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Thermal stability of Al–Mo thin film alloys

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ABSTRACT

Thin $Al_x Mo_{100-x}$ films ($40 \le x \le 90$ with x in steps of 5 at % Al) were prepared by magnetron codeposition onto alumina, glass, and saphire substrates at room temperature. The film thickness was about 400 nm, and they were amorphous for $45 \le x \le 85$. The films' structural changes upon heating were investigated by measurement of the electrical resistivity variation with temperature, $\rho(T)$, during the isochronal heating. Thus obtained results were complemented, and conclusions confirmed, by GIXRD analysis for selected heating temperatures. The dynamical temperatures of crystallization, T_x , were determined from the sharp increase of the derivative of ρ with respect to temperature. No systematic dependence of T_x on film substrate has been observed. Except for the Al₈₅Mo₁₅ film, the ρ of the amorphous films increase on the crystallization. The temperature of crystallization exhibits maximum around 530 °C for alloy compositions with x = 55 and 60. Electrical resistivity of both amorphous and crystallized films show a strong dependence on alloy composition, with a maximum for Al₇₅Mo₂₅ alloy. The resistivity of Al₇₅Mo₂₅ film is very large and amounts to 1000 $\mu\Omega$ cm and 3000 $\mu\Omega$ cm in amorphous and crystallized film, respectively, with the large negative temperature coefficient of $-10 \times 10^{-4} \text{ K}^{-1}$ and -14×10^{-4} K⁻¹, respectively. Although the crystallization temperature observed for the examined amorphous Al-Mo alloys is not very high, it might allow to exploit excellent corrosion properties of such films at some elevated temperatures.

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1. Introduction

The amorphous alloys of highly electrically conductive metal as Al and refractory transition metals, RM, such as the AlMo alloys, are very interesting both from scientific point of view and for practical applications in modern technologies. These alloys exhibit very good mechanical [1,2] and corrosion properties [3–6] and can be used as a diffusion barriers [7–9] in integrated microelectronic circuits. Amorphous alloys can also serve as a precursor for production (by the heat treatment) of novel nanocrystalline or amorphous matrixnanocrystalline materials.

The investigation of the properties of Al-RM alloys is of general interest because their composition is close to the widely investigated early transition/late transition metal (TETL) based amorphous alloys [10], whose transport properties are relatively well understood. Though the transport properties of the amorphous Al-RM are much less investigated, the measurement of the electrical

resistivity [11] and the Hall effect [12] of Al–W amorphous thin films allows interpretation with the same terms as those of TETL alloys, i.e. by the quantum interference at defects (QID) and *sp-d* hybridization.

Al—Mo alloys exhibit a rich phase diagram [13,14] with twelve equilibrium phases, seven of which are high temperature phases still under investigation. It is worth to note that Al—Mo system is close to Al—Mn alloy system in which, in rapidly solidified alloys with 10–14 at% Mn content, first icosahedral quasicrystals, *i*-QC, were found [15]. There were attempts to find *i*-QCs in melt-spun [16] and ball-milled [17] Al—Mo alloys but only the traces of icosahedral order have been found.

In this work we show how structural and electrical properties of magnetron sputtered Al_xMo_{100-x} thin films change with thermal treatment. As prepared films are metastable, the knowledge of structural changes upon heating is of crucial importance for their possible applications. The films were prepared for $40 \le x \le 90$ at% Al in steps of 5 at% Al, and were amorphous for $45 \le x \le 85$ at% Al. The films were investigated by measuring the variation of the electrical resistivity with temperature, $\rho(T)$, during the isochronal heating in vacuum. Further, the structural changes were





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investigated by grazing incidence X-ray diffraction (GIXRD) measurement on the samples consecutively heated to four or five selected temperatures, and the results were correlated with the results of resistivity measurements. The dynamical temperatures of crystallization of amorphous alloys, T_x , were determined from the sharp increase of the derivative of ρ with respect to temperature [18,19]. To investigate the possible effects of film substrate on the film properties, films were prepared on alumina ceramics, glass and sapphire substrates.

