Plasmon excitation in Al by keV Ne and Ar ions

P. Riccardi a,*, P. Barone a, M. Camarca a, A. Oliva a, R.A. Baragiola b

a Laboratorio IIS, Dipartimento di Fisica, Università della Calabria, and INFM Unità di Cosenza 87036 Arcavacata di Rende, Cosenza, Italy
b Laboratory for Atomic and Surface Physics, University of Virginia, Engineering Physics, Charlottesville, VA 22901, USA

Abstract

We present experimental studies of plasmon excitation by keV Ne and Ar single charged ions on Al surfaces. Plasmons are identified through the characteristic energy spectrum of electrons from plasmon decay. At 1 keV incident energy, surface plasmons are excited by Ne‡ but not by Ar‡. For higher energies we observe bulk plasmon excitation resulting, most likely, from excitation by fast electrons, such as Al-2p Auger electrons, traveling inside the solid. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 79.20.Rf; 71.45.Gm; 73.20.Mf; 34.70.+e

1. Introduction

Plasmon excitation in ion-solid interactions is attracting renewed interest since the experimental discovery of the process of potential plasmon excitation [1]. For projectile velocities far below the threshold for direct kinetic excitation [2], potential plasmon excitation occurs at the expense of the potential energy released upon neutralization of the incoming ion by electron capture from the solid. This mechanism thus competes with the well-known Auger Neutralization (AN) process [3–5]. AN can occur if \( E_n > I' - \Phi > \Phi \), where \( E_n \) is the maximum energy released in the neutralization event, \( \Phi \) is the metal work function and \( I' \) is the ionization potential of the parent atom shifted by the image interaction \( \Delta [3] \). Ion neutralization can be accompanied by plasmon excitation provided that \( E_n > E_{pl} \), where \( E_{pl} \) is the plasmon energy. The plasmons then decay by excitation of valence electrons [6,7] that may result in electron emission, which is revealed by a characteristic structure produced in the electron energy distribution [8]. This structure has a maximum energy, \( E_m = E_{pl} - \Phi \), corresponding to the absorption of the plasmon energy by an electron at the Fermi level. Analysis of the energy distributions of electrons emitted by metal surfaces under slow noble gas ions impact [1] reveals clear plasmon structures for those materials that have sharp plasmon resonances, like the free electron metals Al and Mg. In the case of Mg surfaces, the plasmon structure induced by He+ is well separated from the high-energy edge of AN, the energy separation being...
Moreover, the structure due to electron emission from plasmon decay is more important than that of AN, thus leading to the conclusion that potential plasmon excitation should dominate the neutralization behavior whenever energetically allowed.

Potential excitation of surface plasmons has been the subject of several theoretical studies [9,10]. Current theories do not predict bulk plasmon excitation by low energy ions that do not penetrate inside the solid. However, the energy distributions of electrons emitted by Al surfaces under slow He $^+$ and Ne $^+$ impact [1] showed structures whose energies were closely corresponding to that expected from bulk plasmon decay. Theoretical analysis by Monreal [11] showed that neutralization may produce surface plasmons of high momentum $q$, whose energies are shifted approaching those of the $q = 0$ bulk plasmon. However, experimental studies of surface plasmon dispersion in Al have not shown such high energies [12]. Theories have not considered the effect of the hole produced in the solid during neutralization.

Here we report energy distributions of electrons emitted by Al surfaces under the impact of keV, Ne and Ar single charged ions. It is shown that potential excitation of surface plasmons occurs for low energy Ne ions but not for Ar ions. At higher energies, we observe bulk plasmon excitation most likely resulting from fast electrons traveling through the solid.

2. Experiments

The experiments were performed in an ultrahigh vacuum chamber with a base pressure of $3 \times 10^{-10}$ Torr Ne $^+$ and Ar $^+$ ions were produced in a differentially pumped Atomika ion source by electron impact. The discharge voltage was set at 35 eV for Ne $^+$ and 30 eV for Ar $^+$ in order to ensure absence of double charged ions contamination in the ion beam. The ion current was of the order of $10^{-9}$ A and had a Gaussian spatial distribution in both horizontal and vertical directions with a FWHM less than 1 mm, as measured by a movable Faraday cup at the target position.

A polycrystalline Al sample (purity 99.999%) was mounted on a manipulator that allowed variation of the ion incidence angle $\theta$, relative to surface normal. The sample was sputter cleaned by 5 keV Ar$^+$ and Ne$^+$ ions, cleanliness was assured by the absence of oxygen, and carbon signals in Auger spectra induced by 2 keV electrons.

The emitted electrons were collected by a hemispherical electrostatic energy analyzer mounted on a goniometer. This analyzer, lying in the incidence plane, has semi-acceptance angle of 1.5° and was operated at a constant pass energy mode ($\Delta E = 50$ eV) and therefore an approximately constant transmission over the measured energy range. Electron energies are referenced to the vacuum level of the sample with an accuracy of 0.1 eV by comparing the energy of electrons from autoionization lines of Ne $^{2p43s2}$, with published value [14]. To measure accurately low energy electrons the chamber was shielded with $\mu$-metal to reduce the effect of stray magnetic fields in the neighborhood of the sample and analyzer.

