

THE CONCENTRATION ANOMALY OF STRAIN COEFFICIENT BINARY FILM SYSTEM BASED ON Au AND Fe ATOMS

O. V. Pylypenko, L. V. Odnodvoretz, M. O. Shumakova, I. Yu. Protsenko *

Sumy State University, Applied Physics Department, Sumy, Ukraine

(Received July 21, 2016)

The results of the study at the elastic and plastic strain of differential and integral longitudinal strain coefficients in thin films with thickness of 20...40 nm by simultaneous condensation of Au and Fe atoms were obtained. Diffraction and electron microscopic studies indicate that in the concentration range to 55 at. % Fe stabilizes the fcc unordered solid solution (Au), and at concentrations of 55...85 at. % Fe-bcc solid solution (α -Fe). The structural transition is accompanied by dispersing of the crystal structure and, consequently, increase the efficiency of grain-boundary scattering of electrons. This causes an abnormal increase in the integral strain coefficient (from 2 to 80 units) in the concentration range 55...75 at. % Fe.

PACS: 73.90.+f, 77.80.bn

1. INTRODUCTION

At present accumulated considerable theoretical and experimental data concerning the strain effect in film materials. In particular, in our previous work (see., for example, reviews [1, 2]) made a generalization of results on single-layer and single-component films of various metals. Analyzed methods C.R.Tellier and A.J. Tossier [3] calculation electrocarried parameters such as the mean free path electron (λ_0), effective specularity parameter (p) and transmission coefficient at the grain boundary (r) based on depending of the integral coefficient longitudinal strain coefficient $(\gamma_l)_{int} = [R(\varepsilon_l) - R(0)]/R(0)$ (l - longitudinal direction strain) averaged over the entire interval of strain versus the thickness of the film. In [4] was proposed theoretical model for the strain coefficient of the bilayer film, which stores the identity of the individual layers, which was tested in [5] for example film $Ni/V/S$ (S - substrate). The feature of this model is that it, unlike [3] allowed deformation dependence not only λ_0 , but p and r . This idea proved very productive because there is a satisfactory compliance with the calculated and experimental results. In [2] also analyzed the features strain effect in film systems with an unlimited solubility of components or systems, which form intermetallic compounds. This idea proved very productive because there is a satisfactory compliance with the calculated and experimental results. In [2] also analyzed the features strain effect in film systems with an unlimited solubility of components or systems, which form intermetallic compounds. In [6] and [7] for example films solid solution (α -Fe, Cr) and $Ni_{0.75}Fe_{0.25}$ (fcc phase Ni_3Fe), $NiFe$ (fcc phase $NiFe$) and $Ni_{0.25}Fe_{0.75}$ (α -phase film al-

loy Ni - Fe , perhaps - $NiFe_3$) the observed maximum on the dependence for differential strain coefficient $(\gamma_l)_{dif} = d \ln R_i / d \varepsilon_{li}$ (i - strain range number; R_i - initial resistance of i -range; $d \varepsilon_{li}$ - the strain) versus ε_l . Nature specified maximum of dependence associated with the transition from elastic to plastic deformation film samples, causing a nonlinear dependence of the resistivity of the strain ε_l .

Notice that the nature of this maximum, fundamentally different compared to the maximum on concentration depending the integral strain coefficient $(\gamma_l)_{int}$, which goes to in this paper. In [8] found his explanation of the effect of abnormally small values $\gamma_l \sim 1$ in some single-layer metal films. This effect authors explain the abnormal increase in the Poisson ratio of the film to value $\mu_f \geq 0.5$. Realized us a brief analysis leads to the conclusion, to a large extent complete, theoretical and experimental studies of the strain effect in film materials. At the same time, some aspects of this problem and currently remain without attention of researchers. In particular, it is a virtual absence of results strain effect research in film systems based on the metal, which is limited mutual solubility of atoms in a bulk state, although the film materials, depending on the thickness of two-component films temperatures obtaining samples and the concentration of component may stabilize different phase states: alloys eutectic composition; disordered s.s.- ($Me1$) or ($Me2$); ordered s.s.- ($Me1$, $Me2$); quasi-amorphous alloys. According to [9] indicated phase composition under certain conditions realized in the film system based on atoms of Fe and Au. This circumstance was the basis of the study strain effect in this film system.