2. Experimental

The Al–Mo thin films were prepared by a magnetron codeposition of pure aluminium and pure molybdenum in the KJLC CMS-18 sputtering system. The working gas was argon at pressure of 0.67 Pa, in a constant flow mode. Samples were deposited at room temperature onto circular (1 cm dia and 0.3 mm thick) alumina ceramics, glass and sapphire substrates mounted onto substrate holder which rotated with 10 rpm, in order to ensure lateral homogeneity of the films. A typical deposition rate was about 0.17–0.35 nm/s, depending on the film composition, while average film thickness was from 375 to 400 nm. The nominal composition of the alloys was estimated from the measurements of the components' deposition rates, and it was tested on several samples by Rutherford backscattering spectroscopy (RBS). The estimated uncertainty of the film composition is about 10% relative to the minor component.

The GIXRD measurements were carried out on a diffractometer equipped with the Co X-ray tube and tilting specimen stage for adjustment of the sample's surface hight and angle with respect to the incident X-ray beam. The diffracted spectra were collected with curved position sensitive detector (RADICON) in the angle range $2\theta = 25-85^{\circ}$. Beam shaping and monochromatization were performed with Kratky-block collimation system and W/C multilayer, respectively. To enhance the irradiation and diffraction yield of the Al–Mo thin films, the measurements were performed at a fixed grazing incidence angle of $\alpha_i = 1.5^{\circ}$. At this angle, the penetration depth of the X-rays perpendicular to the film surface covers film thickness for all Al–Mo compositions.

The measurements of electrical resistivity were performed in a vacuum chamber at a pressure of about 10^{-3} Pa. The samples were radiatively heated. After heating of the samples, no traces of surface oxidation of the films were detected by the subsequent GIXRD examination. The resistivity measurements were performed by a four-probe method and by a standard ac technique, and the electrical noise was <1 part in 10^4 . The contacts were tungsten rods spring-loaded directly onto the film. An intermittent noise, which was due to the mechanical displacement of contacts during heating-cooling cycle was the greatest source of measurement error. The maximum possible error from the contact displacements was 5%. The heating rate was 2 K/min for all samples, while the cooling rate back to the room temperature was not controlled. The samples on alumina ceramics and sapphire were heated up to 700-800 °C, while those on glass were heated to 500-520 °C only, i.e. below glass softening temperature.

3. Results and discussion

The structure of the as prepared films was first checked by GIXRD diffraction and the patterns for five selected films are shown in Fig. 1. Completely amorphous films were prepared in the composition range from Al₈₅Mo₁₅ to Al₄₅Mo₅₅, while the films for x = 90 and 40, respectively, contained the crystalline phases. Then, the films were isochronally heated, with resistivity measured up to 730–800 °C, except for x = 90 and 85, which have been heated up



As deposited Al_xMo_{100-x}

Fig. 1. GIXRD patterns of five $Al_x Mo_{100-x}$ thin films deposited on alumina ceramics substrates.

to 660 °C because of the low melting temperatures of Al-rich alloys. As we will show, all these temperatures are well above the dynamical temperatures of crystallization of amorphous Al–Mo films (T_x).

In what follows, we present the temperature dependence of electrical resistivity, normalised to room temperature value, $\rho(T)/\rho_{\text{RT}}$, of the examined $Al_x Mo_{100-x}$ films during the first heating—cooling cycle. Films were deposited on alumina ceramics and heated at 2 K/min. In parallel, we present the results of GIXRD investigation of the particular alloy. The sample was sequentially annealed at preselected temperatures T_a , and after each temperature, it was cooled and then GIXRD measurement was conducted. The discrete sequence of T_a (from lowest to the highest T_a) was chosen such that it covers thermally induced changes in the electrical resistivity for each sample.

