

Contents lists available at ScienceDirect

Journal of Fluorine Chemistry

journal homepage: www.elsevier.com/locate/fluor



Fluorine cleavage of the light blue heteroleptic triplet emitter FIrpic

Varatharajan Sivasubramaniam^{a,*}, Florian Brodkorb^a, Stephanie Hanning^a, Hans Peter Loebl^b, Volker van Elsbergen^b, Herbert Boerner^b, Ullrich Scherf^c, Martin Kreyenschmidt^a

^a Department Chemical Engineering, University of Applied Sciences FH Muenster, Stegerwaldstrasse 39, 48565 Steinfurt, Germany

^b Philips Technologie GmbH-Philips Research, Weisshausstr. 2, 52066 Aachen, Germany

^c FB C-Makromolekulare Chemie und Institut fuer Polymertechnologie, U-10.24, Bergische Universitaet Wuppertal, 42097 Wuppertal, Germany

ARTICLE INFO

Article history: Received 31 January 2009 Received in revised form 18 April 2009 Accepted 26 April 2009 Available online 5 May 2009

Keywords: α-NPD (α-4,4'-bis[(1naphthyl)phenylamino]-1,1'-biphenyl) Organic light emitting devices (OLEDs) Triplet emitter FIrpic (bis[2-(4,6-difluorophenyl)pyridyl-N,C2']iridium (III)) Chemical degradation

ABSTRACT

The lifetime stability of devices containing Flrpic as emitter has been a major concern for organic blue light emitting devices (OLEDs). To gain a deeper knowledge about the purity of Flrpic (bis[2-(4,6-difluorophenyl)pyridyl-N,C2']iridium (III)) emitters and how the purity is influenced by sublimation steps, non-sublimated and sublimated Flrpic material was analyzed *via* liquid chromatography coupled with electron spray ionization mass spectrometry (LC/ESI/MS). Cleavage of an electron-withdrawing group from one of the ligands of the heteroleptic phosphorescent emitter could be identified in sublimated Flrpic material *via* LC/ESI/MS. A detailed chemical analysis using LC/ESI/MS was carried out for complete blue emitting devices of the following structure: indium–tin-oxide (ITO)/50 nm (α -4,4'-bis[(1-naphthyl)phenylamino]-1,1'-biphenyl) (α -NPD)/10 nm 4,4',4''-tris(carbazol-9-yl)triphenylamine (TCTA)/100 nm TCTA:8% Flrpic/50 nm 1,1'-biphenyl-4'-oxy)-bis(8-hydroxy-2-methylquinolinato)-aluminum (BAlq)/1 nm LiF/100 nm Al. Two isomers of (Flrpic-1F) could be detected in an aged OLED. Changes in the ligand systems of Flrpic, especially the loss of fluorine during the deposition process can alter the emissive properties of the blue phosphorescent emitter. Beside isomer formation and chemical degradation of Flrpic, substantial degradation was observed for the hole transport material α -NPD in driven OLEDs.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

In 1983, Tang and Van Slyke reported the first thin-film green emitting OLED based on tris(8-hydroxyquinoline) aluminium (Alq₃) [1]. Organic light emitting diodes have attracted great attention in both fundamental research and device fabrication because of their potential application as display components [2-7]. Usually, OLEDs consist of organic layer systems sandwiched between two electrodes. Therefore, different organic layers with multiple functions are used. The various layer thicknesses are typically varied between 10 and 100 nm. The core of an OLED is the emitting layer. Electrons will be delivered from the cathode and the holes from the indium-tin-oxide (ITO) anode on the glass substrate. In the emitting layer electrons and holes will recombine exciting a molecule that can relax radiatively to the ground state. Two modes of light emission have to be considered: fluorescence and phosphorescence. Due to spin statistics, OLEDs using fluorescent materials are limited to an internal quantum efficiency of 25%, whereas in phosphorescent materials the internal quantum efficiency can reach up to 100%. Classical examples of phosphorescent emitting materials are the green emitter $fac \, Ir(ppy)_3$ and the red emitter PtOEP [8,9]. In order to attain blue emission one approach is to change the substituents of the ligands of the Ircomplexes. In FIrpic, a prototypical blue-green emitter, the heteroleptic iridium complex contains two fluoro-substituted phenylpyridine ligands and an anionic 2-picolinic acid.

