XMCDを用いた磁性薄膜の研究

藤森　淳

（東京大学理学系研究科）

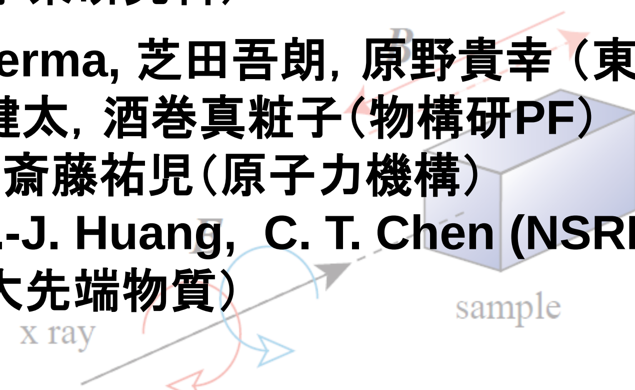
門野利治, V. R. Singh, 石上啓介, V. K. Verma, 芝田吾朗, 原野貴幸（東大理）

PF BL-16A2: 小出常晴，朝倉大輔，雨宮健太，酒巻真粧子（物構研PF）

SPring8 BL23-SU: 竹田幸治，岡根哲夫，斎藤祐児（原子力機構）

TLS BL-11A1: F. H. Chang, H.-J. Lin, D.-J. Huang, C. T. Chen (NSRRC, Taiwan)

多重項計算，クラスター計算: 田中 新（広大先端物質）

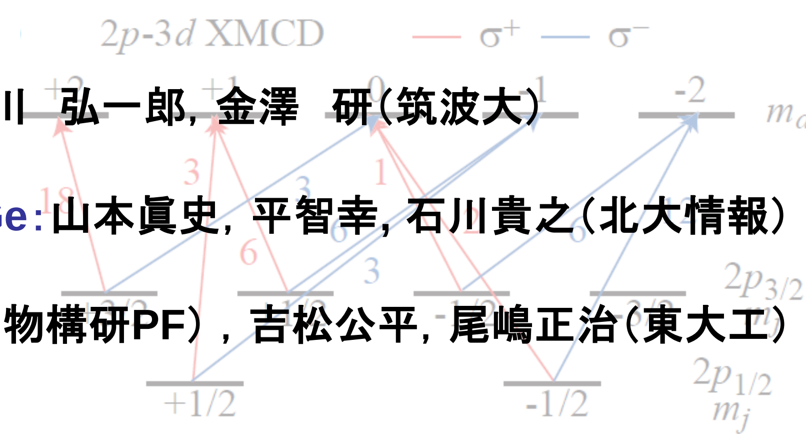


概要

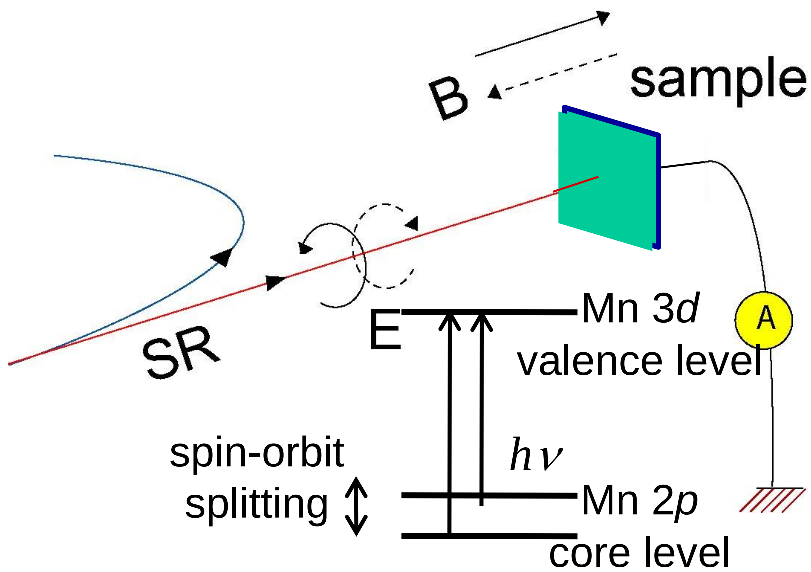
- 測定原理，特徴
- ー希薄磁性半導体薄膜
  - Crドープ$Cd_{1-x}Mn_xTe$: 黒田眞司，石川　弘一郎，金澤　研（筑波大）

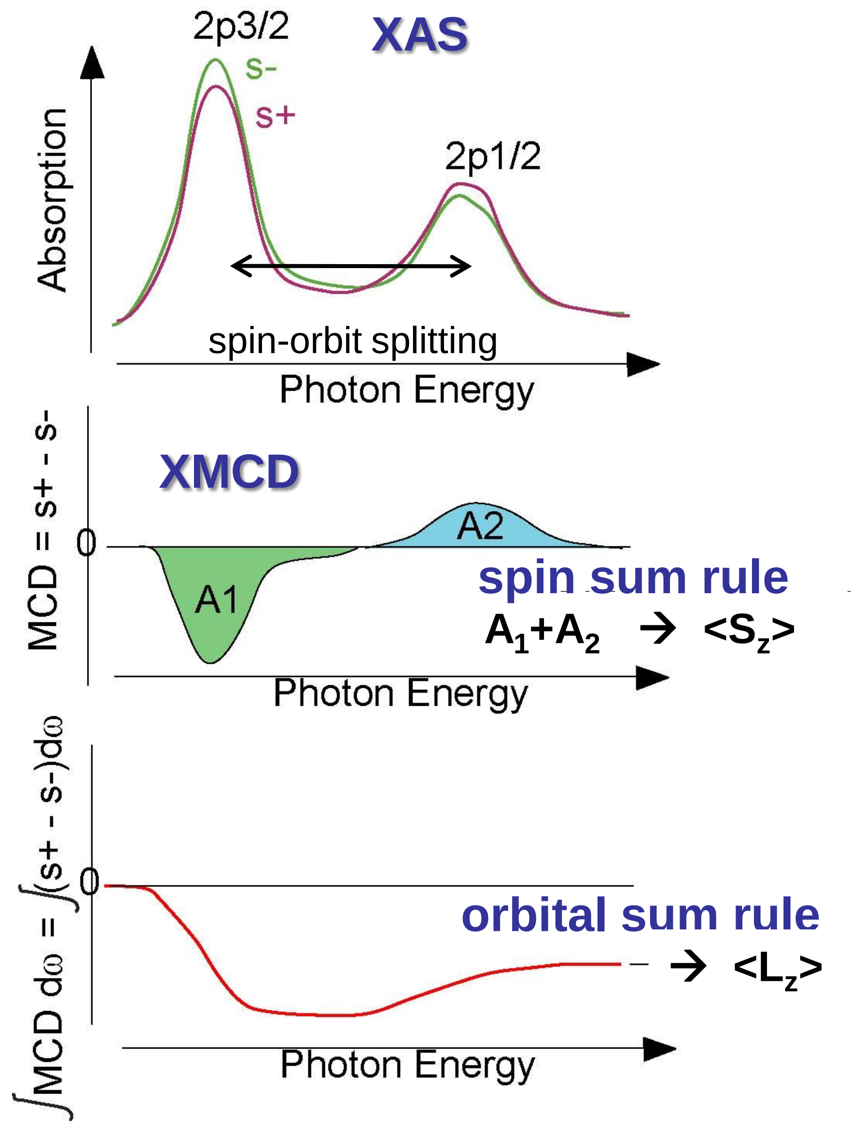
  ー磁気トンネル結合界面
  - ホイスラー$Co_2MnGe/MgO/Co_2MnGe$：山本眞史，平智幸，石川貴之（北大情報）

  ー酸化物薄膜
  - $SrRuO_3$, $La_{1-x}Sr_xMnO_3$：組頭広志（物構研PF），吉松公平，尾嶋正治（東大工）
- 今後の展望



X-ray magnetic circular dichroism (XMCD) in core-level x-ray absorption spectroscopy (XAS)





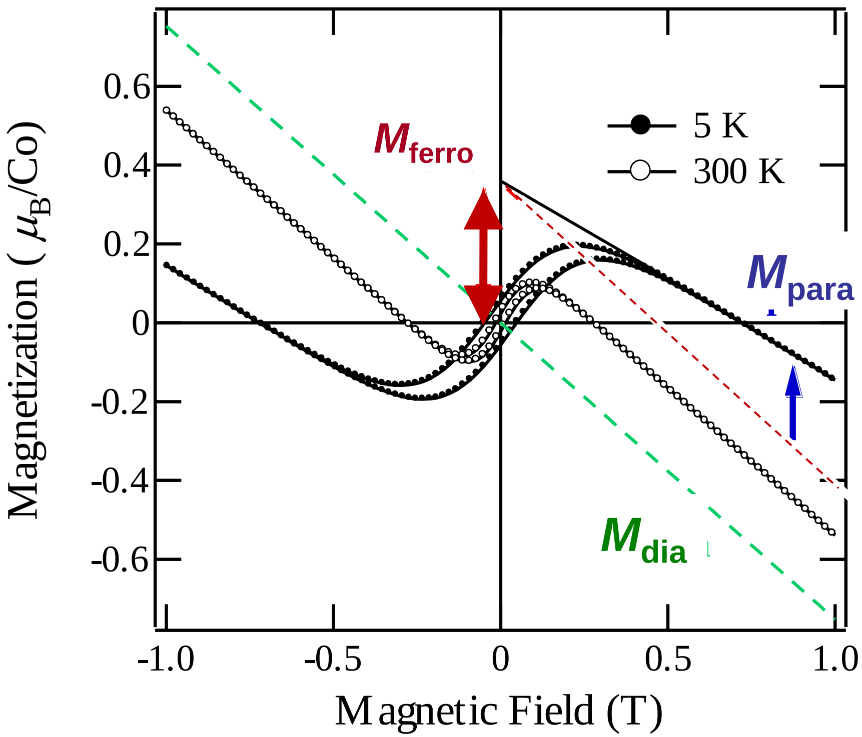
- **Element-specific**
- **Chemical state-selective**
- **Magnetism-selective**

B. T. Thole et al., PRL '01, P. Carra et al., PRL '93

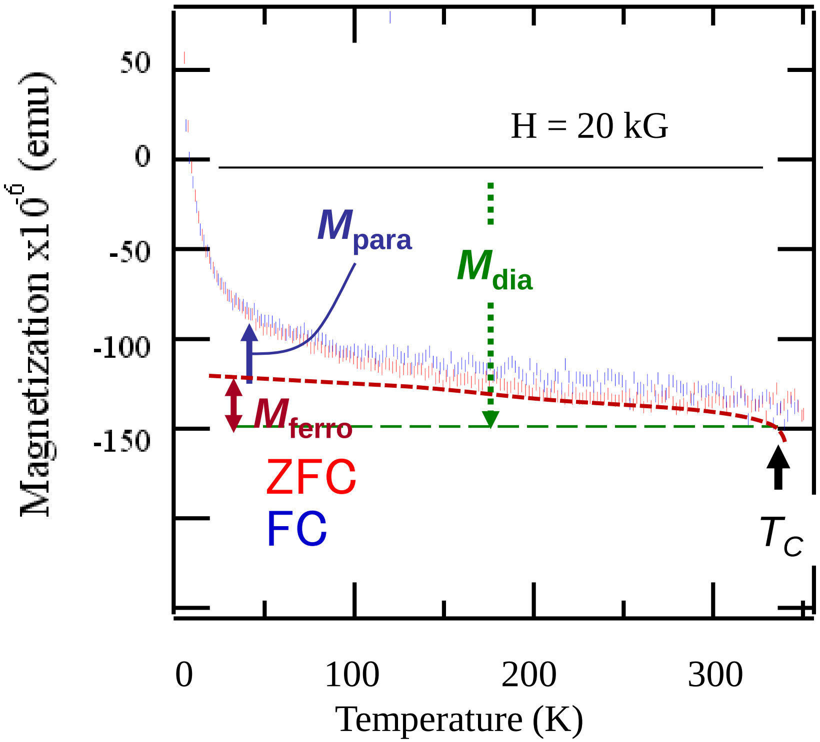
Ferromagnetic and paramagnetic components in magnetization and XMCD signals

