Spin-Orbit Coupling Studied by Low Energy Spin-Polarized (e,2e) Coincidence Spectroscopy

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Introduction

Studies into the scattering dynamics of spin-polarized electrons have employed a number of experimental methods. We have chosen to use a novel technique based on two-electron coincidence spectroscopy (e,2e) (i.e. one electron in with two electrons out) in reflection mode with a low-energy spin-polarized incident electron beam. Our targets have primarily been single crystal insulators, semi conductors and metals, both clean and as substrates for thin films. In this paper we have focused on electron scattering from clean W(110) a case study of spin-orbit coupling effects in surfaces.

Experimental Principles

The scattering of spin polarized electrons from surfaces involves two general processes known as spin-orbit coupling and exchange coupling. Both of these effects are generally present simultaneously, but careful experimental considerations allow each to be studied to some degree separately. Spin-orbit coupling involves the interaction of the incident electron's angular momentum with the attractive potential of the target atom's ion core. This effect is thus most pronounced for heavy, non-magnetic, atoms. Exchange coupling is the direct result of the Pauli exclusion principle. Clearly this effect is most pronounced in magnetic samples, where the number of spin-up and spin-down electrons is uneven.
The spin-polarized electron source for this experimental configuration is based on photoemission from a strained GaAs photocathode activated by Cs and oxygen adsorption. The polarization of electron beam is parallel or anti-parallel to the momentum of photoelectrons depending on the helicity of the incident light [1]. The degree of polarization is estimated to be about 70%. The polarized beam passes through a 90^{o} electrostatic deflector such that the emergent beam is transversely polarized since the electrostatic field acts only on the electron momentum and not on the spin orientation. The polarization direction is chosen perpendicular to the scattering plane containing the incident beam and two detectors. In such a geometrical arrangement one can usually expect a non-vanishing spin-asymmetry in measured spectra because of symmetry considerations [2]. The sample can be rotated about the y-axis to achieve a range of incident angles α. A sketch of the experimental geometry is shown in Figure 1.

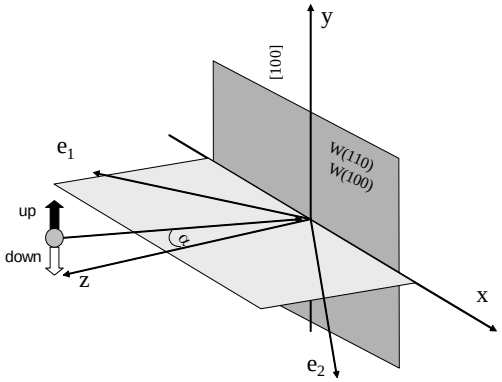

Figure 1: Geometry of the experiment, showing scattering plane as the ZX plane.

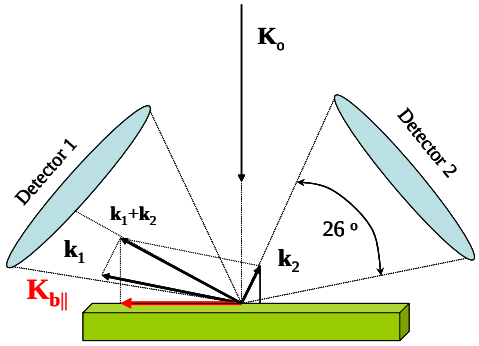

Figure 2: Momentum diagram of incident (K_o), first (K_1), second (K_2) and valence (K_b) electrons

We use a combination of time-of-flight energy analysis and coincidence technique to collect data on the momentum of both electrons. The incident electron beam is pulsed (1 ns pulse width and 2.5 x 10^6 Hz repetition rate) to have a reference point on the time scale. Position sensitive detectors allow detection of electrons in a wide angular range as well as a flight distance correction for electrons arriving at different locations on the detectors. A correlated electron pair generated by a single incident electron and detected by two detectors is represented by six numbers: arrival times of both electrons T_1 and T_2 and coordinates on the detectors X_1, Y_1, X_2, Y_2. This six-dimensional array ((e,2e) spectrum) for each of the two spin polarizations of the incident beam can be projected on various one- or two-dimensional distributions. As an example of a two-dimensional distribution one can quote the number of correlated pairs as a function of electron energies $I(E_1, E_2)$. For a given primary energy and fixed experimental geometry the (e,2e) spectrum was measured for spin-up (I^+) and spin-down (I^-) polarization of the incident beam and then these two spectra were compared in terms of their intensity difference and spin-asymmetry. To avoid the influence of the incident electron current drift or the sample surface modification (contamination) on the spin-asymmetry during the measurements we altered the polarization of the beam every 5 seconds and the (e,2e) spectra were measured for spin-up and spin-down polarization of the incident beam. Since the accumulation of data with satisfactory statistics takes approximately 30 hours we stopped measurements every few hours and cleaned the sample by a high temperature flash to remove adsorbed residual gases even though the base pressure was in the 10^{-11} Torr range.

