

V.F. Zinchenko<sup>1</sup>, G.V. Volchak<sup>1</sup>, O.V. Mozkova<sup>2</sup>, O.H. Yeriomin<sup>1</sup>, P.H. Doha<sup>1</sup>

## Effect of B<sub>2</sub>O<sub>3</sub> Addition on Optical Properties of Zirconium and Hafnium Tetrafluorides in Polycrystalline and Thin Film States

<sup>1</sup>O.V. Bogatsky Physico-Chemical Institute of National Academy of Sciences of Ukraine, Odesa, Ukraine, [vfzinchenko@ukr.net](mailto:vfzinchenko@ukr.net)  
<sup>2</sup>State Enterprise for Special Instrument Making «Arsenal», Kyiv, Ukraine, [olgamozk@ukr.net](mailto:olgamozk@ukr.net)

For the first time, the effect of B<sub>2</sub>O<sub>3</sub> additive on the IR transmission spectra of ZrF<sub>4</sub> and HfF<sub>4</sub> samples and the optical properties of the coatings obtained from them was investigated. A significant difference in the shape of the absorption bands and the position of the vibration peaks of the Zirconium tetrafluoride and Hafnium tetrafluoride bonds was revealed. An assumption is made about the influence of ZrF<sub>4</sub> polymorphism on the ratio of the vapor pressures of the specified compounds in the region of the conditional temperature of evaporation in a deep vacuum. The positive effect of the B<sub>2</sub>O<sub>3</sub> additive on the rate of evaporation of system samples and condensation on substrates is shown. The values of the refractive indices of the coatings are about 1.53. An exception is the refractive index of the HfF<sub>4</sub> coating (1.57), which can be attributed to the alternative (monoclinic) syngony of its crystal structure.

**Keywords:** Zirconium tetrafluoride, Hafnium tetrafluoride, B<sub>2</sub>O<sub>3</sub> additive, IR transmission spectra, thermal evaporation in vacuum, coating, refractive index.

Received 24 December 2022; Accepted 20 July 2023.

### Introduction

Metal fluorides, in particular MgF<sub>2</sub>, ZrF<sub>4</sub>, HfF<sub>4</sub> and some others, are used as film-forming materials (FFM) in interference optics to obtain coatings with a low refractive index, transparent in the UV range of the spectrum [1-3]. A significant disadvantage of fluoride materials is the presence of impurities of oxides of the metals themselves, which negatively affect the optical and operational properties of the coatings obtained from them. The proposed methods of removing or binding impurities into less active forms [4-6] are quite time-consuming and not always effective. We proposed and successfully implemented in the case of zinc sulfide the use of Boron sesquioxide (B<sub>2</sub>O<sub>3</sub>) additive as a binder of ZnO admixture [7] in a complex zinc borate-type compound. When B<sub>2</sub>O<sub>3</sub> interacts with the admixture, the oxide shell of the grains of the base material is additionally destroyed, which should improve the technological parameters of the process of thermal evaporation of FFM in a vacuum. Research on the influence of B<sub>2</sub>O<sub>3</sub> additive on technological parameters of vaporization of metal

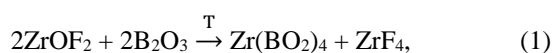
fluorides in vacuum and properties of coatings obtained from them was not carried out. The aim of the work is to study the interaction of B<sub>2</sub>O<sub>3</sub> with oxide impurities in Zirconium (ZrF<sub>4</sub>) and Hafnium (HfF<sub>4</sub>) tetrafluorides and its effect on the properties of materials in crystalline and thin-film states.

It is generally accepted that ZrF<sub>4</sub> has higher volatility (vapor pressure) compared to HfF<sub>4</sub>. At the same time, it is important to evaluate it both in the high-temperature region (boiling or sublimation temperature at P = 1 atm.) and in the region of relatively low temperatures during thermal evaporation in a deep vacuum (P = 10<sup>-5</sup> atm.). The last value is an important technological parameter and it is called the conditional or working temperature of the process of thermal evaporation in a vacuum. At the same time, it should be taken into account that ZrF<sub>4</sub> exists in at least two polymorphic modifications – cubic and monoclinic [8] with a transition temperature of 690°C (according to other data – 450°C [9]).

