Measurement of the Positron Annihilation Induced Auger Electron Spectrum from Ag(100)

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Abstract. Research has demonstrated that Positron Annihilation Induced Auger Spectroscopy (PAES) can be used to probe the top-most atomic layer of surfaces and to obtain Auger spectra that are completely free of beam-impact induced secondary background. The high degree of surface selectivity in PAES is a result of the fact that positrons implanted at low energies are trapped with high efficiency at an image-correlation potential well at the surface resulting in almost all of the positrons annihilating with atoms in the top-most layer. Secondary electrons associated with the impact of the incident positrons can be eliminated by a suitable choice of an incident beam energy. In this paper we present the results of measurements of the energy spectrum of electrons emitted as a result of positron annihilation induced Auger electron emission from a clean Ag(100) surface using a series of incident beam energies ranging from 20 eV down to 2 eV. A peak in the spectrum was observed at ~40 eV corresponding to the N2,3VV Auger transition in agreement with previous PAES studies. This peak was accompanied by an even larger low energy tail which persisted even at the lowest beam energies. Our results for Ag(100) are consistent with previous studies of Cu and Au and indicate that a significant fraction of electrons leaving the sample are emitted in the low energy tail and suggest a strong mechanism for energy sharing in the Auger process.

1. Introduction

In this paper, we present the energy spectrum of Auger electrons emitted from Ag(100) obtained using Positron Annihilation Auger Electron Spectroscopy (PAES). In PAES, the Auger electrons are excited by the creation of core holes through an annihilation process. It has been shown [1] that PAES is significantly more surface selective than Electron stimulated Auger Electron Spectroscopy (EAES) and X-ray induced Auger Electron Spectroscopy (XAES) due to the fact that the positrons are trapped in a surface state localized just above the surface at the time of annihilation. The localization of the positrons in the surface state ensures that almost all of the annihilation induced core hole excitations that result in Auger transitions occur in the topmost atomic layer [2]. More importantly, for the purpose of this paper, the energy of the positron beam used in PAES can be made arbitrarily low making it possible to eliminate most or all of the beam induced secondary electrons leaving the surface [3]. In contrast, the highly penetrating beam used in XAES excites Auger electrons from many inelastic mean free paths below the surface. The beam induced secondary background present in EAES and XAES (which is typically many times larger than the signal) makes the measurement of these spectral features extremely difficult. Here we present the results of measurements of energy spectra of electrons emitted as a result of positron annihilation at the surface of Ag(100). The data indicate that a significant fraction of electrons leaving the sample are emitted in the low energy tail.
The spectral weight of the tail is several times larger than can be accounted for in terms of inelastic backscattering and inelastic processes associated with electron transport through the thin layer of electron gas covering the atomic cores in the top-most layer. This suggests that the tail is intrinsic to the Auger transition and that a significant fraction of the Auger transitions proceed through multi-electron processes in which the energy made available through filling the core hole is shared amongst 2 or more electrons.

2. Experiment

The measurements were performed using a high resolution PAES system at University of Texas at Arlington described more fully in Ref [4]. The incident positron beam, generated from beta decay of Na$^{22}$ source moderated through a thin (1µm) tungsten (W) foil. The beam is electromagnetically guided by 40 Gauss axial magnetic field towards the sample. The sample was cleaned daily by ion sputtering (without annealing) and maintained under UHV conditions ($6 \times 10^{-10}$ Torr) during the time of PAES data collection.

The time of flight of the Auger electrons is obtained by measuring the time interval between the annihilation gamma signal from a BaF$_2$-PMT detector and the signal due to the detection of the Auger electron by a channel plate detector placed after at the end of a ~ 1m flight path. The emission of the Auger electron occurs within ~10$^{-15}$ sec of the annihilation and may be considered to be essentially simultaneous with the detection of the gamma rays emitted when the core electron is annihilated. The overall timing resolution of the system is ~ 1.9 n-sec with a corresponding energy resolution of ~ 3.2 eV at 40 eV and ~ 16.5 eV at 250 eV [4].

![Figure 1. TOF-PAES setup at University of Texas at Arlington. Ref [4,5].](image)

A permanent magnet is placed behind the sample to produce a 50 mT field at the sample surface. Solenoids produce a 4mT in the transport region. The resulting field redirects the momentum of the outgoing electrons toward the beam axis [6] and reduces the time spread due to the angular divergence of the electrons leaving the surface. The flight path consists primarily of a ~ 0.7 m electric field free region inside the T-O-F retarding tube. The energy spectrum is determined from the time of flight spectrum using a conversion function obtained using an empirical calibration procedure [4, 5].

