## Synthesis and study of N, N'-disubstituted derivatives of pyromellitic diimide

E. A. Komissarova,<sup>a,b</sup> V. E. Zhulanov,<sup>b</sup> I. G. Mokrushin,<sup>b</sup> A. N. Vasyanin,<sup>b</sup> E. V. Shklyaeva,<sup>b</sup> and G. G. Abashev<sup>a,b\*</sup>

<sup>a</sup>Institute of Technical Chemistry, Ural Branch, Russian Academy of Sciences, Division of the Perm Federal Center of the Ural Branch of the Russian Academy of Sciences, 3 ul. Akad. Koroleva, 614013 Perm, Russian Federation. Tel.: +7 (342) 237 8289. E-mail: gabashev@psu.ru <sup>b</sup>Perm State National Research University, 15 ul. Bukireva, 614990 Perm, Russian Federation. Tel.: +7 (342) 239 6231. E-mail: ekaterina.komva@gmail.com

New N,N'-bis(4,6-dimethylpyrimidin-2-yl)- and N,N'-bis(2,3,5,6-tetrafluorophenyl)substituted pyromellitic diimides were synthesized. Their properties were studied in comparison with the previously synthesized N,N'-bis(4-fluorophenyl)pyromellitic diimide. Thermogravimetry, UV spectroscopy, cyclic voltammetry, and quantum chemical calculations in the framework of the density functional theory were used to characterize the synthesized compounds. The introduction of the pyrimidine cycle significantly decreases the energy of the lowest unoccupied molecular orbital. The highest occupied molecular orbitals in all compounds synthesized are deep-lying (about -7 eV).

**Key words:** pyromellitic diimide, pyrimidine, fluoroaniline, tetrafluoroaniline, highest occupied molecular orbital, lowest unoccupied molecular orbital, forbidden gap width, quantum chemical calculations.

Targeted synthesis of organic electro- and photoconducting compounds necessary for the development and design of modern materials used in organic electronics is an urgent task. This is indicated by regularly published research articles, reviews, reference books, and monographs.<sup>1-6</sup> Substituted polycyclic carboxydiimides, such as perylene-3,4,9,10-tetracarboxylic acid diimide and naphthalene-1,4,5,8-tetracarboxylic acid diimide, are referred to one of the promising class of small molecules used for the fabrication of organic electronics devices, e.g., organic field-effect transistors,<sup>7,8</sup> various sensors,<sup>9</sup> and solar cells.<sup>10</sup> The studies devoted to the synthesis, properties, and application areas of the derivatives of benzene-1,2,4,5- tetracarboxylic acid diimide, so-called pyromellitic diimide (pyrrolo[3,4-f]isoindole-1,3,5,7(2H,6H)tetraone) are presently published more frequently. N, N'-Disubstituted pyromellitic acid diimides are also used in the fabrication of materials for organic electronics devices.<sup>8,9,11</sup> In addition, it is known that the complexes of N, N'-disubstituted pyromellitic diimide with electron-rich compounds (tetrathiafulvalenes, pyrenes, and naphthalenes) have the properties of segnetoelectrics.<sup>12</sup>

High thermal stability and air stability are among the main advantages of polycyclic carboxyimides. In addition, these molecules are characterized by the planar structure and stacked organization of the packing providing strong  $\pi$ - $\pi$ -interactions favoring an increase in the charge transfer efficiency and, hence, an increase in the mobility of charge carriers.<sup>8</sup> In spite of the fact that the pyromellitic diimide derivatives are most known as fragments of highly insulating polyimide dielectrics, they are often used as semiconductor materials in the structures of organic field-effect transistors.<sup>13-17</sup> Among the advantages of the pyromellitic diimide derivatives is that its major precursor, pyromellitic acid dianhydride, is commercially more accessible than naphthalene-1,4,5,8-tetracarboxylic acid dianhydride. In addition, it is fairly simple to purify the substituted pyromellitic anhydrides.

