Analysis of reflected radiation from a semitransparent mirror of silicon carbide

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Abstract: Within the adapted McMahon theory optical properties of flat mirror based single crystal SiC is researched. The method of assessment share of tinted radiation in total reflected from mirror flow with effect thermal radiation wide spectrum in condition high temperature is offered and tested for polytypes mirror on based 6H-SiC<6> for temperature 293K and 800K.

Introduction
Interest in the research of heterogeneous systems of the reflective type based on silicon carbide (SiC) is at present predominantly stimulated by the further development of power optics, for example, within the development and use of powerful special-purpose lasers, as well as television industrial safety systems resistant to a number of aggressive factors [1-5]. Being a typical representative of refractory semiconductor materials with optical transparency, SiC at the same time stands out among them a whole set of such competing properties as abrasive, chemical and radiation resistance, high thermal conductivity, etc. [6,7]. The listed properties are technologically manageable, both due to the possibility of doping the starting material with various impurities (basic diffusion and ion implantation processes), and due to the well-known phenomenon of polytypism caused by the layered structure of SiC at the level of nanosize and realized in crystallization processes [8,9]. The noted advantages of SiC most fully meet the criteria of optical quality when creating input windows and objective-lens and especially mirrors of a wide range of applications [10-12]. Thus, in [3] the possibility of using a "hot" SiC mirror of a small thickness in the television endoscope for obtaining images of objects under extreme conditions is shown. For a number of technical applications of such endoscopic systems, narrow-band heat-resistant mirrors are of particular interest. Within the framework of this approach, the problem arises of determining the degree of the influence of the color of a semitransparent SiC mirror on the color of the reflected radiation when a wide spectrum of radiation is exposed to it under high-temperature conditions. At present, some works are known, partially addressing this problem for some optical materials, for example [13].

The present work is devoted to the solution of this problem.

Research methodology
When developing the research methodology, plate-like single crystals of silicon carbide, whose color properties are presented in Table 1, were considered as prototypes of mirrors.
Pure silicon carbide with hexagonal structure is colorless crystals with diamond shine. The color of the material depends on the raw material and technology of obtaining crystals and is determined by the type and amount of impurity, and the degree of deviation of the composition from the stoichiometric. SiC can have a variety of colors: white, gray, yellow, green and black [6]. Studies of SiC heterogeneous reflecting systems were carried out within the framework of the adapted theory of MacMagon [14, 15]. In this case the geometric model shown in Figure 1 was used. In this model, a semitransparent mirror, which is in thermodynamic equilibrium with the source of thermal radiation at high temperature \( t \), has the following properties: \( R(\lambda, t) \) - reflection coefficient from the mirror surface, \( T(\lambda, t) \) - transmittancy. The mirror is colored in a certain color, that is, the intensity of its transmission is maximal at a certain wavelength \( \lambda \). At it at an angle, the radiation from the object with intensity \( I_\lambda \) falls. Quantitative estimation of the color content in the reflected radiation was carried out by determining the proportion of the colored radiation \( k_{col}(\lambda, t) \) in the total reflected. At the same time, the possibility of using a color translucent material as a narrow-band mirror was justified by the criterion \( k_{col}(\lambda, t) \rightarrow 100\% \).

**Table 1.** Color properties of some silicon carbide polytypes [6].

| Polytype | Dopant impurity | Color         |
|----------|-----------------|---------------|
| 3C       | pure            | yellow        |
| 3C       | nitrogen (N)    | yellow-green  |
| 8H       | nitrogen (N)    | yellow-orange |
| 6H       | pure            | colorless     |
| 6H       | nitrogen (N)    | green         |
| 6H       | aluminum        | blue - purple |
| 15R      | nitrogen (N)    | pale green    |
| 4H       | pure            | colorless     |
| 4H       | nitrogen (N)    | light brown   |
| 24R      | nitrogen (N)    | purple        |
| 27R      | nitrogen (N)    | red           |
Figure 1. Optical-geometric model of light interaction with a semitransparent SiC mirror.

Then the fraction of the colored radiation is determined from the expression:

\[ k_{col}(\lambda,t) = \frac{I_o(\lambda,t)}{I_{col}(\lambda,t)} \cdot 100\% \]  

(1)

Where: \( I_{otr}(\lambda,t) \) - the intensity of the reflected radiation from the semitransparent mirror, \( I_o(\lambda,t) \) - the intensity of the colored radiation. In general, the intensity of the reflected radiation of the translucent material \( I_{otr}(\lambda,t) \) will be composed of the intensity of the mirror reflected by the surface \( I_{pov}(\lambda,t) \) and transmitted through the mirror as a result of internal reflection \( I_{vn}(\lambda,t) \):

\[ I_{otr}(\lambda,t) = I_{pov}(\lambda,t) + I_{vn}(\lambda,t) \]  

(2)

Proceeding from the MacMahon theory, equality (2) in a more complete form was given by the expression [14]:

\[ I_{otr}(\lambda,t) = I_o(\lambda,t) \cdot R(\lambda,t) + \sum_{m=1}^{m=\infty} \frac{I_o(\lambda,t) \cdot (1 - R(\lambda,t))^2}{R(\lambda,t)} \cdot (R^2(\lambda,t) \cdot T^2(\lambda,t))^m \]  

(3)

where: \( m \) - the number of reflections, \( T(\lambda,t) \) - the transmittance is:

\[ T(\lambda,t) = \exp(-k(\lambda,t) \cdot d) \]  

(4)

\( d \) - plate thickness, \( k(\lambda,t) \) - crystal absorption coefficient.

