PACS numbers: 61.43.Er, 65.60.+a, 68.35.bm, 73.50.Pz, 78.40.Me, 82.35.Np, 83.60.-a

# Features of Relationship Between Rheological and Photogeneration Characteristics of PEPC $C_{60}$ Composites

M. A. Zabolotnyy<sup>1</sup>, L. I. Aslamova<sup>1</sup>, V. P. Vashchyn<sup>1</sup>, D. O. Grynko<sup>2</sup>, A. A. Kolesnichenko<sup>2</sup>, D. S. Leonov<sup>2</sup>, D. O. Krasnovyd<sup>4</sup>, V. V. Vovk<sup>4</sup>, M. M. Petryshyn<sup>4</sup>, R. V. Lytvyn<sup>2,3</sup>, S. O. Rudenkyi<sup>4</sup>, and M. Yu. Barabash<sup>2,4,5</sup>

<sup>1</sup>Taras Shevchenko National University of Kyiv, 60, Volodymyrska Str., UA-01033 Kyiv, Ukraine <sup>2</sup>Technical Centre, N.A.S. of Ukraine, 13, Pokrovs'ka Str., UA-04070 Kyiv, Ukraine  $^3$ I. M. Frantsevych Institute for Problems of Materials Sciences, N.A.S. of Ukraine, 3, Omeljan Pritsak Str., UA-03142 Kyiv Ukraine <sup>4</sup>National Technical University of Ukraine 'Igor Sikorsky Kyiv Polytechnic Institute', 37, Beresteiskyi Ave., UA-03056 Kyiv, Ukraine <sup>5</sup>Gas Institute, N.A.S. of Ukraine, 39, Degtyarivska Str., UA-03113 Kyiv, Ukraine

The process of photogeneration of charges and the temperature of the transition to the viscous-flow state  $(T_v)$  in thin films of polyepoxypropylcarbazole PEPC-C<sub>60</sub> composites fabricated by means of toluene-solution casting in strong external electric fields are investigated. Consistent and correlated changes in the temperature of the transition of the sample material to viscous-flow state  $(T_v)$  and in the effective temperature of the quantum yield of photogeneration  $(T_0)$  are found out. As shown, the difference between  $T_v$  and  $T_0$  for the PEPC-C<sub>60</sub> composites does not exceed 10% of these values, when the concentration of C<sub>60</sub> fullerene changes. This indicates changes in the molecular structure and, consequently, dielectric constant in the vicinity of the centre of photogeneration of electric-charge carriers.

93

Досліджено процес фотоґенерації зарядів і температуру переходу до в'язкоплинного стану ( $T_v$ ) у тонких плівках поліепоксипропілкарбазольних ПЕПК-С<sub>60</sub>-композитів, одержаних литтям з толуольного розчину в сильних зовнішніх електричних полях. Виявлено послідовні та корельовані зміни температури переходу матеріялу зразка у в'язкоплинний стан ( $T_v$ ) та ефективної температури квантового виходу фотоґенерації ( $T_0$ ). Показано, що ріжниця між  $T_v$  і  $T_0$  композитів ПЕПК-С<sub>60</sub> не перевищує 10% цих значень із зміною концентрації фуллерену С<sub>60</sub>. Це вказує на зміни молекулярної структури і, як наслідок, діелектричної проникности в околі центру фотоґенерації носіїв електричного заряду.

Key words: amorphous molecular semiconductor, fullerene, photogeneration, electric charge, current density.

Ключові слова: аморфний молекулярний напівпровідник, фуллерен, фотоґенерація, електричний заряд, густина струму.

(Received 27 December, 2023; in revised form, 12 January, 2024)

## **1. INTRODUCTION**

The magnitude of the quantum yield  $(\eta)$  of photogeneration of electric charge carriers in light-sensitive amorphous molecular semiconductors (AMSs) is one of the basic parameters that determine the fields and possibilities of their use. For the development of photosensitive media, the determining parameter is the amplification of signals using selective plasmon resonance electromagnetic fields. These effects appear in the development of AMSs for solar batteries, reversible layers for the registration and analysis of their 2-and 3-dimensional amplitude-phase optical information, and optical sensors [1-4].