The attachement of electron-withdrawing groups to the nitrogen atom of the imide fragment of polycyclic carboxydiimides increases the mobility of charge carriers in these molecules.<sup>8</sup> Fluorinated alkyl or substituted benzyl groups are used most frequently as electron-withdrawing groups, whereas carboxydiimides containing the electronwithdrawing aromatic fragment directly linked to the nitrogen atom of the imide fragment are studied much poorly.<sup>18–21</sup> One of the aromatic electron-withdrawing fragments promising for the incorporation into polycyclic imide molecules is the pyrimidine cycle: its presence in the structures of the  $\pi$ -conjugated compounds decreases the energy of the lowest unoccupied molecular orbital

Published in Russian in Izvestiya Akademii Nauk. Seriya Khimicheskaya, No. 10, pp. 1944–1948, October, 2020. 1066-5285/20/6910-1944© 2020 Springer Science+Business Media LLC (LUMO), thus favoring the achievement of a high electron mobility.<sup>22</sup>

Polycyclic carboxydiimides are synthesized most frequently by the acylation of primary amines by the corresponding di- or tetracarboxylic acid anhydrides under various conditions, which depend on the nature of the reactants and their solubility. $^{23-25}$  It is known that the reactions characteristic of amines, including acylation, are impeded if the amino group is in the structure of azines, in particular, pyrimidine, which is due to its deactivation by the electron-withdrawing pyrimidine cycle. This completely concerns the reactivity of the amino group of 2-amino-4,6-dimethylpyrimidine. Nevertheless, we earlier synthesized and studied N-(4,6-dimethylpyrimidin-2-yl)phthalimide and N-(4,6-dimethylpyrimidin-2-yl)-1,8naphthalimide and products of their condensation with aromatic aldehydes.<sup>26</sup> The nature of the central imide fragment of the synthesized chromophores was shown to exert a significant effect on the LUMO energy of these molecules. The purpose of the present study is the synthesis of the new pyrimidine-containing N, N'-bis(4,6-dimethylpyrimidin-2-yl)pyromellitic diimide and study of its optical and thermal properties in comparison with the properties of N, N'-disubstituted pyromellitic diimides bearing the 4-fluorophenyl and 2,3,5,6-tetrafluorophenyl electron-withdrawing groups at the nitrogen atoms of the diimide cycle. The determination of the energies of the highest occupied  $(E_{HOMO})$  and lowest unoccupied  $(E_{LUMO})$  molecular orbitals and optical width of the forbidden gap  $(E_g^{opt})$  using both the experimental methods and quantum chemical calculations was also a task of the work.

Target compounds 1-3 were synthesized by the reactions of pyromellitic dianhydride with the amines containing the electron-withdrawing groups, namely, with 2-amino-4,6-dimethylpyrimidine, 4-fluoroaniline, and 2,3,5,6-tetrafluoroaniline (Scheme 1).

## Scheme 1



**Reagents and conditions:** *i* (for 1), glacial AcOH, reflux, 24 h; *ii* (for 2 and 3), DMF, reflux, 8 h.

Compounds 1 and 3 were synthesized and described for the first time, and the synthesis of compound 2 has been described previously.<sup>27,28</sup> 2-Amino-4,6-dimethylpyrimidine necessary for the synthesis of compound **1** was synthesized by the condensation of acetylacetone with urea.<sup>29</sup> Reflux of pyromellitic dianhydride with 2-amino-4,6-dimethylpyrimidine in glacial acetic acid gave (in a yield of 65%) N,N'-bis(4,6-dimethylpyrimidin-2-yl)pyromellitic diimide **1** as a high-melting yellow crystalline substance, which was recrystallized from DMF. Pyromellitic diimide derivatives **2** and **3** containing the fluorinesubstituted benzene fragments were synthesized in high yields of 68–70% by the reactions of pyromellitic dianhydride with the corresponding fluorine-substituted anilines in refluxing DMF.<sup>30</sup> The synthesized N,N'-disubstituted diimides **2** and **3** are high-melting crystalline substances, which were purified by recrystallization from ethanol.

