

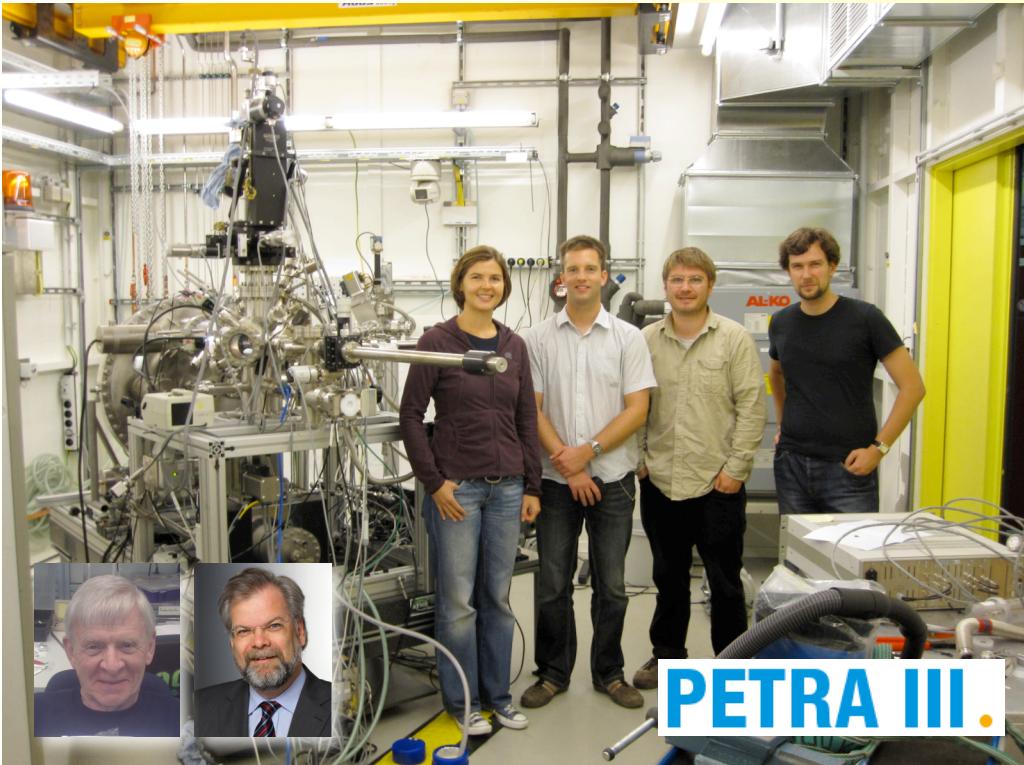
# Electronic Structure of EuO Magnetic Oxide Contacts to Silicon

September 14, 2011 | Martina Müller

Research Center Jülich

Peter Grünberg Institut (PGI-6)

# Acknowledgements



PETRA III.

HAXPES at PETRA III (Hamburg)  
*sample* September 2011

Beamlne P09: SPECS Phoibos 225  
HAXPES Electron analyzer

C. Caspers, M. Müller  
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(*FZ Jülich*)

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C. S. Fadley  
(*UC Davis*)

A. Gloskovskii (*U Mainz*)  
W. Drube (*DESY*)

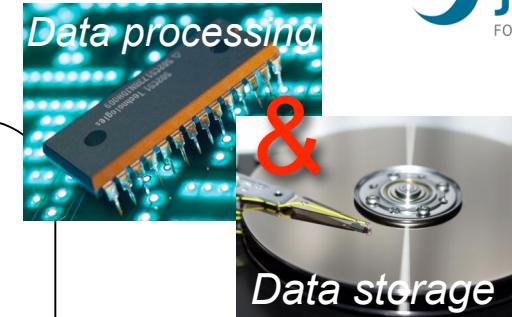
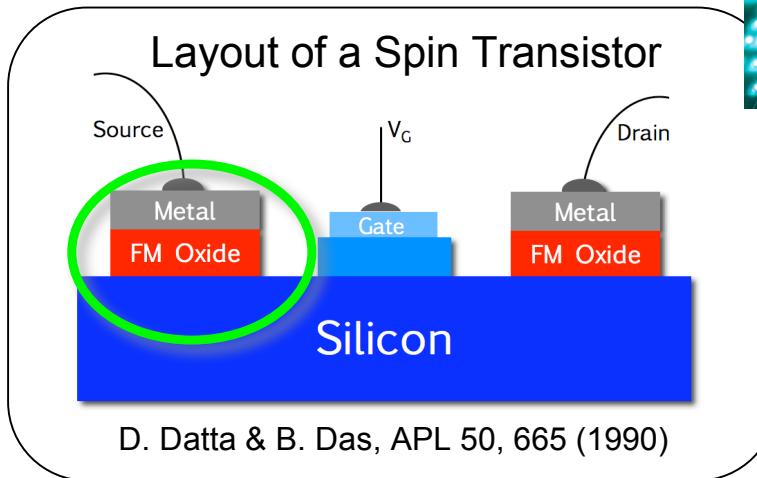
Deutsche  
Forschungsgemeinschaft  
**DFG**

Gefördert vom  
  
Bundesministerium für Bildung und Forschung

# Magnetic Oxides for Spintronics

*...the three central issues:*

1. Spin Injection



3. Spin Detection

2. Spin Transport / Gate Control

→ Requirements for spin contacts

Large spin polarization  
&  
Conductance match

G. Schmidt et al., PRB 62, R4790 (2000)

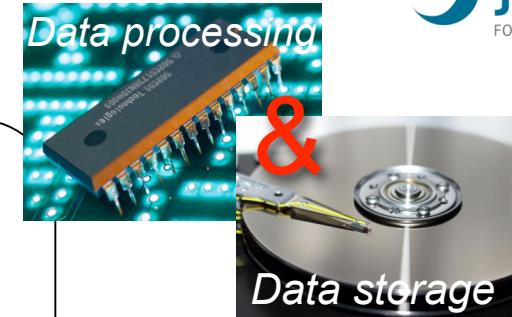
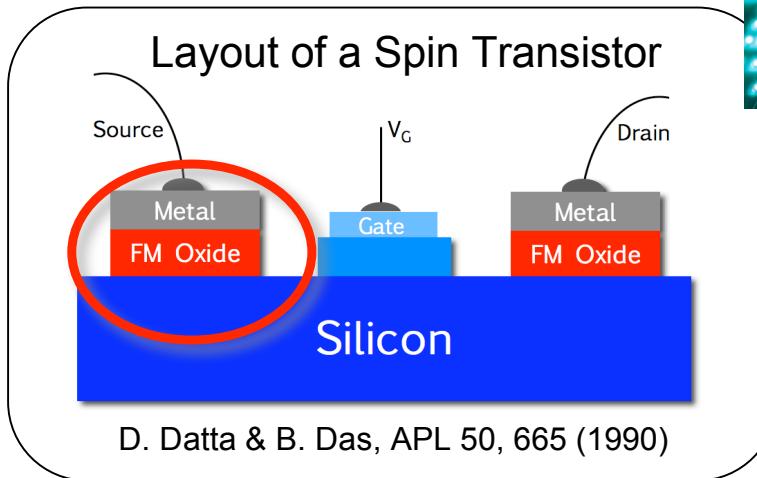
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- ✓ Large spin filtering property
- ✓ Spin filter tunneling transport
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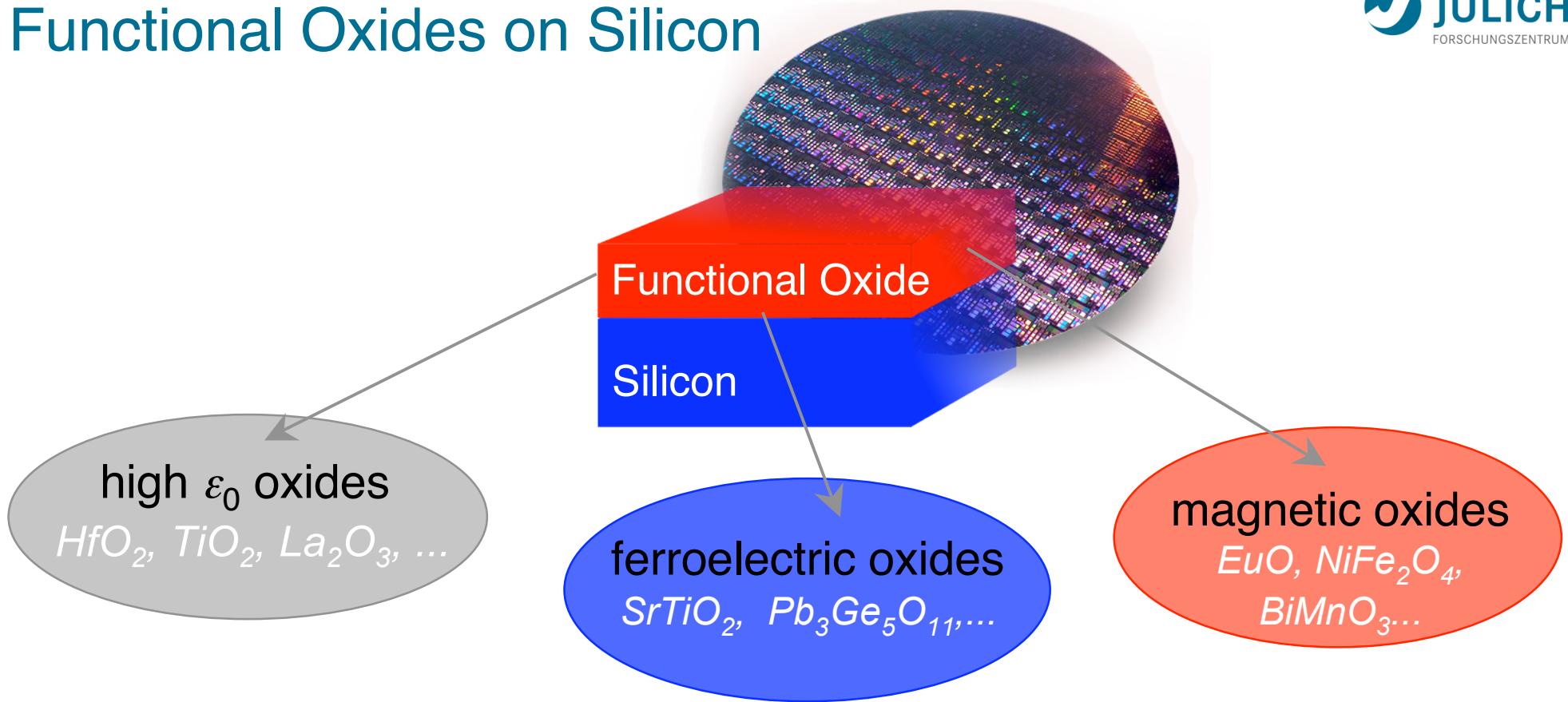
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# Functional Oxides on Silicon