According to the literature [5-7], the quantum yield of photogeneration depends significantly on the molecular composition and structure of the material. In the AMSs, the photogeneration process [2, 5-7] is determined by the features of the structure of the photosensitive medium directly in the centre of charge photogeneration. The mobilities of charge carriers of different signs differ significantly. In particular, PEPC and polyvinylcarbazole (PVC) sensitized by electron-acceptor impurities have linear dimensions of the zone, beyond which the movement of twin charge carriers ceases to be correlated, and the charges become independent of each other and are determined by the Onsager radius.

At the same time, there is no satisfactory explanation of the linear dependence of the logarithm of photocurrent  $(J_{PhC})$  on the inverse thermodynamic temperature  $(T^{-1})$  of the medium [8]. This phenomenon is observed under strong (pre-breakdown) electric fields. There is no explanation of the nature of the characteristic temperature  $(T_0)$  [8, 9]. By means of the analysis of the quantum yield of photogeneration of charge carriers and their mobility, the temperature is renormalized, *i.e.*,  $T^{-1}$  is replaced by  $T_{\rm eff}^{-1} = T^{-1} - T_0^{-1}$ . According to Ref. [8], the occurrence of  $T_0$  is determined by the relative probabilities, when overcoming the Coulomb barrier of the charged centre of localization of a mobile charge due to the activation and tunnelling transitions. In Refs. [2, 3, 10], the temperature  $T_0$  was registered; however, the physical factors that caused this phenomenon were not discussed. Therefore, it is necessary to find out which characteristics (local or integral) of a sensitized AMS determine the process of photogeneration of charge carriers and to investigate the dependence of the effective temperature on the structure and parameters of the material.

The aim of the work was to study the dependence of the effective temperature  $(T_0)$  in the layers of PEPC doped with  $C_{60}$  fullerenes on the concentration of dopants, and to determine the correlation between  $T_0$  and the temperature of the transition of the material into the viscous-flow state.

#### 2. EXPERIMENTAL TECHNIQUES

Samples of PEPC films doped with  $C_{60}$  fullerene were investigated, which were produced by the techniques of toluene solution casting and deposition by thermal evaporation in vacuum. It was taken into account that the properties of nanocomposites are determined by the characteristics of their constituents and the method of their production [8]. The photoluminescence spectra of the PEPC +  $C_{60}$ composite also indicate significant differences in the production of the samples. Therefore, the use of a certain technology for obtaining samples provides a specific nature of their properties and the interaction of existing structures in the PEPC +  $C_{60}$  composite.

With aim to prepare cast samples, a fixed amount of  $C_{60}$  was previously dissolved in toluene heated up to 50°C. After the fullerene powder had been completely dissolved, the solution was weighed, which made it possible to determine its weight and volume concentration. PEPC powder was used for the preparation of composite samples. The PEPC powder was dissolved in toluene without heating. The prepared solutions were mixed with each other in such a way that the concentration of the composite was equal 0; 0.5; 0.7; 2.5 and 3 wt.%. Then, these solutions were cast onto a rigid base with a thickness of d = 0.9-1.2 µm to produce thick films. After casting, the samples were dried in a thermal cabinet at 80°C for 4 hours. Rigid rectangular 1 cm×2 cm quartz plates were used as substrates. A translucent conductive SnO<sub>2</sub> (ITO) layer with a resistance

of 30 Ohm per square centimetre was applied to the surface of the substrate. The surface AMS layer was applied on the plate from the  $SnO_2$  side. A conductive silver contact was deposited onto the free surface of the AMS layer. The optical absorption spectra were obtained at a Specord M-40 spectrophotometer. The photocurrent density of the samples was measured when they were irradiated with monochromatic light of the visible range. An incandescent lamp with a set of light filters was used to irradiate the samples. The light intensity was varied using neutral light filters and was in the range of 0.2-5 W/m<sup>2</sup>. The electric field strength between the silver contacts and  $SnO_2$  was measured in the range of  $(1-20)\cdot 10^7$  V/m. The kinetics of the current during irradiation and after turning off the light was recorded using a memory oscilloscope.