In this work, we compared the thermal, optical, electrochemical, and electronic properties of compounds **1–3**. Thermal stability is an important characteristic of materials for organic electronics, since it directly affects the operation durability of the devices based on these materials. The thermogravimetric analysis of compounds 1 and 3 shows that they are thermally stable highly melting substances. The decomposition onset temperature of diimide 1 is 215 °C, and that for tetrafluorophenyl-substituted diimide 3 is 288 °C. Pyrimidine-containing diimide 1 is characterized by the two-step decomposition at 233 and 384 °C accompanied by consecutive mass losses of 28.6 and 49.5% of the substance weight. The complete decomposition of diimide 3 occurs at 380 °C. It has previously<sup>27</sup> been shown that diimide 2 containing the fluorine atom in position 4 of the benzene cycle at the nitrogen atom is also thermally stable: the range of its decomposition is 340–432 °C.

The electronic absorption spectra in a DMF solution  $(C = 4 \cdot 10^{-5} \text{ mol } \text{L}^{-1})$  were recorded for the studied carboxydiimides 1-3 (Fig. 1). The absorption band maxima ( $\lambda_{max}),$  absorption edge ( $\lambda_{onset}),$  and molar absorption coefficients ( $\epsilon$ ) are given in Table 1. The character of the absorption spectra of pyromellitic diimide 1 differs considerably from the absorption spectra of fluorine-containing pyromellitic diimide derivatives 2 and 3. The intense short-wavelength maximum of the absorption band of bis(4,6-dimethylpyrimidin-2-yl)pyromellitic diimide 1  $(\lambda_{max} = 293 \text{ nm})$  is red-shifted by 26 nm relative to the maxima of the corresponding absorption bands of compounds 2 and 3 ( $\lambda_{max}$ = 267 nm) (see Fig. 1, Table 1). In addition, the absorption spectrum of compound 1 exhibits a pronounced low-intensity long-wavelength absorption band at  $\lambda_{max} = 394$  nm corresponding to the intramolecular charge transfer. The absorption edge of compound 1 ( $\lambda_{onset}$ ) is also bathochromically shifted, due to which diimide 1 is characterized by the lowest optical width of the forbidden gap equal to 2.99 eV. The spectra of compounds 2 and 3 exhibit broadened absorption bands in a range of 320-330 nm.



Fig. 1. Normalized absorption spectra of the DMF solutions of compounds 1-3 ( $C = 4 \cdot 10^{-5}$  mol L<sup>-1</sup>). The spectra were normalized to the maximum absorption intensity in this spectrum.

The energies of the HOMO  $(E_{HOMO})$  and LUMO  $(E_{\rm LUMO})$  of compounds 1–3 were estimated from the data obtained by cyclic voltammetry (Fig. 2). In addition, the HOMO and LUMO energies were calculated using the density functional theory (DFT) (see Table 1).

Diimide 1 containing two electron-withdrawing pyrimidine cycles (see Table 1) has the lowest LUMO energy calculated from the experimental data ( $E_{LUMO} = -3.75 \text{ eV}$ ). The close  $E_{\text{LUMO}}$  values equal to -3.57 and -3.58 eV were obtained for diimides 2 and 3, respectively, containing fluorinated phenyl rings at the nitrogen atom. These values of the LUMO energies are confirmed by the quantum chemical calculations:  $E_{LUMO} = -3.49$  (1) and -3.44 eV (compounds 2 and 3). According to the experimental data, carboxydiimides 1-3 have the deep-lying HOMO, which was also confirmed by the quantum chemical calculation (see Table 1). The energies of the neighboring HOMO and HOMO-1 orbitals, as well as those of LUMO and LUMO+1, were shown to be very close (degenerated) (Fig. 3). According to the quantum chemical calculations, the electron density of the LUMO is localized on the naphthalene fragment and carbonyl group of the imide



Fig. 2. CV curves of compounds 1-3 (DMF-CH<sub>2</sub>Cl<sub>2</sub>(1:4)) recorded in the cathodic potential range (glassy carbon working electrode, platinum wire as an auxiliary electrode, Ag/AgCl reference electrode,  $Et_4NClO_4$  supporting electrolyte,  $v_{scan} =$ = 100 mV s<sup>-1</sup>). Inset: CV curves detected in the anodic potential range.

fragment of the molecule, while at the LUMO+1 level the electron density is also distributed over the nitrogen atom and over the pyrimidine or fluorophenyl substituents at the nitrogen atoms of pyromellitic diimide (see Fig. 3). As it was expected, the introduction of the pyrimidine fragment into the chromophore structure resulted in an decrease in the HOMO energy by -3.75 eV and a decrease in the optical bandgap value to 2.99 eV as compared with the corresponding parameters determined for the fluorinecontaining derivatives of pyromellitic diimide.

