UCRL-JRNL-208358

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Spin Polarized Electron Energy Loss Spectroscopy on Fe(100) Thin Films Grown on Ag(100)

T. Komesu, G. D. Waddill, J. G. Tobin

December 2, 2004

Journal of Physics: Condensed Matter

Spin Polarized Electron Energy Loss Spectroscopy on Fe(100) Thin Films Grown on Ag(100)

Takashi Komesu, G.D. Waddill,
University of Missouri-Rolla, Department of Physics, Rolla, MO 65401-0249
and J.G. Tobin
Lawrence Livermore National Laboratory, Livermore, CA 94550

Abstract

We report sharp spin-dependent energy loss features in electron scattering from bcc Fe(100) thin films grown on Ag(100). Majority spin features are observed at ~1.8 and 2.5 eV energy loss, and a minority spin feature is observed at ~2.0 eV energy loss. The majority spin peaks are attributed to spin-flip exchange scattering from the Fe films, with the lowest energy feature corresponding to the exchange splitting for the Fe. The minority spin peak is attributed to non-flip exchange scattering with an energy corresponding to the separation between occupied and unoccupied minority spin bands.

Introduction

Spin-polarized electron energy loss spectroscopy (SPEELS) developed in the 1980s and has become a valuable technique for probing Stoner excitations[1-8] and more recently spin waves[9]. In so-called spin flip exchange scattering, an incident electron of a given spin occupies an empty state of the target material and an electron of opposite spin is excited and detected. This process produces a Stoner excitation and gives SPEELS its sensitivity to the occupied and unoccupied parts of the spin-split electronic structure of materials. Consequently SPEELS is a complementary technique to spin-resolved photoemission and inverse photoemission that more directly probe the occupied and unoccupied spin-split band structure respectively. SPEELS studies have been done using unpolarized electron sources with scattered electron spin detection[1], with spin-polarized sources without scattered electron spin detection[2,3], and with both spin-polarized sources and scattered electron spin detection[4-8]. In general, these studies report rather broad featureless data in both energy and angle dependence, and this has been attributed to nonconservation of the perpendicular momentum component in the scattering process[7], nonuniform exchange splitting throughout the Brillouin zone[2], and umklapp scattering together with the structure of interband densities of Stoner states in the material[10]. Only in the study of Cr_2O_3[11] and bcc Co/GaAs(001)[3] are sharp loss features reported. However, a subsequent study of fcc Co/Cu(001)[7] did not observe any sharp energy loss features.

It is useful to describe the SPEELS experiment in terms of the four basic spin-dependent scattering processes. These are divided into flip and non-flip scattering for incident electrons with spins parallel or anti-parallel to the majority spin orientation. For flip scattering, an incident electron occupies an empty state just above the Fermi energy and transfers its energy to an electron of the opposite spin. This electron may now escape the material and be detected. This process results in an electron-hole excitation with opposite spins for the electron and hole; a configuration identical with a Stoner excitation. Non-flip processes can occur via both direct and exchange scattering. In the former, the incident electron scatters from long range electric field fluctuations associated with elementary excitations of the target, and the scattering process occurs well outside the target. It has been shown that direct non-flip scattering preserves the polarization of the incident beam[12]. In non-flip exchange scattering, the incident electron penetrates the target, and short range interactions produce electron-hole pairs, with the electron and hole having the same spin orientation.

