Surface Roughness and Photoemission*

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Analysis of experimental data for several metals is found consistent with the surface photoelectric theory of Mitchell and Makinson. Surface roughness is invoked to account for the observed angular dependence of photoelectric yields.

The observation that optical absorption for some metals is enhanced by surface roughness, and the identification of the enhancement mechanism with surface plasmon generation,[1] has prompted renewed interest in the surface photoelectric effect. Endriz and Spicer have found that the photoyield of Al correlates with surface roughness,[2] and have given the interpretation that this is due to the decaying surface plasmons coupling with electrons.[2,3] Support for the *surface* photoelectric effect stems from agreement of the measured results[2] with calculations using the radiation field of the surface polarization wave instead of the incident light wave. It is the purpose of this Letter to show that there is also convincing evidence for *direct* coupling of the light wave to the electrons in the surface region, when an appropriate quantitative treatment for surface roughness is used in the analysis of published photoemission data.[4]

Although the Mitchell-Makinson (MM) theory of surface photoemission for a clean, smooth surface is unable to account for the appearance of photocurrents when the electric vector for the incident light is parallel to the emitter surface, Mitchell[5] and Makinson[6] have argued that surface roughness can be responsible for photoemission when the light is s polarized; it also follows that surface roughness might be expected to influence the angular dependence of the photoelectric yield. Makinson[6] sketched a derivation of roughness factors to be used for either s- or p-polarized light.

Following Makinson,[6] we introduce roughness effects by writing

$$\hat{n}\cdot\vec{\mathrm{E}}=[\hat{z}\cos\alpha+(\hat{y}\cos\beta+\hat{x}\sin\beta)\sin\alpha]\cdot[E_p(\pm\hat{z}\sin\theta\mp\hat{y}\cos\theta)\pm xE_x], \tag{1}$$

where $\vec{\mathrm{E}}$ represents the incident (or reflected) light wave and $\hat{n}$ describes the *local* surface normal. (The upper and lower signs are for incident and reflected waves, respectively.) θ is the angle between the incident electric vector and the normal to the mean surface plane. α and β are spherical polar angles defining the normals of the microscopic surface elements, relative to the mean surface plane and the plane of light incidence, respectively. Since the factor $|\hat{n}\cdot\vec{\mathrm{E}}|^2$ appears in the photoexcitation rate for a flat surface ($\alpha=0$), the electron-photon coupling is modified for the case of a rough surface by now using Eq. (1) with the wave vectors for the electron states described relative to the *local* surface normal. This geometrical approach applies when (i) the light wavelength is sufficiently large compared to the rms height variation of the surface (i.e., the asperity parameter σ) and (ii) the momentum distribution of the electrons is approximately isotropic. The first condition provides a description of the radiation field for the mean surface in the factors $|\vec{\mathrm{E}}(\theta)|^2$, while condition (ii) permits the use of the factor $|\hat{n}\cdot\vec{\mathrm{E}}(\theta)|^2$ to describe the variation of surface photoemission with $\hat{n}$.

We proceed to obtain expressions for comparison with experimental data by introducing distributions for the angles α and β, and carrying out the appropriate averages of $|\hat{n}\cdot\vec{\mathrm{E}}|^2$ over unit emitter surface area. Assuming that the azimuth β is randomly distributed, and the polar angle α has a distribution function $f(\alpha)$, the fraction of the microscopic surface with α in $\delta\alpha$, we obtain

$$\langle|\hat{n}\cdot\vec{\mathrm{E}}|^2\rangle=\tfrac{1}{2}\vec{\mathrm{E}}_s\cdot\vec{\mathrm{E}}_s\sin^2\overline{\alpha}+\vec{\mathrm{E}}_p\cdot\vec{\mathrm{E}}_p(\cos^2\overline{\alpha}\sin^2\theta+\tfrac{1}{2}\sin^2\overline{\alpha}\cos^2\theta), \tag{2}$$

where the roughness parameter $\overline{\alpha}$ is defined by

$$\sin^2\overline{\alpha}=\int f(\alpha)\sin^2\alpha\,d\alpha,\quad \int f(\alpha)\,d\alpha=1.$$

Roughness factors R_π' $(\pi = s, p)$ can be defined from $\langle |\hat{n}\cdot E|^2\rangle$ by using Eq. (2):

$$\cos^2\bar{\alpha}\sin^2\theta + \tfrac{1}{2}\sin^2\bar{\alpha}\cos^2\theta \equiv R_p'\sin^2\theta. \tag{3a}$$

$$\tfrac{1}{2}\sin^2\bar{\alpha} \equiv R_s'\sin^2\theta. \tag{3b}$$

The meaning of Eq. (3b) is that photoemission for light at normal incidence $(\theta = 0)$ can be calculated from the photocurrent J_p using a value of θ for which $\sin^2\theta = \frac{1}{2}\sin^2\bar{\alpha}$.