Thus, the N, N'-disubstituted derivatives of pyromellitic diimide, two of which were not described previously, were synthesized in this work. Their electronic absorption spectra were recorded, the electrochemical properties were studied by the CV method, and the energies of the frontier orbitals were estimated. The quantum chemical calculations of the main energy characteristics of molecules of the synthesized compounds were performed. It is shown experimentally and by the quantum

Compound	$\begin{array}{c} \lambda_{max}/nm \\ (\epsilon/L \ mol^{-1} \ cm^{-1}) \end{array}$	λ <sub>onset</sub> /nm	$E_{\rm g}^{\rm opt}$ /eV	$-E_{\rm HOMO}/{\rm eV}$		$E_{\rm LUMO}/{\rm eV}$		$\Delta E$
				experiment <sup>a</sup>	calculation <sup>b</sup>	experiment <sup>a</sup>	calculation <sup>b</sup>	/eV
1	293 (12760), 394 (890)	414	2.99	6.74	7.87	3.75	3.49	4.38
2	267 (16500)	345	3.59	7.16	7.16	3.57	3.44	3.72
3	267 (12950)	352	3.52	7.10	7.58	3.58	3.44	4.14

Table 1. Optical characteristics and the HOMO/LUMO energy values (E) for compounds 1-3

*Notes:*  $\lambda_{max}$  is the absorption band maximum,  $\varepsilon$  is the molar absorption coefficient,  $\lambda_{onset}$  is the absorption edge wavelength,<sup>31</sup> and

 $E_{g}^{opt}$  is the optical bandgap value  $(E_{g}^{opt} = 1240/\lambda_{onset})$ .<sup>32</sup> <sup>*a*</sup> Calculated by the CV data:  $E_{LUMO} = [-e(E_{onset}^{red} - E^{1/2}_{Fc/Fc+vsAg/AgCl} + 4.80)]$ , where e is the electron charge,  $E_{onset}^{red}$  is the onset reduction potential, <sup>31</sup>  $E^{1/2}_{Fc/Fc+vsAg/AgCl}$  is the experimentally determined half-wave potential of the Fc/Fc<sup>+</sup> pair vs Ag/Ag<sup>+</sup> electrode<sup>33</sup> equal to 0.68 V, and  $E_{\text{HOMO}} = E_{\text{LUMO}} - E_{\text{g}}^{\text{opt}}$ .

<sup>b</sup> Data of quantum chemical calculations (PBE0-D3/Def2-TZVPD).



Fig. 3. Shapes of the frontier molecular orbitals of compounds 1-3 calculated by the PBE0-D3/Def2-TZVPD method (controlling value of the isocontour 0.02 a.u.).

chemical calculations that the synthesized N, N'-disubstituted carboxyimides have deep-lying LUMO and HOMO. In addition, pyrimidine-containing pyromellitic diimide is characterized by a deeper-lying LUMO (-3.75 eV), a higher-lying HOMO (-6.74 eV), and a narrower bandgap (2.99 eV) than pyromellitic diimides containing fluorophenyl substituents.