The melting point was measured by the well-known optical method of determining the rheological characteristics of thin films [10]. The block-diagram of the device is shown in Fig. 1.

According to the method of [11], the layer of AMS material was electrically charged to the pre-breakdown potential difference. During heating, the thin film reaches the temperature of the transition to the viscous-flow state. Therefore, it becomes possible to form a phase diffraction grating on the free surface of the sample due to the ponderomotive forces caused by the electrocapillary effect.

The melting point of the sample was measured using optical method [3]. The method consists in measuring the logarithmic decrements (w) of the change in the amplitudes of the harmonic relief



Fig. 1. Block diagram of device for measuring melting point: 1—thin film; 2—SnO<sub>2</sub>; 3—glass; 4—measuring probe; 5—unit for measuring the potential of thin film; 6—high-voltage generator; 7—block for isothermal heating of thin film; 8—LG-38 laser; 9—Fourier lens; 10–15—photoreceivers; 16—electric contacts.

(h) formed on the free surface of the thin AMS film deposited on a planar substrate and heated above the glass transition temperature. The values of w depend on both the rheological characteristics of the material and the spatial frequency (k) of the relief on the free surface of the layer [3]. The dynamics of h changes over time according to the law

$$h(k,t) = h_0 \exp(w(k)t)\sin(ky), \qquad (1)$$

where  $h_0$  is the amplitude at the moment t = 0.

The logarithmic decrement of the change in the deformation amplitude of an electrically neutral layer of deformed material is determined by the forces of surface tension and viscosity and can be written as [4, 8]:

$$w(k) = -\frac{\Delta}{2\eta d} \left[ \frac{0.5 \operatorname{sh}(2kd) - kd}{\operatorname{ch}^2(kd) + (kd)^2} \right],$$
(2)

where  $\Delta$  is the coefficient of surface tension of the sample,  $\eta$  is the dynamic viscosity of the sample, and *d* is the sample thickness.

A harmonic relief formed on the surface of the sample; the dynamics of the amplitude of this relief was studied by measuring the first-order intensity of light diffracted on the grating. The intensity of the diffracted light, which is proportional to the square root of the relief amplitude, was taken into account. The rheological parameters of the sample were determined by analysis of the dynamics of the diffraction pattern and using relations (1) and (2). Using the Newton model of the dynamics of heated sample, the kinetics of the logarithm of the ratio of the intensity of diffracted light I(t) to the intensity of light  $I_0$  at the initial moment of time is described by the relationship

$$\ln\left(\frac{I(t)}{I_0}\right) \propto -\frac{\Delta}{\eta}t, \qquad (3)$$

At the temperature  $T_v$ , the linear dependence (3) begins to break that indicates the transition of the sample from a viscous to a highly-elastic state [12]. The accuracy of  $T_v$  measurements is determined by the minimum value of the registered residual relief. The error of this method does not exceed 1.5-2%.

With aim to select the wavelength of the excitation light, optical absorption spectra (A) of composite  $PEPC + C_{60}$  film samples were measured at room temperature. The results of the measurements are shown in Fig. 2.

A comparison of curves 1 and 2 (Fig. 2), which correspond to the spectra of PEPC without dopants and PEPC with 0.5 wt.%  $C_{60}$ ,



Fig. 2. Absorption spectra of cast samples; radiation source is a hydrogen lamp, T = 300 K, quartz substrate: 1—PEPC; 2—PEPC with 0.5 wt.% C<sub>60</sub>; 3—PEPC with 3 wt.% C<sub>60</sub>.

shows that the dopant at small concentrations increases the intensity of absorption in the short-wavelength region of the spectrum  $(\lambda < 375 \text{ nm})$  and does not affect the absorption in the longwavelength region  $(\lambda > 375 \text{ nm})$ . This may indicate the additive nature of absorption of the components of the composite. When the concentration of the dopant increases (at least up to 1 wt.%), the absorption spectra change significantly: a wide diffuse band appears in the region  $\lambda > 375$  nm. This effect can occur due to the formation of new absorption centres in the region  $\lambda > 375$  nm with dimers involved [13].