Journal of  
**MATERIALS RESEARCH**

Welcome

Comments

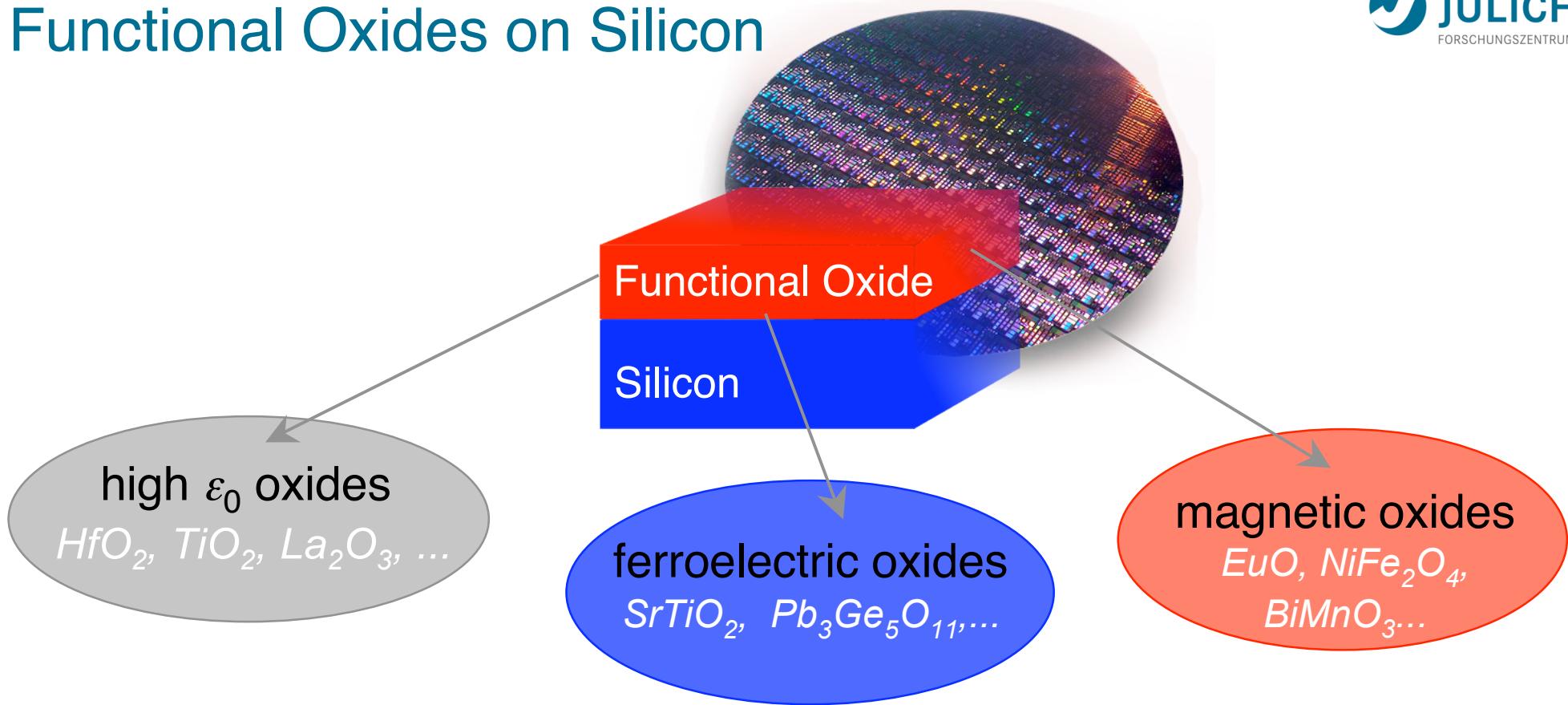
## Thermodynamic stability of binary oxides in contact with silicon

K.J. Hubbard<sup>a)</sup> and D.G. Schlom

Department of Materials Science and Engineering, The Pennsylvania State University,  
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(Received 8 June 1995; accepted 26 April 1996)

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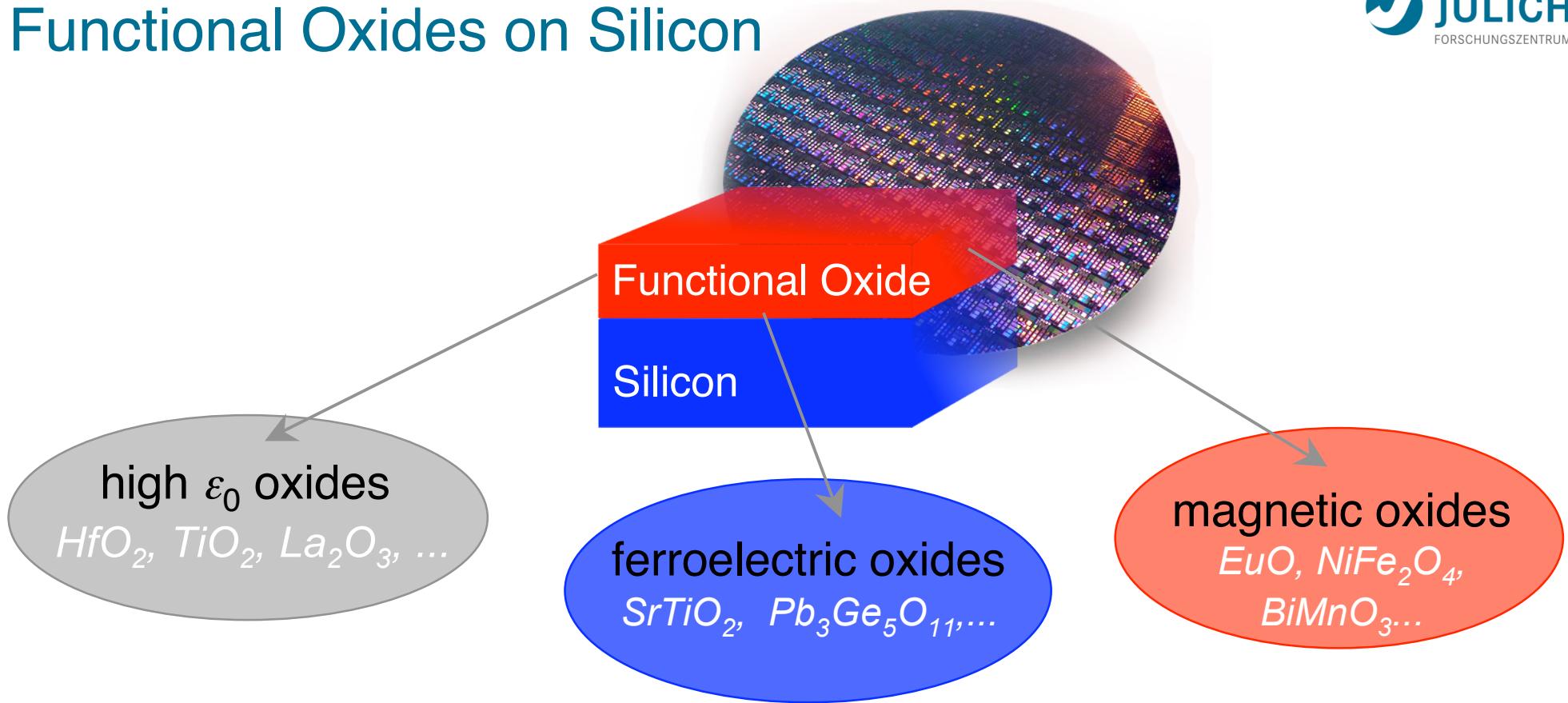
**High- $\epsilon_0$  Oxide on Si**  
A. Kingon, Nature 406 (2000)  
„Alternative dielectrics  
to silicon dioxide for  
memory and logic devices“

**Ferroelectric Oxide on Si**  
D. Schlom, Science 32 (2009)  
„A ferroelectric oxide  
made directly  
on silicon“

**Magnetic Oxide  
on Silicon**

?

