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Energy Characteristics of Electron-Stimulated Desorption of Lithium Atoms from Lithium Layers on the Li_xAu_y Surface

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The formation of 2D Li_xAu_y semiconductor layers on the surface of gold deposited on a tungsten substrate has been studied. The processes of electron-stimulated desorption of Li atoms in the $Li/Li_xAu_y/Au/W$ system are considered. The presence of two peaks in the kinetic energy distribution of desorbed lithium atoms is shown: a high energy peak at an energy of 0.3 eV and a low energy peak at an energy of 0.11 eV. The high energy peak is associated with the desorption of lithium atoms from the adsorbed lithium layers, and the low energy peak is associated with the Li_xAu_y intermetallic compound. The influence of the number of deposited gold and lithium atoms on the process of formation of 2D semiconductor LixAuy layers is studied. It is shown that the processes of electron-stimulated desorption occur in the Li monolayer and the Li_xAu_y layer closest to it. A model of electron-stimulated desorption of Li atoms in the $Li/Li_xAu_y/Au/W$ system is proposed.

Keywords: electron-stimulated desorption, lithium, gold, semiconductor, intermetallic compound.

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1. Introduction

An intermetallide or intermetallic compound — is a compound of at least two different metals of a crystalline structure. Since ancient times, a known traditional intermetallic compound is bronze, which a compound of tin and copper. As a result, the compound of two metals may have totally different properties as compared to pure metals, from which it is produced. As a separate matter, one should mention gold intermetallic compounds, for example, purple gold (Al_2Au) [1], which is used for jewellery. There are also gold intermetallic compounds with alkali metals. The gold intermetallic compound with an alkali metal was first mentioned in 1911 [2], when existence of the intermetallic compound $NaAu_2$ was attested. The first report of the non-metallic nature of the gold intermetallic compounds with the alkali metals was published in 1943 [3]. The gold intermetallic compound with cesium was subsequently studied in detail in [4]. It was amazing that CsAu unlike the Cs and Au metals turned out to be a wide-bandgap semiconductor. In the gold intermetallic compounds with the alkali metals, gold is an anion, not a cation as in the most of the gold compounds [5]. There was an opinion in [4] that the RbAu intermetallic compound was also a semiconductor. However, a later study [6] showed that RbAu was a metal. As shown by the further studies, the gold intermetallic compounds with potassium (sodium) turned out to be metals [7]. Calculations of the electron structure of the gold-alkali metal intermetallic compounds have confirmed the earlier experimental data [8–12]. However, transition from bulk samples to 2D-films demonstrated that the 2D- films of the K_xAu_y [13] and Na_xAu_y [4] intermetallic compounds produced at $T = 300$ K were semiconductors. Note that the Na_xAu_y intermetallic compound [15] produced at $T \sim 1000$ K is a wide-bandgap semiconductor with the band gap of 2.7 eV. It was also shown that the K_xAu_y intermetallic compound produced at $T \sim 1000$ K was also a semiconductor [16]. The paper [17] has shown formation of the semiconductor 2D-film of the Li_xAu_y intermetallic compounds.

One of the methods of production of the gold-alkali metal intermetallic compounds is to deposit atoms of the alkali metals onto a gold film. At the room temperatures, the process of formation of the intermetallic compound consists in two stages. At the first stage, when depositing a pre-monolayer coating of alkali metal atoms onto gold there is no diffusion of the alkali metal atoms into the gold film, but generation of an adsorbed layer of the alkali metal atoms. At the second stage, when depositing more than one monolayer of the alkali metal atoms there is diffusion of the alkali metal atoms into the gold film to form the gold-alkali metal intermetallic compound, whose stoichiometry depends on a quantity of the interacting gold and alkali metal atoms. Note that the gold monolayer nearest to the tungsten surface is not involved in formation of the gold-alkali metal intermetallic compounds [18]. At high temperatures, the intermetallic compound can occur immediately.

An electron-stimulated desorption of the atoms was selected to be a method of studying the formation of the 2D-film of the Li_xAu_y intermetallic compounds. When irradiating the surface with the electrons of the energy of at most 200 eV, there can be the evident desorption of the neutral atoms from the surface [19,20]. Note that an electron flux used does not heat a surface of the sample. The electron-stimulated desorption method is advantageous in that it can be observed from a semiconductor or dielectric surface only. It is not observed on metals as there is fast relaxation of excited states. But a lifetime of the excited states on the semiconductor surface is as long as to pass through the Auger processes, which lead to formation of the neutral atom with its subsequent desorption [19,20].

The paper tasked to further investigate the electron-stimulated desorption of the lithium atoms when forming the 2D-films of the $\mathrm{Li}_x\mathrm{Au}_y$ intermetallic compounds, paying special attention to studying the distribution across kinetic energies of the desorbed atoms.

