Investigation of the InSb(110) + Ag system with $\theta = 0$–20 monolayers by Auger electron spectroscopy and low-energy diffraction methods at temperatures 10–300 K

V. Yu. Aristov, I. L. Bolotin, and V. A. Grazhulis

Institute of Solid State Physics, Academy of Sciences of the USSR, Chernogolovka, Moscow Province

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The Auger electron spectroscopy and low-energy electron diffraction methods were used in an investigation of the processes of growth of silver films with thicknesses in the range $\theta = 0$–20 monolayers at temperatures of 10 and 300 K on a (110) face of InSb cleaved in high vacuum. A study was also made of the evolution of the samples during heating to room temperature after evaporation of Ag at 8 K and also during cooling to 10 K after evaporation at 300 K. A comparison of the Auger signals obtained during evaporation at 10 and 300 K, and also during heating of films evaporated at the low temperature, showed that at 10 K the distribution of Ag atoms across the thickness was random, whereas at room temperature a film grew by forming islands. The Auger spectra, particularly those obtained during heating of the samples, demonstrated that In atoms diffused across a silver film. Evaporation at 300 K simply increased a homogeneous ($\theta \lesssim 10$–12) or an inhomogeneous ($\theta \gtrsim 10$–12) background but the 1×1 reflections of the (110) InSb substrate were retained. Cooling resulted in reversible ordering of a silver film. Evaporation at 10 K created a strong background and all the reflections disappeared at $\theta \approx 1$. In the range $\theta \gtrsim 4.5$ a structure appeared and it was retained during heating up to 300 K: it corresponded to the (110) plane of the bcc structure of Ag. This particular structure was parallel to the (110) plane of InSb and the crystallographic directions of the two structures coincided in the (110) plane. Heating of samples with $\theta = 1$–4.5 formed at 10 K to room temperature gave rise to reflections of the substrate and to additional reflections due to the presence of adsorbed silver.

I. INTRODUCTION

Many investigations have been made of the adsorption of metals on semiconductors (see, for example, the reviews in Refs. 1-3 and the references given there) and almost all of them were carried out at room or higher temperatures. However, several investigations have shown[4–6] that cooling to near-helium temperatures gives rise to a number of interesting physical effects.

Our main task was to investigate the processes of formation of ultrathin Ag films on the (110) surface of InSb at low and room temperatures. In contrast to other surfaces of elemental semiconductors investigated by us earlier,[4,5] this surface has a fundamentally different atomic structure. It is worth noting that an ultrathin Ag film on the Si(111) and Ge(111) surfaces repeats the symmetry and orientation of the substrate.[4,5] If the InSb(110) substrate is used, we would expect to obtain new atomic structures because of the interaction of the Ag atoms with the surface of this substrate. Preliminary results of an investigation of the InSb(110) + Ag system were reported by us in brief communication.[6] In the present paper we shall provide a fuller account of the investigation.

II. EXPERIMENTAL METHOD

Our investigation was carried out using the ESCALAB-5 system with a hemispherical energy analyzer and a two-grid low-energy electron diffraction (LEED) analyzer. In the course of our experiments the pressure in a vacuum chamber did not exceed 4×10^{-10} Torr. We investigated n-type samples with a dopant concentration of $\sim 2 \times 10^{16}$ cm^{-3} Silver (99.9999 at.%) was evaporated at 10 and 300 K on a (110) face of InSb cleaved at room temperature. The rate of evaporation could be varied within the range 10^{-4}–5×10^{-2} Å/sec and was measured with a quartz thickness meter. The absolute value of the thickness (coverage) θ expressed in terms of monolayers of In and Sb atoms on the (110) surface ($\theta = 1$ was equivalent to 6.74×10^{14} Ag atoms per cm^2 of the surface), was subject to a systematic error of $\pm 30\%$ because of the possible errors in the calibration procedure. The amplitudes of the *MVV* Auger peaks of Ag, In, and Sb at energies of 356, 404, and 454 eV were determined directly during evaporation at 10 or 200 K, and also during heating of the films evaporated at the low temperature. The LEED patterns were recorded on photographic film. The other details of the experimental procedure were described in Ref. 4.