SQUID data of thin film sample

M-H curve



M-T curve

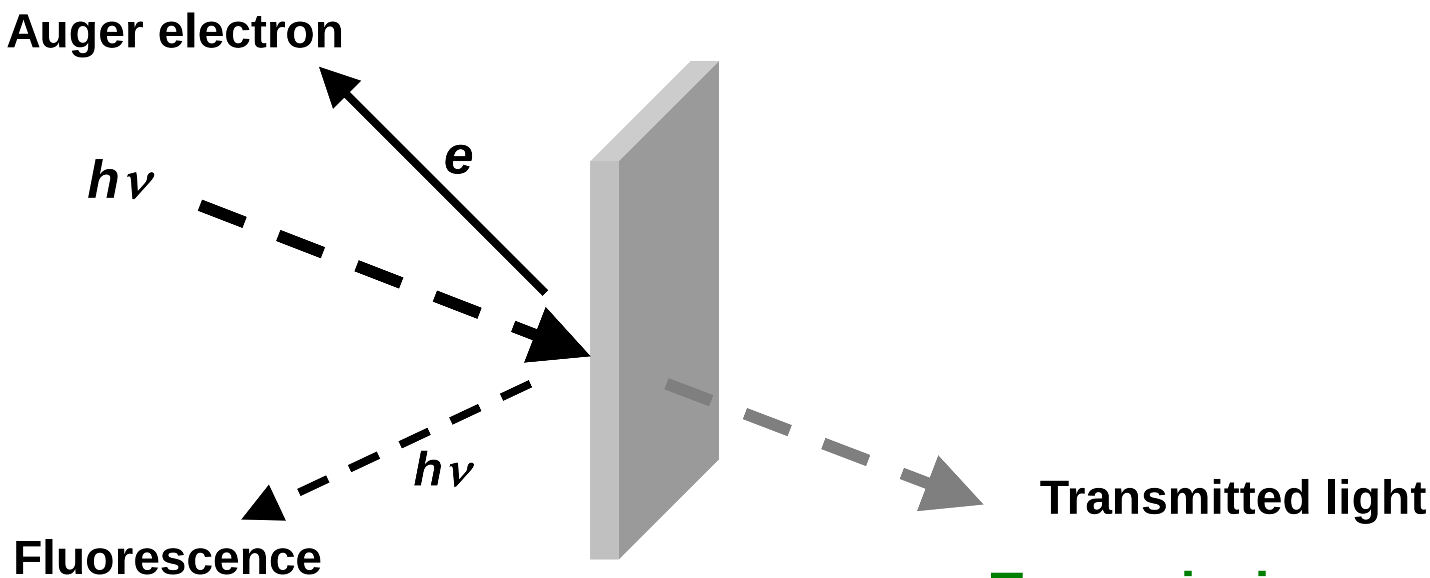


$M = M_{dia} + M_{ferro} + M_{para}$ → XMCD signals

Surface- and bulk-sensitive detection modes of XAS and XMCD measurements

Total electron yield (TEY) mode

probing depth ~ 3-5nm



Transmission mode

Bulk

Prohibited by ~mm thik substrate

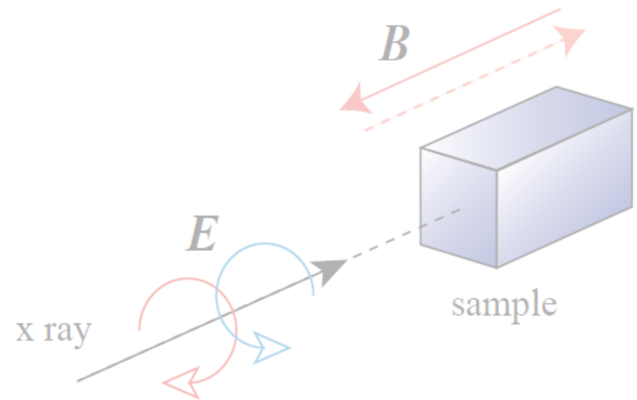
Total fluorescence yield (TFY) mode

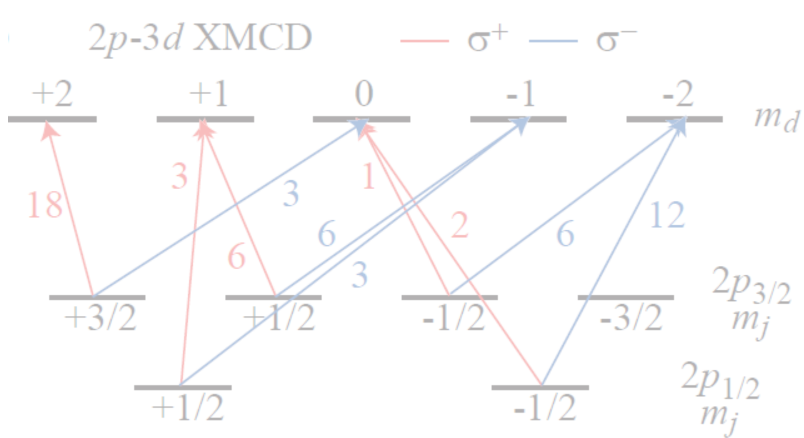
probing depth ~ 100nm ~ film thickness

Disadvantage: Self-absorption → Partial fluorescence yield (PFY) mode

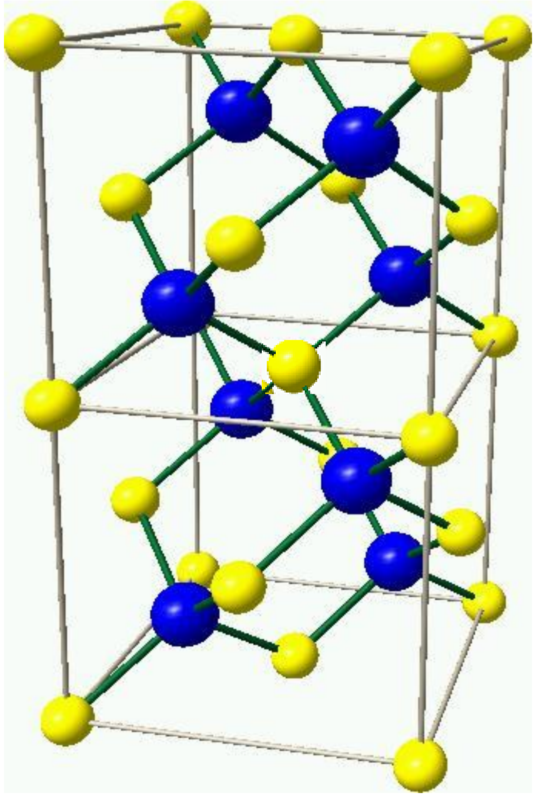
A. J. Achkar, PRB '11

希薄磁性半導体薄膜


B
E
x ray
sample

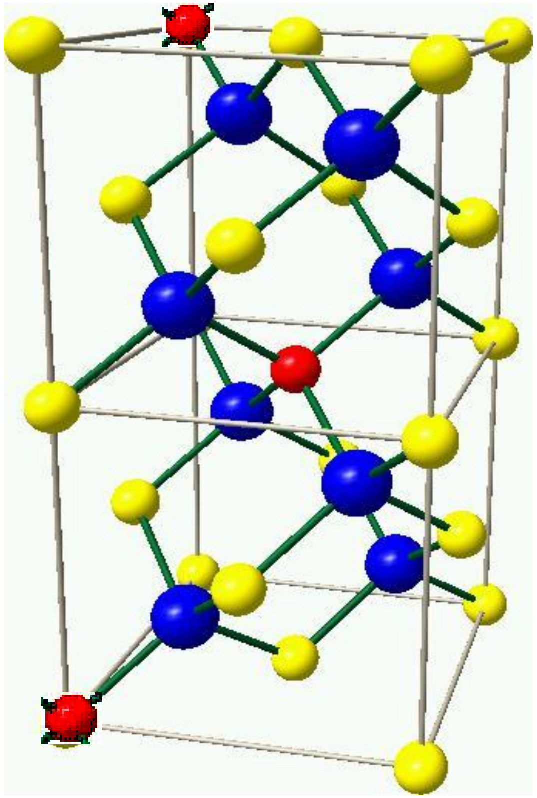

2p-3d XMCD
σ+
σ−
+2
+1
0
-1
-2
m_d
18
3
3
1
6
6
2
3
6
12
+3/2
+1/2
-1/2
-3/2
$2p_{3/2}$ m_j
+1/2
-1/2
$2p_{1/2}$ m_j

Prototypical diluted magnetic semiconductor $Cd_{1-x}Mn_xTe$



Random
Mn substitution

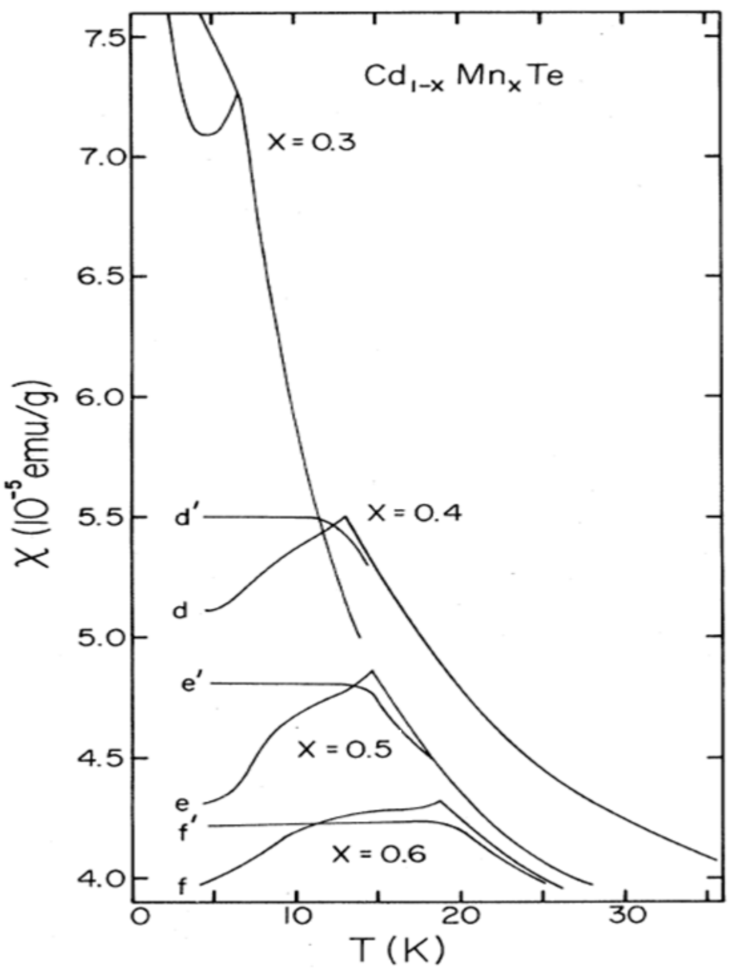
Insulating
AF/spin glass



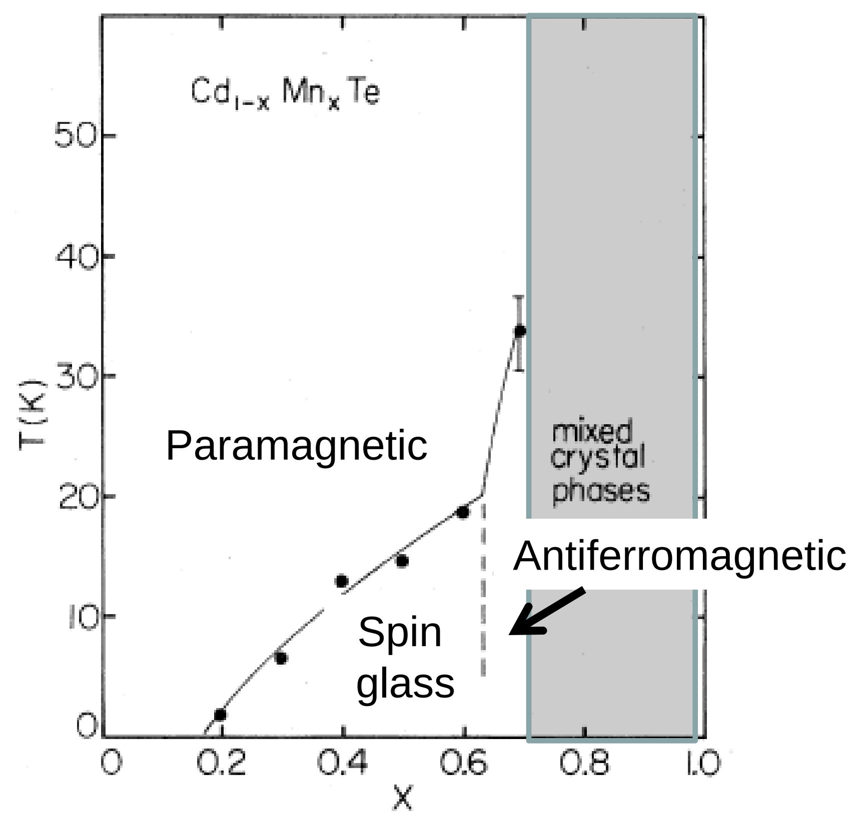
$Cd^{2+}Te$ → $Cd^{2+}_{1-x}Mn^{2+}_{x}Te$: Giant Faraday rot.
→ Optical isolators

Prototypical diluted magnetic semiconductor $Cd_{1-x}Mn_xTe$

Magnetic susceptibility



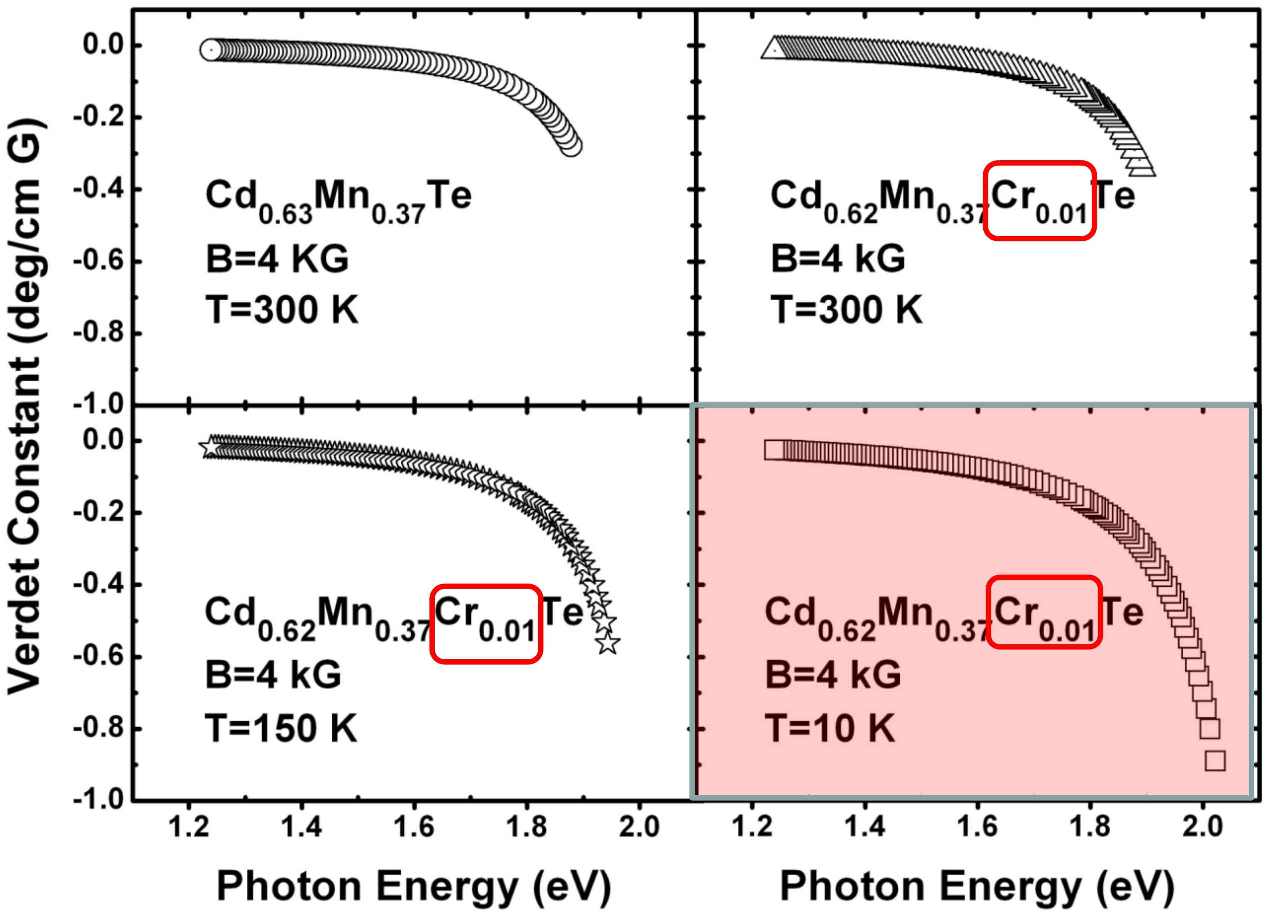
Phase diagram



R. R. Galazka, et al., PRB ‘80

Enhanced magneto-optical properties of $Cd_{1-x}Mn_xTe$ by Cr doping

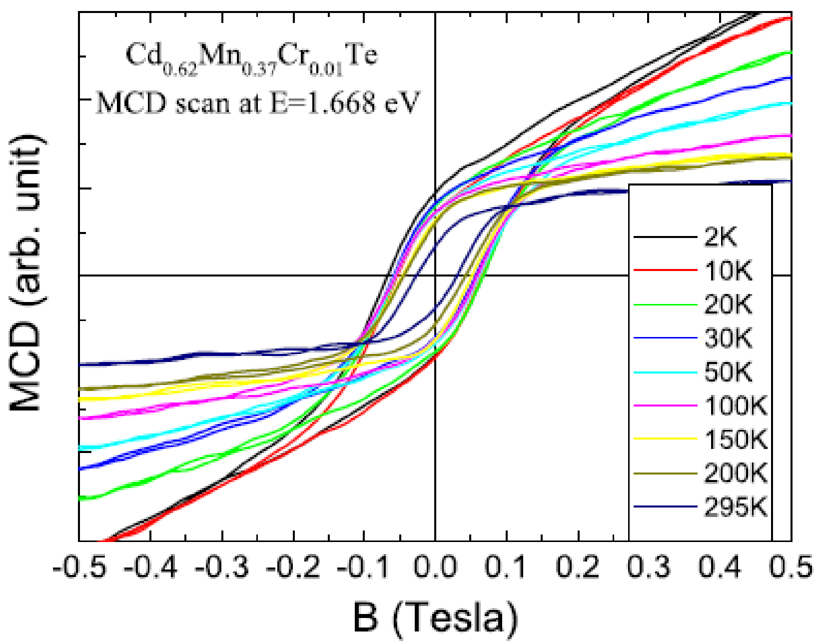
Faraday rotation



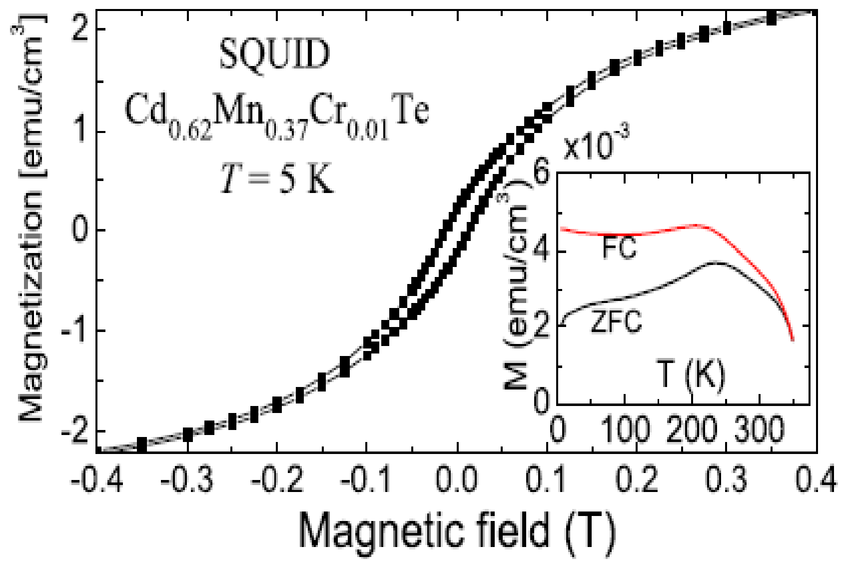
Y. Um et al., J. Kor. Phys. Soc., '09.

