radiation electrical field; d_{mn}, dipole moment matrix element; k, wave vector of the light wave; Ω, retuning from resonance equal to the difference between the light frequency ω and transition frequency ω_{mn}; η, viscosity coefficient.

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HIGH REFLECTIVITY COATINGS USED IN CRYOVACUUM TECHNOLOGY

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UDC 536.3

A method is proposed for calculating the absorption capability of crysosystem reflective surfaces and reducing such absorption to the theoretical minimum.

In connection with developments in cryovacuum technology, a need has recently arisen for creation of metallic surfaces which are highly reflective at low temperatures.

The numerous experimental data collected in [1] permit the conclusion that vacuum deposition is one of the most promising methods for production of high reflectivity coatings. Encouraging results have already been obtained with this technique. Adsorption factor values of $6.5 \cdot 10^{-3}$ and $7.2 \cdot 10^{-3}$ for silver films deposited in a vacuum were announced in [2]. Values of $6 \cdot 10^{-3}$ for Al and $5.5 \cdot 10^{-3}$ for Cu were obtained in [3] for deposition in a helium flow.

To optimize the choice of metal and the conditions under which the reflective coating is prepared a strict analysis of the dependence of reflectivity on those electrophysical parameters of the film which determines its optical absorption is necessary. However the anomalous skin effect theory which is currently generally accepted for description of the optical properties of metals at low temperature is not very useful in practical applications because of the extreme cumbersomeness and complexity of the integrodifferential equations which form its mathematical base. Therefore in [4]* and later in [5-8] a relatively simple method was developed, sufficient for an exact analytical description of metal properties over a wide spectral and temperature range, including helium temperatures, based upon a physically clear piecewise-continuous approximation of the spectral dependence of absorption for various modifications of the skin effect.†

Such an approach allowed quantitative explanation of various absorption data [2, 3] for reflective coatings of cryovacuum systems without use of any empirical relationships as well as proposal of physically clear criteria for choice of metal and film preparation conditions. Moreover, limiting theoretical minimum absorption values were calculated for various metals and temperatures.

A comparison of experimental (in the given case, from [3]) and calculated absorption values (Table 1) shows satisfactory agreement.

*We will note that an arithmetical error was introduced into the calculations of [4], resulting in lowered values of absorption capability.

†Programs have been written which permit calculation of absorption for various metals and temperatures.

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TABLE 1. Calculated (p = 0) and Experimental Absorption (A) Values

Metal	Calc. values		Exptl. values	
	ρ_{ei}, Ω·cm	A·10³	ρ, Ω·cm	A·10³
Cu	10^{-6}	8,8	10^{-8}	5,7
	10^{-10}	5,4		
Al	10^{-6}	7,6	10^{-7}	3,6
	10^{-10}	3,5		
Ag	10^{-6}	4,7	$7 \cdot 10^{-9}$	4,2
	10^{-10}	3,6		

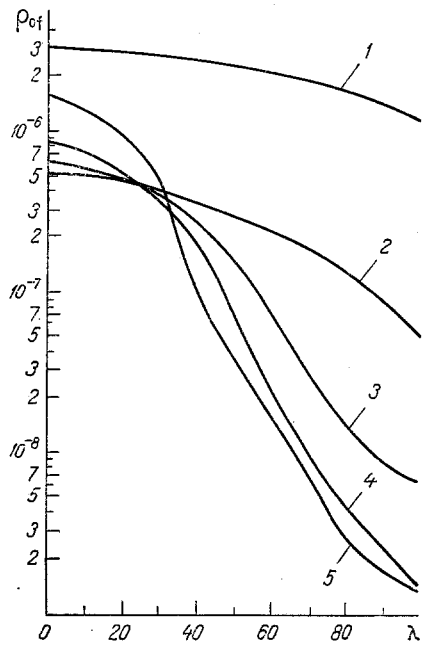

Fig. 1. Quantity ρ_{of} (Ω·cm) vs λ (μm) for various metals at temperature 4.2 K: 1) Pb; 2) Au; 3) Ag; 4) Cu; 5) Al.

Analysis of the proposed expressions permits derivation of criteria for selection of a metal at concrete temperatures of the radiating (see below) and receiving surfaces. The analysis is based on the existence of a contribution of absorption which is not negligible with decrease in temperature from electron scattering on phonons excited by the incident radiation [9]. The dependence of the corresponding component of hf electrical resistivity (ρ_{of}) on wavelength (λ) for various metals is shown in Fig. 1, from which it follows that to obtain minimum absorption it is necessary to choose that metal whose ρ_{of} has the lowest value at $\lambda = \lambda_{max}$, where λ_{max} is determined by Winn's law [10]. The corresponding change in absorption is illustrated in Table 2. For example, use of Al in place of Ag for a surface located in the equilibrium radiation field of a cavity at T = 300 K leads to an increase in absorption by 1.7 times.

The existence of this electrical resistance component which is not negligible as temperature decreases permits formulation of a simple condition for the weak effect on absorption of electron scattering on impurities and lattice defects (the corresponding component of electrical resistivity is ρ_{ei}):

$$\rho_{ei} \leqslant \rho_{ei}^{*} = \rho_{0f}^{*}, \tag{1}$$

where $\rho_{of}^{*} = \rho_{of}|_{\lambda = \lambda_{max}}/10$.