III. EXPERIMENTAL RESULTS

A. Auger electron spectroscopy

1. Evaporation at 10 K. The experimental dependences of the amplitudes of the Auger peaks of In, Sb, and Ag on θ, obtained in the course of evaporation of Ag at 10 K (white circles), are plotted in Figs. 1a–1c. The dependences can be seen to fit well exponential functions (continuous curves). Figure 2 gives the ratio of the amplitudes of the same Auger peaks as a function of θ. The results obtained during evaporation of Ag on a substrate cooled to 10 K, followed by heating to room temperature or above, are given in Fig. 1. The kinetics of changes in the Auger peaks during heating was not investigated. (Each experimental point took 2 min to obtain and the total time, including heating, was about 15 min per measurement; this time was approximately the same

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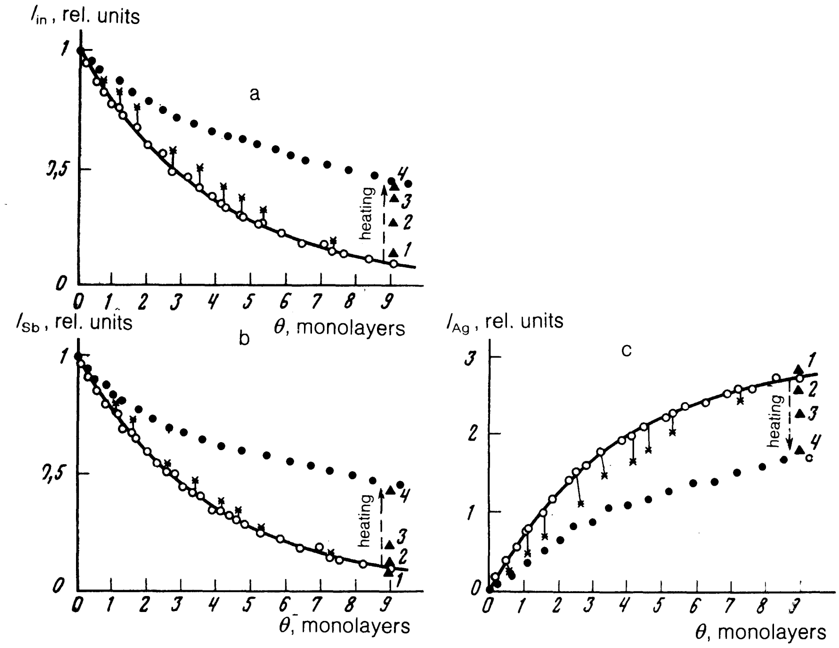

FIG. 1. Dependences of the amplitudes of the Auger signals of In (a), Sb (b), and Ag (c) on the coverage θ: ○) evaporation at 10 K; ●) evaporation at 300 K; *) results of heating to 300 K of samples prepared at 10 K; ▲) amplitudes of an Auger peak of samples with $\theta \approx 9$ after evaporation at 10 K and heating to: 1) 300 K; 2) 330 K; 3) 370 K; 4) 410 K. The continuous curves are calculated using Eqs. (1) and (2).

for all the experimental points in Figs. 1–3.) The asterisks are used for the Auger peak amplitudes obtained after heating to room temperature for various values of θ and the triangles represent the results obtained between room and higher temperatures when $\theta \approx 9$.

2. Evaporation at 300 K. The dependences of the amplitudes of the Auger peaks of In, Sb, and Ag on θ, recorded in the course of evaporation of Ag on a substrate kept at room temperature, are represented by black dots in Fig. 1. It is worth noting that the dependences are less steep than those recorded at 10 K. Moreover, the Auger signals of In and Sb recorded after evaporation to $\theta \approx 9$ at 300 K are approximately 5 times stronger than those obtained after evaporation at 10 K. Cooling to 10 K and the subsequent heating to 300 K of the samples obtained by evaporation on the substrate kept at room temperature had practically no effect on the amplitude of the Auger spectra.

B. Low-energy electron diffraction

Before describing the LEED results obtained in the course of evaporation, we must mention the following. According to Ref. 7, the InSb(110) surface obtained by cleaving at 300 K always demonstrates the 1×1 diffraction pattern. Our experiments showed that cooling to 10 K and the subsequent heating to room temperature do not alter significantly the diffraction patterns. Therefore, in this range of temperatures an atomically cleaved surface does not undergo any phase transitions giving rise to substructure reflections. Possible changes in the intensity of the background or in the diffraction reflections during heating or cooling were not studied by us.