## Experimental

<sup>1</sup>H and <sup>13</sup>C NMR spectra were recorded on a Bruker Avance Neo IIIHD spectrometer (400 MHz) using Me<sub>4</sub>Si as the internal standard. The signals from the pyrimidine cycle protons are designated as Pyrim, and the signals of the pyromellitic diimide protons are designated as PDI. Elemental analysis was carried out using a CHNS-932 LECO Corp analyzer. UV spectra were recorded on a Shimadzu UV-2600 UV-VIS spectrophotometer using a concentration of the solutions of  $10^{-5}$  mol L<sup>-1</sup>. Electrochemical studies were carried out at room temperature on a Potentiostat/Galvanostat/ZRA Interface 1000 in a standard three-electrode cell using a glassy carbon working electrode, an auxiliary platinum electrode (wire, ERL-02), and silver chloride reference electrode. A DMF-CH<sub>2</sub>Cl<sub>2</sub> (1 : 4) mixture served as the solvent, and Et<sub>4</sub>NClO<sub>4</sub> was used as the supporting electrolyte ( $C_{sup} = 0.1 \text{ mol L}^{-1}$ ,  $C_{compd} = 1 \cdot 10^{-3} \text{ mol L}^{-1}$ , potential sweep rate ( $v_{scan}$ ) = 100 mV s<sup>-1</sup>). Thermogravimetric analysis was carried out on an STA 449 F1 Jupiter<sup>®</sup> instrument for simultaneous thermal analysis (Netzsch-Geratebau GmbH, Germany) coupled with a QMS 403 C Aëolos<sup>®</sup> mass spectrometer using DSC/TG pan Al<sub>2</sub>O<sub>3</sub> crucible, and the heating rate was 5 °C min<sup>-1</sup>. Quantum chemical calculations were performed at the PBE0-D3/Def2-TZVPD level in a DMF medium using the Firefly program partially based on the initial code of the GAMESS system (US) using a PSU-Kepler supercomputer.

2,6-Bis(4,6-dimethylpyrimidin-2-yl)pyrrolo[3,4-*f*]isoindole-1,3,5,7(2*H*,6*H*)-tetraone (1). A mixture of pyromellitic dianhydride (0.18 g, 0.8 mmol) and 2-amino-4,6-dimethylpyrimidine (0.2 g, 1.6 mmol) in glacial AcOH (10 mL) was refluxed for 12 h. The reaction mixture was cooled down to room temperature and poured to water, and the formed precipitate was filtered off, washed with water on the filter, and dried in air. The product was recrystallized from DMF. The yield of compound **1** as a yellow crystalline substance was 0.22 g (65%), m.p. 235 °C. Found (%): C, 61.41; H, 3.82; N, 19.04. Calculated (%): C, 61.68; H, 3.76; N, 19.62. <sup>1</sup>H NMR (DMSO-d<sub>6</sub>),  $\delta$ : 2.25 (s, 12 H, 4 CH<sub>3</sub>); 6.46 (s, 2 H, Pyrim), 8.16 (s, 2 H, PDI). <sup>13</sup>C NMR (DMSO-d<sub>6</sub>),  $\delta$ : 22.8, 108.9, 130.2, 134.9, 161.51, 166.8, 167.1. UV (DMSO),  $\lambda_{max}/nm$  ( $\varepsilon$ /L mol<sup>-1</sup> cm<sup>-1</sup>): 293 (12 750), 394 (890).

The thermal decomposition of the samples occurred in two stages. A mass loss of 28.6% of the sample weight occurred in an endothermal range of 180-270 °C. The peak of the decomposition rate was 11% per min and was observed at 233 °C. In a range of 270-410 °C, the sample underwent endothermal decomposi-

Komissarova et al.

tion with a mass loss of 49.5%. The peak of the decomposition rate in this temperature range was observed at  $384 \text{ }^{\circ}\text{C}$  (11% per min). The further mass loss (11.5%) occurred in a range of 410–540 °C and corresponded to the decomposition of the carbonized residue.

**Synthesis of compounds 2 and 3 (general procedure).** A mixture of pyromellitic dianhydride (0.28 g, 1.3 mmol), the corresponding fluorine-substituted aniline (2.6 mmol), and anhydrous DMF (10 mL) was refluxed for 12 h. The reaction mixture was cooled down to room temperature and poured to water, and the formed precipitate was filtered off, washed with water on the filter, dried in air, and recrystallized from EtOH.

2,6-Bis(4-fluorophenyl)pyrrolo[3,4-f]isoindole-1,3,5,7(2H,6H)tetraone (2). The yield of compound 2 as a light green crystalline substance was 0.35 g (68%). The physicochemical and spectral characteristics coincide with the previously published values.<sup>27,28</sup> UV (DMSO),  $\lambda_{max}$ /nm ( $\epsilon$ /L mol<sup>-1</sup> cm<sup>-1</sup>): 267 (16 500).

