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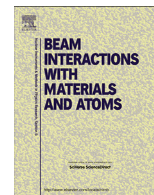

Energy and impact angle dependence of sub-threshold external electron emission

C. Heuser *, A. Wucher

Fakultät für Physik, Universität Duisburg-Essen, D-47048 Duisburg, Germany

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ABSTRACT

The kinetic electron emission induced by Ar^+ ions impinging onto a polycrystalline Ag surface is studied as a function of the projectile impact angle in the energy range 5–10 keV well below the classical threshold. The resulting emission yield is compared to published model descriptions of sub-threshold electron emission. We find reasonable agreement with the prediction of the hot spot model proposed by Sroubek, which is shown to become equivalent with a Richardson–Dushman-type description of thermionic emission when converted to three dimensions. The model is further extended to describe the impact angle dependence and shown to fit the corresponding experimental data reasonably well.

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1. Introduction

When an ion impinges onto a solid surface, its energy is dissipated via nuclear and electronic stopping mechanisms. The first one describes the scattering of the projectile by means of elastic collisions with the target atoms, which can lead to collisional cascades and to the emission of particles into the vacuum ("sputtering"). The second mechanism involves the interaction of the penetrating ion with the electronic subsystem of the solid, which manifests in a spatially and temporally localized heating of the valence electrons. If an electron gains enough excitation energy to overcome the work function, it can be emitted into vacuum, leading to ion-induced (external) electron emission.

In case of normal incidence of the projectile, the energy of the ion is deposited along the track of the moving ion, leading to a certain energy loss distribution as a function of the penetration depth. Due to inelastic scattering processes only excited electrons produced close to the surface can be detected, which limits the amount of electrons contributing to the external electron yield. By changing the impact angle of the impinging ion from normal to grazing incidence, the penetrating ion spends more time closer to the surface, so that the energy loss distribution is compressed towards the surface, which results in an impact angle-dependent increase of the electron yield [1,2].

At sufficiently high projectile energy, the kinetic electron emission process appears to be fairly well understood [3–5]. A simple but rather successful approach to describe the underlying kinetic excitation is to consider the energy loss of the moving projectile ion via direct scattering of quasi-free valence electrons. In this picture, the maximum possible excitation energy an electron can gain in such a scattering process is directly related to the kinetic energy of the ion, leading to a threshold impact energy as the lower limit for the projectile ion to excite electrons that can still overcome the work function and be emitted. Although it is well known that electron emission also occurs well below this classical threshold energy, the theoretical understanding of this sub-threshold emission process is still rudimentary. In a number of papers, Sroubek and coworkers have developed several scenarios of the underlying excitation processes, which include a shakeup mechanism induced by the rapid non-adiabatic passage of the ion across the surface as the boundary between solid and vacuum environment ("surface assisted KEE" [6]), the inclusion of many-electron scattering processes ("many electron surface assisted KEE" [7]) as well as electron promotion of deep levels in close ion–atom collisions [8]. In a recent paper, Sroubek proposed a simplified emission model assuming an electronically heated "hot spot" with a locally and temporarily elevated electron temperature to be generated around the projectile impact point and demonstrated that the resulting predictions are formally indistinguishable from those derived from the more complicated descriptions [9].

The goal of this work is to examine the validity of Sroubek's hot spot model in the light of available experimental data (in the present case: $Ar^+ \rightarrow Ag$) for both the impact energy and impact angle dependence of the external electron emission yield in the sub-threshold energy range. We use this comparison to extract relevant

* Corresponding author. Tel.: +49 2033793568
E-mail address: Christian.Heuser@uni-due.de (C. Heuser).

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microscopic parameters like the inverse decay length of the projectile-surface interaction potential and the projectile-induced elevation of the local electron temperature in the impact region.

2. Experiment

The experiments are carried out in an UHV apparatus with a base pressure of about 10^{-9} mbar. The setup is subdivided into three individual, inline-connected chambers, which allow the transfer, creation and analysis of thin silver films under UHV conditions.

2.1. Sample preparation

The samples investigated here were prepared as polycrystalline silver films of about 25 nm thickness on a glass plate. The glass substrate was used in order to insulate the films from the sample holder. This was done in order to measure their electrical conductivity, which has been found to be a good indicator for the film quality (homogeneity and thickness) [10]. The films were created by vapor deposition under UHV conditions a rectangular mask with geometrical dimensions of 20×5 mm^2. Deposition was performed at room temperature, leading to an average film roughness of about 1–3 nm [11]. The specially shaped sample carriers are made of molybdenum in order to avoid cold fusing with the sample holder. The films were electrically connected via lines of conductance silver drawn on the glass substrate prior to its introduction into the vacuum system (see Fig. 1). After preparation the carriers are transferred to a *xyz*-manipulator in the analysis chamber, where the bombardment with energetic argon ions takes place.

2.2. Measurement procedure

The sample is bombarded using singly positively charged argon ions with kinetic energies of 5–10 keV and an incidence angle of 0–85° with respect to the surface normal. The primary ion current amounts to 0.2–2 nA and is measured by means of a Faraday cup. The beam spot diameter is about 100 μm and elongates along the incidence plane with increasing angle of incidence.