Fig. 2a) shows $\rho(T)$ of Al-rich Al₉₀ Mo₁₀ and Al₈₅ Mo₁₅ alloys, while their GIXRD spectra are presented in Fig. 3a) and b). As prepared Al₉₀ Mo₁₀ thin film is crystalline; the peaks in GIXRD correspond to fcc Al(Mo) solid solution. Since the solubility of Mo in Al is low (approx. 8 at% [13]), Al₉₀ Mo₁₀ films are probably oversaturated solid solution of Mo in crystalline Al with certain fraction of Mo atoms located in thin Al(Mo) grain boundaries or interlayers. Around 360 °C the formation of compound starts, and the resistivity starts to increase. Also, the GIXRD spectra taken on another film of the same alloy heated up to 350 °C still does not show any changes when compared with as deposited film. Spectra taken at $T_a = 500 \,^{\circ}\text{C}$ shows that a change in the structure is complete with the total disappearance of fcc Al and formation of cubic Al₁₂ Mo phase [20]. The resistivity behaviour above 500 °C is not clear to us at present. GIXRD taken after annealing at $T_a = 650$ °C shows a small fraction of rhombohedral Al₅ Mo phase [21], which probably developed at the expense of Al_{12} Mo and unreacted Mo. This would be consistent with the increase of the resistivity in the range ~620-670 °C. Above 670 °C, the resistivity starts sharply to increase (not shown here), due to the degradation and melting of the films, until the electrical contacts are lost.



Fig. 2. The temperature dependence of electrical resistivity of crystalline Al_{90} Mo_{10} and initially amorphous, Al_{85} Mo_{15} (a) and Al_{80} Mo_{20} (b) thin films. Vertical bars denote temperatures T_a at which GIXRD measurements were performed (see Fig. 3).

As deposited Al_{85} Mo₁₅ alloy is amorphous and on the first heating, the resistivity, depicted on Fig. 2a), starts sharply to fall at ≈ 460 °C indicating transition to the crystalline state. GIXRD of the film shows that it is still amorphous after heating up to 450 °C (Fig. 3b)). A decrease of the electrical resistivity is what one would generally expect for the transition from disordered amorphous to ordered crystalline state in metallic systems. GIXRD of the film heated up to $T_a = 500$ °C show the major peaks indexed as the crystalline rhombohedral Al₅ Mo phase. With further annealing, the Al₅ Mo grains grow. It should be noted that few peaks in Fig. 3b) does not match the Al₅ Mo phase. Thus, although the Al₅ Mo phase is the main product of crystallization in this film, the existence of small traces of Al₁₂ Mo phase or some other phase is possible. Above 670 °C resistivity starts sharply to increase, as in Al₉₀ Mo₁₀ films, until the electrical contacts are lost.

In Fig. 2b) is presented the temperature dependent electrical resistivity of two Al₈₀ Mo₂₀ thin films which were heated to different maximum temperature: 730 and 800 °C. The agreement between results for heating are quite satisfactory up to 560 °C, i.e. some 100 °C above the start of the crystallization (that is 460 °C). Even the small kink at around 520 °C appears in both of the samples. Above around 560 °C, the two $\rho(T)$ curves starts to differ, which may be caused by the small inhomogeneities in the composition. However, we think that these differences are of lesser importance as compared to the similarity of the main characteristics. The most interesting is the apparent tendency of the resistivity to increase exponentially with the decrease of temperature during cooling. However, the preliminary measurements down to 77 K have shown that the increase of resistivity slow down below the room temperature and there is no tendency of $\rho(T)$ to diverge at lower temperatures.

In Fig. 3c) the GIXRD scans from Al_{80} Mo₂₀ films, as deposited and annealed at four different temperatures, are presented. The



Fig. 3. GIXRD spectra of the as deposited and annealed Al_{90} Mo_{10} (a), Al_{85} Mo_{15} (b) and Al_{80} Mo_{80} (c) thin films. Each annealing temperature is indicated above the corresponding curve.

film is amorphous up to $T_a = 450$ °C, while at 540 °C it crystallizes. Due to the small grain size and grazing geometry, the peaks are considerably widened. This hinders the analysis and phase identifications as many of the peaks are overlapped and hard to identify. Nevertheless, the best matching of GIXRD spectra for Al₈₀ Mo₂₀ film in the range $T_a = 540-820$ °C is achieved with the monoclinic Al₄ Mo phase [22]. With increasing T_a the Al₄ Mo grains grow, while a small fraction of monoclinic Al₈ Mo₃ phase [23] was found at $T_a = 800$ °C.