Enhanced magnetic and magneto-optical properties of $Cd_{1-x}Mn_xTe$ through Cr doping

Vis-MCD *vs H* curves



Magnetization *vs H* curves

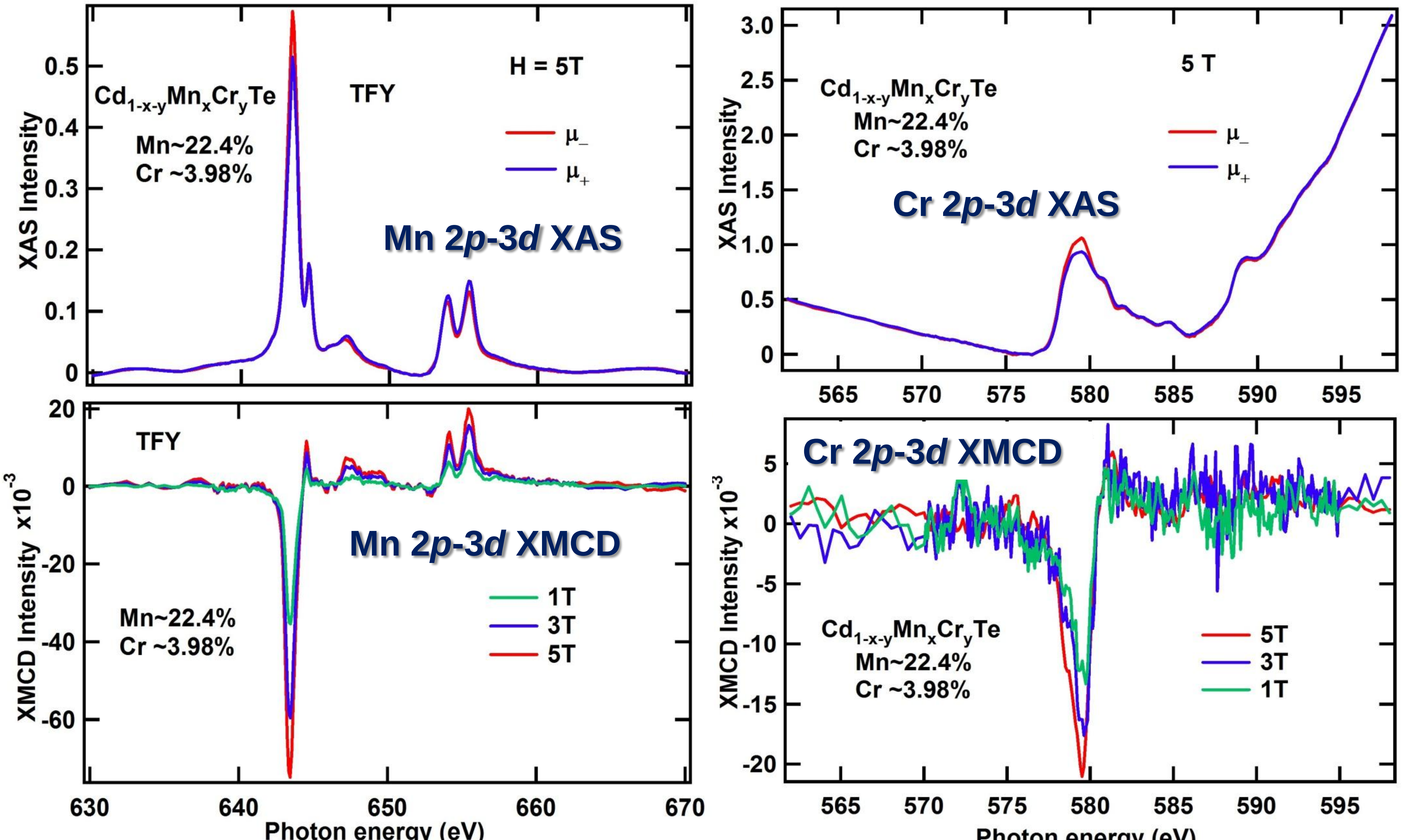


S. Shen et al., APL '09

→ $Cd_{0.76}Mn_{0.20}Cr_{0.04}Te$/GaAs (001)

***H*= 5T, *T*=15K, TFY mode**
@ KEK-PF BL-16A

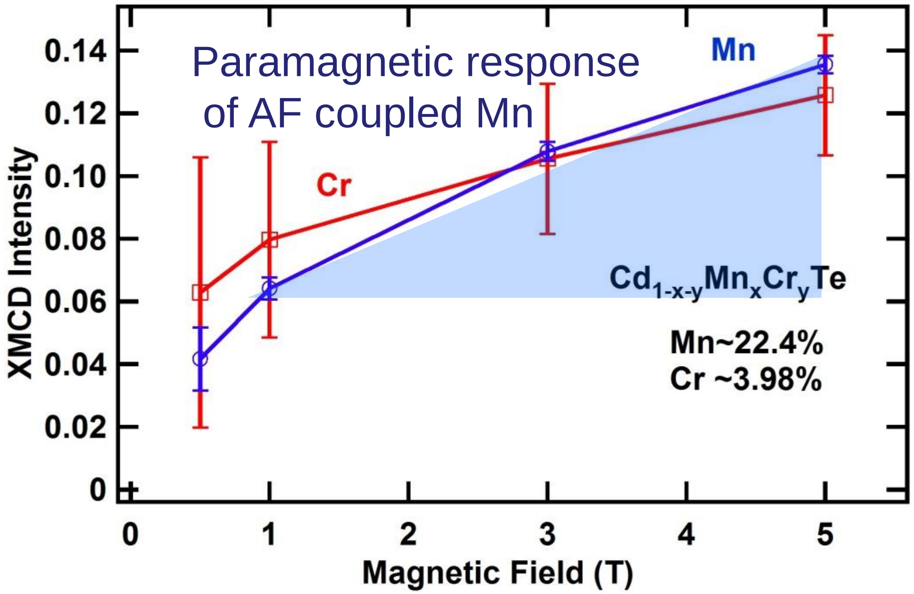
Mn and Cr 2*p* → 3*d* XMCD of $Cd_{1-x-y}Mn_xCr_yTe$



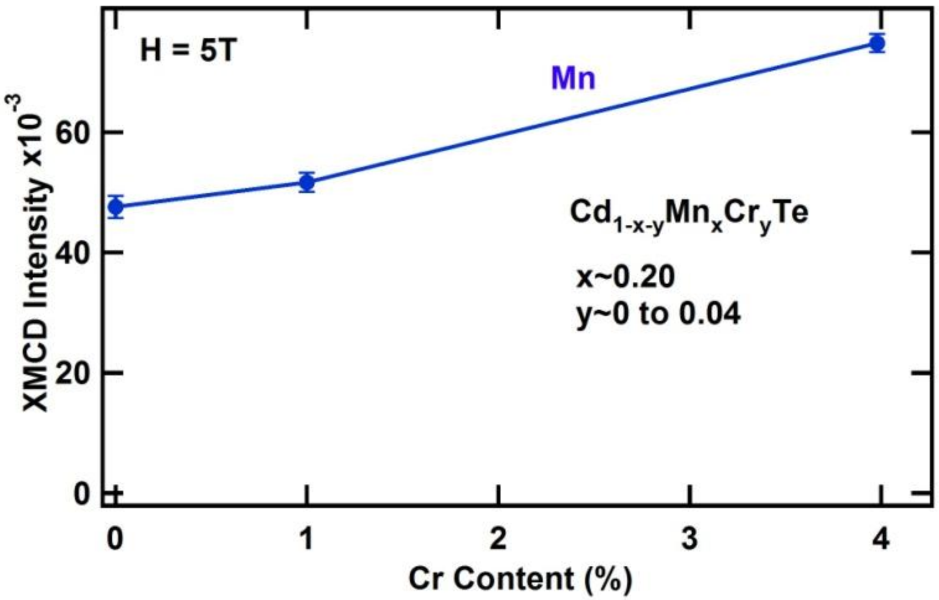
V. K. Verma et al.

Mn and Cr 2*p* → 3*d* XMCD of $Cd_{1-x-y}Mn_xCr_yTe$

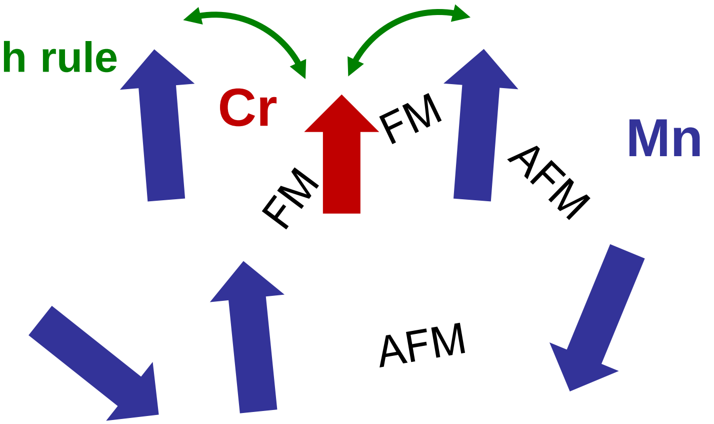
XMCD intensity *vs H*



XMCD intensity *vs* Cr content

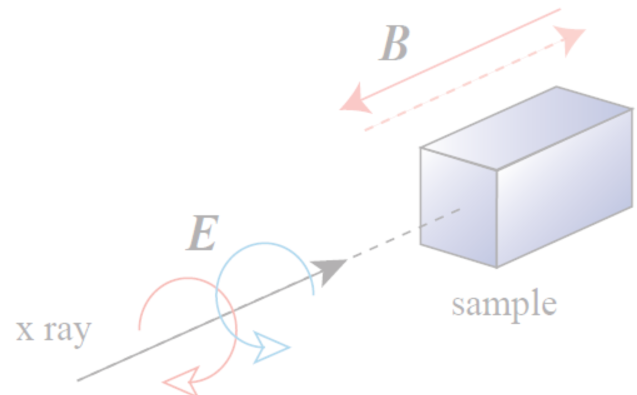


Kanamori-Goodenough rule

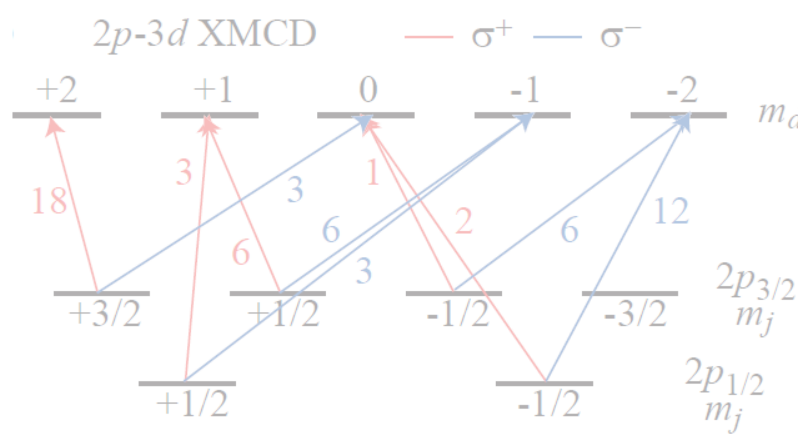


V. K. Verma et al.

磁気トンネル接合界面



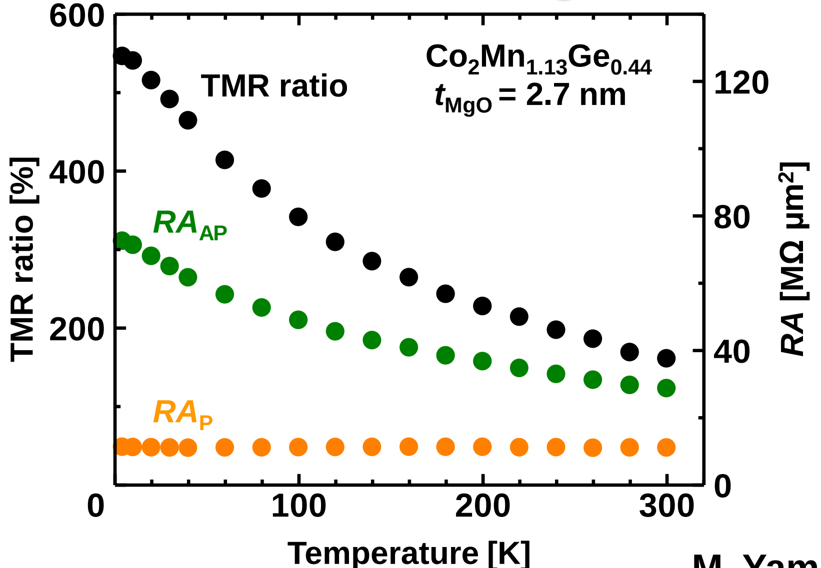
B
E
x ray
sample



2p-3d XMCD
σ+
σ−
+2
+1
0
-1
-2
m_d
18
3
6
3
6
3
1
2
6
12
+3/2
+1/2
-1/2
-3/2
$2p_{3/2}$ m_j
+1/2
-1/2
$2p_{1/2}$ m_j

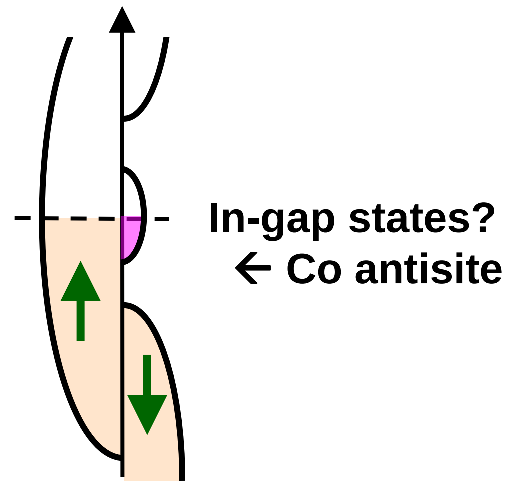
$Co_2MnGe/MgO/Co_2MnGe$ magnetic tunnel junction

TMR ratio of CMG/MgO/CMG



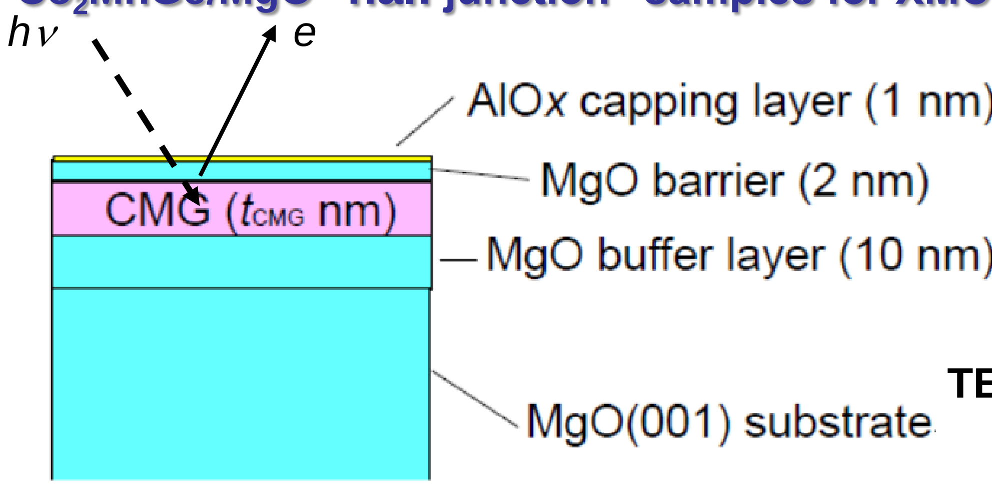
M. Yamamoto et al.