The sample holder (with the inserted sample carrier) can be moved in all three directions and can be rotated along the *x*-axis perpendicular to the incoming ions. As can be seen in Fig. 1, a half cylindrically shaped slotted electrode is mounted on the sample holder, which covers the sample and acts as a shielding collector. This electrode can be biased with respect to the sample by ±100 V.

The slit (i) allows the incoming ions to approach and (in case of reflection) depart from the sample without hitting the collector to avoid the emission of secondary particles (ions and electrons) and (ii) prevents the ions to hit the glass substrate, which might lead to charging effects.

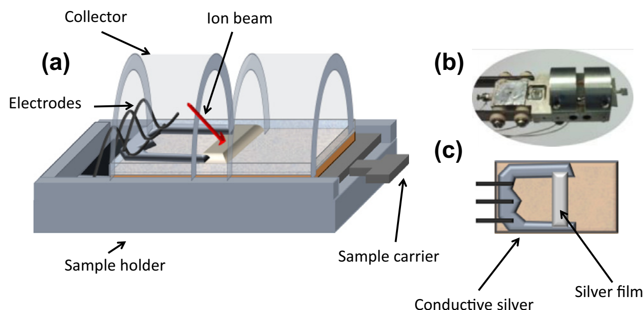

Fig. 1. Sketch of the experimental setup. (a) Shows the sample holder with the collector and inserted sample carrier in 3D. The direction of the incoming ion is indicated with a red arrow. (b) Shows the sample holder in reality, and (c) gives a top view on a sample carrier.

Prior to the measurement, the sample is sputter cleaned under grazing incidence using 5-keV Ar^+ ions with a primary ion current density of about 45 μA/cm^2. During the irradiation with an applied collector bias of +100 V a decrease in the measured stage current is observed, which is attributed to a surface cleaning process. The voltage of +100 V is applied to the collector in order to extract all the emitted electrons from the sample surface. It is well known that surface adsorbates (e.g. oxygen) generally lead to an enhanced electron emission yield (as well as to a strongly modified ionization probability of sputtered secondary particles) as compared to a clean metal surface. Since the positively biased collector attracts negative secondary particles (mostly electrons) emitted from the sample surface, the net stage current measured under these conditions is larger than the actual projectile ion current and decreases with decreasing secondary electron yield. At the time the measured sample current saturates, the bombarded area is interpreted to be dynamically sputter cleaned. Using the residual gas pressure of 10^{-9} mbar and assuming a sticking probability of unity in connection with a sputter yield of about 10 atoms/ion, one can estimate a residual surface contamination of the order of several ten ppm under these conditions.

The external electron emission yield is determined by measuring the net sample current for different collector bias voltage [5,12]. The measured current consists of several contributions, namely (i) the current of the primary argon ions and (ii) the current of emitted charged secondary particles (electrons and secondary ions). Biasing the collector to either positive or negative potential acts to suppress the current of positive or negative secondary particles, since particles emitted with kinetic energies below the bias potential are being forced back to the sample surface. Since the emission energy distribution of all secondary particles is peaked at low kinetic energies in the 1–10 eV range, a bias potential of ±100 V is sufficient to completely eliminate the respective current contribution. In order to determine the electron emission yield, different measurements of the sample current for a bias voltage of +100 V and −100 V are compared for each impact energy and angle.

- In case of the positive collector voltage, the emitted electrons are extracted from the sample and the measured current $I_{+100\mathrm{V}}$ consist of the primary ion current I_{Ar^+}, the emitted electron current I_{e^-} and the current induced by the emission of negatively charged secondary ions I_{SI^-}:

$$I_{+100\mathrm{V}} = I_{\mathrm{Ar}^+} + I_{e^-} + I_{\mathrm{SI}^-} \tag{1.1}$$

- In case of the negative collector voltage, the emitted electrons are pushed back onto the surface, so that the overall sample current $I_{-100\mathrm{V}}$ only consists of the primary ion current I_{Ar^+} and the positively charged secondary ions I_{SI^+}:

$$I_{-100\mathrm{V}} = I_{\mathrm{Ar}^+} - I_{\mathrm{SI}^+} \tag{1.2}$$

For a clean metal surface, it is known that the ionization probability of sputtered atoms is low (of the order of 10^{-5} for silver [13]) for positive and even lower for negative ions, so that the secondary ion contribution to the measured current is negligible. Moreover, it was verified that the current measured under normal incidence with negatively biased collector was equal to the ion current I_{Ar^+} measured in the Faraday cup. Therefore, we calculate the total electron emission yield as

$$\Gamma_{Total}(\Theta) = \frac{I_{+100V(\Theta)} - I_{-100V(\Theta)}}{I_{100V(\Theta=0^\circ)}} \approx \frac{I_{e^-}}{I_{\mathrm{Ar}^+}} \tag{1.3}$$

where $\Gamma_{\mathrm{Total}} = \Gamma_{\mathrm{KEE}} + \Gamma_{\mathrm{PEE}}$ contains both the kinetic and the potential emission induced by the projectile's kinetic and ionization energy, respectively. In order to isolate the kinetically induced contribution, the potential emission yield needs to be subtracted.

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