For an initially unpolarized electron beam, the polarization of the scattered electrons can be written as $P = \frac{\left(F^{\uparrow} - F^{\downarrow}\right) + \left(N^{\uparrow} - N^{\downarrow}\right)}{F^{\uparrow} + F^{\downarrow} + N^{\uparrow} + N^{\downarrow}}$ where *F* and *N* refer to flip and non-flip scattering, and the arrows refer to the spin of the scattered electron. Since direct non-flip scattering preserves the incident beam polarization[12] we will only consider non-flip exchange scattering. Then $N^{\uparrow}$ results in an electron in a previously unoccupied majority spin state and should be negligible because of the relatively low density of empty majority spin states. A similar argument suggests that the probability of $F^{\downarrow}$ should be small because this involves occupation of a previously unoccupied majority spin state. This leaves $F^{\uparrow}$ and $N^{\downarrow}$ as the only remaining non-negligible scattering processes. Consequently, majority spin features in the energy loss spectrum are associated with spin-flip scattering, and these features occur at energies separating occupied majority spin bands and unoccupied minority spin bands. Minority spin features, however, are associated with non-flip exchange scattering where an incident minority spin electron occupies an empty minority spin state above the Fermi energy producing a minority spin scattered electron. These features will be observed at energies separating occupied and unoccupied minority spin bands. In this paper, we present the experimental results of spin polarized electron energy loss spectroscopy on bcc Fe thin films grown on a Ag(100) crystal where we see sharp energy loss features in both the majority and minority electron spectra. We interpret the spin-dependent energy loss features in terms of spin-flip scattering for the majority spin features and non-flip exchange scattering for the minority spin peak.

Experimental Procedure

The main components of the SPEELS experiment are shown in Figure 1. The electron source is a commercial LEED/Auger electron gun. The data were acquired using an incident kinetic energy of 300 eV. After scattering from the sample, the electrons are collected in a hemispherical electron energy analyzer (Physical Electronics Model 3057) with multichannel electron detection. For spin-resolved work, the multichannel detector has a central hole that allows passage of the energy analyzed electrons into the electron optics for the mini-Mott detector. In this case, the high voltages on the channel plates are turned off and the channel plates and anode assembly become part of the first lens stack, directing the electrons into a 90° spherical sector. The 90° sector is run at relatively high pass energy: energy resolution is determined by the hemispherical analyzer pass energy and the electron source. The 90° sector allows the simultaneous resolution of spin-polarization both normal to the sample and in the plane of the sample along the electron emission direction. After the 90° sector, the electrons travel through another lens stack, into the Mini-Mott detector. In the Mini-Mott, the electrons are accelerated to ~25 kV, with four channeltrons positioned horizontally and vertically used for electron counting. More details of this system may be found in Ref. 13. For the SPEELS measurements, the total scattering angle is fixed at 135° with the electrons incident at 67° with respect to the sample normal. The overall energy resolution for the SPEELS measurements (electron source and energy analyzer is about 0.6 eV or better at full width at half maximum). The experiments were carried at 2×10^{-10} Torr.

Thin films of Fe grown on Ag(100) have been characterized in previous studies using many techniques[14, 15]. The Ag crystal was cleaned with Ar^{+} sputtering followed by annealing to 450 °C. Fe films are deposited using e-beam evaporation. The films have a p(1x1) LEED pattern and no observable contamination as judged from XPS measurements. Because of the reactive nature of the Fe films, the SPEELS data is acquired in less than 4 or 5 hours, after which the Fe is sputtered off and a fresh film is produced for additional measurements. Here we focus on in-plane magnetism which can be achieved for bcc Fe films more than 3 ML thick film. We have concentrated our measurements on 20 ML Fe films, and use the ratio of Fe 2p and Ag 3d photoemission peaks as a thickness monitor. The magnetic character of the films has been confirmed using x-ray magnetic circular dichroism (XMCD) acquired using beamline 4ID-C at the Advanced Photon Source at Argonne National Laboratory[16]. Fe L-edge x-ray absorption and XMCD spectra for a typical Fe film are shown in Figure 2. The sample was magnetized parallel and antiparallel to the [001] direction between successive energy loss spectra using a pulsed magnetic field applied with a nearby coil. The measurements were carried out at room temperature.