DOS at interface



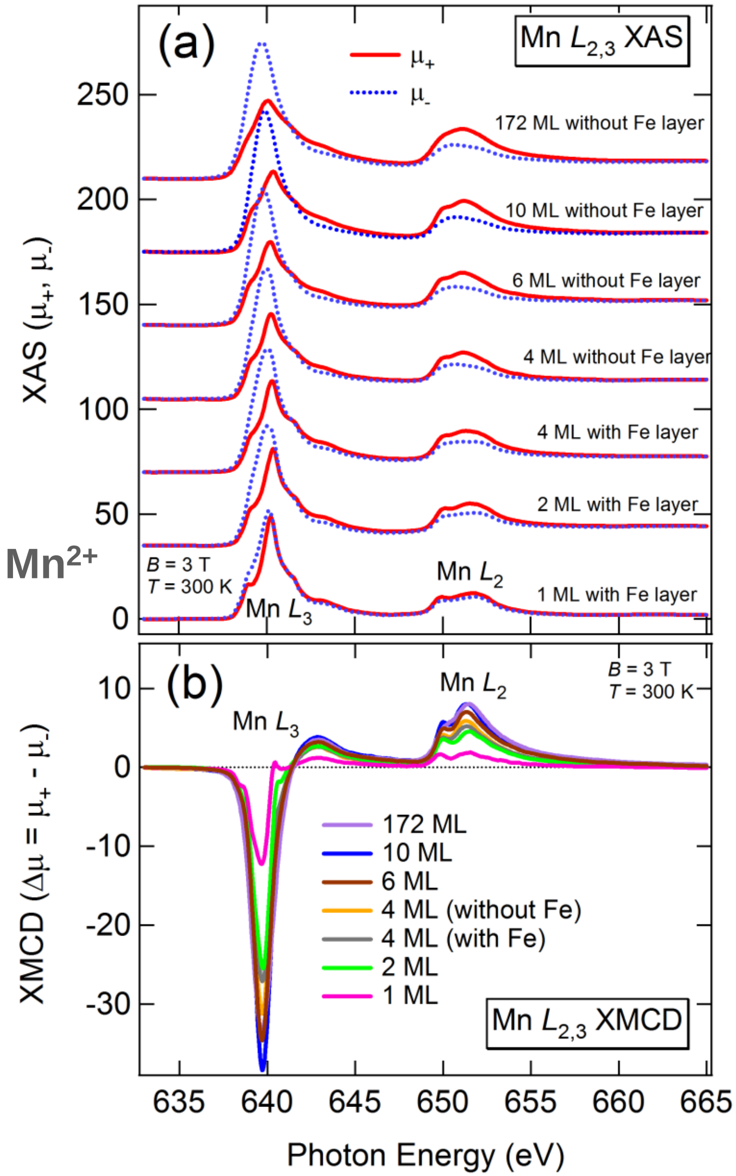
S. Picozzi et al., PRB '04

Co_2MnGe/MgO "half junction" samples for XMCD

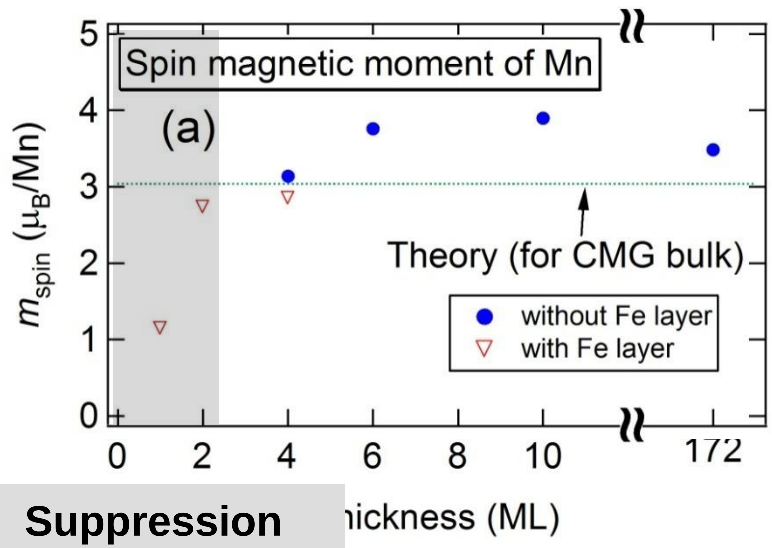


XMCD measurements
TEY mode, @ KEK-PF BL-16A

Mn 2*p* core-level XMCD of Co_2MnGe/MgO



Mn magnetic moments



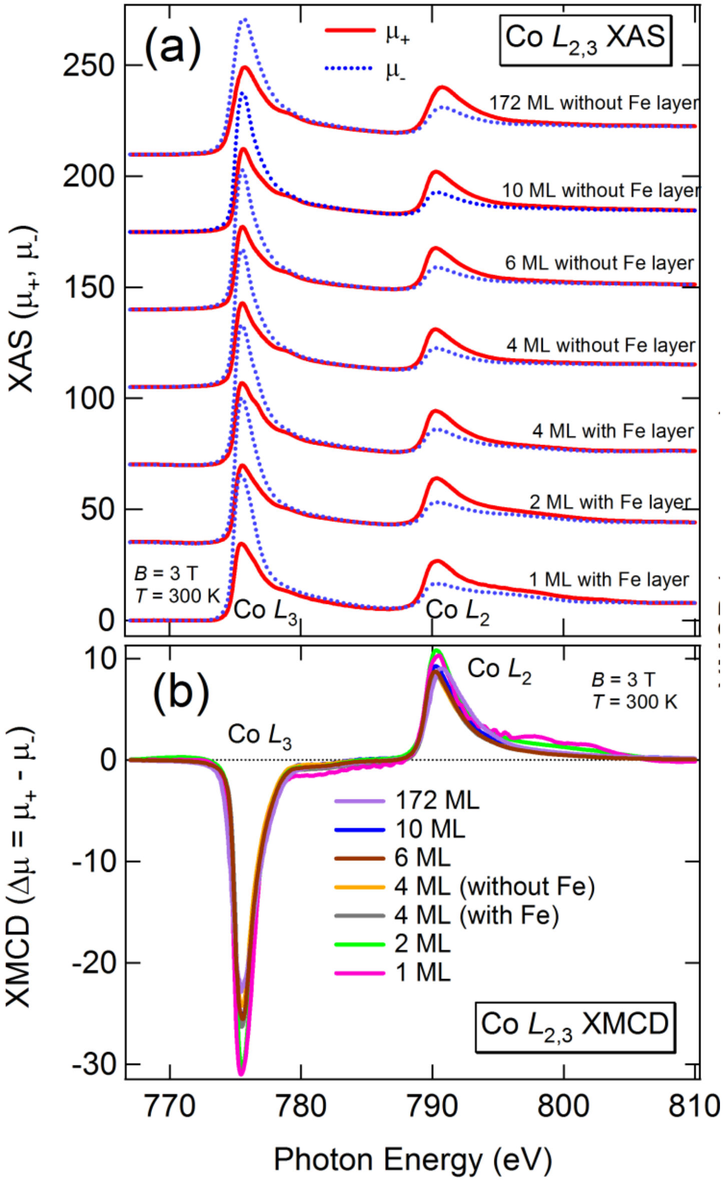
Suppression due to oxidation

cf. No oxidation in Co_2MnSi

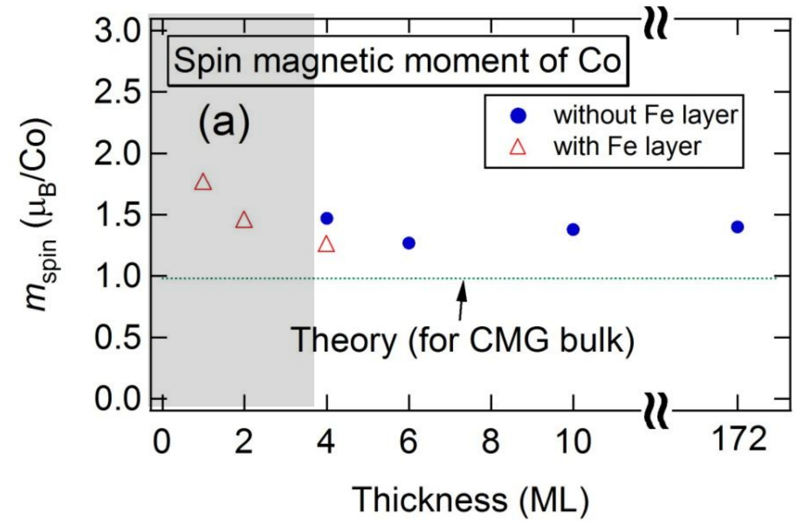
T. Saito et al., PRB '10

D. Asakura et al., PRB '10

Co 2*p* core-level XMCD of Co_2MnGe/MgO



Co magnetic moments

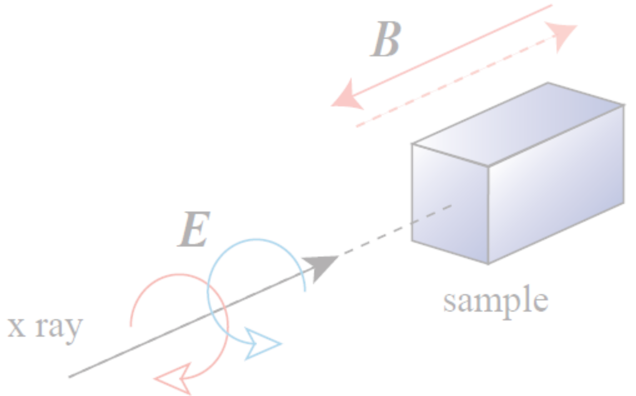


Enhancement due to Co antisite?

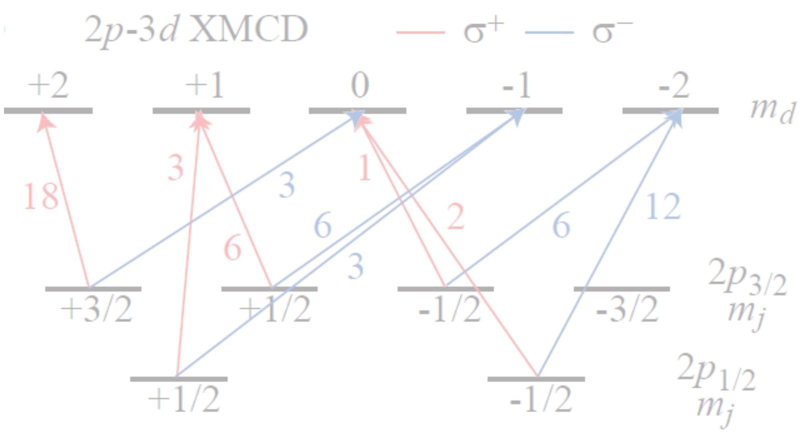
S. Picozzi et al., PRB '04

D. Asakura et al., PRB '10

酸化物薄膜



B
E
x ray
sample



2p-3d XMCD
σ+
σ−
+2
+1
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-1
-2
m_d
18
3
3
1
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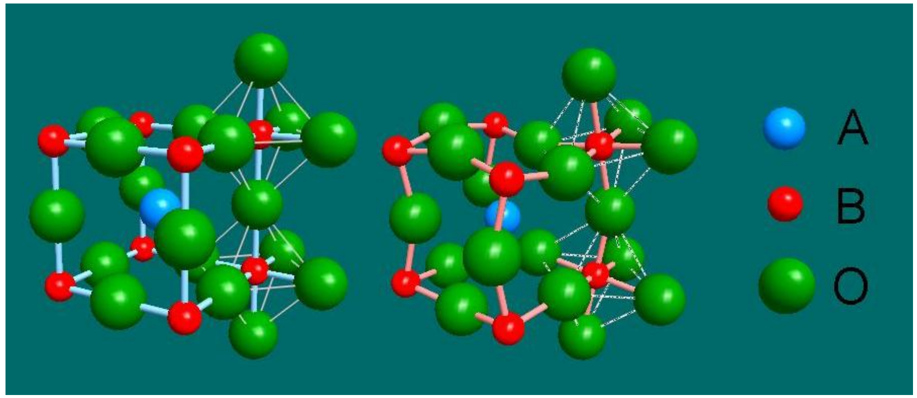
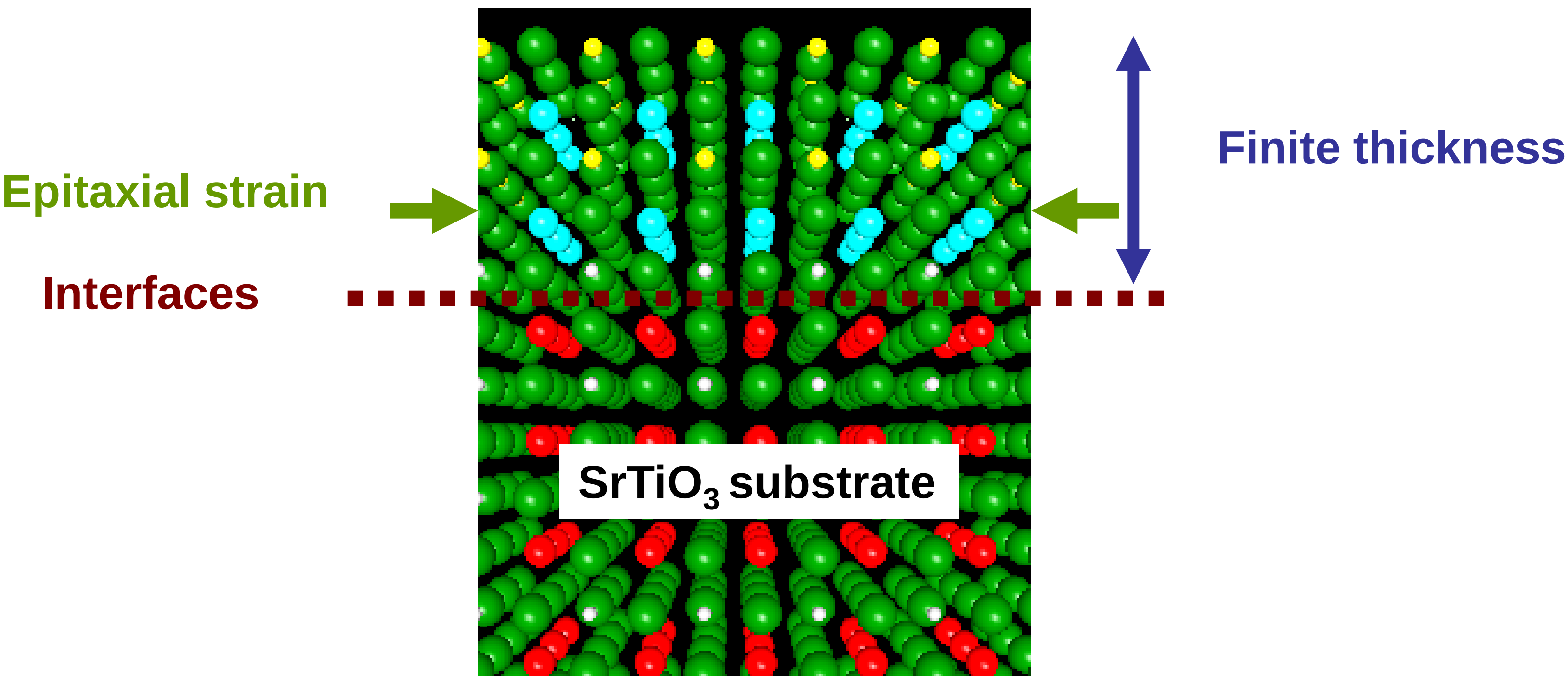
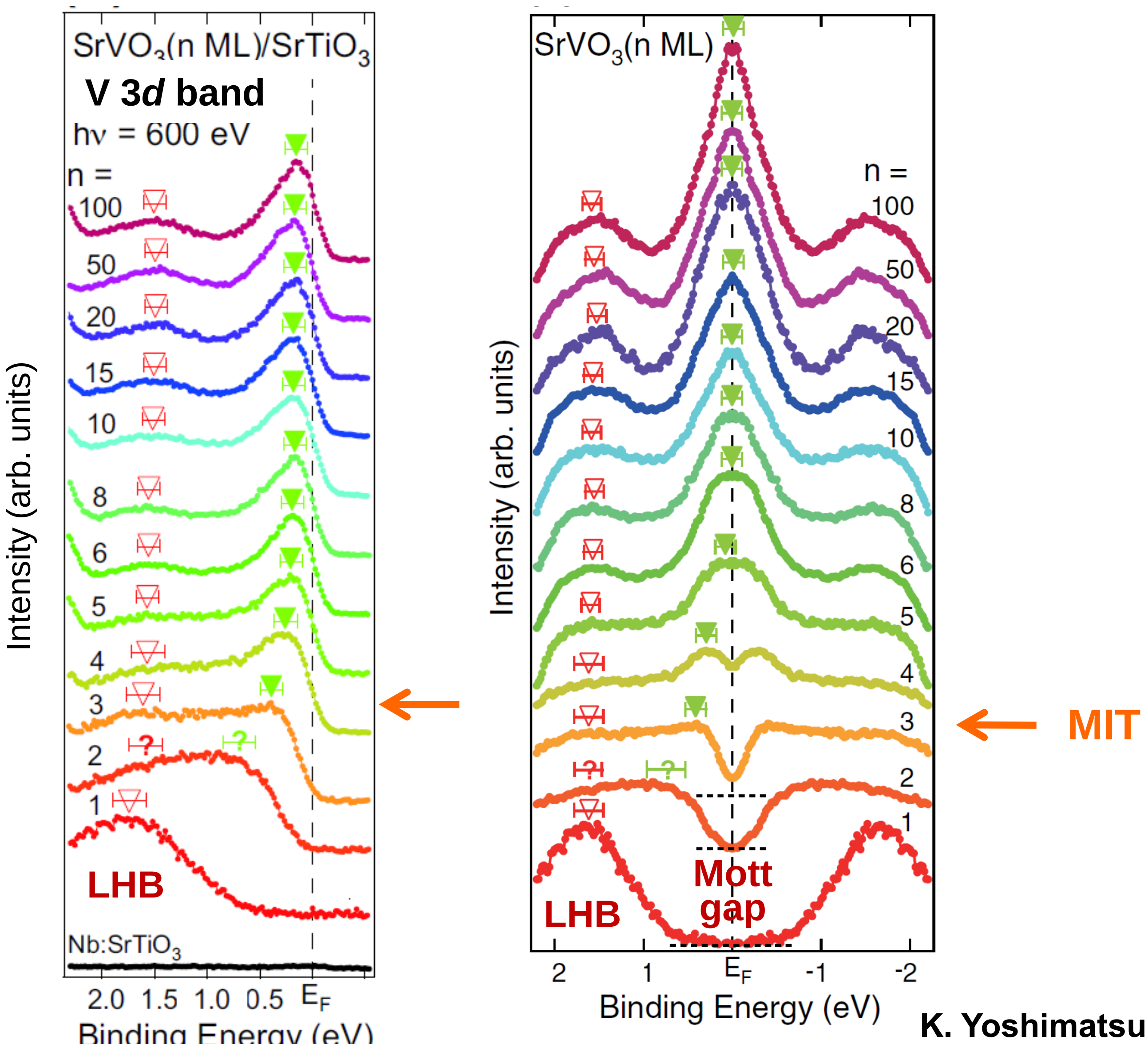
6
3
2
6
12
+3/2
+1/2
-1/2
-3/2
2p_3/2 m_j
+1/2
-1/2
2p_1/2 m_j