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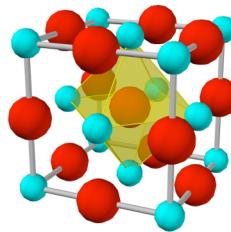
**Magnetic Oxide  
on Silicon**

**EuO**

# Europium Oxide Synthesis

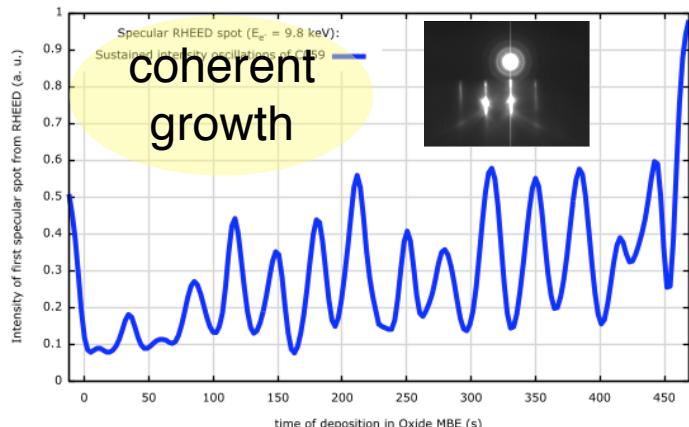
- Heisenberg Ferromagnet

$$T_c = 70 \text{ K} \text{ and } M_S = 7 \mu_B / \text{Eu}^{2+}$$

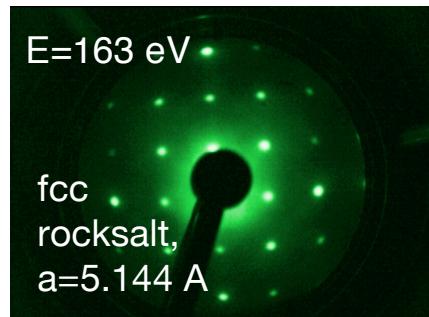


- Metastable,  
high reactivity towards  $\text{Eu}_2\text{O}_3$

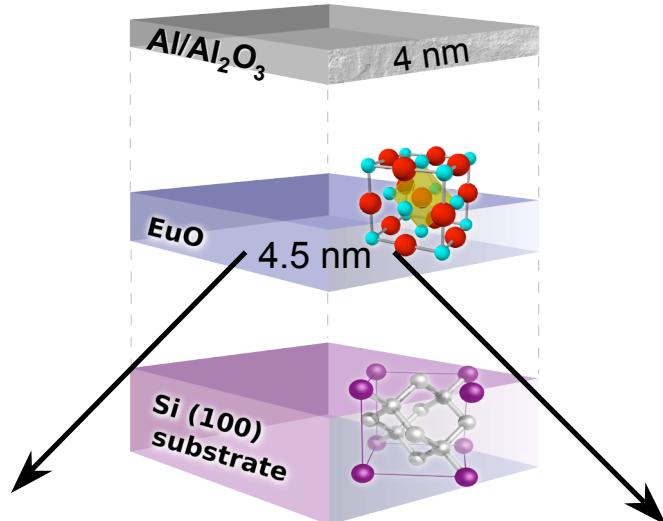
**EuO/YSZ(001)**



→ sustained layer-by-layer growth



→ EuO on Silicon



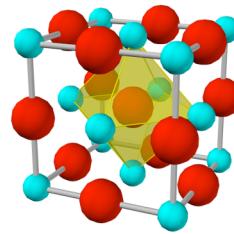
*Type I* EuO  
stoichiometric EuO

*Type II* EuO  
Oxygen-rich Eu<sub>1</sub>O<sub>1+x</sub>

# Europium Oxide Synthesis

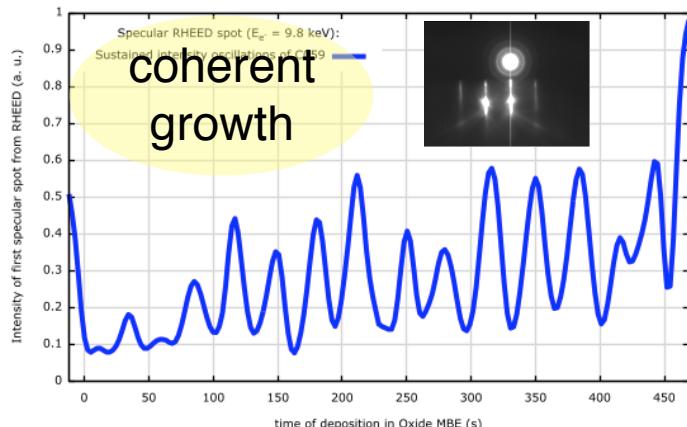
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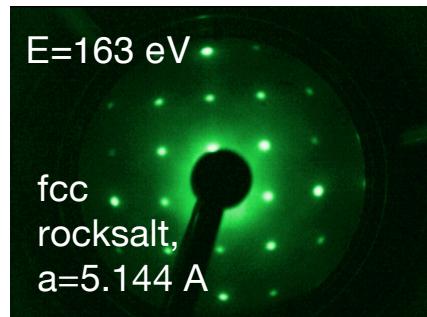


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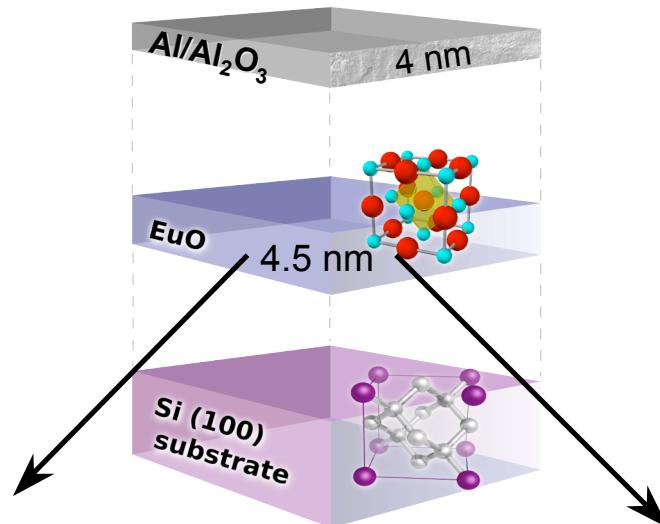
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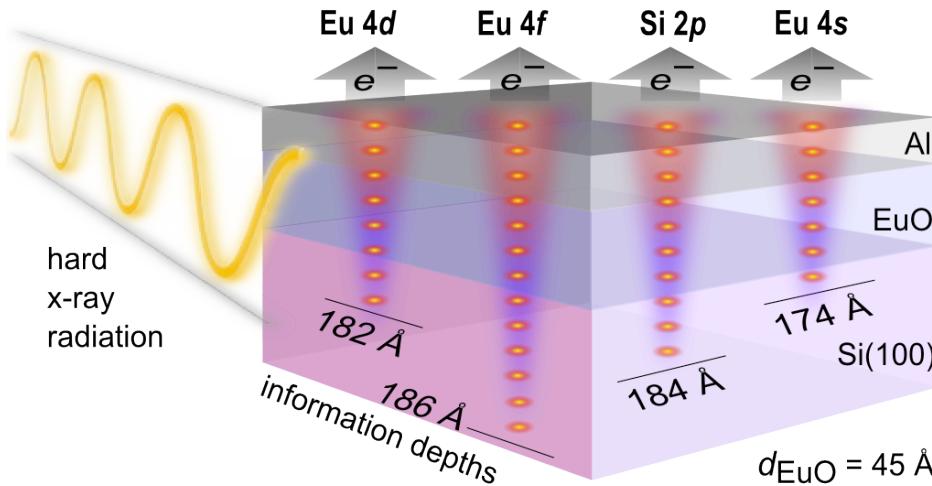
→ EuO on Silicon