3. Results and discussion

Fig. 1 shows representative electron energy spectra of the electrons emitted from the Al surface by incident 1 and 5 keV Ne$^+$ ions and 2 keV electrons. The electron induced spectrum shows two structure commonly attributed to electron emission from decay of $q = 0$ surface and bulk plasmon excited by fast electrons. The derivative of the spectrum make these structures evident [8] by revealing two minima at energies $E_{\text{m}} = E_{\text{pl}} - \Phi$. The minima occur at 6.5 and 11.2 eV for the surface and bulk plasmon, respectively.

Ion induced spectra compare well with previous results [1,13] and show features due to kinetic electron emission [19]: a low energy peak of cascade electrons and the two Ne$^{**}$ autoionization lines around 20–25 eV [14]. The spectrum for 5 keV Ne$^+$ impact on Al shows a broad feature whose derivative has a minimum closely corresponding in energy to that of the bulk plasmon in the electron induced spectrum. This structure has already been observed for 4.5 keV Ne$^+$ [13] and attributed to bulk plasmon decay. A similar
structure appears in the spectrum induced by 1 keV Ne⁺. This structure was also attributed to decay of bulk plasmons excited upon neutralization of the incoming ions [1]. However, in agreement with previous observations [1], we notice that the minimum in the derivative spectrum for 1 keV Ne⁺ impact is shifted by about 1 eV to lower energy from that observed in the electron and 5 keV Ne⁺ spectra.

In previous research [15], we studied the variations with angle of incidence of the energy distributions of the electrons emitted from Al surfaces under impact by 1–5 keV Ne⁺ ions. We observed that the energy and the intensity of the plasmon structure for 1 keV Ne⁺ impact is largely independent on the incidence angle. This finding suggested that plasmons are excited at or above the surface and is consistent with the idea of excitation by the shake up due to the sudden disappearance of the dipole formed by the incoming ion and the image charge [1]. The observation that the energy of the plasmon excited by 1 keV Ne⁺ ions is lower than that of even the $q\hat{0}$ bulk plasmon, along with the observation that excitations occur at or above the surface, supports the interpretation of surface plasmons of high momenta, postulated by Monreal [11]. This would imply that surface plasmons can exist with energies higher than previously reported.

At higher impact energies a transition from surface plasmon excitation to bulk plasmon excitation occurs. Angular measurements for 5 keV Ne⁺ on Al have shown that the plasmon energy is close to that of the $q\hat{0}$ bulk plasmon and that plasmon intensities increase as the incidence angle deviates from the surface normal. This is consistent with the idea that plasmon excitation occurs mainly in the bulk of the solid and that the intensity of the emission from plasmon decay depends on the depth were excitation occurred.

In Fig. 2, we report energy distributions of electrons emitted from Al surfaces by Ar⁺ ions as a function of incident energy. Ions were impinging on the surface at an incidence angle $\theta_i = 60^\circ$ and the observation angle was $\theta_e = 0^\circ$. The spectra are shown normalized so that their integrals equal known electron yields [16]. The main feature of the spectrum induced by 1 keV Ar⁺ on Al is the broad distribution that results in the minimum at about 5 eV in the derivative spectrum. We have shown [15] that Ar⁺ neutralization at Al surface is not mediated by plasmon excitation and the minimum at 5 eV in the derivative correspond to the high energy edge of Auger neutralization. As the ion energy increases, the spectra show the evolution from the potential electron emission to the kinetic electron emission regime. The dip in the derivative at 5 eV decreases and a broad structure appears. This structure results in the minimum in the
derivative observed around 11 eV. Comparison with Fig. 1 shows that the energy of this structure corresponds to that of the structure appearing in the spectrum of the electrons emitted by an Al surface under electron and 5 keV Ne\(^{+}\) irradiation. Therefore, it is assigned to electron emission from bulk plasmon decay. Bulk plasmon excitation in experiments of Ar\(^{+}\) ions bombardment on Al have been observed in the past [17] but at much higher incident energies than those reported here. A dip in the derivatives close to 6.5 eV due to a \(q = 0\) surface plasmons is apparent in the spectra, but cannot be clearly resolved.

The results of Fig. 2 indicate that bulk plasmon excitation in the case of Ar ions on Al is related to kinetic electron excitation. This idea is also supported by the behavior of the intensity of the plasmon structure as a function of ion energy, plotted in Fig. 3. Plasmon intensities have been evaluated following the procedure outlined in [18]. The energy dependence suggests that there is a threshold incident energy for bulk plasmon excitation. A precise evaluation of this threshold is made difficult because electron emission from bulk plasmon decay is masked by the background of secondary electrons. To understand the origin of this kinetic plasmon excitation we note that so-called plasmon loss satellites have been observed in the past in the Al-2p Auger spectra excited by electron impact as well as by electron promotion in violent atom–atom collisions in our energy range [20,21]. Our data are consistent with the idea that, at the threshold, plasmon may be excited by fast Auger electrons traveling inside the solid, consistent with the explanation for sub-threshold plasmon excitation by keV protons recently published [22].

In conclusion, we have studied the excitation of Al plasmons by keV Ne\(^{+}\) and Ar\(^{+}\) ions. In the case of low energy Ne\(^{+}\) on Al, data are consistent with theoretical prediction of potential excitation of surface plasmons of short wavelength. At higher incident energies, bulk plasmon excitation occurs and the reported data show that plasmons can be efficiently excited by fast electrons traveling inside the solid.
Acknowledgements

This research has been supported by Istituto Nazionale per la Fisica della Materia, INFM and the National Science Foundation.

References