## I. Methods of synthesis and experimental research

As basic materials – Zirconium and Hafnium tetrafluorides – reagents of the qualification of *puriss.* are used: (VO Vilnohirs'k mining and metallurgical plant, Vilnohirs'k, Dnipropetrovsk region), and as an additive material – Boron oxide – a reagent of qualification of *puriss. spec.* (REAKHIM enterprise, Donetsk).

Samples of the ZrF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> and HfF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> systems weighing of 35 g each were obtained by mixing the initial components (ZrF<sub>4</sub> and HfF<sub>4</sub> with B<sub>2</sub>O<sub>3</sub>) in the ratio provided by the content of the oxygen-containing impurity – the hypothetical compound ZrOF<sub>2</sub> (HfOF<sub>2</sub>) in 10% wt. At the same time, it was considered that the interaction between the impurity and the B<sub>2</sub>O<sub>3</sub> additive occurs according to the following schemes:



According to the calculations, the B<sub>2</sub>O<sub>3</sub> content is about 4.80 %wt. and 3.07%wt. for the ZrF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> and HfF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> systems, respectively.

Samples of the above systems were subjected to heat treatment in a high-temperature tubular (vertical) furnace in an inert gas (helium) medium. The batch was placed in a tube made of quartz glass, and it, in turn, was placed in a sealed reactor made of the same material. Heat treatment was carried out in two stages. The first of them was heated with holding under a shallow vacuum (10<sup>-2</sup> atm.) at a temperature of 450°C for 1 hour. Next, inert gas was introduced to a pressure slightly higher than atmospheric (1.05-1.1 atm.), and the temperature was raised to 750°C, at which the samples were kept for 3 hours until the appearance of a white coating on the cold parts of the reactor. After cooling, the samples of the systems were weighed on analytical balances; mass loss was 0.2286 g, or 0.65 %wt. and 0.2565 g or 0.73 %wt. for the ZrF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> and HfF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> systems, respectively. In terms of the amount of substance that flew out, it is 1.367·10<sup>-3</sup> and 1.008·10<sup>-3</sup> mol, respectively, for the ZrF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> and HfF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> samples. Judging by the latest data, the volatility of ZrF<sub>4</sub> at a temperature of 750°C is significantly higher than that of HfF<sub>4</sub>. The film-forming material ZrF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> (HfF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub>) is a white sintered sample with a slight greyish tint.

The starting reagents, the heat obtained and the residues after thermal evaporation in a vacuum were studied by the method of IR transmission spectroscopy. IR transmission spectra were recorded for the samples pressed into the CsI matrix of the qualification *puriss. spec.* (Institute of Single Crystals of the National Academy of Sciences of Ukraine, Kharkiv), pre-dehydrated by heating at 180°C, in the mass ratio sample: matrix as 1:20. Spectra were recorded on a Frontier Fourier transform spectrophotometer (Perkin-Elmer, USA) in the range of wave numbers ( $\tilde{\nu}$ ) 4000 -200 cm<sup>-1</sup>. All the studied materials were ground in an agate mortar immediately before recording the spectra.

Thin-film coatings were obtained by thermal evaporation (resistive version) in a vacuum on the VU-1A installation and condensation on substrates heated to 200°C, of two types: TF-4 glass (heavy flint, wedge-shaped plate with a wedge angle of 12°) and calcium fluoride (plane-parallel plate 1 mm thick).

The crushed material was placed in a molybdenum evaporator, which was placed in a vacuum unit, evacuated, and the heater was turned on. Evaporation and coating mode: current through molybdenum evaporator – 120 - 140 A; duration of evaporation and coating – 20 -30 min.

The relative volatility of vaporized materials was estimated according to the formula proposed by us earlier [10]:

$$f = \frac{d_{\text{opt.}}}{\tau \cdot I^2 \cdot n}, \quad (3)$$

where  $d_{\text{opt.}}$  – optical thickness, which is a constant value of 2000 nm;  $\tau$  – coating duration, min.;  $I$  is the current through the evaporator, A;  $n$  is the refractive index.