Research directions with oxide thin films



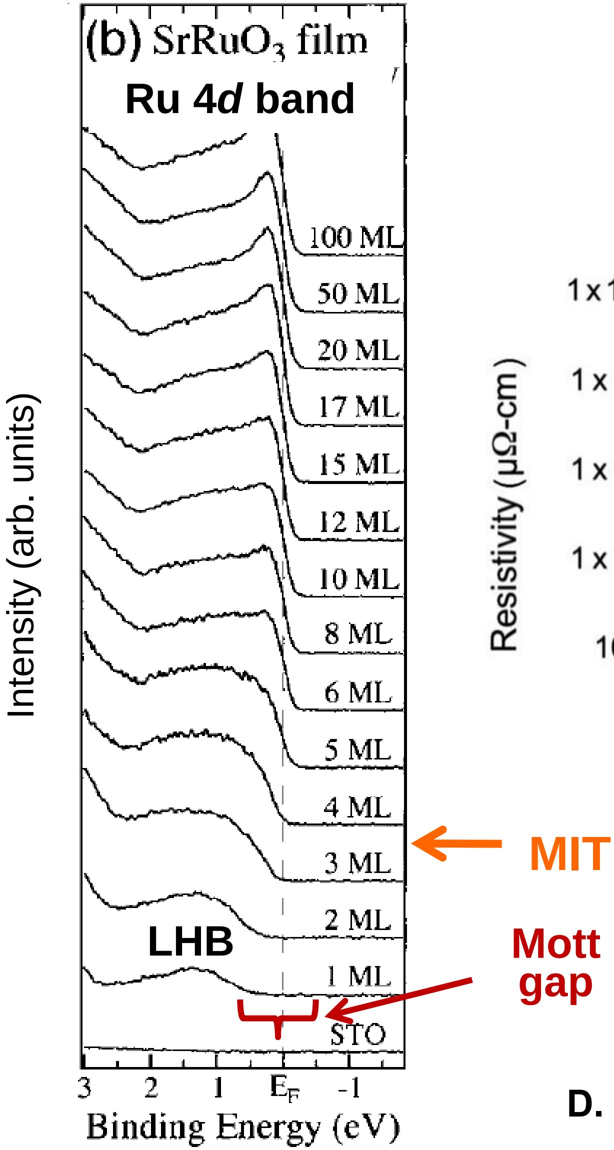


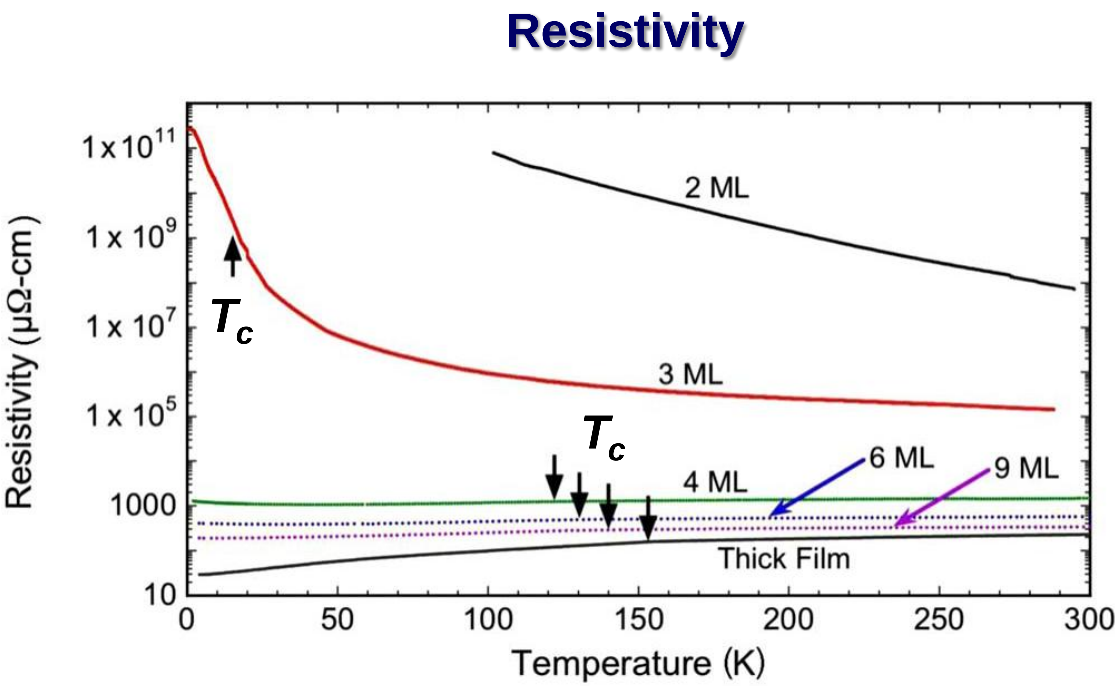
Metal-to-insulator transition in $SrVO_3$ with decreasing film thickness



K. Yoshimatsu et al., PRL '10

Metal-to-insulator transition in $SrRuO_3$ with decreasing film thickness



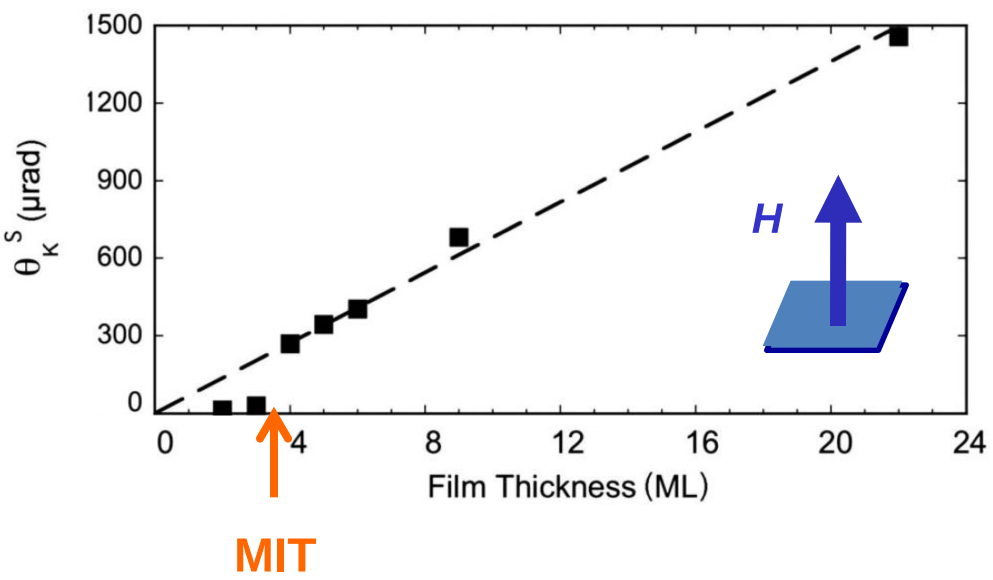


J. Xia et al., PRB ‘09

D. Toyota et al., APL ‘05

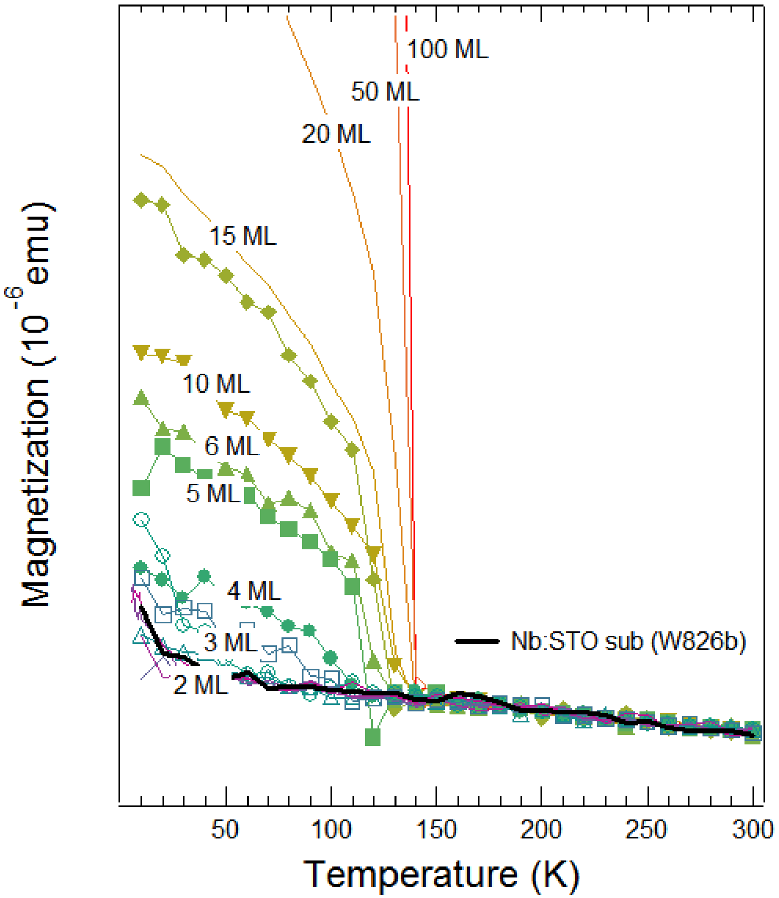
Concomitant ferromagnetic-to-paramagnetic transition in $SrRuO_3$ thin films

Polar Kerr effect



J. Xia et al., PRB '09

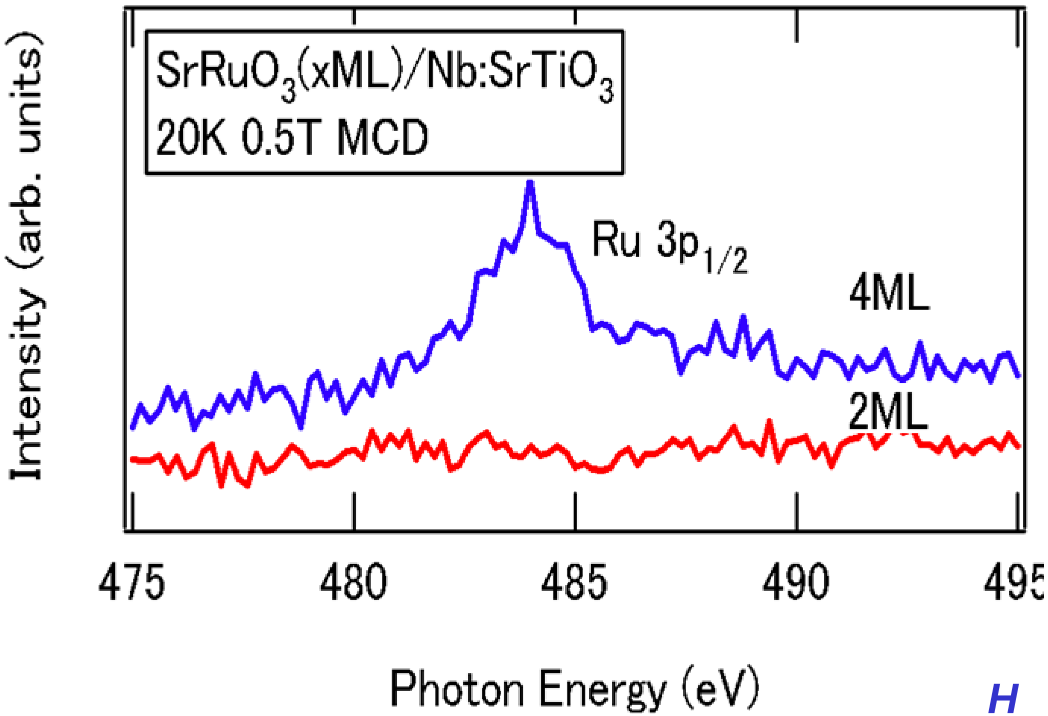
Magnetization measured by SQUID



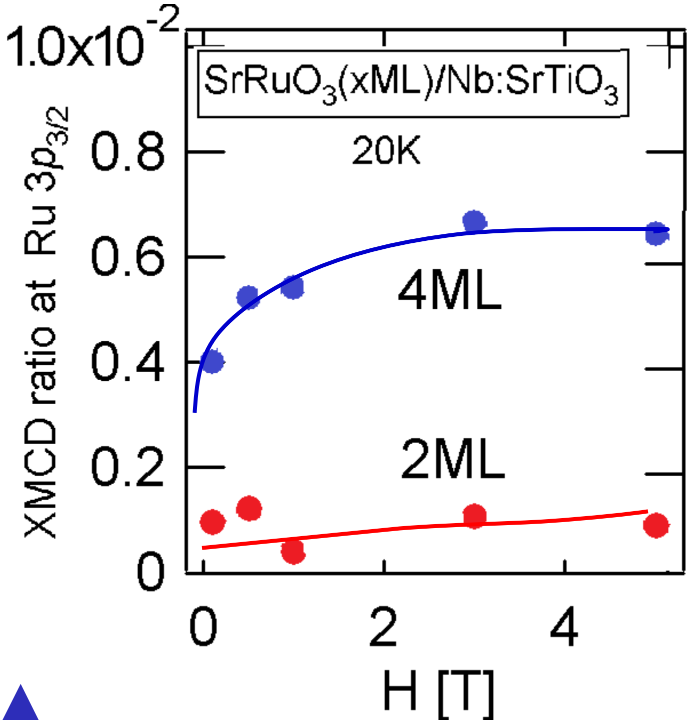
M. Takizawa et al.