Since the report of this light blue phosphorescent material from Adachi et al. [7], intense research was performed on many similar six-membered complex molecules like FIrpic. Unfortunately, the achieved lifetimes of blue emitter materials are still insufficient, with the exception of a blue emitting material from Konica Minolta [10].

In some cases, devices degradation was attributed to luminescence quench induced by metal migration. Therefore different analytical techniques were employed to investigate surface, interfacial electronic structures and morphology of such emitting devices, such as X-ray photoelectron spectroscopy (XPS) [11], inverse photoemission spectroscopy (IPES), ultraviolet photoelectron spectroscopy (UPS) and scanning electron microscopy (SEM) [12]. Other techniques for thin-film analysis of organic devices, such as dynamic secondary mass spectrometry (SIMS) [13,14] were used as well. Similar to the organic light emitting diodes,

^{*} Corresponding author. Tel.: +49 2551962 291; fax: +49 2551962 711. *E-mail address:* sivasubramaniam@fh-muenster.de (V. Sivasubramaniam).

^{0022-1139/\$ –} see front matter \circledcirc 2009 Elsevier B.V. All rights reserved. doi:10.1016/j.jfluchem.2009.04.009

indium diffusion from indium–tin-oxide has also been identified as one of the failure mechanisms in polymer devices [15]. Nevertheless these techniques all detect responses related to specific atoms. However, the first chemical analysis of devices using HPLC/ MS, in regarding degradation processes was performed by Kondakov et al. [16]. Dissolving the organic layers of the devices and direct analysis using high pressure liquid chromatography (HPLC), matrix assisted laser desorption ionization time-of-flight mass spectrometry (MALDI/TOF/MS), nuclear magnetic resonance (NMR) were done to get information about the degradation mechanism [16–18]. Recently Scholz et al. analyzed fully processed organic devices *via* LDI/TOF/MS technique [19]. In this paper, we report on an investigation of the degradation pathways of FIrpic, using HPLC coupled with mass spectrometry (MS). It has been demonstrated that LC/MS is an efficient analytical tool for the analysis of OLED materials and devices [16]. To analyze the molecular changes of the polar analyte FIrpic, an ion trap MS with electron spray ionization (ESI) was used as interface tool between HPLC and MS.

In order to investigate the steps in which degradation of FIrpic occurs, non-sublimated and sublimated materials were compared. In addition two diodes with identical architecture – one pristine and one stressed – were compared in order to examine emitter degradation during device operation.



Fig. 1. (a) EIC m/z 718 and (b) EIC m/z 573 of unprocessed material FIrpic. (c) MS spectra of the FIrpic isomers (I + II). Cleavage of picolinate from FIrpic (d) at t_R = 7 min (t_R = time elapsed between the injection point and the peak maximum).

2. Results and discussion

Homoleptic and heteroleptic iridium complexes have different isomers. Homoleptic d^6 transitions Ir(III) complexes have only the fac and mer isomers, whereas in heteroleptic systems four different isomers are possible [20]. At first the nonsublimated and sublimated FIrpic materials were analyzed using a specially developed HPLC method, which is able to separate the different isomers. The analytes were detected by ESI/MS coupled to the HPLC. Moreover in order to determine if the vapor deposition process and the electrical driving of the OLEDS posses an influence on the FIrpic emitter material, pristine and stressed device doped with 8% FIrpic were also studied. As the first step of these investigations, the purity of the nonsublimated FIrpic complex was investigated using the mentioned HPLC/ESI/MS method. Fig. 1(a) and (b) shows the extracted ion current (EIC) signals of the non-sublimated material FIrpic with the corresponding masses of m/z 718 and m/z 573. m/z 718 corresponds to the molecule (FIrpic + Na⁺) and m/z 573 to (FIrpic-picolinate).