2. Experiment

2.1. Materials

Tungsten tapes were taken as substrates of the samples under study. The tapes were pre-heated at 1800 K in an oxygen atmosphere at the pressure of $1 \cdot 10^{-6}$ Torr during 3 h. The gold was deposited at 300 K out of a direct-heated tungsten tube with pieces of a gold foil of the purity of 99.99% therein, while lithium was deposited on the tape at 300 K out of a direct-heated evaporator by thermally reducing the lithium oxide with aluminum. The concentration of the lithium atoms on the tape surface has been determined by the time of constant-flux deposition, whose intensity was measured by a surface ionization current on an Ir tape, and it was $1.0 \cdot 10^{15}$ atom/cm^{-2} in the monolayer (MLs) of the Li atoms. The concentration of the deposited Au was determined by the time of constant-Au flux deposition, which was calibrated by means of the thermal desorption spectroscopy, and it was $1 \cdot 10^{15}$ atom/cm^2 in the monolayer of the Au atoms. The experiments were carried out at 300 K.

2.2. Preparation of samples

Two methods of preparation of samples were used. The first method: a definite quantity of gold was deposited on the clean tungsten tape at the room temperature, which was followed by depositing a variable number of the lithium atoms as required for ESD measurement. After the measurements, the tungsten surface was cleaned and prepared again. The second method: a variable quantity of gold was deposited to the clean tungsten tape as required for ESD measurement at the room temperature, which was followed by depositing a definite quantity of the lithium atoms. After the measurements, the tungsten surface was also cleaned and prepared again. Note that the monolayer of the Au atoms nearest to the tungsten surface is not involved in formation of the $\mathrm{Li}_x\mathrm{Au}_y$ compound in these two methods.

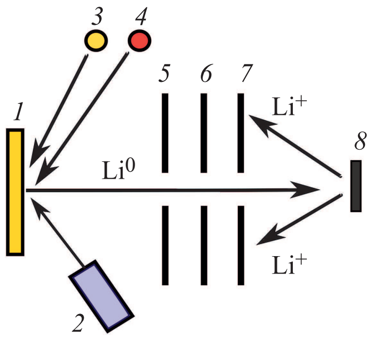

Figure 1. Experiment diagram. *1* — sample, *2* — a source of electrons, *3* and *4* — Au and Li evaporators, *5, 6* — electrodes retaining ions being desorbed when the sample is irradiated by electrons, *7* — an ion collector, *8* — surface ionization tape.

2.3. Experimental unit

The studies presented in the present paper were carried out in an ultrahigh-vacuum unit „Spectrometer ESD“, and experimental diagram thereof is shown in the Fig. 1. The pressure of residual gases in the unit was below $5 \cdot 10^{-10}$ Torr. The experiments were carried out at $T = 300$ K. The tungsten tape with the $\mathrm{Li}_x\mathrm{Au}_y$ layer deposited thereon was irradiated with an electron beam of the energy within the range of 0–300 eV. The Li ions being desorbed were ionized on the iridium tape heated to 2000 K. At this temperature, the probability of the surface ionization of the Li atoms is equal to one [21].

The atom ESD is characterized by an ESD output q, which is equal to a density of atom flux being desorbed to a flux density of the ESD-exciting electrons. The „Spectrometer ESD“ unit allowed recording the ESD output of the cesium atoms (q), measuring a dependence of this output q on the energy of the exciting electrons, measuring the distribution across the kinetic energies of the atoms being desorbed and the quantity of Li and gold deposited on the substrate.

3. Results and discussion

The Fig. 2 shows the dependence of the output q of the Li atoms during ESD from tungsten covered with two gold monolayers at $T = 300$ K, depending on a dose of deposited adsorbed lithium n_{Li} for the energy of the bombardment electrons 64 eV. When the dose of lithium atom deposition is below one monolayer, then no ESD of the Li atoms is observed and there is an adsorbed layer of the lithium atoms on the gold surface. Such an effect was also observed when depositing other atoms of the alkali metals to the surface of the gold [13,14,17,22]. Further increase in the dose of deposited lithium leads to occurrence of ESD of the Li atoms, thereby meaning the formation of the semiconductor 2D-layer of $\mathrm{Li}_x\mathrm{Au}_y$ with $x < y$.