1. Evaporation at 10 K. Evaporation at the low temperature of ~10 K gives rise[6], even at low values of θ, to a homogeneous background in the LEED pattern; the reflections of InSb are strongly weakened and beginning from $\theta \approx 1$–1.5 only a homogeneous back-ground is in practice visible. If $\theta \approx 4$, then in some places of the diffraction pattern we can distinguish an increase in the intensity demonstrating the formation of a new LEED pattern on increase in θ. When $\theta \approx 4.5$ is reached, the new diffraction pattern described in Ref. 6 is completely distinguishable. At $\theta \approx 5$ the pattern is sufficiently sharp and a further increase in θ (right up to $\theta \approx 20$) does not change its intensity significantly. Moreover, the pattern is not modified qualitatively even after heating of a sample to 300 K. It should be noted that the new LEED pattern is not that expected for a film of Ag. This point will be discussed in detail in Sec. IV.

The influence of heating on the samples formed at the low temperature depends strongly on the coverage. The whole investigated range of coverages can be divided into three intervals. In the first one, where $\theta \lesssim 1$–1.5, there are practically no changes in the LEED patterns during heating to room temperature, i.e., in the same way as at 10 K only the 1×1 reflections of the InSb(110) substrate against the homogeneous background can be seen. In the second interval, $1\text{–}1.5 \lesssim \theta \lesssim 4.5$, heating restores the 1×1 pattern of the InSb(110) substrate that had disappeared on increase in θ

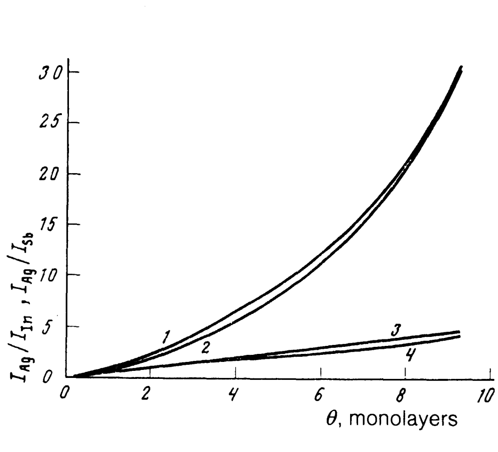

FIG. 2. Ratio of the amplitudes of the Auger signals I_{Ag}/I_{In} (2,4) and I_{Ag}/I_{Sb} (1,3) plotted as a function of the coverage θ: 1), 2) evaporated at 10 K; 3), 4) evaporated at 300 K.

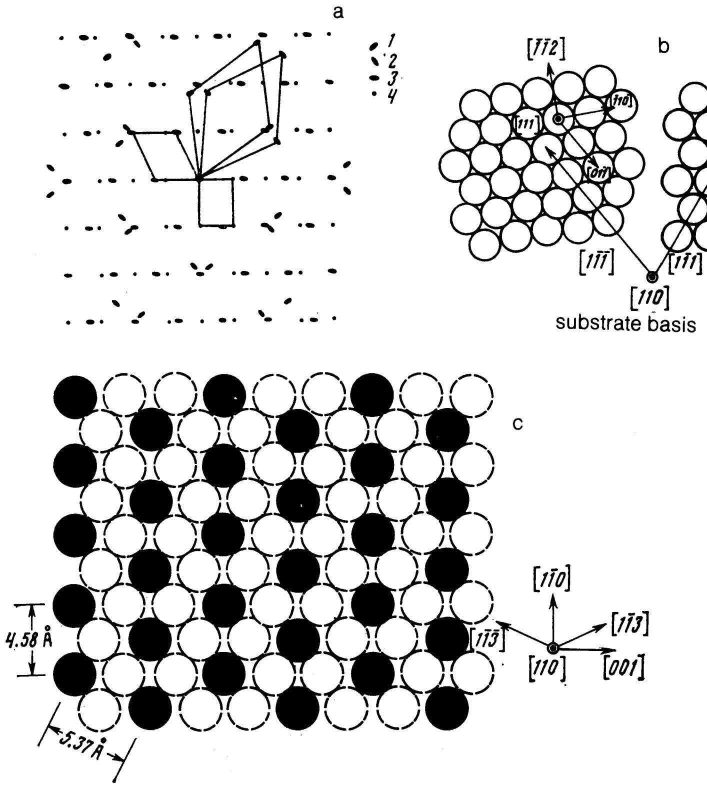

FIG. 3. a) Schematic representation of the diffraction pattern obtained for the InSb(110) + Ag system after evaporation at 10 K and subsequent heating to 300 K ($1\text{–}1.5 \lesssim \theta \lesssim 4.5$); 1, 2, and 3 are the groups of additional reflections due to the silver film; 4) reflections of InSb(110). b) Schematic representation of a possible distribution of Ag atoms on the InSb(110) surface corresponding to the first and second groups of reflections (see text). c) Schematic representation of a possible distribution of Ag atoms on the surface of InSb(110) corresponding to the third group of reflections (see text).