Results and Discussion

Figure 3 shows the results of SPEELS measurements from the clean Ag(100) surface. The majority spin (parallel to the magnetic field) and the minority spin (anti-parallel to the magnetic field) spectra are indicated with upward and downward triangles in the lower spectra respectively. The spin-integrated data is shown as circles in the upper spectra, and shows peaks at ~4 and 7.8 eV due to excitation of surface and bulk plasmons. This is in very good agreement with previously published EELS data on Ag(100)[17]. There is no distinguishable difference between the majority and minority spin spectra indicating that the polarization is zero within experimental error over the entire energy loss region examined as is anticipated.

On the other hand, Figure 4 shows the SPEELS result for 20 ML bcc Fe films on Ag(100). The top panel shows the spin integrated spectrum, the middle panel shows the majority spin spectrum, and the bottom panel the minority spin spectrum. The spin-integrated results show a slowly varying energy dependence with a broad loss peak centered near 2.2 eV. This is in reasonable agreement with previous published electron energy loss spectra from single crystal Fe(110)[1,4]. The spin resolved data, however reveal differences in the energy loss spectra for majority and minority electrons. The data reveal relatively sharp majority spin peaks at 1.8 and 2.5 eV and a minority spin peak at approximately 2.0 eV. These relatively sharp features have not been reported previously for SPEELS from Fe(110). The measured spin polarization in these peaks is approximately +15% in the majority peak at 1.8 eV, +10% in the majority peak at 2.5 eV, and -10% in the minority spin peak at 2.0 eV. Elsewhere in the energy loss spectrum the spin polarization is zero.

As previously mentioned, polarization in the scattered electrons can be attributed to exchange scattering, with spin-flip exchange scattering giving rise to majority spin peaks and non-flip exchange scattering producing minority spin peaks. The majority spin peaks are therefore associated with incident electrons that occupy empty minority spin states near the Fermi energy and transfer energy to excited majority spin electrons. The lowest energy peak at ~1.8 eV is thought to derive from electron promotion between conjugate minority and majority spin bands with an excitation energy corresponding to the exchange energy. This energy is in relatively good agreement with the previously reported exchange energy for Fe using SPEELS of between 2.0 and 2.5 eV[1,4]. The higher energy loss feature at ~2.5 eV is thought to be from a transition between opposite spin bands with different band indices and corresponds to a secondary Stoner transition. The minority spin peak is, on the other hand, attributed to incident minority spin electrons occupying empty minority spin states above the Fermi energy and exciting minority spin electrons from the Fe. The energy of the loss peak then corresponds to the splitting between occupied and unoccupied minority spin bands in the Fe.

In summary, we have observed sharp spin-dependent energy loss features for electron scattering from bcc Fe films on Ag(100). We observe both minority and majority spin features and attribute these to exchange scattering of incident electrons with spin-flip scattering responsible for the majority spin peaks and non-flip scattering the minority spin peak.

Acknowledgment

This work was performed under the auspices of the U. S. Department of Energy by UC, Lawrence Livermore National Laboratory under contract W-7405-Eng-48. We would like to thank the scientific and technical staff of Sector 4 of the Advanced Photon Source for their technical assistance in supporting this work.

References

[1] H. Hopster, R. Raue, and R. Clauberg, Phys. Rev. Lett. **53**, 695 (1984).

[2] J. Kirschner, D. Rebenstorff, and H. Ibach, Phys. Rev. Lett. **53**, 698 (1984).

[3] Y. U. Idzerda, D. M. Lind, D. A. Papaconstantopoulos, G. A. Prinz, B. T. Jonker, and J. J. Krebs, Phys. Rev. Lett. **61**, 1222 (1988); J. Appl. Phys. **64**, 5921 (1988).

[4] J. Kirschner, Phys. Rev. Lett. **55**, 973 (1985).

[5] D. Venus and K. Kirschner, Phys. Rev. B **37**, 2199 (1988).

[6] D. L. Abraham and H. Hopster, Phys. Rev. Lett. **62**, 1157 (1989).

[7] K. –P. Kämper, D. L. Abraham, and H. Hopster, Phys. Rev. B **45**, 14335 (1992).