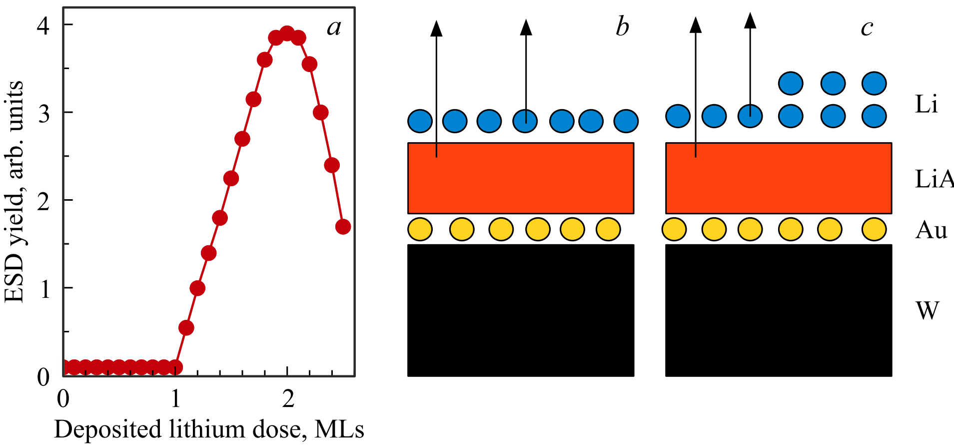

Figure 2. *a* — Li atom output q during ESD from tungsten covered with two gold monolayers at $T = 300\,\mathrm{K}$, depending on a dose of deposited lithium atoms n_{Li} for the energy of the bombardment electrons 64 eV. Diagram in depositing Li and Au to W: *b* — for 2 Au monolayers and 2 Li monolayers with formation of the LiAu 2D-layer, *c* — for 2 Au monolayers and 2.5 Li monolayers with formation of the LiAu 2D-layer. The arrows indicate Li atoms being desorbed.

There is a linear increase in the ESD output of the Li atoms together with increase in the dose of lithium atom deposition. When depositing the dose of lithium atoms equal to the two monolayers, then there is a maximum ESD output of Li atoms, thereby meaning the formation of the stoichiometric intermetallic semiconductor 2D-layer of LiAu (Fig. 2, *b*). Note that the gold monolayer nearest to the tungsten surface in not involved in formation of the 2D-layer of $\mathrm{Li}_x\mathrm{Au}_y$. With further deposition of the lithium atoms, there is decrease in the ESD output of Li atoms, which can be attributed to no diffusion of the lithium atoms into the layer, formation of a layer of the lithium atoms above the adsorbed lithium atoms and impediment of desorption of the lithium atoms (Fig. 2, *c*). That is, it means excitation of the ESD process in the interface between the surface of the 2D-layer of $\mathrm{Li}_x\mathrm{Au}_y$ — the $\mathrm{Li}_x\mathrm{Au}_y$ monolayer of the lithium atoms nearest to the surface.

If a coating of atoms of less than one monolayer is deposited to the gold film of any thickness, then no ESD of the Li atoms is observed. There is neither evident ESD of the Li atoms when depositing any quantity of the Li atoms to the gold film of less than one monolayer. Let us consider which dependences of the ESD output of the Li atoms will be observed when depositing a definite quantity of the lithium atoms to the gold films of various thicknesses. It is shown in the Fig. 3 for two doses of a deposited quantity of the lithium atoms: 1.5 MLs and 2.0 MLs. The ESD of the Li atoms will be observed only when depositing the lithium atoms to the gold film of the thickness of more than one monolayer, thereby meaning the formation of the semiconductor 2D-layer of $\mathrm{Li}_x\mathrm{Au}_y$. With increase in the quantity of adsorbed gold, there is a linear increase in the ESD output of Li atoms. For the gold film of the two-monolayer thickness, there is a maximum ESD output of the Li atoms. It can be assumed that the semiconductor 2D-layers of the various stoichiometry $\mathrm{Li}_x\mathrm{Au}_y$ are formed: LiAu_2 for $n_{\mathrm{Li}} = 1.5$ MLs and LiAu for $n_{\mathrm{Li}} = 2$ MLs. Further increase in the thickness of the adsorbed gold film leads to slow decrease in the ESD output of the Li atoms. When depositing the lithium atoms to the gold film of the 5-monolayer thickness, it is assumed that the semiconductor 2D-layers of $\mathrm{Li}_x\mathrm{Au}_y$ are formed with a decrease content of the Li atoms in the intermetallic compound: LiAu_8 for $n_{\mathrm{Li}} = 1.5$ MLs and LiAu_4 for $n_{\mathrm{Li}} = 2$ MLs. If the lithium atoms slowly diffuse into the gold film through the $\mathrm{Li}_x\mathrm{Au}_y$ intermetallic compound, the semiconductor 2D-layer of the $\mathrm{Li}_x\mathrm{Au}_y$ variable stoichiometry can be formed with the increasing content in the compound while distancing from the surface.

