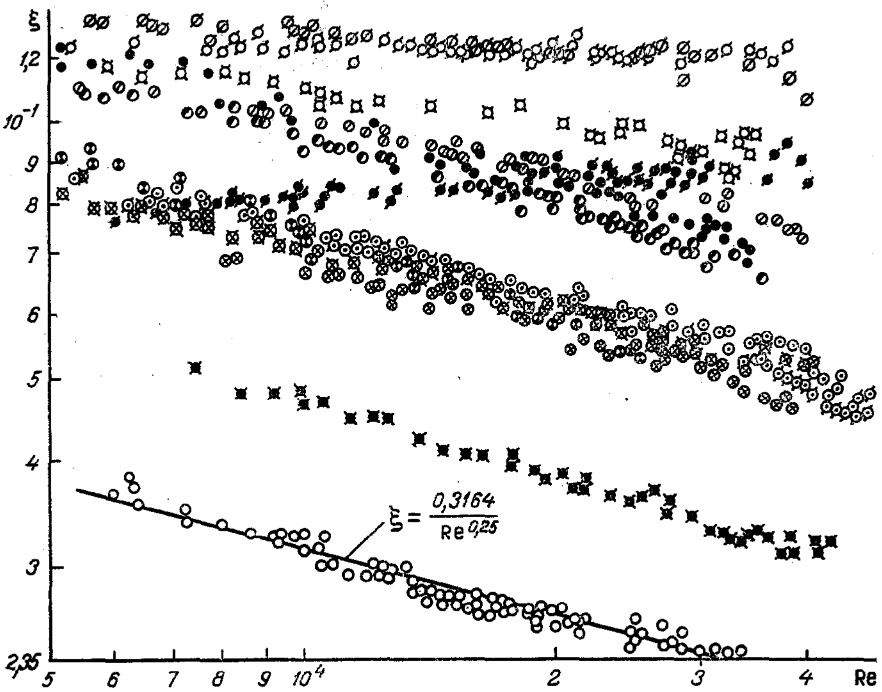

Fig. 4. Hydraulic resistance in contractor-diffusor type tubes; point notation the same as in Fig. 2.

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CALCULATION OF THE INTEGRATED COEFFICIENTS OF ABSORPTION AND TRANSMISSION OF SOLAR RADIATION FOR SEMICONDUCTOR FILMS

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UDC 535.341:535.345.1:539.216.2

A method is described for calculating the absorption and transmission of solar radiation by thin semiconductor films as a function of the thickness of the films. Computational results are presented.

Photoelectric transducers based on thin semiconductor films appear to be most promising for solar power, since they will be able to provide a higher electricity output per unit weight than single-crystalline cells. To calculate the efficiency and thermal stability of such transducers it is necessary to determine the integrated optical characteristics of the films. The experimental measurement of solar integrated coefficients of absorption, reflection, and transmission involves significant difficulties and cannot always be performed. In addition, films with different thickness are characterized by different optical coefficients, since these coefficients themselves depend on the thickness of the films.

Knowing the values of the refractive and absorption indices n and k in a wide spectral range it is possible to calculate the integrated coefficients of absorption and transmission

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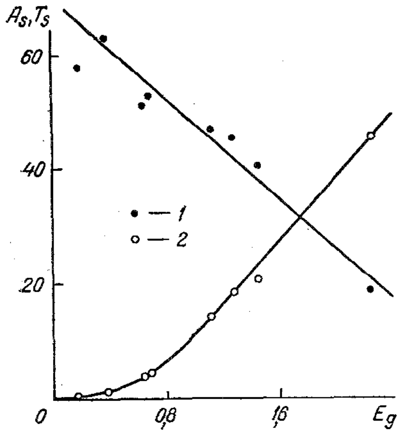

Fig. 1 Integrated absorption A_s (1) and transmission T_s (2) coefficients of the film versus the gap width of the semiconductors for a film thickness of 500 μm. A_s, T_s, %; E_g, eV.

of solar radiation A_s and T_s for any semiconductor material, but the fact that multiple reflections of the light rays on all optical boundaries of the film-substrate system must be taken into account significantly complicates these calculations, even in the case of monochromatic radiation.

