Anomalies in the vector photoelectric effect of the W(110)-Cs system in submonolayer films

G. V. Benemanskaya and M. N. Lapushkin
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad

(Submitted 29 March 1989)
Pis'ma Zh. Eksp. Teor. Fiz. **49**, No. 9, 515–517 (10 May 1989)

Different submonolayer coverages of the surface by Cs correspond to quite different angular dependences of the threshold photoemission during excitation with *p*-polarized light. These results cannot be explained by the standard theoretical model of a vector photoelectric effect. They are interpreted as a manifestation of surface electron states.

The vector photoelectric effect consists of a difference in the angular dependence of the threshold photoemission of metals for *s*- and *p*-polarized excitation. Experiments[1,2] on metal single crystals have shown that during *s*-polarized excitation the photoemission I_s decrease swith increasing angle of incidence γ, while I_p (for *p*-polarized excitation) increases. It has been assumed that the reason for this behavior lies in a difference in the absorbed power levels for the light of different polarizations. A more detailed analysis of the effect can be carried out on the basis of the theory of surface and bulk photoemission.[3] The photoemission I_s is associated with the excitation of bulk electron states in the periodic lattice potential and is proportional to the absorbed density N_s. In the case of the *p* polarization, with a nonvanishing normal component of the electric vector of the light ($\gamma \neq 0$), there can be a surface photoemission, which is associated with the excitation of electrons from the region of the change in the surface potential $V(z)$ at the metal-vacuum interface, where z is the normal to the surface. The corresponding matrix element is

$$M_{ij} = (\mathbf{e}\cdot\mathbf{z}) \langle \Psi_j | \frac{\partial}{\partial z} V(z) | \Psi_i \rangle ,$$

where **e** is the polarization vector of the exciting light. The wave functions of the initial and final states, Ψ_i and Ψ_j, respectively, are chosen as in the case of bulk photoemission. The substantial discrepancies which have been found between the theoretical and experimental results have forced the introduction of some additional conditions, which have been imposed on either the surface potential[4] or the surface quality, in the form of a macroscopic roughness.[5]

In the present study we have observed that a submonolayer film of Cs deposited on the (110) face of a W single crystal leads to a dramatic change in the magnitude of the vector photoelectric effect, $I_p(\gamma) - I_s(\gamma)$. The reflection coefficients and surface quality of the (110)W surface remain constant. The features found in the behavior of the angular dependence $I_p(\gamma)$ for the various submonolayer coverages can be explained in terms of a modification of the spectrum of surface states in the W(110)-Cs system.

On the (110)W face of a single-crystal sample we deposited films of Cs with various degrees of submonolayer coverage, $\theta \leqslant i$. Emission was excited by an s- or p-polarized laser beam at $\lambda = 6328$ Å (1.96 eV) with a power of 2 mW. For each coverage we recorded the behavior of the integral photoemission current I_s or I_p as a function of the angle of incidence of the light ($0 \leqslant \gamma \leqslant 75°$). We monitored the optical reflection coefficients $R_s(\gamma)$ and $R_p(\gamma)$. Within 0.5% they remained the same over the entire range of coverages studied. The measurements were carried out in high vacuum ($p \sim 10^{-10}$ torr).

Depositing a Cs film on the (110)W face reduces the work function φ. The angular dependence $\varphi(\theta)$ for this system is not monotonic (Fig. 1), going through a minimum at $\theta_{\min} = 0.61$ (Ref. 6). To eliminate the influence of $\varphi(\gamma)$ on the nature of the effect, we studied pairs of submonolayer coverages corresponding to the same work function. Photoemission curves, $I_p(\gamma)$, were normalized to the emission at normal incidence ($\gamma = 0$). Note that we have $I_s(0) = I_p(0)$.

Over the entire range of submonolayer coverages θ which we studied, the angular dependence $I_s(\gamma)$ remains the same (curve 1 in Fig. 1) and can be described successfully in terms of the absorbed power $N_s(\gamma)$ calculated for $n = 3.64$ and $k = 2.92$ (Ref. 7). Between $I_p(\gamma)$ and $N_p(\gamma)$, on the other hand, there is no correlation. Experimental curves 3 and 4 in Fig. 1 show that even coverages which are just slightly different from $\theta_{\min}$, specifically, $\theta = 0.57$ ($\varphi = 1.52$ eV), and $\theta = 0.64$ ($\varphi = 1.52$ eV), correspond to different magnitudes of the vector photoelectric effect. The anomalous scatter in the $I_p(\gamma)$ curves increases dramatically when we compare the curves for coverages further from $\theta_{\min}$, e.g., $\theta = 0.45$ ($\varphi = 1.78$ eV) and $\theta = 0.85$ ($\varphi = 1.78$ eV) (curves 2 and 4 in Fig. 2).