Two signals were obtained at a mass of m/z 718 for the nonsublimated FIrpic, which is shown in Fig. 1(a). One signal occurs at $t_R = 9$ min and the second one at $t_R = 12$ min. Using EIC m/z573 delivers also the two signals at $t_R = 9$ min and at $t_R = 12$ min. These findings lead to the conclusion that at least two FIrpic isomers were produced in higher concentrations during the synthesis of the material. For both isomers ($t_R = 9$ min and $t_R = 12$ min) identical mass spectra were obtained which is illustrated in Fig. 1(c). Outlining from Fig. 1(a) and (b) two isomers of FIrpic and FIrpic decorated only with the two *dfp* ligands were detected in non-sublimated material FIrpic. Additionally in non-sublimed material a derivative of FIrpic molecule in which one of the ligands has only one fluorine atom was observed. Fig. 2(a) and (b) shows the EIC of m/z 700 and m/z 555. EIC of m/z 700 corresponds to (FIrpic-1F + Na⁺) and m/z 555 to (FIrpic-picolinate-1F). The corresponding mass spectrum is given in Fig. 2(c).

These results demonstrate that in non-sublimated FIrpic two of the four FIrpic isomers, (FIrpic-picolinate) and especially a FIrpic derivative with only three fluorine atoms (FIrpic-1F) can be identified.

Next, the analysis of the sublimated FIrpic was carried out applying the same LC/ESI/MS conditions. A LC/ESI/MS chromatogram using EIC mode with the mass of m/z 718 and m/z 573 of sublimated FIrpic is shown in Fig. 3(a) and (b).

EIC mode with the masses m/z 718 and m/z 573 indicates that the sublimated FIrpic material only contains one of the isomers with the retention time $t_{\rm R} = 12$ min. The chromatogram does not display any signals before and after the retention time $t_{\rm R} = 12$ min no signals with the masses of m/z 573 and m/z 718 could be observed. Therefore the sublimation process is suitable to separate the two isomers formed during the synthesis of the material FIrpic.

In order to investigate if FIrpic derivatives with three fluorine atoms are also separated in the sublimation process, EIC-MS investigations for the mass of m/z 700 and m/z 555 were performed on the cleaned materials. Fig. 3(a) and (b) clearly reveals that one sublimation step alone is not suitable to eliminate the derivative (FIrpic-1F) completely from the mixture. Comparing the concentrations of sublimated and



Fig. 2. (a) EIC of *m*/*z* 700 of unprocessed material FIrpic. (b) EIC of *m*/*z* 555 of unprocessed material FIrpic which corresponds to (FIrpic-picolinate-1F). (c) Mass spectra of the peak at *t*_R = 13.5 min.



Fig. 3. (a) EIC of *m*/*z* 718 and (b) EIC of *m*/*z* 573 which show the signals for the FIrpic isomer (II) in sublimed material FIrpic. (c) and (d) Corresponds to (FIrpic-1F + Na⁺) and (FIrpic-picolinate-1F) in sublimed material FIrpic.

non-sublimated material, it is nevertheless evident that the amount of (FIrpic-1F) is decreased substantially. The relative decrease in the intensity of the formed analyte (FIrpic-1F) is likely due to the one step sublimation process. Because it is necessary to decrease the molar amount of the analyte (FIrpic-1F) this would suggest and suppose that for application of pure FIrpic, many sublimation cycles have to be performed in order to get a pure material.

The sublimation process is therefore a suitable cleaning procedure for FIrpic. To look for similar effects, analyses of pristine and aged blue emitting FIrpic devices were carried out. Fig. 4(a) and (b) shows the EIC of m/z 718 and m/z 573.

The peaks at $t_{\rm R}$ = 12 min indicate the presence FIrpic isomer (II) (Fig. 4(a) and (b)). Interestingly the extracted ion chromatograms of m/z 718 and m/z 573 show dramatic changes, comparing sublimated FIrpic with doped FIrpic devices. An additional signal was observed at $t_{\rm R}$ = 12 min, which indicates the formation of

Flrpic isomer (III). Isotopic patterns and mass spectra confirmed the identity of the formation of Flrpic isomer (III).

Beside the identification of FIrpic isomers (II) and (III) in unstressed devices, no indication of the FIrpic isomer (I) could be found (Fig. 4(c)).

Overall, this experiment confirms that during the deposition process isomerization of the FIrpic emitter is taking place and the newly formed isomers can be already detected in pristine devices.