In Fig. 4 the electrical resistivity of Al_{75} Mo₂₅ and Al_{70} Mo₃₀ thin films as a function of temperature for a different heating cooling cycles is presented. For both alloys the first heating—cooling cycle up to 700 °C of the as-deposited amorphous alloy is presented. In the first heating cycle the resistivity of both alloy exhibits well defined transition above 450 °C and a large increase after the crystallization.

The GIXRD spectra for Al₇₅ Mo₂₅ and Al₇₀ Mo₃₀ alloys, heated up to four different temperatures T_a (up to 800 °C) are presented in Fig. 5a) and b), respectively. These two alloys show similar structural evolution with T_a : they are amorphous until 450 °C and at 520 °C the Al₈ Mo₃ grains appears which further grow with heating. Only notable difference between x = 75 and x = 70 film is small

Fig. 4. The temperature dependence of the electrical resistivity of initially amorphous $AI_{75} Mo_{25}$ and $AI_{70} Mo_{30}$ thin films. Amorphous $AI_{75} Mo_{25}$ was first isochronally heated up to 700 °C, then kept for 10 h at that temperature. For $AI_{70} Mo_{30}$, in addition to the first isochronal heating cycle up to 700 °C, the result of the subsequent isochronal heating cycle up to 800 °C is shown. Vertical bars denote temperatures T_a at which GIXRD measurements were performed (see Fig. 5).

Fig. 5. GIXRD spectra obtained from as deposited and annealed Al_{75} Mo_{25} (a) and Al_{70} Mo_{30} (b) thin films. Each annealing temperature is indicated above the corresponding curve.

traces of cubic AlMo₃ phase [24] found in Al₇₀ Mo₃₀ film annealed at $T_a = 820$ °C.

On cooling, the resistivity exhibits non linear behaviour with tendency to increase faster with lowering of the temperature. In this respect the behaviour of Al_{80} Mo_{20} , Al_{75} Mo_{25} and Al_{70} Mo_{30} alloy is similar but the preliminary measurements of electrical resistivity down to 77 K have shown that the resistivity of Al_{75} Mo_{25} and Al_{70} Mo_{30} alloys exhibits further exponential increase on lowering the temperature, in contrast to the resistivity of Al_{80} Mo_{20} alloy.

In order to get some insight into the exponential behaviour of $\rho(T)$ upon cooling, the crystallized Al₇₅ Mo₂₅ film have been annealed for 10 h at 700 °C and the heating-cooling cycle after the annealing is shown together with the first cycle in Fig. 4a). We see that $\rho(T)$ curves on heating and cooling overlap, indicating that the structure is stabilized. What is more important is that the curvature of $\rho(T)$ almost disappeared. We also heated already crystallized Al₇₀ Mo₃₀ film further up to 800 °C and here too the $\rho(T)$ curve becomes more linear. From this we conclude that nonlinearity of $\rho(T)$ in these two alloys, especially notable in Al₇₅ Mo₂₅ film, is not an intrinsic property of Al₈ Mo₃ crystalline phase, since it disappears with the grain growth and increasing purity of the grains. It is rather caused by the disordered nanocrystalline structure, small size of the grains and large amount of the grain boundaries, combined with the small mobility of the conducting electrons. Here we are apparently dealing with two competing factors - the intergrain and intragrain contributions.

Fig. 6. The temperature dependence of the electrical resistivity during the first heating cycle of Al_{60} Mo₄₀ and Al_{50} Mo₅₀ (a), and Al_{45} Mo₅₅ (b) amorphous films, and crystalline Al_{40} Mo₆₀ (c) thin film.