*All details on EuO Synthesis*

→ P01 Christian Caspers

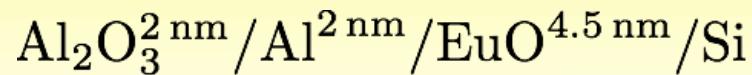
# Depth profiling via HAXPES



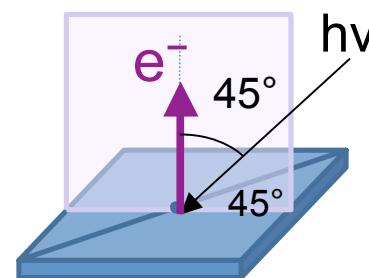
→ EuO thin film chemical state:  
Stoichiometry & homogeneity

- Excitation energy: 4.2 keV
- Energy resolution: 500meV

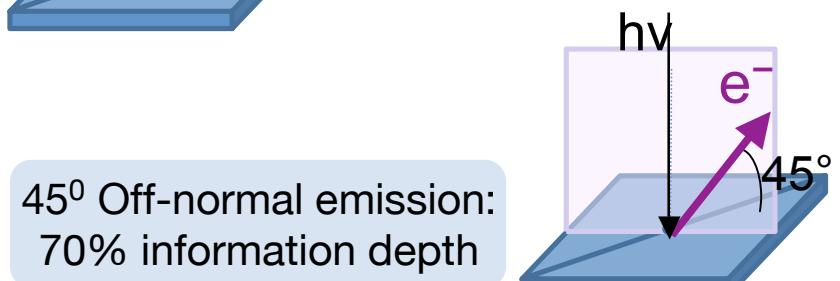
→ EuO/Si: Bulk vs. Interface



$$I(\lambda(E_{kin}), \alpha) = 95\% \int_0^{\infty} e^{\frac{x}{\lambda \cos(\alpha)}} dx$$



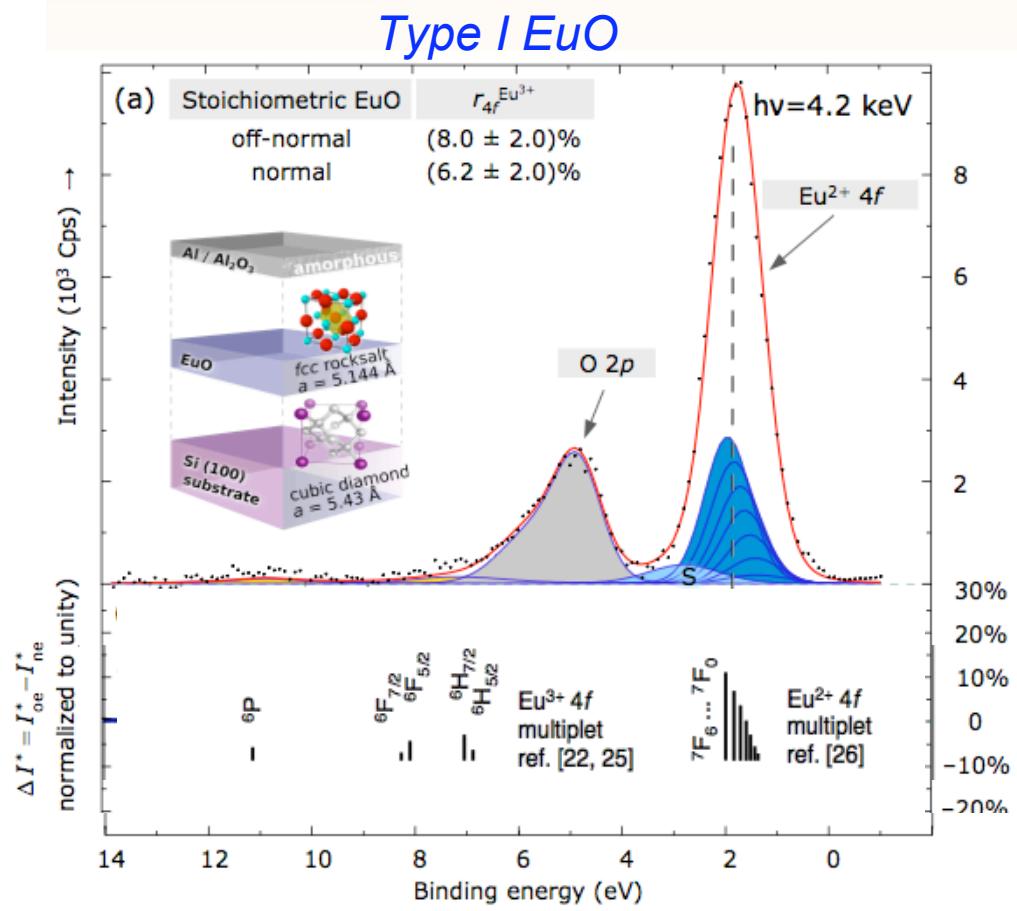
Normal emission:  
100% information depth



45° Off-normal emission:  
70% information depth

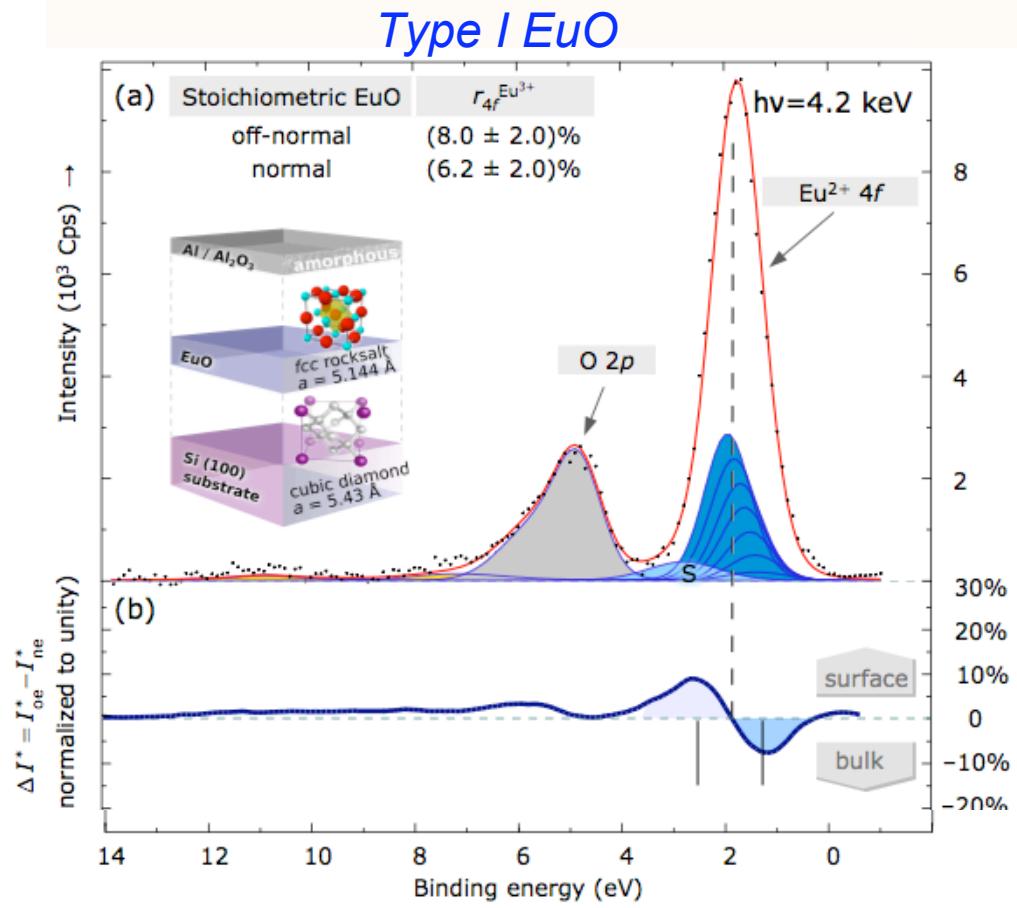
# The $4f$ valence bands

- Eu  $4f$  : strongly localized & weak hybridization
- Divalent Eu $^{2+}$ :  $4d^{10} \ 4f^7 \rightarrow$  Ferromagnetic moment  $7 \ \mu_B$