(see above) and new reflections are observed (they are shown schematically in Fig. 3a). These additional reflections can be divided into three groups and they are denoted in the figure by 1, 2, and 3.

In the third interval where $\theta \gtrsim 4.5$, heating to 300 K does not alter qualitatively the diffraction pattern obtained in the course of evaporation of Ag to $\theta \gtrsim 4.5$ on a substrate cooled to 10 K.

We shall conclude this section by noting that for any value of θ the LEED pattern obtained as a result of heating does not change qualitatively during the subsequent cooling to 10 K and second heating to 300 K. It should also be noted that heating of the samples with $\theta \gtrsim 4.5$ to room temperature fails to reveal the LEED patterns of the substrate, but heating to $T \gtrsim T^*(\theta)$, where $T^*(\theta) > 300$ K, gives rise to the substrate reflections and the temperature $T^*(\theta)$ at which the 1×1 reflections of InSb(110) appear increases on increase in the value of θ right up to $\theta \sim 20$.

2. Evaporation at 300 K. When the substrate used during evaporation of Ag is kept at room temperature or at 10 K, a homogeneous background appears immediately in the LEED pattern and the relative intensity of the reflections from InSb decreases. However, in contrast to evaporation at 10 K, some of the substrate reflections remain visible right up to $\theta \approx 16$ (thicker coatings were not deposited at 300 K). In the range $\theta \gtrsim 10\text{–}12$ the background becomes inhomogeneous.

Cooling of the samples formed by evaporation at room temperature gives rise to interesting effects in the range $\theta \gtrsim 4$. If $\theta \lesssim 4$, then cooling does not alter the diffraction pattern, but if $\theta > 4$ then not only the 1×1 reflections of InSb(110) are retained, but a pattern begins to form reversibly from the homogeneous background and it consists of the main reflections of silver similar to the pattern obtained in the course of evaporation at $T \approx 10$ K right up to $\theta \gtrsim 4.5$. The only difference is in the profiles of the satellites. This effect is manifested clearly already at $\theta \approx 9$.

IV. DISCUSSION OF RESULTS

Deposition of evaporated Ag atoms on a substrate cooled to ~ 10 K is characterized by a high rate of cooling of these atoms during the adsorption time.[8] We can assume the absence of volume and surface diffusion and, consequently, mixing of adsorbed atoms with those in the substrate should not take place. Since, as suggested in Ref. 4, we can expect the Ag atoms across the film to have a Poisson distribution in view of the random nature of the evaporation process.

We shall now analyze the results of Auger electron spectroscopy (AES) on the basis of the above considerations. We can see from Figs. 1a–1c that the experimental dependences of the Auger signals on the thickness recorded in the course of evaporation of Ag on a substrate cooled to 10 K can be described satisfactorily by the dependences of the type

$$I_{\mathrm{Ag}} \propto 1 - \exp\{-c_1\theta\}, \tag{1}$$

$$I_{\mathrm{In,\,Sb}} \propto \exp\{-c_{2,3}\theta\}. \tag{2}$$

Bearing in mind the Poisson nature of the distribution of the number of atoms across the film thickness in the case of adsorption on a substrate cooled to helium temperature, we readily obtain[4]

$$c_{1,2,3} = \alpha\{1 - \exp[-d/l(\varepsilon_{1,2,3})]\}, \tag{3}$$

where $\varepsilon_1 = 356$ eV, $\varepsilon_2 = 404$ eV, and $\varepsilon_3 = 454$ eV are the energies of the Auger electrons of Ag, In, and Sb; d is the average distance between the neighboring monolayers in the silver film; α is a coefficient equal to the ratio of the density of the substrate atoms on the InSb(110) plane to the density of the Ag atoms in a plane parallel to the film surface; $l = l(\varepsilon_i)$ is the effective path of electrons of energy ε_i in the silver film if there are no energy losses. We shall now estimate the parameters α and d. The density of the silver films formed in the experiments described above is not equal to the density of bulk silver because, as shown below (in the course of our discussion of the LEED results), in the range of thicknesses $\theta \gtrsim 4.5$ these films clearly have the bcc lattice with the (110) plane of the bcc Ag parallel to the (110) plane of InSb. The parameter of this bcc lattice is $a \approx 3.35$ Å. We shall therefore assume that $\alpha \approx 0.53$ and $d \approx 2.4$ Å. Therefore, using the dependences (1)–(3), we obtain $l(\varepsilon_1) \approx 4 \pm 1.1$ Å, $l(\varepsilon_2) \approx 4.3 \pm 0.9$ Å, and $l(\varepsilon_3) \approx 4.5 \pm 1$ Å.

