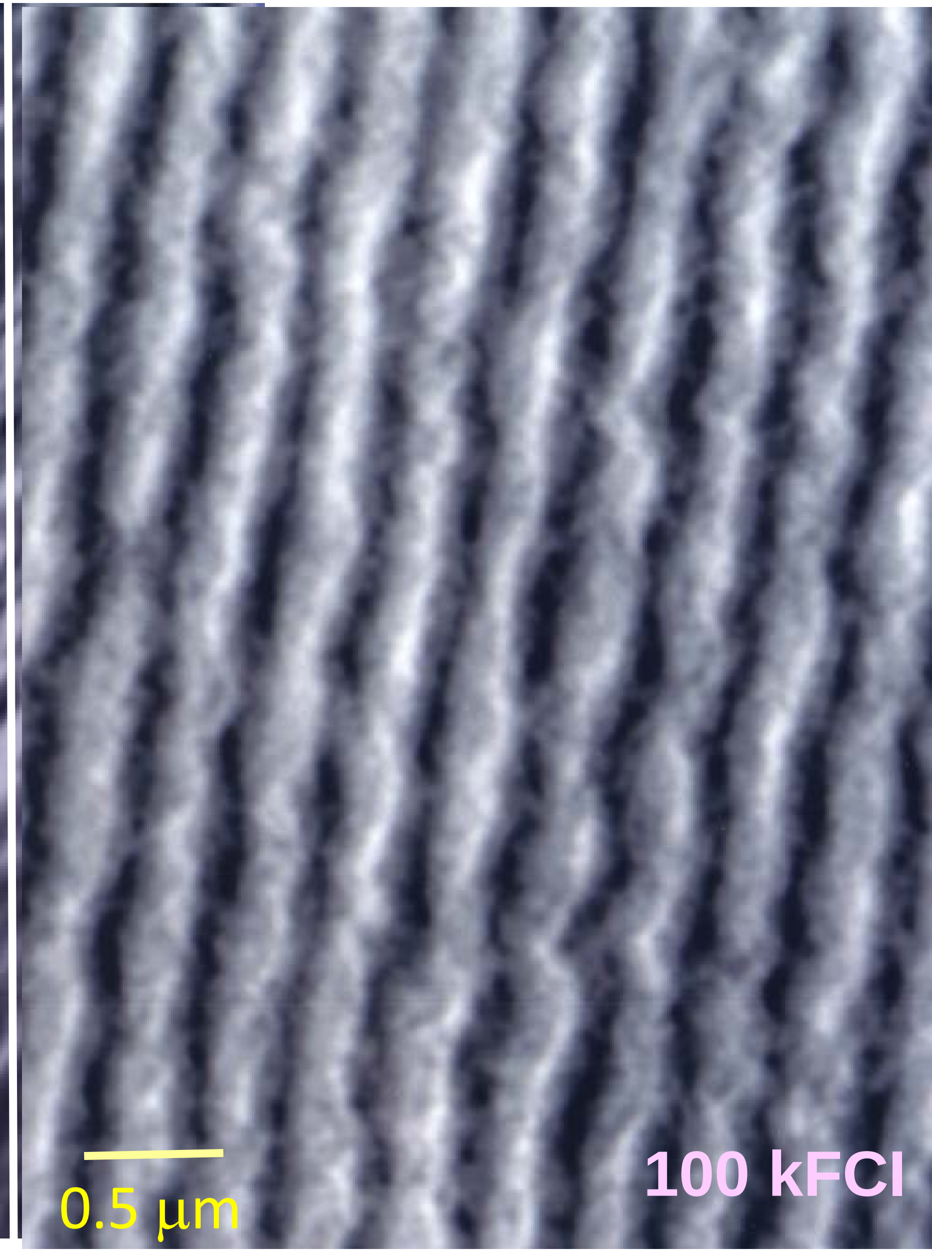
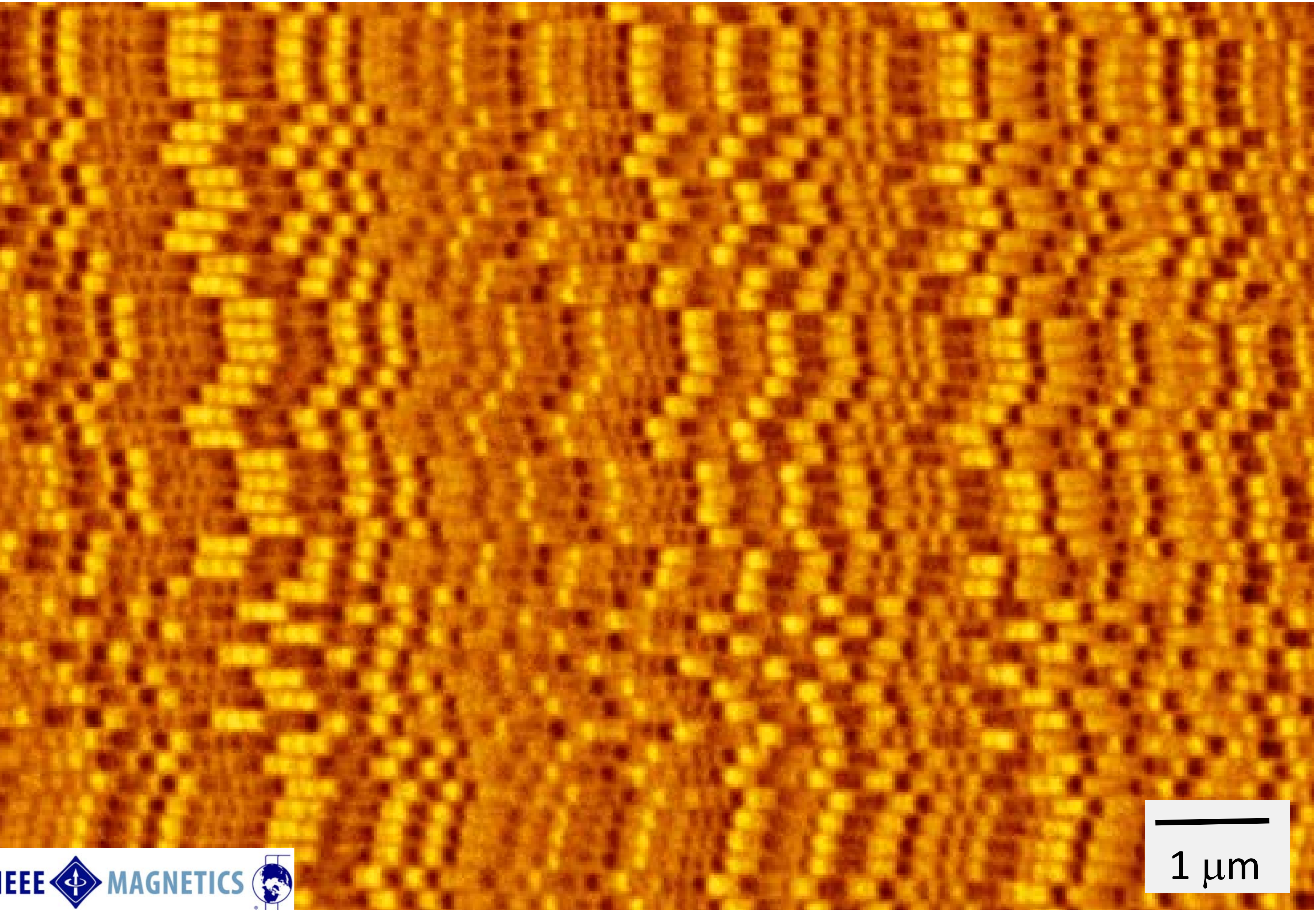
Magnetization Structure of CoCrTa Medium



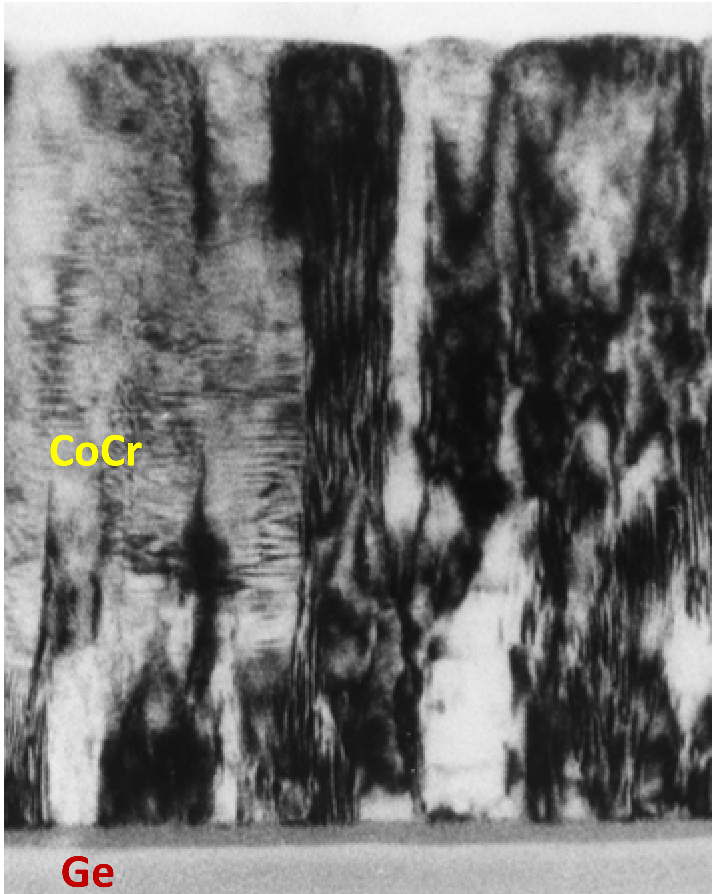


Magnetization Structure of CoCrPt+Oxides Medium



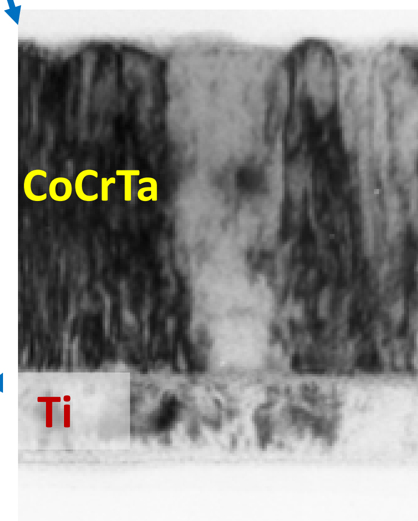
Scaling Down of Media Microstructure in ¼ Century

Year :1985



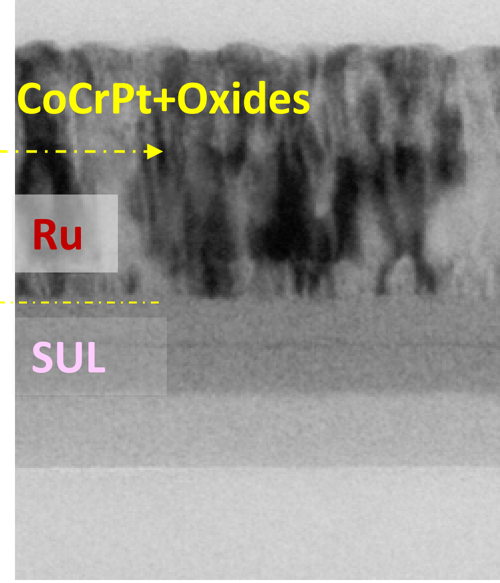
Recording layer :CoCr
h=300 nm, d=30-50 nm
Hc=0.85 kOe

Year :1995



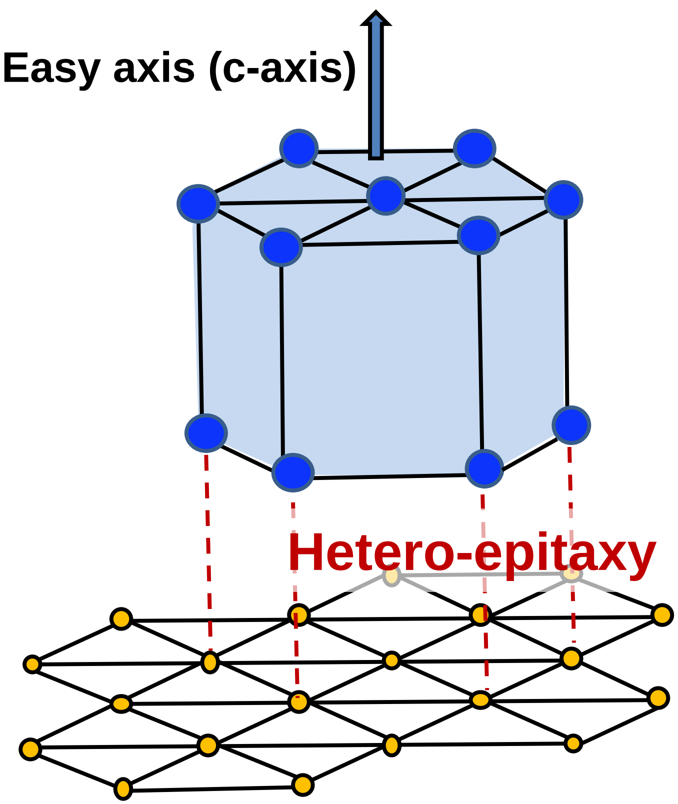
Recording layer :CoCrTa
h=100 nm, d=15-20 nm
Hc=2.2 kOe

Year :2010



Recording layer :CoCrPt+Oxides
h=15 nm, d=7-9 nm
Hc=4.2 kOe

C-axis Alignment perpendicular to the surface



	Materials	References
hcp	**Ru**	IEEE Trans. Magn. 30, 5115(1994).
	Ti	Dig. 6th Conf. MSJ, p.42(1985).
	TiCr	IEEE Trans. Magn. 32, 3789(1996).
	Ta	IEEE Trans. Magn.MAG20,776(1984).
	CoCr	IEEE Trans. Magn. 25, 4168(1989).
	CoCrRu	IEICE Trans. Electron. E84-C, 1132(2001).
	Ru/Ta	IEEE Trans. Magn. 42, 2382(2006).
	Ru/NiW	J. Appl. Phys.105, 07B723(2009).
	Ru/Ru-oxide	IEEE Trans. Magn. 40, 3193(2005).
	Ti/Ge	J .de Phys. Coll. C8, suppl.12,1979(1988).
fcc	Au, Al	IEEE Trans. Magn. 27, 4903(1991).
	Pt	IEEE Trans. Magn. 36, 2387(2000).
	Pt/Ti, Pd/Ti	J. Mag. Mag. Mater. 242, 311(2002).
Others	Ge, Si	IEEE Trans. Magn. MAG21, 1426(1985).
	C	IEICE Trans. Electron. E85-C, 1745(2002).
	Al_2O_3(0001)	IEICE Trans. Electron. E85-C, 1733(2002).
	MgO(111)	IEEE Trans. Magn. 45, 2519(2009).

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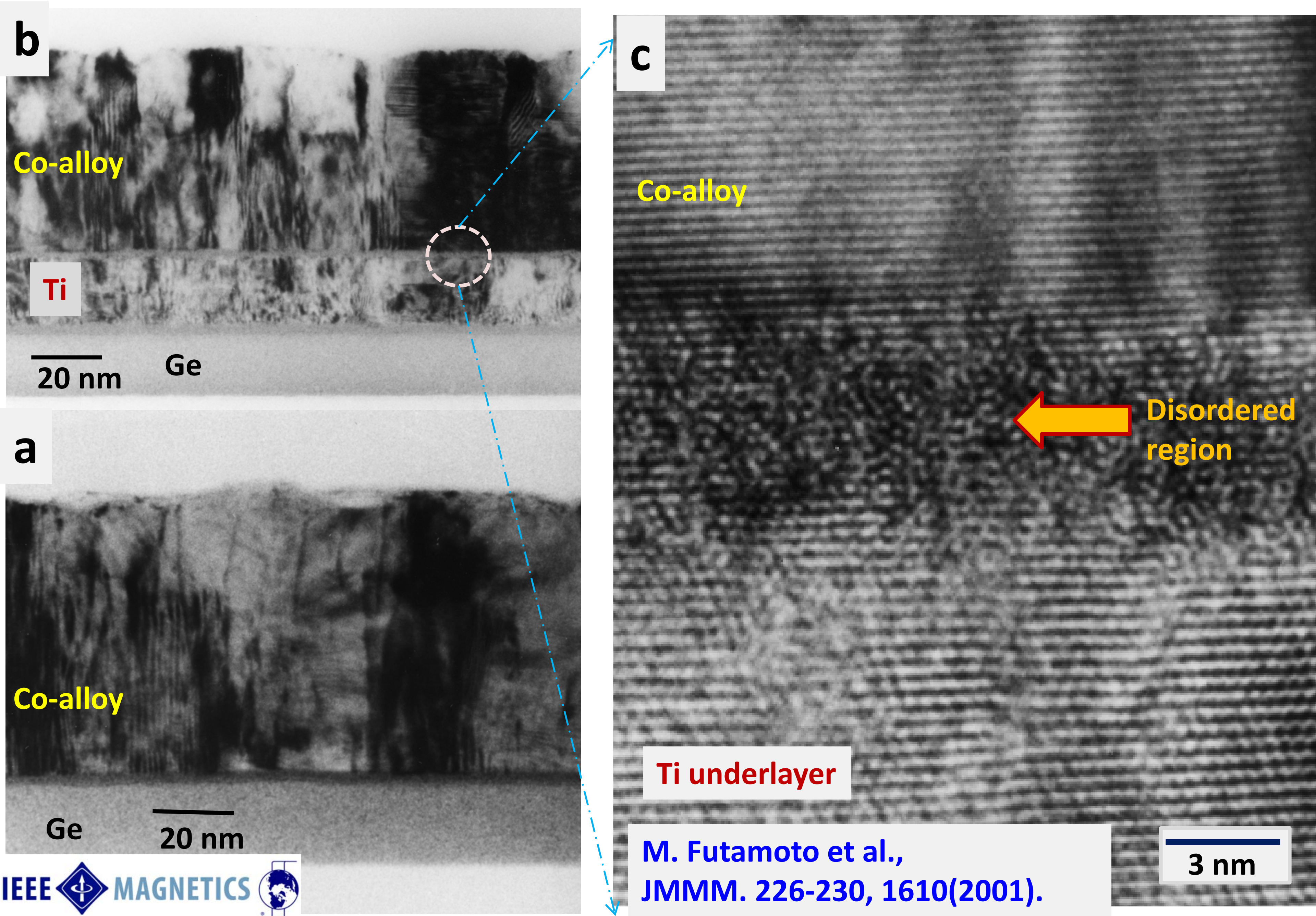
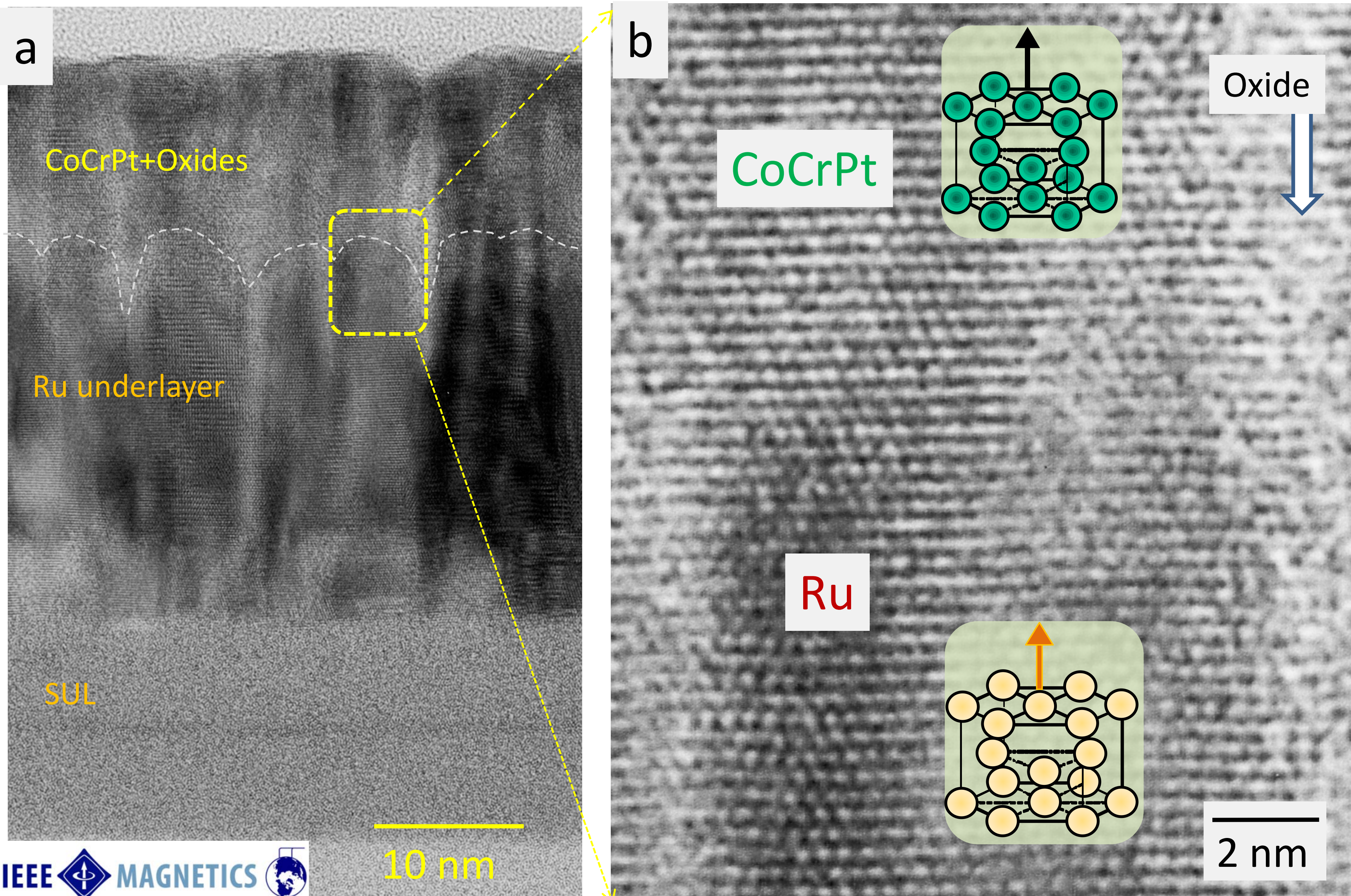
Interface Structure between Co-alloy/Underlayer