The occurrence of bands in the spectra of PEPC nanocomposite with fullerenes, which are not observed for pure PEPC and pure  $C_{60}$ , is explained by the formation of charge-transfer complexes (CTCs) in the PEPC +  $C_{60}$  system. The formation of these CTCs should lead to the formation of new energy levels, which form zones of jump transport of charge carriers [13].

The characteristics of the quantum yield of the photogeneration of charge carriers were determined by studying the photocurrent. For a reasonable use of this technique, the following factors should be fulfilled: the approximation of small charge drift (the field of volume charge carriers is much lower than the external electric field E), the blocking nature of the electrical contacts of the samples, an insignificant contribution of the processes of thermally activated generation of charges and recombination to the density of current through the sample.

The analysis of weak absorption of light passing through the

sample layer is implemented in the case of  $\alpha d \ll 1$ , where  $\alpha$  is the absorption coefficient of the sample material. When the irradiation is uniform and the approximation of small charge drift is fulfilled, the stationary distributions of concentrations of holes p(y) and electrons n(y) inside the sample layer are determined by the equations (4) and (5). These equations are valid, when the electric field E is directed along the *OY* axis:

$$G + G_{dark} - \gamma n(y)p(y) + \mu_n E \frac{dn(y)}{dy} = 0, \qquad (4)$$

$$G + G_{dark} - \gamma n(y)p(y) - \mu_p E \frac{dp(y)}{dy} = 0.$$
 (5)

The boundary conditions should take into account the possibility of injection (or exit) of charge carriers and the volume of AMS; so, they have the following form:

$$p(y=0) = p_0,$$
 (6)

$$n(y=d)=n_0. (7)$$

Here, G is the efficiency of photogeneration of electrons (holes) per unit time,  $G_{dark}$  is the efficiency of thermofield photogeneration of charge carriers,  $n_0(p_0)$  is the concentration of electrons (holes) in the near-contact region near the injecting contacts, which determine the injection current,  $\mu_n(\mu_p)$  is the mobility of electrons (holes),  $\gamma$  is the constant of geminate recombination of charge carriers, which determines the intensity of recombination processes and governs the nonlinear character of transport processes.

The current density passing through the sample without its illumination  $(j_{dark})$  under a weak effect of recombination processes is described by the equation

$$j_{dark} = e\mu_p E p_0 + e\mu_n E n_0 + eG_{dark} d, \qquad (8)$$

where e is the elementary electric charge.

When the sample is irradiated, the current density  $j_{light}$  is determined by the expression:

$$j_{light} = \frac{e}{d} \int_{0}^{d} \left[ \mu_{p} E p(y) + \mu_{n} E n(y) \right] dy .$$
(9)

The solution to the problem (4)–(7) has a rather complex form, which is significantly simplified by taking into account only expressions, which depend on no more than the first order of  $\gamma$ . In this

case, the following relation holds:

$$j_{light} = eGd + j_{dark} - e\gamma \left[ dn_0 p_0 + \frac{d^2 G j_{dark}}{2\mu_n \mu_p eE^2} + \frac{d^3 G^2 j_{dark}}{6\mu_n \mu_p E^2} \right], \quad (10)$$

For a given  $j_{dark}$ , the maximum possible value  $n_0 p_0 = \frac{(j_{dark})^2}{\mu_n \mu_p e^2 E^2}$ .

Thus, when the following condition is met:

$$eGd + j_{dark} \gg \frac{e\gamma}{\mu_n \mu_p E^2} \left[ d \frac{\left(j_{dark}\right)^2}{e^2} + \frac{d^2Gj_{dark}}{2e} + \frac{d^3G^2}{6} \right], \quad (11)$$

we have

$$j_{light} \approx eGd + j_{dark}, \ j \equiv j_{light} - j_{dark}.$$
 (12)

According to this expression, the current through the irradiated AMS sample is the sum of the injection current and the currents caused by the processes of thermofield generation and photogeneration of electric charge carriers. To fulfil condition (11), a small recombination coefficient, small sample layer thicknesses, and a strong external electric field are needed. The condition (11) is a criterion for the validity of using the results of the investigation of stationary photocurrents in flat layers of low-conductive materials with non-blocking contacts to study the quantum yield of photogeneration of electric charge carriers.