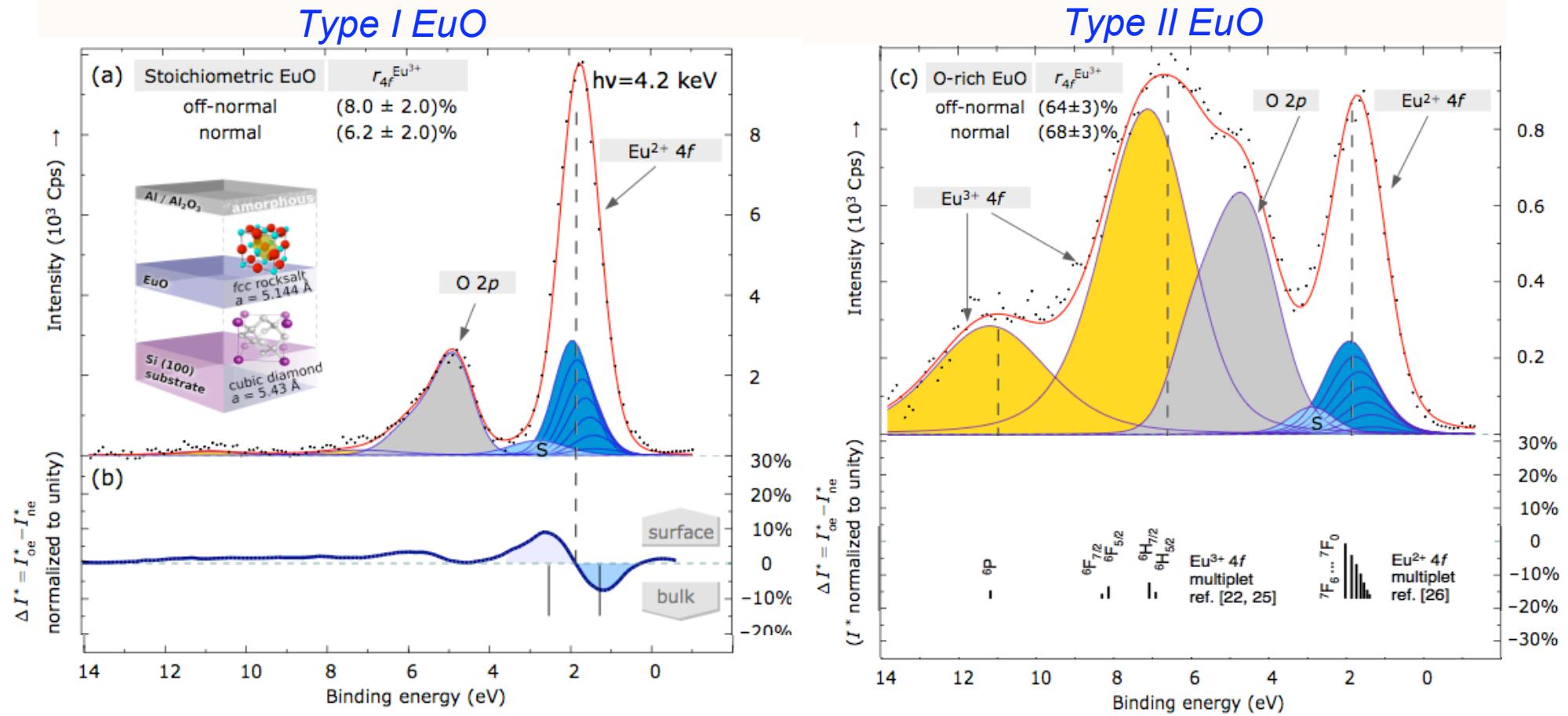
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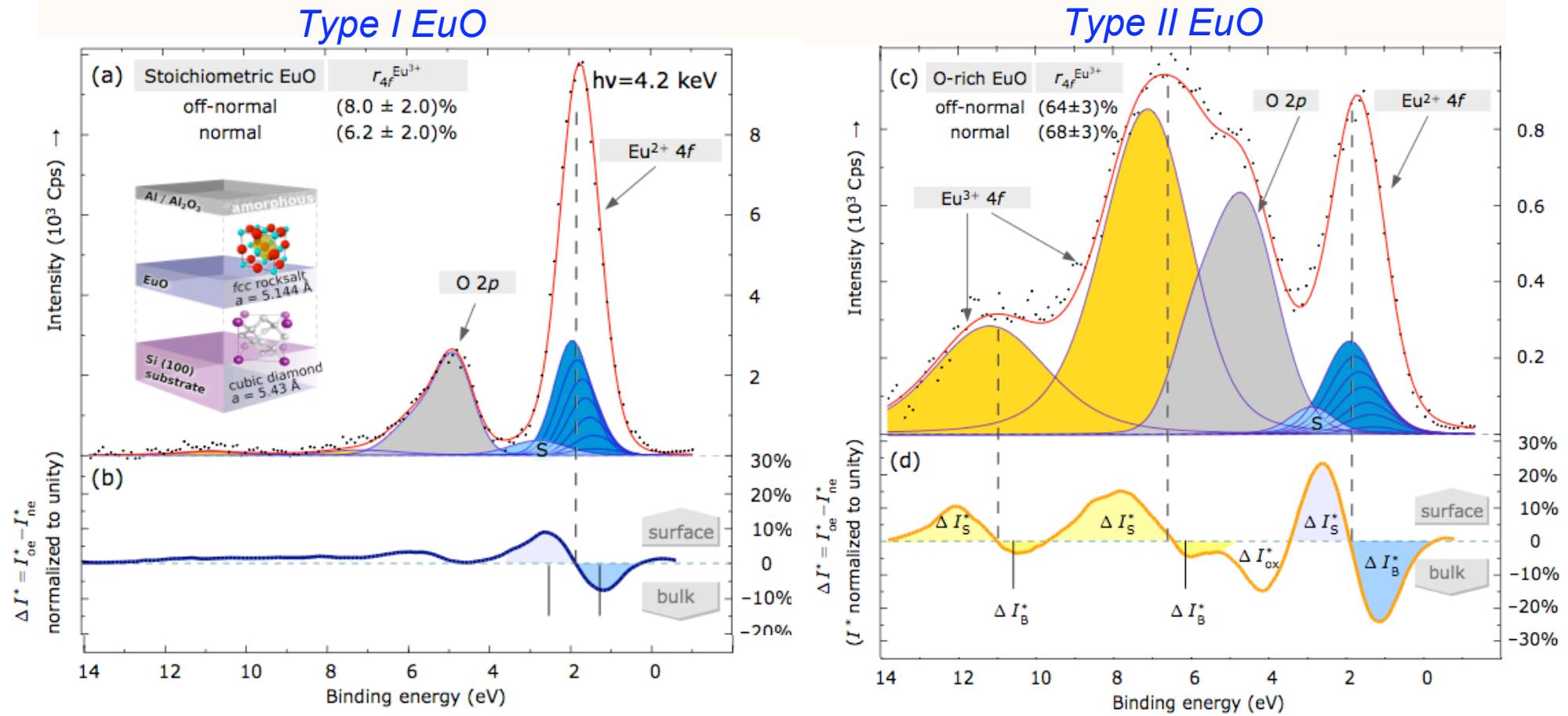
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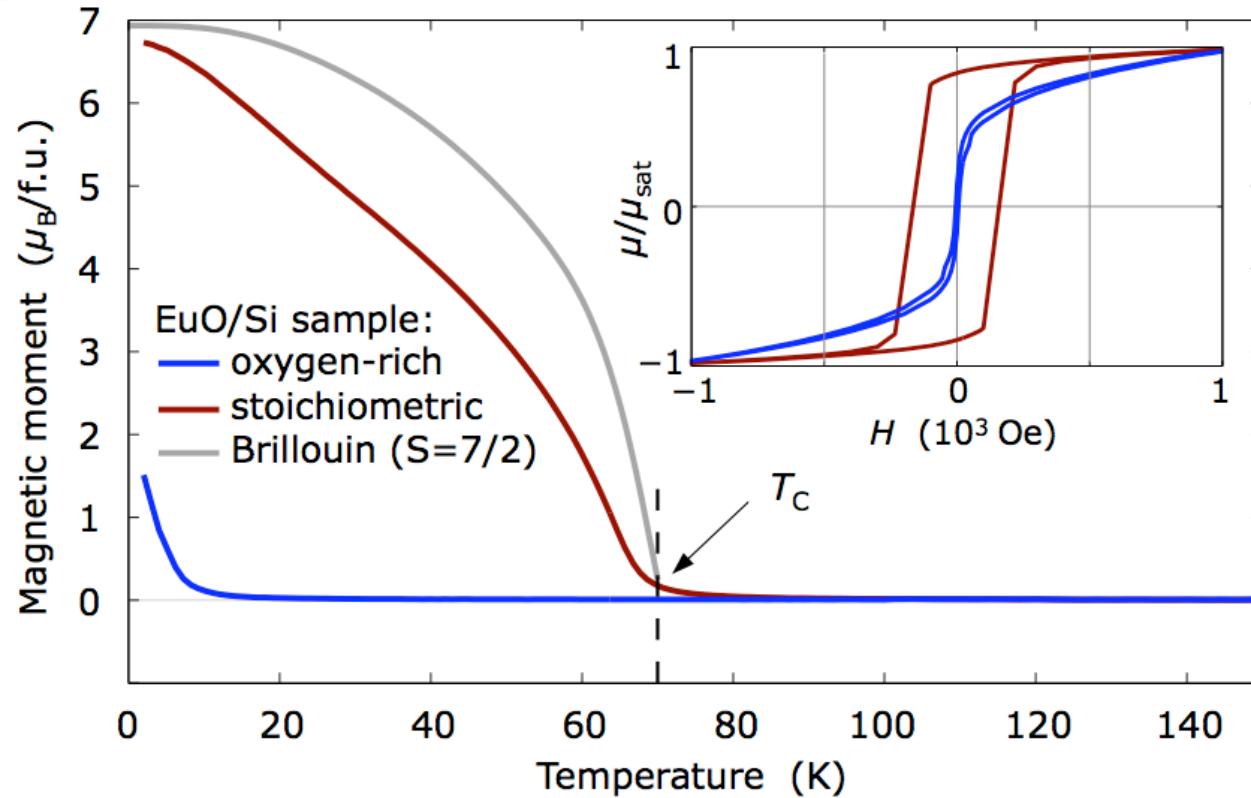