M. Futamoto et al.,
JMMM. 226-230, 1610(2001).

Interface Structure between Co-alloy/Ru-Underlayer



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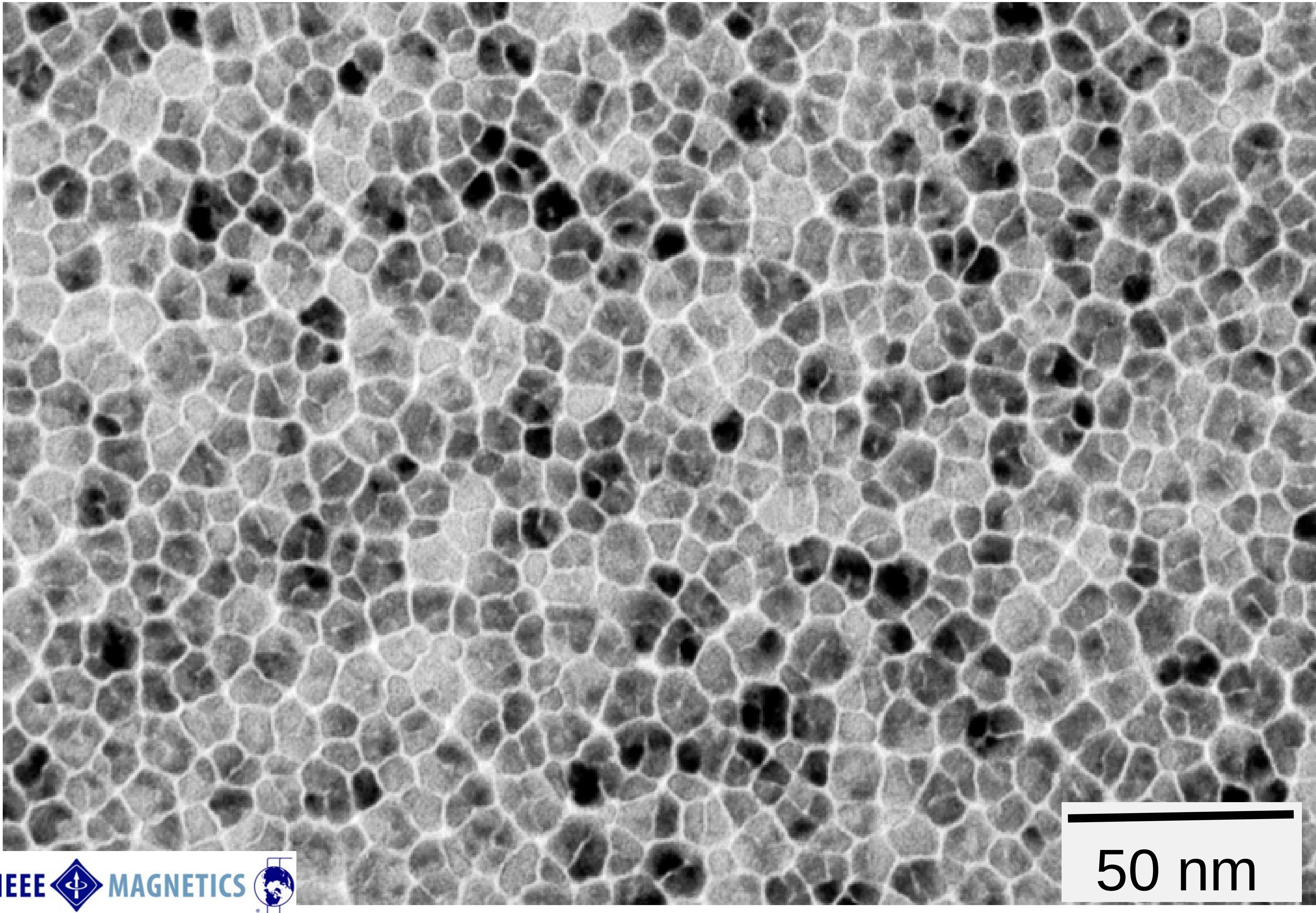
Plan-view TEM of CoCrPt+Oxide Layer



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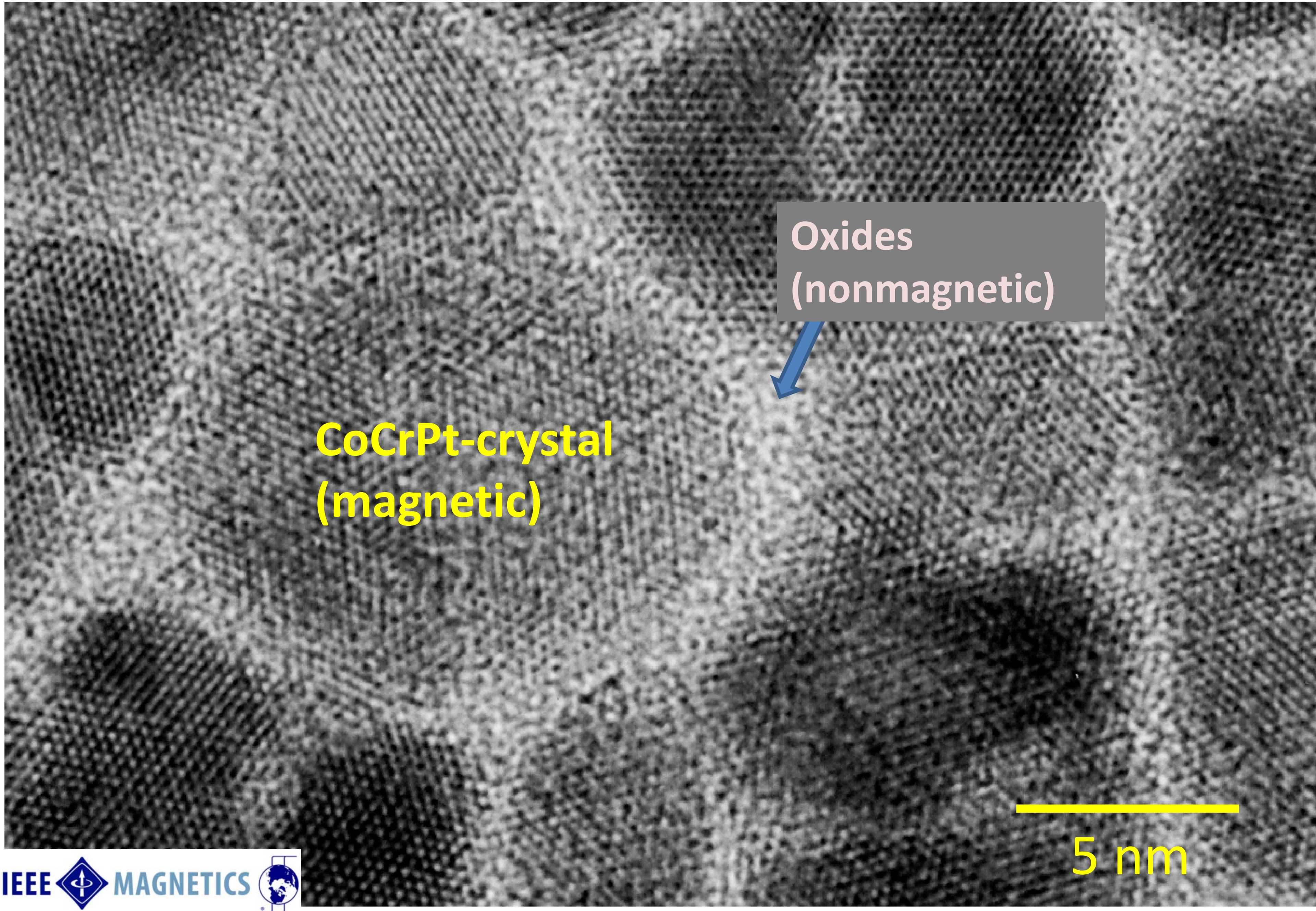
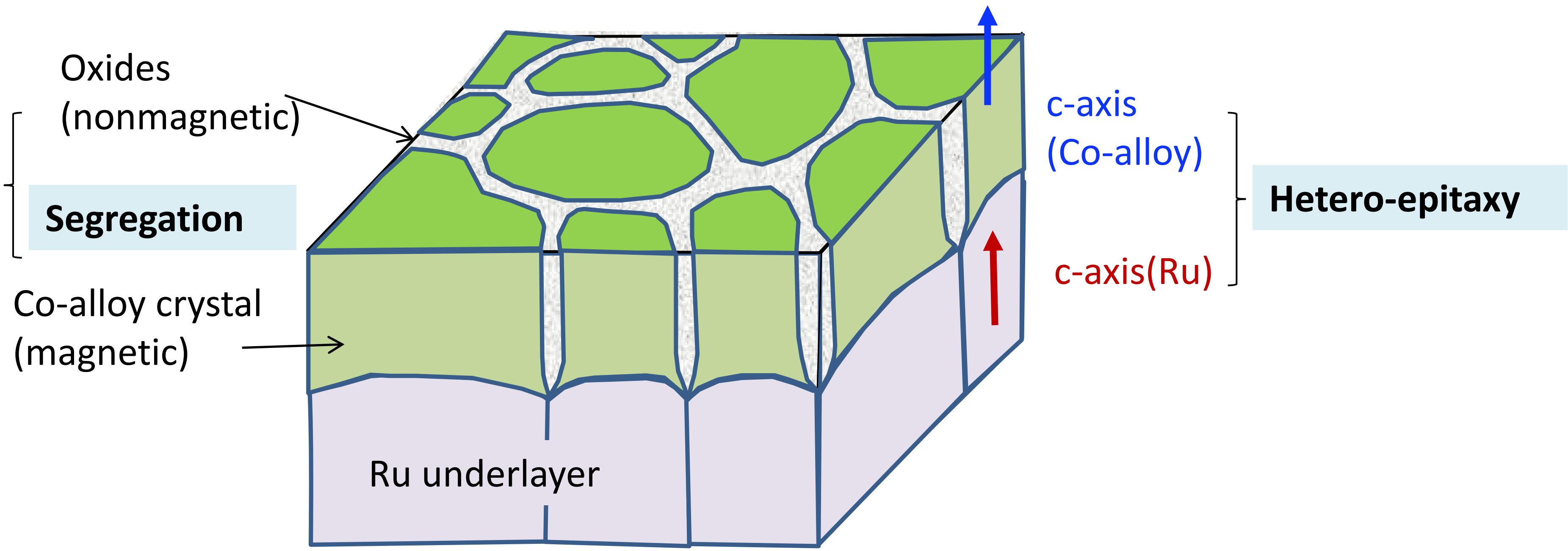
Plan-view TEM of CoCrPt+Oxides Layer



Magnetic Crystal Isolation by Oxides Segregation



	Materials	References
Oxides	**SiO_2**	IEEE Trans. Magn. 38, 1976(2002).
	TiO_2	J. Mag. Mag. Mater. 28,167(2005).
	MgO, Ta_2O_5	IEEE Trans. Magn. 41, 3142(2005).
	Cr_2O_3	J. Appl. Phys., 95, 102507(2009).
	Y_2O_3	IEEE Trans. Magn. 46, 2260(2010).
Others	C	IEEE Trans. Magn. 34, 1132(1998).
	Ag, Au, Cu, etc.	Many references

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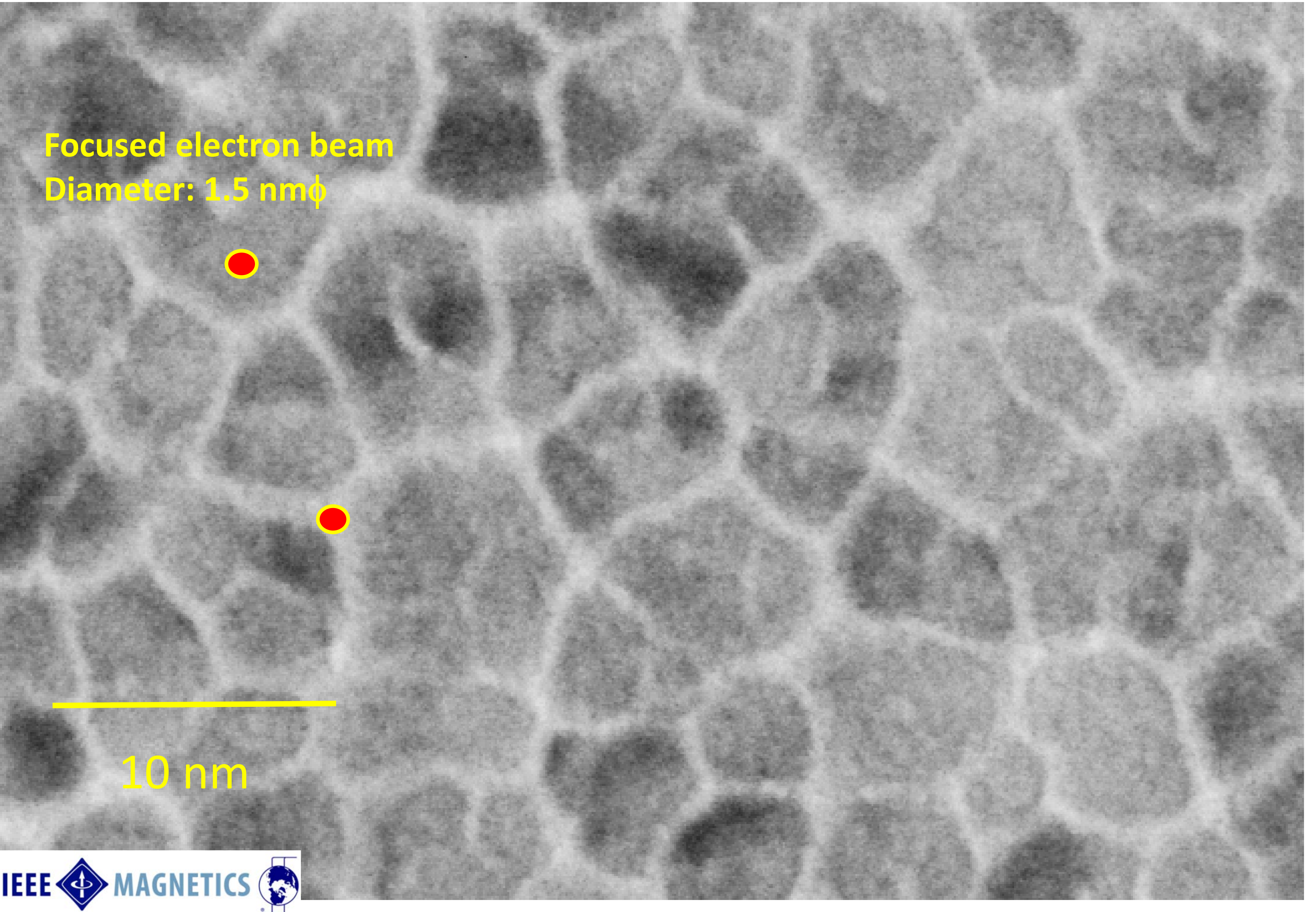
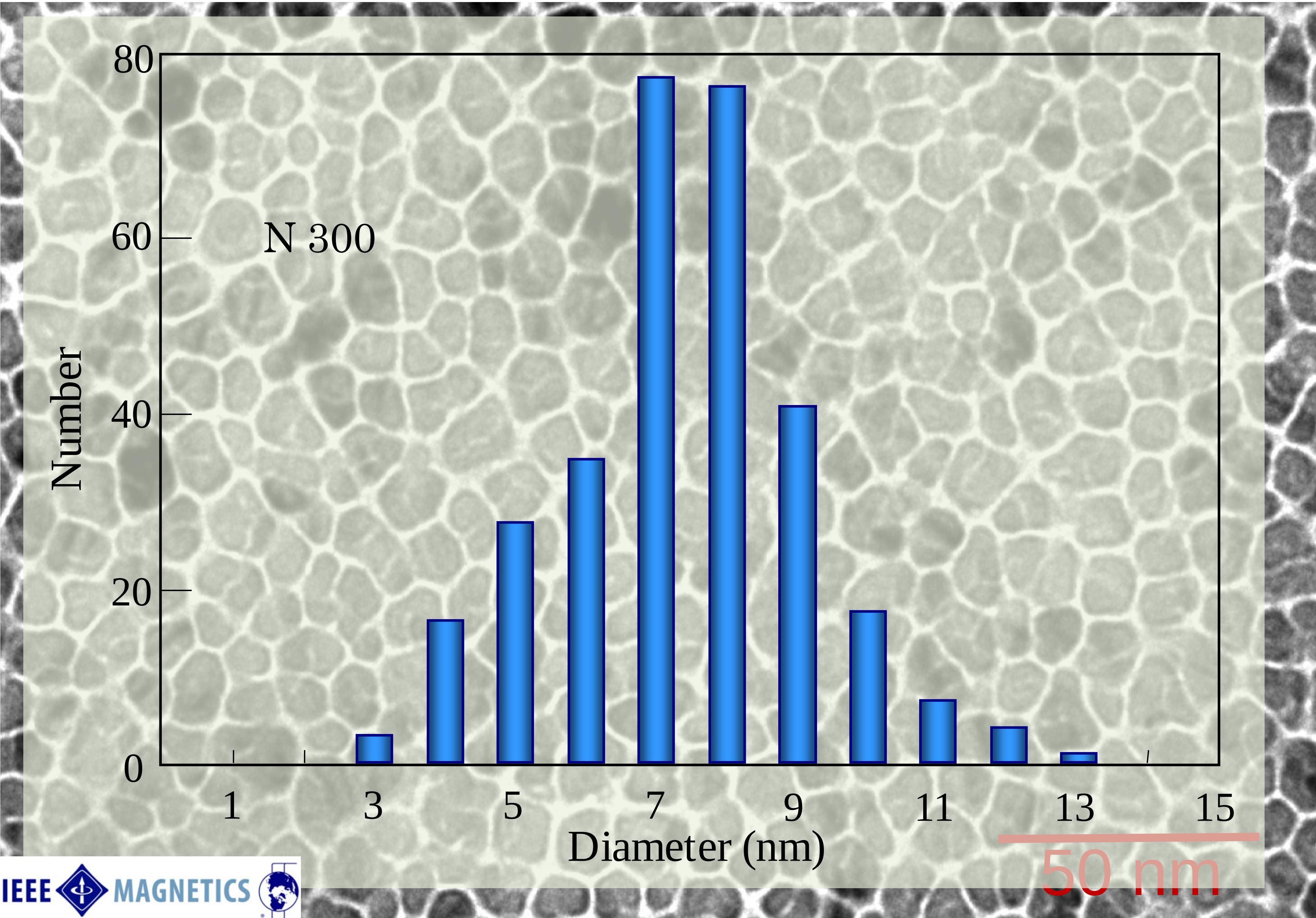
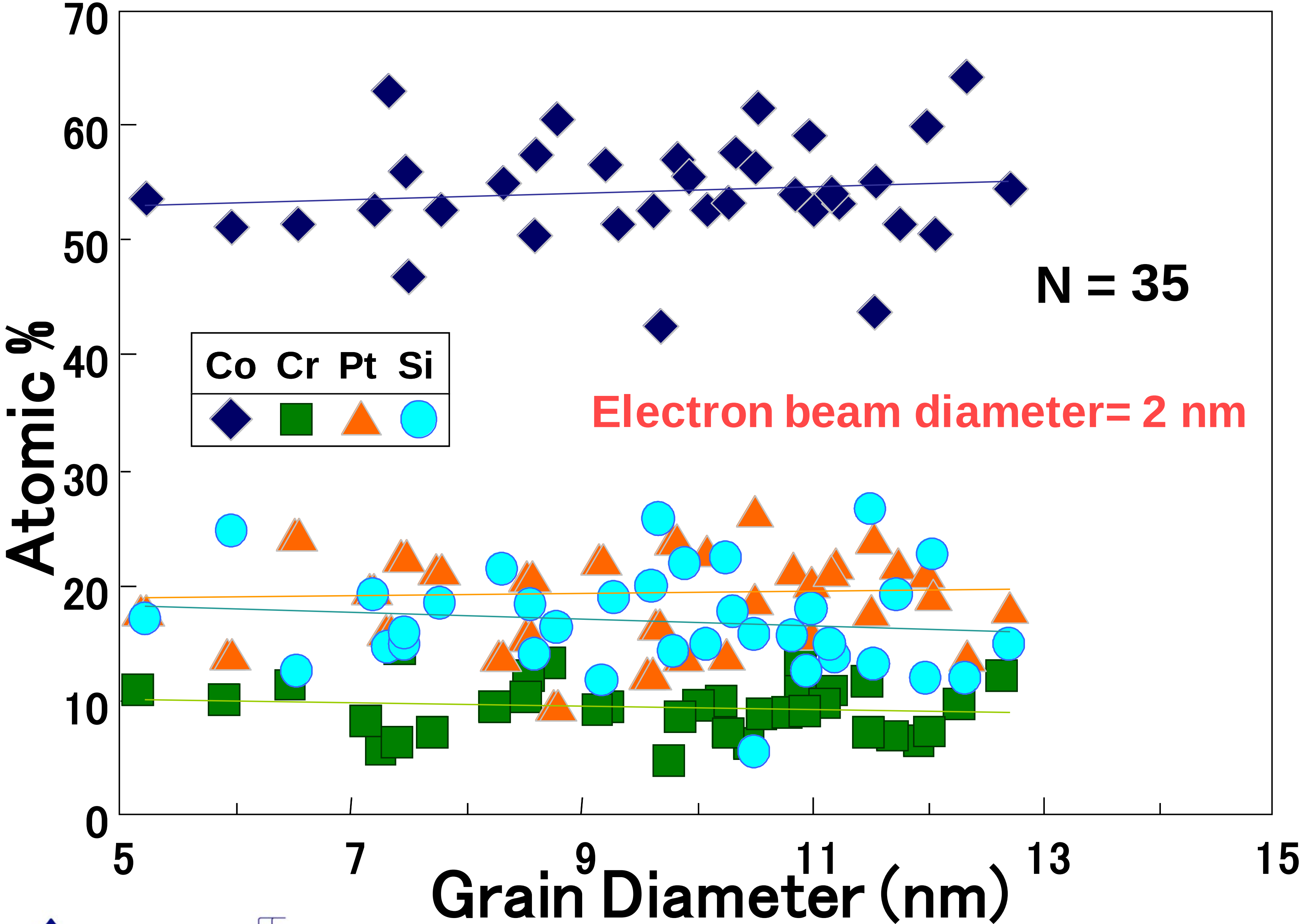
Local Composition Measurement by EDX-TEM