The formulas for R_π' can be used to modify the analysis for calculations of the photocurrent for a plane surface $(\alpha = 0)$ to include roughness.[7] These modified formulas have been used to analyze the θ dependence of photoelectric yields measured for molybdenum,[8] and also the results obtained for potassium[9]; data reported in Ref. 2 can also be treated in this manner.

For *direct* excitation of electrons at the surface, the photoelectric yield has the angular dependence

$$Y(\theta) \propto \langle |\hat{n}\cdot\vec{\mathrm{E}}(\theta)|^2\rangle/\cos\theta, \tag{4}$$

where $\cos\theta$ is the cross section of the incident light (beam) illuminating unit surface area. We can eliminate factors depending on photon energy $h\nu$ and the distribution of electrons by forming the ratios

$$\frac{Y_\pi(\theta)}{Y_\pi(0)} = \frac{\langle |\hat{n}\cdot\vec{\mathrm{E}}_\pi(\theta)|^2\rangle/\cos\theta}{\langle |\hat{n}\cdot\vec{\mathrm{E}}_\pi(0)|^2\rangle} = \frac{|\vec{\mathrm{E}}_\pi(\theta)|^2}{|\vec{\mathrm{E}}_\pi(0)|^2\cos\theta}\,\frac{R_\pi'}{R_s'}, \tag{5}$$

or

$$\frac{Y_p(\theta)}{Y_s(\theta)} = \frac{|\vec{\mathrm{E}}_p(\theta)|^2}{|\vec{\mathrm{E}}_s(\theta)|^2}\,\frac{R_p'}{R_s'}, \tag{6}$$

which is the vector ratio at angle θ. In Eq. (6), we notice that $R_\pi'\sin^2\theta = \frac{1}{2}\sin^2\bar{\alpha} = R_s'\sin^2\theta$ when $\theta \to 0$.

Substituting Eq. (3a) into Eq. (5), we obtain

$$\frac{Y_p(\theta)}{Y_p(0)}\cos\theta = \frac{|\vec{\mathrm{E}}_p(\theta)|^2}{|\vec{\mathrm{E}}_p(0)|^2}(\cos^2\theta + 2\cot^2\bar{\alpha}\sin^2\theta) = \frac{A_p(\theta)}{A_p(0)}[1 + (2\cot^2\bar{\alpha} - 1)\sin^2\theta]; \tag{7}$$

$A_p(\theta)$ is the optical absorption, proportional to the light intensity at the surface. The data for checking this θ dependence are given in Fig. 4 of Ref. 8 in which are plotted experimental values of the photoelectric yield and absorbed power versus angle for clean molybdenum. The measured yield ratios have been multiplied by $\cos\theta$ and replotted versus $\sin^2\theta$ in our Fig. 1. It can be seen that $Y_p(\theta)\cos\theta/Y_p(0)$ varies linearly with $\sin^2\theta$ for $0 \lesssim \theta \lesssim 50°$, which, if $|\vec{\mathrm{E}}_p(\theta)|^2/|\vec{\mathrm{E}}_p(0)|^2$ remains nearly constant, would be in agreement with our analysis. The absorption data given in Fig. 4 of Ref. 8 confirm the latter; the absorption ratio $A_p(\theta)/A_p(0)$ is relatively flat for $\theta \lesssim 50°$, increasing slightly (compared to the yield ratio) for larger angles. The nearly linear result is thus in agreement with Eq. (7); the slope of the line gives a roughness parameter $\bar{\alpha} = 38°$. We might expect difficulties due to diffraction and reflection at larger incidence angles $(\theta \gtrsim 50°)$, and these are apparent in the figure. Because the photon energy, 4.88 eV, for this data is close to the photoelectric threshold of 4.19 eV for Mo, we expect the MM surface photoelectric theory to be applicable. To study the regime of applicability of the MM theory and the effects of roughness at higher photon energies, we turn to the measurements of the vector ratio for potassium for the energy range $2.25 < h\nu < 5.20$ eV.[9]

