

Optical Constants of Non-Transparent Chrome Layers for Wavelengths of 0.22–25 μm

The reflection factor of opaque chrome layers has been measured for wavelengths of 0.22–25 μm. The integral $\varphi^k(\omega)$ determining the contribution of measurable frequencies (0.22–25 μm) to the phase of the reflected wave has been calculated from the Kronig–Kramers dispersion formulae. The remaining phase components $\Delta\varphi(\omega)$, which determine the contribution from unmeasurable frequencies, have been calculated from known optical constants of the layers in the narrow frequency range 0.4–2.2 μm. Optical constants for opaque chrome layers in the wavelength region 0.22–25 μm have been calculated on the basis of the measured reflection factor R and calculated phase $\varphi(\omega) = \varphi_k + \Delta\varphi$.

1. Calculation of the phase shift at reflection

The method of finding the optical constants of metals based on the measurement of reflection factor R for normal incidence has been widely used recently. The method makes use of the Kronig–Kramers dispersion formulae and requires the measurement of the reflection factor of the studied metal within a wide range of wavelengths. Details of the method can be found in the monograph by STERN [1] and several other authors, including [2–4].

The amplitude reflection factor r for normal incidence upon the studied metal may be written as:

$$r = \frac{n+ik-1}{n+ik+1} = |r|e^{i\varphi}, \quad (1)$$

where:

$R = |r|^2$ — the energy reflection factor, and φ — phase change at reflection, n and k — the optical constants of metal.

The complex function r may be written as:

$$\ln r = \ln |r| + i\varphi. \quad (2)$$

For the $\ln r$ function we obtain the Kronig–Kramers dispersion formulae which relates the real and imaginary parts of the $\ln r$ function

$$\varphi(\omega) = -\frac{\omega}{\pi} \int_0^{\infty} \frac{\ln R(x) dx}{x^2 - \omega^2}. \quad (3)$$

Formula (3) allows to calculate the phase change at reflection when the energy reflection factor $R(\omega)$ has been measured in the $0 - \infty$ frequency range.

Since the measurements of $R(\omega)$ are always performed within the limited frequency range $\omega_1 \leq \omega \leq \omega_0$, the phase of the reflected wave (3) may be written as a sum of two components

$$\varphi(\omega) = \varphi_k(\omega) + \Delta\varphi(\omega). \quad (4)$$

The first of the two expressions

$$\varphi_k(\omega) = -\frac{\omega}{\pi} \int_{\omega_1}^{\omega_0} \frac{\ln R(x) dx}{x^2 - \omega^2} \quad (5)$$

can be calculated by the numerical integration method [5] using a computer. The expression $\varphi_k(\omega)$ deter-

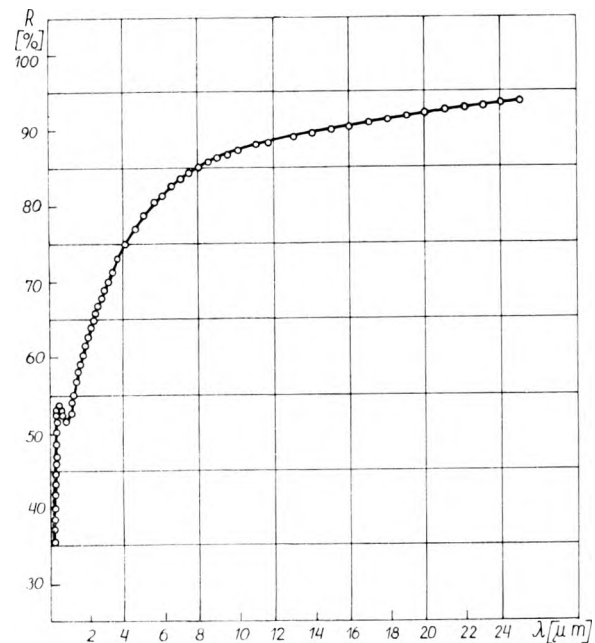


Fig. 1. Spectral dependence of the reflection factor R for non-transparent chrome layers

* Instytut Fizyki Technicznej Politechniki Wrocławskiej, 50-370 Wrocław, Wybrzeże Wyspiańskiego 27, Poland.