Crystal Grain Size Distribution



Composition Dependence on Crystal Grain Diameter



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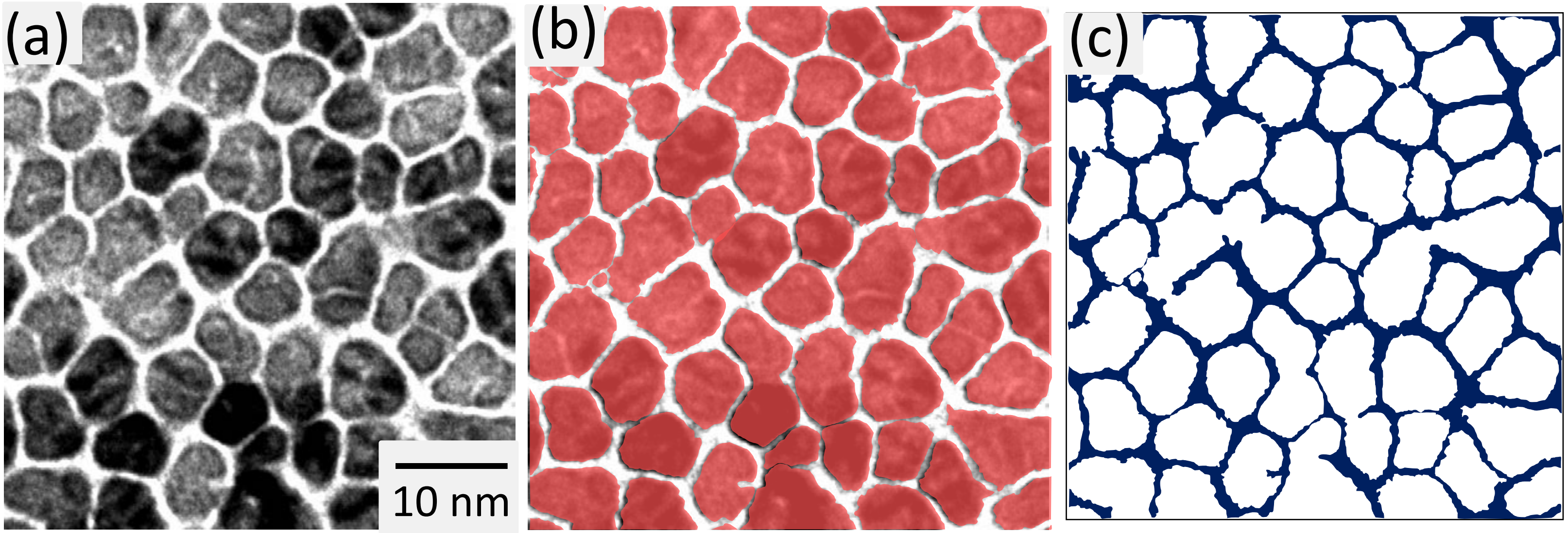
M. Futamoto et al., IEEE Trans. Magn. 44, 3488 (2008).

Estimation of Crystal Grain Boundary Composition



Plan-view TEM

Extraction of crystal grain profiles

Grain boundaries

Total volume * Average composition (grain + boundaries) - Grain volume * Grain composition = Boundary volume * Boundary composition

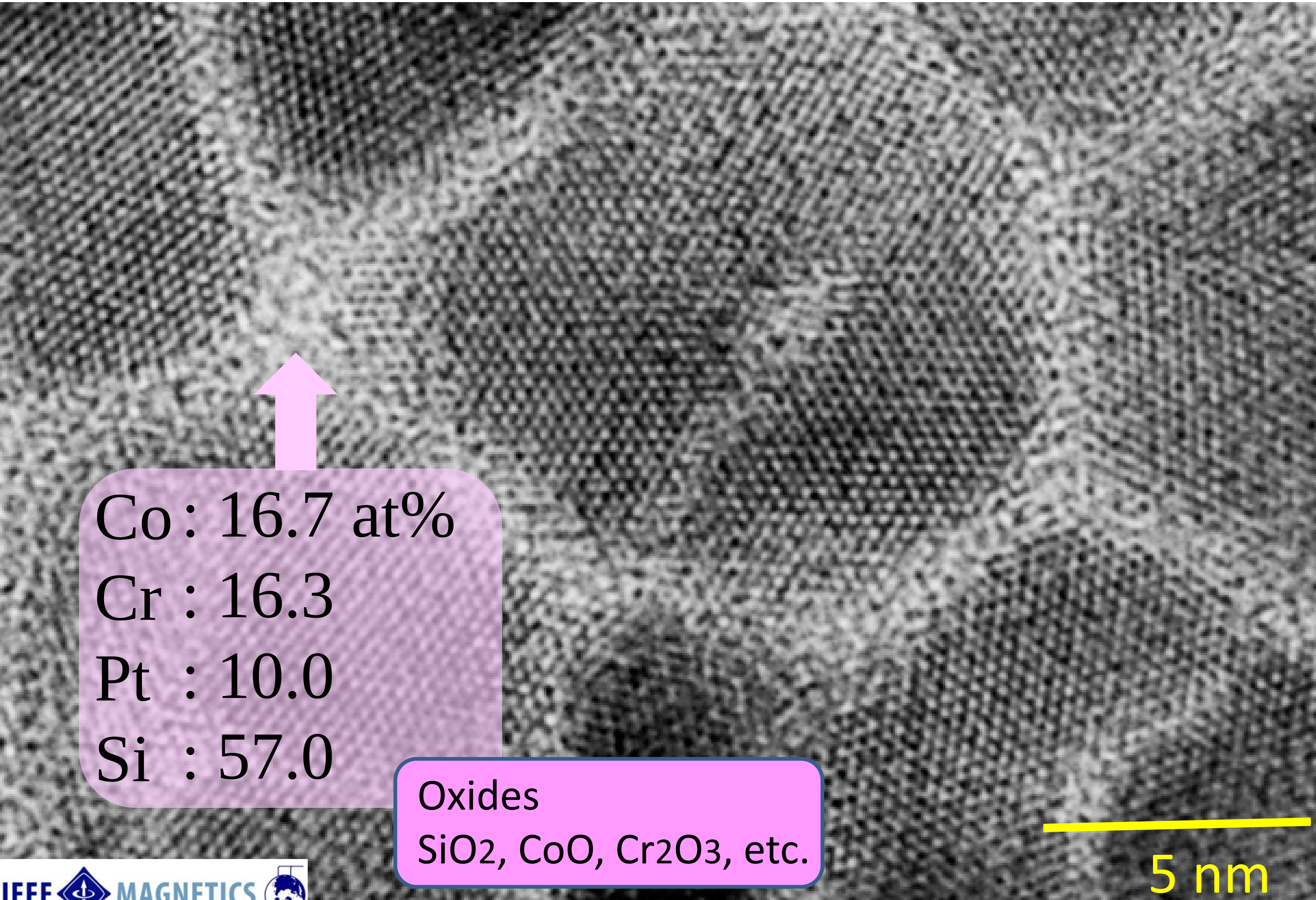
Co	: 48.2 at%
Cr	: 10.5
Pt	: 17.9
Si	: 23.4

Co	: 54.2 at%
Cr	: 9.4
Pt	: 19.4
Si	: 17.0

Co	**: 16.7 at%**
Cr	**: 16.3**
Pt	**: 10.0**
Si	**: 57.0**

M. Futamoto et al., J. Phys: Conf. Ser., 200, 102001(2010).

Average Composition of Crystal Grain Boundaries



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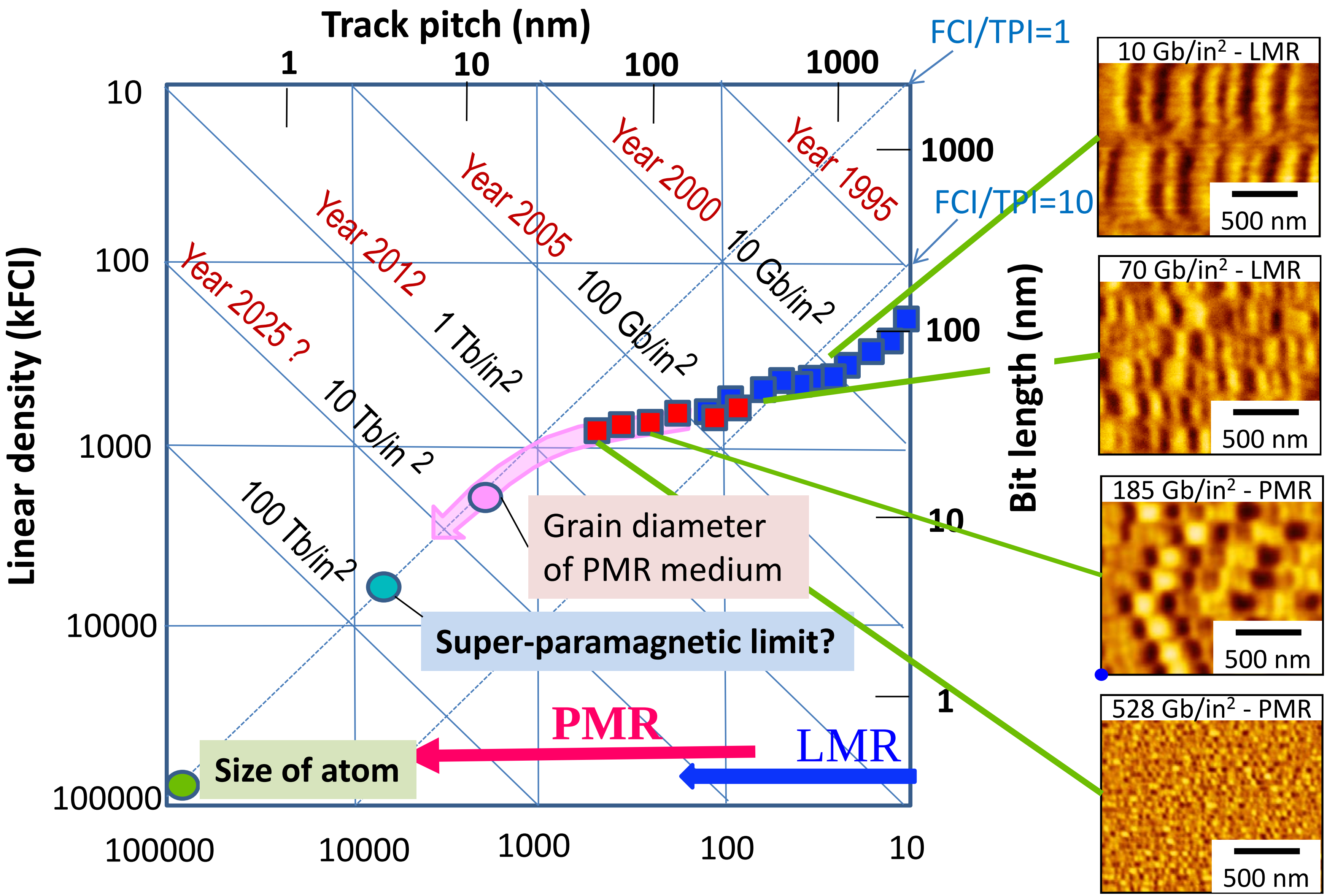
Decreasing Trend of Recording Bit Size in HDDs



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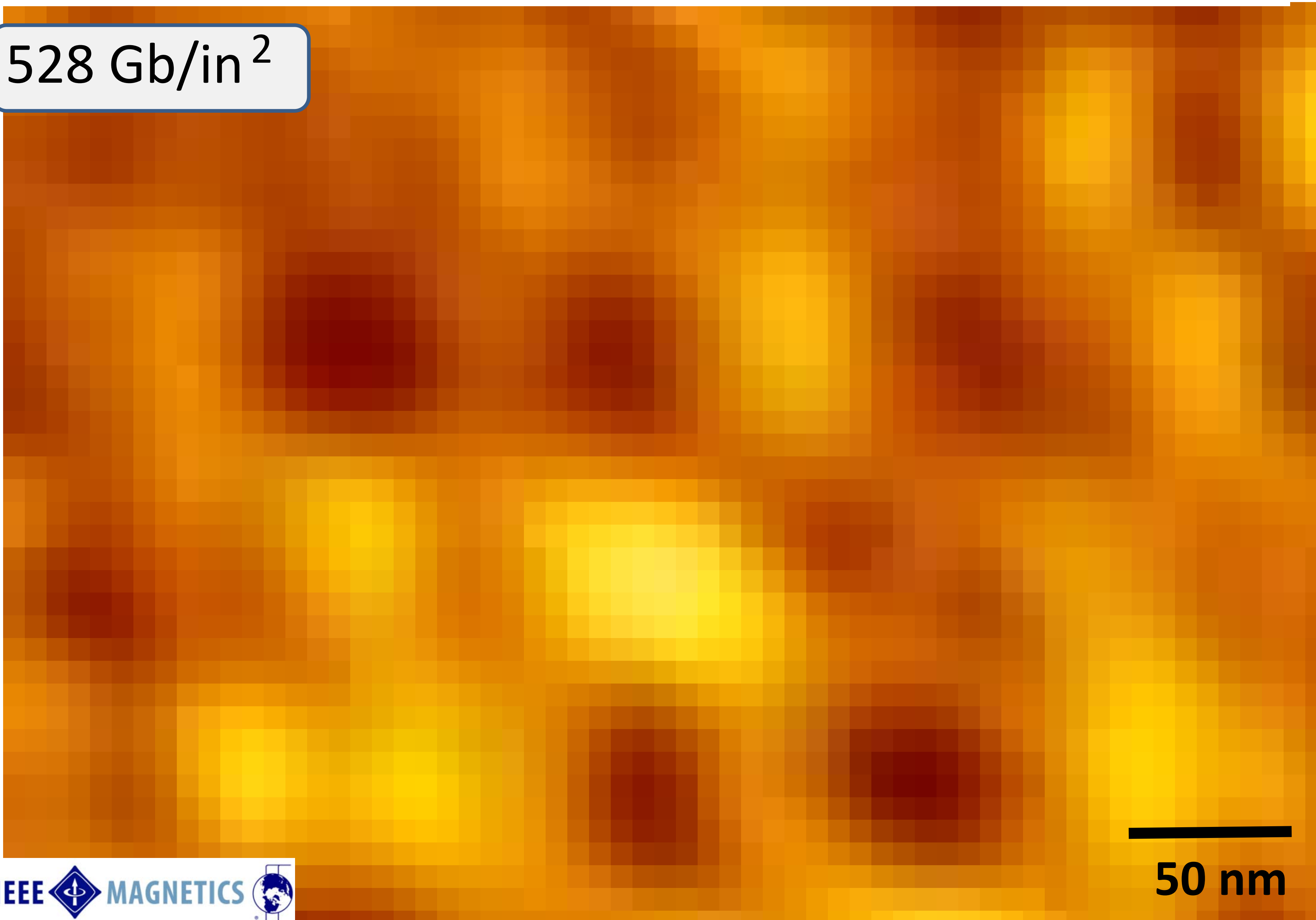
Relation between Bit Size and Crystal Grains