## **3. DISCUSSION**

Current density measurements were carried out in PEPC samples doped with  $C_{60}$  without irradiation. The results of  $j_{dark}$  measurements at room temperature for various *d* are shown in Figs. 3, *a*, *b*.

The values of current density  $j_{dark}$  between the deposited contacts in the general case were determined by the thermofield generation of charge carriers and the processes of injection from the metal into the AMS layer. As can be seen, the current density is weakly dependent on the electric field at  $E > 7 \cdot 10^7$  V/m. This indicates the dominant role of the thermofield generation of charge carriers, and the field dependence of the injection currents should be described by an exponential relationship of the Richardson–Schottky type [4, 8]. A comparison of the plots in Figs. 3, *a*, *b* shows that  $j_{dark}$  increases with the concentration of C<sub>60</sub>. This is explained by the clustering of fullerene molecules in the process of forming solid compo-



Fig. 3. Dependence of current density  $j_{dark}$  on magnitude of applied external electric field at room temperature for samples: a—PEPC+0.7 wt.% C<sub>60</sub>:  $1-d=0.9 \mu m$ ,  $2-d=1.2 \mu m$ ; b—PEPC+2.5 wt.% C<sub>60</sub>:  $1-d=0.95 \mu m$ ,  $2-d=1.17 \mu m$ .

sites based on the AMS matrix.

The studies of the dependence of the photocurrent density j on the intensity of the excitation light (Fig. 4) showed a proportional relationship between them, taking into account the relationship (12).

It is shown that the dependence (1) in Fig. 4 was obtained at field strength  $E = 1.25 \cdot 10^7$  V/m, and the dependence (2), at  $E = 1.67 \cdot 10^7$  V/m. A comparison of the currents in Figs. 3, 4 shows that the relationship  $j_{dark} \ll j_{light}$  holds. This provides an opportunity to use the



Fig. 4. Dependence of photocurrent for PEPC + 2 wt.%  $C_{60}$  sample on power density of excitation light for different values of field strength.

measurements of steady-state photocurrents and to investigate the quantum yield properties of the photogeneration of charge carriers.

Further analysis shows that the dependence of the photocurrent density (as well as the efficiency of the photogeneration quantum yield) on the intensity of the applied field is well described by the following relationship [4, 7, 8]:

$$j(E) = j_0 \exp\left[\frac{\beta_{PF}\sqrt{E}}{k_B}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right],$$
(13)

where  $j_0$  is a value weakly dependent on E,  $\beta_{PF} = \sqrt{q^3/\pi\varepsilon\varepsilon_0}$  is the Poole–Frenkel constant, T is the sample temperature,  $T_0$  is the effective temperature,  $\varepsilon\varepsilon_0$  is the dielectric constant of the material, and  $k_B$  is the Boltzmann constant. This dependence well describes the features of the behaviour of the photocurrent density of previously studied samples of fullerene-containing polymers with various sensitizers. The following expression was used for the analysis of the experimental data (13):

$$\ln j(E) \propto \sqrt{E} \frac{\beta_{\Pi \Phi}}{k_B} \left( \frac{1}{T} - \frac{1}{T_0} \right). \tag{14}$$

As can be seen, the value of the Poole–Frenkel constant depends on the dielectric constant of material. For thin-film PEPC +  $C_{60}$ composites produced by toluene solution casting, this parameter is not precisely determined. Therefore, the value of the Poole–Frenkel constant was calculated for several values of the dielectric constant:  $\varepsilon = 3$ , 3.5 and 4.