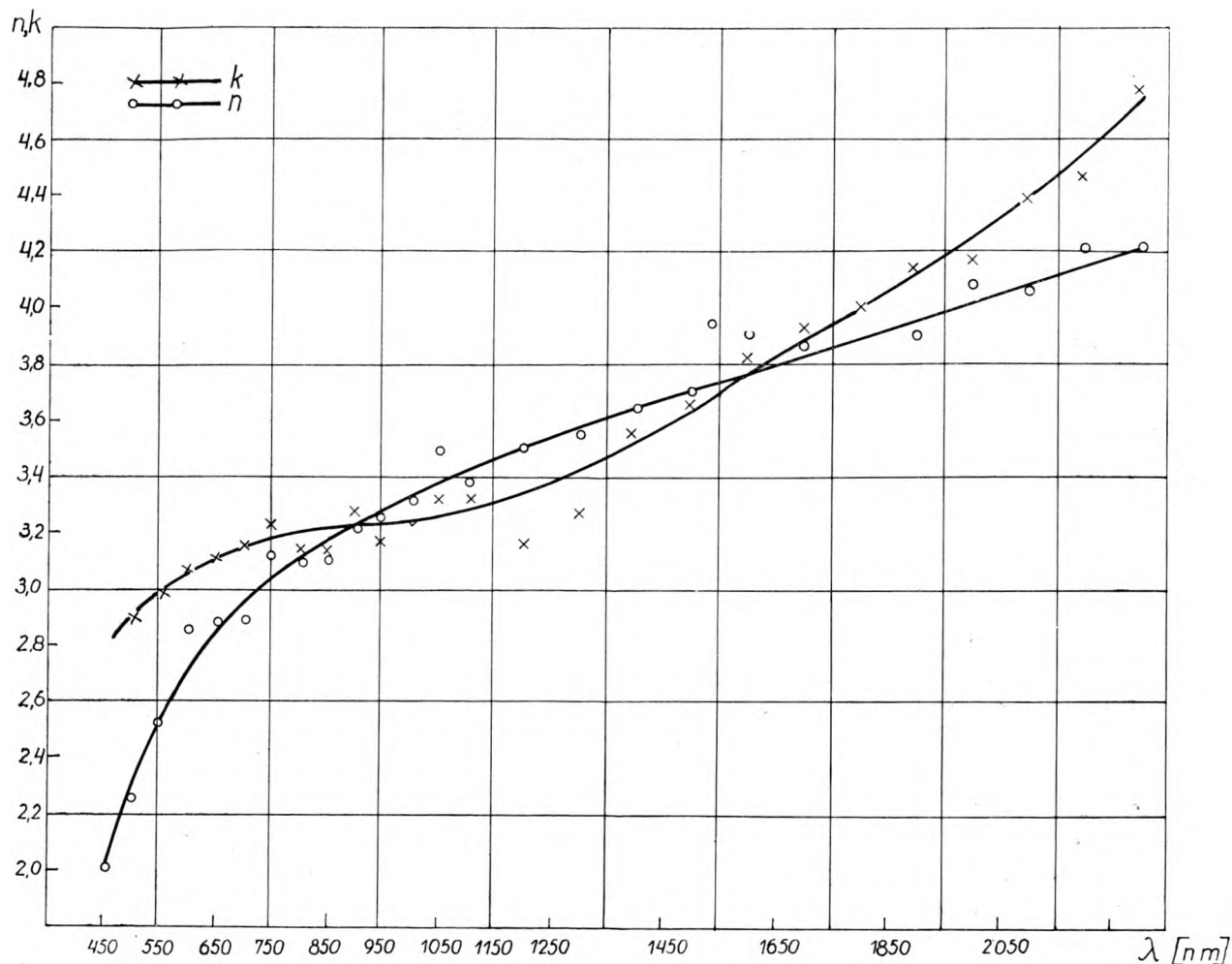


Fig. 2. Spectral dependence of optical constants of chrome layers determined by the polarization method

mines the phase of the reflected wave which results from the limited range of the $R(\omega)$ measurement.

The remaining phase terms may be written

$$\Delta\varphi(\omega) = -\frac{\omega}{\pi} \int_0^{\omega_1} \frac{\ln R(x) dx}{x^2 - \omega^2} - \frac{\omega}{\pi} \int_{\omega_0}^{\infty} \frac{\ln R(x) dx}{x^2 - \omega^2} \approx -\frac{\omega}{\pi} \int_{\omega_0}^{\infty} \frac{\ln R(x) dx}{x^2 - \omega^2}$$

When the measurements of $R(\omega)$ are performed within the range 0.05–5 eV, then the expression

$$-\frac{\omega}{\pi} \int_0^{\omega_1} \frac{\ln R(x) dx}{x^2 - \omega^2}$$

will be very small ($R \approx 1$, and

the integration range $\omega < \omega_1$ very small) for the visible and infra-red range [6] and may be omitted during the calculation of $\Delta\varphi(\omega)$.