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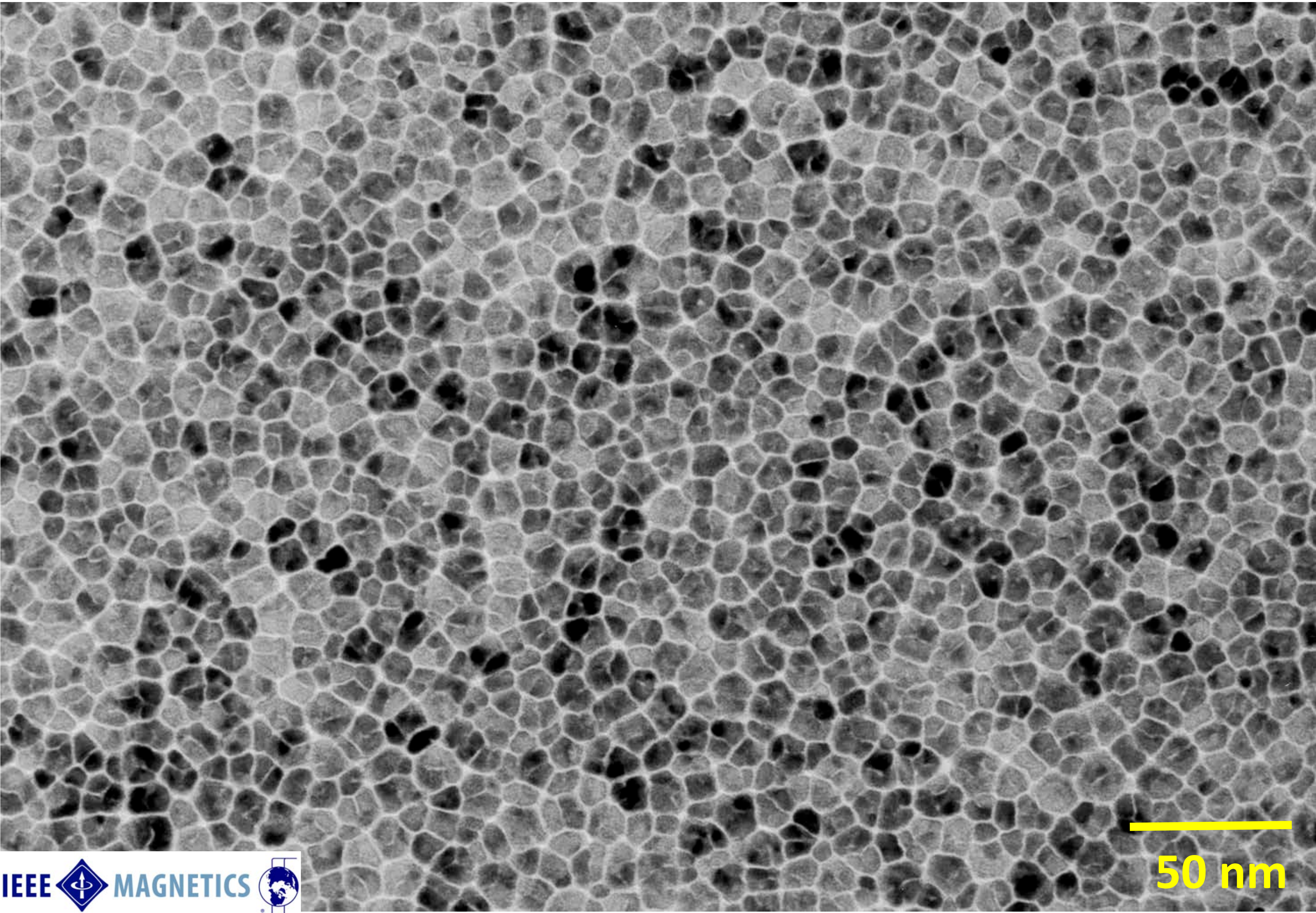
Relation between Bit Size and Crystal Grains



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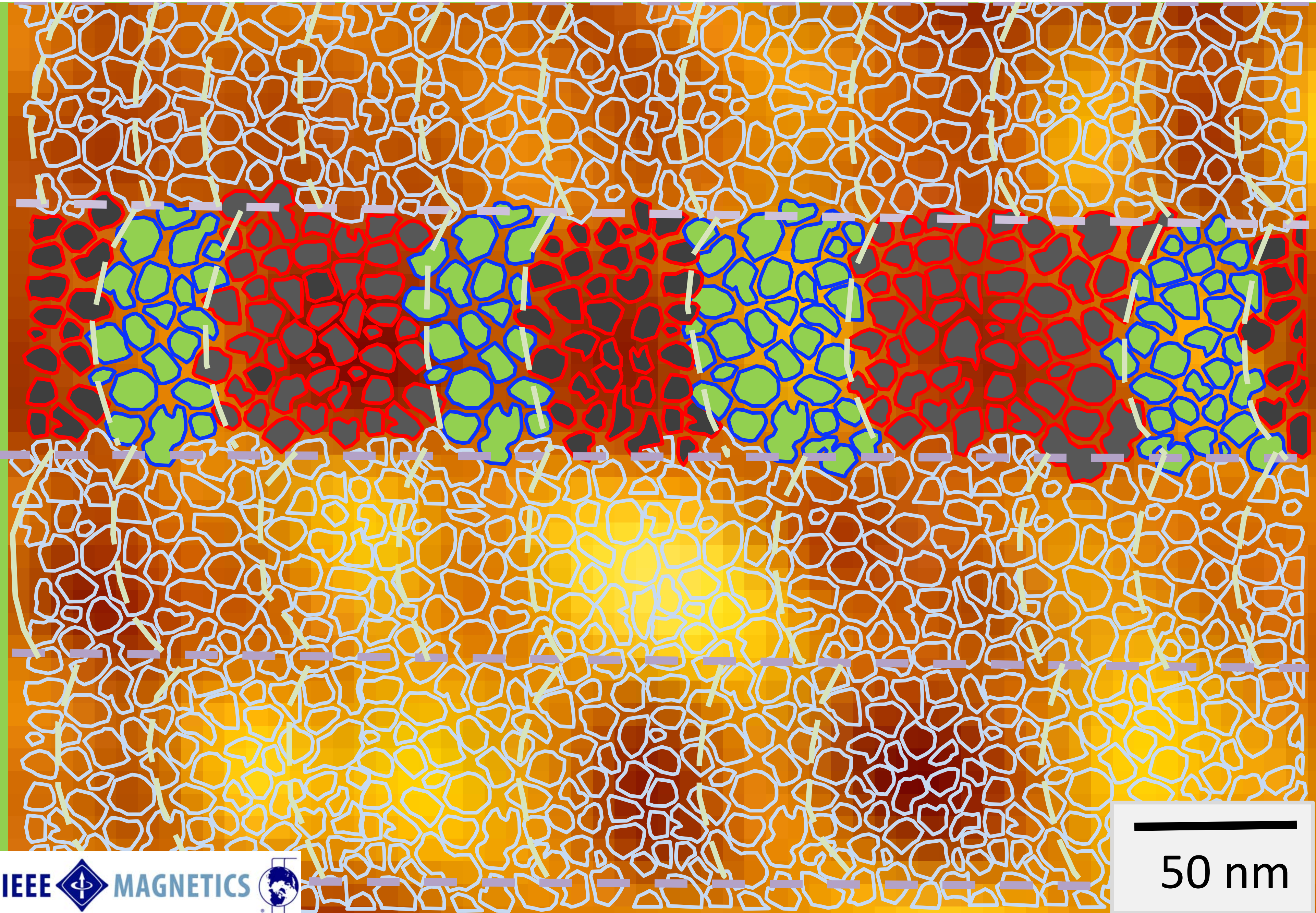
Relation between Bit Size and Crystal Grains



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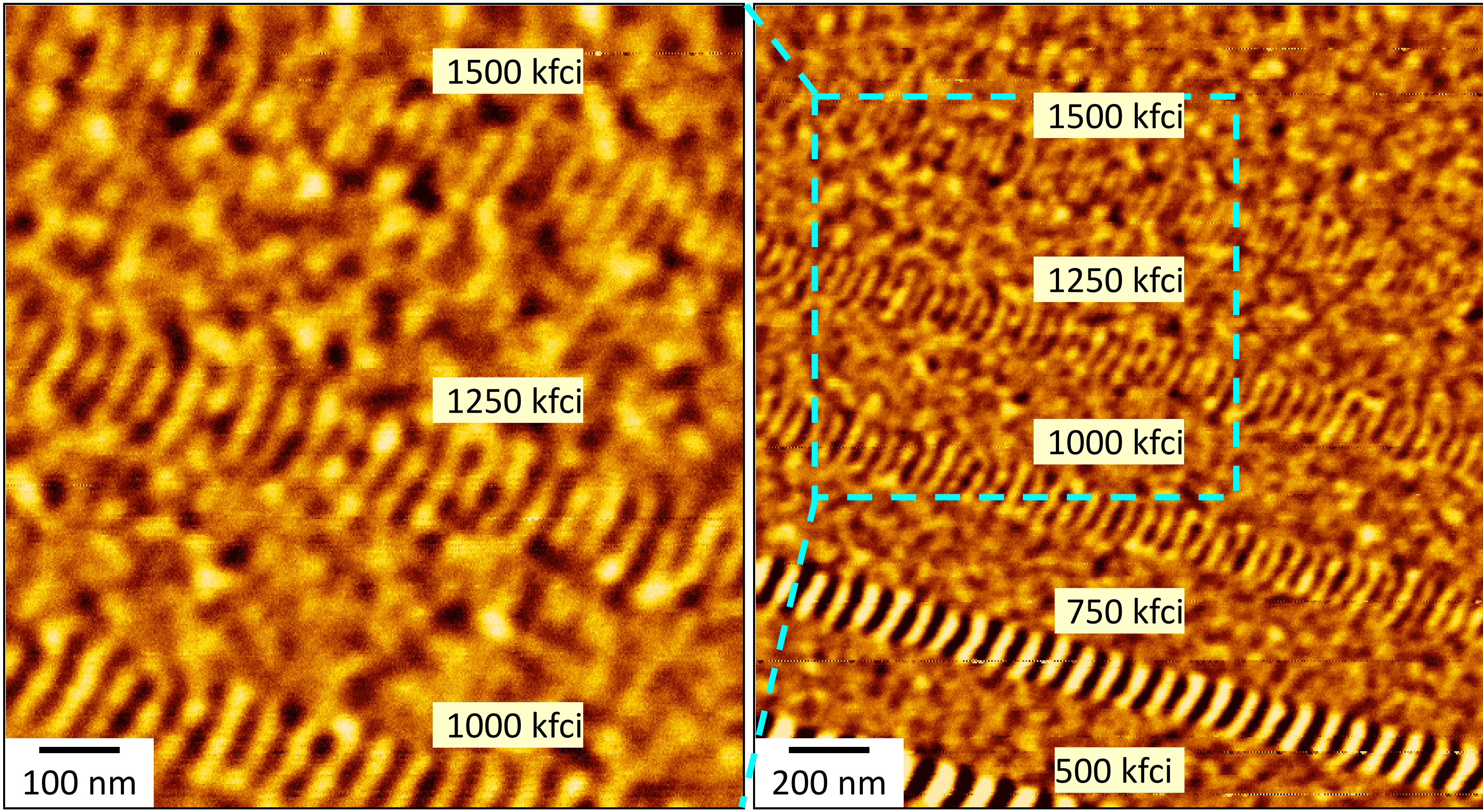
Recording Density Possibility of PMR Media



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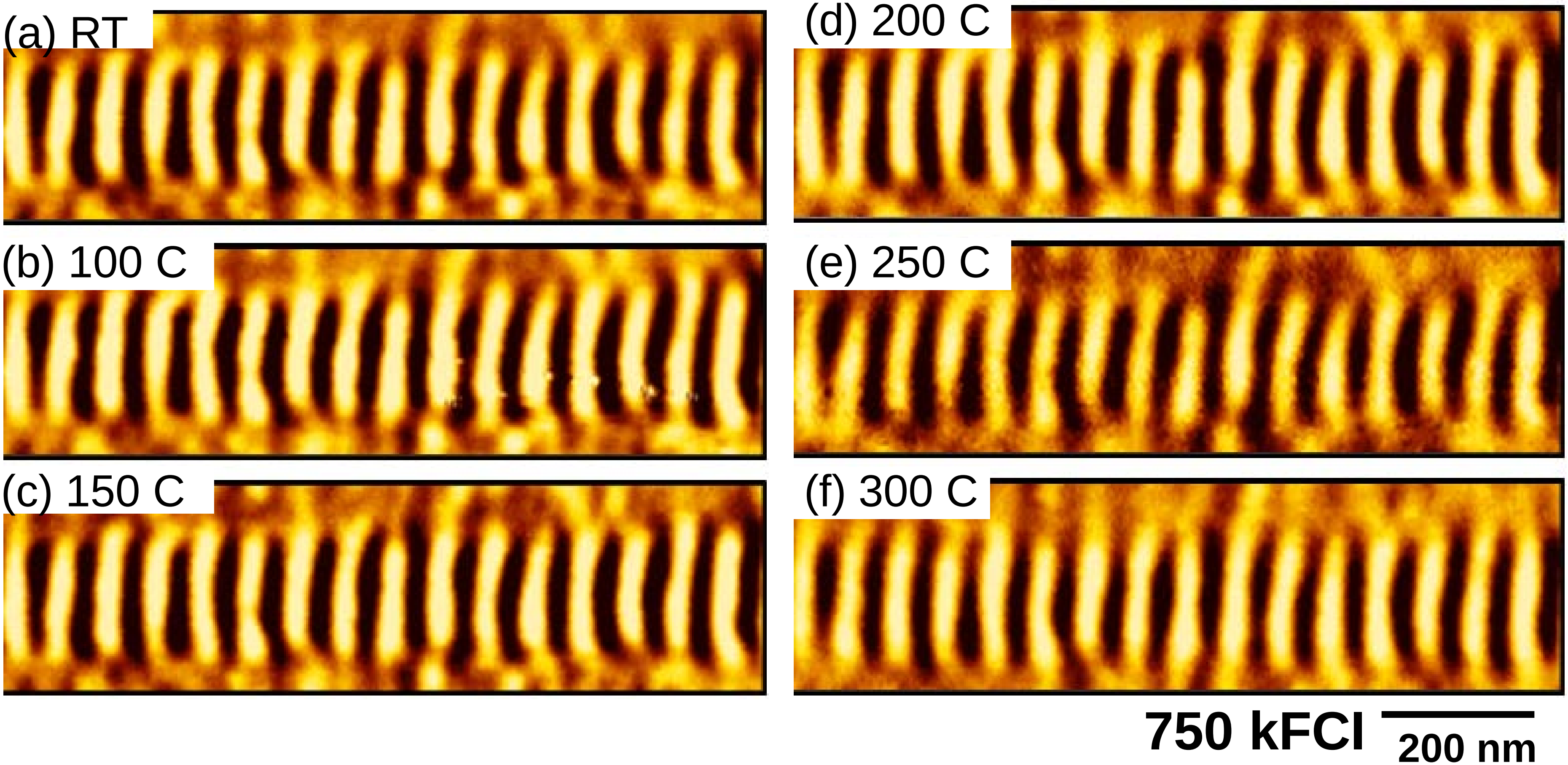
K. Soneta et al., Intermag-2011 (April 28, Taipei), ES-03.

Stability of Recorded Bit Information (Thermal)



300 °C

300

MFM observation

250 °C

200 °C

200

150 °C

100 °C

100

Heating time: 60 min at every temperature

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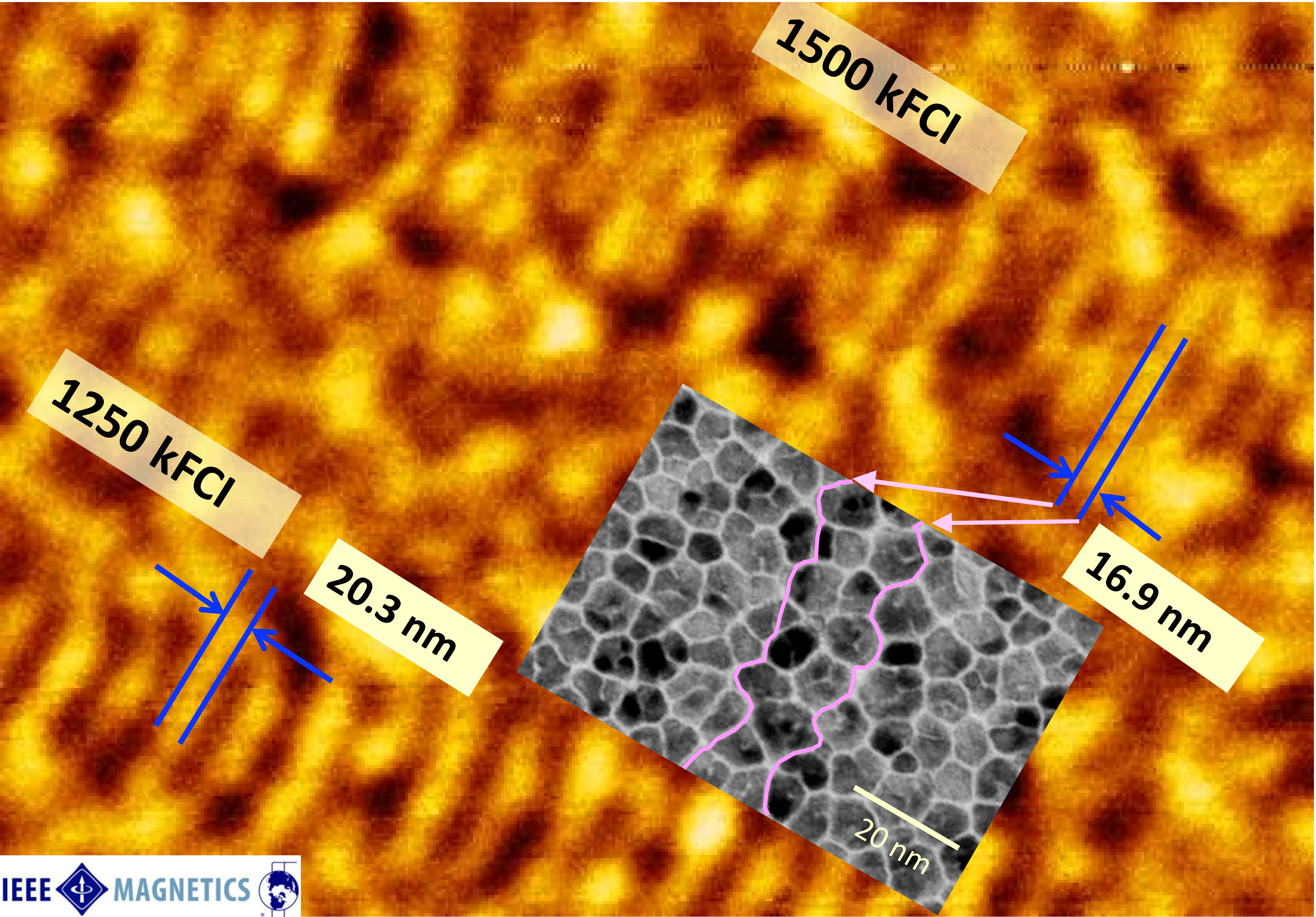
Time