In a single collision event the energy E_o of primary electron and the energies E_1, E_2 of the two outgoing electrons define the binding energy of the valence electron: $E_b = E_1 + E_2 - E_o$. The number of correlated electron pairs as a function of the total (sum) energy $E_{tot} = E_1 + E_2$ then represents the "total energy distribution" or, as a function of the binding energy, a "binding energy spectrum". For a fixed total energy the two electrons of the pair can share this energy in different ways depending on the scattering dynamics and electronic properties of the surface. The number of electron pairs as a function of the difference energy $(E_1 - E_2)$ presents an "energy sharing distribution" for a given total energy.

In the case of a crystal surface, the component parallel-to-the-surface of the electron momentum is a good quantum number for four relevant electronic states of the scattering event, as shown in Figure 2. Therefore: $\mathbf{K}_{o\|} + \mathbf{K}_{b\|} = \mathbf{K}_{1\|} + \mathbf{K}_{2\|}$, where $\mathbf{K}_o$, $\mathbf{K}_b$, $\mathbf{K}_1$, $\mathbf{K}_2$ are the momenta of the incident, bound, first detected and second detected electrons, respectively. Hence, we can present our measured spin-polarized (e,2e) spectra as projections on the binding energy, on $K_{b\|}$, or as energy sharing distributions within a certain total energy band.

Results and Discussion

Single crystal tungsten was employed to study spin-orbit coupling. The (e,2e) coincidence spectra of clean W(110) was collected and analysed using the above techniques.

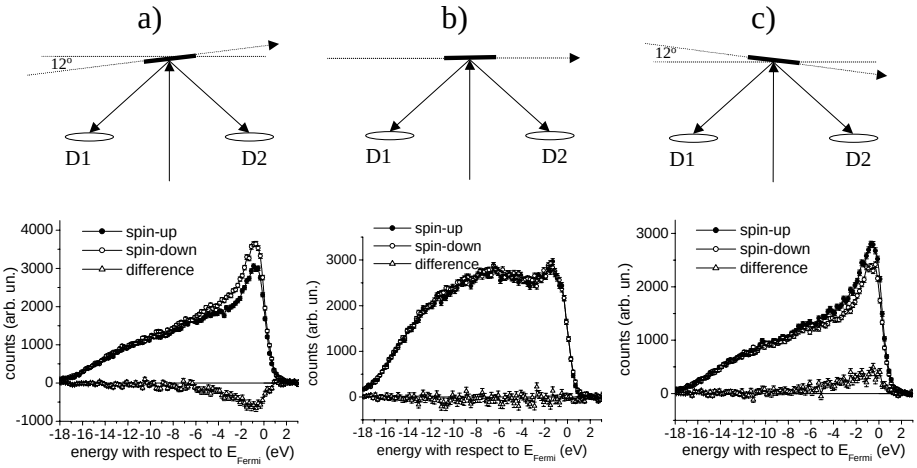

Figure 3: Binding energy spectra of W(110) recorded at three positions of the sample and primary electron energy 25.5 eV.

Figure 3 represents binding energy spectra measured at 25.5 eV primary energy for three different positions of the sample: normal incidence (panel b) and two off-normal (panels a and c). The angle of incidence was changed by rotating the sample around the axis perpendicular to the scattering plane by $\pm 12^o$. We note that the shape of the binding energy spectrum depends on the incident angle. At normal incidence there are two maxima in the spectrum: one at about 1 eV below the Fermi level and the second at about 7 eV below the Fermi level. In contrast, for both off-normal (±12 degrees) positions of the sample the binding energy spectrum contains a single pronounced maximum located at 1 eV below the Fermi level. Regarding the spin dependence, the normal incidence spectra (panel b) for "spin-up" and "spin-down" primary beam are identical and the difference spectrum is zero. For off-normal incidence the "spin-up" and "spin-down" spectra are different for both positions (a) and (c) and difference spectra have opposite signs: negative for the sample position (a) and positive for the position (c). The difference between spin-up- and spin-down spectra is located in the energy range within a few eV below the Fermi level. It was shown [3-4] that in this energy range the major contribution to the (e,2e) spectrum comes from the two-electron binary collisions whereas for lower energies the contribution from multi-step collisions is substantial. Therefore we analyze how two correlated electrons share energy within 2 eV total (binding) energy just below the Fermi level.