*Corresponding author E-mail address: i.protsenko@aph.sumdu.edu.ua

2. EXPERIMENTAL TECHNIQUE

Film samples were obtained by simultaneous condensation in vacuum 10^{-4} Pa known weight Fe and Au with a predetermined calculated concentration of the component ($c_{Fe} = 20...85$ at.% with step 5 at.%). The accuracy of the calculated concentrations controlled by method XMA, which made it possible to examine the concentration dependence l of fcc s.s.(Au), bcc s.s.(α - Fe) and quasi-amorphous alloy based on α - Fe . For the realization this phase composition of sample the thickness should be 20...30 nm. At the condensation layer can be implemented phase composition s.s.-(Au) + (α - Fe) or s.s.-(α - Fe) + fcc Au .

Diffraction and electron microscopy studies were performed on the electron microscope TEM-125K (company "SELMI", Ukraine). The temperature of the substrate was value $T_S = 300, 450$ and 550 K.

Experimental strain depending $\Delta R/R(0)$ versus ε_l ($\Delta R = R(\varepsilon_l) - R(0)$; $R(\varepsilon_l)$ and $R(0)$ – electric resistance at the strain ε_l and at the $\varepsilon_l = 0$) were obtained using automated hardware system for measuring the value $(\gamma_l)_{int}$ in the elastic and plastic range strain.

This technique is described in detail by us in [5] and [6]. The values of strain ε_{ltr} , at which the transition from elastic to plastic strain, we determined the point of intersection of two areas contiguous to strain dependence (example of this procedure is shown on Fig.1).

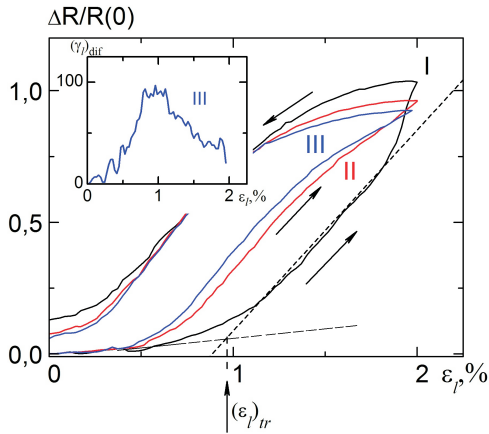


Fig.1. To explain the methodology the determination of ε_{ltr} based on strain dependency. On the insert-dependence $(\gamma_l)_{dif}$ versus ε_l . Concentration $c_{Fe} = 70$ at.%. I - III – the numbers of strain cycles

Experimental studies of the structure and strain effect were performed after cooling of the samples at the 300 K. In addition to clarifying the value ε_{ltr} . used data of works [10-12], and to take account of size effects on mechanical properties used analysis, carried out in [13].

3. EXPERIMENTAL RESULTS

Diffraction and electron microscopic studies indicate that the film samples thickness of 20...40 nm immediately after simultaneous condensation component stabilizes the fcc phase s.s.-(Au) to a concentration $c_{Fe} \cong 55$ at.% depending on the thickness of the sample, while at the values $c_{Fe} \cong 65...85$ at.% quasi-amorphous and crystalline s.s.-(α - Fe). The dependence of the lattice parameter of these s.s. versus c_{Fe} , of which is consistent with the data [9] and [14], shown in Fig.2,a. More clearly fcc lattice transformation is illustrates dependence interplanar distances or effective interplanar distance which calculated by the first diffraction peak (Fig.2,b). At the same time we have not observed s.s.-(γ - Fe), as is the case [15].

Series micropictures and diffraction patterns (Figs. 3, 4) illustrate the change in structural phase state of films by changing the concentration of components.