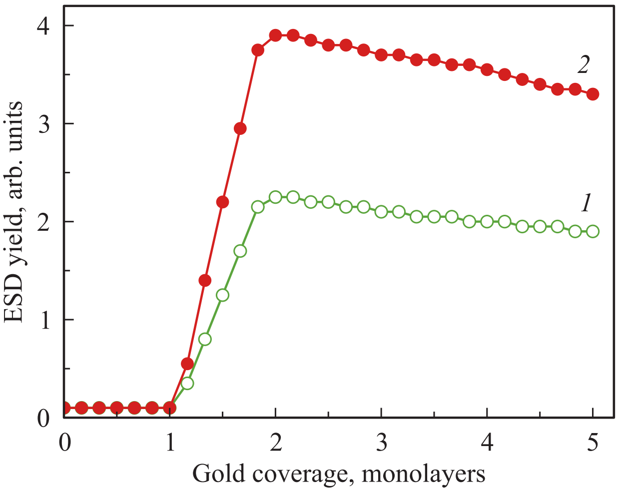

Figure 3. Output q of the Li atoms during ESD from tungsten covered with gold at $T = 300\,\mathrm{K}$, depending on a gold coating for the two doses of lithium deposition n_{Li}: *1* — 1.5 MLs ($1.50 \cdot 10^{15}\,\mathrm{atom/cm^2}$), *2* — 2.0 MLs ($2.0 \cdot 10^{15}\,\mathrm{atom/cm^2}$). The energy of the bombardment electrons is 64 eV.

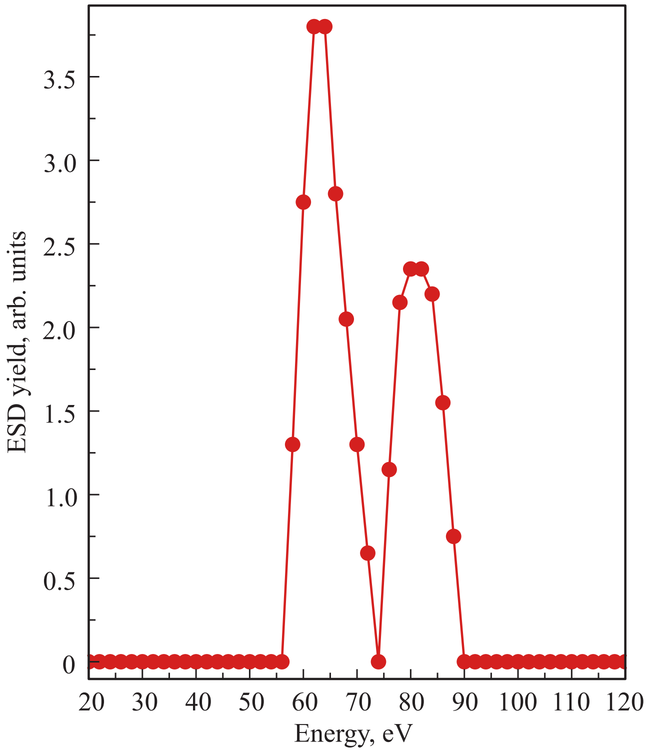

Figure 4. Output q of the Li atoms during ESD from the tungsten surface covered with two gold monolayers, and at the deposition dose of the two Li monolayers, at $T = 300\,\mathrm{K}$ in dependence on the energy of the bombardment electrons E_e.

The metal nature of the 2D-layer of Li-Au on Re [23] may be attributed to differences in the formation of the 2D-layer of Li-Au on Re and in our experiments: it is possible that the semiconductor-metal transition occurs when depositing the Li atoms to the gold film of the thickness about 6 MLs.

The Fig. 4 shows the dependence of the ESD output of the lithium atoms on the energy of the exciting electrons when the deposition dose is composed of two lithium monolayers and two gold monolayers. There are two wide peaks with the maximums 63.5 and 81.4 eV. These peaks are correlated to excitation of the core levels of Au $5p_{3/2}$ and Au $5p_{1/2}$ by the bombardment electrons. The full width at the half-height is 8.8 and 9.4 eV, respectively, for the core levels of Au $5p_{3/2}$ and Au $5p_{1/2}$. A peak area ratio is 0.72, which is close to the ration for the spin-orbital splitting equal to 2/3. There is no evident contribution by the Li core level of 1s with the bond energy $E_b = 54.7\,\mathrm{eV}$, as its excitation should lead to broadening of the peak with the maximum of 63.5 eV towards the lesser energies and a dependence of the peak shape on the quantity of the deposited lithium. As there is no broadening of the peak with the maximum of 81.4 eV towards the bigger energies, then it can be stated that there is no excitation of the core levels of Au $4f_{7/2}$ ($E_b = 84.0\,\mathrm{eV}$) and Au $4f_{5/2}$ ($E_b = 87.6\,\mathrm{eV}$).

