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H. Rothard, K. Kroneberger, M. Burkhard, C. Biedermann, J. Kemmler, et al.. REFRACTION OF DIRECTED SHOCK ELECTRONS AT PLANAR SOLID SURFACES. Journal de Physique Colloques, 1989, 50 (C2), pp.C2-105-C2-110. 10.1051/jphyscol:1989219 . jpa-00229417

HAL Id: jpa-00229417

<https://hal.science/jpa-00229417>

Submitted on 4 Feb 2008

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REFRACTION OF DIRECTED SHOCK ELECTRONS AT PLANAR SOLID SURFACES

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RÉSUMÉ

»Shock electrons« sont des électrons secondaires de faible énergie ($E_e < 20$ eV) qui sont produits par des ondes de choc dans le plasma d'électrons (»wake«) d'un solide bombardé avec des ions lourds de grande vitesse ($V_F > V_{Bohr}$). Ils ont été observés en mesurant la distribution en angle et en énergie des électrons secondaires émergeant d'une cible mince. Ces électrons, qui traversent le volume du solide perpendiculairement quant au cône de l'onde de choc, peuvent être utilisés pour étudier la diffraction des électrons lents à la surface du solide.

ABSTRACT

Shock electrons are ejected in a direction perpendicular to the shock front of the wake cone, the ion induced collective electron density fluctuation in the electron plasma of the solid. They have been observed by measuring doubly differential secondary electron distributions from thin solid foils in forward direction. Shock electrons represent a unique internal source of directed secondary electrons and thus offer the possibility to study the refraction of electrons at a solid surface. Nearly planar, smooth solid foil surfaces are obtained by sputter-cleaning in ultrahigh vacuum. The smoothing can be observed by scanning electron microscopy.

PACS: 79.20 rf, 79.20 nc

INTRODUCTION

The interaction of swift ions ($V_F \geq V_B$) with condensed matter results in the production of internal secondary electrons by the primary ions, recoil ions, secondary electrons and, possibly, photons [1]. The **internal flux** of the secondary electrons (i.e. their energy- and angular distribution) depends on both the primary processes and the transport of electrons through the solid [2]. The distribution of secondary electrons **outside of the solid** is strongly influenced by the transmission of secondary electrons through the surface potential barrier. Secondary electron creation is important e.g. for radiation physics, -chemistry and -biology [1]; fusion research for controlled thermonuclear power production (plasma-wall-interactions) [2]; ion induced desorption of molecules from solids (Plasma Desorption Mass Spectrometry, PDMS) [3] and nuclear track formation [2]. Therefore, it is desirable to know both the **internal and the external energy- and angular distribution of secondary electrons**.

The measurement of energy- and angular distributions of secondary electrons emitted from a solid surface yields valuable information about production, transport and transmission of secondary electrons. In particular, the measurement of secondary electron distributions from **thin foils in forward direction** yields more detailed information than measuring secondary electrons emission from **thick samples in backward direction**. This is due

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to the following reasons: 1. δ -electrons from binary collisions are mostly ejected in forward direction. 2. Convoy-electrons [2] are observed strongly peaked in forward direction. Also, 3. the directed shock electrons are ejected in forward direction and offer an elegant possibility to study the refraction and transmission of low energy electrons created in the bulk at the surface potential barrier.

"WAKE" AND SHOCK ELECTRONS

"It is conceivable that the rich spatial shock-wave structure of electron density fluctuations in the wake of an ion may have interesting manifestations in experiment and important consequences for the behaviour of matter under high-intensity ion-beam bombardment." (Ritchie, Echenique, Brandt and Basbas 1979 [4])

The collective response of the electron plasma of a solid to a penetrating swift heavy ion manifests as an electron density fluctuation with axial symmetry [4]. This dynamic polarization "wake" shows the characteristic behaviour of Mach shock waves propagating in cones through the solid [5]. It has been shown that this leads to the directed emission of shock electrons in a direction perpendicular to the shock wave front [5,6,7].