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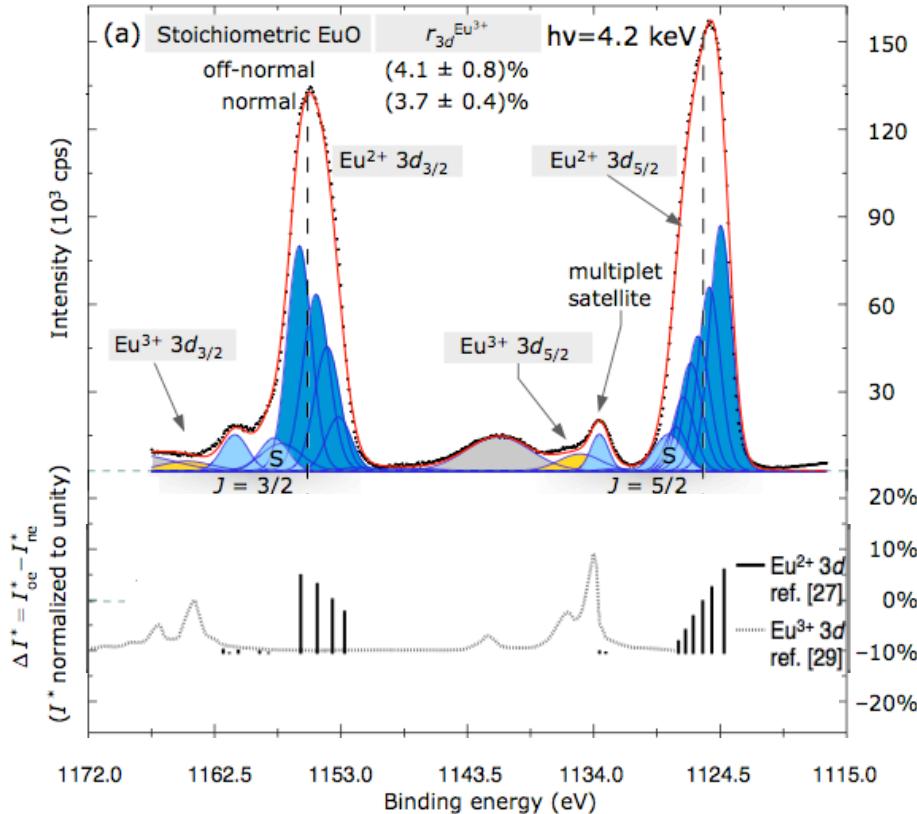
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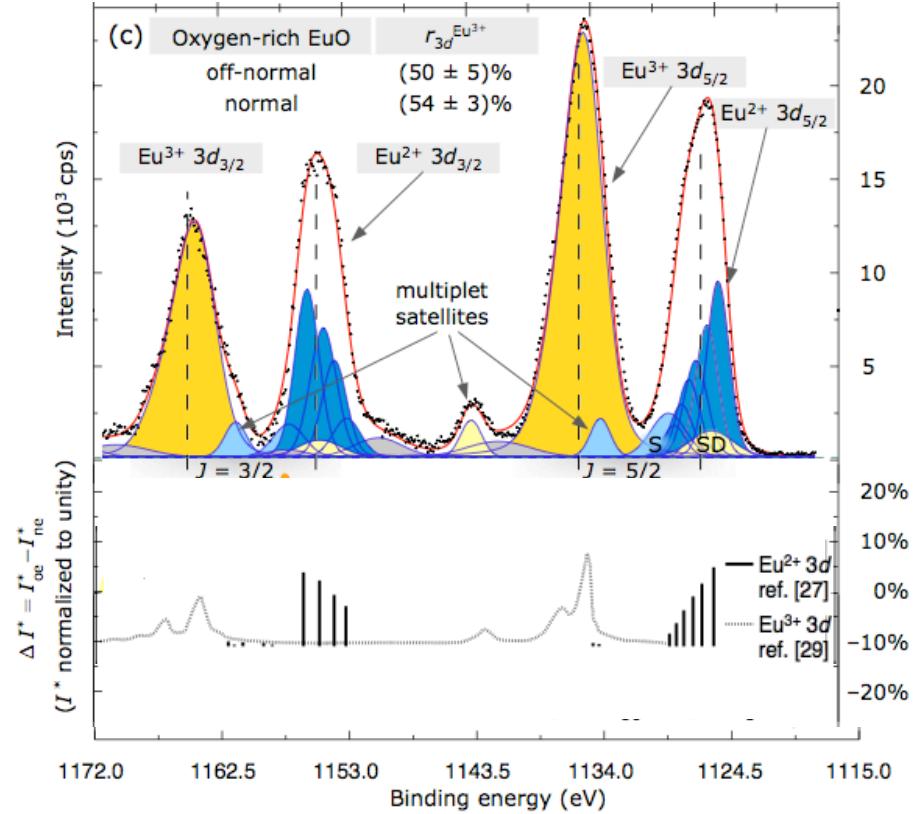