It should be stressed that these data on the effective path of electrons in the silver film are obtained subject to the following assumptions: a) when the temperature of the InSb substrate is low, Ag is adsorbed on the surface forming a film of uneven thickness (and having a Poisson distribution); b) the density of the Ag atoms in a plane parallel to the substrate is calculated from the diffraction measurements and, as shown below, it is equal to the density of the Ag atoms in the (110) plane when silver forms a bcc lattice; c) the distance between the atomic planes is assumed to be equal to the distance between the (110) planes of the bcc lattice of silver with the parameter $a \approx 3.35$ Å.

The mechanism of growth of a silver film can be understood by comparing the dependences of the amplitudes I_{In} and I_{Sb} of the Auger peaks on θ recorded during evaporation when the substrate is kept at 10 K or 300 K. It is clear from Fig. 1 that these dependences are influenced greatly by the substrate temperature. The In and Sb signals recorded at 10 K lie well below those recorded at room temperature and are described well by an exponential dependence of the type given by Eq. (2). The Ag signal at 10 K is also well described by an exponential dependence and its amplitude at this temperature is higher than that recorded at room temperature for identical coverages. There is also a characteristic difference between the ratios of the intensities in the range $\theta \approx 0$–10. Whereas at the low temperature the values of $I_{\text{Ag}}/I_{\text{In}}$ and, consequently, of $I_{\text{Ag}}/I_{\text{Sb}}$ are described approximately by exponential laws, at 300 K in the same range of coverages they are approximately linear and a deviation from linearity sets in only subsequently. The less steep dependences $I_{\text{Ag}}(\theta)$, $I_{\text{In}}(\theta)$, and $I_{\text{Sb}}(\theta)$ (Fig. 1) at 300 K demonstrate that the growth of a film at this temperature involves formation of islands. Had the growth been in accordance with the Frank–van der Merwe mechanism, when each nth monolayer grows after completion of the $(n-1)$st monolayer, then the dependences under discussion would have been steeper at 300 K than at 10 K (because at low temperatures the film is of uneven thickness owing to the absence of diffusion and because of the random nature of the distribution of Ag atoms). The conclusion about the island mechanism of growth of a silver film on a cleaved surface of InSb(110) at 300 K is confirmed also by the LEED measurements. In fact, whereas at 10 K the diffraction spots of the substrate disappear completely when $\theta \approx 1$–1.5, at room temperature they can be distinguished throughout the investigated range of coverages, i.e., up to $\theta \approx 16$. Our measurements are insufficient to decide whether the growth occurs in accordance with the Stranskiĭ-Krastanov mechanism (when the formation of islands precedes filling of the first monolayer) or in accordance with the Volmer-Weber mechanism (when the growth of islands begins directly).

Samples formed by low-temperature evaporation were heated to 300 K or higher. Asterisks are used in Fig. 1 for the intensities of the Auger signals of Ag, In, and Sb obtained after evaporation of a film at 10 K up to certain coverage and during the subsequent heating to 300 K. It is clear from Fig. 1 that in the range $\theta \lesssim 1.5$ we can assume that the intensities of the Auger spectra recorded after heating have values typical of the process of evaporation at 300 K. However, if $\theta \gtrsim 1.5$, then on attainment of room temperature the values of $I_{\text{Sb}}(\theta)$ remain practically the same as at 10 K. On the other hand, the signals of In and Ag change somewhat in the middle of the investigated range of coverages, but already at $\theta \approx 10$ they become equal to the values obtained at low temperatures. Clearly, if $\theta \gg 1$, then a film remains continuous after heating to 300 K and the surface of the substrate is not "bared" during an experiment. This is supported also by the retention of the Auger signal during heating. Our LEED data are also in agreement. In fact, if $\theta \gtrsim 4.5$, then after heating to room temperature we observed no substrate reflections (moreover, a sample with $\theta \approx 20$ was kept in the chamber for ~170 h at 300 K and showed no changes in the LEED pattern, apart from the appearance of a background due to gradual contamination of the sample). Only heating of a sample to $T > 300$ K resulted in the appearance of substrate reflections. On the other hand, changes in the Auger signals of In and Ga during heating to 300 K were correlated and were probably associated with the breaking of the In–Sb bonds and the diffusion of In into the silver film. The absence of changes in the In and Ag Auger signals at $\theta \approx 9$ was probably due to the large thickness of the film and the short maintenance of the temperature after heating to 300 K.