In Fig. 6a), the resistivity of Al₆₀ Mo₄₀ and Al₅₀ Mo₅₀ alloys is presented, while $\rho(T)$ of Al₄₅ Mo₅₅, i.e. the minimum Al-content alloy which is completely amorphous in the series of investigated amorphous alloys, is shown in Fig. 6b). We may conclude that general behaviour of resistivity during the first heating cycle and crystallization of the as-deposited amorphous Al_xMo_{100-x} thin films with greater Mo content are similar to those of Al₇₅ Mo₂₅ and Al₇₀ Mo₃₀ alloys. The degree of changes in resistivity during the crystallization decreases systematically with the increase of Mo content. The non-linearity in $\rho(T)$ of crystallized films with greater Mo content at lower temperatures.

The Al_xMo_{100-x} films with 45 \leq x \leq 65 also showed structural dependence on heating temperatures similar to the Al₇₅ Mo₂₅ and Al₇₀ Mo₃₀ films. They are amorphous after the deposition, while crystallization starts around 500 ° C, followed by the grain growth as T_a increases. No additional phase transformation was found after the crystallization. In these films we found a coexistence of Al₈ Mo₃ and AlMo₃ phases. The fraction of AlMo₃ phase increases as x decreases.

This is illustrated in Fig. 7, where GIXRD spectra for x = 70, 60, 50 and 40, after annealing at 820 °C, are shown. In order to evaluate and compare low intensity peaks, which are important for the quantification of Al₈ Mo₃ and AlMo₃ phases, the GIXRD spectra for these films are reported in logarithmic scale.

Fig. 6 c) shows the electrical resistivity of $Al_{40} Mo_{60}$ thin film which is crystalline after the deposition. GIXRD spectra of this alloy (Fig. 1) shows that it is a crystalline bcc Mo(Al) solid solution. During the first heating cycle the resistivity starts slowly to increase at about 200 °C, with a maximum around 600 °C. At 600 °C, the GIXRD spectra shows that it is still bcc Mo(Al) solid solution while spectra taken after the heating up to 820 °C show (Fig. 7) that a change in the structure occurred with the total transformation into AlMo₃ phase.

Further, we address the dependence of $\rho(T)$ on film substrate. For comparison, in Fig. 8a) the temperature dependence of resistivity of Al₇₅ Mo₂₅ films deposited on alumina ceramics and glass substrates during the first heating is presented. It can be stated that around the transition, close to 470 °C, two $\rho(T)$ curves are similar

Fig. 7. GIXRD spectra obtained from annealed Al_xMo_{100-x} thin films for $70 \le x \le 40$. As x decreases, the fraction of AlMo₃ phase increases.

Fig. 8. (a) The temperature dependence of the electrical resistivity of Al_{75} Mo₂₅ films deposited on alumina and glass substrates which exhibit a similar behaviour around the dynamical temperature of crystallisation T_{x} . (b) The difference between measured resistivity normalised to the room temperature value and a linear extrapolation of resistivity $1+\alpha(T-25 \ ^{\circ}C)$ in Al_{75} Mo₂₅ films deposited on alumina and glass substrates.

and shifted one with respect to another by about 20 °C. At the same, for temperatures between about 50 °C and temperatures of crystallization (where these films are still amorphous), a rather large deviation from linear behaviour is observed. This deviation amounts up to 25% and is dependent on the film substrate. The deviation from linear behaviour of $\rho(T)$ is ascribed to the relaxation processes which in Al–W amorphous alloys also may amount up to 25 % [25]. To get further insight into the relaxation effects and its relation to different substrates, we subtracted linear term $1 + \alpha_{\rm RT}(T-25 \ ^{\circ}{\rm C})$ from $\rho(T)/\rho_{\rm RT}$. The resulting non-linear contributions in resistivity (before the crystallization) for Al₇₅ Mo₂₅ films deposited on glass and alumina substrates are shown in Fig. 8b). We note that for films with Al content about 75 at% Al, the effects are specially large. Moreover, for these films the relaxation term in films on glass (and sapphire, not shown here) substrates is positive, as in AlW thin films [25]. On the contrary, in films on alumina the relaxation is negative and first decreases up to around 200 °C when it starts to increases to positive values up to the temperature of crystallization. The relaxation effects in AIW alloys do not depend so strongly on the substrate and there is no negative term in films deposited on alumina. For the Al-Mo alloys with higher Mo content, the relaxation in films deposited on different substrate becomes similar. In these films, for lower heating temperatures we found much smaller positive relaxation term, as compared to the films with about 75 at%. At higher temperatures a positive term disappears, and only the negative one remains. The positive relaxation effect was, and still may be, plausibly explained by the increase of order and hence increase of *sp-d* electron interaction through the increase of electron hybridisation. However, the origin of substrate dependence relaxation effects remains unclear at this