Based on these calculations, the dependence of the product of the Poole–Frenkel constant on the difference between the inverse tem-

perature and the inverse effective temperature  $\delta = \frac{\beta_{PF}}{k_B} \left( \frac{1}{T} - \frac{1}{T_0} \right)$  on

the value of the effective temperature (this value determines the inclination angle of the dependence  $\ln j(E)$ ) was determined. The results are shown in Fig. 5.

As seen from Fig. 5, the angle of inclination of the dependence  $\ln j(E)$  depends significantly both on the dielectric constant of material and on  $T_0$ . Using the dielectric constant 3, which is close to the value for pure PEPC [4], the theoretical dependence  $\ln j(E)$  for PEPC samples with various concentrations of fullerenes was calculated.

The calculated and experimental dependences,  $\ln j(E)$ , were compared. The angle of inclination of the theoretical dependence changed due to the change in  $T_0$ . The  $T_0$  value was chosen in such a way that the root-mean-square difference between the theoretical



Fig. 5. Dependence of parameter  $\delta$  on value of effective temperature for various values of dielectric constant: 3, 3.5 and 4.

and experimental curves was minimal. The results of this comparison for the PEPC +  $C_{60}$  nanocomposites with different fullerene content are shown in Figs. 6, *a*, *b*. Using the experimental and theoretical results, the effective temperature of the samples was determined.

As can be seen from the above data, the effective temperature for PEPC samples with different concentrations of fullerenes increases with  $C_{60}$  content, which may indicate decreasing role of tunnelling processes in the electron-hole pair separation [2, 8].



Fig. 6. Dependence of theoretical (solid line) and experimental (red squares) of photocurrent density *j* logarithm on applied field for samples: a—PEPC + 0.7 wt.% C<sub>60</sub>, for dielectric constant  $\varepsilon = 3$ , temperature 300 K, effective temperature 360 K; *b*—PEPC + 2.5 wt.% C<sub>60</sub> for dielectric constant  $\varepsilon = 3$ , temperature 300 K, effective temperature 380 K.



Fig. 7. Dependence of temperature of transition into viscous-flow state on fullerene content in composites.

The temperatures of the transition to the viscous-flow state  $T_v$  of PEPC samples with 0, 0.7, 2.5, and 3 wt.% C<sub>60</sub> were determined; the results are shown in Fig. 7.

Figure 7 shows that the temperature  $T_v$  increases with  $C_{60}$  content. This indicates either an increase in the intensity of intermolecular interaction, or the formation of undeformed hard nanostructures that contain  $C_{60}$ ; the size of these nanostructures depends on fullerene content. It is worthwhile to note that the  $T_v$  values coincide with the values of the effective temperature with an accuracy of 10% ( $T_0 \approx T_v$ ). This effect may indicate that the effective temperature, as well as the melting point, are determined by the forces of intermolecular interaction in the nanocomposite, or both these parameters are determined by the processes of  $C_{60}$  coagulation in the polymer matrix.

#### 4. SUMMARY

At low concentrations of fullerenes in the PEPC matrix (less than 0.5 wt.%), the absorption spectrum in the visible region is formed by independent optical transitions in PEPC and  $C_{60}$ . When the concentration of  $C_{60}$  dopant increases (above 1 wt.%), new bands appear in PEPC composites with fullerenes. This non-linear nature of the effect of  $C_{60}$  concentration may indicate the dominant role of the interaction of PEPC molecules with  $C_{60}$  dimers. The dependence of the density of photocurrent generated in volume of PEPC +  $C_{60}$  films on the electric field is consistent with the modified Poole–Frenkel law, which indicates a jump mechanism of the transport of charge carriers during their photogeneration. The modified Poole–Frenkel

constant depends on the  $C_{60}$  concentration that indicates a change in the local dielectric constant in the vicinity of the photogeneration centre when the  $C_{60}$  concentration changes.

The temperature of the transition to the viscous-flow state in the PEPC +  $C_{60}$  composite samples depends on the  $C_{60}$  concentration; it increases with concentration, which indicates increasing intensity of intermolecular interaction, or the formation of undeformed hard nanostructures containing  $C_{60}$ . The characteristic temperature coincides with an accuracy of 10% with the value of the melting point of the PEPC +  $C_{60}$  composite that indicates that the photogeneration of charge carriers and melting depend on the same processes.