The intensity of the radiation reflected from the surface of the crystal was considered a constant value, independent of the color of the material. Since within the visible spectrum the change in wavelength slightly affects the refractive index, the monochromatic reflection coefficient \( R(\lambda,t) \) remains practically unchanged, and the color of the rays reflected by the transparent colored materials does not change.

Expression (3) was used in the calculation as follows:
\[ I_{\text{int}}(\lambda, t) = I_A \cdot R(\lambda, t) - \frac{I_A \cdot (1 - R(\lambda, t))^2 \cdot R(\lambda, t) \cdot T^2(\lambda, t)}{1 - R^2(\lambda, t) \cdot T^2(\lambda, t)} \]  

(5)

The radiation intensity after passing through the material layer due to internal reflection will be maximum at wavelength \( \lambda \) corresponding to the color range of the material, while radiation of other wavelengths will be absorbed rather intensively, that is, it can be written:

\[ I_{\text{in}}(\lambda, t) = I_{\text{wn}}(\lambda, t) \]  

(6)

Due to the fact, that the intensity of radiation weakens, passing through the material, it will be less than the intensity of radiation reflected from the surface. To determine the radiation fraction, we substitute the values of \( I_{\text{int}}(\lambda, t) \) and \( I_{\text{wn}}(\lambda, t) \) from (5) in (1):

\[ k_{\text{col}}(\lambda, t) = \frac{x}{x+1} \cdot 100\% \]  

(7)

where \( x = \frac{(1 - R(\lambda, t))^2 \cdot T^2(\lambda, t)}{1 - R^2(\lambda, t) \cdot T^2(\lambda, t)} \)  

(8)

It should be noted that this technique is adapted to the influence of only thermal radiation, while using a narrow-band light source, as is well known, can lead to the imposition of spectra. To determine the color in such cases, special diagrams are used [13].

The results of the research and their discussion

Consider the effect of the color of a heat-resistant mirror made of semitransparent single-crystal SiC on the color of the reflected radiation. Figure 2 shows graphs of the theoretical dependences of the transmission coefficient \( T(\lambda, t) \) for SiC crystals on the wavelength of the radiation: colorless, green and blue colors.

\[ \text{Figure 2. Spectral dependence of the transmittance of a flat SiC mirror of colorless (1), green (2), and blue (3) color. The thickness of the plate crystal is } d = 0.1 \text{ mm.} \]

To calculate the numerical values \( T(\lambda, t) \), the well-known technique was used [15], taking into account the SiC absorption coefficients according to [16]. It is well known that due to the doping of the most widespread and sufficiently studied 6H polytype with nitrogen during the growth process, the...
color of the SiC crystal acquires a green tint (Table 1). That is, the maximum of its transmission falls on the green region of the spectrum. The remaining radiation with wavelengths of the visible spectrum is absorbed quite intensively. The studies carried out for this case using the Fresnel formula [13] showed (Fig. 3) that the intensity of the reflected radiation from the surface of the flat mirror 6H-SiC <N> in a wide range of wavelengths remains practically constant.

Figure 3. Dependence of the reflectivity of the surface of a planar 6H-SiC <N> mirror on the wavelength of the radiation. The thickness of the mirror is d = 0.1 mm, $N_d^* N_a = 4 \times 10^{18} \text{cm}^{-3}$.

The scientific and practical interest in the problem being solved is the influence of the angle of incidence of radiation relative to the reference surface of the 6H-SiC <N> mirror on the spectral composition of the reflected radiation. As follows from the geometric model, Figure 1), the radiation reflected from the inner surface will be colored and spatially separated from the non-color radiation reflected by the outer surface. Since the reflection coefficient of the surface is constant in the visible range and the transmittance has a maximum at a wavelength of 0.5 μm, only the intensity of the light of the inside of the crystal affects the increase in the fraction of the colored reflection. Due to the shift of the absorption coefficient to the long-wave part of the spectrum with increasing temperature, an analogous shift in the dependence of the fraction of the reflected radiation is observed. Examples of the results of the study are shown in Figure 4.
Figure 4. Dependence of the proportion of the colored radiation in the total reflection from the radiation wavelength at different temperatures for a planar 6H SiC <N> mirror. The thickness of the mirror is \(d = 0.1 \text{ mm}\), \(N_d - N_a = 4 \times 10^{18} \text{cm}^{-3}\). The angle of incidence of radiation is 0 grad. 1 - T=293K, 2 – T=800K.

Conclusions
The proposed analytical expression allows one to adequately calculate the fraction of the reflected radiation of a partially transparent SiC heterogeneous system at the wavelength characterizing its transmission maximum at high temperatures. The fraction of the colored radiation in general reflected for flat mirrors based on 6H-SiC <N> crystals of green color with thickness \(d = 0.1 \text{ mm}\) is less than <30%, therefore the color of the reflected radiation will depend almost completely on the color of the incident radiation. With increasing temperature of a plane mirror based on a 6H-SiC <N> crystal, the spectral dependence of the reflected radiation shifts to the long-wavelength region of the spectrum.

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