time. Regardless of this, we note that for the general composition dependence of resistivity and transition to the crystalline state, the relaxation effects are of lesser importance and we neglect them in further analysis of $\rho(T)$ curves.

From measured $\rho(T)$ curves, we further determined technologically important parameters of Al–Mo alloys: the room temperature electrical resistivity, ρ_{RT} , the corresponding temperature coefficient of resistivity, $\alpha_{\text{RT}} = 1/\rho \times d\rho/dT$, and the dynamical temperature of crystallisation, T_x .

Fig. 9a) shows ρ_{RT} as a function of x in the as deposited and crystallized Al_xMo_{100-x} thin films. $\rho_{\rm RT}$ of both amorphous and crystallized films exhibits a pronounced maximum around x = 75 at % Al which in the as deposited film amounts to around 1000 $\mu\Omega$ cm (that is rather high even for the amorphous alloys). Interestingly, ρ_{RT} of Al₇₅ Mo₂₅ and Al₇₀ Mo₃₀ increases 3 times upon crystallization. In a similar Al_xW_{100-x} system, a maximum in $\rho_{\rm RT}$ of 480 $\mu\Omega$ m is observed for as deposited amorphous alloys Al_{80} W_{20} [12], which upon crystallization increases for some 50 % [26]. For comparison, the resistivities of TETL amorphous metals are typically around 200 $\mu\Omega$ cm [10]. The high resistivity of Al-transition metal, and therefore Al-refractory metal alloys is ascribed to the strong sp*d* hybridization of electron bands [27–29]. Hybridization cause a minimum in the electron density of states and, if the Fermi level falls within that minimum, the effective number of conducting electrons decreases and hence resistivity increases. From the results for amorphous Al–Mo and Al–W [12] alloys, the hybridisation is strongest for Al:RM ratios equal to 3:1 and 4:1. respectively. The resistivity of crystallized alloys may be further increased by the strong Fermi level-Brillouin zone interaction which flattens electronic bands. This flattening of electronic bands further lowers the

Fig. 9. Room temperature electrical resistivity of (a), and the corresponding temperature coefficient of resistivity (b) of as deposited and crystallised Al_xMo_{100-x} thin films.

minimum in electronic density of states, increases effective mass and lowers the Fermi velocity v_F [28,29].

Composition dependence of α_{RT} is shown in Fig. 9b). For the as deposited, as well for crystallized Al–Mo alloys, the α_{RT} exhibits negative minimum for x = 75, while for lower x it goes toward zero. In amorphous Al₇₅ Mo₂₅, α_{RT} amounts to -10×10^{-4} K⁻¹, which is rather large negative value. In comparison, $|\alpha_{RT}|$ of TETL amorphous metals are not larger than $1 \times 10^{-4} \text{ K}^{-1}$ [10]. Moreover, a correlation between the resistivity and its temperature coefficient is evident from Fig. 9. These results are in accordance with Mooij correlation [30] and the generalization of the Mooij correlation to quasicrystals recently proposed by Rapp [31]. For x < 75, generally we found similar temperature coefficients for as deposited and crystallized alloy. However, for two crystallized Al-rich alloys Al₉₀ Mo_{10} and Al_{85} Mo_{15} , we emphasize that the α_{RT} is rather large and positive. This might be due to somewhat lower maximum applied heating temperatures for these two alloys, as indicated with the vertical dash line in Fig. 9.