The energy sharing distributions of these data show dramatic effects on both shape and spin-dependence as a function of angle (Figure 4). For normal incidence the distribution is symmetric with respect to the zero point where $E_1 = E_2$. For off-normal incidence (panels a and c) the distributions are not symmetric relative to the zero point. For the sample position (a) there is a maximum at $E_1 - E_2 = -10$ eV whereas for the position (c) the maximum is located at $E_1 - E_2 = 10$ eV. If we take the medium total energy $E_{tot} = 19.5$ eV, then the two maxima correspond to the following combinations of electron energies: ($E_1 = 4.75$ eV; $E_2 = 14.75$ eV) for the sample position (a) and ($E_1 = 14.75$ eV; $E_2 = 4.75$ eV) for the sample position (c).

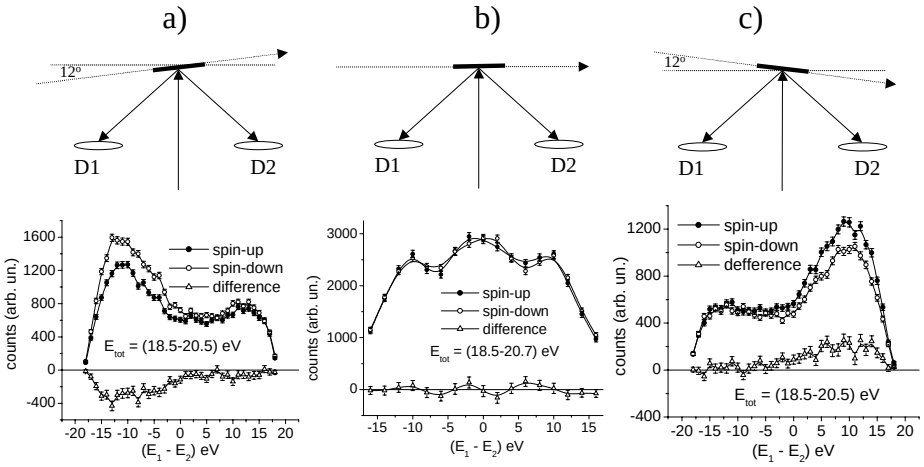

Figure 4: Energy sharing distributions of correlated electron pairs excited by 25.5 eV primary electrons from W(110) at three different positions of the sample.

The combinations of momenta would be (K_1 = 1.12 Å^{-1}, K_2 = 1.97 Å^{-1}) and (K_1 = 1.97 Å^{-1}, K_2 = 1.12 Å^{-1}), respectively. Assuming for the sake of simplicity that electrons are detected in the centers of the detectors, the total momentum of the pair would be close to the direction of the specularly reflected primary beam. This means simply that the total momentum of the pair carries the parallel component of the incident electron momentum because of the momentum conservation law. One can see that the sharing distributions for off-normal incidences exhibit large differences between spin-up and spin-down spectra. The difference spectra possess broad maxima located at (E_1 - E_2) = -10 eV for positions (a) and at (E_1 - E_2) = 10 eV for position (c). The asymmetry $A = (I^+ - I^-)/(I^+ + I^-)$ reaches –10% and 10%, respectively. The I^+ and I^- spectra and difference spectrum $D = (I^+ - I^-)$ show again an interesting symmetry property. Let us denote by I_a and I_c spectra recorded at geometry (a) and geometry (c), respectively. Reflection at the (y,z)-plane reverses the spin of the primary electron and transforms the geometry (a) into geometry (c) with interchange of the outgoing electrons. It implies that $I_a^+(E_1 - E_2) = I_c^-(E_2 - E_1)$ and, by consequence, $D_a(E_1 - E_2) = - D_c(E_2 - E_1)$. Comparing the spectra in panels (a) and (c) one can see that difference spectra exhibit such a symmetry.

Summary

Using spin-polarized (e,2e) spectroscopy we have observed spin-orbit coupling in the electrons scattering from W(110). This technique may provide unique information about the spin-dependent scattering and spin-related band structures of heavy metals and other surfaces.

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