3. Results and Discussion

The energy spectrum of electrons emitted in the energy range of 20 eV to 600 eV as a result of 18 eV positrons incident on the surface of Ag(100) is shown in Figure 2. A peak may be seen at ~40 eV which is due to the annihilation induced N$_2$VV and N$_3$VV Auger transitions [7]. Small peaks, containing and order of magnitude less integrated intensity, may also be observed at energies of ~160 eV, ~240 eV, and ~380 eV. The origin of these peaks can be attributed to the bulk impurities Sulphur (~146 eV and ~373 eV) and Carbon (~263 eV) diffusing to the surface after sputtering. The effect on the intensity of these peaks of incorporating sample annealing into the sputtering cycle will be studied and investigated in future. Figure 3 shows the variation in the secondary electron peak as a function of
the sample bias. The beam energy used in this experiment was approximately 2 eV. We can clearly see that the secondary electron peak has a broad maximum at the lagging edge which is increasing as the sample bias is increasing.

![Figure 2. Energy spectrum of Ag(100) at 18 eV beam energy. The upper spectrum is a magnified version of the lower spectrum (×10). The arrow ~40 eV indicates the position of a peak associated with the N 23VV Auger transition. The arrows pointing to the magnified spectrum at point to much lower intensity peaks of Sulphur at ~146 eV, ~373 eV and of Carbon at ~263 eV.](image)

Figure 2 shows the 2 eV positron beam induced electron spectrum for positrons incident on a Ag(100) surface at different sample bias (and hence kinetic energies) of 0 V, 1 V, 5 V and 10 V. The Ag NVV Auger peak can be seen at ~40 eV in each case. The results obtained are consistent with the experimental results of Mukherjee et al. [7] for the Cu(100) surface.

![Figure 3. The low energy portion of the PAES spectrum obtained using a beam of positrons incident on a Ag(100) surface at energies of 2 eV, 3 eV, 7 eV and 12 eV. The spectrum has been smoothed using a 3 eV moving average [5].](image)

The observed shift in the steep negative slope below 15 eV is in qualitative agreement with the equation for the maximum kinetic energy of the beam impact induced secondary electrons derived in ref. 8 (eq. 1) based upon consideration of the energy released when a positron makes a transition from a scattering state above the vacuum level to a bound state at the surface given by eq. 1:
where $KE_{\text{max}}$ is the maximum kinetic energy of the impact induced secondary electrons, $KE_{e^+}$ is the kinetic energy of the incident positron, $E_b$ is the positron surface state binding energy, and $\phi^-$ is the electron work function. Using eq. 1 with calculated values of $E_b = 3.12 \text{ eV}$, $\phi^- = 4.5 \text{ eV}$, we obtain the upper bounds on the beam induced secondary electron energies of approximately 0 eV, 1 eV, 5 eV and 10 eV, for the incident positron beam energies of 2 eV, 3 eV, 5 eV and 12 eV respectively. It may be seen that the significant low energy tail does not disappear even as the positron beam energy is reduced to the point the incident beam can no longer directly knock out secondary electrons. Mukherjee et al. suggested that the similarly large low energy tail that was observed in Cu and Au was due to multi-electron Auger processes [9]. Another possible explanation is that valence electrons are ejected as a result of the sudden creation of the core hole via the annihilation process. In this case conservation of energy would require that the sum of the energies of the two annihilation gammas would be given by eq. 2:

$$E_{\gamma_1} + E_{\gamma_2} = 2m_0c^2 - (BE_{e^+} + BE_{\text{core}} + \sum_i BE_{\text{valence}_i}),$$  

where $E_{\gamma_1,2}$ are the energies of the two gamma rays, $m_0c^2$ is the rest mass energy of the positron and electron, $E_{e^+}$ is the total energy of the positron in the surface state, $BE_{\text{core}}$ is the binding energy of the core electron, and $\sum_i BE_{\text{valence}_i}$ is the sum of the binding energy of the low energy valence electrons emitted during the annihilation process.

**Summary**

In this paper we have presented the results of measurements of the spectrum of electrons emitted as a result of positron annihilation induced Auger transitions on an Ag(100) surface. The measurements were carried out for a series of positron beam energies ranging from 18 eV down to 2 eV. All the spectra show a prominent but broad peak at ~40 eV corresponding to the N 2,3VV Auger transition in agreement with previous PAES studies. The presence of a large low energy tail (LET) in the spectrum below the Auger peak at the lowest beam energies is consistent with previous experiments with Cu and Au, respectively. Mukherjee et al. present arguments that extrinsic processes such as Auger electrons undergoing inelastic backscattering [9] are not sufficient to account for the majority of the LET observed. They suggest that the majority of the LET is due to intrinsic Auger processes in which the energy associated with the filling of the core hole is shared amongst 2 or more valence electrons. Another possible explanation is that a significant fraction of the tail is due to low energy electrons that are emitted during the core hole creation process. Future experiments are planned that will be aimed at determining the relative importance of these different contributions.

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