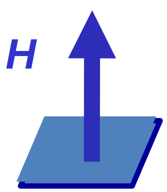
Ru 3*p* → 3*d* XMCD of $SrRuO_3$ thin films near critical thickness

XMCD spectra



XMCD intensity *vs H*

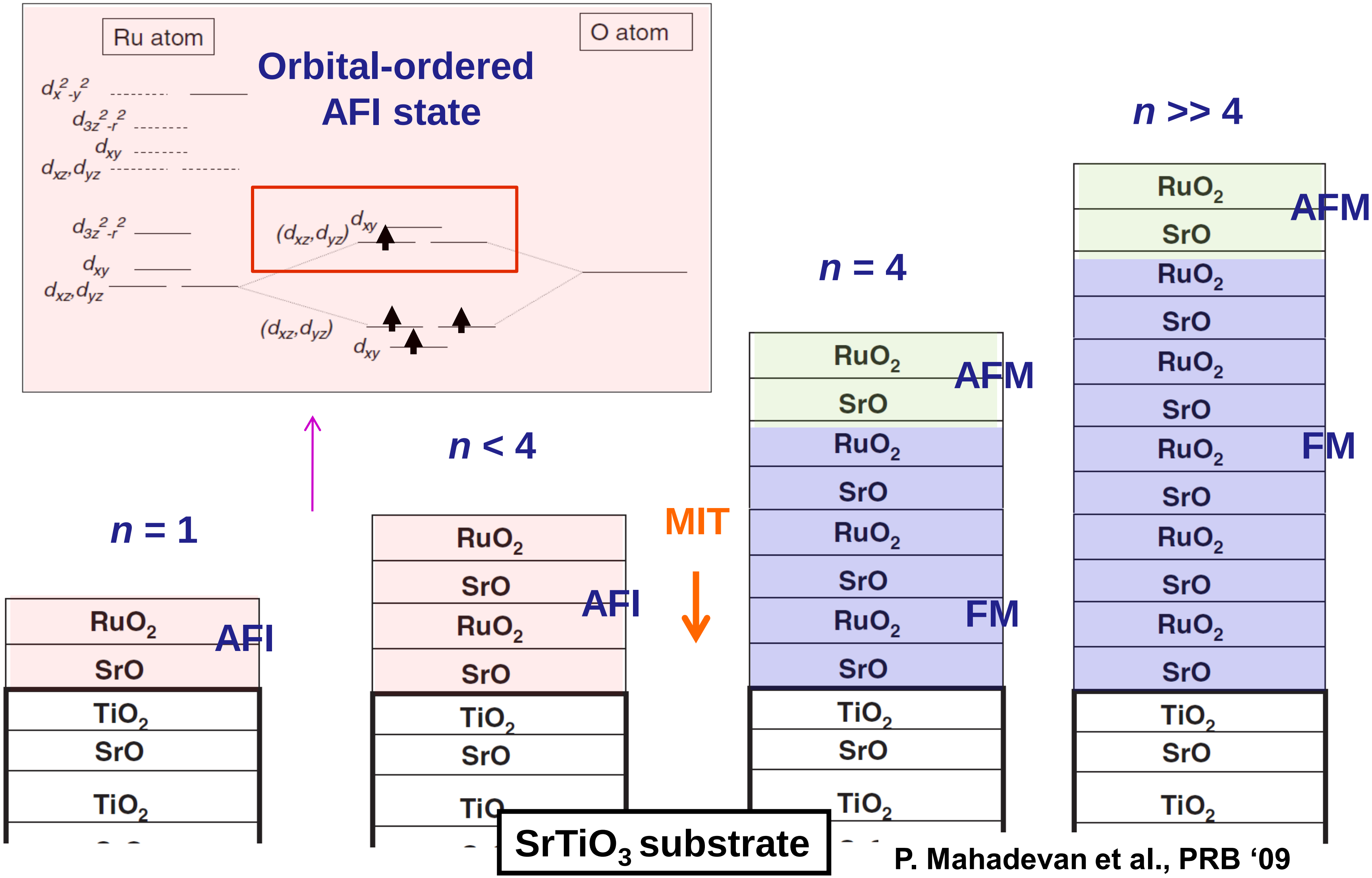




@ SPring-8 BL23-SU

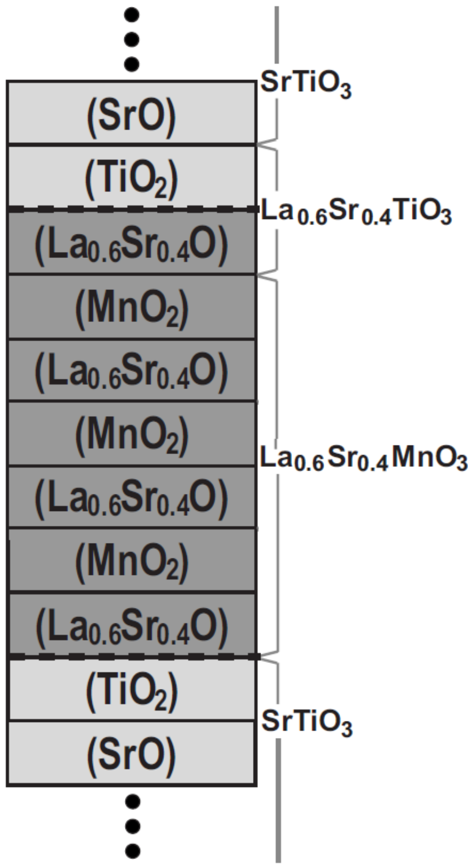
K. Ishigami et al.

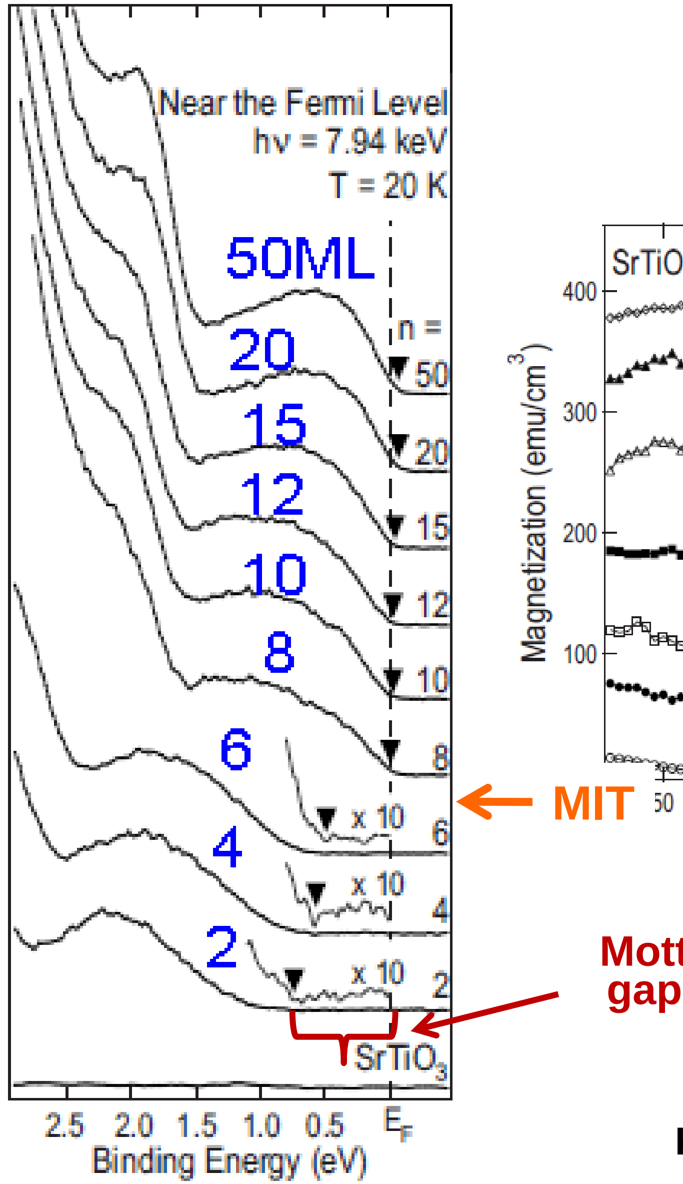
LDA+U calculation of $SrRuO_3$ thin films



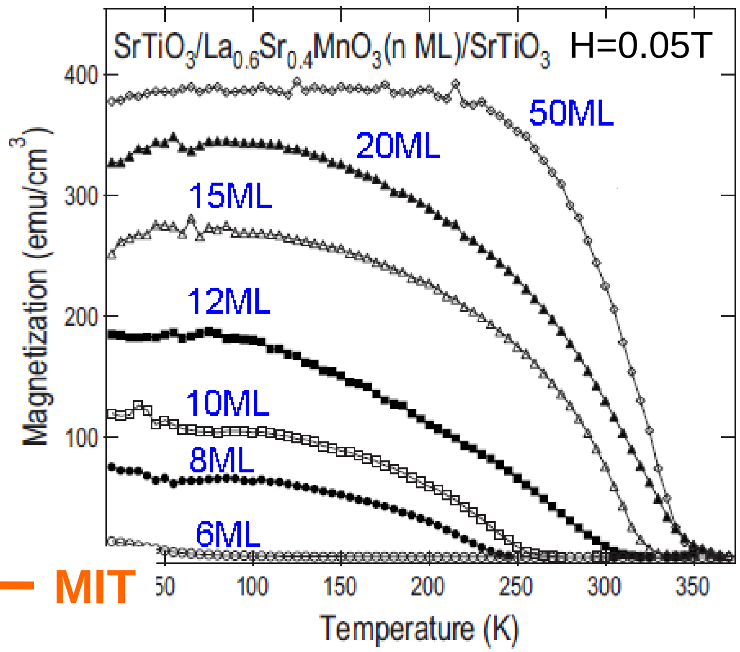
P. Mahadevan et al., PRB '09

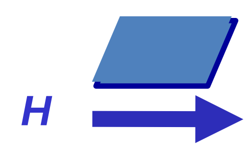
Metal-to-insulator transition in $La_{1-x}Sr_xMnO_3$ with decreasing film thickness





Magnetization measured by SQUID

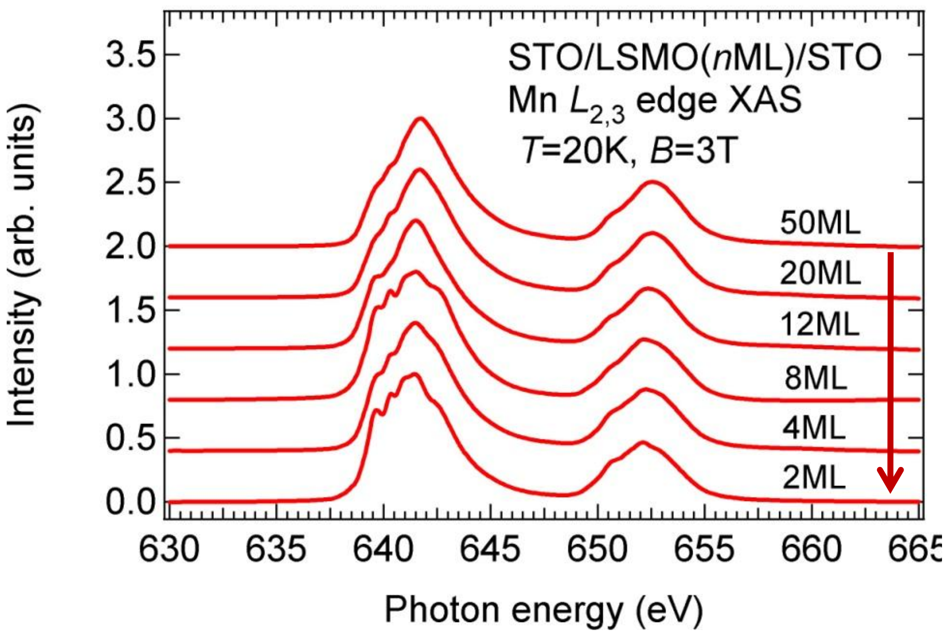




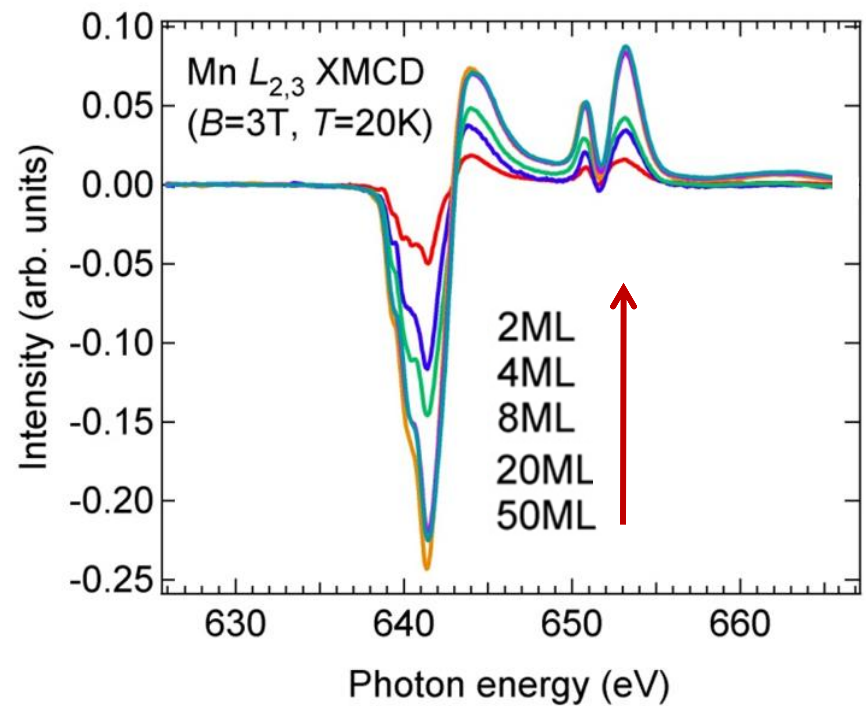
K. Yoshimatsu et al., APL '09

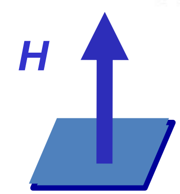
Mn 2*p*→3*d* XAS and XMCD of $La_{1-x}Sr_xMnO_3$ thin films