Attention is drawn status of ultra-dispersion state samples at $c_{Fe} \cong 55...75$ at.%, which is accentuated attention in the analysis of the results studying strain effect. On the Fig.5 are examples of strain dependency

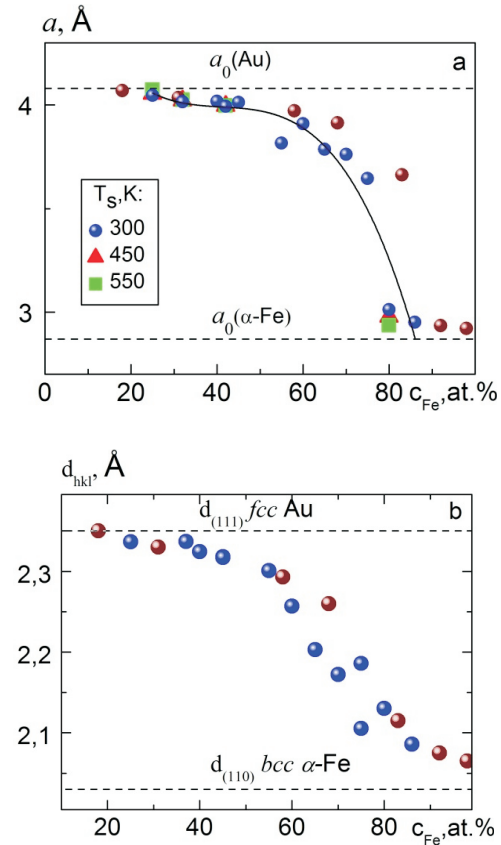


Fig.2. Dependence fcc lattice parameter (a) and interplanar distance which corresponds to the first diffraction peak (b), for s.s.-(Au) and s.s.-(α - Fe) at the $T = 300$ K. Blue-• – data of [9].

The line section shown by the dotted line corresponds to a transition area on the dependence from s.s.-(Au) to s.s.-(α - Fe) – (a)

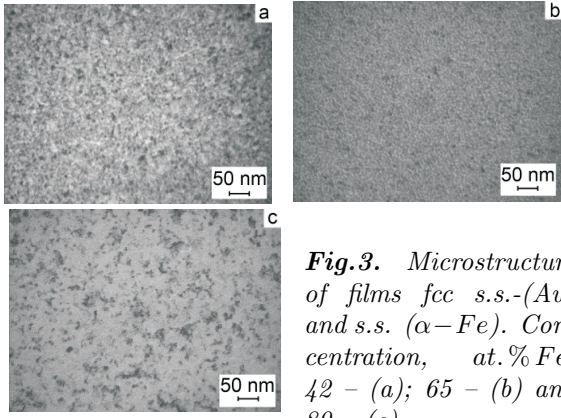


Fig.3. Microstructure of films fcc s.s.-(Au) and s.s. (α -Fe). Concentration, at.% Fe: 42 - (a); 65 - (b) and 80 - (c)

$\Delta R/R(0)$ and $(\gamma_l)_{dif}$ versus ε_l . As already noted, depending on the maximum $(\gamma_l)_{dif}$ versus ε_l also observed by us earlier [6, 7] the example of other film materials. The nature of it is related to the transition from elastic to plastic strain of the samples. Results of processing the dependency on Fig.6 are presented.