The power of the current was chosen in such a way that the speed of applying coatings from different materials was close to each other.

The refractive index of the coating was determined on a wedge-shaped plate made of TF-4 glass by measuring the reflection coefficient ( $R$ ) from it, determining the extreme values of  $R$  in the interference pattern. It should be noted that the optical ( $d_{\text{opt.}}$ ) and physical ( $d$ ) thicknesses are related by the ratio through  $n$ :

$$d_{\text{opt.}} = n \cdot d, \quad (4)$$

where  $d$  is the physical thickness of the coating.

The optical thickness was determined by the number of minima (maxima) in the interference pattern according to the formula [1]:

$$d_{\text{opt.}} = m \cdot \lambda / 4, \quad (5)$$

where  $m$  is the number of minima (maxima);  $\lambda$  is the wavelength, nm.

Measurements were performed on an Epsilon device (Izovak, Belarus) and calculated using the OptiLayer program. The spectral transmittance curves of the calcium fluoride substrate and the coatings applied to it were recorded using a Shimadzu UV 2501-PS device (Shimadzu, Japan).

## II. Experimental results and their discussion

IR transmission spectra of samples of ZrF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> (a) and HfF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> (b) systems are presented in Fig. 1, and the position of the bands is in Tab. 1.

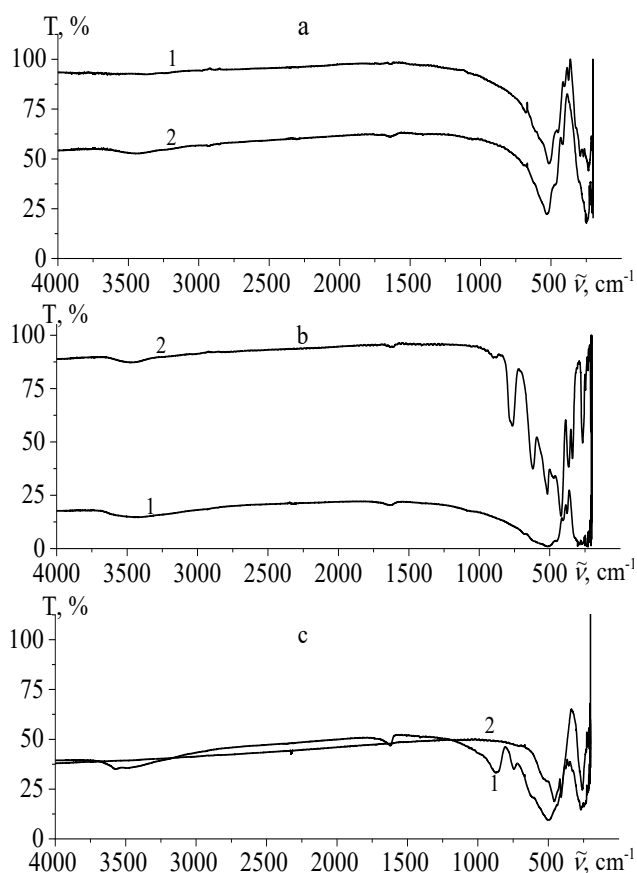
In general, they are quite similar to each other. All of them contain characteristic peaks in the bands corresponding to lattice stretching vibrations of Zr(Hf)-O bonds near 500 cm<sup>-1</sup> and bending vibrations near 250 cm<sup>-1</sup>.

**Table 1**

Positions of absorption peaks on the IR spectra of crystalline Zirconium and Hafnium tetrafluorides

Sample	Wave number, cm <sup>-1</sup>
Initial ZrF <sub>4</sub>	3420 1637 1410 1060 668 <b>515</b> 375* <b>293</b> 270
ZrF <sub>4</sub> , residue after evaporation	<b>3426</b> 2319 <b>1636</b> 1066* 678* 612* <b>515</b> 451* 406 376 285
ZrF <sub>4</sub> -B <sub>2</sub> O <sub>3</sub> , sintered	<b>3568</b> 3487 <b>1622</b> 1411* 873 744 670 609 <b>502</b> 439* 376 355 282* 270 255 238
Initial HfF <sub>4</sub>	<b>3451</b> <b>1644</b> 694* 670 624* <b>531</b> 467* 416 301* 254 248 244 225
HfF <sub>4</sub> , residue after evaporation	3489 1630 901 <b>763</b> <b>619</b> <b>516</b> 470 420 <b>365</b> <b>338</b> <b>266</b>
HfF <sub>4</sub> -B <sub>2</sub> O <sub>3</sub> , residue after evaporation	2328* 707* 531* 514* <b>457</b> 410 259

