Functional Materials 6, No.5 (1999)

Contribution of the grain-boundary and surface scattering of conductivity electrons to the size effect of tensosensibility

O.B.Lasyuchenko, I.Yu.Protsenko, A.M.Chornous

Sumy State University, 2 Rimskogo-Korsakova St., 40007 Sumy, Ukraine

Received December 27, 1999

Theoretical relations have been obtained allowing to estimate the contribution of volume, surface and grain boundary scattering electrons of cjnductivity to the longitudinal tensosensibility coefficient of metal films. These contributions can be additively presented as $\gamma = C_1\gamma_{0l} + C_2\gamma_{gbl} + C_3\gamma_{dl}$ where C_1–C_3 are the statistical weights of individual components. The relationships derived have been proven taking Cr, Co, Ni and Cu thin films as examples.

Получены теоретические соотношения, позволяющие оценить вклад объемного, поверхностного и зернограничного рассеяния электронов проводимости в величину коэффициента продольной тензочувствительности металлических пленок. Показано, что эти вклады можно представить аддитивно таким образом: $\gamma = C_1\gamma_{0l} + C_2\gamma_{gbl} + C_3\gamma_{dl}$, где C_1–C_3 — статистический вес отдельных слагаемых. Полученные соотношения апробированы на примере тонких пленок Cr, Co, Ni и Cu.

Study of the size effect in the field of thin metal films tensosensibility (see, for example, [1]) allow to conclude that the absolute value of the longitudinal tensosensibility coefficient (γ_1) is defined mainly by the internal size effect electron scattering on grain boundaries while the dependence on thickness, by the external one (the scattering on the outer film surfaces). However, quantitative correlations between γ_t components connected with the scattering of electrons on grain boundaries, are still unknown. In contrast to the specific resistance of a thin film (ρ), to which the scattering on phonons and crystal structure defects (ρ_0), on grain boundaries (ρ_{gb}) and on outer surfaces (ρ_d) contribute additively, the correlation between γ_0, γ_{gb} and γ_d is more complicated in the case of tensosensibility. The purpose of the present work is to obtain and to check these correlations.

Proceeding from the definition of the coefficient γ_l, it is possible to write

$$\gamma_l = \frac{1}{\rho}\cdot\frac{d\rho}{d\varepsilon_l} = \frac{1}{\rho}\left(\frac{d\rho_0}{d\varepsilon_l} + \frac{d\rho_{gb}}{d\varepsilon_l} + \frac{d\rho_d}{d\varepsilon_l}\right), \quad (1)$$

where $\rho = \rho_0 + \rho_{gb} + \rho_d = \rho_g + \rho_d$ (ρ_g is specific resistance of the film at $d\to\infty$, i.e. that of a bulk condensate); ε_l, the longitudinal deformation.

Multiplying both left-hand and right-hand parts of (1) by ρ, and multiplying and dividing of each addend in the right part by ρ_0, ρ_{gb} and ρ_d, respectively, the relation (1) is transformed into the form

$$\gamma_l\rho = \gamma_{0l}\rho_0 + \gamma_{gb}\rho_{gb} + \gamma_{dl}\rho_d = \gamma_g\rho_g + \gamma_{dl}\rho_d, \quad (2)$$

where γ_{gl} is the longitudinal tensosensibility coefficient at $d\to\infty$.

A specific additivity rule for the tensosensilility coefficient follows from the last relation

Table 1. Experimental values used in calculations (T = 300 K)

Metal	$\rho_0 \cdot 10^8$, $\Omega \cdot$m [3]	$\rho_g \cdot 10^8$, $\Omega \cdot$m [2]	$\rho_{gb} \cdot 10^8$, $\Omega \cdot$m [2]	γ_{0l}	γ_{gl} [4]	Notes
Cr	13.0	26	12.29	1.0	2.0	γ_{0l} — estimated values
Co	6.5	50	32.70	2.0	3.0	– " –
Ni	7.1	10	1.04	1.5	1.9	– " –
Cu	1.5	1.6	0.19	1.6 [4]	2.2	– " –
Re	21.1	58	15.21	1.5	2.5	γ_{0l}, γ_{gl} — estimated values

$$\gamma_l = \gamma_{0l}\frac{\rho_0}{\rho} + \gamma_{gbl}\frac{\rho_{gb}}{\rho} + \gamma_{dl}\frac{\rho_d}{\rho},$$

where ρ_0/ρ, ρ_{gb}/ρ and ρ_d/ρ are statistical weights of individual addends of the tensosensibility coefficient.