Shock electrons can be detected as peak structures in the angular distributions of secondary electrons at energies $E_e \approx 5$ eV, superimposed on the "true" secondary electron background [7]. Experimental details are described in [7,8]. The calculated preferential emission angle θ_{em}^{theo} of shock electrons depends mainly on the plasma frequency ω_P of the target and the projectile velocity v_p and is given by the Mach relation:

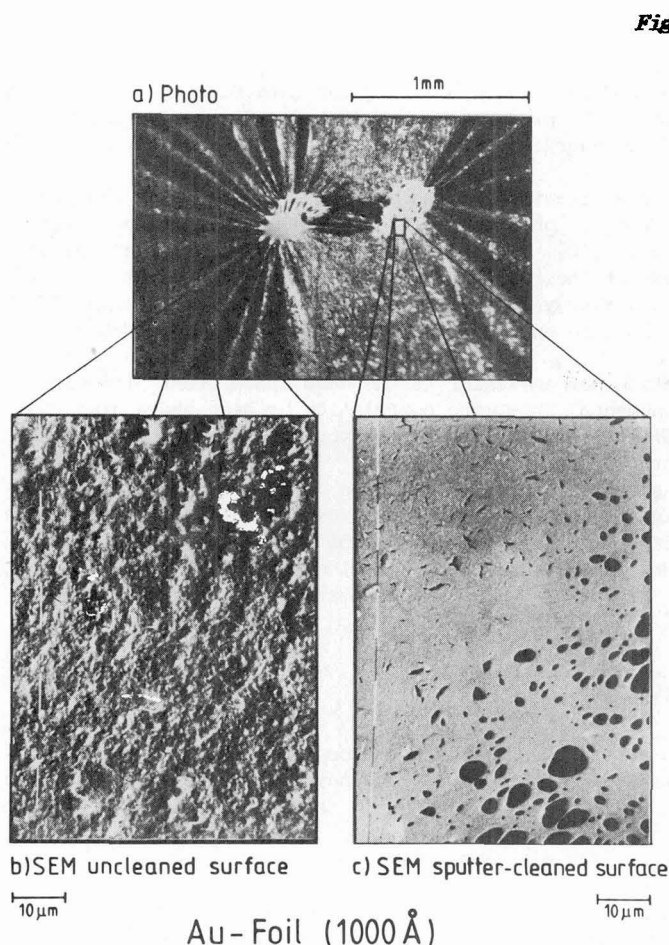
$$(1) \quad \theta_{em}^{theo} = \arccos v_s/v_p$$

($v_s = f(\omega_P)$ is the velocity of the shock wave). It has been observed that the emission of shock electrons as well as the emission of electrons from the single-electron deexcitation of heavy-ion-induced plasmons, a collective effect closely related to wake phenomena [9], depend on surface properties such as the coverage with impurities and the roughness of the surface [7]. In this paper, we will discuss the following topics: 1. Nearly planar solid surfaces obtained by sputtering of thin solid foil surfaces with noble gas ions, 2. Refraction of low energy electrons at a planar surface potential barrier, 3. Application of this model to the emission of shock electrons: The experimentally observable mean shock electron emission angle θ_{em}^{exp} becomes a function of θ_{em}^{theo} (given by the opening angle of the Mach cone of the wake) and the height of the surface potential barrier U .

REFRACTION OF ELECTRONS AT A PLANAR SURFACE BARRIER

Secondary electron emission depends strongly on both the coverage of solid surfaces with impurities and the roughness of the surface [8,10]. To study secondary electron emission from clean solid foil surfaces, they have to be sputter-cleaned with noble gas ions (Kr^+ , 2 MeV) in ultra high vacuum ($p \leq 10^{-7}$ Pa). The sputtering process at the entrance surface of the beam (backward sputtering) and at the exit surface in forward direction (transmission sputtering) results in both a cleaning and a smoothing of the surface by preferential sputtering. The composition of the surface can be supervised by Ion Induced Auger Electron Spectroscopy (IAES), Secondary Electron Spectroscopy (SES), Rutherford Forward/Backward Scattering Spectroscopy (RFS/RBS) and Elastic Recoil Detection (ERD). In addition, it is important to analyze the residual gas with a quadrupole mass spectrometer, especially to verify that a vacuum almost free of hydrocarbons has been obtained [11]. AES and SES are very sensitive methods to control the surface, whereas RFS, RBS and ERD can be used to control the composition of the whole target volume. Furthermore, RFS and ERD allow the detection of light elements such as H, which can play an important role for secondary electron emission [10]. Before cleaning, the foil surfaces are covered mainly with C, O and H, mostly by hydrocarbons and water [10,12].