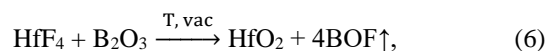
Note: \* – Bend, shoulder. High intensity peaks are highlighted in bold.



**Fig. 1.** IR transmission spectra of samples of the ZrF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> (1) and HfF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> (2) systems: a – initial samples (ZrF<sub>4</sub>, HfF<sub>4</sub>); b – residues after evaporation of ZrF<sub>4</sub>, HfF<sub>4</sub> in a vacuum; c – sintered ZrF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> sample, residue after evaporation of HfF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> in vacuum.

There are also bands of valence and O-H bending vibrations of sorption (crystallization) water, especially for samples based on ZrF<sub>4</sub>. IR spectra of ZrF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> samples reveal bands characteristic of B-O bond oscillations of various types. The transmission spectrum of the residue after evaporation of HfF<sub>4</sub> with a significant number of well-separated peaks of high intensity is interesting. Obviously, in this case, the monoclinic modification of HfF<sub>4</sub> was found in a more or less individual form. The high level of transmission of the

material of this modification in the IR range of the spectrum is also characteristic (twice as high as other samples). At the same time, the level of transmittance of the residue after evaporation of ZrF<sub>4</sub> is extremely low (about 10%), which perhaps indicates the favor of the cubic modification of this FFM sample. In all other cases, there is obviously a mixture of tetragonal (cubic) and monoclinic modifications. The complete absence of vibration peaks of B-O bonds in the transmission spectrum of the residue after evaporation of the HfF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> sample is incomprehensible. Obviously, a reaction occurs between the B<sub>2</sub>O<sub>3</sub> additive and Hafnium fluoride during thermal evaporation in a vacuum according to a possible scheme:



as a result of which the additive is removed by evaporation of the volatile boron-containing product.

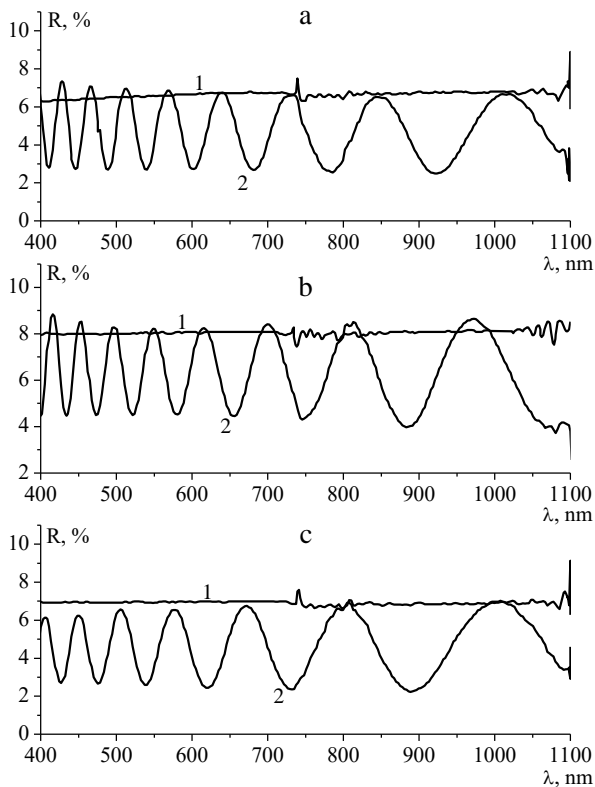
Wedge-shaped substrates made of TF-4 glass (heavy flint) with a high refractive index coated with ZrF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub>, HfF<sub>4</sub>, and HfF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> are obscured optical systems, since the interference pattern is located below the contoured spectral reflectance curve of the substrate.