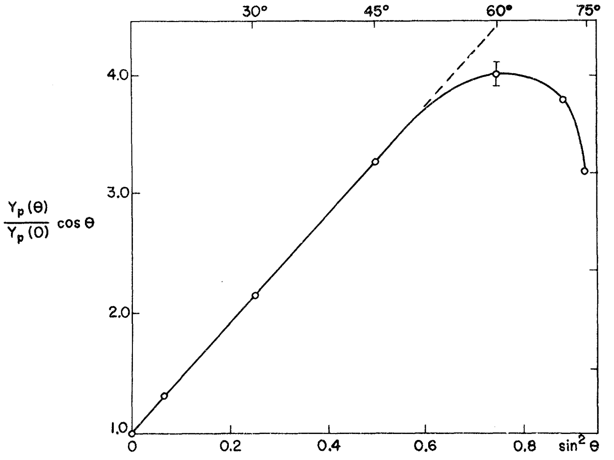

FIG. 1. $Y_p(\theta)\cos\theta/Y_p(0)$ as a function of $\sin^2\theta$. The data are taken from Juenker *et al.* (Ref. 8); the dashed curve is given by Eq. (5) of the present work with $A_p(\theta) = A_p(0)$. Error bars have been estimated from the data given in Ref. 8.

Assuming that the vector ratio has an angular dependence determined by surface roughness, we can write

$$\frac{Y_p(\theta)}{Y_s(\theta)} = \frac{|\vec{\mathrm{E}}_p(\theta)|^2}{|\vec{\mathrm{E}}_s(\theta)|^2}[1 + (2\cot^2\bar{\alpha} - 1)\sin^2\theta], \tag{8}$$

which is the same as $Y_p(\theta)\cos\theta/Y_p(0)$ given by Eq. (7). If we restrict θ and also ν to values for which $A_p(\theta)/A_s(\theta)$ does not vary by more than 20%, say, the previous analysis can be used again.

Because Brauer's measurements for each frequency include only the points $\theta = 0°$, $30°$, and $45°$ below $50°$, the potassium data available for comparison with Eq. (8) are not very complete; nevertheless, the curves appear linear in $\sin^2\theta$ for photon energies up to about 3.0 eV. When the experimentally deduced values of $\overline{\alpha}$ are compared for different photon energies it is found that the roughness parameter $\overline{\alpha}$ decreases as photon energy increases; this is also apparent from Brauer's Fig. 3, where he plots measured vector ratios for potassium as a function of angle which exhibit nearly linear increases of Y_p/Y_s with $h\nu$ for fixed θ, up to about 3.2 eV. The ν dependence for $\overline{\alpha}$ is easily interpreted as consistent with a nearly free-electron-like metal exhibiting a surface photoelectric effect.

We first note that it is the electrons close to the surface which respond to the surface roughness; also, increasing the photon energy produces an increase in the *mean* de Broglie wavelength for those electrons which are emitted following photoexcitation. Thus, keeping the rms height variation fixed while increasing the mean electron wavelength will produce the observed decrease in the effect of surface roughness as the photon energy is increased. (We may note that the light wavelength, very much larger than the scale of surface roughness, does not enter these considerations.) It can also be shown that for a quadratic dispersion of the electron energies and constant effective mass, the mean wave number $\langle k\rangle$ decreases nearly linearly with photon energy when a surface effect for photoexcitation is assumed.[7]

At larger photon energies ($h\nu > 3.3$ eV), Brauer's vector-ratio data show a (slower) decrease in Y_p/Y_s for fixed incident angles, as ν is increased. Since this is the regime for a volume effect, our surface-roughness analysis is not expected to be applicable. Nonetheless, a nearly linear dependence of the vector ratio on $\sin^2\theta$ is still found, but with intercept (for $\theta = 0$) different from $Y_p(0)/Y_s(0) = 1$. Skibowski *et al.*[10] have reported a similar variation in $Y_p(\theta)/Y_p(0)$ for Al films at photon energies producing a plasma resonance absorption.