Recording Density Possibility of Current PMR Media



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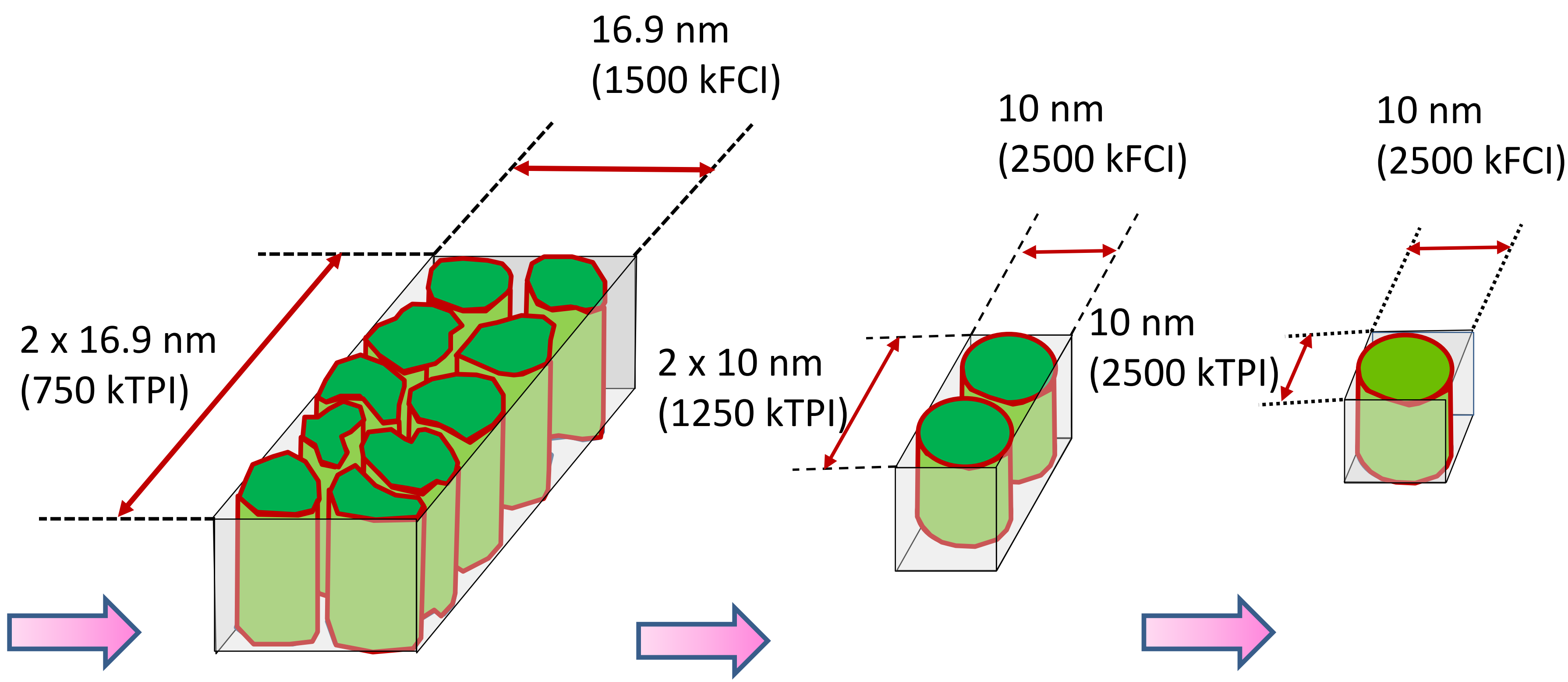
Recording Density Possibility of Future PMR Media



Area density
1.1 Tb/in²

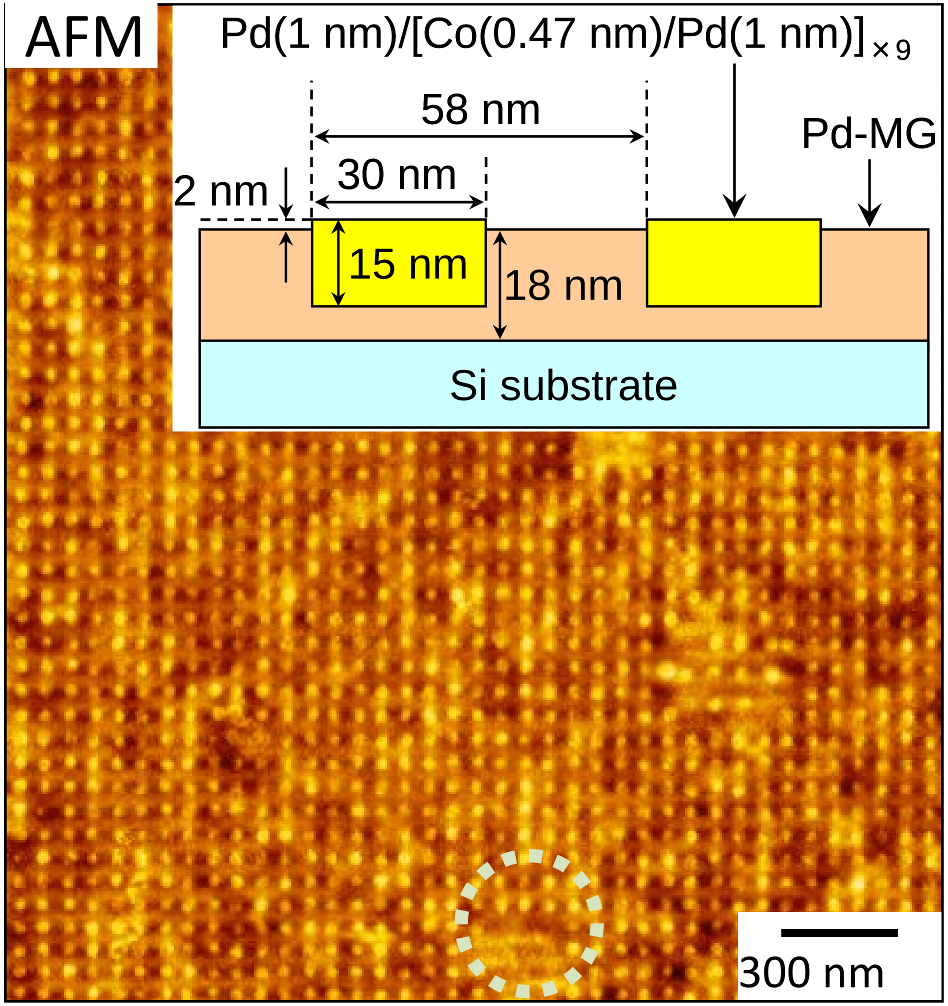
3.1 Tb/in²

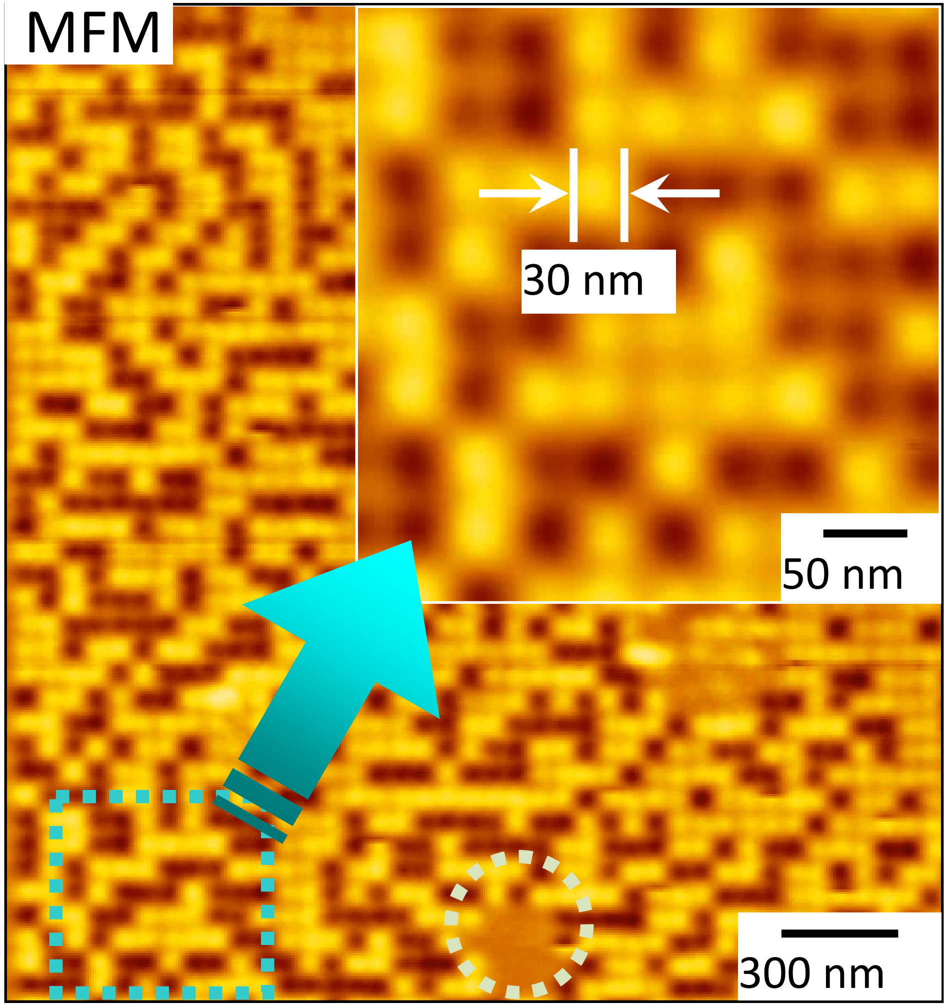
6.3 Tb/in²

Recording Density Possibility of Future PMR Media

Diameter & Position Control : Bit Patterned Media

- Diameter: 30 nm
- Pitch: 58 nm

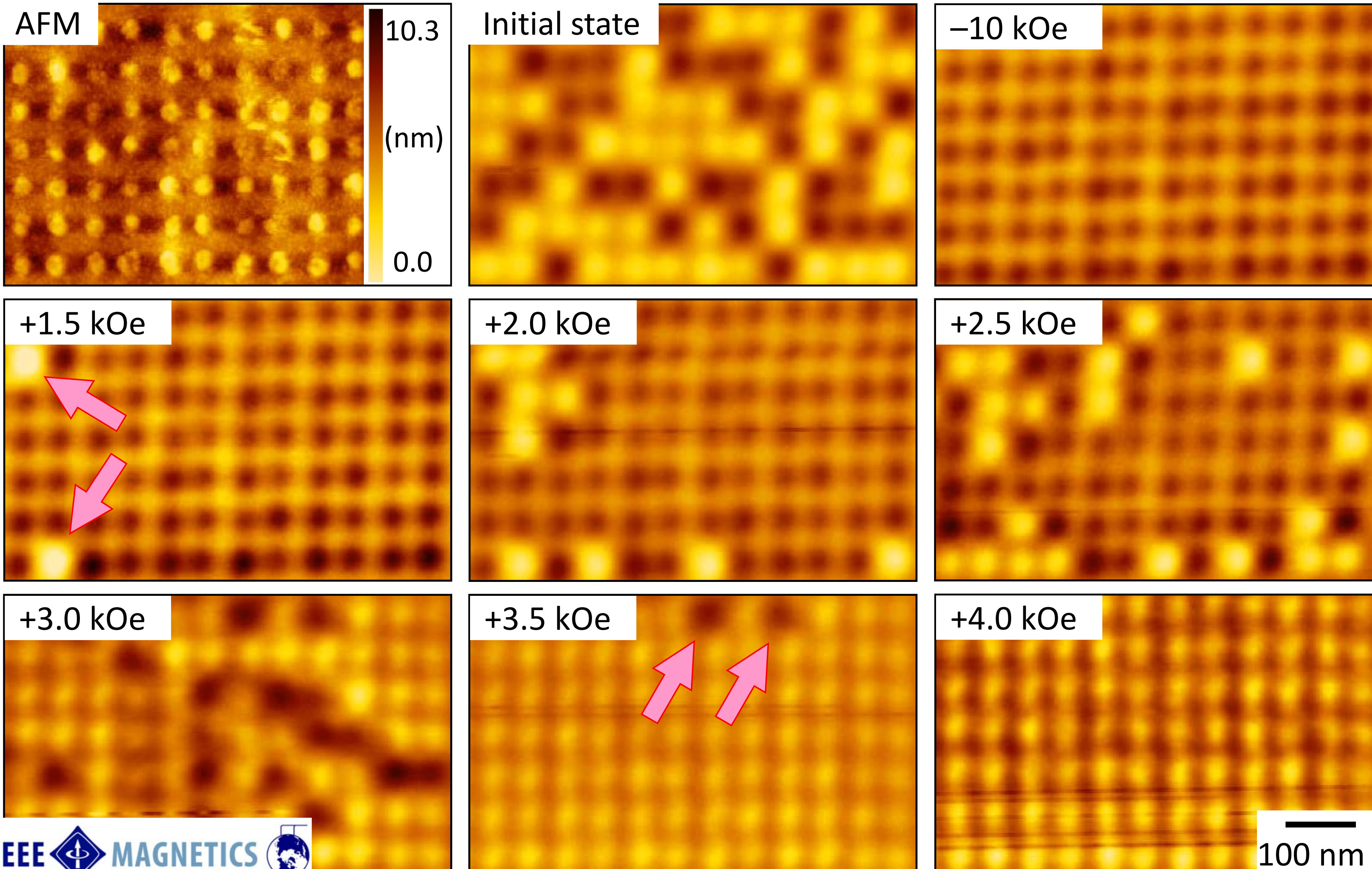




K. Nagano et al., ICAUMS-2010, (Dec. 8, Jeju, Korea) IS-06, IR-14.

Recording Density Possibility of Future PMR Media

Diameter & Position Control : Bit Patterned Media



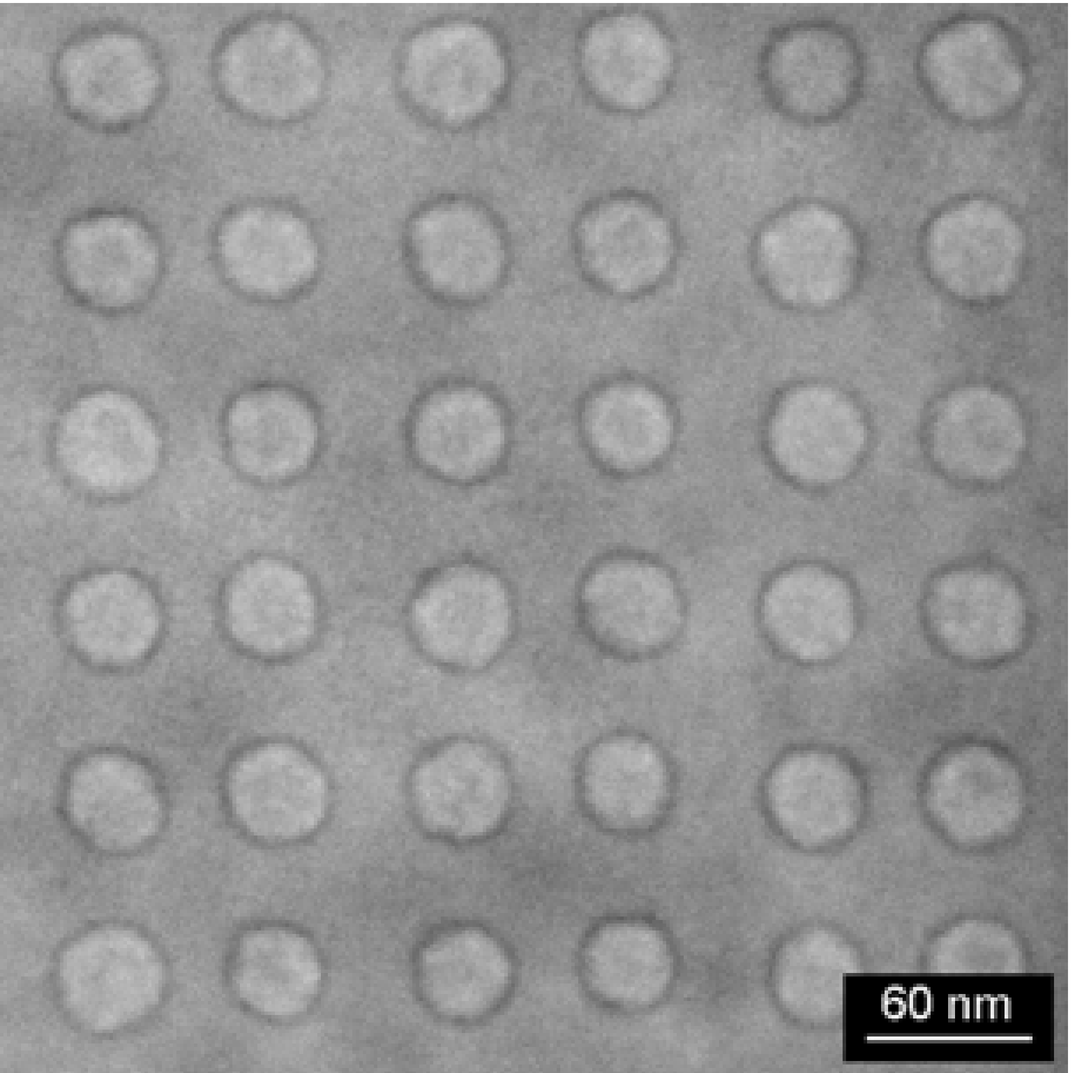
Summary for PMR Media

1. Brief history of PMR research & development
   * Co-alloy media microstructure developments
2. Current PMR Media
   * Nano-crystallographic, nano-compositional, and nano-magnetization structures
3. Future possibilities of PMR Media
   * Up to several Tb/in2 seems feasible

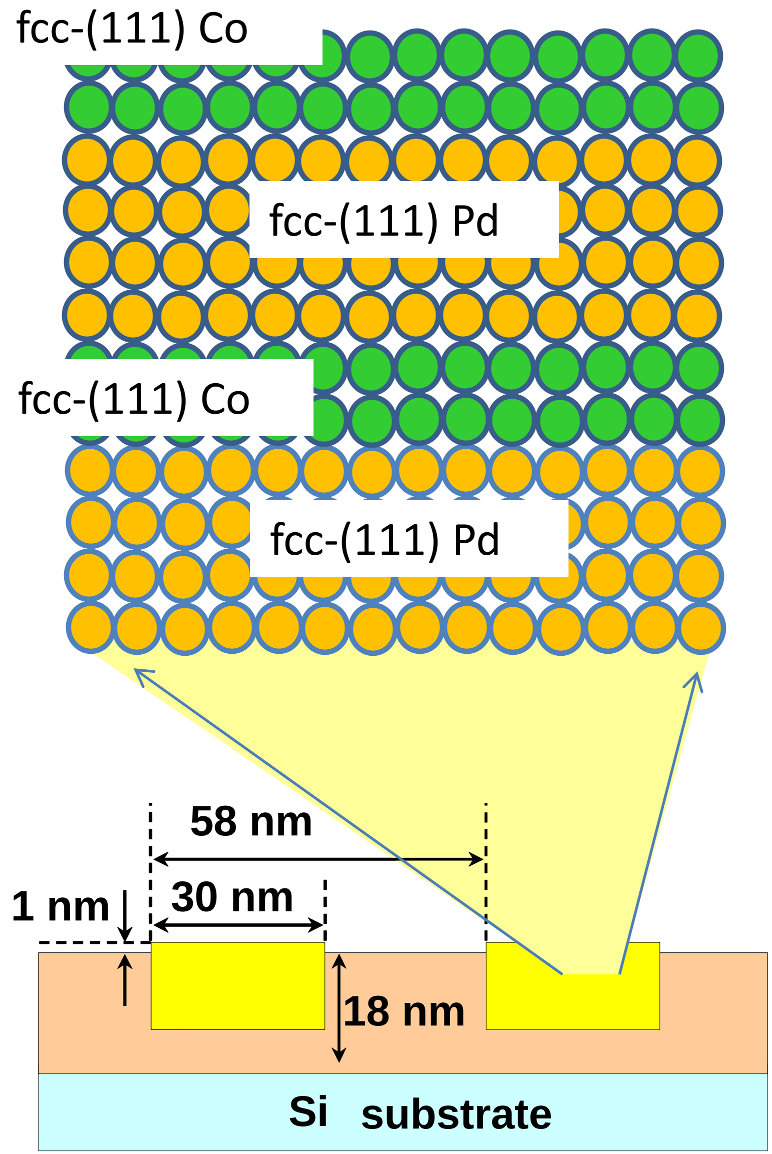
   → Various parameter control required
   * Grain diameter
   * Two-dimensional grain distribution
   * Magnetization switching field distribution, etc.

