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Ion induced high energy electron emission from copper

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ABSTRACT

We present measurements of secondary electron emission from Cu induced by low energy bombardment (1–5 keV) of noble gas (He^+, Ne^+ and Ar^+) and Li^+ ions. We identify different potential and kinetic mechanisms and find the presence of high energetic secondary electrons for a couple of ion-target combinations. In order to understand the presence of these fast electrons we need to consider the Fermi shuttle mechanism and the different ion neutralization efficiencies.

1. Introduction

The electron emission induced by the interaction of low energy ions (SEE) with solids is a very complex process, which has been studied for several years. One of the problems conspiring against the understanding of such a phenomenon is the fact that the production of low energy electrons is actually a convolution of several mechanisms. Thus, the typical spectra is a broad curve peaked below 10 eV where the contribution of the cascade electrons, i.e. all electrons whose energies have been degraded through several collisions, is important shadowing the presence of different physical processes for the secondary electron production. In spite of this, several mechanisms have been identified along the time. For instance, we can mention the Auger neutralization [1] process (AN), where one electron tunnels the surface barrier to neutralize the incoming ion and the potential released energy is taken by a second electron of the solid that can be ejected to the vacuum. If the second electron belongs to the incoming ion, then the process is known as Auger de-excitation (AD). Other mechanisms, like the kinetic emission produced by the direct collision among the incoming ion and target electrons are only important, due to the large mass differences, for low mass and fast incoming ions [2]. On the other hand, the promotion of the atomic inner shell due to the kinetic energy of incoming ions is a currently accepted model for SEE [3]. More recently, two new mechanisms for ion induced electron emission have been proposed: the decaying of ion induced excited plasmons [4] (in Al) and excitons [5] (in HOPG).

There are a few number of secondary electrons produced in these collisions whose kinetic energy is beyond the expected one in both these kind of mechanisms, i.e. the potential and kinetic ones [6]. Different explanations, like inner shell promotion [2] and Fermi shuttle mechanism (FS) [7], have been proposed. Within the FS model, the electron suffers multiple elastic collisions among the incoming ion and target atoms increasing their velocity after each collision by 2V, being V the incoming ion velocity. Independent consecutive electronic scattering events [8] have also been proposed to understand the presence of these high energy electrons. Although the FS mechanism is usually discussed for experiments involving high energy and highly charged impinging ions [9–11] (MeV/amu), as in the independent collisions model, Jakas [12] has shown its feasibility for collisions in the keV range. In this work we present measurements of copper SEE induced by different impinging ions in the low (1–5 keV) energy range. Our results favor the interpretation based on the Fermi shuttle mechanism against the inner shell promotion model.

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2. Experimental setup

The experiments were performed in a commercial Auger electron spectrometer, Perkin Elmer mod 590A. The base pressure was 2×10^{-10} Torr reaching 1×10^{-9} Torr during noble gases ion gun operation. Li^+ beam was produced by commercial solid state electrochemical reaction gun Kimball Physics ISG-4A-052. Secondary electron emission spectra were acquired by means of a single pass cylindrical mirror analyzer. Ion current density was kept in the range of 10 nA/cm^2 to assure the non contamination (especially in the case of Li ions bombardment) of the sample by ion implantation. In the experimental arrangement Li^+ and ionized rare gases beams impinge the surface with angles of 54° and 60°, respectively. The Cu(1 0 0) sample was cleaned by 1.5 keV Ar^+ bombardment and 800 K annealing cycles until carbon and oxygen Auger signals were below the sensitivity of the spectrometer.

3. Results and discussion

Measurements over a polycrystalline Cu (not shown) were performed. Since no differences with crystalline ones were found we do not present them here, but they allow us to determine that no diffraction effects are responsible for any of the discussed results.

In Fig. 1 we show the SEE spectra for different ions and bombarding energies. The spectra are not corrected for the energy transmission of the analyzer in order to enhance the high kinetic energy region of the spectra. Although the SEE yields are given in arbitrary units, the relative yields maintain the right relation, i.e. Li–Cu yields are the lowest, followed by Ar^+ and so on.