The spectral characteristics of all systems are very similar to each other, which reflects the proximity of the thicknesses and refractive indices of the coatings and their approximately the same optical heterogeneity. However, certain differences still exist. Thus, in the case of FFM coatings not doped with B<sub>2</sub>O<sub>3</sub> additive, the interference curves slightly cross the reflection characteristic of the substrate, and the number of peaks is somewhat different. The interference curve of the HfF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub> coating slightly bends below the base reflectance curve of the substrate, which indicates greater optical homogeneity of the system.

From the reflection spectra presented in Fig. 2, the optical parameters of the coatings were calculated (Tab. 2). The technological parameters of thermal evaporation of FFM in a vacuum are also given there, from which the evaporation coefficient (volatility) is calculated.

**Table 2**Parameters of thermal evaporation in vacuum and characteristics of coatings of MF<sub>4</sub> (M – Zr, Hf)–B<sub>2</sub>O<sub>3</sub> systems

Sample	I, A	τ, min.	n (λ = 500 nm)	d <sub>opt.</sub> , nm	f · 10 <sup>3</sup> , nm/min · A <sup>2</sup>
ZrF <sub>4</sub>	140	25	1.53	2000	2.66
ZrF <sub>4</sub> –B <sub>2</sub> O <sub>3</sub>	120	30	1.53	2000	3.03
HfF <sub>4</sub>	140	20	1.57	2000	3.25
HfF <sub>4</sub> –B <sub>2</sub> O <sub>3</sub>	120	20	1.53	2000	4.54

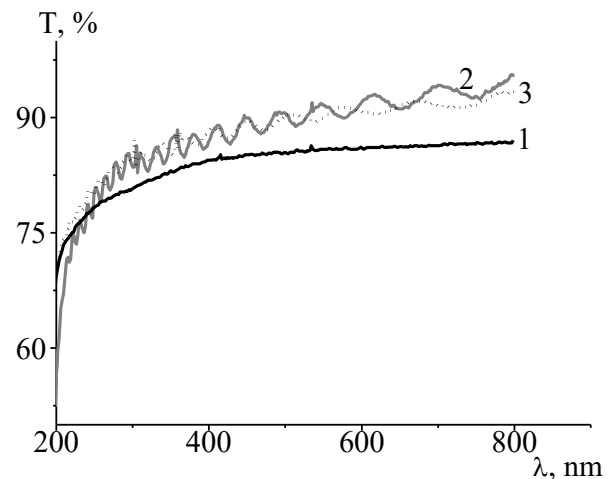
**Fig. 2.** Spectral characteristics of reflection from wedge-shaped samples of TF-4 glass without coating (1) and with coating (2): a) ZrF<sub>4</sub>–B<sub>2</sub>O<sub>3</sub>; b) HfF<sub>4</sub>; c) HfF<sub>4</sub>–B<sub>2</sub>O<sub>3</sub>.

It should be noted that the value of the refractive index of the coatings is practically constant (1.53), except for the HfF<sub>4</sub> sample. Perhaps this indicates the partial formation of some side compounds in the process of evaporation of HfF<sub>4</sub>. In general, *f* values increase noticeably from ZrF<sub>4</sub> to HfF<sub>4</sub> and when adding B<sub>2</sub>O<sub>3</sub> compared to the initial ZrF<sub>4</sub> and HfF<sub>4</sub> samples. The former purportedly indicates the higher volatility of HfF<sub>4</sub> initial to ZrF<sub>4</sub> under conditions of high vacuum and sufficiently low temperatures, which is a somewhat unexpected result that needs further verification.

