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Electron characteristics of chromium layers produced under various technological conditions

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The electron characteristics of chromium layers, i.e., the concentration and the collision frequency of conductivity electrons have been estimated on the basis of the said optical constants. The measurements of resistivity of the examined layers carried out both in the room temperature and in the helium temperature, as well as the measurements of density together with earlier determination of the optical constants allow to determine both the collision frequency of the conductivity electrons with phonons in both static field and the field of high optical frequency and the collision frequency of the conductivity with dopings. The average dimensions of crystallits and the average free path conductivity electrons have been estimated.

1. Introduction

When the optical constants (n, k) of chromium layers in the wide spectral range (0.2–25 μm) [1] and the electric conductivity in both room and helium temperature are known, it is possible to determine the electron microcharacteristics of the layers examined. The technology of layer production has been described in [1]. The layer thickness ranged from 150 to 200 nm. The layers were evaporated onto the substrate of fused quartz of various temperatures (35–600°C). The deposition rate was being altered from 1 Å/s to 50 Å/s.

2. Results of examinations

On the basis of the known optical constants of the examined chromium layers the spectral dependence of the real $\varepsilon_1 = n^2 - k^2$ and virtual $\varepsilon_2 = 2nk$ parts of the electric permittivity, and the spectral dependence of the optical conductivity $\sigma = 2nk\omega\varepsilon_0$ of the examined chromium layers have been calculated (Fig. 1). The existence of the absorption band has been stated for all the examined layers obtained under various technological conditions (evaporation rate: 1–50 Å/s, substrate temperature: 37, 200, 300, 400, 500 and 600°C). The maximum of this band appears for energies of about 2 eV in the visible range of the spectrum irrespective of the layer evaporation rate v and the substrate temperature T_s. However, the optical transmittivity increases with the increasing substrate temperature for the layers obtained at higher substrate

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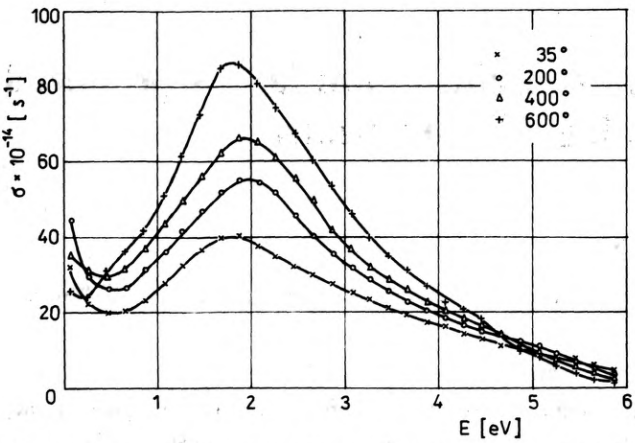

Fig. 1. Spectral dependence of the optical conductivity σ for the chromium layers evaporated at the rate $v \sim 20$ Å/s onto the heated substrate of different temperatures

temperature, and forming of the absorption and is then more distinct. This is connected with structural changes. The structural examinations pointed out that with the increase of substrate temperature the sizes of crystals creating the polycrystalline layer increase from about 20 Å for $T_s = 35°C$ to about 1000 Å for $T_s = 600°C$.

For the spectral range, in which ε_1 and ε_2 change monotonically with the increasing wave frequency, the intraband transitions of conductivity electrons are of decisive significance. Within this range the formulae determining the optical properties of the transition metals have the forms [2], [3]:

$$\varepsilon_1(\omega) = n^2 - k^2 = 1 - \frac{\Omega^2}{\omega^2 + \gamma^2} + \varepsilon_1',$$

$$\varepsilon_2(\omega) = 2nk = \frac{\Omega^2 \gamma}{\omega(\omega^2 + \gamma^2)} + \varepsilon_2'$$

where: $\Omega^2 = \dfrac{Ne^2}{m\varepsilon_0}$,

N – conductivity electron concentration,

γ – collision frequency for electrons,

m – electron mass,

ε_1', ε_2' – contributions from the quick relaxing electrons ($\gamma \gg \omega$).