The relation for γ_{dl} has been obtained from (2)

$$\gamma_{dl} = (\gamma_l\rho - \gamma_g\rho_g) \cdot \rho_d^{-1}, \quad (3)$$

where $\rho_d = \rho - \rho_0 - \rho_{gb}$ — is the fraction of the film specific connected with the electron scattering on the surface.

According to [2], the value ρ_g at a specified temperature can be calculated from the relation

$$\rho_{gb}(T) = (\beta_g\rho_g - \beta_0\rho_0)T + (\rho_g(0) - \rho_0(0)) \quad (4)$$

where β is the temperature coefficient of the film resistance; $\rho_g(0)$ and $\rho_0(0)$, the specific resistance of the bulk condensate and the single crystal at $T \to 0$ K, respectively.

To find γ_{gbl}, it is necessary to make use of the relation for $\rho_g = \rho_0 + \rho_{gb}$. After derivation with respect to deformation and the transformations similar to (1) and (2), it is possible to write

$$\gamma_{gl} \cdot \rho_g = \gamma_{0l} \cdot \rho_0 + \gamma_{gb} \cdot \rho_{gb}, \quad (5)$$

where γ_{0l} and ρ_0 are tensosensibility coefficients and specific resistance of the single crystal (in calculation, we will use the data for recrystallized polycrystalline samples [3]).

From (5), we obtain

$$\gamma_{gb} = (\gamma_{gl} \cdot \rho_g - \gamma_{0l} \cdot \rho_0) \cdot \rho_{gb}^{-1}. \quad (6)$$

The relation between γ_{gbl} and γ_{dl} is obtained from (3) and (6):

$$\frac{\gamma_{gbl}}{\gamma_{dl}} = \frac{(\gamma_{gl} \cdot \rho_g - \gamma_{0l} \cdot \rho_0) \cdot \rho_d}{(\gamma_l \cdot \rho - \gamma_{gl} \cdot \rho_g) \cdot \rho_{gb}}. \quad (7)$$

From (5), we can find also the quantity $\dfrac{\partial\rho_d}{\partial\varepsilon_l}$:

$$\frac{\gamma_l}{\gamma_{gl}} = \frac{1}{\rho}\left(\rho_g + \frac{1}{\gamma_{gl}} \cdot \frac{\partial\rho_d}{\partial\varepsilon_l}\right), \quad (8)$$

$$\frac{\partial\rho_d}{\partial\varepsilon_l} = \left(\frac{\gamma_l \cdot \rho}{\gamma_{gl}} - \rho_g\right) \cdot \gamma_{gl}. \quad (9)$$

Using both own [4] and literary [2, 3] data, we have estimated the quantities γ_{dl}, γ_{gbl} and relative contributions of electron scattering on surfaces and grain boundaries to the γ_l value. The initial data for the estimation are presented in Table 1. It is to note especially that experimental values of γ_{gl} and γ_l are obtained with a change of resistance during deformation while it is just γ_l, γ_{dl} values connected with specific resistance that are used in operating relations hips. The recalculation γ_{gl} and γ_l was carried out using the relation

$$(\gamma_l)_R = (\gamma_l)_\rho + 1 + 2\mu_f,$$

where μ_f is the Poisson coefficient for the film material in calculations, values for massive materials were used [3]. Note that, since data on γ_{0l} values, except for Cu are absent in literature, those were estimated basing on the correlation presented in [2]. The calculated results for T = 300 K are shown in Tables 2 and 3.