As for the effect of adding B<sub>2</sub>O<sub>3</sub> to ZrF<sub>4</sub> and HfF<sub>4</sub> on the growth of their volatility, its explanation is clear. It is known that fluorides and chalcogenides of metals, as a rule, contain impurities of oxides that are localized on the surface of the grains of the main FFM and, having higher melting and boiling temperatures, prevent its evaporation. The addition of B<sub>2</sub>O<sub>3</sub> contributes to the destruction of these «shells» and thereby unlocks the process of

evaporation of FFM. A similar phenomenon of increased volatility was observed in the case of ZnS purified from zinc oxide impurities compared to the original material. It should be noted that the effectiveness of the addition of B<sub>2</sub>O<sub>3</sub> in the case of ZrF<sub>4</sub> is significantly lower compared to HfF<sub>4</sub> (the ratio of *f* values is 1.14 and 1.40, respectively); on the one hand, this should indicate the weak durability of oxide «shells» in and, on the other hand, the higher activity of B<sub>2</sub>O<sub>3</sub> with respect to HfO<sub>2</sub> «shells» in HfF<sub>4</sub>.

Spectral characteristics of substrates made of different materials with different refractive indices and coatings of various FFMs are presented in Fig. 2, 3.

**Fig. 3.** Spectral characteristics of coating samples on a Calcium fluoride substrate: 1 – substrate without coating; 2 – HfF<sub>4</sub>-coated substrate; 3 – substrate with HfF<sub>4</sub>–B<sub>2</sub>O<sub>3</sub> coating.

In the case of coatings on a substrate of Calcium fluoride, which has a lower refractive index than that of HfF<sub>4</sub>, the coating is translucent, and the transmission spectra lie above the corresponding curve for the substrate in a significant interval; only in the region below 400 nm do they converge. At a wavelength of about 250 nm, the spectral transmittance curve of the HfF<sub>4</sub> coating crosses the corresponding curve for the substrate, indicating the position of the short-wavelength limit of the transparency region. Taking into account the value of the refractive index of HfF<sub>4</sub> and HfF<sub>4</sub>–B<sub>2</sub>O<sub>3</sub> coatings, which are 1.57 and 1.53, respectively, it is possible to explain the ratio of their optical transparency limits. As follows from Moss's law, their ratio is:

$$\lambda_1/\lambda_2 = (n_1/n_2)^4. \quad (7)$$

In the region where the fundamental absorption begins (transmission less than 70 %), the values of  $\lambda_1$  and  $\lambda_2$  are respectively equal to 220 and 200 nm, which qualitatively corresponds to the equation written above: indeed, the ratio on the left side of the equation is  $\approx 1.10$ , while with of the right side – 1.11. The interference coatings are located above the substrate transmission curve in almost the entire spectral range for both HfF<sub>4</sub> and HfF<sub>4</sub>-B<sub>2</sub>O<sub>3</sub>.

## Conclusions

1. The nature of the IR transmission spectra of the starting substances ZrF<sub>4</sub> and HfF<sub>4</sub> and composites with the addition of B<sub>2</sub>O<sub>3</sub> indicates the influence of the latter on the crystal structure of the material with stabilization of low-temperature modification, probably cubic (tetragonal) for ZrF<sub>4</sub> and monoclinic for HfF<sub>4</sub>.

2. The value of the refractive index of the studied

samples was established, which is 1.53 (1.57 for HfF<sub>4</sub>). The introduction of the B<sub>2</sub>O<sub>3</sub> additive significantly increases the rate of application of coatings, and therefore the volatility of materials. The volatility of HfF<sub>4</sub> when evaporated in a deep vacuum and at room temperature exceeds that of ZrF<sub>4</sub>.

**Zinchenko V.F.** – Professor, Doctor of Chemistry, Head of the in Chemistry of Functional Inorganic Materials Department;