Thus:

$$\Delta\varphi(\omega) = -\frac{\omega}{\pi} \int_{\omega_0}^{\infty} \frac{\ln R(x) dx}{x^2 - \omega^2} \quad (6)$$

The principle difficulty arises when it is necessary to calculate $\Delta\varphi(\omega)$, because the function $R(\omega)$ is not known in the unstudied frequency range. Some investigators calculate $\Delta\varphi(\omega)$ on the basis of a presumable character of function $R(\omega)$, although this is unjustified and may lead to serious errors in the calculation of phase $\varphi(\omega)$ [7]. Others propose to choose an appropriate integration range. This is, however, possible only when narrow reflection bands occur in the spectrum. In paper [6] the expression $\Delta\varphi(\omega)$ is calculated as $\Delta\varphi(\omega) = \varphi_1 - \varphi_k$, where φ_1 — phase of the reflected wave calculated from well known optical constants for two wavelengths.

A detailed analysis of the expression $\Delta\varphi(\omega)$ is carried out in paper [5]. It asserts that the contribution to the phase of the reflected wave given by $\Delta\varphi(\omega)$ depends on the character of function $R(\omega)$

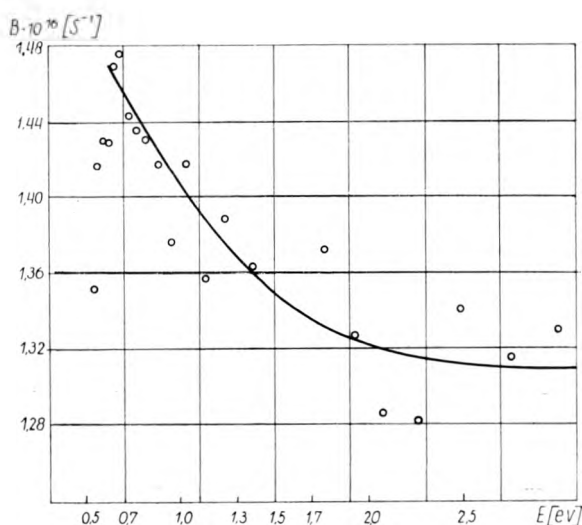


Fig. 3. Frequency dependence of the coefficient B for chrome layers. The solid line corresponds to the mean value of $B = 1.31 \cdot 10^{-16}$ s used for calculation of the reflected wave phase

in a very narrow frequency range $\omega \geq \omega_0$. For metals, in which no rapid changes in $R(\omega)$ are observed in the region of $\omega \approx \omega_0$, the expression may be calculated from the formula:

$$\Delta\varphi(\omega) = B\omega \left[1 + \frac{1}{3} \left(\frac{\omega}{\omega_0} \right)^2 \right]. \quad (7)$$

The coefficient B in (7) is determined as a mean value of the quantity B being averaged over the spectral range of waves

$$B = \frac{\varphi_{\text{exp}} - \varphi_k}{\omega} \quad (8)$$

for which the phase of the reflected waves is known exactly. Phase φ_{exp} may be calculated from known optical constants n, k measured in that region by the polarization method. Thus the phase shift at a reflection from the studied metal can be determined according to the formula:

$$\varphi(\omega) = \varphi_k(\omega) + B\omega \left[1 + \frac{1}{3} \left(\frac{\omega}{\omega_0} \right)^2 \right]. \quad (9)$$

Rearranging expression (1) we obtain the following formulae for the optical constants of metals:

$$k = \frac{2\sqrt{R} \sin \varphi}{1 - 2\sqrt{R} \cos \varphi + R}, \quad (10)$$

$$n = \frac{1 - R}{1 - 2\sqrt{R} \cos \varphi + R}. \quad (11)$$

By using the measured reflection factor $R(\omega)$ of the studied metal and the calculated phase shift $\varphi(\omega)$ at

reflection (9) for that spectral region one may calculate the optical constants of metals from formulae (10) and (11).