Beside the formation of the two isomers of the heteroleptic emitter FIrpic no evidence of chemical cleavage of picolinate from FIrpic molecule during the vapor deposition process could be observed. This compound would appear at $t_{\rm R}$ = 7 min.

From the chromatographic analysis of the unprocessed and sublimated material FIrpic the loss of one fluorine atom from the emitter molecule FIrpic could be detected. In fact using EIC of m/z 700, the presence of the molecule (FIrpic-1F) can also be shown in pristine devices, which is illustrated in Fig. 5.



Fig. 4. (a) EIC of *m*/*z* 718, (b) EIC of *m*/*z* 573 of pristine device and (c) zoomed chromatogram of EIC of *m*/*z* 573.

However, it is an important result that during the manufacture processes not only the two FIrpic isomers were generated but also the molecule (FIrpic-1F).

The LC/ESI/MS spectra utilizing EIC and focusing on the masses of m/z 718 and m/z 573 are shown in Fig. 6(a) and (b) for a driven device.

To get further information into the role of the emitter degradation during device operation, LC/ESI/MS measurements were carried out on aged devices.

Fig. 6(a) and (b) indicates that FIrpic isomers (II) and (III) are present in 24 h aged devices and moreover the FIrpic isomer (I) (Fig. 6(c) at $t_{\rm R}$ = 9 min) could be detected as well, which was not the



Fig. 5. EIC of m/z 700 of unstressed device.



Fig. 7. EIC of m/z 700 of aged device.

Time [min]

Annun

case in unstressed devices. The presence of FIrpic isomer (I) could be due to the thermal heat during device operation. The detailed analysis of Fig. 6(c) further reveals that beside the formation of the FIrpic (I) isomer an addition signal with m/z 573 using EIC at a retention time $t_{\rm R}$ = 7 min could be detected. This compound is a cleavage product of the emitter molecule FIrpic, in which the weakest ligand, the anionic picolinate is separated.

This dissociation of the picolinate was only observed in aged devices (24 h). Therefore the fragmentation of FIrpic is a direct result of the operation of the OLED. To further explore the degradation process of the aged device, EIC profiles with m/z 700 were carried out. Fig. 7 shows the EIC of m/z 700 of stressed device.

The relative intensity of the molecule (FIrpic-1F) increased during device operation. This indicated that more (FIrpic-1F) are formed during the aging process. The most significant observation is the appearance of an additional signal at $t_{\rm R}$ = 15 min using EIC m/z 700. This signal was confirmed by several injections of different extracts of stressed devices. It is another further isomer of the molecule (FIrpic-1F). Theoretically sixteen different isomers of the (FIrpic-1F) molecule are possible. All sixteen isomers of the cleavage of one electron-withdrawing group fluorine atom of the emitter FIrpic are given in Fig. 8.

These results were verified repeating the experiments several times, always leading to the same results. The isotopic patterns analyses revealed that the compound with a molecular mass of m/z



Fig. 8. Sixteen possible theoretical isomer products of loss of one fluorine atom from the emitting material FIrpic.

Table 1

Components of FIrpic in non-sublimated, sublimated, pristine and aged devices.

	FIrpic isomer (I)	FIrpic isomer (II)	FIrpic isomer (III)	Flrpic-picolinate	FIrpic-1F	FIrpic-1F isomer
Non-sublimated FIrpic	+	+	-	+	++	-
Sublimated FIrpic	-	+	-	-	+	-
Pristine OLED	-	+	+	-	+	-
24 h aged OLED	+	++	+	+	++	+

(-): not detected.

(+): detected.

(++): observed in higher amounts.

700 contains the metal atom iridium further confirming the interpretation. As the intensity increases, it becomes clear that formation of isomerization species during device operation will play an important role in the investigation of degradation mechanisms of the PhOLEDs.

In summary, comparing the pristine with the aged devices, three different degradation products of the emitter FIrpic were detected using LC/ESI/MS. One important indication is the formation of the dissociation product (FIrpic-picolinate). Furthermore the formation of FIrpic isomer (I) could only be detected in aged devices. Finally another isomer of (FIrpic-1F) was identified. Table 1 summarizes the results.