The Fig. 5 shows the normalized distributions across the kinetic energies (E_{kin}) of the Li atoms being desorbed from the W surface for the three doses of depositing lithium to the gold film of the two-monolayer thickness: $n_{\mathrm{Li}} = 1.25\,\mathrm{MLs}$, $n_{\mathrm{Li}} = 1.75\,\mathrm{MLs}$ and $n_{\mathrm{Li}} = 2.25\,\mathrm{MLs}$. The two peaks are observed: a low-energy one (LE), whose maximum is at the energy of 0.11 eV and the high-energy (HE) around 0.29 eV, whose position depends on the dose of deposited lithium. The increase in the dose of deposited lithium leads to shifting the HE peak towards the lesser energies. The LE peak position does not depend on the dose of deposited lithium. The LE and HE peaks are well described by the Gauss distribution. The Fig. 6, *a* shows how the position of the HE peak maximum changes with increase in the dose of deposited lithium. Thus, for the lithium deposition dose of $n_{\mathrm{Li}} = 1.25\,\mathrm{MLs}$ the HE peak maximum is at 0.31 eV and with the increase in the dose of deposited lithium the position of the HE peak maximum is linearly shifting towards the lesser energies. For the lithium deposition dose of $n_{\mathrm{Li}} = 2.25\,\mathrm{MLs}$, the HE peak maximum is at 0.28 eV. Similar behavior of the HE peak depending on the dose of alkali metal deposition to gold was found, e.g., in desorption of the atoms Cs [22], K [23] and Na [14]. Note that for Li the HE peak maximum is observed at 0.29 eV. With increase in an atomic number of the alkali metal, the HE peak maximum is shifting towards the bigger energies: it is at 0.34, 0.39 and 0.45 eV for Na, K and Cs, respectively. The shift of the HE peak maximum with the increase in the dose of deposited lithium may be correlated to the increase in a distance between the adsorbed lithium atom and the formed layer of the $\mathrm{Li}_x\mathrm{Au}_y$ intermetallic compound due to increase in lateral interaction between the lithium atoms in the surface layer.

It is clear from the Fig. 5 that the full width of the LE peak at the half-height does not change on the dose of deposited lithium and is equal to 0.11 eV, which is three

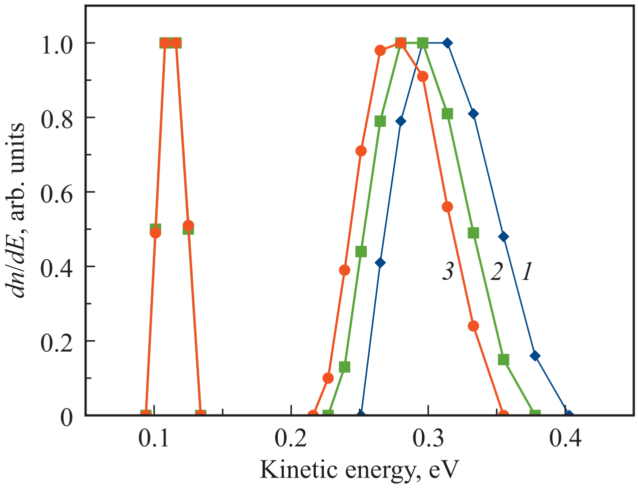

Figure 5. Normalized distributions across the kinetic energies E_{kin} of the Li atoms during ESD from the W surface covered with two Au monolayers, at 300 K, for the energy of the bombardment electrons 64 eV for the three Li deposition doses of 1.25 MLs (*1*), 1.75 MLs (*2*) and 2.25 MLs (*3*).