The described method may also be used to calculate the optical constants of non-transparent metal layers. The optical constants of non-transparent chrome layers within the wavelength region 0.22–25 μm have been calculated in accordance with this method.

2. Technology of obtained layers and the method of measurement

The studied chrome layers were formed in Edward's apparatus at the mean speed of 1 nm/s and a pressure lower than 10^{-4} mm Hg from a wolfram heater. The layers were evaporated onto rectangular glass plates made of BK-7. The plates were placed at a distance of 26 cm and rotated during the evaporation [9].

The reflection factor thus obtained for non-transparent chrome layers was measured at the air-facing surface in the wavelength region 0.22–25 μm [10]. The measurements were performed at normal incidence using the all-purpose VSU 1 Zeiss spectrometer with a reflective attachment in the wavelength range 0.22–25 μm and the UR-20 spectrometer for

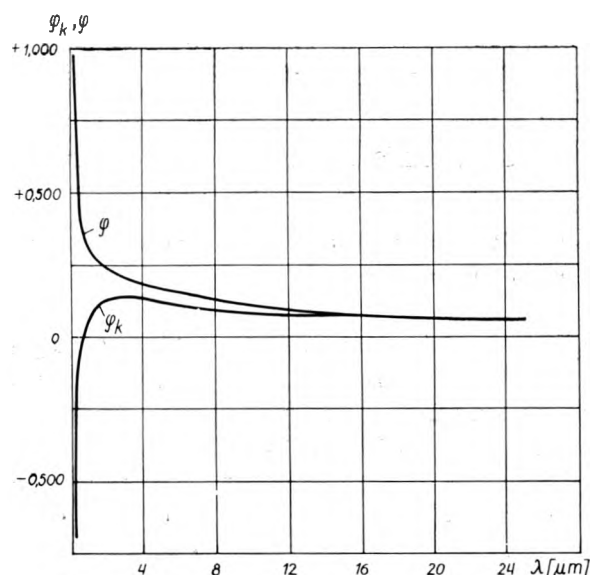


Fig. 4. Spectral dependence of the reflected wave phase φ for chrome layers
 φ_k — phase calculated from the Kronig-Kramer formula in the limited range of R measurement;
 φ — phase calculated with allowance for the remaining phase component