[8] T. G. Walker and H. Hopster, Phys. Rev. B **48**, 3563 (1993).

[9] M. Plihal, D.L. Mills, and J. Kirschner, Phys. Rev. Lett. **82**, 2579 (1999).

[10] R. Saniz and S. P. Apell, Phys. Rev. B **63**, 14409 (2000).

[11] H. Hopster, Phys. Rev. B **42**, 2540 (1990).

[12] H. Hsu, M. Magugumela, B.E. Johnson, F.B. Dunning, and G.K. Walters, Phys. Rev. B **55**, 13972 (1997).

[13] J.G. Tobin, P.J. Bedrossian, T.R. Cummins, G.D. Waddill, S. Mishra, P. Larson, R. Negri, M. Miller, E. Peterson, P. Boyd, and R. Gunion, Mat. Res. Soc. Symp. Proc. **524**, 185 (1998).

[14] Franco Ciccacci and Stefano De Rossi, Phys. Rev. B **51**, 11538 (1995).

[15] D. P. Pappas, C. R. Brundle, and H. Hopster, Phys. Rev. B **45**, 8169 (1992).

[16] APS XMCD paper

[17] S. Tougaard and J. Kraaer, Phys. Rev. B **43**, 1651 (1991).

Figure Captions

Figure 1 Schematic of the experimental SPEELS system.

Figure 2 a) Fe L-edge X-ray absorption spectra (XAS) for parallel and antiparallel orientation of the photon helicity and sample magnetization, and b) x-ray magnetic circular dichroism derived from the XAS results in a).

Figure 3 Experimental SPEELS results for clean Ag(100). Majority spin and minority spin data are indicated up upward and downward triangles respectively. The circles indicate the total intensity. The data were acquired with a primary beam energy of 300 eV. We observe no difference between majority and minority spin spectra as expected.

Figure 4 Experimental results for 20 ML bcc Fe films on Ag(100). Top panel: Spin integrated energy loss spectrum. Middle panel: Majority spin energy loss spectrum showing a sharp peak at ~1.8 eV and a broader peak at ~2.5 eV. Bottom panel: Minority spin energy loss spectrum showing a peak at ~ 2.0 eV. The data were acquired with a primary beam energy of 300 eV.