Having shown that some experimental data[8,9] are consistent with a direct photon-electron interaction in the surface region, we examine the relationship between photoyield and surface roughness. Equation (3a) can be rearranged to read

$$R_p' \equiv \langle \sin^2\theta\rangle = \sin^2\theta + [\tfrac{1}{2}\cot^2\theta - \sin^2\theta]\sin^2\overline{\alpha},$$

to show that, if $\tan^2\theta$ is less than $\frac{1}{2}$, the photoyield increases with roughness, as observed in Ref. 2. Comparing Brauer's vector ratios obtained for (rougher) thick films with those of Thomas[11] for thin films on polished quartz substrates (and both at $\theta = 45°$), we find qualitative support, predicted in our analysis, for the dependence of vector ratios on the roughness parameter. Similarly, the angular dependence for the photoyields from Al, given in Fig. 12 of Ref. 2b, produces a variation of $\overline{\alpha}$ with ν rather similar to that already noted for Brauer's data for $h\nu \lesssim 3.0$ eV. Thus, using the present surface-roughness analysis based on *direct* coupling of photons and electrons, we can consistently explain two of the experimental findings used by Endriz and Spicer[2] in their alternative photon-plasmon-electron excitation mechanism to describe surface photoemission.

Ritchie and co-workers[1,12] have studied photon coupling with surface plasmons using several mathematical models for the surface roughness distribution function. Their results yield correlation lengths that are several times larger than those needed to excite the surface plasmons that couple strongly to the conduction electrons.[13] It may be that the fairly large $\overline{\alpha}$'s which are found here lend some support to the smaller correlation lengths that are required for the model of Endriz and Spicer.

To summarize, in the photon energy region where direct coupling for surface photoexcitation is expected, the present work provides a fairly easy way to examine the microscopic roughness of a nearly free-electron metal surface. Our analysis lends support for the MM theory[5,6] of surface photoemission and also reveals considerable atomic roughness to be present on the experimental surface analyzed in this study.

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Generation of Intense Ion Beams in Pulsed Diodes*

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The generation of high-current ($\sim 10^5$ A) pulsed ion beams with ion energy in the range 0.5–10 MeV appears to be possible by modifications of present electron-beam technology.

The success achieved in generating high-current pulsed relativistic electron beams[1] suggests the possibility of producing high-current ($\sim 10^5$ A) pulsed ion beams in the 0.5–10 MeV range by modifications of this technology. Such ion beams would have a number of important applications: (a) Intense ion beams could be used to heat rapidly a plasma to fusion temperatures. The ion beam may be expected to interact directly with the plasma ions by collective processes provided the electron thermal velocity is greater than the ion beam velocity. (b) Ion beams of say D_2 with energy of the order of 1 MeV can produce fusion reactions directly when used to bombard a suitable target plasma. A net gain in energy is possible provided the electron temperature of the target is 5 keV.[2] Such electron temperatures could be produced by auxiliary means. (c) Intense ion beams could find use in nuclear studies which are beyond present capabilities, for producing intense neutron fluxes, isotope fluxes, and multiple nuclear reactions. It is clear that development of intense ion beams would provide a new technology which may have unforeseen uses.

Important problems for the efficient generation of intense ion beams are the suppression of the normally occuring electron current and the preparation of the anode surface so as to allow ions to be emitted readily. This Letter discusses conditions for the suppression of the electron current by application of a transverse magnetic field, requirements on an (externally produced) anode plasma in order for this plasma to serve as the ion source, and the expected space-charge–limited ion current. (A preliminary experiment[3] aimed at generating an ion beam in a pulsed diode has been done using a laser-heated metallic anode but without a transverse magnetic field. Preliminary experiments[4] have also been done on the suppression of the electron current with a magnetic field; however, a previous theoretical study[5] on the effect of a transverse magnetic field is inapplicable to the situation considered here because of the neglect of the electron space charge.)

By way of introduction it is noted that the high-current electron beams are produced basically by the application of a high-voltage (0.5–10 MeV) pulse (of typical length 50 nsec) to a diode consisting of two closely spaced metal surfaces. Electrons from the cathode surface are accelerated across the diode and extracted. The electron current across the diode is described ap-