Several features of the ion induced electron emission from copper have been already studied; see for instance the work of Grizzi et al. [13] concerning hydrogen and noble gas ions. Although the ion energy used in that work is larger than ours ($E > 5$ keV), some of the characteristics corresponding to our experiments are still present. The first structure that can be identified, beyond the true secondary electron peak belonging to the electron cascade, is the Auger one. The maximum energy expected in Auger neutralization corresponds to the ionization level minus twice the work function (vertical lines in the figure), thus the broader SEE peak should correspond to He^+ followed by Ne^+ and Ar^+, as it actually happens. While, the Auger peaks can be clearly identified for He^+ and Ne^+, it falls completely within the true SEE peak for Ar^+.

There are a couple of typical features that may be used as fingerprints of the potential (Auger) emission, being the energy dependence the most characteristic one. Since Auger neutralization is a tunneling process occurring along the ion approximation, its importance decreases as the ion energy increases. This effect can be appreciated in Fig. 1 for He^+ and Ne^+, where the SEE is almost constant for the lowest energies. The relative importance of kinetic and potential emission can also be inferred from our results. For instance, while Ne^+ SEE yield is larger than He^+ one for larger energies, it falls down faster for the lower ones, when the Auger neutralization turns to be more important. Thus, we can conclude that potential emission is more important for He^+ than for Ne^+ and the opposite occurs for the kinetic emission. For lower energies, the SEE yields tend to be constant for both these ions, pointing out again to the importance of AN within this energy range. Following the same reasoning, one could conclude that for Ar^+ the kinetic mechanisms are more important and certainly it is for Li^+ where the SEE yield almost vanishes for 1 keV.

The startling result appearing in Fig. 1 we want to focus our attention on, is the long energy tail mainly observed for Ar^+ and Li^+ and also for Ne^+. In Fig. 2 we present the results for the largest energy (5 keV) for all ions and with the energy spectra corrected in this case by the energy transmission of the analyzer (N(E)). We use the logarithmic scale in order to observe the results in a more detailed way. While the spectra for He^+ and Ne^+ are almost linear, non exponentially decaying tail are observed for Li^+ and Ar^+. The exponential decay is a fingerprint of the broadening due to kinetic effects.

If we limit our analysis to the noble gas ions, we find that the effect responsible of the long tail increases with the mass and the energy of the projectile. This finding is in agreement with the experimental results of Baragiola et al. [4,2] and correspondingly we could propose a similar explanation, i.e. a higher number of promoted filled orbital should conduct to larger kinetic energies for the emitted electrons. On the other hand, the calculation of Jakas [12] based on the Fermi shuttle model also predicts a larger effect as larger are the mass of either the projectile or the target, also compatible with our experimental results.

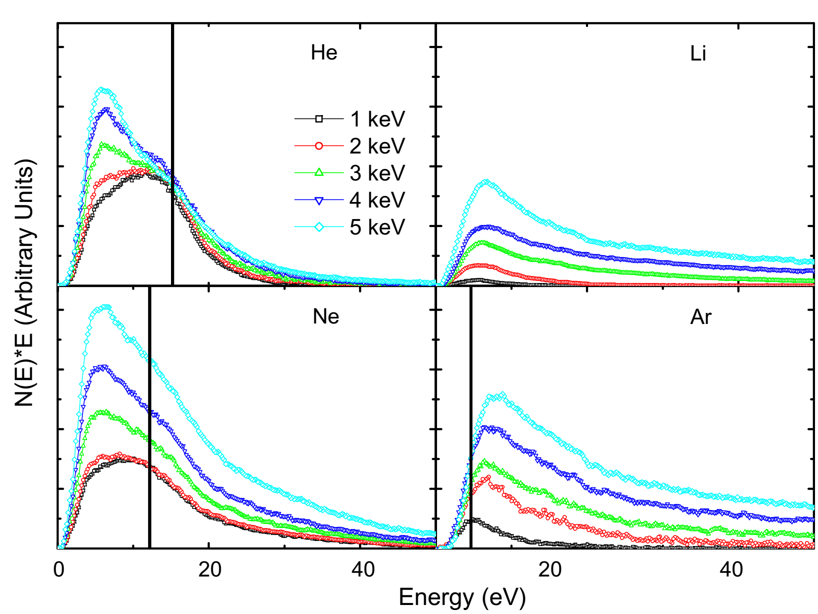

Fig. 1. Secondary electron versus kinetic energy for different impinging ions at different energies. Vertical lines represent the maximum energy expected for Auger neutralization with non perturbed levels [3]. For He^+ and Ne^+ the lowest energy corresponds to 1.5 keV.