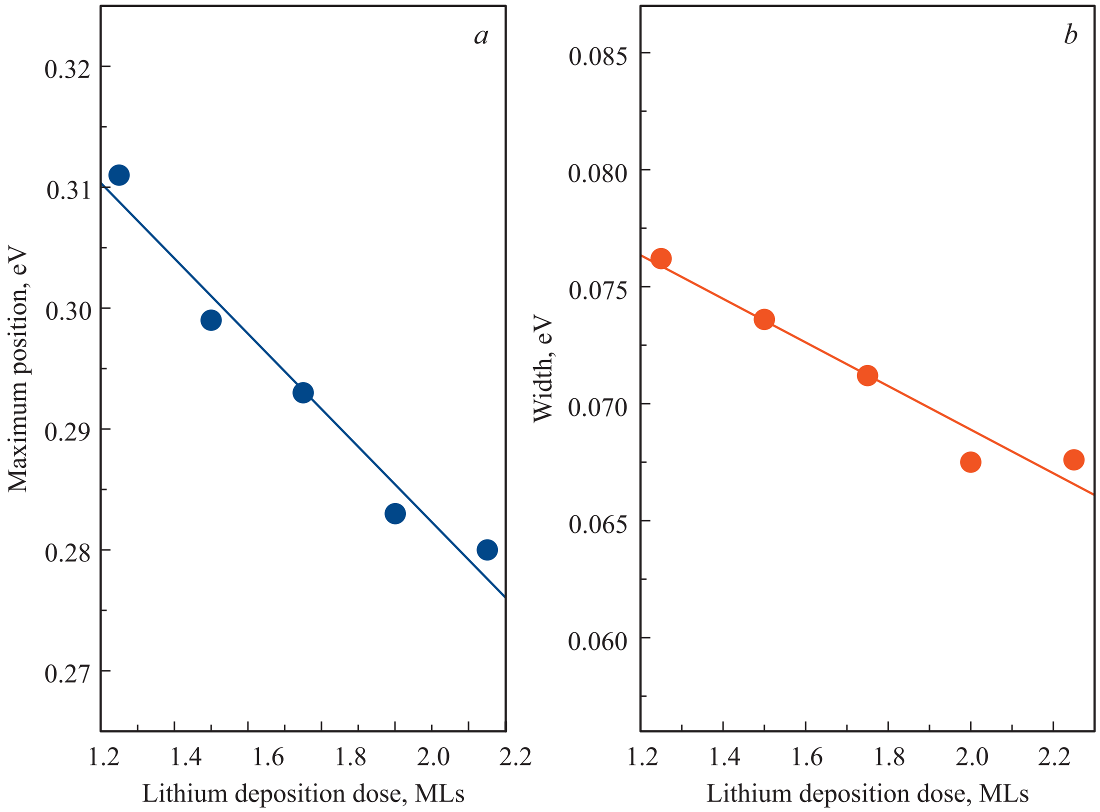

Figure 6. Positions of the high-energy peak maximum of the normalized distribution across the kinetic energies E_{kin} (a) and the full width at the half-height (b) of the Li atoms during ESD from the W surface covered with two Au monolayers, at 300 K, for the energy of the bombardment electrons 64 eV depending on the dose of deposited lithium.

times less than the HE peak width. The Fig. 6, *b* shows the dependence of the changing full width of the HE peak at the half-height depending on the dose of deposited lithium. Thus, for the lithium deposition dose of $n_{\text{Li}} = 1.25$ MLs the HE peak width is 0.076 eV and with the increase in the number of the deposited lithium atoms the HE peak width is linearly decreasing. For the lithium deposition dose of $n_{\text{Li}} = 2.25$ MLs the HE peak width is 0.068 eV.

As in the previous papers [14,22,23], it is logical to assume that the LE peak is correlated to excitation of desorption of the lithium atoms from the intermetallic compound layer, and the HE peak is correlated to excitation of desorption of the lithium atoms from the Li atoms' monolayer nearest to the intermetallic compound surface. Let us consider possible processes, occurring during ESD of the lithium atoms for the deposition dose of $n_{\text{Li}} = 1.25$ MLs on the gold film of the 2 monolayer thickness. Thus, on a surface under the lithium monolayer there is a nascent layer of the intermetallic compound either with the stoichiometry of 4 : 1, or, for example, as islands of the intermetallic compound with the stoichiometry 1 : 1. Further deposition will either reduce the stoichiometry of the intermetallic compound, or increase a portion of the islands of the intermetallic compound with the stoichiometry of 1 : 1. When depositing two lithium monolayers, the following system is formed: the monolayer of the lithium atoms, which is at the surface of the monolayer of the intermetallic compound with stoichiometry of 1 : 1. Further deposition of lithium leas to decrease in the ESD output, thereby meaning the formation of the second layer of the lithium atoms on the surface of the intermetallic compound with stoichiometry of 1 : 1 and no diffusion of lithium atoms into the intermetallic compound. Let us consider how a structure of the intermetallic compound layer will affect the LE and HE peaks.

Let us consider the first option of forming the intermetallic compounds of variable stoichiometry. The surface will hold the lithium atoms' monolayer up to deposition of the 2 monolayers of lithium atoms (Fig. 2, *b*). For the LE peak the lithium atoms will desorb from combinations of the intermetallic compounds with different stoichiometry and the lithium atoms will make their way through the adsorbed layer of the lithium atoms, which are located, however, at different distances from the intermetallic compound. Then, it is logical to expect the unchanged LE peak on the dose of deposited lithium and the form and position of the LE peak should not be affected by a change of the distance between the adsorbed layer of the Li atoms and the intermetallic compound. Apparently, it is indifferent to which stoichiometry of the intermetallic compound the lithium atom is desorbing from. The HE peak correlated to output from the adsorbed lithium layer can expect an