In order to calculate the elctron collision frequency γ, the dependence of $\varepsilon_2\omega$ on the $1-\varepsilon_1$ should be plotted [4], [5]. The slope of the straight line segment allows to calculate immediately the effective electron collision frequency γ (Fig. 2). After calculation of the value Ω the plasma vibration γ may be determined. For this purpose, the dependence of $1-\varepsilon_1$ on $(\omega^2+\gamma^2)^{-1}$ should be plotted for the calculated value of γ. The slope of the straight line $1-\varepsilon_1 = f(\omega^2+\gamma^2)^{-1}$ defined Ω^2 (Fig. 3).

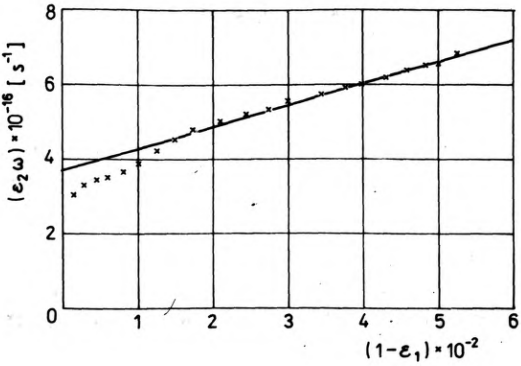

Fig. 2. Dependence of ε_2 on $1-\varepsilon_1$ for the chromium layers evaporated in the temperature $T_s = 200°C$

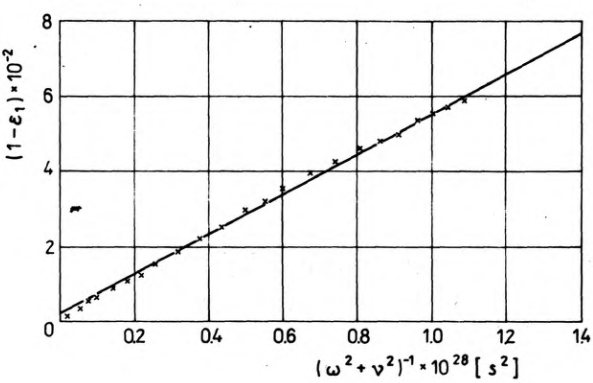

Fig. 3. Dependence of $1-\varepsilon_1$ on $(\omega^2+\gamma^2)^{-1}$ for the chromium layers evaporated in the temperature $T_s = 200°C$

From the obtained values Ω the values of concentration of conductivity electrons have been calculated using the formula

$$\Omega^2 = Ne/m\varepsilon_0.$$

The results of calculations of electron characteristics of N and γ of the chromium layers are collected in Tab. 1.

Table 1

T_s[°C]	$N\times10^{-21}$ [cm^{-3}]	$\gamma\times10^{-14}$ [s^{-1}]
35	0.96	0.51
200	1.19	0.56
400	1.13	0.54
500	1.07	0.51

The effective electron collision frequency γ may be represented as a sum of component frequencies [5]

$$\gamma = \gamma_{ep} + \gamma_{ed}.$$

In this sum, the interelectron frequency of collisions γ_{ee} has been omitted, which in the room temperature is less than γ_{ep} and γ_{ed} by several orders of magnitude (where γ_{ep} – frequency of electron-phonon collisions, γ_{ed} – that of electron-doping collision).

In order to estimate the components of this sum, the measurements of static conductivities ϱ_{st} and ϱ_r of the examined chromium layers at the room and helium temperatures, respectively, have been performed.

The measurements of electric resistance of the chromium layers obtained under various technological conditions have been carried out on the chromium meanders produced by the photolitographic method with evaporated gold contacts. The measurement results have been collected in Tab. 2.