Structure of Co/Pd multilayer magnetic dots

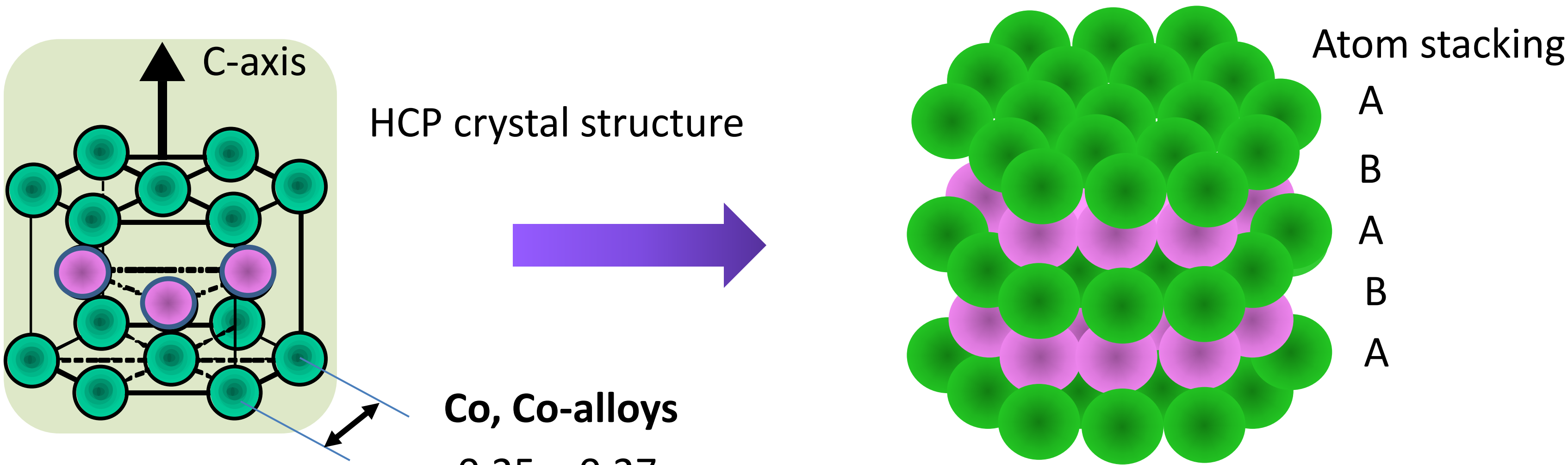
Pd(1 nm)/[Co(0.47 nm)/Pd(1 nm)]x9



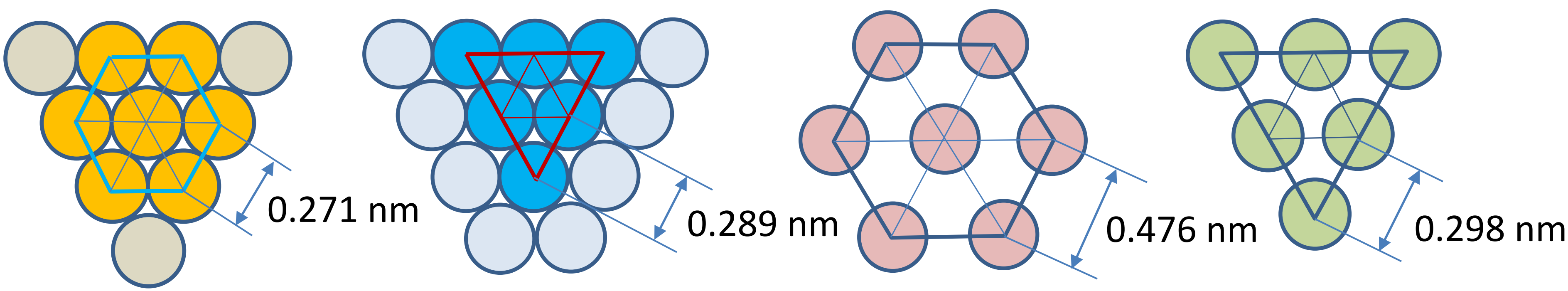
SEM of magnetic dots



Epitaxial Growth of hcp-Co film on underlayers



[Underlayers for hetero-epitaxial growth of Co, Co-alloy crystals]



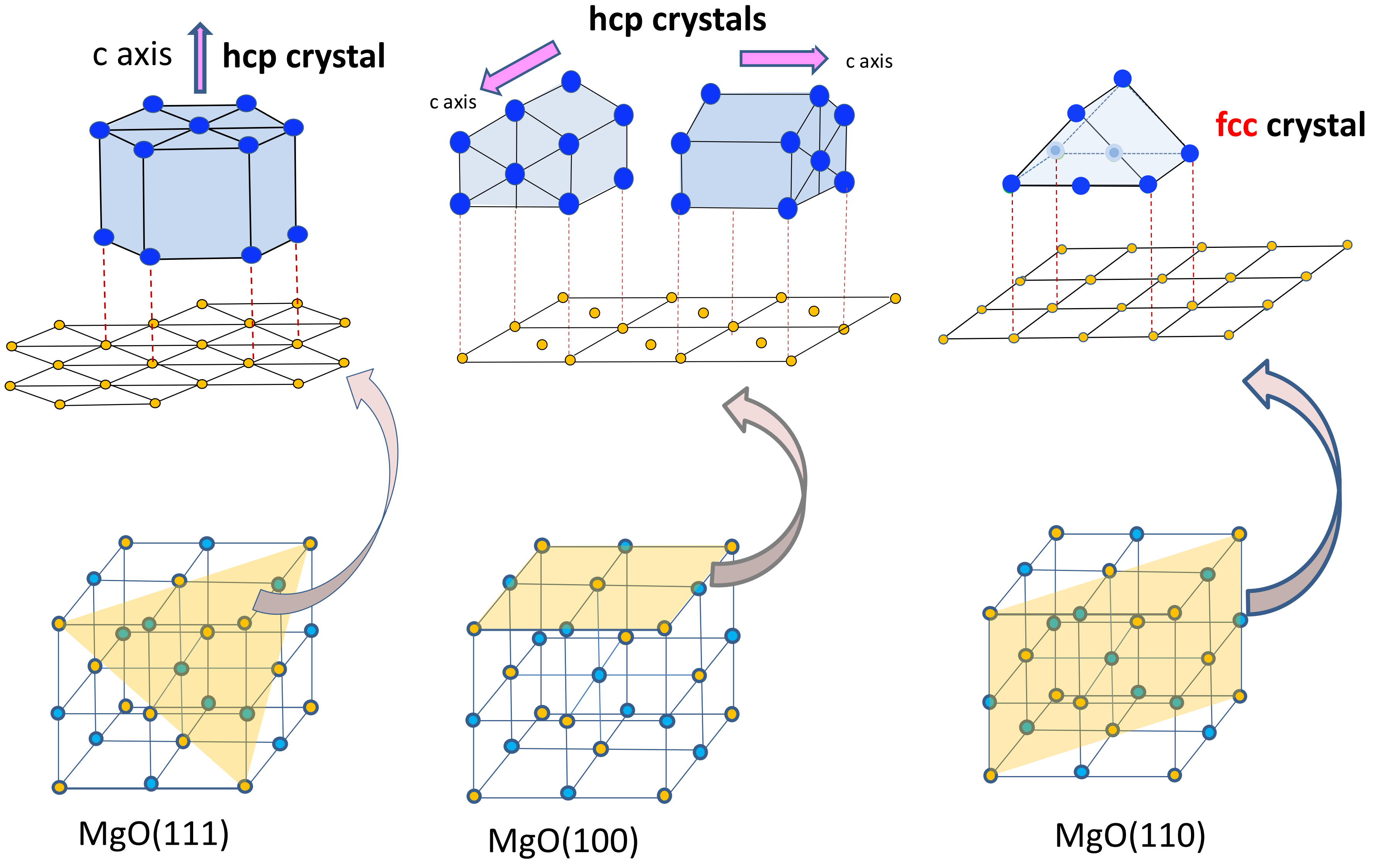
(0001)Ru hcp structure

(111)Ag fcc structure

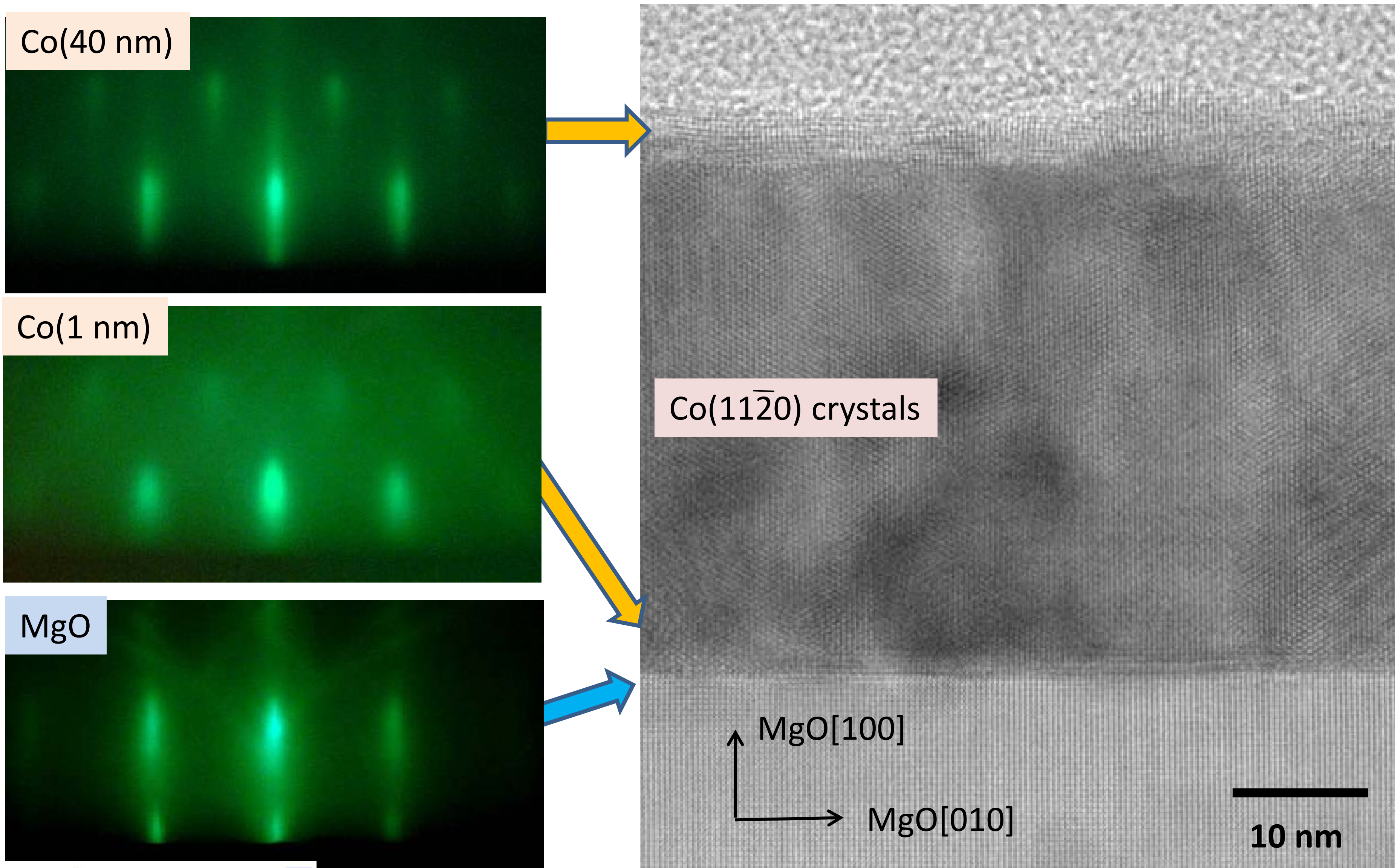
(0001)Al_2O_3 corundum structure

(111)MgO rock salt structure

Epitaxial Growth of Co Film on MgO Crystals

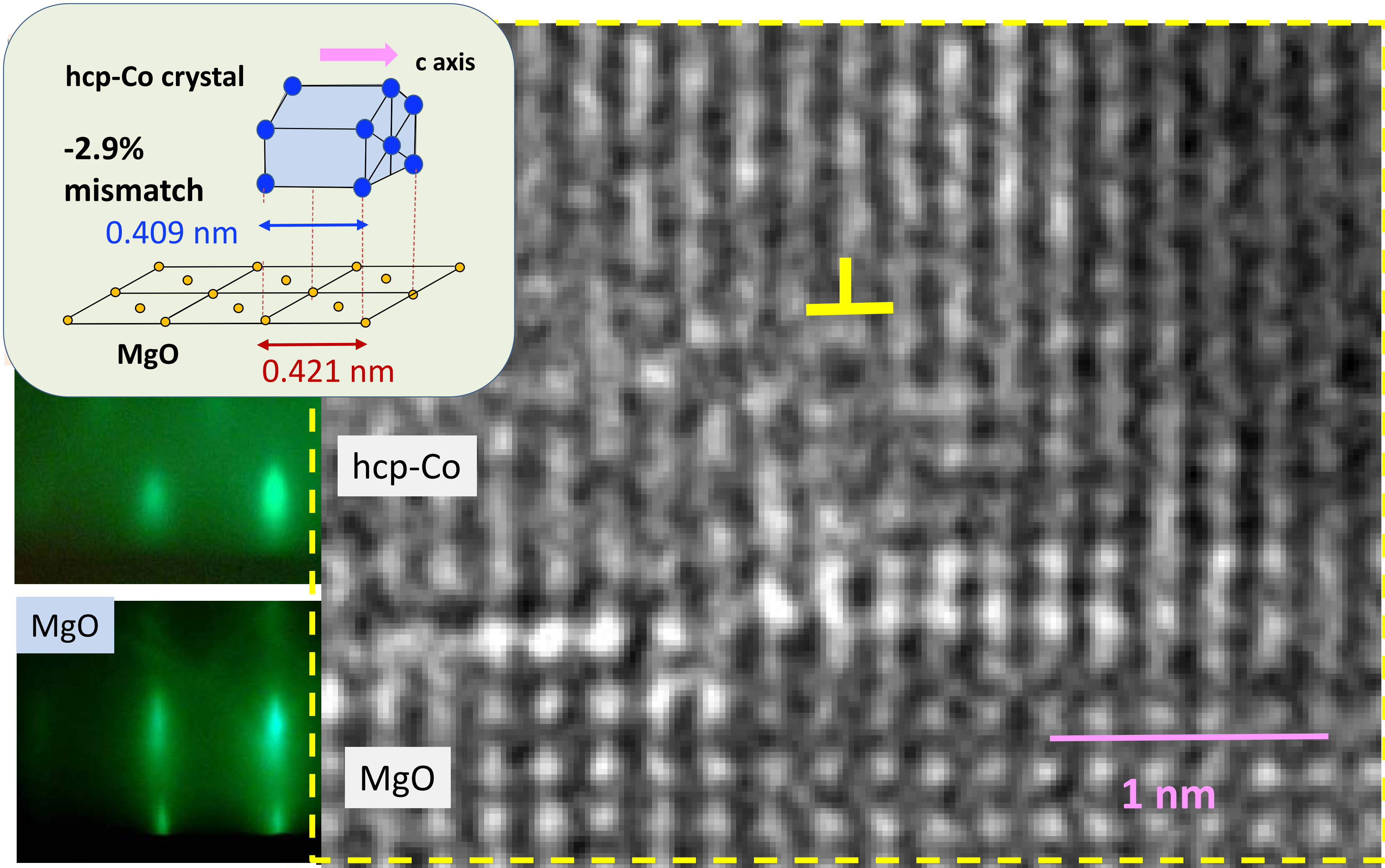


Growth of hcp-Co on MgO(100) Crystal Surface



Y. Nukaga et al., J. Mag. Soc. Japan., 34, 508 (2010).

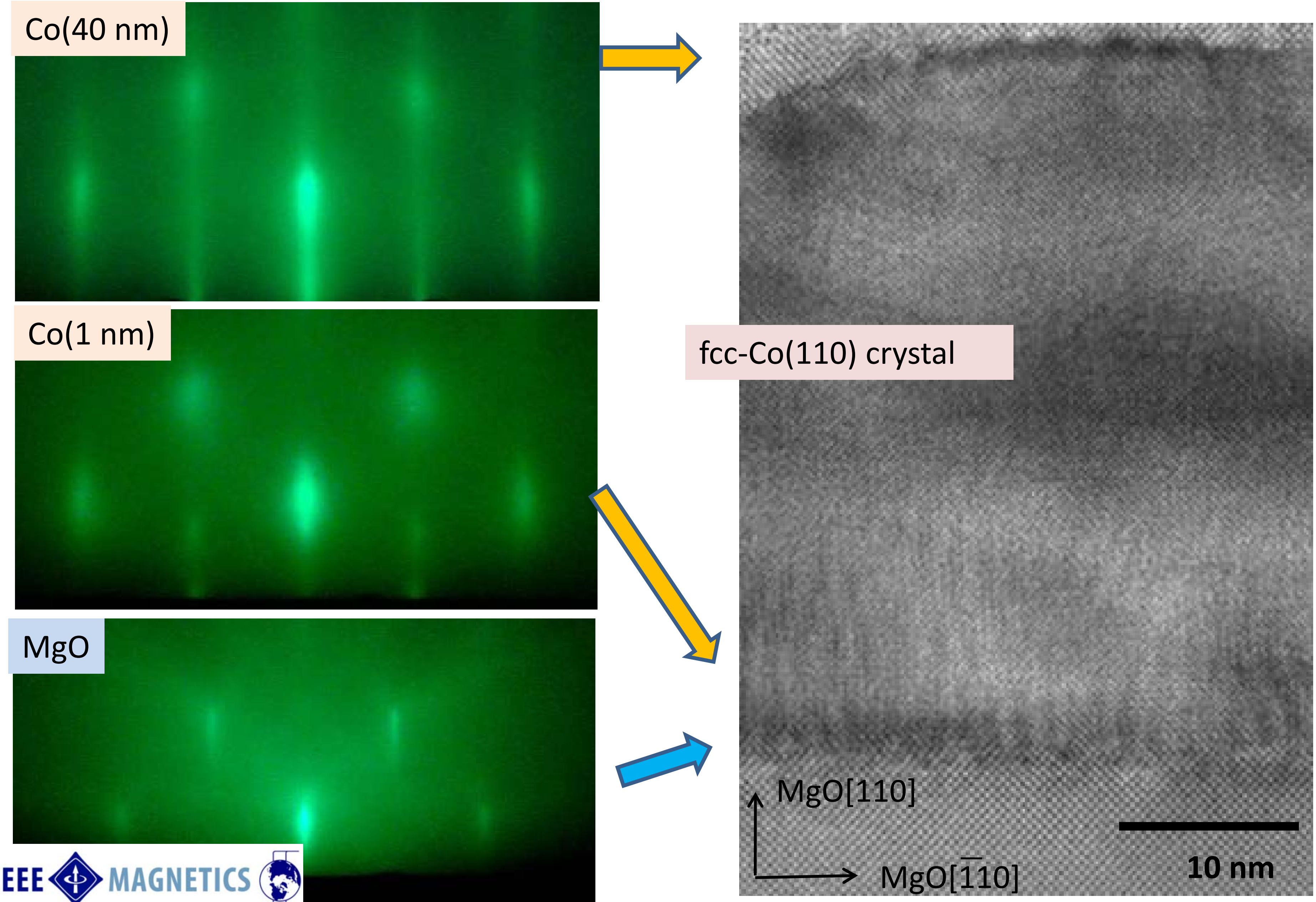
Growth of hcp-Co on MgO(100) Crystal Surface