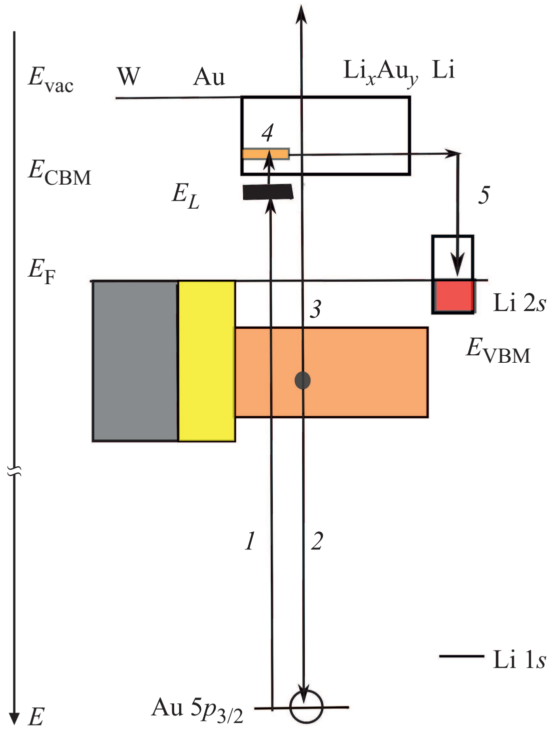

Figure 7. Diagram of the ESD processes in the system of the Li monolayer/Li_xAu_y layer/Au monolayer/W substrate. E_{VBM} — the energy corresponding to a maximum of a valence band.

increasing change of the intermetallic compound–adsorbed lithium layer distance and, therefore, decrease in the kinetic energy. But deposition of at least three monolayers of the lithium atoms leads in the formation of the second layer of the Li atoms and creates a barrier for desorption of the lithium atoms (Fig. 2, *c*). The Li atoms being desorbed from the intermetallic compound (the LE peak) will have to pass through the two monolayers of the lithium atoms, thereby increasing the path and, consequently, leading to disappearing desorption. The Li atoms being desorbed from the adsorbed Li layer (the HE peak) also create an additional barrier and the adsorbed lithium layer–intermetallic compound distance is also increasing. Therefore, the HE peak will be shifted towards the lesser energies. The second option includes the following. When the islands of the intermetallic compound with stoichiometry of 1:1 are formed, as deposition of the lithium atoms progresses, there is only increase in an area occupied by the intermetallic compound under the monolayer of the lithium atoms and the adsorbed layer Li--intermetallic compound distance is remaining the same. For the lithium atoms being desorbed from the adsorbed Li layer (the HE peak) the conditions will be fixed, if nano roughness due to the LiAu islands is neglected, thereby leading to the unchanged position of the HE peak. Therefore, we can assume the formation of the intermetallic compounds of the variable stoichiometry during absorption of the Li atoms on Au.

To explain the Li atoms' ESD process in the system of the Li/Li_xAu_y/Au/W, we will use the ideas proposed earlier [13]. Let us consider the process diagram by exemplifying it with excitation by the bombardment electrons of the Au $5p_{3/2}$ level (Fig. 7) in the example of the HE peak of the lithium atoms' ESD. The electrons with the energy above 55 eV bomb the sample surface, thereby leading to excitation of the Au $5p_{3/2}$ level with hole formation at this level while capturing the electron into an area of local states near the Fermi level (1). As the 2D-layer of Li_xAu_y is a semiconductor, a hole's lifetime at the Au $5p_{3/2}$ is long, thereby leading to various Auger processes [19,20]. Then, the hole is neutralized due to transition of the electron from the valence band (2) with ejection of the electron into vacuum (3). The electron in the local state E_{L} is located near a conductivity band bottom E_{CBM} (for the Cs/CsAu system it can be located lower by 50 meV [24]) and can be easily captured into the conductivity band (4). The electron in the conductivity band can be easily captured to vacant states in the lithium atoms' monolayer (5), thereby leading to the formation of the neutral lithium atom and, consequently, to increase in a Li atom size with its subsequent expulsion from the surface. But, in case of the LE peak of the lithium atoms' ESD the electron is captured into the conductivity band, which is mainly composed of the lithium states. As atoms of the alkali metals in the gold-alkali metal intermetallic compounds have a charge close to 1+ [9,11], then this capture forms the neutral lithium atom while increasing the size and expelling it from the surface. It should be noted that the Li atoms' ESD process is correlated to electron transitions within the interface: the monolayer of the Li atoms and the Li_xAu_y layer nearest thereto. The neutralization of the Au $5p^+$ hole can also be contributed by the electron from the Li 1s core level. But as these levels are quite close, then the nascent hole Li $1s^+$ requires to be additionally neutralized. But, the probability of the two electron process is substantially lower than the single-electron one.