**Volchak G.V.** – PhD (in chem.), Senior Research Fellow in Chemistry of Functional Inorganic Materials Department;

**Mozkova O.V.** – Head of the laboratory of optical coatings;

**Yeriomin O.H.** – PhD (in chem.) in Chemistry of Functional Inorganic Materials Department;

**Doha P.H.** – Junior Researcher in Chemistry of Functional Inorganic Materials Department.

- [1] Okatov M.A., Antonov E.A., Baygozhin A. Optic Engineer's Handbook, St. Petersburg: Politekhnik, 2004, 679 p.
- [2] H.A. Abilsiitov, V.H. Hontar, A.A. Kolpakov, L.A. Novitskii & all. Technological lasers: Handbook Issue 2, Vol. 2. Mashinostroenie, M., 1991, 436 p.
- [3] Consumables for PVD applications. Evaporation materials and accessories. Leybold Optics (GmbH Catalogue, Alzenau, 2003).
- [4] V.F. Zinchenko, O.G. Eryomin, Ye.V. Timukhin, N.P. Efryushina, O.V. Mozkova, N.M. Belyavina, *Thin-film coatings on the base of complex RE fluorides*, Physics and Chemistry of Solid State, 6(3), 442 (2005).
- [5] V.F. Zinchenko, *Fluorides of some s-, p-, d-, and f-metals as perspective materials for interference optics: present status and development*, J. Fluorine Chem., 131(2), 159 (2010); <https://doi.org/10.1016/j.jfluchem.2009.12.001>.
- [6] V.F. Zinchenko, *Solid-phase complex compounds and composites of metal oxides, fluorides, and chalcogenides as materials for interference coatings: a review*, Theoretical and Experimental Chemistry, 57(4), 262 (2021); <https://doi.org/10.1007/s11237-021-09694-2>.
- [7] V.F. Zinchenko, I.R. Magunov, G.V. Volchak, O.V. Mozkova, G.I. Kocherba, *Effect of B<sub>2</sub>O<sub>3</sub> additive on the properties of ZnS-Ge system and the resulting thin-film coatings*, Materials Today: Proceedings, 62(9), 5767 (2022); <https://doi.org/10.1016/j.matpr.2022.03.477>.
- [8] E.H. Rakov, Yu.N. Tumanov, Yu.P. Butylkin & all, Basic properties of inorganic fluorides. Handbook. Atomizdat, M., 1975, 400 p.
- [9] D.C. Bradley, P. Thornton, Zirconium and hafnium. Ch. 33 in Comprehensive Inorganic Chemistry (Pergamon Press, Oxford - New York - Toronto - Sydney - Paris - Braunschweig, 1975).
- [10] V.F. Zinchenko, V.E. Chyrynov, O.V. Mozkova, V.P. Antonovych, *Optical and operational parameters, rate of evaporation and condensation, systems chalcospinel-germanium, thin-film coatings, volatility*. Bulletin of the Ukrainian Material Science Society of I.M. Frantsevich - Kiev: Frantsevich Institute for Problems of Materials Science NASU, 2018, N11. <http://www.materials.kiev.ua/article/2937>.

В.Ф. Зінченко<sup>1</sup>, Г.В.Вольчак<sup>1</sup>, О.В. Мозкова<sup>2</sup>, О.Г. Єрємін<sup>1</sup>, П.Г. Дога<sup>1</sup>

## Вплив добавки $B_2O_3$ на оптичні властивості тетрафторидів Цирконію та Гафнію у полікристалічному й тонкоплівковому станах

<sup>1</sup>Фізико-хімічний інститут ім. О.В. Богатського НАН України, Одеса, Україна, [vzinchenko@ukr.net](mailto:vzinchenko@ukr.net)

<sup>2</sup>Казенне підприємство спеціального приладобудування «Арсенал», Київ, Україна, [olgamozk@ukr.net](mailto:olgamozk@ukr.net)

Уперше досліджено вплив добавки  $B_2O_3$  на ІЧ спектри пропускання зразків  $ZrF_4$  та  $HfF_4$  та оптичні властивості одержаних з них покриттів. Виявлено суттєву відмінність форми смуг поглинання та положення піків коливальних зв'язків тетрафториду Цирконію та тетрафториду Гафнію. Висунуто припущення про вплив поліморфізму  $ZrF_4$  на співвідношення пружностей пари зазначених сполук в області умовної температури випаровування у глибокому вакуумі. Показано позитивний вплив добавки  $B_2O_3$  на швидкість випаровування зразків систем та конденсації на підкладках. Значення показників заломлення покриттів становлять біля 1,53. Виняток становить показник заломлення покриття з  $HfF_4$  (1,57), який можна віднести на рахунок моноклінної сингонії його кристалічної структури.

**Ключові слова:** тетрафторид Цирконію, тетрафторид Гафнію, добавка  $B_2O_3$ , ІЧ спектри пропускання, термічне випаровування у вакуумі, покриття, показник заломлення.