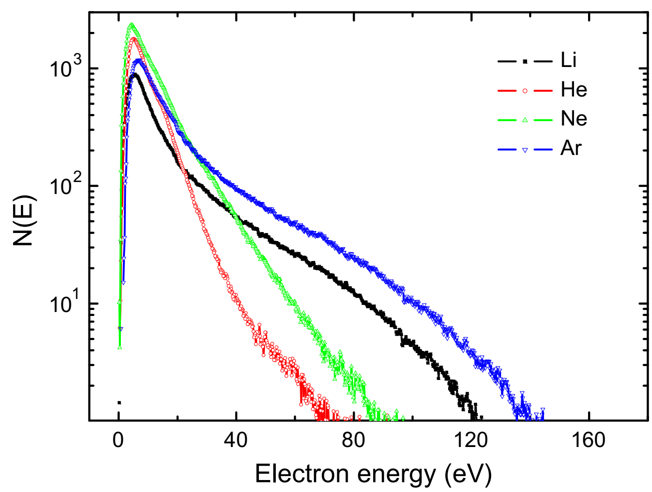

Fig. 2. Energy spectra for Li^+, He^+, Ne^+ and Ar^+ on Cu(1 0 0) for 5 keV incident energy. Spectra are corrected by the energy transmission of the analyzer.

A clue may be obtained by including Li^+ results in the analysis. Although mass and velocity features of Li^+ are close to He^+, its spectra looks closer to the Ar^+ one. The Li^+ produced tail is even longer than the Ne^+ one, against the inner shell promotion idea. If Li^+ versus Ne^+ results cannot be explained based in an inner shell promotion effect, how can it be compared to the Ar^+ case within the FS model. Since the neutralization probability of incoming ions is important in our energy range, it appears reasonable to think in the ion charge dependence of the FS effect [12]. Thus, Li^+ ions may be less effective than Ne^+ in producing high energy secondary electrons in each collision, but while Ne^+ ions are neutralized far from the surface, the FS mechanism is operative for Li^+ for almost the whole trajectory.

Shortly after fast particle measurement in slow ion collisions were ascribed to be electrons [6], an alternate explanation considering them as negative sputtered Cu, or even negative backscattered (He) ions was proposed [14]. Although this hypothesis was hardly criticized [15], van Someren et al. [16], through Time of Flight measurements, determined the presence of high energy recoil Cu negative ions during heavy ion collisions on Cu(1 1 0). Although the magnitude of each effect may be matter of discussion, they correctly conclude that in ascribing electron spectra to heavy particle impact, extreme care should be taken to exclude possible contributions from negative ions. Comparison of our measurements on Li with the noble gas ones can give us some insight about this point. In fact, any model based on sputtered efficiency, keeping a fixed geometry, will predict a larger effect for Ne than for Li ions, against our experimental results depicted in Figs. 1 and 2. Trying to explain this effect on the basis of negative backscattered ions will also fail. In fact, although we can discuss about the survival probability of He^- [6,14,15] we have no doubts about the Li^- one, i.e. simply looking at the electron affinities, there is no chance that we can have Li^- yields larger than He^- one, as we would need to explain our experimental results. In summary, since neither sputtered Cu^- (Li > Ne) nor backscattered negative ions (Li > He) can be the responsible for the high energy part of our measured spectra, following our previous line of thought, we have to ascribe them to high energy electrons accelerated through the Ping Pong effect of the Fermi shuttle mechanism.

4. Conclusion

We have found the presence of high energy electron emission induced by the bombardment of low energy Li^+ and noble ions. We found that the emission of Li^+ is larger that He^+ and Ne^+ ones and comparable to Ar^+ case. We can fully explain the experiment within the Fermi shuttle model and by taking into account that from all the used projectiles, the only one unable of suffering either Auger or resonant neutralization is Li^+. Thus, the Ping Pong effect produced within the FS model is more efficient as larger the mass of projectile and target are, as well as the longer the time which the projectile survives as ion. Thus, we understand our results within the FS model, taking into account that the mass gives the observed dependence for Ar^+, Ne^+ and He^+ and the large ion survival probability of Li^+ justifies its long tail.

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