

# PROBING THE ELECTRONIC AND MAGNETIC PROPERTIES OF BULK MATERIALS AND BURIED LAYERS AND INTERFACES WITH STANDING-WAVE AND HARD-X-RAY PHOTOEMISSION

C.S. Fadley

*Department of Physics, University of California Davis Materials Sciences Division,  
Lawrence Berkeley National Laboratory*

\*e-mail: fadley@physics.ucdavis.edu

In this lecture, I will discuss some new directions in soft x-ray photoemission (XPS, SXPS) and hard x-ray photoemission (HXPS, HAXPES, HIKE) by my group and its several collaborators [1-12], including experiments carried out at the ALS, BESSY, SPring8, Petra III, and SLS. These involve combined SXPS and HXPS studies of buried layers and interfaces in magnetic and transition-metal oxide multilayers [5,6,8,10], hard x-ray photoemission studies of the bulk electronic structure of some spintronic materials [4,7,11]; including band-offset measurements in oxide multilayers[12]; the use of

standing waves from multilayer mirrors to enhance depth contrast in spectroscopy [5,6,10], as well as in angle-resolved photoemission (ARPES) [1,5] and photoelectron microscopy [3]; and the prospects for carrying out bulk sensitive hard x-ray ARPES (HARPES) [9] and hard x-ray photoelectron diffraction (HXPD) [2].

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## References

- [1] C.S. Fadley, "X-ray photoelectron spectroscopy: progress and perspectives," *J. Electron. Spectrosc. Relat. Phenom.* **2** (2010) 178 – 179 (invited review).
- [2] A. Winkelmann, J. Garcia de Abajo, and C.S. Fadley, "High energy photoelectron diffraction: model calculations and future possibilities," *New J. Phys.* **10** (2008) 113002.
- [3] F. Kronast, R. Ovsyannikov, A. Kaiser, C. Wiemann, S.-H. Yang, D.E. Bürgler, R. Schreiber, F. Salmassi, P. Fischer, H.A. Dürr, C.M. Schneider, W. Eberhardt, and C.S. Fadley, "Depth-resolved soft x-ray photoelectron emission microscopy in nanostructures via standing-wave excited photoemission," *Appl. Phys. Lett.* **93** (2008) 243116; A.X. Gray, F. Kronast, C. Papp, S.H. Yang, S. Cramm, I.P. Krug, F. Salmassi, E.M. Gullikson, D.L. Hilken, E.H. Anderson, P.J. Fischer, H.A. Dürr, C.M. Schneider, and C.S. Fadley, "Standing-wave excited soft x-ray photoemission microscopy: application to nanodot Co magnetic arrays," *Appl. Phys. Lett.* **97** (2010) 062503.
- [4] Z. Boekelheide, A.X. Gray, C. Papp, B. Balke, D.A. Stewart, S. Ueda, K. Kobayashi, F. Hellman, and C.S. Fadley, "Band gap and electronic structure of an epitaxial, semiconducting  $\text{Cr}_{0.80}\text{Al}_{0.20}$  thin film," *Phys. Rev. Lett.* **105** (2010) 236404.
- [5] A.X. Gray, C. Papp, B. Balke, S.-H. Yang, M. Huijben, E. Rotenberg, A. Bostwick, S. Ueda, Y. Yamashita, K. Kobayashi, E.M. Gullikson, J.B. Kortright, F.M.F. de Groot, G. Rijnders, D.H.A. Blank, R. Ramesh, and C.S. Fadley, "Interface properties of magnetic tunnel junction  $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3/\text{SrTiO}_3$  superlattices studied by standing-wave excited photoemission spectroscopy," *Phys. Rev. B* **82** (2010) 205116, and A.X. Gray *et al.*, to be published.
- [6] S. Döring, F. Schönbohm, U. Berges, R. Schreiber, D.E. Bürgler, C.M. Schneider, M. Gorgoi, F. Schäfers, C. Papp, B. Balke, C.S. Fadley, C. Westphal, "Hard x-ray photoemission study using standing-wave excitation applied to the  $\text{MgO}/\text{Fe}$  interface," *Phys. Rev. B* **83** (2011) 165444; and S.H. Yang, B. Balke, C. Papp, S. Döring, U. Berges, L. Plucinski, C. Westphal, C.M. Schneider, S.S.P. Parkin, and C.S. Fadley, "Determination of layer-resolved magnetic and electronic structure of  $\text{Fe}/\text{MgO}$  by soft x-ray standing-wave core- and valence- photoemission," *Phys. Rev. B* **84** (2011) 184410.
- [7] A.X. Gray, J. Karel, J. Minar, C. Bordel, H. Ebert, J. Braun, S. Ueda, Y. Yamashita, L. Ouyang, D.J. Smith, K. Kobayashi, F. Hellman, and C.S. Fadley, "Hard X-ray photoemission study of near-heusler  $\text{Fe}_x\text{Si}_{1-x}$  Alloys," *Phys. Rev. B* **83** (2011) 195112.
- [8] A.X. Gray, A. Janotti, J. Son, J.M. LeBeau, S. Ueda, Y. Yamashita, K. Kobayashi, A.M. Kaiser, R. Sutarto, H. Wadati, G.A. Sawatzky, C.G. Van de Walle, S. Stemmer, C.S. Fadley, "Insulating state of ultrathin epitaxial  $\text{LaNiO}_3$  thin films detected by hard x-ray photoemission," *Phys. Rev. B* **84** (2011) 075104.
- [9] C. Papp, A. Gray, B. Balke, S. Ueda, K. Kobayashi, S. Sakai, H. Yoshikawa, Y. Yamashita, S.L. He, E. Yylvisaker, L. Plucinski, C. Schneider, J. Minar, J. Braun, H. Ebert, W.E. Pickett, C.S. Fadley, "Probing bulk electronic structure with hard X-ray angle-resolved photoemission," *Nature Materials* **10** (2011) 759; see also companion News and Views article: D.L. Feng, *Nature Materials* **10** (2011) 729-730.
- [10] A.M. Kaiser, A.X. Gray, G. Conti, J. Son, A. Greer, A. Perona, A. Rattanachata, A.Y. Saw, A. Bostwick, S. Yang, S.-H. Yang, E.M. Gullikson, J.B. Kortright,

- S. Stemmer, and C.S. Fadley, "Suppression of near-Fermi level electronic states at the interface in a  $\text{LaNiO}_3/\text{SrTiO}_3$  superlattice," *Phys. Rev. Lett.* **107** (2011) 116402.
- [11] 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 directly on silicon observed by hard X-ray photoemission spectroscopy," *Phys. Rev. B* **84** (2011) 205217.
- [12] G. Conti, A.X. Gray, A.M. Kaiser, A. Greer, J. Karel, S. Ueda, Y. Yamashita, A. Gloskovskii, A. Jannotti, C. G. Van de Walle, K. Kobayashi, W. Drube, S. Stemmer, and C.S. Fadley, "Determination of band offsets in complex oxide thin-film heterostructures by hard X-Ray photoelectron spectroscopy", to be published.