**2,6-Bis(2,3,5,6-tetrafluorophenyl)pyrrolo[3,4-f]isoindole-1,3,5,7(2***H***,6***H***)-tetraone (3). The yield of compound 3 as a light yellow crystalline substance was 0.46 g (70%), m.p. 274 °C. Found (%): C, 51.41; H, 0.95; N, 5.06. Calculated (%): C, 51.58; H, 0.79; N, 5.47. <sup>1</sup>H NMR (DMSO-d<sub>6</sub>), \delta: 8.11–8.20 (m, 2 H, 2 C<sub>6</sub>F<sub>4</sub>H); 8.38 (s, 1 H, PDI); 8.62 (s, 1 H, PDI). <sup>13</sup>C NMR (DMSO-d<sub>6</sub>), \delta: 108.7, 116.7, 118.2, 119.8, 136.1, 136.8, 137.8, 162.5, 162.8, 165.8. UV (DMSO), \lambda\_{max}/nm (\epsilon/L mol<sup>-1</sup> cm<sup>-1</sup>): 267 (12 950).** 

The thermal decomposition of the sample proceeds in three stages. A mass loss of 2.8% of the sample weight occurs in an endothermic range of 110–220 °C along with the removal of the solvent and low-molecular-weight impurities. A minor broad endoeffect ( $\Delta H \approx 2 \text{ J g}^{-1}$ ) is observed at 218 °C, after which (in a range of 220–390 °C) the sample endothermally decomposed with a mass loss of 84.9%. The melting of the sample ( $\Delta H \approx 90 \text{ J g}^{-1}$ ) is observed at 274 °C in the DSC curve. At this stage, a mass loss of 10% of the sample weight occurs at 295 °C. The maximum decomposition rate is observed at 350 °C (16% per min). The further mass loss in a range of 390–540 °C corresponds to the decomposition of the carbonized residue (4%).

This study was financially supported by the Russian Foundation for Basic Research (Project No. 18-33-00323mol\_a).

## References

- Organic Electronic Materials and Devices, Ed. S. Ogawa, Springer, Tokyo—Heidelberg—New York—Dordrecht—London, 2016.
- R. Mertens, The OLED Handbook. A Guide to OLED Technology, Industry & Market, edition 2019, Metalgras LTD, 2019.
- Solution-Processable Components for Organic Electronic Devices, Eds J. Ulanski, B. Luszczynska, K. Matyjaszewski, Wiley-VCH, Weinheim, 2019.
- M. C. Petty, Organic and Molecular Electronics: from Principles to Practice, 2nd ed., Wiley-VCH, Weinheim, 2019.
- Handbook of Organic Materials for Electronic and Photonic Devices, 2nd ed., Ed. O. Ostroverkova, Woodhead Publ., Cambridge, 2018.
- E. V. Nosova, S. Achelle, G. N. Lipunova, V. N. Charushin, O. N. Chupakhin, *Russ. Chem. Rev.*, 2019, 88, 1128.
- J. Langford, A. Insuasty, S. Carrera, L. Tang, C. Forsyth, C. Hogan, C. McNei, *ChemPlusChem*, 2019, 84, 1638.