Finally, the dynamical temperatures of crystallization T_x were deduced from the derivative of the resistivity with respect to temperature, $d\rho(T)/dT$. Before taking the derivation, the results for $\rho(T)$ were smoothed somewhat so that results for the derivation appear less scattered than original resistivity data. We defined T_x as the onset of the rapid change of the derivative of resistivity vs. temperature curve [18,19]. As an example, Fig. 10 shows a T_x determination for Al₇₅ Mo₂₅ and Al₅₅ Mo₄₅ films deposited on the alumina substrates. We also examined possible influence of different substrates on the dynamical temperatures of crystallization. For illustration, we plotted in Fig. 10, the $d\rho(T)/dT$ for Al₇₅ Mo₂₅ alloy on alumina, glass and sapphire substrates and for Al₅₅ Mo₄₅ on alumina and sapphire substrates. We note that the differences between the 3 $d\rho(T)/dT$ curves for Al₇₅ Mo₂₅ are about 15 ° C, while it is negligible for the 2 $d\rho(T)/dT$ curves for Al₅₅ Mo₄₅.

The dynamical temperatures of crystallization of Al_xMo_{100-x} films as a function of alloy composition for films deposited on different substrates are presented in Fig. 11. As seen, the general variation of T_x upon composition is independent on the film substrate. The small differences in T_x measured for different substrates are scattered randomly within 20 °C and can be ascribed to the error in resistivity measurement and/or to the small fluctuations in composition of the films. Further, the measured T_x is found in temperature range of 450–530 °C, which is relatively small

Fig. 10. The temperature derivative of electrical resistivity in Al_{75} Mo_{25} and Al_{55} Mo_{45} films deposited on alumina, glass and sapphire, and alumina and sapphire substrates, respectively, which were used for the determination of the dynamical temperatures of crystallization T_{x} .

Fig. 11. The dynamical temperatures of crystallization of the amorphous $Al_x Mo_{100-x}$ thin films deposited on alumina, glass and sapphire substrates. The rate of isochronal heating was 2 K/min.

variation of T_x for compositional range of 45 < x < 85. Interestingly, the crystallization temperature was found to increase with an increase in Al concentration to around 55 at.% Al, and then decreased with further increasing Al concentration. This means that around this concentration, the highest activation energy is needed for the rearrangement of the reacting Al and Mo atoms in order to form crystals. We note that the local arrangement of the atoms in amorphous phase might highly depend on the kinetics of the depositing atoms. In other words, different deposition conditions used to obtain nominally same alloy might result in different short range order of the amorphous phase, which consequently influence the crystallization temperature.

4. Conclusions

About 400 nm thick $Al_x Mo_{100-x}$ films ($40 \le x \le 90$ with x in steps of 5 at% Al) were prepared on alumina, glass and sapphire substrates at room temperature by magnetron codeposition. A fully amorphous films were obtained for 45 < x < 85, while for x = 90and x < 45 the aluminium and molybdenum solid solutions crystalline phases were obtained, respectively. Thermal stability of the as deposited alloys were investigated by the temperature variation of the electrical resistivity. The dynamical temperatures of crystallization of the amorphous films, T_x , were determined from the onset of rapid change of the resistivity derivation with respect to the temperature. The crystallization temperatures of amorphous Al_xMo_{100-x} films are in the range 450–530 °C, with a maximum for 55 < x < 60. No systematic dependence of T_x on film substrate has been observed. The phase composition and stability of the alloys were analysed by GIXRD, which was measured subsequently for samples annealed at selected temperatures. During heating, amorphous films show strong relaxation effects of the amorphous structure. However, contrary to the crystallization, the relaxation is highly dependent on the film substrate.

Electrical resistivity at room temperature of amorphous and crystallized films exhibits similar dependence on alloy composition with a maximum for x = 70-75 films. This maximum amounts to 1000 $\mu\Omega$ cm in amorphous films and to 3000 $\mu\Omega$ cm in crystallized films. Concurrently, we found for x = 75 a large negative temperature coefficient of resistivity ($-10 \times 10^{-4} \text{ K}^{-1}$ and $-14 \times 10^{-4} \text{ K}^{-1}$ for amorphous and crystallized alloys, respectively), which for lower *x* tends to zero.

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