Figure 1 shows the results of heating to $T > 300$ K (triangles) of samples formed by evaporation on the substrate kept at 10 K (in the specific case when $\theta \approx 9$). We can see that even weak heating (up to $T \approx 300$ K) alters strongly the In signal (by a factor of about 2), whereas the Ag and Sb signals remain practically unaffected. This supports the above hypothesis of the breaking of the In–Sb bonds and of a strong diffusion of In across the silver film. When $T \approx 410$ K is reached all the Auger signals assume amplitudes typical of the samples evaporated at 300 K.

It follows therefore from the results of heating of the samples formed at 10 K that the In–Sb bonds are broken and that In shows a significant solubility and diffusion in the silver film. This conclusion is not unexpected if we bear in mind that at room temperature the range of solid solutions of In in bulk silver can reach 19 at.%.

We shall now consider the LEED data. Very unexpected is the disappearance of all the substrate reflections, leaving only a homogeneous background, which occurs for just 1–1.5 monolayers of Ag evaporated at 10 K on InSb(110). Clearly, even at such a low temperature there is a strong chemical interaction between a disordered Ag film and the substrate, resulting in a disturbance of the translational symmetry on the substrate surface.

Another observation is also worth noting. In the course of evaporation of silver on a substrate maintained at 10 K only the background can be observed at $\theta \approx 4$, new spots appear at $\theta \approx 4.5$, and a clear new diffraction pattern described in Ref. 6 is observed at $\theta \approx 5$. Further increase of θ (right up to $\theta \approx 20$) has little effect on the intensities of the reflections in the pattern. Therefore, when the coating is altered by an amount less than one monolayer the background → structure transformation occurs in the diffraction pattern. This allows us to postulate that a phase transition from an amorphous to a crystalline film takes place when the film thickness exceeds such a critical value.[9,10] This diffraction pattern can be used to construct a Bravais lattice in which the translation vectors are oriented along $\langle 111 \rangle$ directions of the substrate and the constant of the two-dimensional unit cell is $a \approx 2.9 \pm 0.1$ Å. The angle between the translation vectors is set by the crystallography of the substrate and it amounts to 109.5°. The atoms of Ag located at the sites of this lattice form a certain two-dimensional crystallographic plane. At atmospheric pressure and at all temperatures below the melting point the structure of bulk silver is fcc and the unit cell period is ≈ 4.08 Å. However, our two-dimensional direct lattice does not fit any crystallographic plane of fcc Ag. This suggests that at 10 K and for $\theta \gtrsim 4.5$ the crystallization of silver on the InSb(110) surface occurs in a different modification, namely bcc instead of the usual fcc. This produces an Ag(110) plane on the surface and in this plane the nearest distance between the Ag atoms is invariant. The shortest interatomic distance in the three-dimensional bcc structure is the separation between atoms at the center of a cube and at its vertices. The parameter of a cubic unit cell of such a structure is approximately equal to 3.35 Å.

The direct two-dimensional lattice plotted by us on the basis of the diffraction pattern corresponds to the (110) plane of the proposed bcc structure of Ag. The following relationships apply between the orientations in the film and the substrate: $(110)\mathrm{Ag}_{\mathrm{bcc}} \| (110)\mathrm{InSb}$; $[110]\mathrm{Ag}_{\mathrm{bcc}} \| [110]\mathrm{InSb}$; $[100]\mathrm{Ag}_{\mathrm{bcc}} \| [100]\mathrm{InSb}$. Therefore, at 10 K and for $\theta \gtrsim 4.5$ Ag a disorder-order phase transition occurs on the InSb(110) surface and the subsequent epitaxial growth of the Ag film occurs in an unusual (bcc) modification.

The distribution of Ag atoms in such a two-dimensional lattice repeats the distribution of atoms in the first layer of InSb(110) if the "voids" between the atoms in this layer are filled with several atoms in an amount representing one monolayer. The period of the resultant two-dimensional silver lattice differs by just 4% from the period of the first layer of InSb(110), on condition that all the atoms in this layer are of one kind. This is an important argument in support of the possibility of crystallization of Ag in the bcc form. Our results suggest that in the course of such a disorder-order transition the atoms of Ag in the first monolayer occupy "voids" above the atoms in the second monolayer of the substrate. This means that an intermediate monolayer is formed between InSb(110) and the bcc silver plane and it consists of Ag (50%), In (25%), and Sb (25%) atoms.

