Figure 3 shows the temperature dependence of $\mu_{pv}$ (curve 1) and $\mu$ (curve 2) for holes in the spectral region $\lambda \approx 600$ nm. On the other hand, in the low-temperature region $\mu \sim T^{-2}$, the mobility $\mu_{pv}$ of holes responsible for BPE does not depend on temperature in the entire interval studied. This situation leads to the fact that at $T = 300$ K, $\mu_{pv} \gg \mu$, and at $T \approx 150$ K, $\mu_{pv} \approx \mu \approx 100$ cm$^2$ \cdot V$^{-1}$ \cdot s$^{-1}$.

Thus the results of measurements of BPE in ZnS have indicated the presence of a Hall effect for BPE, linear with respect to the magnetic field, as well as a difference in the temperature dependence of thermalized and nonthermalized carriers.

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Electron-stimulated ordering of adsorbed films

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A partial electron-stimulated ordering in freshly adsorbed hydrogen films on the (011)Mo face has been detected by low-energy electron diffraction. The films were adsorbed at $T = 5$ K and were not brought to equilibrium by annealing.

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Bombardment with low-energy electrons has been observed to cause disorder in submonolayer films of light elements (H, D, and Li) at temperatures below the threshold for the appearance of a significant thermal mobility.1–3 The effect was inferred from the decay of the features in the pattern of low-energy electron diffraction (LEED). In experiments with Li films, additional features in the diffraction pattern...
fade completely when the films are exposed a sufficiently long time to an electron beam, but in the cases of H and D the intensities of the features in the pattern decrease only partially for certain lattices, demonstrating that a competing ordering process is occurring. In an effort to identify this process we have studied the effect of low-energy electrons on H films adsorbed on the (011)Mo surface. Judging from the results of Ref. 4, a preliminary annealing is not required in order to produce a chemisorbed atomic phase, in contrast with the case in adsorption on (001)W. Furthermore, in the case of molybdenum the effect of the bombardment by the low-energy electrons can be seen not only in an adsorbed film, which has been ordered beforehand by annealing, but also in nonequilibrium film adsorbed at a low temperature.

The procedure used in the present experiments differs from that of Refs. 1–3 in that the experiments were carried out not in a glass apparatus but in a Riber metal apparatus, modified to allow the samples to be cooled with liquid helium. The concentration of H atoms in the adsorbed film was estimated from an analysis of the adsorption kinetics and of the thermal-desorption spectra. These spectra consist of two phases: $\beta_2$ and $\beta_1$, which at saturation contain $7 \times 10^{14}$ and $14 \times 10^{14}$ atoms/cm$^2$, respectively$^5$; the corresponding degrees of surface coverage are $\varphi = 1/2$ and 1.

At $T = 5$ K the films which have been brought to equilibrium (by annealing for 10 s at 300 K) exhibit a single LEED pattern with additional features characteristic of a (2×2) structure. Comparison of the changes in the intensities of these additional features during a progressive increase in the adsorption dose, on the one hand, with the changes in the thermal-desorption spectrum, on the other, showed that the filling of the $\beta_2$ state corresponds to maximum development of the ordered (2×2) structure, while the filling of the state $\beta_1$ corresponds to a transition to a (1×1) structure. Of the several possible types of film lattice which would produce the same LEED pattern (2×2), the lattice shown in Fig. 1 has the appropriate value $\varphi = 1/2$. The arrangement of adsorbed atoms in the elementary cell corresponds to the interpretation that these atoms are bound to the substrate by the orbitals of surface Mo atoms, and these orbitals make an angle of 45° with the normal (e$_g$ orbitals). Figure 2 shows the change in the intensity of the (2×2) features during bombardment of a film with $\varphi \approx 1/2$ by electrons with $E = 7.5$ eV at a current density $i = 3 \times 10^{-4}$ A/cm$^2$. The fact that the intensity does drop all the way to zero corresponds to a partial disordering of the film caused by the low-energy electrons, as has been observed previously$^1,2$ for the p(2×1) structure of H and D on (011)W.