The reduction of the surface roughness can be observed in two ways. 1. Visually (in situ), because the targets become mirror-like with a highly enhanced reflectivity at the beam spot, and 2. by Scanning Electron Microscopy (SEM) of the target surface. In the pre-



sent case, the SEM micrographs have been taken outside the scattering chamber. Therefore, we chose an inert gold foil to demonstrate the smoothing of the surface under the assumption that the structure does not change strongly during the transport from the experiment to the electron microscope.

Fig.1a shows a photograph of the exit surface of a 1000 Å gold foil. Two bright beam spots are clearly visible. They have a highly enhanced reflectivity compared to the environment. Fig.1b presents a SEM micrograph of the uncleaned surface region with pronounced structures in the μm range. In contrast, Fig.1c shows a SEM micrograph of a sputter-cleaned beam spot. No structures can be detected (resolution better than $0.05 \mu\text{m}$), except for micro holes (black, no secondary electron emission). Such micro holes appear when the target has been bombarded with heavy ions for an extended period of time. Eventually, the ion bombardment results in the destruction of the thin foil.

The clean, smooth surface can be described in a good approximation by a planar electrostatic surface potential. When a secondary electron (e^-) produced inside the solid approaches the surface with sufficient kinetic energy to overcome the nearly planar surface potential barrier $U(x)$, it is subject to a diffraction phenomenon (Fig.2). The components of the electron velocity vector parallel to the surface remain unchanged ($v_1^{\parallel} = v_e^{\parallel}$), whereas the component perpendicular to the surface is reduced according to the height of the surface barrier U ($v_e^{\perp} < v_1^{\perp}$). The kinetic energy of the electron is reduced ($E_e = E_1 - U$).

REFRACTION OF SHOCK ELECTRONS

An internal source of directed electrons is needed to study directly the refraction of low energy secondary electrons produced inside the solid at the interface between the solid and the vacuum. Secondary electrons can be produced by a multitude of superimposed production mechanisms. Only two kinds of secondary electrons are ejected and strongly peaked in one direction:

1. **Convoy electrons** are emitted in the direction of the beam, but they are not the appropriate tool to study surface refraction phenomena: It has been shown that their velocity is equal to the projectile velocity [12]. They are not accelerated or decelerated by the surface potential barrier because of their strong correlation to the projectile [2,10,12]. In contrast, the yield of low energy convoy electrons depends on the height of the surface potential barrier [10]. This resembles the reflection of a wave packet at a potential step.
2. **Shock electrons** move in a direction perpendicular to the wake shock front. The wake is a long-range and nonlocalized phenomenon. Thus, the correlation between shock electrons and the projectile is not so strong as in the case of convoy electrons. They represent a unique internal source of directed electrons.

When shock electrons are transmitted through the surface, they are refracted as discussed in the previous section (Fig.2). The experimentally expected emission angle Θ_{em}^{exp} becomes a function of the height of the surface barrier U , the mean energy of the shock electrons outside the solid E_e , the "theoretical" mean emission angle Θ_{em}^{theo} (given by the opening angle of the wake cone $\Theta_{em}^{theo} = f(\omega_P, v_P)$) and the target tilt angle δ (see Fig.2):

$$(2) \quad \Theta_{em}^{exp} = f(\Theta_{em}^{theo}, U, E_e, \delta) \\ = \delta + \arcsin[(1+U/E_e)^{1/2} \sin(\Theta_{em}^{theo}-\delta)]$$

It should even be possible to detect shock electrons from the **backside** of a **solid target**, if the target tilt angle is large, the plasma frequency is low and the projectile velocity is high (say, $\hbar\omega_P < 9$ eV, $v_P > 2.5 v_B$, $\delta > 60^\circ$). In this case, Θ_{em}^{exp} is given by

$$(3) \quad \Theta_{em}^{exp} = 180^\circ - \delta - \arcsin[(1+U/E_e)^{1/2} \sin(180^\circ - \delta - \Theta_{em}^{theo})]$$