Corresponding calculated absorption values confirm the validity of condition (1). The values of ρ_{of}^{*} for copper at λ_{max} = 35 μm (radiating surface temperature 78 K) is equal to $1.5 \cdot 10^{-7}$ Ω·cm. Experiment shows that copper films obtained by vacuum deposition at a residual gas pressure of $P = 1 \cdot 10^{-3}$ Pa, deposition rate V_{dp} = 300 Å/sec, substrate temperature 100-400°C have $\rho_{ei} \approx 8 \cdot 10^{-9}$ Ω·cm. Consequently further improvement of experimental conditions directed toward decreasing ρ_{ei} values of the copper condensates does not lead to a drop in absorption.

TABLE 2. Absorption Values for Various ρ_{of}^{*}; Radiating Surface Temperature 300 K ($\lambda_{max} \approx$ 10 μm), Receiving Surface 4.2 K, ρ_{ei} = $2 \cdot 10^{-10}$ Ω•cm

Metal	ρ_{of}, Ω•cm	p	$A \cdot 10^3$
Al	$1,2 \cdot 10^{-6}$	0	7,8
		1	4,7
Ag	$4,9 \cdot 10^{-7}$	0	4,5
		1	1,92
Cu	$6,2 \cdot 10^{-7}$	0	5,4
		1	2,96

TABLE 3. Minimum Possible Calculated Absorption Values; $\rho_{ef} = 2 \cdot 10^{-10}$ Ω•cm, T_1, T_2, Temperature of Radiating and Receiving Surfaces

Metal	p	T_1, K	T_2, K	$A \cdot 10^3$
Cu	0	300	78	5,56
	1			3,06
	0	78	4,2	3,7
	1			3,64
Ag	0	300	78	4,76
	1			2,1
	0	78	4,2	3,58
	1			3,42
Al	0	300	78	7,78
	1			4,51
	0	78	4,2	3,52
	1			3,05

An approach to minimal theoretical absorption values (see below) upon achieving $\rho_{ei} < \rho_{ei}^{*}$ is possible by increasing the parameter p which characterizes the specularity of electron reflection from the external boundaries of the film. This parameter is determined by the mean square roughness (r_r) of the film surface [11], and also, as experimental studies have shown, by the film grain size (D) and the degree of perfection of its structure. For $r_r <$ 200 Å p increases with decrease in r_r, which agrees qualitatively with the data of [11] and is explainable by the same theoretical considerations. For 200 Å < r_r < 600 Å p is close to zero. For film condensation conditions corresponding to formation of large, quite perfect single-crystal grains, which naturally leads to abrupt increase in film roughness, the locally specular reflection of electrons from the surface of the grain–single-crystals proposed in [4] is achieved and p increases to a value of 0.98.

Experiment has shown that one such preparation variant is film deposition in a flow of pure helium with appropriate choice of V_{dp} and t_s^o. It is obvious that the limitingly high value of p is the cause of the low absorption of films prepared by this technique.

Analysis has shown that the effect of other film electrophysical parameters appearing in the computation expressions, such as electron concentration, electron velocity at the Fermi level, etc., is insignificant as compared to the effect of those considered above.

Condition (1) permits calculating the minimum theoretically possible absorption values for various temperatures and metals. These values correspond to absorption values (Table 3) at $\rho_{ei} = 2.2 \cdot 10^{-10}$ Ω•cm, since this value of $\rho_{ei} \ll \rho_{ei}^{*}$ for all the metals considered.

We will note in passing that the one extremely low absorption value among the experimental data, equal to $6 \cdot 10^{-4}$ presented in [12], apparently requires further verification, first, because it is not supported by the results of similar experiments presented in [3], and second, because it lies below the minimum possible absorption value.

As for the experimental dependence of absorption on resistivity ρ obtained in [3], the calculations presented for $\rho \leq 10^{-7}$ Ω•cm (i.e., for the ρ values most interesting for producing high reflectivity coatings) show agreement of calculated and experimental absorption values

equal to $(3.6\text{-}5.7)\cdot10^{-3}$ (Table 1), which in contrast to absorption values at $\rho \geq 10^{-7}$ $\Omega\cdot$cm are strictly speaking not described by the empirical expression relating absorption and ρ proposed in [3].

A more accurate calculation than that performed in compiling Table 1 will not be performed, since values of ρ_{ei} and p are not given in [3]. This also makes it impossible to use the data presented for a strict analysis of the dependence of absorption on film electrophysical properties.

NOTATION

ρ_{of}, electrical resistivity caused by electron scattering on phonons excited by hf electromagnetic radiation; λ, radiation wavelength; ρ_{ei}, electrical resistivity caused by electron scattering on impurities; P, residual gas pressure in vacuum chamber; V_{dp}, rate of film deposition on substrate; t_s^o, substrate temperature; D, grain size (correlation length); r_r, mean square surface roughness; p, parameter characterizing degree of specularity of reflection from film surface.

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