IEEE MAGNETICS

Y. Nukaga et al., J. Mag. Soc. Japan., 34, 508 (2010).

Growth of fcc-Co on MgO(110) Crystal Surface



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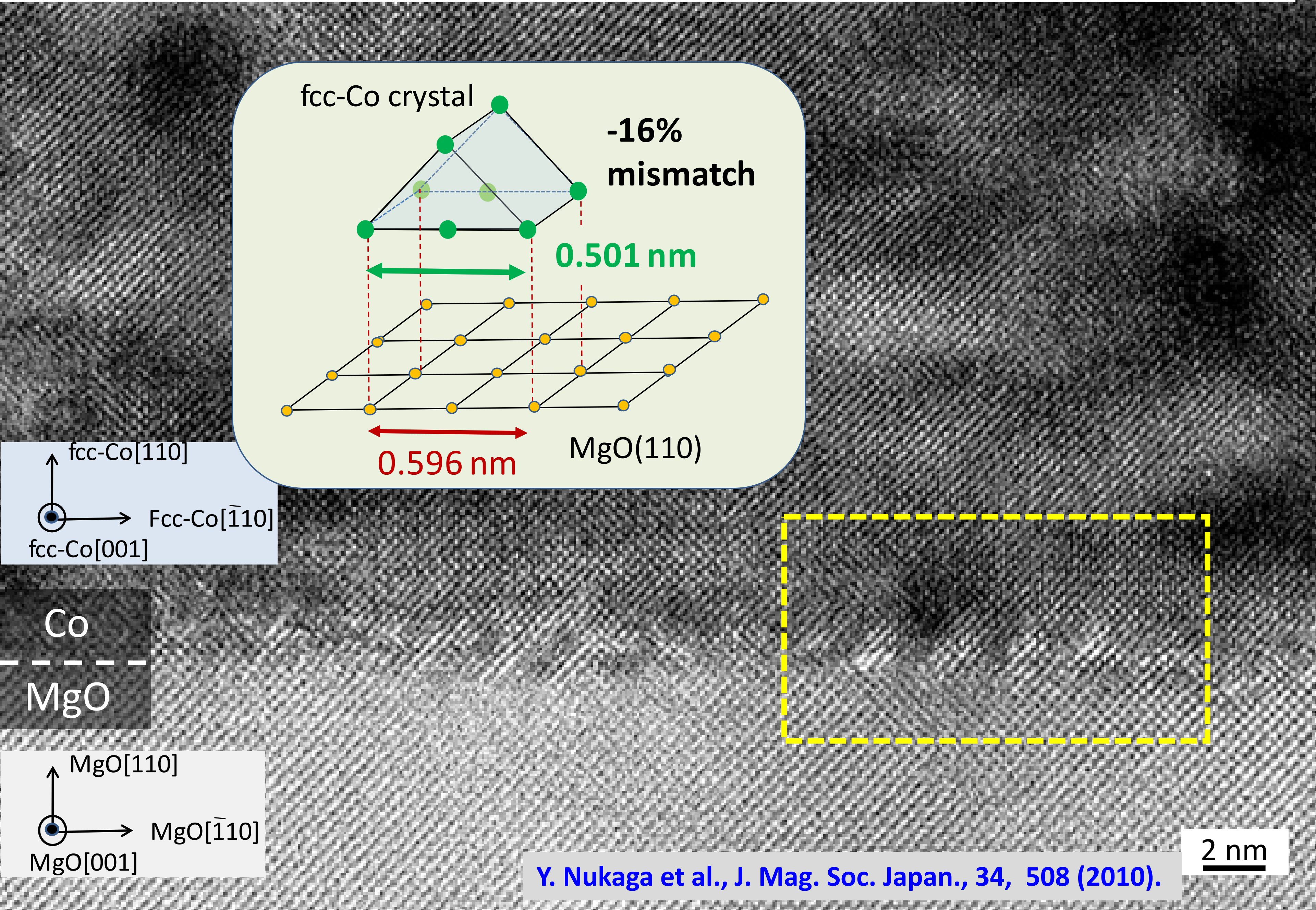
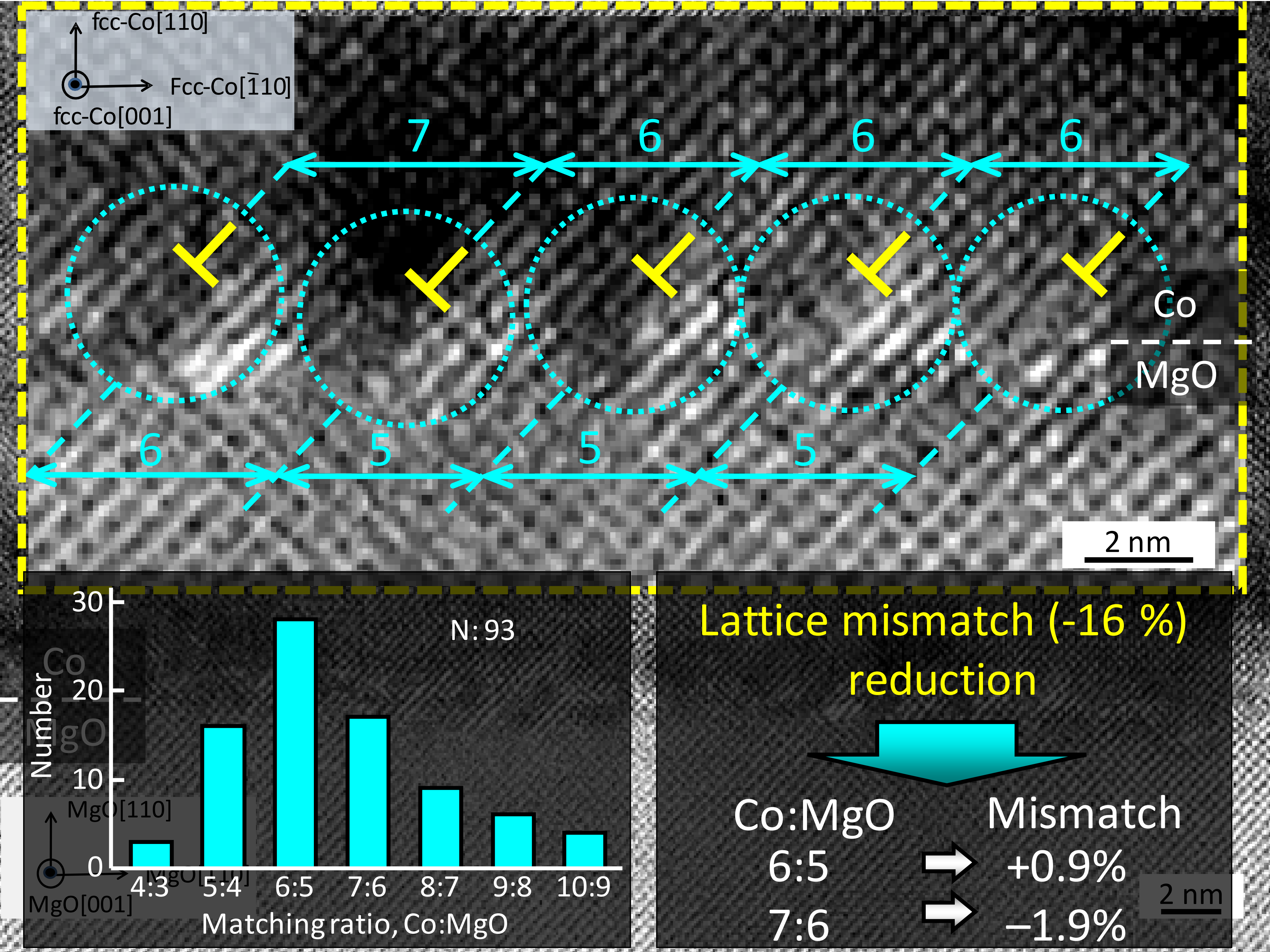
Growth of fcc-Co on MgO(110) Crystal Surface



Y. Nukaga et al., J. Mag. Soc. Japan., 34, 508 (2010).



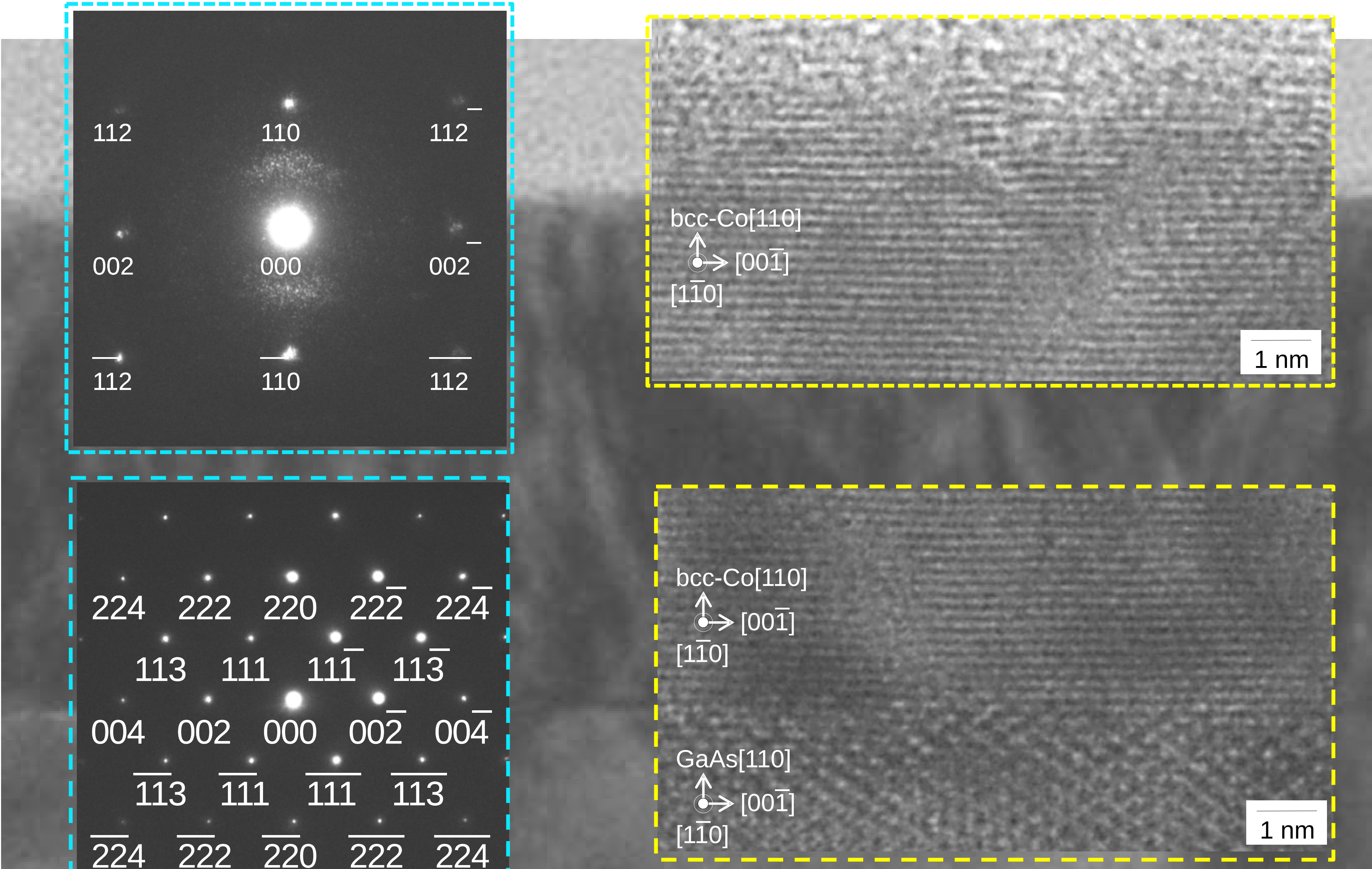
fcc-Co[110]
Fcc-Co[1̄10]
fcc-Co[001]
7
6
6
6
Co
MgO
6
5
5
5
2 nm
30
20
10
0
Number
N: 93
4:3
5:4
6:5
7:6
8:7
9:8
10:9
Matching ratio, Co:MgO
MgO[110]
MgO[001]
Lattice mismatch (-16 %)
reduction
Co:MgO
Mismatch
6:5
+0.9%
7:6
–1.9%
2 nm

Co Film Growth on Different Planes of MgO Crystal

Plane / Temp.	MgO(100)	MgO(110)	MgO(111)
100 °C	hcp-Co(11$\bar{2}$0): -4% + fcc-Co(100):-16%		fcc-Co(111) -16%
300 °C	hcp-Co(11$\bar{2}$0) -4%	fcc-Co(110) -16%	hcp-Co(0001) -16%
500 °C			

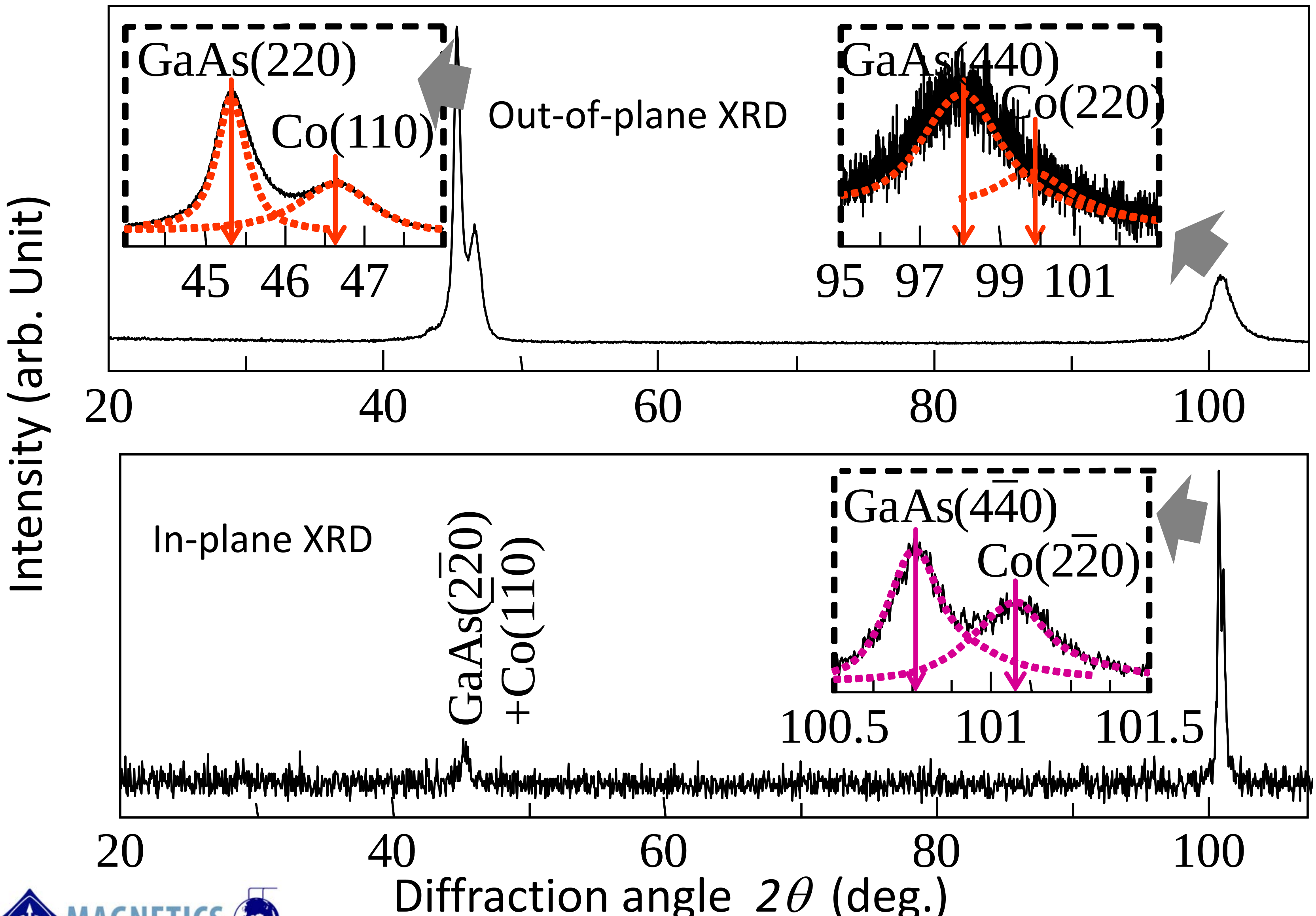
Y. Nukaga et al., J. Mag. Soc. Japan., 34, 508 (2010).

bcc-Co Film Growth by Heteroepitaxy on GaAs(110)



M. Ohtake et al., Appl. Phys. Express, 4, 013006 (2010).

bcc-Co Film Growth by Heteroepitaxy on GaAs(110)



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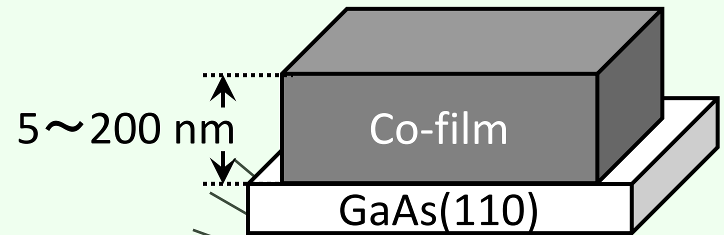
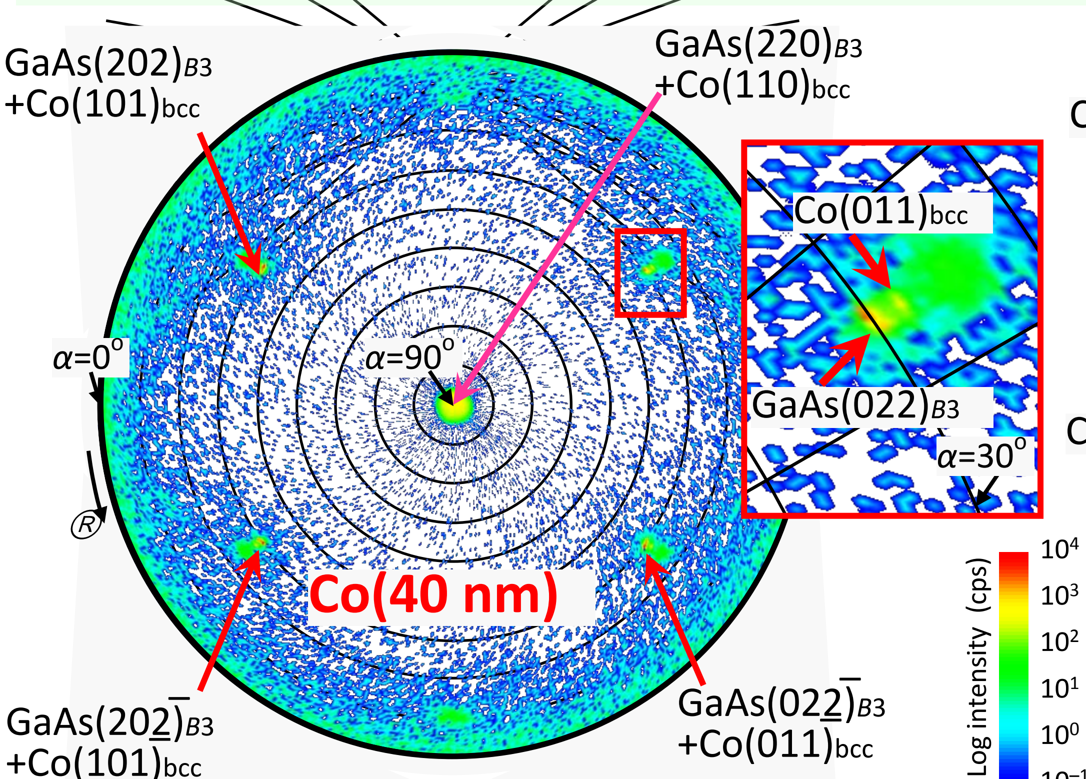
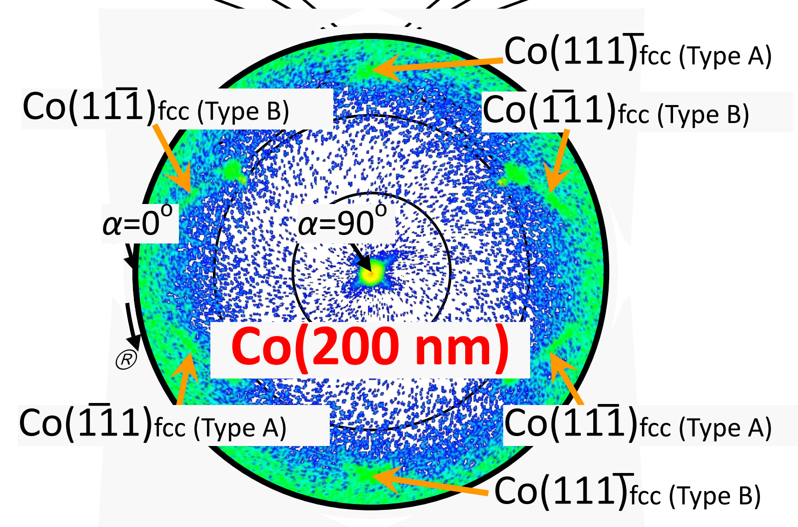
bcc-Co Film Growth by Heteroepitaxy on GaAs(110)