Fig.3 shows the observed mean shock electron emission angle Θ_{em} for carbon targets ($\hbar\omega_P \approx 21$ eV) as a function of the projectile velocity v_P (open circles, from [7]). The (measured!) mean energy of shock electrons outside the solid is $E_e \approx 5$ eV ($\delta = 45^\circ$). The dashed line shows Θ_{em}^{theo} , neglecting the surface potential ($U = 0$, from [5]). The dotted line shows Θ_{em}^{exp} if U is chosen to be $U = \Phi + E_F$ (≈ 20 eV for carbon). In theoretical considerations concerning secondary electron emission the total electrostatic surface potential U is often chosen as effective surface potential [1]. This choice fails in describing the experimental data, because shock electrons originate from the electron plasma of the solid with initial energies close to the Fermi energy, E_F . The appropriate choice of an effective surface potential in this case should be $U = \Phi$, where Φ is the electron work function. The same argument is valid for electrons resulting from the decay of plasmons, which can be observed at energies $E < \hbar\omega_P - \Phi$ [9,13]. Indeed, the expected mean emission angle of shock electrons Θ_{em}^{exp} (solid line, with Θ_{em}^{theo} taken from [5] and $U = \Phi = 5$ eV) according to eq. (2) is in good agreement with the experimental data (Θ_{em} , open circles)!

CONCLUSION AND OUTLOOK

The heavy-ion-wake-induced shock electrons can be used to study the refraction of low energy secondary electrons, which have been produced in the bulk of a solid, at the surface. There are interesting questions, as e.g. "Is the wake reflected at the surface?", "How many shock electrons can overcome the surface potential barrier and how many shock electrons are retained by the surface potential barrier?". They may possibly be addressed by measuring the mean emission angle Θ_{em} and energy E_e of shock electrons as a function of the target tilt angle δ .

Fig.2: Refraction of shock electrons at a planar solid surface (see text).

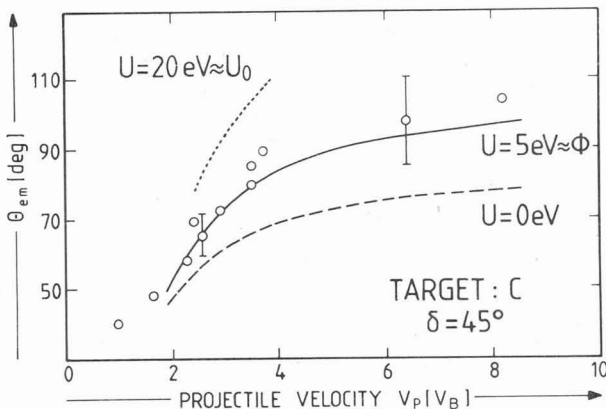
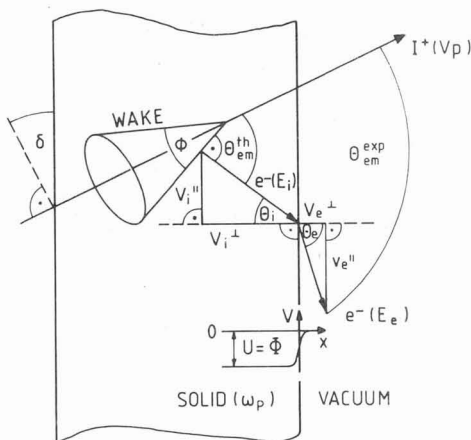


Fig.3: The observed preferential emission angle θ_{em} of shock electrons (open circle) as a function of the projectile velocity v_p . Dashed line: θ_{em}^{theo} neglecting electron refraction at the surface ($U = 0$), Dotted line: θ_{em}^{exp} ($U = 20 \text{ eV} = E_F + \Phi$), Solid line: Expected preferential emission angle θ_{em}^{exp} ($U = \Phi = 5 \text{ eV}$).

Another interesting experiment may be the measurement of the angular distribution of heavy ion induced photons emitted from solids. Possibly, photons may be produced by the fast ion-induced electron density fluctuations. These photons are expected to be emitted coherently in a preferential direction depending on the opening angle of the wake cone [14]. Their energy is estimated to be in the range $10 \text{ eV} \leq h\nu \leq 1000 \text{ eV}$. Also, experiments on the temperature dependence of secondary electron emission and, in particular, shock electron emission, may give important information about thermal and electrical transport properties, not only in metals, but even in superconductors [11].

This work has been supported by the German Bundesminister für Forschung und Technologie (BMFT) / Bonn, under contract number 06 OF 173/2 Ti476, and DFG / Bonn. One of us (H.R.) acknowledges a grant from the Willkomm Stiftung, Frankfurt am Main.

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