The calculations performed allow to make the following conclusions. The contribution of volume electron scattering to the tensosensibility coefficient increases with growing thickness, while that of the

Table 2. Estimation of γ_{dl} and γ_{gbl} values for thin films

Film	d, nm	$\rho \cdot 10^8$, $\Omega \cdot m$ [2]	$\rho_d \cdot 10^8$, $\Omega \cdot m$	γ_l [5,6]	$\gamma_l - 1 - 2\mu_f$	μ_f [3]	γ_{dl}	γ_{gbl}	$\left\lvert \frac{\gamma_{gbl}}{\gamma_{dl}} \right\rvert$	$\frac{\partial \rho_d}{\partial \varepsilon_l} \cdot 10^8$, $\Omega \cdot m$
Cr	36	56.7	30.7	3.80	2.2	0.30	2.37	3.1	1.34	72.74
	60	40.8	14.8	2.25	0.65		−1.72		1.84	−25.48
	76	37.5	11.5	2.10	0.50		−2.89		1.10	−33.25
	100	35.0	9.0	2.05	0.45		−4.03		0.79	−36.25
	200	30.8	4.3	2.05	0.45		−8.87		0.36	−38.14
Co	45	94.0	44.0	6.0	4.38	0.31	5.49	4.19	0.7	261.72
	60	74.8	24.8	6.0	4.38		7.16		0.58	177.62
	110	69.6	19.6	5.7	4.08		6.84		0.61	133.97
Ni	37	11.4	1.4	27.5	25.86	0.32	197.00	8.03	0.04	275.8
	83	10.7	0.7	10.0	8.36		100.65		0.08	88.00
	75	3.6	2.0	3.5	1.8		1.48		3.98	2.96
	130	3.1	1.5	2.4	0.7		−0.90		6.55	−1.35
	380	1.6	0.01	2.2	0.5		−272.0	0.02	−2.72	
Re	100	69.7	11.7	2.5÷3.0	0.98÷1.48	0.26	−6.56÷−3.58	7.45	1.14÷2.08	−76.69−÷−41.84

Table 3. Statistical weight of addends of the longitudinal tensosensibility coefficient

Film	d, nm	ρ_0/ρ	ρ_{gb}/ρ	ρ_d/ρ
Cr	36	0.23	0.22	0.54
	60	0.32	0.30	0.36
	76	0.35	0.33	0.31
	100	0.37	0.35	0.26
	200	0.42	0.40	0.14
Co	45	0.07	0.35	0.47
	60	0.09	0.44	0.33
	110	0.09	0.47	0.28
Ni	37	0.62	0.90	0.12
	83	0.66	0.10	0.07
Cu	55	0.38	0.05	0.62
	75	0.42	0.05	0.56
	130	0.48	0.06	0.48
	380	0.94	0.12	0.01
Re	100	0.30	0.22	0.017

grain boundary scattering remains essentially the same at any thickness. As to the contribution of surface scattering, there is a trend to decrease of γ_{dl} value with the subsequent sign inversion for Cr, Cu and Re. From the physical point of view, a negative γ_{dl} value means that starting from a certain thickness, the surface electron scattering does not cause a tensoeffect, and even, on the contrary, cancels the increase of the resistance volume addend at the film deformation.

References

1. S.V.Petrenko, I.E.Protsenko, V.G.Shamonya, *Metally*, **1**, 180 (1989).
2. S.I.Protsenko, A.N.Chornous, *Vopr.Atomn. Nauki i Tekhn.*, **2(10)**, 107 (1999).
3. Physico-Chemical Properties of Elements: A Reference Book. Ed. By V.G.Samsonov, Naukova dumka, Kiev (1965) [in.Russian].
4. E.B.Lasyuchenko, I.E.Protsenko, *Vopr.Atomn. Nauki i Tekhn.*, **2(10)**, 94 (1999).
5. I.E.Protsenko, A.N.Chornous, *Metallofiz. i Noveishie Tekhn.*, **16(18)**, 18 (1994).
6. Yu.M.Ovcharenko, N.M.Opanasyuk, I.E.Protsenko et al., *Ukr.Fiz.Zh.*, **42(7)**, 19 (1999).

Внесок зернограничного і поверхневого розсіювання електронів провідності у розмірний ефект тензочутливості

Одержано теоретичні співвідношення, які дозволяють оцінити вклад об'ємного, поверхневого і зернограничного розсіювання елктронів провідності у величину коефіцієнту повздовжньої тензочутливості металевих плівок. Показано, що ці внески можна представити адитивно таким чином $\gamma = C_1\gamma_{0l} + C_2\gamma_{gbl} + C_3\gamma_{dl}$, де C_1–C_3 — статистична вага окремих доданків. Одержані співвідношення були апробовані на прикладі тонких плівок Cr, Co, Ni і Cu.