X-ray absorption spectroscopy (XAS) spectra



X-ray magnetic circular dichroism (XMCD) spectra



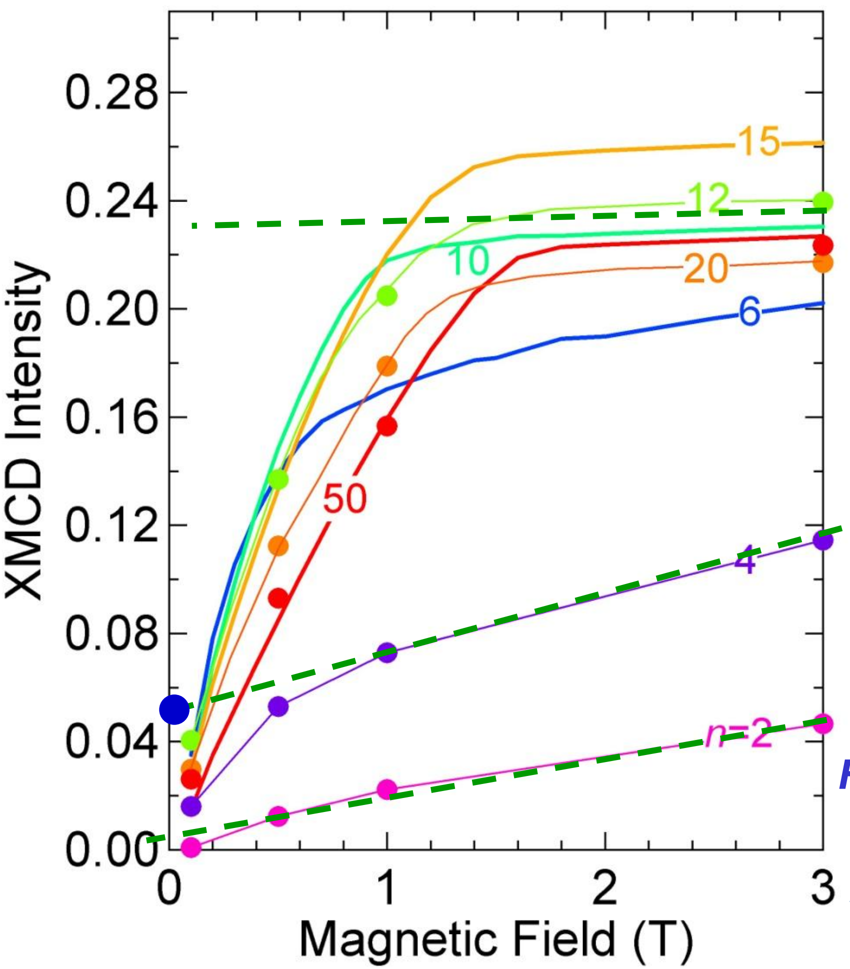


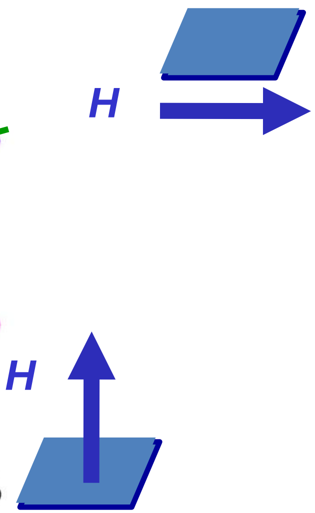
@ KEK-PF BL-16A

G. Shibata et al.

Mn 2*p* → 3*d* XMCD of $La_{1-x}Sr_xMnO_3$ thin films

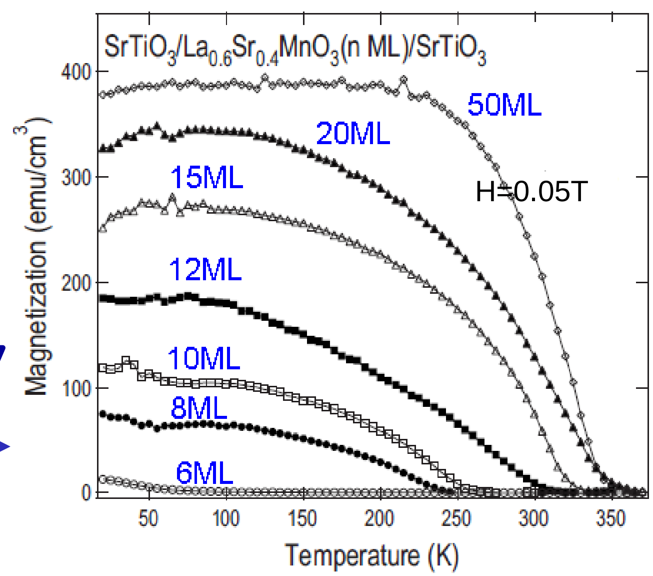
XMCD intensity *vs H*





G. Shibata et al.

Magnetization



K. Yoshimatsu et al., APL '09

Summary of oxide thin films

- **Metallic transition-metal oxide undergoes an MIT with decreasing film thickness. Critical thickness for MIT is:**

  ~3-4 ML ($SrVO_3$, $SrRuO_3$)

  ~6-8 ML ($La_{1-x}Sr_xMnO_3$)

- **Orbital states evolve as:**

  Band metal → Quantum well → Orbital ordering

  MIT

- **Spin states evolve as:**

  PM → intermediate phase? → AFI ($SrVO_3$)

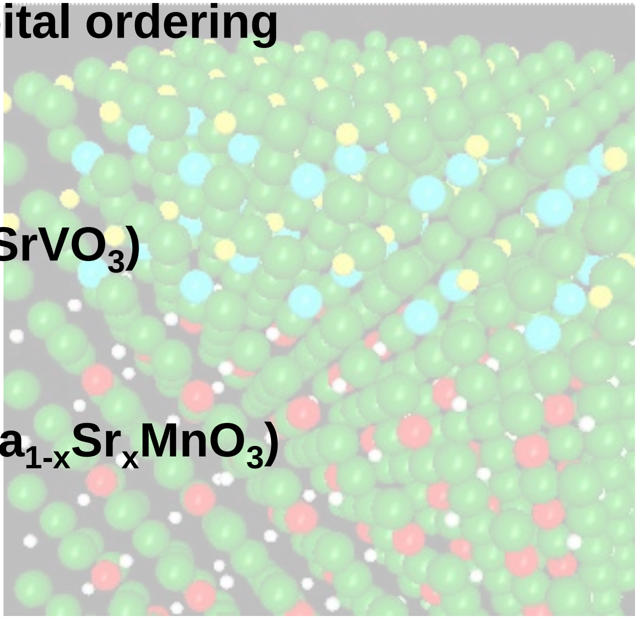
  MIT

  FM → FM(+AFM?)→ AFI ($SrRuO_3$)

  MIT

  FM → *H*-induced CAFI? … → AFI ($La_{1-x}Sr_xMnO_3$)

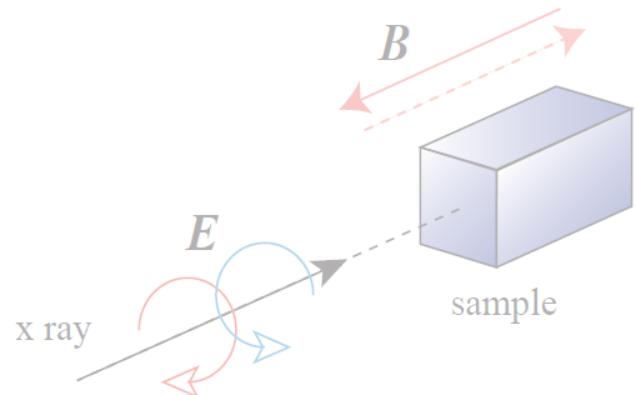
  MIT

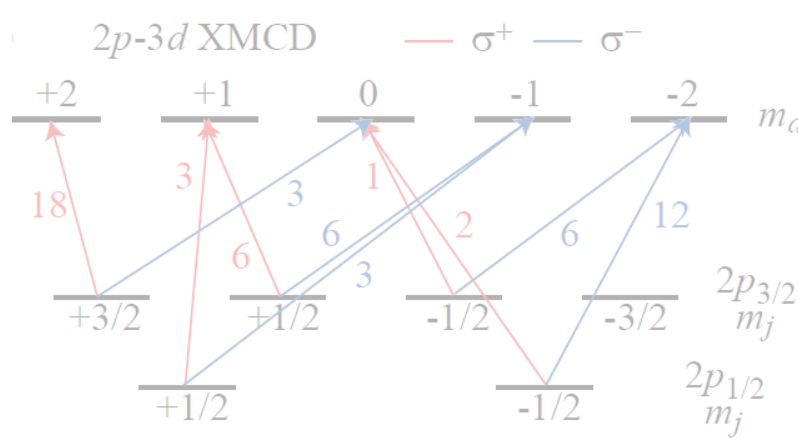


Summary

- 希薄磁性半導体薄膜: Crドープ$Cd_{1-x}Mn_xTe$
  - Mn-Cr間の強磁性的相互作用，Crから離れたMnの常磁性（+反強磁性）的な振る舞いが見出された.
- 磁気トンネル結合界面: ホイスラー$Co_2MnGe/MgO/Co_2MnGe$
  - TMRを劣化させるCoアンチサイトの大きなスピンモーメント，TMRを劣化させないMnアンチサイトの逆向きスピンモーメントが確認された.
- 酸化物薄膜: $SrRuO_3$, $La_{1-x}Sr_xMnO_3$
  - 薄膜化による強磁性と金属性の同時消失は，軌道整列・反強磁性状態の出現による？

今後の展望

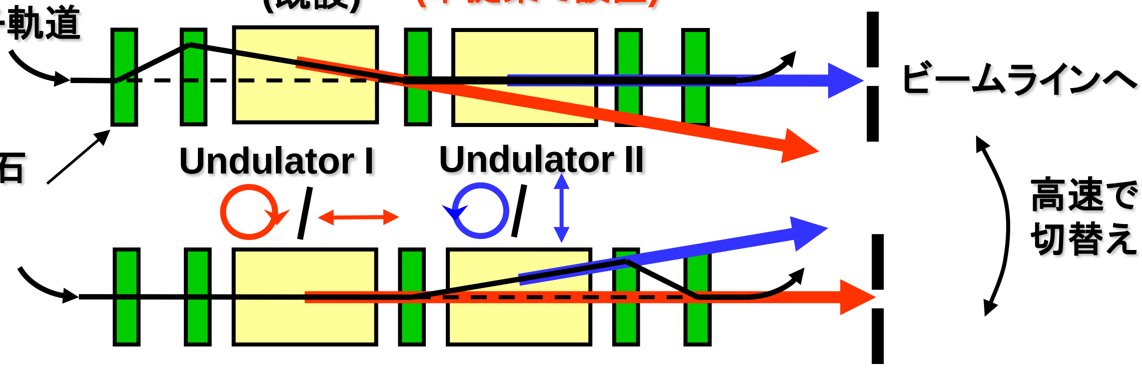

B
E
x ray
sample


2p-3d XMCD
σ+
σ−
+2
+1
0
-1
-2
md
18
3
3
1
6
6
2
6
12
3
+3/2
+1/2
-1/2
-3/2
2p3/2 mj
+1/2
-1/2
2p1/2 mj

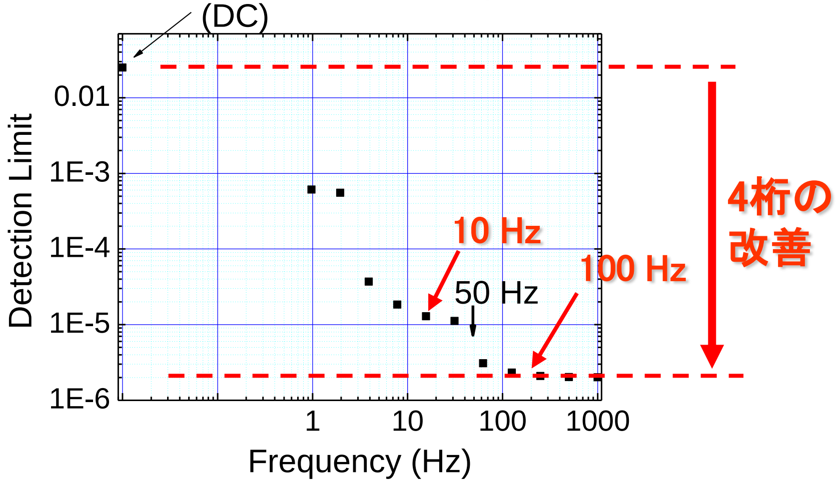
高速偏光スイッチングアンジュレータ

(1) 高速偏光スイッチング

Photon Factory
BL-16A



(2) ロックイン法による極微小な二色性シグナルの検出



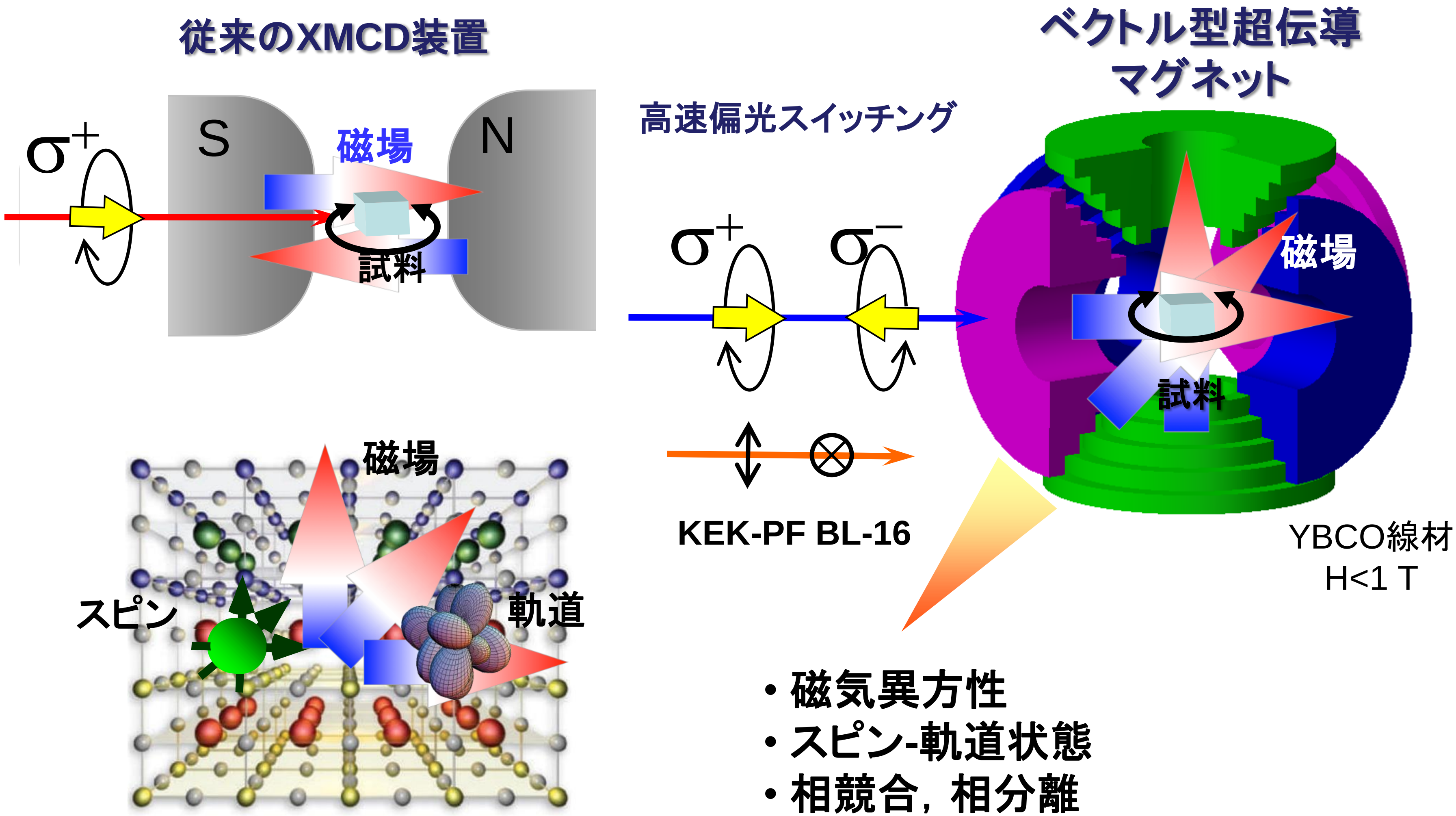
円二色性： 左右円偏光に対するシグナルの差
直流(DC)測定では 1 %程度が検出限界

偏光の交流スイッチング
⇒ 10^{-4}—10^{-5} の円二色性・線二色性の観測
※ 現時点での報告例： 10^{-3} 程度 (1 Hz利用)