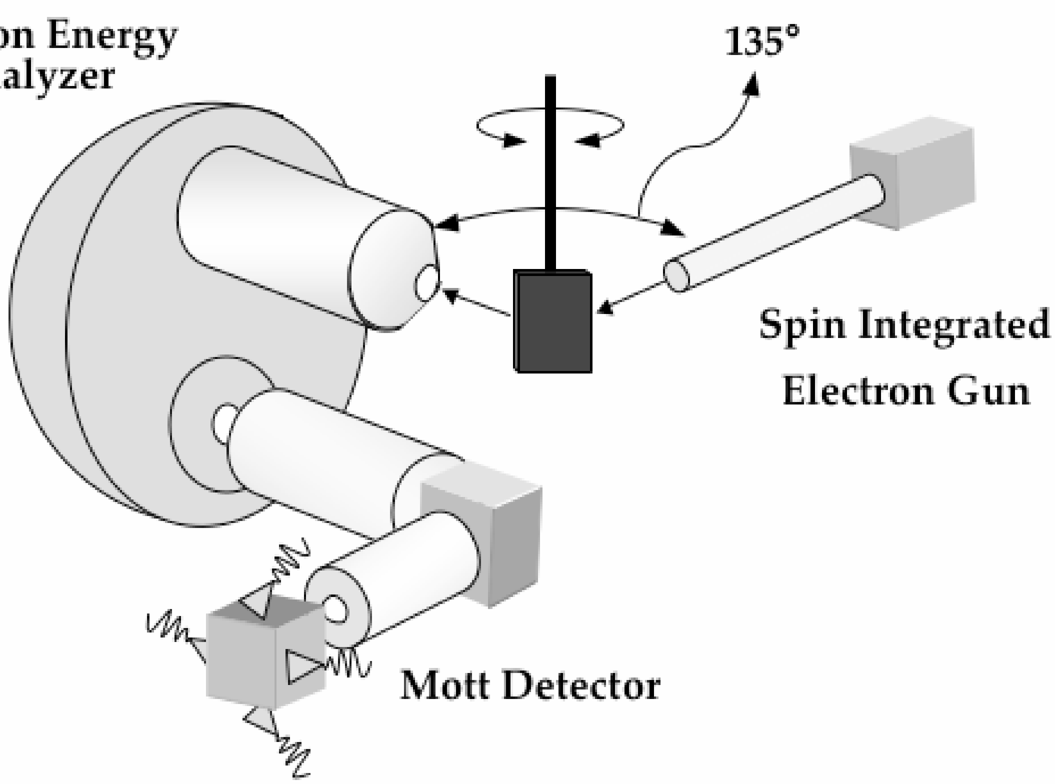

Fig. 1 T. Komesu et. al.