We are not aware of any other reports of the existence of the bcc modification of Ag. However, a similar effect is reported for Cu in Ref. 11. It was found in Ref. 11 that at room temperature the first 100 Å layer of copper on the (100)Ag surface forms the bcc lattice during evaporation. It is then found that $(100)\mathrm{Cu}_{\mathrm{bcc}} \| (100)\mathrm{Ag}$ and $[011]\mathrm{Cu}_{\mathrm{bcc}} \| [001]\mathrm{Ag}$. Only a further increase in the film thickness ($\gtrsim 100$ Å) gives rise to the fcc structure of Cu. It is also known that at atmospheric pressure the bulk Cu has the fcc structure at all temperatures below the melting point, exactly as for Ag.

Up to two additional reflections appear between the main reflections in the diffraction pattern obtained at $T \approx 10$ K for $\theta \gtrsim 4.5$ (Ref. 6). It is worth noting that the distance between the centers of the main and additional reflections is not a multiple of the distance between the main reflections. Therefore, the new reflections cannot be attributed to a superstructure. Moreover, it is worth noting the considerable broadening of the additional reflections along the $\langle 111 \rangle$ directions of the substrate (and of the film, if we assume that it has the bcc structure). These additional reflections can be explained if we assume that the outer surface of a silver film evaporated at low temperatures is a set of long and narrow steps or terraces whose height may amount to one atom (according to the model described in Ref. 12). It should also be noted that there are two systems of domains and each of them represents a set of these terraces, and some of these domains are rotated by 109.5° relative to the others.

We shall now consider the results of heating to 300 K of the samples formed at the low temperature. As reported in Sec. III, the full investigated range of coverages can be divided into three intervals in accordance with the behavior during heating. In the first interval, where $\theta \lesssim 1$–1.5, there are practically no changes in the diffraction pattern, i.e., the 1×1 reflections of InSb(110) and the background remain in the pattern. In the second interval, where 1–$1.5 \lesssim \theta \lesssim 4.5$, the 1×1 diffraction pattern of InSb(110) is recovered from the homogeneous background and fairly weak and quite broad additional reflections are observed (they are shown schematically in Fig. 3a. These additional reflections can be divided into three groups identified by the numbers 1, 2, and 3. Clearly, the first two groups of the reflections correspond to a two-domain fcc 1×1 structure of Ag(111) where $\langle 110 \rangle$ are parallel to two equivalent $\langle 111 \rangle$ axes of InSb, i.e., the domains are rotated relative to one another by $\sim 10.5°$ (Fig. 3b). The third group of reflections is correlated with the substrate: the ratios of the periods between the reflections in this structure and of the 1×1 reflections of InSb(110) along the $\langle 100 \rangle$ directions in the substrate is 3:4, whereas in the $\langle 233 \rangle$ direction it is 3:1. Figure 3c shows one of the possible distributions of silver atoms on the substrate, which corresponds to the third group of reflections in the diffraction pattern in the case when the atoms of Ag are located at the sites of the direct lattice. We can therefore assume that when the samples evaporated at 10 K and characterized by 1–$1.5 \lesssim \theta \lesssim 4.5$ are heated to 300 K, a strongly disordered film forms islands with the fcc structure (groups of reflections 1 and 2) and between the islands there is a submonolayer coating where the atoms are distributed as shown in Fig. 3c (group of reflections 3). Moreover, heating reveals the 1:1 reflections of InSb(110). This is supported also by the results of Auger spectroscopy showing that the Auger signal of silver decreases in the range of small coverages, whereas the signals of In and Sb increase. One should also mention that the boundaries of the second interval are very approximate, since the additional reflections shown in Fig. 3a are weak and the limits of this interval are difficult to determine.

In the third interval ($\theta \gtrsim 4.5$) we find that after evaporation at the low temperature only some of the reflections can be observed simultaneously, but heating to 300 K makes it possible to observe all the reflections simultaneously and this can be done in a fairly wide range of energies of the primary beam E_p. The subsequent cooling of a sample does not alter the observed pattern but simply makes it clearer. The LEED pattern is retained during the second heating but its contrast decreases.