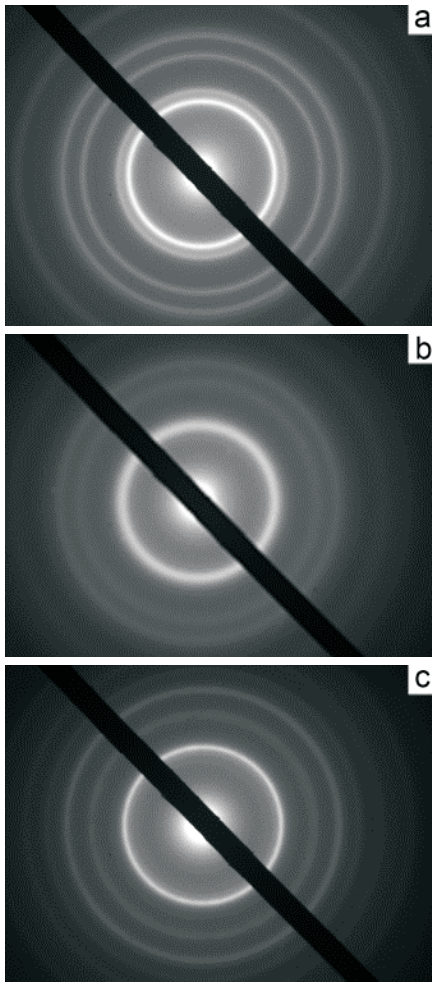


Fig.4. Diffraction patterns of films fcc s.s.-(Au) and s.s. (α -Fe). Concentration, at.% Fe: 42 - (a); 65 - (b) and 80 - (c)

Of them follows that in the concentration range $c_{Fe} \cong 55...75$ at.% there is an abnormal increase in value $(\gamma_l)_{int}$.

This result can be explained by dispersing s.s.-(Au) at the increasing values c_{Fe} (see Fig.3). According to theoretical models of effective free path of electrons by C.Tellier and A.Tosser [3] value $(\gamma_l)_{int}$ completely determined by the grain-boundary scattering of electrons, because their surface scattering affects only the character of the dependence $(\gamma_l)_{int}$ from the thickness of the film sample. Thus, increasing the efficiency of grain-boundary scattering of electrons in the concentration range $c_{Fe} \cong 55...75$ at.% is a cause of abnormal increase in value $(\gamma_l)_{int}$.

Based on the basic ratio for the strain longitudinal coefficient

$$(\gamma_l)_{int} = -\frac{1}{\lambda_0} \frac{\Delta\lambda_0}{\Delta\varepsilon_l} + 2(1 + \mu_f), \quad (1)$$

we can conclude the main contribution to the value $(\gamma_l)_{int}$ strain coefficient $-\frac{1}{\lambda_0} \frac{\Delta\lambda_0}{\Delta\varepsilon_l}$, because the second term in (1) so-called the geometric factor makes contributions up to 3 units. The decrease $\Delta\lambda_0$ is due to direct dependence on λ_0 versus ε_l ($\Delta\lambda_0$) $_{\varepsilon_l}$ and indirect dependence λ_0 versus ε_l on the parameters p and r : $(\Delta\lambda_0)_{p(\varepsilon_l)}$ and $(\Delta\lambda_0)_{r(\varepsilon_l)}$.

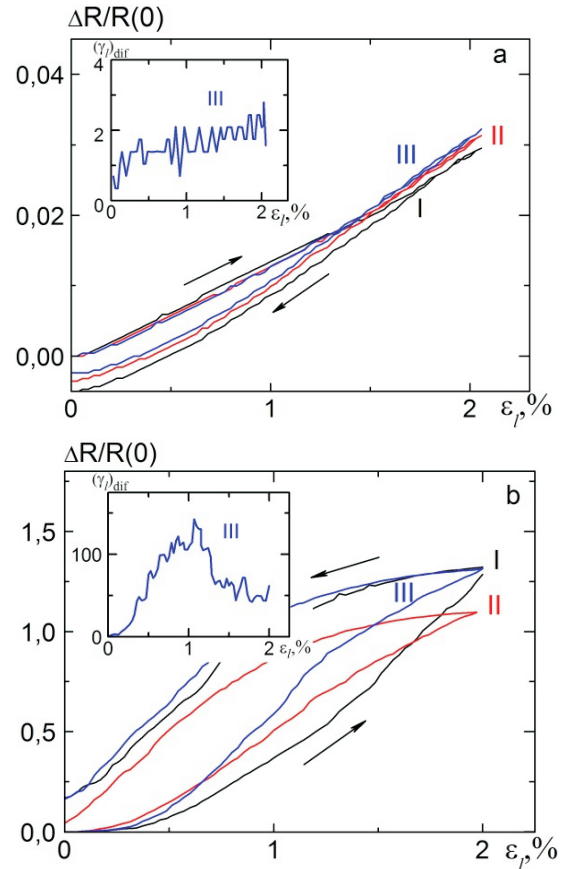


Fig.5. The examples of strain dependencies for the films fcc s.s.-(Au). Concentration, at.% Fe: 32 - (a); 55 - (b). On the insert - dependence $(\gamma_l)_{dif}$ versus ε_l