- C. Wang, H. Dong, W. Hu, Y. Liu, D. Zhu, *Chem. Rev.*, 2012, 112, 2208.
- M. Al Kobaisi, S. V. Bhosale, K. Latham, A. M. Raynor, S. V. Bhosale, *Chem. Rev.*, 2016, **116**, 11685.
- A. Nowak-Król, K. Shoyama, M. Stolte, F. Würthner, *Chem. Commun.*, 2018, 54, 13763.
- Organic Electronics II: More Materials and Applications, Vol. 2, Ed. H. Klauk, Wiley-VCH, Weinheim, 2012.
- A. S. Tayi, A. K. Shveyd, A. C.-H. Sue, J. M. Szarko, B. S. Rolczynski, D. Cao, T. J. Kennedy, A. A. Sarjeant, C. L. Stern, W. F. Paxton, W. Wu, S. K. Dey, A. C. Fahrenbach, J. R. Guest, H. Mohseni, L. X. Chen, K. L. Wang, J. F. Stoddart, S. I. Stupp, *Nature*, 2012, **488**, 485.
- S. Kola, J. H. Kim, R. Ireland, M.-L. Yeh, K. Smith, W. Guo, H. E. Katz, ACS Macro Lett., 2013, 2, 664.
- 14. Q. Zheng, J. Huang, A. Sarjeant, H. E. Katz, J. Am. Chem. Soc., 2008, 130, 14410.
- S. Kola, N. J. Tremblay, M.-L. Yeh, H. E. Katz, S. B. Kirschner, D. H. Reich, *ACS Macro Lett.*, 2012, 1, 136.
- T.-F. Yang, S.-H. Huang, Y.-P. Chiu, B.-H. Chen, Y.-W. Shih, Y.-C. Chang, J.-Y. Yao, Y.-J. Lee, M.-Y. Kuo, *Chem. Commun.*, 2015, **51**, 1377.
- M.-L. Yeh, S.-Y. Wang, J. F. M. Hardigree, V. Podzorov, H. E. Katz, J. Mater. Chem. C, 2015, 3, 3029.
- Z. Liu, G. Zhang, Z. Cai, X. Chen, H. Luo, Y. Li, J. Wang, D. Zhang, *Adv. Mater.*, 2014, 26, 6965.
- S. V. Bhosale, C. H. Jani, S. J. Langford, *Chem. Soc. Rev.*, 2008, 37, 331.
- 20. Z. Li, Q. Yang, R. Chang, G. Ma, M. Chen, W. Zhang, *Dyes Pigm.*, 2011, 88, 307.
- H. Cao, V. Chang, R. Hernandez, M. D. Heagy, J. Org. Chem., 2005, 70, 4929.
- 22. S. S. Gunathilake, P. Huang, M. P. Bhatt, E. A. Rainbolt, M. C. Stefan, M. C. Biewer, *RSC Adv.*, 2014, **4**, 41997.
- 23. S.-L. Suraru, F. Würthner, Angew. Chem., Int. Ed., 2014, 53, 7428.
- 24. S. V. Bhosale, C. H. Jani, S. J. Langford, *Chem. Soc. Rev.*, 2008, **37**, 331.
- 25. H. Langhals, Heterocycles, 1995, 40, 477.
- E. A. Komissarova, A. N. Vasyanin, V. E. Zhulanov, I. V. Lunegov, E. V. Shklyaeva, G. G. Abashev, *Russ. Chem. Bull.*, 2019, 68, 1702.
- 27. W. A. Mosher, S. J. Chlystek, J. Heterocycl. Chem., 1972, 9, 319.
- 28. Y. Peng, L. Cao, Zh. Li, Appl. Surf. Sci., 2017, 420, 355.
- T. F. Scholz, N. J. Somerville, G. M. Smith, US Pat. 2660579, *Chem. Abstrs*, 1954, 48, 12184.
- H. Nakayama, J. Nishida, N. Takada, H. Sato, Y. Yamashita, Chem. Mater., 2012, 24, 671.
- Y.-J. Huang, W.-C. Lo, S.-W. Liu, C.-H. Cheng, C.-T. Chen, J.-K. Wang, *Sol. Energy Mater Sol. Cells*, 2013, 116, 153.
- 32. H. Meng, J. Zheng, A. J. Lovinger, B.-C. Wang, P. G. Van Patten, Z. Bao, *Chem. Mater.*, 2003, **15**, 1778.
- 33. E. V. Verbitskiy, E. M. Cheprakova, J. O. Subbotina, A. V. Schepochkin, P. A. Slepukhin, G. L. Rusinov, V. N. Charushin, O. N. Chupakhin, N. I. Makarova, A. V. Metelitsa, V. I. Minkin, *Dyes Pigm.*, 2014, **100**, 201.

Received December 24, 2019; in revised form January 29, 2020; accepted March 2, 2020