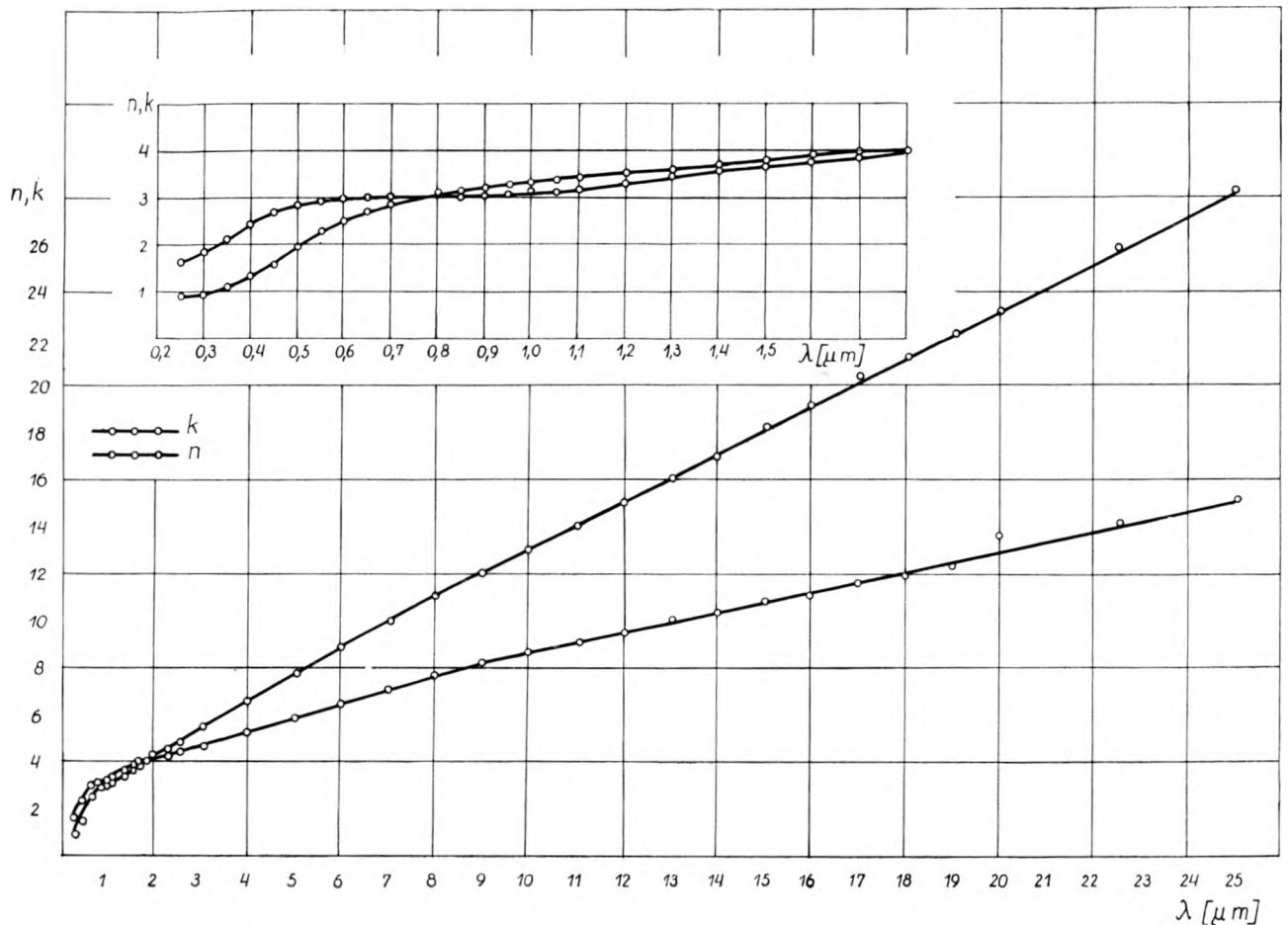


Fig. 5. Spectral dependence of optical constants of non-transparent chrome layers

the region 2–25 μm . The thickness of the studied layers was of the order of 1500 \AA , determined by the interferometric method.

3. Results of the measurements

The mean values of the measured reflection factor R for non-transparent chrome layer in the wavelength region 0.22–25 μm have been presented in fig. 1. On the basis of the measurements of $R(\omega)$ the integral $\varphi_k(\omega)$ determining the contribution into the phase of the reflected wave due to the measured frequencies (0.22–25 μm) have been calculated in the respective range, using an electronic computer. In order to compute the remaining phase components $\Delta\varphi(\omega)$, it is necessary to know the optical constants of the studied layers. The optical constants n , and k in the region 0.4–2.2 μm , of the chrome layers have been determined for this purpose by the Beattie's polarization method [11] (fig. 2). Control measurements of optical constants of the layers carried out by the

Shklyarevsky–Miloslavsky polarization method [12] in the wavelength range 0.45–0.65 μm gave consistent results (fig. 2). The optical constants of chrome layers in the wavelength range 0.4–2.2 μm were measured in the Physical Optics Department at Charkov University USSR.

The coefficient B (fig. 3) has been calculated by utilizing the experimentally determined optical constants of chrome layers for wavelengths of 0.4–2.2 μm . Having obtained B , the remaining components of the reflected phase could be found using formula (7), and then the phase of the reflected wave $\varphi(\omega)$ (fig. 4).

The optical constants n and k of non-transparent chrome layers have been calculated for the broad frequency range (0.22–25 μm) from the formulae (10) and (11) on the base of the measurements of the reflection coefficient $R(\omega)$ and the previously estimated phase difference.

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Оптические постоянные непрозрачных плёнок хрома в диапазоне волн 0,22—25 мкм

Измерен был коэффициент отражения непрозрачных плёнок хрома в диапазоне волн 0,22—25 мкм. Из дисперсионных соотношений Кронига-Крамерса рассчитан был интеграл $\varphi_k(\omega)$, определяющий внесённую часть в фазу отражённой волны измеряемых частот (0,22—25 мкм). Остальной член фазы $\Delta\varphi(\omega)$, определяющий внесённую часть неизмеряемых частот, рассчитан был из известных оптических постоянных этих же плёнок в узком диапазоне частот 0,4—2,2 мкм. На основе измеренного коэффициента отражения R и рассчитанной фазы $\varphi(\omega) = \varphi_k(\omega) + \Delta\varphi$ вычислены были оптические постоянные непрозрачных слоёв хрома в диапазоне волн 0,22—25 мкм.

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