Table 2

T_s[°C]	35	200	400	600
$\varrho_{st} \times 10^8 [\Omega m]^{-1}$	59.5	54.8	47.8	39.7

The measurements of electric resistance of the examined layers at the helium temperature allowed us to determine the residual resistivity ϱ_r the mean value of which for the chromium layers amounted to

$$\varrho_r = 16.4 \times 10^{-8} [\Omega m].$$

Knowing the residual value of ϱ_r, the electron-doping collision frequency may be calculated on the basis of the following formula:

$$\gamma_{ed} = \varrho_r e^2 N/m$$

where the value of the conductivity electrons density N is determined from the optical measurements. The calculated collision frequency of electron-doping type for the layers examined amounted to

$$\gamma_{ed} = 0.05 \times 10^{-14} [s^{-1}],$$

which constitutes about 10% of the effective frequency of collisions ($\gamma = 0.55 \times 10^{14} s^{-1}$).

On the basis of the known γ and γ_{ed} the average free path for the conductivity electrons (l) as well as the average sizes of crystallites (L) have been estimated for the layers using the formulae:

$$l = \langle v_f \rangle / \gamma \quad \text{and} \quad L = \langle v_f \rangle / \gamma_{ed}$$

where $\langle v_f \rangle$ is the average electron frequency on the Fermi surface. The average conductivity electron frequency on the Fermi surface $\langle v_f \rangle$ has been estimated from

the known density of the examined layers $d_w = 6.411$ g/cm^3 by assuming that the valence for Cr is 3. The calculated value of the average velocity of the conductivity was $\langle v_f \rangle = 1.5 \times 10^5$ m/s, the average free path and the sizes of crystallites are $l = 2.8 \times 10^{-9}$ m and $L = 30 \times 10^{-9}$ m, respectively. These results seem to be reasonable.

Knowing the resistivity ϱ_{st} of the examined layers at the room temperature and the residual resistivity ϱ_r, it is possible to determine the classical frequency of electron collisions with phonons γ from the following formula:

$$\frac{\varrho_r}{\varrho_{st}} = \frac{\gamma_{ed}}{\gamma_{ep}^{cl} + \gamma_{ed}}.$$

The obtained results for γ have been collected in Tab. 3, where the values of the electron-phonon collision frequency calculated from the optical measurements are given for the sake of comparison.

Table 3

T_s[°C]	35	200	400	600
$10^{-14}\gamma_{ep}^{cl}$ [s^{-1}]	0.13	0.12	0.09	0.07
$10^{-14}\gamma_{ep}$ [s^{-1}]	0.46	0.51	0.49	0.47

As it follows from Table 3, there occurs a high discrepancy between the frequency of collision electrons and phonons in the static fields (γ_{ep}^{cl}) and that in the fields of optical frequency (γ_{ep}) the latter being always several times (from 5 to 7) higher. Similar discreapancies were observed by another authors [6]–[8]. Even a joining factor has been calculated theoretically by GURZHY [7]. The attempts to estimate this factor resulted in the value 1.4 which provides no explanation of the discrepancies observed. It might be more suitable to apply a double-band model of conductivity for the chromium layers since the Fermi surface for Cr is formed by the carriers belonging to two conductivity bands (s and d), while only one type of carrier has been taken into account in our considerations; the quick-relaxing carriers are neglected. The estimations in this direction are intended.

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Электронные характеристики плёнок хрома, полученных в различных технологических условиях

На основе оптических постоянных исследуемых плёнок хрома в широкой области спектра определялись электронные характеристики этих плёнок, т.е. концентрация, а также частота соударений электронов проводимости. Измерения удельного сопротивления исследуемых плёнок как в комнатной, так и в гелиевых температурах а также измерения их плотности совместно с оптическими постоянными дали возможность определить частоту соударений электронов проводимости с фонами в статических и оптических полях. На основе этих измерений определена также частота соударений электронов проводимости с примесями. Проведена оценка размеров кристаллов и средней длины свободного пробега электронов проводимости.