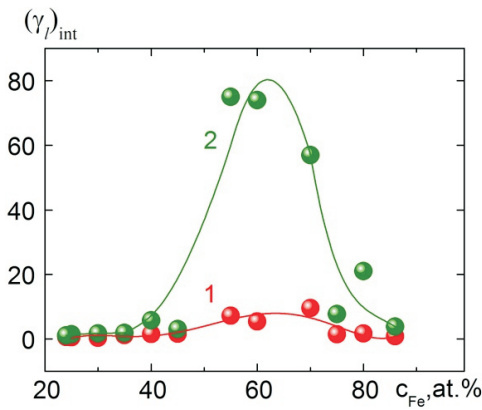


Fig. 6. Dependence $(\gamma_i)_{int}$ versus c_{Fe} at the elastic (1) and plastic (2) strain of samples

The work was done in the frame of state project N0115U000689 (2015 - 2017 years).

4. CONCLUSIONS

In thin films ($d \cong 20...40 \text{ nm}$) obtained by simultaneous condensation of Fe and Au atoms are formed disordered s.s. fcc (Au) and s.s. bcc ($\alpha-Fe$). The structural transition of the oversaturated s.s.- (Au) to ($\alpha - Fe$) accompanied by dispersing grain structure and, consequently, there is an abnormal increase of the strain longitudinal coefficient. This effect can be used for forming the sensitive element displacement sensors or strain sensors. ‘

References

1. I. Protsenko, L. Odnodvoretz, A. Chornous. Electroconductivity and tensosensibility of multilayer films // *Metallofiz. Noveishie Tekhnol.* 1998, v.20, p.36-41 (in Russian).
2. S.I. Protsenko, L.V. Odnodvoretz, I.Y. Protsenko. Future strain properties of multilayer films materials, (in: O. Fesenko, L. Yatsenko Eds.) *Nanocomposites, nanophotonics, nanobiotechnology, and applications*, Springer International Publishing Switzerland, Cham-Heidelberg-New York - Dordrecht - London, 2015, 345-374 p.
3. C.R. Tellier, A.J. Tosser. *Size effects in thin films*. Elsevier, Amsterdam - Oxford - New York, 1982.
4. O. Lasyuchenko, L. Odnodvoretz, I. Protsenko. Microscopic theory of thensosensibility of multilayer polycrystalline films // *Cryst. Res. Technol.* 2000, v.35, p.329-332.
5. L. Odnodvoretz, S. Protsenko, O. Synashenko, D. Velykodnyi, I. Protsenko. Electrophysical properties of Ni/V and Cr/Fe Multilayer films // *Cryst. Res. Technol.* 2009, v.44, p.74-81.
6. S.I. Protsenko, D.V. Velykodnyi, V.A. Kheraj, M.S. Desai, C.J. Panchal, I.Yu. Protsenko. Electrophysical properties of Cu/Cr and Fe/Cr film systems within elastic and plastic deformation range // *J. Mater. Sci.* 2009, v.44, p.4905-4910.
7. K.V. Tyschenko, I.Yu. Protsenko. Nonlinear effects in piezoresistive features of Fe and Ni based film alloys // *Metallofiz. noveishie tekhnol.* 2012, v.34, p.907-917 (in Russian).
8. I.Yu. Protsenko, L.V. Odnodvoretz, K.V. Tyschenko, M.O. Shumakova. Features strain properties thin-films: anomalous small of strain coefficient // *J. Mech. Eng. Technol.* 2013, N.1, p.34-39.
9. Y.H. Hyun, Y.P. Lee, Y.V. Kudryavtsev, R. Gontarz. Properties of Au-Fe disordered alloy films near the fcc-bcc structural transformation // *J. Korean Phys. Soc.* 2003, N.43, p.625-628.
10. C.A. Neugebauer. Tensile properties of thin, evaporated gold films // *J. Appl. Phys.* 1960, N.31, p.1096-1101.
11. I.P. Buryk, D.V. Velykodnyi, L.V. Odnodvoretz, I.E. Protsenko, E.P. Tkach. Tensoresistive effect in thin metal films in the range of elastic and plastic strain // *Tech. Phys.* 2011, N.81, p.232-237.
12. O.P. Tkach, L.V. Odnodvoretz, S.I. Protsenko, D.V. Velykodnyi, K.V. Tyschenko, I.Yu. Protsenko. Mechanical properties of micron and nanodimensional metal films // *J. Nano- Electron. Phys.* 2010, N.2, p.22-29.
13. Y. Choi, S. Suresh. Size effects on the mechanical properties of thin polycrystalline metal films on substrates // *Acta Materialia.* 2002, N.50, p.1881-1893.
14. E. Bosco, P. Pizzi, M. Baricco. Phase transformations in Au-Fe melt spun alloys // *Mater. Sci. Eng.* 2004, N.375-377, p.468-472.
15. P. Mukherjee, Y. Zhang, M.J. Kramer, L.H. Lewis, J.E. Shield. L10 structure formation in slow-cooled Fe-Au nanoclusters // *Appl. Phys. Lett.* 2012, N.100, p.211911-211913.
16. P. Mukherjee, L. Zhou, M.J. Kramer, J.E. Shield. Formation of non-equilibrium Fe-Au solid solutions in nanoclusters // *Appl. Phys. Lett.* 2013, N.102, p.243103.