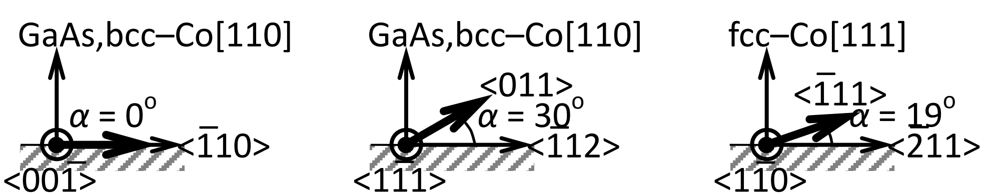
Experimental

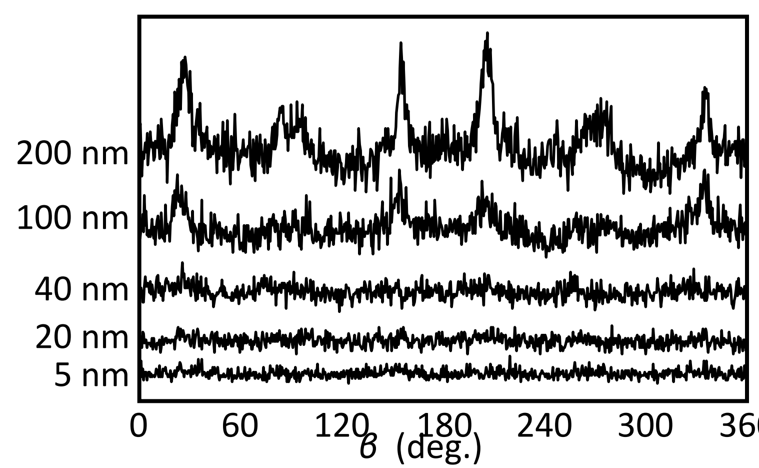
- RF-Magnetron Sputtering
- Substrate Temperature: Room Temperature



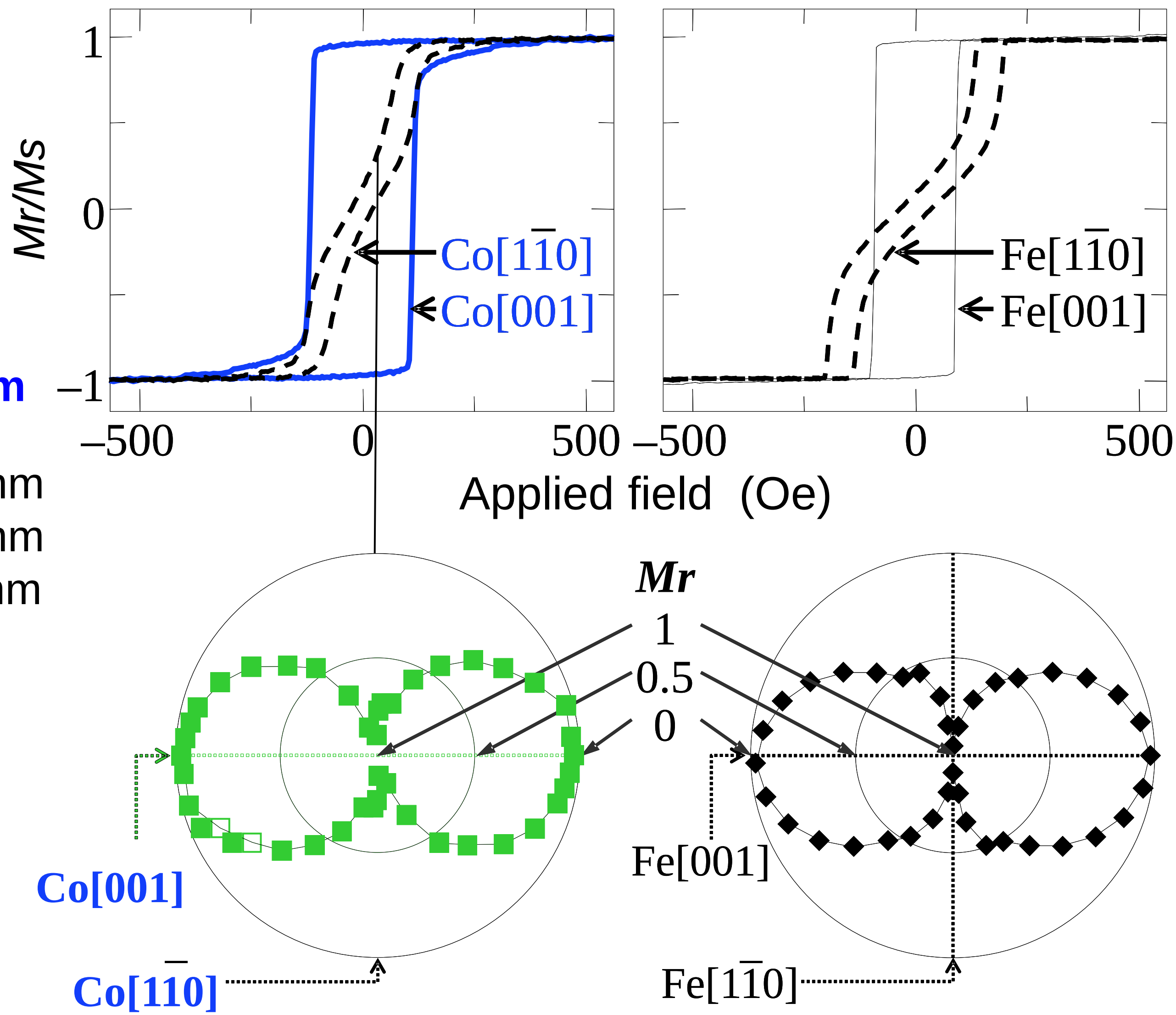








Magnetic Property of bcc-Co Single-Crystal Film



bcc-Co film

a=0.2789 nm
b=0.2789 nm
c=0.2825 nm
c/a=1.013

bcc-Fe

a=b=c
=0.28665 nm
c/a=1.0

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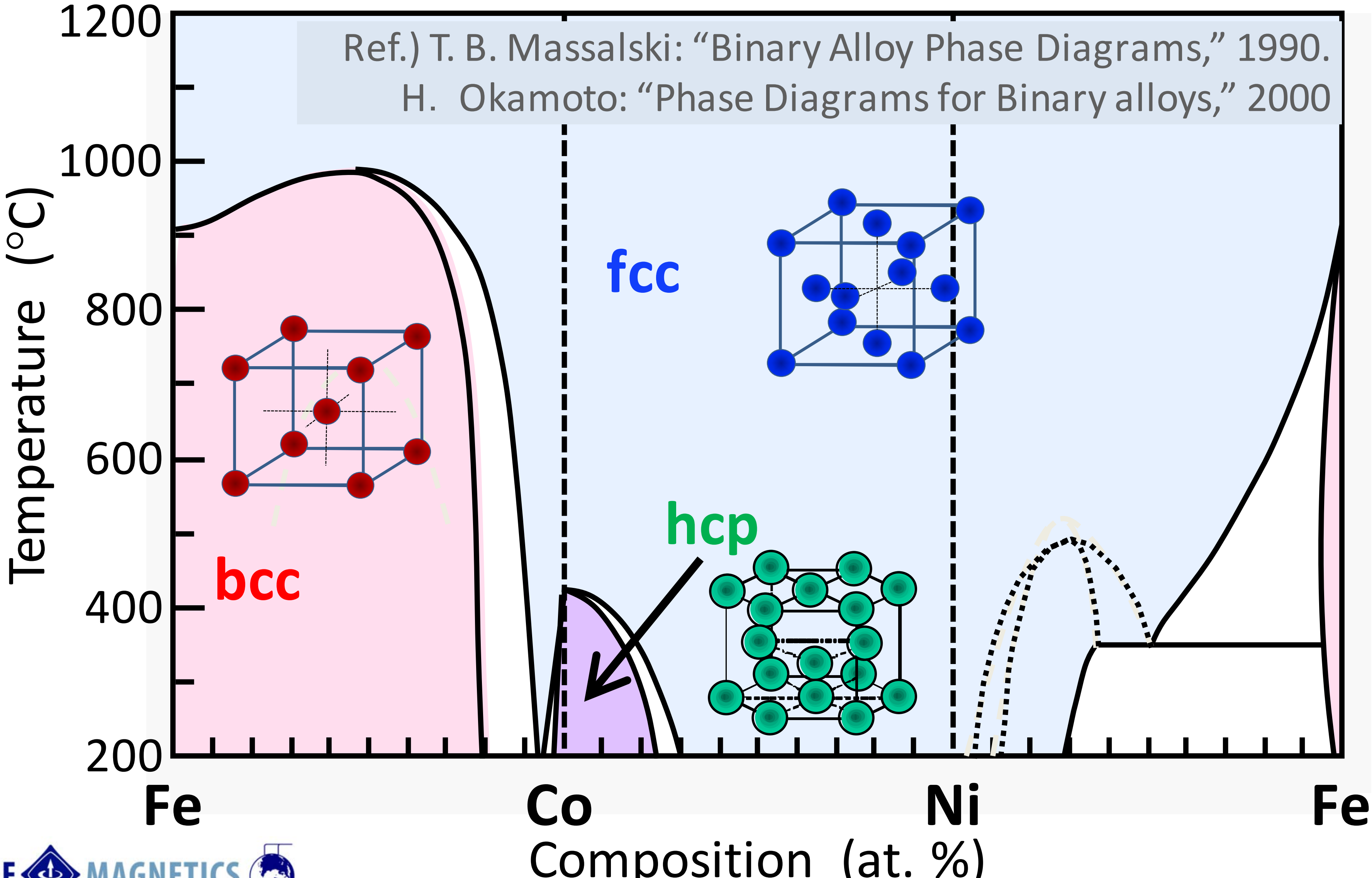
M. Ohtake et al., Appl. Phys. Express, 4, 013006 (2010).

Binary Alloy Phase Diagrams: Fe, Co, Ni Systems



Thin Film Growth of Co-Ni, Ni-Fe, Fe-Co on MgO

>>MgO(100)

<table>
<tr><th>Temp.</th><th>Co</th><th>Co$_{80}$Ni$_{20}$</th><th>Co$_{20}$Ni$_{80}$</th><th>Ni</th><th>Ni$_{80}$Fe$_{20}$</th><th>Ni$_{20}$Fe$_{80}$</th><th>Fe</th><th>Fe$_{65}$Co$_{35}$</th><th>Fe$_{50}$Co$_{50}$</th></tr>
<tr><td>100 °C</td><td></td><td colspan="4" rowspan="3">hcp(11$\bar{2}$0) + fcc(100)
−16%</td><td colspan="4" rowspan="3">bcc(100): −4%</td></tr>
<tr><td>300 °C</td><td rowspan="2">hcp(11$\bar{2}$0)
−4%</td></tr>
<tr><td>500 °C</td></tr>
</table>

>> MgO(110)

<table>
<tr><th>Temp.</th><th>Co</th><th>Co$_{80}$Ni$_{20}$</th><th>Co$_{20}$Ni$_{80}$</th><th>Ni</th><th>Ni$_{80}$Fe$_{20}$</th><th>Ni$_{20}$Fe$_{80}$</th><th>Fe</th><th>Fe$_{65}$Co$_{35}$</th><th>Fe$_{50}$Co$_{50}$</th></tr>
<tr><td>100 °C</td><td colspan="5" rowspan="3">fcc(110): −16%</td><td colspan="4" rowspan="3">bcc(211): −17%</td></tr>
<tr><td>300 °C</td></tr>
<tr><td>500 °C</td></tr>
</table>

>> MgO(111)

<table>
<tr><th>Temp.</th><th>Co</th><th>Co$_{80}$Ni$_{20}$</th><th>Co$_{20}$Ni$_{80}$</th><th>Ni</th><th>Ni$_{80}$Fe$_{20}$</th><th>Ni$_{20}$Fe$_{80}$</th><th>Fe</th><th>Fe$_{65}$Co$_{35}$</th><th>Fe$_{50}$Co$_{50}$</th></tr>
<tr><td>100 °C</td><td></td><td></td><td colspan="3" rowspan="3">fcc(111): −16%</td><td></td><td colspan="3" rowspan="3">bcc(110): −22%</td></tr>
<tr><td>300 °C</td><td rowspan="2">hcp(0001)
−16%</td><td rowspan="2">hcp(0001)
fcc(111)</td><td></td></tr>
<tr><td>500 °C</td><td>fcc(111)
bcc(110)</td></tr>
</table>

Thin Film Growth of Co, Ni, Fe on fcc Noble Metals

>> Au, Ag, Cu(100)

<table>
<tr><th></th><th colspan="3">Co</th><th colspan="3">Ni</th><th colspan="3">Fe</th></tr>
<tr><td>Temp.</td><td>Au</td><td>Ag</td><td>Cu</td><td>Au</td><td>Ag</td><td>Cu</td><td>Au</td><td>Ag</td><td>Cu</td></tr>
<tr><td>100 °C</td><td>hcp($11\bar{2}0$)</td><td colspan="2" rowspan="2">fcc(100)</td><td>hcp($11\bar{2}0$)</td><td colspan="2" rowspan="2">fcc(100)</td><td colspan="3" rowspan="2">bcc(100)</td></tr>
<tr><td>300 °C</td><td>hcp($11\bar{2}0$)
fcc(100)</td><td>hcp($11\bar{2}0$)
fcc(100)</td></tr>
</table>

>> Au, Ag, Cu(110)

<table>
<tr><th></th><th colspan="3">Co</th><th colspan="3">Ni</th><th colspan="3">Fe</th></tr>
<tr><td>Temp.</td><td>Au</td><td>Ag</td><td>Cu</td><td>Au</td><td>Ag</td><td>Cu</td><td>Au</td><td>Ag</td><td>Cu</td></tr>
<tr><td>100 °C</td><td>hcp($1\bar{1}00$)</td><td colspan="5" rowspan="2">fcc(110)</td><td colspan="3" rowspan="2">bcc(211)</td></tr>
<tr><td>300 °C</td><td></td></tr>
</table>

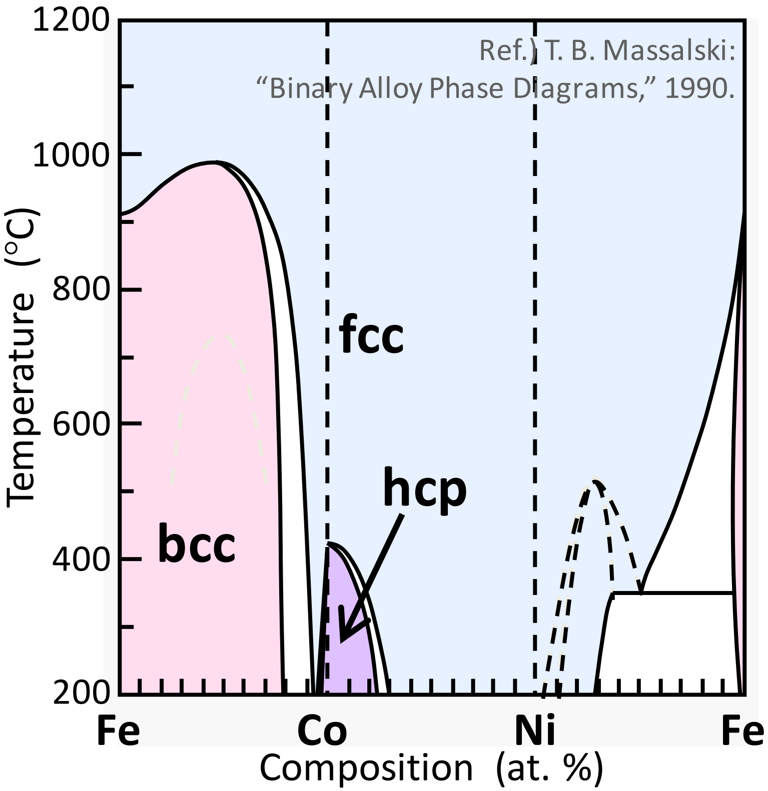
>> Au, Ag, Cu(111)

<table>
<tr><th></th><th colspan="3">Co</th><th colspan="3">Ni</th><th colspan="3">Fe</th></tr>
<tr><td>Temp.</td><td>Au</td><td>Ag</td><td>Cu</td><td>Au</td><td>Ag</td><td>Cu</td><td>Au</td><td>Ag</td><td>Cu</td></tr>
<tr><td>100 °C</td><td>hcp(0001)
fcc(111)</td><td></td><td>hcp(0001)
fcc(111)</td><td colspan="3" rowspan="2">fcc(111)</td><td colspan="3" rowspan="2">bcc(110)</td></tr>
<tr><td>300 °C</td><td colspan="2">hcp(0001)</td><td></td></tr>
</table>

Structure Control of Co Films by Heteroepitaxy (I)

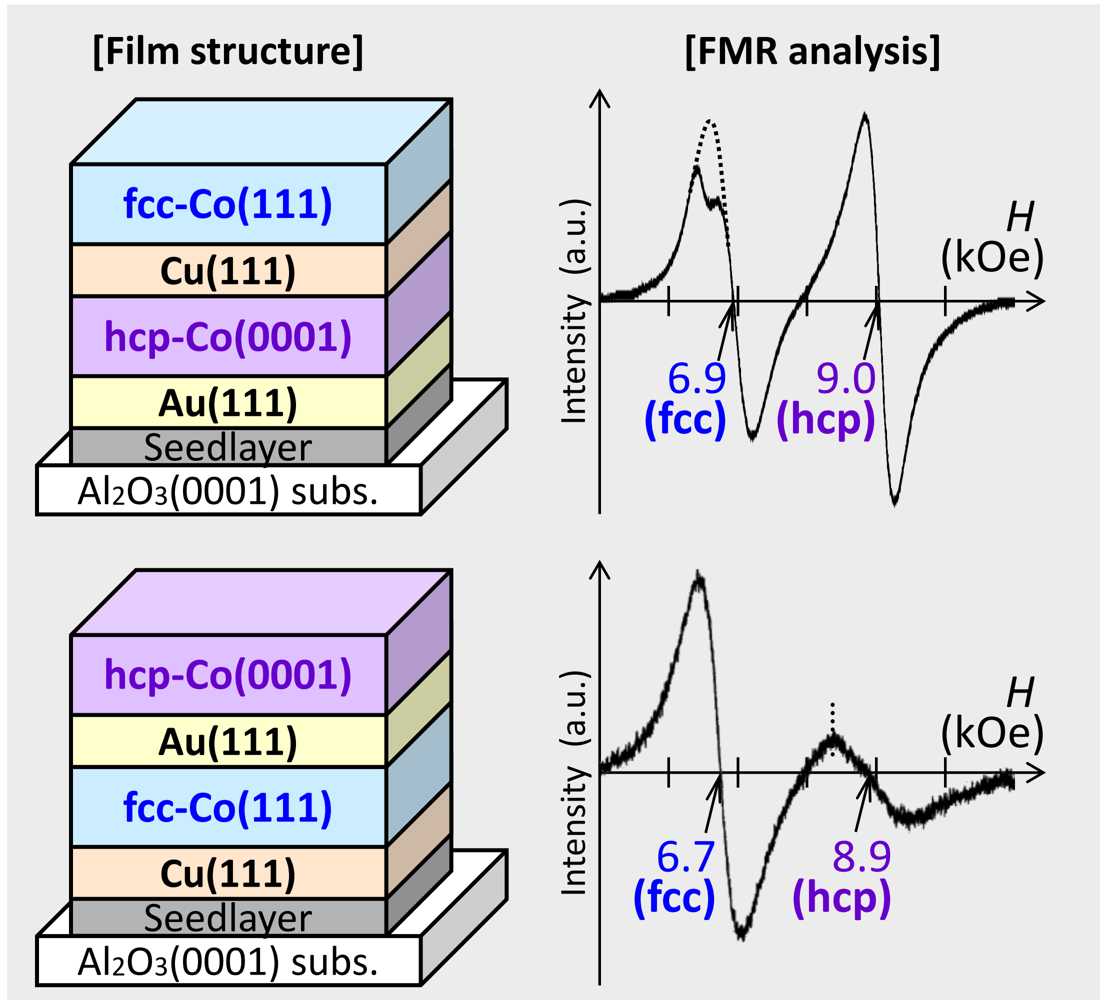
	Co		
Temp.	Au(111)	Ag(111)	Cu(111)
100 ℃	hcp(0001) fcc(111)		hcp(0001) fcc(111)
300 ℃	hcp(0001)		fcc(111)

[Bulk Binary-alloy Phase Diagram]



fcc
(K_1: 6×10^5 erg/cm^3)

hcp
(K_u: 5×10^6 erg/cm^3)



Summary

1. Epitaxial film growth is a very important technology in controlling the film nanostructure

2. Proper selection of underlayer material and deposition condition will make it possible to control the crystal structure, orientation, strain, stress, etc. in magnetic thin films.

3. Magnetic thin films with meta-stable structures are one of the hopeful possibilities in the future development of magnetic devices