For freshly adsorbed films, by which we mean films adsorbed in the absence of an

![FIG. 1. Model of the H(2×2)-Mo(011) structure. Small circles—adsorbed atoms; large circles—substrate atoms.](image-url)

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electron beam at $T = 5 \text{ K}$, without a subsequent annealing, we again see a LEED pattern with features corresponding to a $(2 \times 2)$ structure when the electron beam is applied. This pattern is similar to that of the annealed films, but the additional features are far fainter. As the duration of the exposure to the beam is increased, the intensity of these features increases, approaching but not actually reaching the same level as during the electron-stimulated disordering (Fig. 2). This fact, combined with the equality of the time constants for the intensity rise and decay (Fig. 2), indicates that the reason for the change in the LEED intensity induced by the electron bombardment is the same for the freshly adsorbed films and the annealed films. In one case, the process in question causes a partial ordering of an originally disordered structure, while in the other it causes a partial disordering of a structure which was originally completely ordered. The process in question may be the migration of nonequilibrium long-lived vibrational excitations of the adsorbed hydrogen atoms induced by the electron beam. This conclusion also agrees with the presence of a nonzero initial order in the freshly adsorbed film, since an energy sufficient for exciting vibrations of adsorbed atoms is liberated in each adsorption event.

The $(2 \times 2)$ structure exists over the entire interval $\varphi < 1$, initially (at $\varphi < 1/2$) at equilibrium with the lattice gas of adsorbed atoms and later (at $1/2 < \varphi < 1$) at equilibrium with a $(1 \times 1)$ structure. Curves similar to those in Fig. 2 for $\varphi = 1/2$ were obtained at other adsorption doses of $L$. Figure 3 shows some typical intensities $I_0$ of the features in the diffraction pattern of the ordered $(2 \times 2)$ structure found from these curves for various of $L$ (these intensities were found at $T = 5 \text{ K}$ for the annealed film). Also shown here at the relative intensities $I/I_0$ for the following states of the film: freshly adsorbed and after prolonged exposure ($\sim 10^3 \text{ s}$) of freshly adsorbed and annealed films to an electron beam. The quantity $(I/I_0) dI/dt$ shown in this figure is the initial rate of change of the intensity induced by the beam, divided by $I_0$. In the first stage of the adsorption (at $\varphi < 1/2$, to the left of $\max I_0$), the $\beta_2$ phase with the $(2 \times 2)$ structure evidently grows through a first-order phase transition. The characteristic parameters of the effect of the electrons on the structure, shown in Fig. 3, remain the same. In the second stage ($\varphi > 1/2$) these parameters change in a complicated way,
FIG. 3. Effect of the adsorption dose \( L \) on various properties. 1—Intensity of the \( (2\times2) \) features in the diffraction pattern of low-energy electrons for an annealed film; 2—the intensity level \( I/I_0 \) for a freshly adsorbed film before exposure to the beam; 3—the same, after exposure to the beam; 4—intensity \( I/I_0 \) for an annealed film after exposure to the beam; 5—rate of electron-stimulated disordering; 6—rate of electron-stimulated ordering.

apparently because of an interaction between excited components of the \( \beta_1 \) and \( \beta_2 \) phases.

In the absence of the electron beam at \( T = 5 \) K we do not observe (over a time of several hours) an ordering in the freshly adsorbed film above the level shown by curve 2 in Fig. 3. This fact is evidence that no significant quantum ordering (tunneling) occurs under these conditions. The electron-stimulated ordering of chemisorbed atomic oxygen on \((011)\)Mo observed in this study suggests that in \( H_p(2\times1) - W(011) \) films\(^2\) this process, rather than the quantum mobility, is responsible for the incomplete electron-stimulated disordering.

We thank O. M. Braun for a useful discussion.


\(^3\)A. G. Naumovets and A. G. Fedorus, Zh. Eksp. Teor. Fiz. 68, 1183 (1975) [sic].


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