**КОНЦЕНТРАЦИОННАЯ АНОМАЛИЯ КОЭФФИЦИЕНТА
ТЕНЗОЧУВСТВИТЕЛЬНОСТИ ДВУХКОМПОНЕНТНОЙ СИСТЕМЫ НА ОСНОВЕ
АТОМОВ Au И Fe**

А. В. Пилипенко, Л. В. Одноворец, М. О. Шумакова, И. Е. Проценко

Представлены результаты исследования дифференциальных и интегральных коэффициентов продольной тензочувствительности в области упругой и пластической деформаций в тонких плёнках толщиной 20...40 нм, полученных методом одновременной конденсации атомов Au и Fe. Дифракционные и электронно-микроскопические исследования указывают на то, что и в диапазоне концентраций до 55 ат.% Fe стабилизирует ГЦК неупорядоченный твердый раствор (Au), а при концентрациях 55...85 ат.% Fe – ОЦК-твёрдый раствор (α -Fe). Структурный переход сопровождается диспергированием кристаллической структуры и, как следствие этого, повышением эффективности зернограничного рассеяния электронов. Это вызывает аномальное увеличение интегральной величины коэффициента тензочувствительности (от 2 до 80 единиц) в интервале концентраций 55...75 ат.% Fe.

**КОНЦЕНТРАЦІЙНА АНОМАЛІЯ КОЕФІЦІЄНТА ТЕНЗОЧУТЛИВОСТІ
ДВОКОМПОНЕНТНОЇ СИСТЕМИ НА ОСНОВІ АТОМІВ Au І Fe**

О. В. Пилипенко, Л. В. Одноворець, М. О. Шумакова, І. Ю. Проценко

Представлено результати дослідження диференціального і інтегрального коефіцієнтів поздовжньої тензоцутливості в області пружної і пластичної деформацій у тонких плівках товщиною 20...40 нм, отриманих одночасною конденсацією атомів Au і Fe. Дифракційні і електронно-мікроскопічні дослідження вказують на те, що і в інтервалі концентрацій до 55 ат.% Fe стабілізує ГЦК-неупорядкований твердий розчин (Au), а при концентраціях 55...85 ат.% Fe – ОЦК-твердий розчин (α -Fe). Структурний перехід супроводжується диспергуванням кристалічної структури, як наслідок цього, збільшенням ефективності зерномежового розсіювання електронів. Це спричиняє аномальне збільшення інтегральної величини коефіцієнта тензоцутливості (від 2 до 80 одиниць) в інтервалі концентрацій 55...75 ат.% Fe.