It is interesting to mention also the results obtained when samples evaporated at 300 K are cooled. Unfortunately, a few such coatings were investigated. The most interesting is the observation that cooling of the samples with, for example, $\theta \approx 9$, not only results in retention of the main 1×1 reflections of InSb(110), but also transforms the homogeneous backgrounds into a quite clear LEED pattern, which differs from that shown in Ref. 6 simply by the profile of the subsatellites and by the presence of the 1×1 reflections of InSb(110). This transformation is reversible: a second heating restores the initial diffraction pattern, i.e., it produces the 1×1 reflections of InSb(110) against a homogeneous background (the degree of homogeneity of the background was estimated visually). This reversible transition in the LEED patterns can be explained if we identify the form of silver on the surface of InSb(110) with the 1×1 structure after evaporation of silver at $T \approx 300$ K to form films with fairly high values of θ. Since throughout the investigated range of θ (up to $\theta \approx 16$) there are reflections from the substrate, it is clear that silver islands form on the substrate surface. This is supported also by the AES data (see above). These data allow us to assume that a considerable amount of indium is dissolved in the islands. The absence from the LEED patterns of reflections due to the islands can be explained by two factors: either a disorder in the orientation of microcrystallites (islands) relative to one another and relative to the substrate or the absence of the crystal structure in the islands (which may be "liquid"). In the former case it is difficult to account for the reversible transition (on the temperature scale) between the states of a disordered orientation of microcrystallites and of an epitaxial orientation of Ag microcrystallites with the bcc lattice relative to the substrate. In the latter case we can however assume that there is a reversible transition from melting to crystallization of these islands.

V. CONCLUSIONS

A comparison of the processes of formation of ultrathin Ag films on Si(111)–1×1 and Ge(111)–2×1 surfaces in the range 10–300 K has demonstrated that they are quite different.[4,5] This difference is due to the different nature of the interaction of Ag with the Si(111) and Ge(111) surfaces. In the latter case the absence of a potential barrier (or a smallness of this barrier) ensures that the Ag atoms are in a chemisorbed state even at 10 K. In this respect the Ge(111) + Ag and InSb(110) + Ag systems are similar. However, there is also a basic difference between them. A new modification of the Ag film may form at low temperatures on the InSb(110) surface and its crystallographic parameters are practically identical with the parameters of the substrate. This means that the InSb(110) crystallographic structure plays an exceptionally important role in the formation of ultrashort Ag films and of the InSb(110)-Ag interface. The new modification of the crystal structure in Ag films may be of considerable interest from the point of view of its electronic properties which we hope to investigate later. It should also be pointed out that some of the effects reported above will require further studies. In particular, it would be worth investigating further why a new modification of Ag does not appear at 300 K. An explanation of the observed effects would require additional investigations of the properties of ultrathin Ag films on semiconductor surfaces and these should be carried out using a wider range of experimental methods.

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[1] L. J. Brillson, Surf. Sci. Rep. **2**, 123 (1982).
[2] G. Le Lay, Surf. Sci. **132**, 169 (1983).
[3] G. Le Lay, J. Vac. Sci. Technol. B **1**, 354 (1983).
[4] V. Yu. Avistov, I. L. Bolotin, V. A. Grazhulis, and V. M. Zhilin, Zh. Eksp. Teor. Fiz. **91**, 1411 (1986) [Sov. Phys. JETP **64**, 832 (1986)].
[5] V. Yu. Aristov, V. A. Grazhulis, and V. M. Zhilin, Poverkhnost' No. 8, 84 (1987).
[6] V. Yu. Avistov, I. L. Bolotin, and V. A. Grazhulis, Pis'ma Zh. Eksp. Teor. Fiz. **45**, 49 (1987) [JETP Lett. **45**, 62 (1987)].
[7] A. U. MacRae and G. W. Gobeli, J. Appl. Phys. **35**, 1629 (1964).
[8] A. S. Novick, Comments Solid State Phys. **2**, 155 (1970).
[9] B. G. Lazarev, V. M. Kuz'menko, A. I. Sudovtsov, and V. I. Mel'nikov, Dokl. Akad. Nauk SSSR **194**, 302 (1970) [Sov. Phys. Dokl. **15**, 846 (1971)].
[10] V. M. Kuz'menko, B. G. Lazarev, V. I. Mel'nikov, and A. I. Sudovtsov, Ukr. Fiz. Zh. **21**, 883 (1976).
[11] L. A. Bruce and H. Jaeger, Philos. Mag. **36**, 1331 (1977).
[12] M. Henzler, Appl. Surf. Sci. **11-12**, 450 (1982).

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