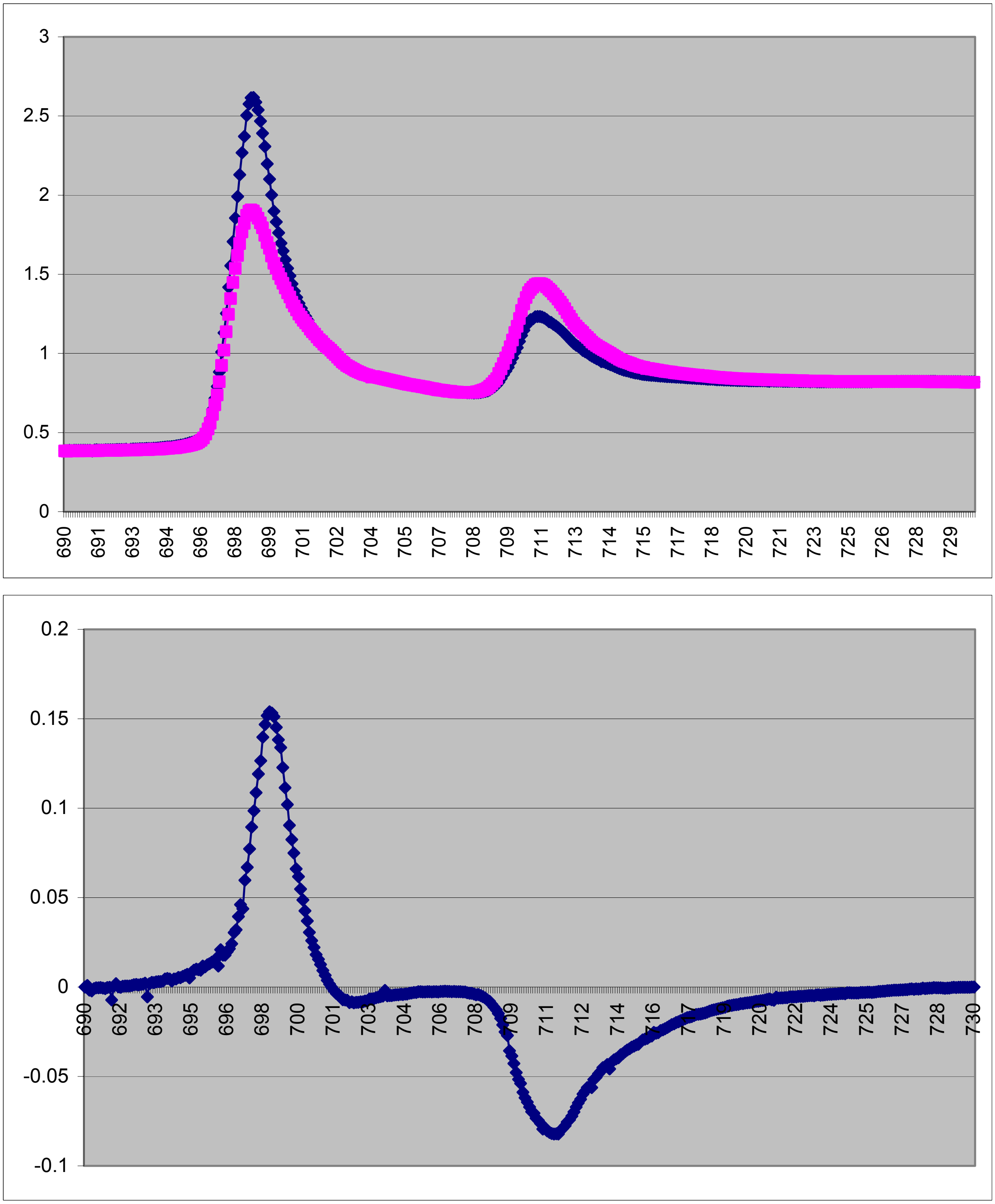

Fig. 2 T. Komesu et. al.

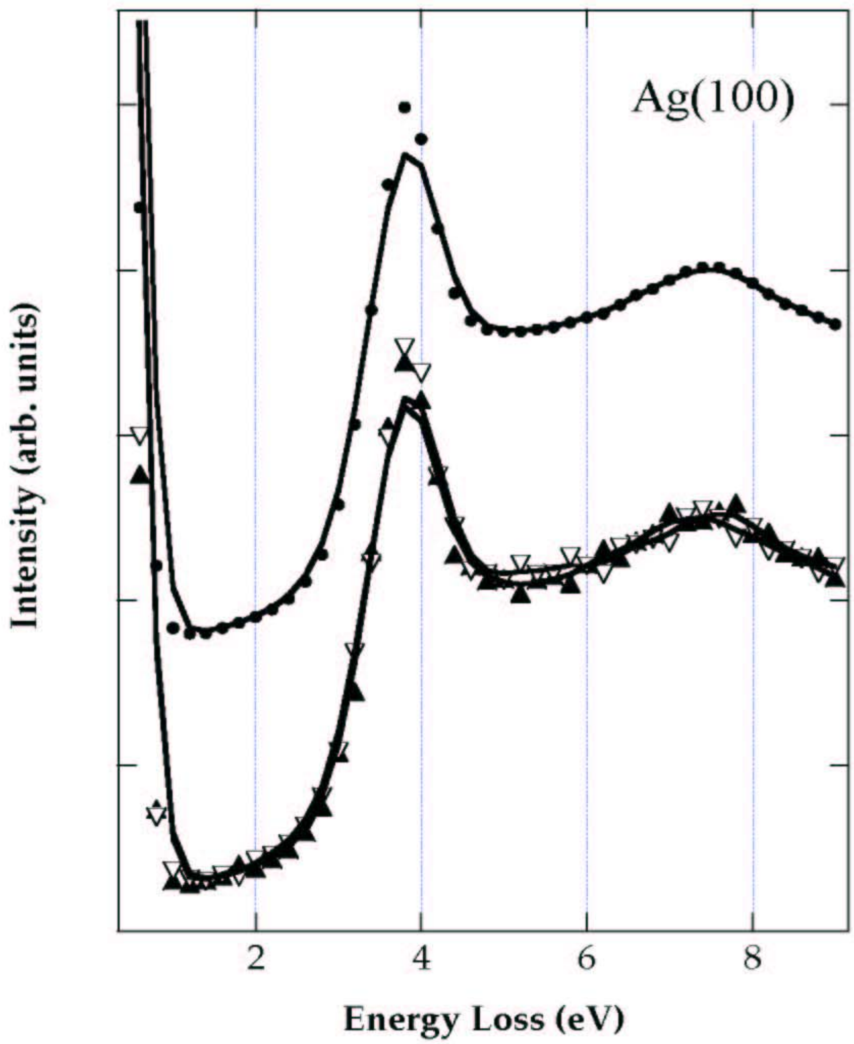

Fig. 3 T. Komesu et. al.