4. Conclusion

The electron-stimulated desorption of the Li atoms in the Li/Li_xAu_y/Au/W system has been studied. It is shown that after adsorption of the lithium atoms on the gold layer's surface the semiconductor 2D-layer of Li_xAu_y is formed within the adsorbed layer of lithium atoms — gold layer interface. It is deposition of two lithium monolayers to the surface of the two-monolayer gold surface, which forms LiAu. Deposition of the two lithium monolayers to the gold layers of the thickness of more than two monolayers forms the 2D-layers with various stoichiometry Li_xAu_y with a lack of the lithium atoms. There is evident resonance dependence of the ESD output of the Li atoms on the energy of the exciting electrons, which is correlated to excitation of the core levels of Au $5p_{3/2}$ and Au $5p_{1/2}$. The distribution across the kinetic energies of the lithium atoms being desorbed from the surface has been studied, wherein the two peaks are observed: the low-energy one at the energy of 0.11 eV correlated to desorption from the 2D-layer of $\mathrm{Li}_x\mathrm{Au}_y$ and the high-energy one at the energy about 0.29 eV correlated to desorption from the lithium atoms' layer of $\mathrm{Li}_x\mathrm{Au}_y$ nearest to the intermetallic compound surface. The position of the low-energy peak does not depend on a number of deposited lithium atoms, while the position of the high-energy peak is shifting towards the lesser energies with increase in the dose of deposited lithium, which is caused by the distance between the surface of the 2D-layer $\mathrm{Li}_x\mathrm{Au}_y$ — the adsorbed layer of the lithium atoms due to increase in lateral interaction between the lithium atoms in the adsorbed layer. A model of processes in the $\mathrm{Li}/\mathrm{Li}_x\mathrm{Au}_y/\mathrm{Au}/\mathrm{W}$ system is proposed. The ESD process captures atoms located in the adsorbed layer of the Li atoms and the $\mathrm{Li}_x\mathrm{Au}_y$ layer nearest thereto.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] C. Cretu, E. van der Lingen. Gold. Bull. **32**, *4*, 115 (1999).
[2] C.H. Mathewson. Int. Z. Metallographie **1**, 81 (1911).
[3] A.N. Sommer. Nature **152**, *3851*, 215 (1943).
[4] W.E. Spicer, A.N. Sommer, J.G. White. Phys. Rev. **115**, *1*, 57 (1959).
[5] M. Jansen. Chem. Soc. Rev. **37**, *9*, 1826 (2008).
[6] C. Wallden, L. Norris. Phys. Status Solidi A **381**, 2 (1970).
[7] K.-J. Range, F. Rau, U. Klement. Acta Crystallographica C **44**, *8*, 1485(1988).
[8] N.E. Christensen, J. Kollar. Solid Status. Commun. **46**, 72 (1983).
[9] G.H. Grosch, K.-J. Range. J. Alloys Comp. **233**, *1–2*, 30 (1996).
[10] R. Sarmiento-Perez, T.F.T. Cerqueira, I. Valencia-Jaime, M. Amsler, S. Goedecker, S. Botti, M.A.L. Marques, A.H. Romero. New J. Phys. **15**, *11*, 115007 (2013).
[11] G.H. Grosch, K.-J. Range. J. Alloys Comp. **233**, *1–2*, 39 (1996).
[12] G. Yang, Y. Wang, F. Peng, A. Bergara, Y. Ma. J. Am. Chem. Soc. **138**, *12*, 4046 (2016).
[13] Yu.A. Kuznetsov, M.N. Lapushkin. Physics of the Solid State **62**, *11*, 1949 (2020).
[14] V.N. Ageev, Yu.A. Kuznetsov. Physics of the Solid State **50**, *2*, 365 (2008).
[15] M.V. Knat'ko, M.N. Lapushkin, V.I. Paleev. Technical Physics **68**, *10*, 108 (1998).
[16] M.V. Knat'ko, M.L. Lapushkin, V.I. Paleev. Phys. Low-Dime. Struct. **9–10**, 85 (1999).
[17] Yu.A. Kuznetsov, M.N. Lapushkin. Physics of the Solid State **63**, *10*, 1701 (2021).
[18] V.N. Ageev, E.Yu. Afanas'eva. Physics of the Solid State **48**, *12*, 2217 (2006).
[19] V.N. Ageev. Prog. Surf. Sci. **47**, *1*, 55 (1994).
[20] T.E. Madey. Surf. Sci. **299/300**, 824 (1994).
[21] U.Kh. Rasulev, E.Ya. Zandberg. Prog. Surf. Sci. **28**, *3–4*, 181 (1988).
[22] V.N. Ageev, Yu.A. Kuznetsov, N.D. Potekhina. Technical Physics **83**, *6*, 85 (2013).
[23] J.A. Rodriguez, J. Hrbek, Y.-W. Yang, M. Kuhn, T.K. Sham. Surf. Sci. **293**, *3*, 260 (1993).
[24] Yu.A. Kuznetsov, M.N. Lapushkin. Physical & chemical aspects of study of clusters, nanostructures and nanomaterials **7**, 333 (2015).