The integrated coefficient of absorption A for radiation with the spectral energy density e_ν is calculated from the spectral absorption coefficient A_ν by integration:

$$A = \int_0^\infty A_\nu e_\nu d\nu \Big/ \int_0^\infty e_\nu d\nu. \quad (1)$$

The exoatmospheric solar spectrum is approximated well by the radiation spectrum of an absolute black body with the temperature T_0 = 5630.7°K [1]. Under the given conditions

$$A_s = \frac{2\pi h}{\sigma c^2 T_0^4} \int_0^\infty A_\nu \nu^3 \left[\exp\left(\frac{h\nu}{k_B T_0}\right) - 1\right]^{-1} d\nu. \quad (2)$$

The spectral absorption coefficient of the film is determined from the relation $A_\nu = 1 - R_\nu - T_\nu$. The spectral reflection and transmission coefficients R_ν and T_ν for a film on a transparent substrate for normal incidence of the radiation can be obtained by summing the amplitudes of the coherently reflected and transmitted rays [2]. Then the coefficients T, R, and R' are expressed as follows:

$$T = \left| \frac{t_1 t_2 \exp(-i\gamma d)}{1 + r_1 r_2 \exp(-2i\gamma d)} \right|^2, \quad (3)$$

$$R = \left| \frac{r_1 + r_2 \exp(-2i\gamma d)}{1 + r_1 r_2 \exp(-2i\gamma d)} \right|^2, \quad (4)$$

$$R' = \left| \frac{r_2 + r_1 \exp(-2i\gamma d)}{1 + r_1 r_2 \exp(-2i\gamma d)} \right|^2, \quad \gamma = \frac{2\pi}{\nu}(n - ik). \quad (5)$$

The indices 1 and 2 refer to the front and back surfaces of the film, respectively. Equations (3) and (4) can be generalized for a thin film on a transparent substrate of finite thickness, taking into account the multiple reflection of light in the substrate [2]:

$$R_\nu = R + \frac{T^2 R_0}{1 - R_0 R'}, \quad (6)$$

$$T_\nu = \frac{T(1 - R_0)}{1 - R_0 R'}, \quad R_0 = \left(\frac{1 - n_s}{1 + n_s}\right)^2. \quad (7)$$

TABLE 1. Dependence of the Integral Coefficients of Absorption A_s (1) and Transmission T_s (2) of Solar Radiation [%] on the Thickness of the Semiconductor Films

d, μm	InSb		InAs		Ge		GaSb	
	1	2	1	2	1	2	1	2
0,01	15,4	36,4	12,2	44,2	12,9	35,1	13,3	37,3
0,05	31,9	22,9	29,4	30,2	25,2	25,3	27,1	26,3
0,10	37,7	18,1	38,0	23,0	30,3	21,2	32,5	21,8
0,50	48,1	9,10	55,3	7,70	42,3	11,3	44,4	11,8
1,00	51,3	6,35	59,3	4,05	46,2	7,89	48,1	8,47
5,00	55,6	2,50	62,4	1,07	50,3	4,13	52,5	4,52
10,0	56,6	1,62	62,6	0,89	50,6	3,81	52,9	4,11
50,0	57,8	0,56	62,7	0,86	50,7	3,76	53,0	4,03
100,0	58,0	0,34	62,7	0,86	50,7	3,76	53,0	4,03

d, μm	Si		InP		GaAs		GaP	
	1	2	1	2	1	2	1	2
0,01	3,63	50,4	7,87	51,3	7,31	48,6	3,00	58,4
0,05	6,75	48,0	20,1	41,4	16,3	41,4	4,21	56,0
0,10	8,85	46,4	27,1	35,4	21,2	37,4	7,41	54,8
0,50	16,6	40,2	42,2	21,9	33,7	26,7	10,5	52,1
1,00	21,0	36,6	45,0	19,3	37,5	23,2	11,5	51,3
5,00	32,6	26,8	45,8	18,4	40,4	20,5	14,6	48,6
10,0	37,3	22,7	45,8	18,4	40,4	20,5	16,1	47,4
50,0	45,4	15,5	45,8	18,4	40,4	20,5	18,1	45,5
100,0	47,1	13,9	45,8	18,4	40,4	20,5	18,3	45,3

For a fused quartz substrate it may be assumed that $n_s = 1.5$ and $k_s = 0$ in the entire spectral range.

To calculate R_ν and T_ν using the formulas (6) and (7) it is necessary to know the values of n and k in the widest possible spectral range. Data for A^3B^5 type semiconductors, as well as germanium and silicon, in the interval 1.5-6 eV are presented in [3]. The values of the optical constants for the range 0-1.5 eV were determined by extrapolating the values of n and k corresponding to the absorption edge on the energy scale:

$$n = a - \frac{b}{h\nu - f}, \quad \lg k = mh\nu + g.$$

In so doing only the characteristic absorption of the semiconductors was taken into account, i.e., the refractive index was assumed to equal zero at energies less than the gap width.