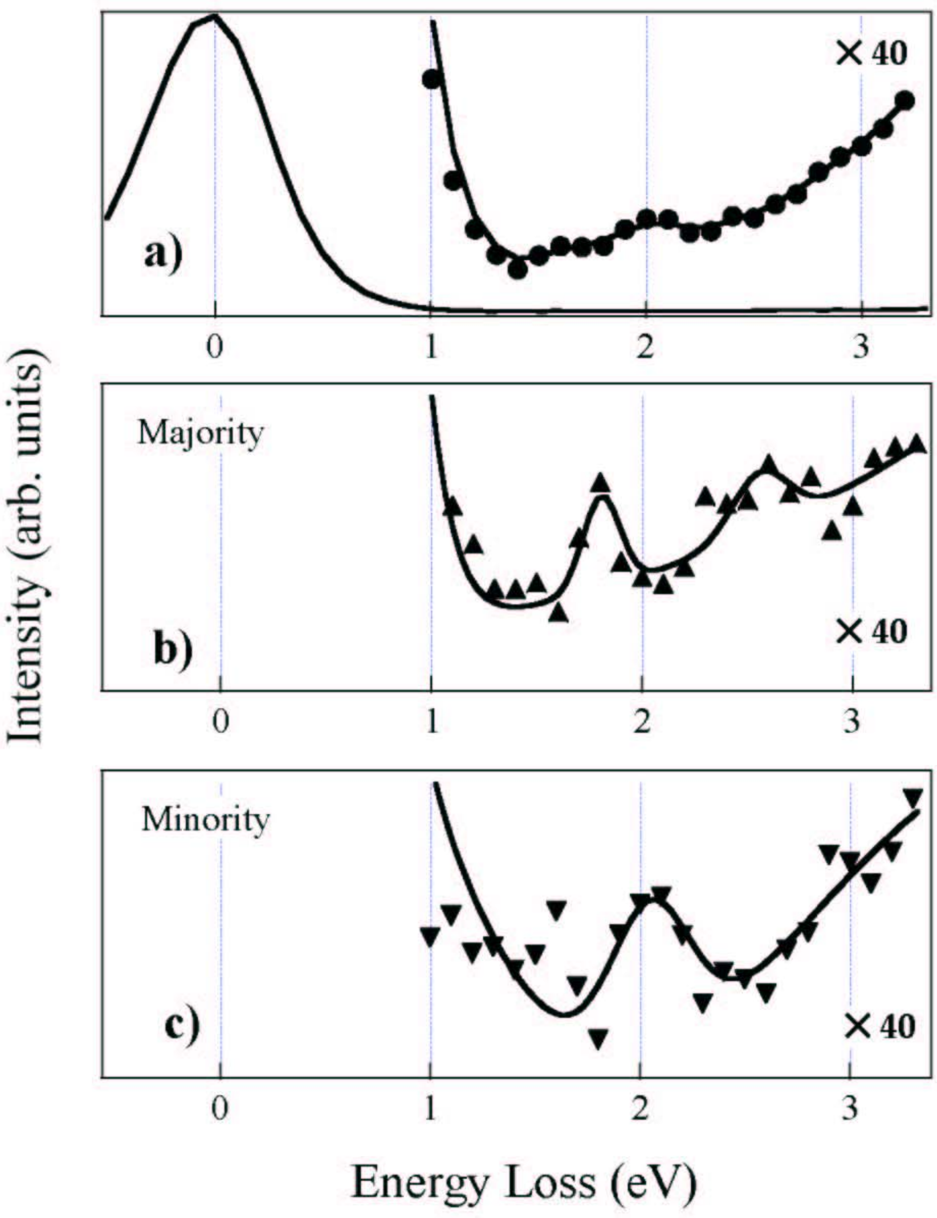

Fig. 4 T. Komesu et. al.