#### REFERENCES

- G. Dennler, N. S. Sariciftci, and C. J. Brabec, Conjugated Polymer-Based Organic Solar Cells, Semiconducting Polymers: Chemistry, Physics and Engineering (Eds. G. Hadziioannou and G. G. Hunray) (Weinheim: Wiley: 2006), vol. 1, p. 455-519.
- M. A. Zabolotnyi, L. I. Aslamova, E. M. Boboshko, A. A. Kolesnichenko, D. S. Leonov, R. V. Lytvyn, A. Yu. Sezonenko, M. M. Yamshinskij, and M. Yu. Barabash, *Nanosistemi, Nanomateriali, Nanotehnologii*, 21, Iss. 2: 261 (2023); https://doi.org/10.15407/nnn.21.02.261
- V. Anand, T. Tahara, and W. M. Lee, Advanced Optical Holographic Imaging Technologies. Appl. Phys. B, 128: 198 (2022); https://doi.org/10.1007/s00340-022-07921-9
- H. H. Vlaikov, M. Yu. Barabash, M. A. Zabolotnyi, D. O. Hrynko, Yu. M. Barabash, and L. Yu. Kunytska, *Formuvannya Nanostruktur Templantnym Syntezom* [Formation of Nanostructures by Template Synthesis] (Kyiv: G. V. Kurdumov Inst. For Metal Physics, N.A.S. of Ukraine: 2010) (in Ukraine).
- Piotr Grygiel, Karol Falkowski, Daniel Pelczarski, and Waldemar Stampor, Organic Electronics, 39: 328 (2016); https://doi.org/10.1016/j.orgel.2016.10.023
- 6. G. Pfister and D. J. Williams, J. Chem. Phys., 61: 2416 (1974); https://doi.org/10.1063/1.1682344
- 7. V. Gulbinas, Lithuanian Journal of Physics, 60, No. 1: 1 (2020); https://doi.org/10.3952/physics.v60i1.4160
- 8. N. H. Kuvshynskyi, N. A. Davydenko, and B. M. Komko, *Physics of Amorphous Molecular Semiconductors* (Kyiv: Lybed': 1994) (in Russian).
- Kye-Si Kwon, Md Khalilur Rahman, Thanh Huy Phung, Stephen D Hoath, Sunho Jeong, Jang Sub Kim, *Flex. Print. Electron.*, 5: 043003 (2020); https://doi.org/10.1088/2058-8585/abc8ca
- N. P. Kulish, Yu. M. Barabash, M. A. Zabolotny, D. A. Grinko,
   O. P. Dmitrenko, and E. S. Kobus, *Physics of the Solid State*, **50**: 1374 (2008); https://doi.org/10.1134/S1063783408070305
- Shantharama and Sreeram K Kalpathy, Electrocapillary Effect in Liquid Films with an Electrically Charged Interface, Materials Today: Proceedings, 44, part 2: 3006 (2021); https://doi.org/10.1016/j.matpr.2021.02.406

## 106 M. A. ZABOLOTNYY, L. I. ASLAMOVA, V. P. VASHCHYN et al.

- 12. Seher Ozkan and Roger L. McMullen, *Rheological Characterization of N-Vinyl Pyrrolidone and N-Vinyl Caprolactam-Based Polymers* (Wiley Online Library: 2021); https://doi.org/10.1002/9781119468769.hpcbm019
- M. A. Zabolotnyj, E. S. Kobus, O. P. Dmitrenko, N. P. Kulish, N. M. Belyj, E. V. Stasjuk, Yu. M. Barabash, G. I. Dovbeshko, E. M. Fesenko, Yu. P. Pirjatinskij, and D. A. Grin'ko, *Fizika Tverdogo Tela*, 52, Iss. 4: 826 (2010) (in Russian); https://journals.ioffe.ru/articles/viewPDF/1807