According to our estimates, the relative fraction of the solar radiation in the energy range above 6 eV equals only 0.35%, so that the upper limit of integration in the expression (2) can be replaced by 6 eV. The numerical integration in accordance with (2) was carried out with a step of 0.5 eV, which corresponds to the data of [3]. The calculations were performed for films 0.01-500 μm thick with a uniform step on a logarithmic scale. The results of the calculations are presented in Table 1. The expression for T_s is analogous to the expression (2).

One can see from Table 1 that the integral coefficients for different materials no longer vary for film thicknesses from 5 to 100 μm. The optical properties of films 500 μm thick no longer differ from those of the crystals.

It should be noted that the formulas (3)-(7) are valid for commensurate radiation wavelengths and thicknesses of the layer only for uniform films. In this case the uniformity of the medium means that the change in the dielectric constant at distances comparable to the wavelength of the radiation is small. Therefore the computed values of A_s and T_s for films up to 1 μm thick can differ significantly from the experimentally determined values.

The effect of the gap width of the semiconductor on A_s and T_s is shown in Fig. 1. It should be noted that the dependence $A_s(E_g)$ is approximated well by a straight line, while $T_s(E_g)$ is also approximated well by a straight line at energies above 1 eV. Since the integrated absorption and transmission coefficients are related to the individual properties of the films and substrates, the presented dependences on the gap width are of an approximate, qualitative character. They enable estimation of the integrated coefficients of absorption, reflection, and transmission of solar radiation for other semiconductor materials using the gap width known for them.

NOTATION

A_S and T_S, integrated coefficients of absorption and transmission of solar radiation; n and n_S, refractive indices of the film and substrate; k and k_S, absorption coefficients of the film and substrate; A, integrated absorption coefficient; ν, radiation frequency; A_ν, R_ν, T_ν, spectral absorption, reflection, and transmission coefficients; T_0, temperature of an absolute blackbody; h, Planck's constant; σ, Stefan–Boltzmann constant; c, velocity of light in a vacuum; T, coefficient of transmission of light through a film into an infinitely thick substrate; r and t, Fresnel coefficients; d, thickness of the film; R and R', coefficients of reflection of light incident on the film from its free surface and from the substrate; R_0, reflection coefficient of the substrate; a, b, f, g, and m, extrapolation constants; E_g, gap width; and γ, absorption coefficient of the film.

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EMISSIVITY OF ALUMINOSILICATE REFRACTORIES

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UDC 536.5

Experimental data was obtained on the dependence of the emissivity of refractories on temperature and chemical composition.

Industry currently produces and uses about 50 grades of aluminosilicate refractories. The content of the main components, alumina and silica, is usually regulated in these refractories. Since the refractories are made by different plants, the content of other oxides differs significantly and causes an appreciable change in the radiative properties of the products. Most experimental studies [1] have covered a limited range of refractory grades. No detailed analysis has therefore been made of the effect of chemical composition on the emissivity of refractories. There have also been no studies of the emissivity of refractories upon heating in air to temperatures above 1600°K.

The present article reports results of a study of the integral normal emissivity of different grades of aluminosilicate refractories (see Table 1) in relation to their chemical composition and temperature during heating in air in the temperature range 600-2100°K and during heating in vacuum, with a vacuum pressure to 10^{-3} mm Hg, in the temperature range 600-1800°K. The refractory specimens were bars measuring 35 × 35 × 3 mm or 40 × 40 × 5 mm, depending on the grade of refractory. The roughness parameters of the specimens were measured on an MIS-11 binary microscope.

The emissivity of the specimens in air was measured by the radiation method on the unit described in [2]. Here, the specimens were heated to 900°K by a tubular resistance furnace, while they were heated to temperatures in the range 900-2100°K by the flame from an oxygen–propane burner. The measurement of the radiant surface of the specimens was measured with Chromel–Alumel thermocouples with a thermoelectrode diameter of 0.2 mm. The measurements at the higher temperatures were obtained with PR-30/6 platinum-rhodium thermocouples. The thermocouples were placed in a groove so that they were located 0.4 and 0.8 mm from the surface and were covered with a layer of refractory paste. The layer of paste was applied so that it was flush with the radiant surface of the specimen. The temperature of the radiant surface was determined by extrapolating the thermocouple readings to the lowest level of the thermocouples in the specimen.

The main component of the unit used to measure the emissivity of the refractories in vacuum during heating (Fig. 1) was a vacuum chamber 1 which contained a molybdenum heating

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Kazan Institute of Chemical Engineering. Translated from Imzhenerno-Fizicheskii Zhurnal, Vol. 53, No. 3, pp. 406-411, September, 1987. Original article submitted May 27, 1986.

0022-0841/87/5303-1027$12.50