# The 3d core levels

Type I EuO



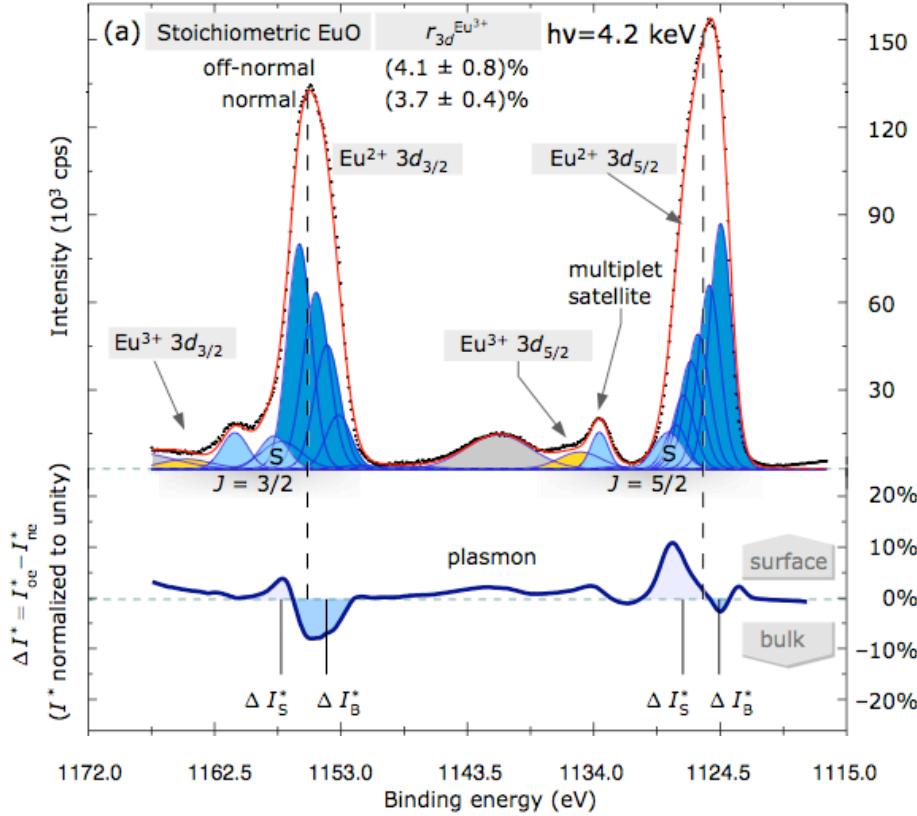
Type II EuO



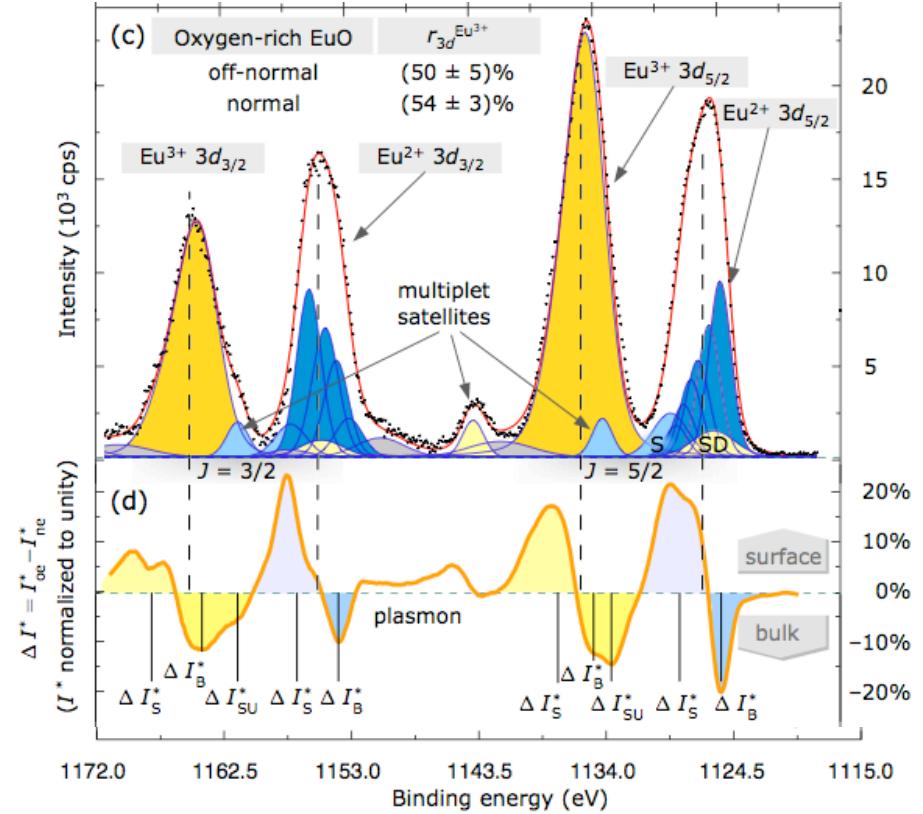
- Weak SO-splitting & large photoionization cross section
- $3d_{5/2}$  and  $3d_{3/2}$  multiplet &  $\text{Eu}^{3+}$  shake-up spectral contributions
- about 40% increased surface sensitivity compared to 4f

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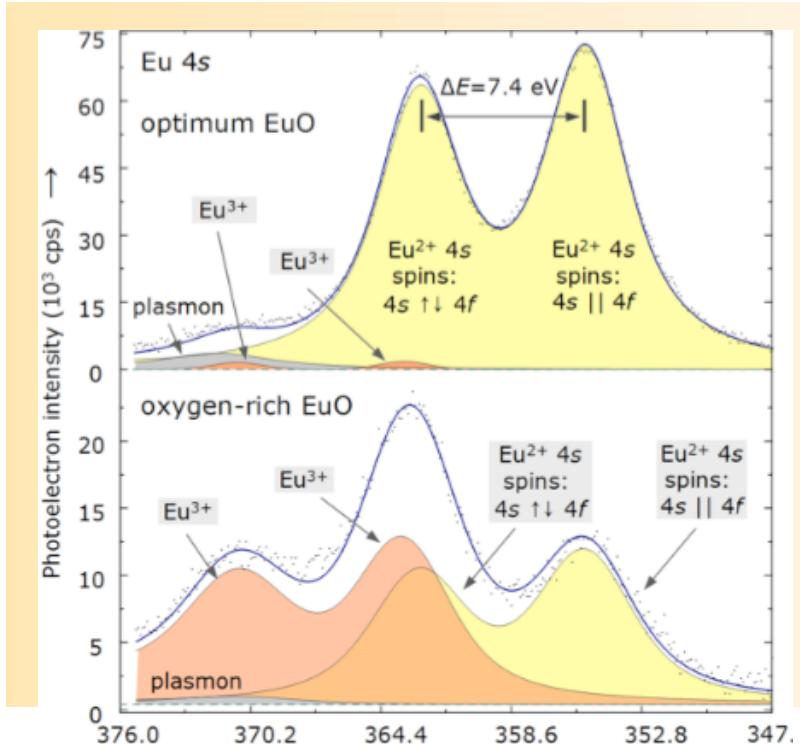


Type II EuO



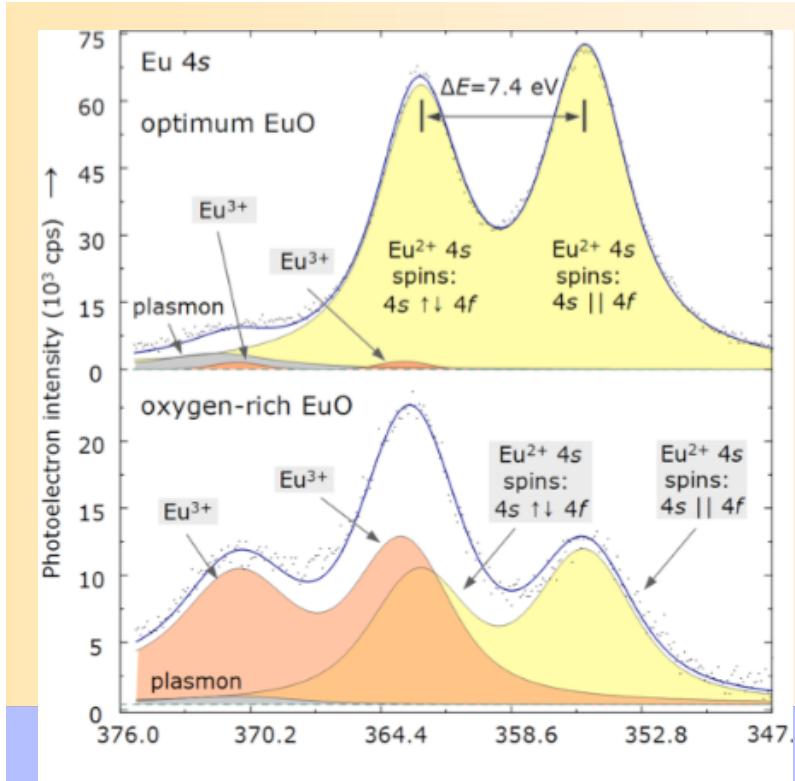
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# The $4s$ and $4d$ core levels

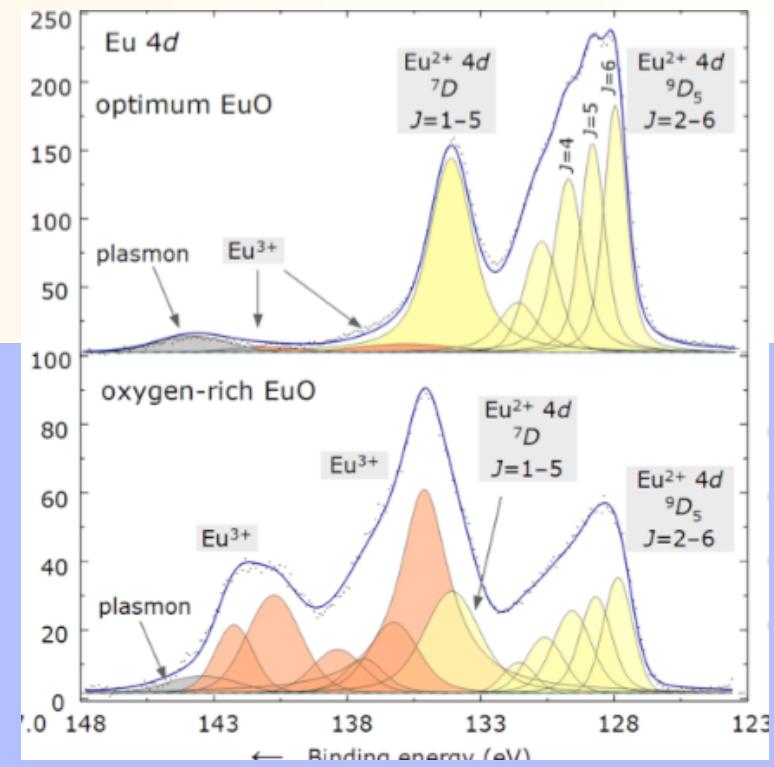


- $4s$   $\text{Eu}^{2+}$  doublet
- Exchange splitting  
 $4s$  (inner shell) -  $4f$  (localized moments)