スイッチング周波数： 10 Hzを確実に実現
100 Hzを目指した技術開発

量子ビーム基盤技術開発プログラム
「軟X 線の高速偏光制御による機能性材料の探究と創製」@KEK-PF

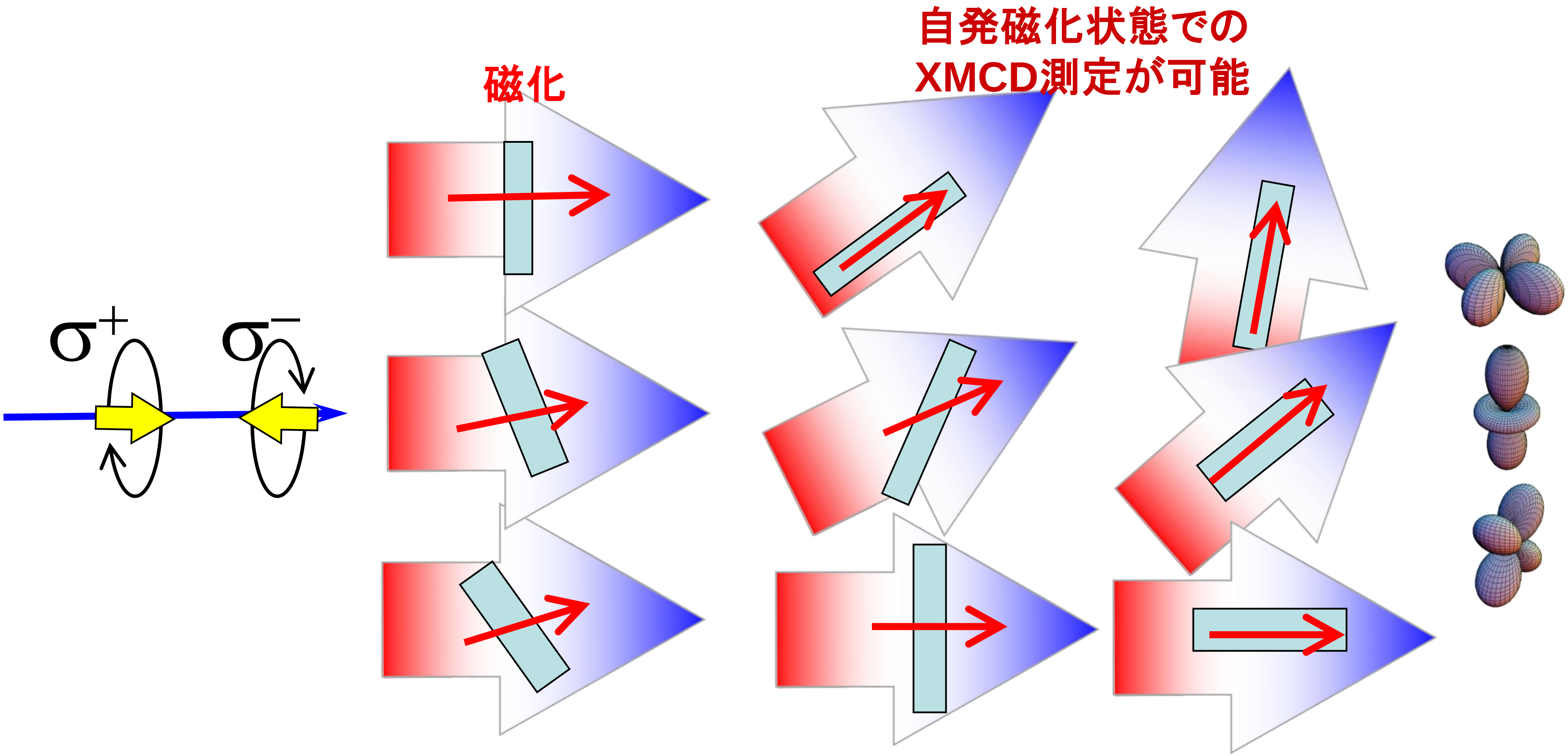
ベクトル型マグネットと高速偏光スイッチングを用いたXMCD



- 磁気異方性
- スピン-軌道状態
- 相競合，相分離

基盤研究S「多自由度放射光X線二色性分光による強相関系界面新規電子相の研究」

方向可変磁場を用いたXMCD



磁場と偏光が同時回転
両者の効果が分離できない

従来のXMCD

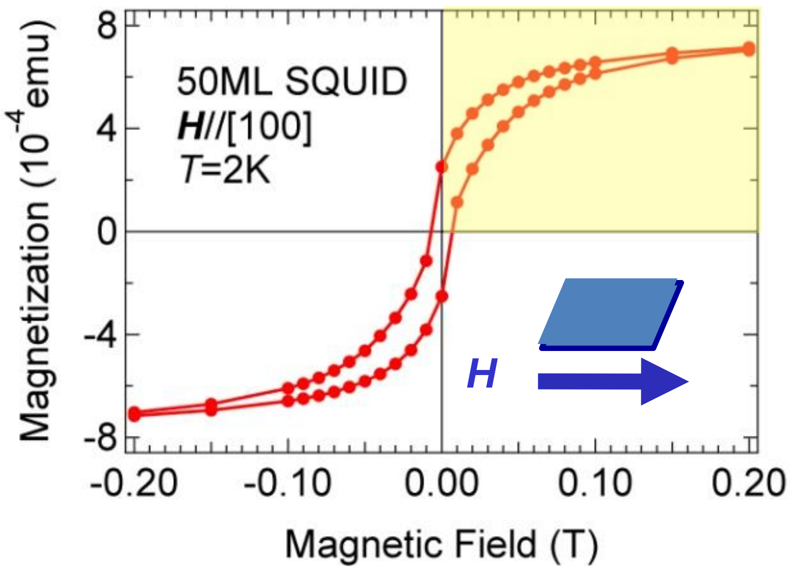
→ 磁気異方性

→偏光依存XMCD
→軌道依存磁気モーメント

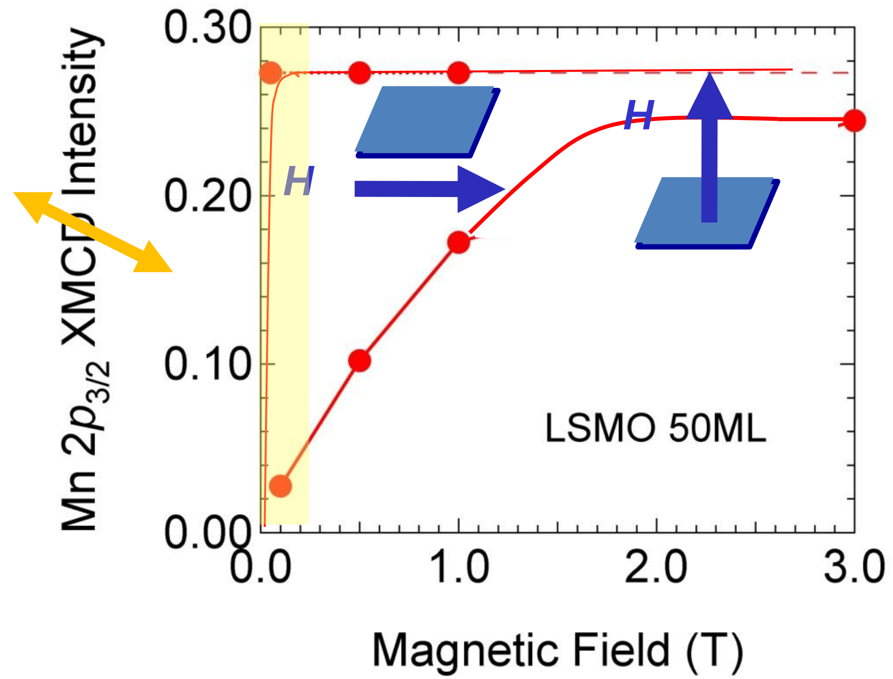
新XMCD装置

$La_{1-x}Sr_xMnO_3$薄膜の磁気異方性

Magnetization measured by SQUID



XMCD intensity *vs H*

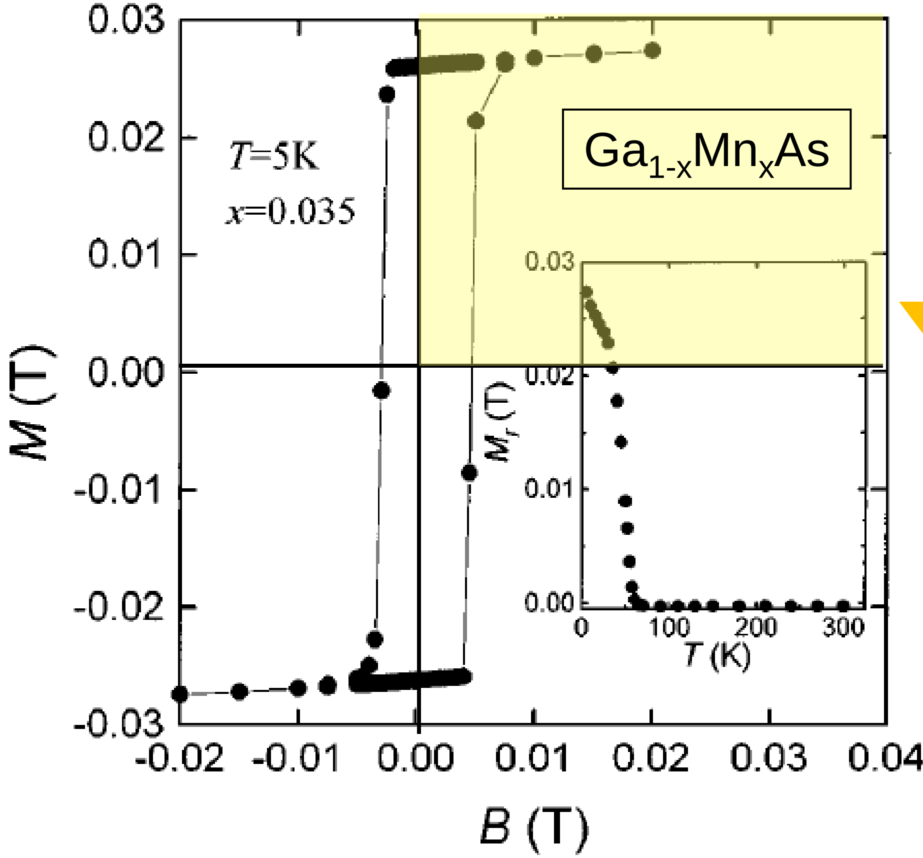


K. Yoshimatsu et al., APL '09

G. Shibata et al.

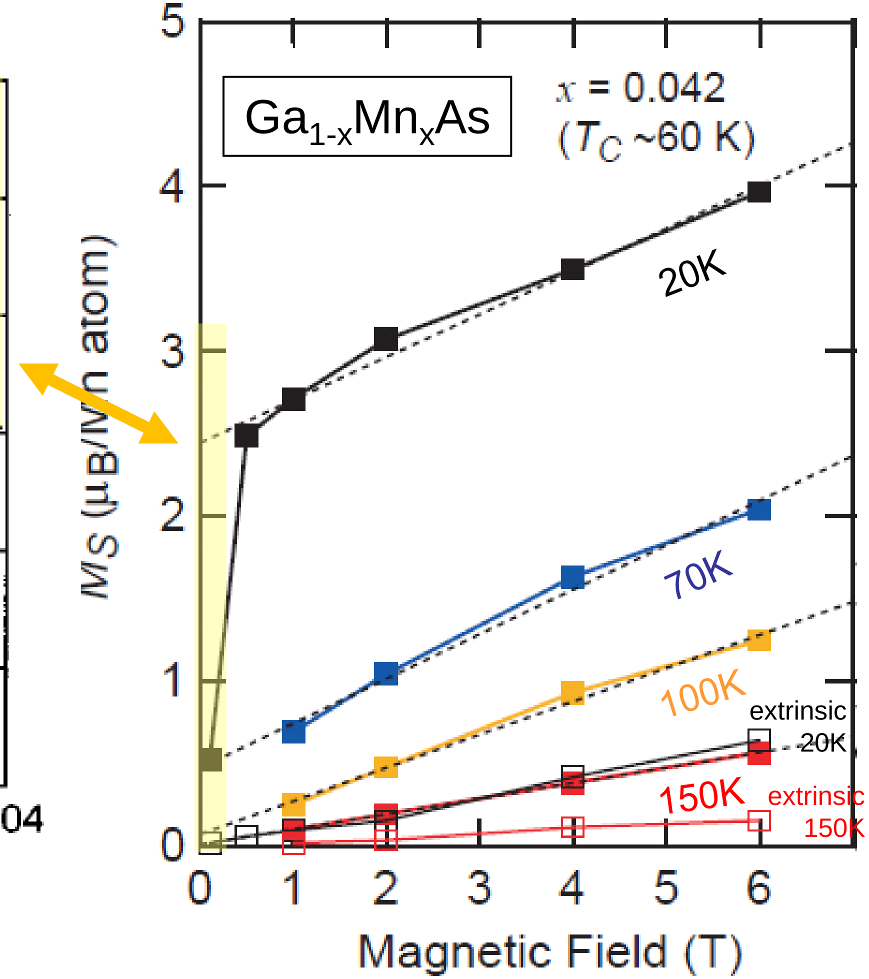
$Ga_{1-x}Mn_xAs$（薄膜試料）の磁気異方性

Magnetization measured by SQUID



H. Ohno e al. APL '96

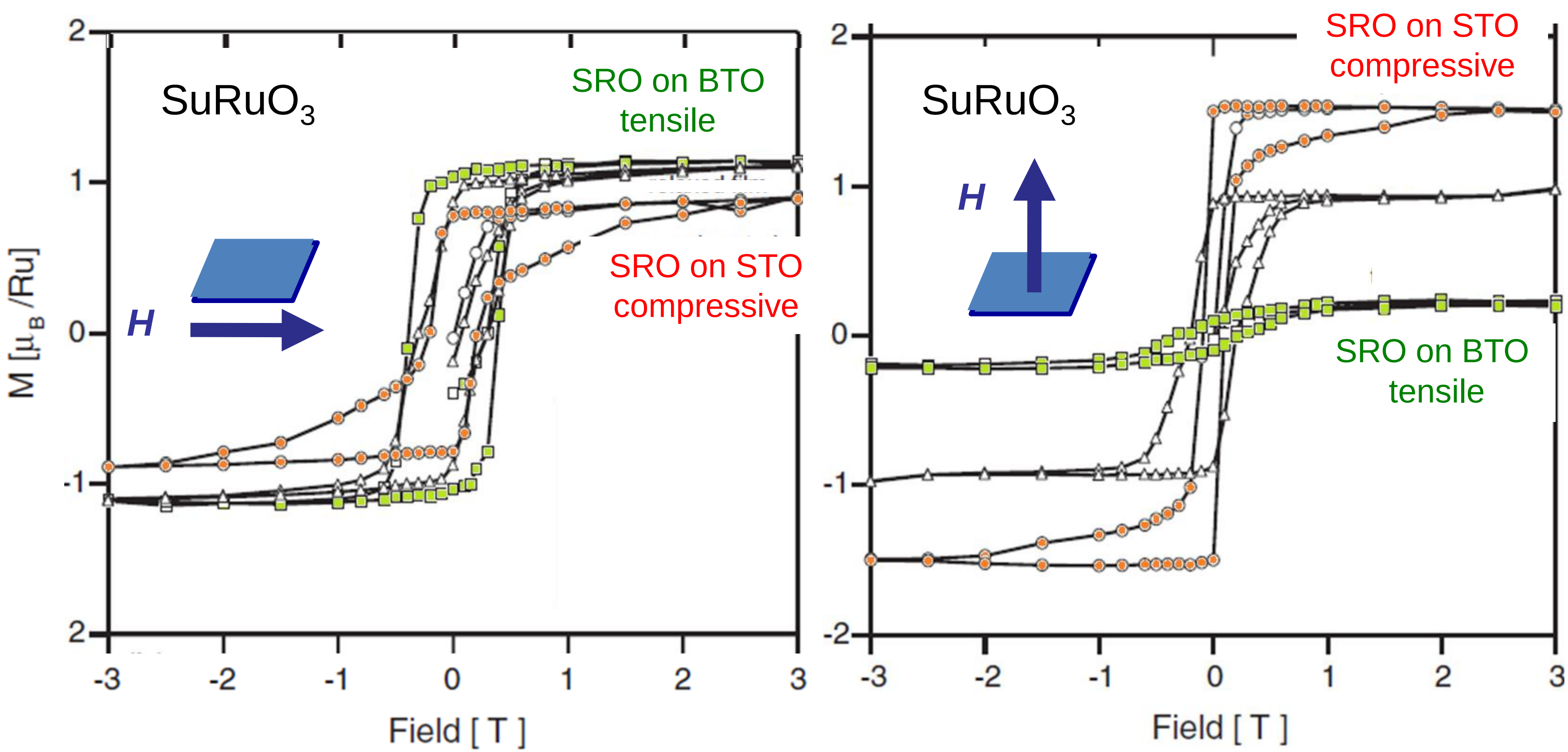
XMCD intensity *vs H*



Y. Takeda et al. PRL '08

スピン-軌道相互作用に起因する$SrRuO_3$薄膜の異常な磁気異方性

Magnetization measured by SQUID



K. Terai et al., JJAP '04