Analyzing the results, we see the following basic tendencies: a) The magnitude of

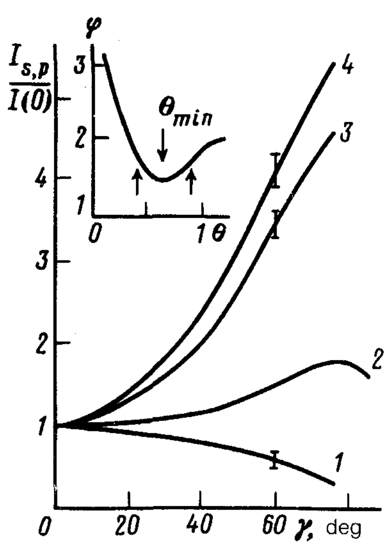

FIG. 1. Angular dependence of the photoemission (curves 1, 3, 4) of the W(110)-Cs system for various submonolayer coverages, during excitation by s- and p-polarized light at $\lambda = 6328$ Å. 1—$I_s(\gamma)/I(0)$; 3—$I_p(\gamma)/I(0)$ at $\theta = 0.57$; 4—$I_p(\gamma)/I(0)$ at $\theta = 0.64$. 2—Calculated absorbed power $N_p(\gamma)$ (curve 2). The inset shows the work function $\varphi(\theta)$ from Ref. 6.

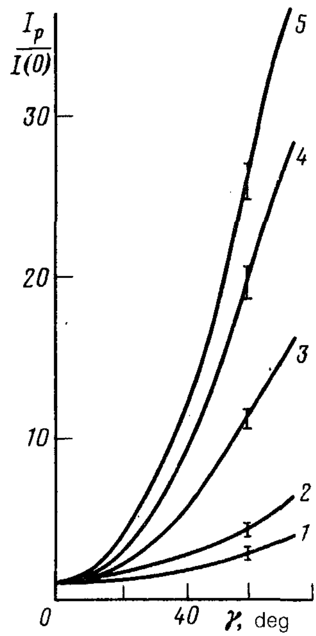

FIG. 2. Angular dependence of the photoemission, $I_p(\gamma)/I(0)$, of the W(110)-Cs system for various submonolayer coverages: 1—$\theta = 0.61$; 2—$\theta = 0.45$; 3—$\theta = 0.77$; 4—$\theta = 0.85$; 5—$\theta = 1.00$.

the vector photoelectric effect, $I_p(\gamma) - I_s(\gamma)$, decreases as the coverage is increased to $\theta_{\min}$. b) The smallest effect is observed at the coverage $\theta_{\min}$. c) The effect intensifies as the coverage is increased from $\theta_{\min}$ to $\theta = 1$.

These new results rule out an explanation of the anomalies in the vector photoelectric effect in terms of a surface roughness. Furthermore, doubt is cast on the second conventional explanation, based on simply the shape of the surface potential $V(z)$. This conclusion is supported not only by the results which we have reported here but also by an experiment in which we used p-polarized laser light at $\lambda = 3371$ Å to excite photoemission. Over the coverage range from $\theta_{\min}$ to $\theta = 1$, in which the surface potential increases, we saw no changes in the dependence $I_p(\gamma)$.

We would like to suggest that a leading role in the explanation of the vector photoelectric effect is played by the nature of the initial and final electronic states which participate in the surface photoemission. For metals, these are two-dimensional surface states which are localized in specifically the region in which the surface potential varies. The behavior of the vector photoelectric effect for p-polarized excitation at $\lambda = 6328$ Å agrees well with data on the modification of the surface-state spectrum in the W(110)-Cs system. As a result of adsorption, the intrinsic surface states of the (110)W face shift away from the Fermi level E_F, in the direction of a higher binding energy.[8] At coverages $\theta > \theta_{\min}$ we observe the formation of induced states of the Cs film,[9] which lie near E_F and whose state density increases with increasing θ. This tendency is manifested in the observed increase in the vector photoelectric effect at the corresponding coverages.

During high-energy p-polarized excitation at $\lambda = 3371$ Å, the quantum yield for the emission of induced surface states in the Cs film decreases sharply.[9] This result is evidence of a change in the nature of the interaction of the light with the electron states of the crystal. In this case the p-polarized light apparently excites bulk states, and the angular dependence $I_p(\gamma)$ does not depend on the deposited film.

[1]D. W. Juenker, J. P. Waldron, and R. J. Jaccodine, Opt. Soc. Am. **54**, 216 (1964).
[2]P. O. Gartland, S. Berge, and B. J. Slagsvold, Phys. Rev. Lett. **30**, 916 (1973).
[3]C. D. Mahan, Phys. Rev. B **2**, 4334 (1970).
[4]I. Adavi, Phys. Rev. A **134**, 788 (1964).
[5]K. Mitchell, Proc. R. Soc. A **146**, 442 (1934).
[6]V. S. Fomenko, *Emission Properties of Materials*, Nauk. Dumka, Kiev, 1981.
[7]J. H. Weaver, D. W. Lynch, and G. G. Olson, Phys. Rev. B **12**, 1293 (1975).
[8]P. Soukiassian, R. Riwan, J. Leconte, *et al.*, Phys. Rev. B **31**, 4911 (1985).
[9]G. V. Benemanskaya and M. N. Papushkin, Pis'ma Zh. Eksp. Teor. Fiz. **45**, 423 (1987) [JETP Lett. **45**, 540 (1987)].

Translated by Dave Parsons