# The $4s$ and $4d$ core levels



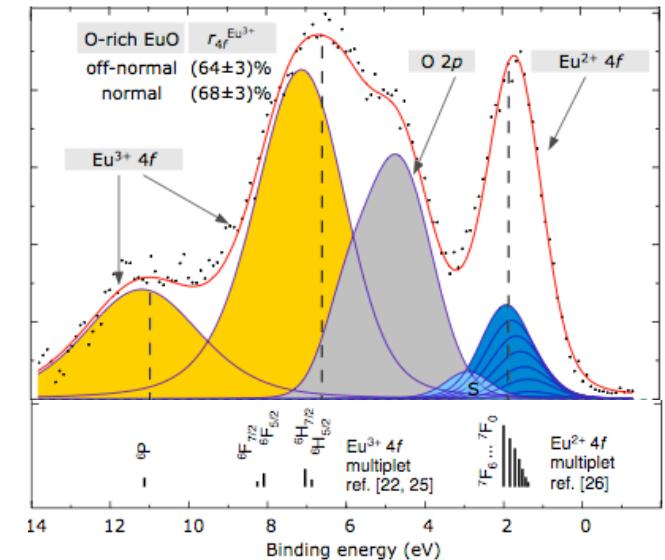
- $4s$  Eu<sup>2+</sup> doublet
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- Complex  $4d$  Eu<sup>2+</sup> multiplet
- Strong  $4d$  -  $4f$  exchange, weak SO
- $J = L - S$  components resolved

# Chemical State of EuO on Silicon

- Complementing spectral information from ***4f, 4s, 4d, 3d valence and core-level states***
- Fit with convoluted Gaussian-Lorentzian curves
- Three tunable parameters:  
Eu<sup>2+/3+</sup> energy distance, intensity ratio & FWHM



→ Determination of EuO stoichiometry

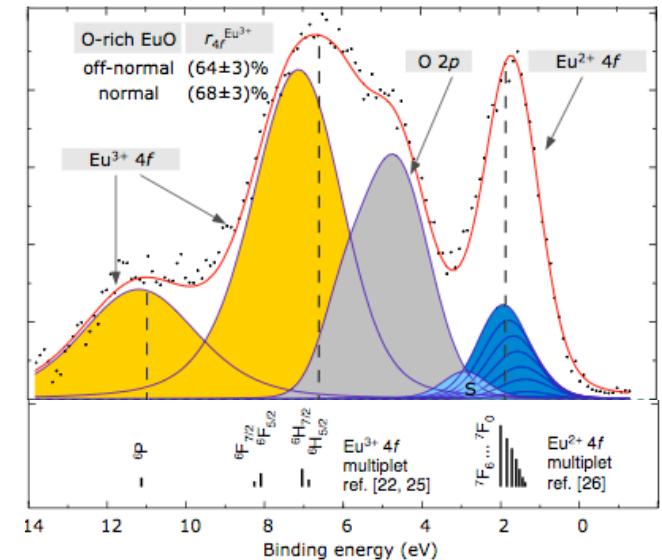
|                            | Type I EuO | Type II EuO |
|----------------------------|------------|-------------|
| divalent Eu <sup>2+</sup>  | 97%        | 40 %        |
| trivalent Eu <sup>3+</sup> | 3%         | 60%         |

*Integral spectral intensity ratio:*

$$r^{\text{Eu}^{3+}} = \frac{A^{\text{Eu}^{3+}}}{A^{\text{Eu}^{2+}} + A^{\text{Eu}^{3+}}}$$

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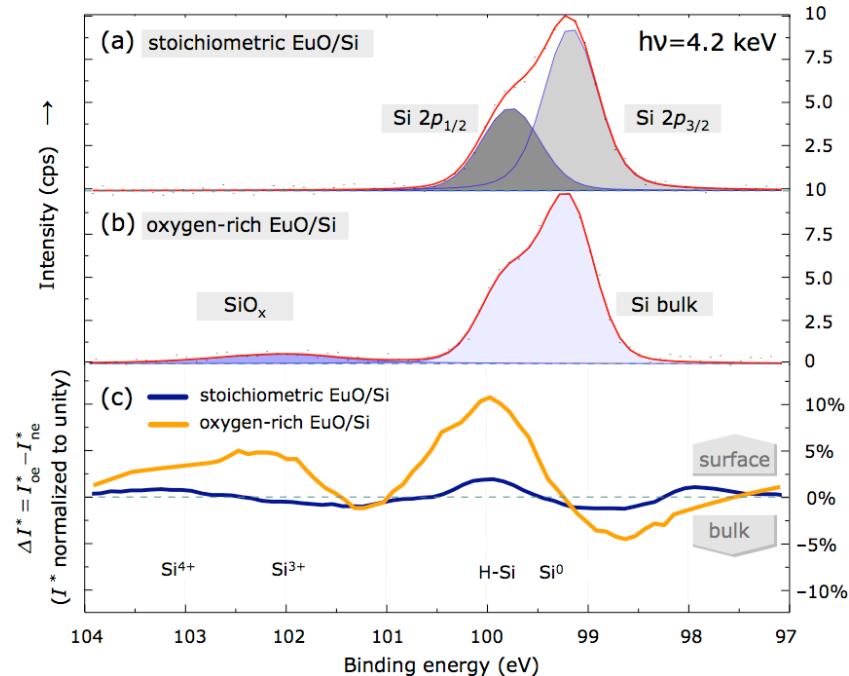
|                            | Stoichiometric | Oxygen-rich |
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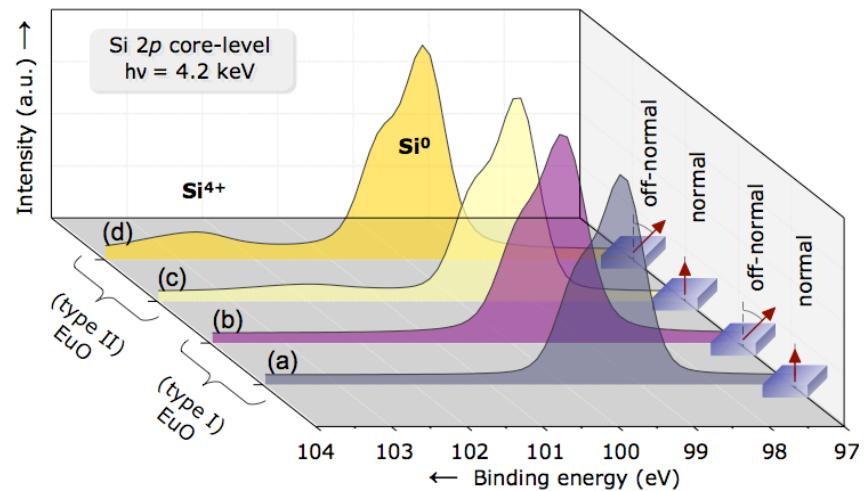
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→ *Difference in Synthesis:*  
 $\Delta p_{\text{O}_2} = 2 \times 10^{-9} \text{ mbar}$

# The EuO/Silicon Interface

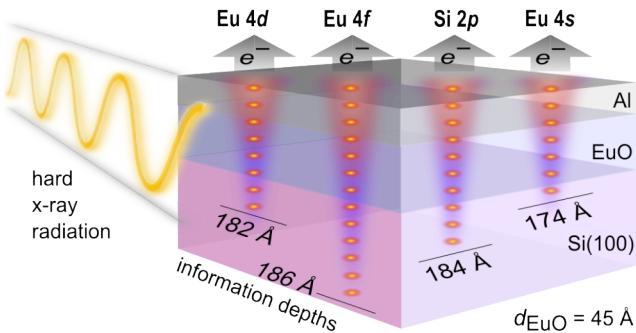


- Si 2p core level
- Normal ( $0^\circ$ ) and off-normal ( $43^\circ$ ) emission  
*Si bulk  $\leftrightarrow$  EuO/Si interface*
- LEED: H-Si(001) surface (HF etching)



- Stoichiometric EuO:  
→ **NO  $\text{SiO}_x$  at interface !!**
- Oxygen-rich EuO:  
→  $\text{Si}^{3+}/\text{Si}^{4+}$  at interface
- **High-quality magnetic oxide EuO chemically stable on Si**

# Conclusions and Summary



- ✓ Stoichiometric EuO stabilized directly on Si
- ✓ Proof of homogeneity of EuO thin films
- ✓ Chemically clean EuO/ Silicon interface

→ *Chemical integration of a Magnetic Oxide with Silicon*

P01 Christian Caspers

Read more soon: C. Caspers, M. Müller, A. X. Gray, A. M. Kaiser, A. Gloskovskii, C. S. Fadley, W. Drube, and C. M. Schneider

„*Chemical Stability of the Magnetic Oxide EuO on Silicon observed by HAXPES*“

under review at Phys. Rev. B

„*Electronic properties of EuO spin filter tunnel contacts directly on silicon*“

under review at phys. stat. solidi (RRL)