In summary, it was shown that in using an appropriate LC/MS method, the identification of the different species from the light blue emitter material FIrpic. Direct chromatographic separation of enantiomers on chiral stationary phases by liquid chromatography has been extensively developed. With ordinary chromatographic method, it has been shown that the different species from FIrpic could be separated on a non-chiral column. This method will be useful not only for the determination of the purity of the sublimated material of the iridium complexes FIrpic but also for obtaining the possible degradation products from pristine and stressed devices.

To estimate the concentration of the materials was a challenging task. Degradation products from the cyclometalated iridium (III) complex FIrpic are presently unknown. Several repetitions of the measurements and comparing the signal ratio of the analytes leads to the results that the amount of isomerization products of the cyclometalated iridium (III) complex FIrpic increases especially during the device operation. Both degradation and isomerization products increase in their intensity gradually if pristine and aged devices were compared. This similar observation and information was not only found for the emitting material, but also for the degraded product from the hole transport material α -NPD.

These results support the hypothesis that isomerization is taking place during device operation which could have a significant impact on the lifetime of the OLED. Similar observations were made in other phosphorescent emitter materials as well.

Furthermore the characteristics of the hole transport material α -NPD in pristine and aged devices was investigated. First of all HPLC/ESI/MS analysis of the sublimed material α -NPD was performed. No fragmentations of the substituents of α -NPD could be detected in these investigations.

However in vacuum-deposited devices one signal with the mass of m/z 469 at $t_{\rm R}$ = 10.5 min (Fig. 9(a)) could be detected *via* LC/ ESI/MS. This corresponds to the loss of one naphthyl group. Such a dissociation process during the evaporation process has not been reported for the case of α -NPD. The N–C bond of α -NPD seems to be prone to rupture during the heating process. Interestingly the EIC experiments delivered two signals at different retention times with a mass of m/z 463. Fig. 9(b) shows the EIC with the mass of m/z 463 of 24 h aged device.

The signal at $t_{\rm R}$ = 10.5 min corresponding to the molecule (α -NPD-naphthyl) is significantly increased in stressed devices. The additional signal with m/z 463 is detected at a retention times $t_{\rm R}$ = 9 min and is only found in aged devices. Comparing the mass spectra of the signal (α -NPD-naphthyl) at $t_{\rm R}$ = 10.5 min with the mass spectra of the new signal at $t_{\rm R}$ = 9 min identical spectra were obtained. This is a strong indication that another isomer of the molecule (α -NPD-naphthyl) was generated during operation.

However the amounts of both signals with the mass of m/z 463 are too low to isolate them for determining the absolute configuration *via* NMR.

No signs of chemical degradation of the host material TCTA and of the electron transport material BAlq were found *via* LC/ESI/MS.

LC/ESI/MS is a powerful analytical technique to characterize the structural transformations of the d^6 transition heteroleptic Ir(III) complex FIrpic during device operation. In conclusion, one isomer was formed during the deposition process and the other one during device operation. Chemical transformations were observed after device operation, resulting in (FIrpic-1F) and (FIrpic-picolinate).

Two different aspects have to be considered regarding the degradation of the emitter material. Cleavage of one fluorine atom from FIrpic may cause a significant spectral change in the emitted light. Secondly, the cleavage product can undergo further chemical reactions with other organic materials nearby. Among the various factors that may contribute to the degradation phenomena in OLED, isomerization and the loss of an electron-withdrawing group may have a considerable influence on the electroluminescent lifetime of blue OLEDs based on FIrpic.

As in the report of the dissociation process of the molecule CBP from Kondakov et al. [16], cleavage of N–C bonds was shown for α -NPD in stressed devices.

3. Experimental

3.1. Materials

Unprocessed material FIrpic and pure sublimed standard substances 4,4',4"-tris(carbazol-9-yl)triphenylamine (TCTA), α -4,4'-bis[(1-naphthyl)phenylamino]-1,1'-biphenyl (α -NPD), 1,1'-biphenyl-4'-oxy)-bis(8-hydroxy-2-methylquinolinato)-aluminum (BAlq) and bis(2-[4,6-difluorophenyl)pyridyl-N,C2']iridium (III) (FIrpic) were kindly delivered from Philips Research Aachen. Solvent dioxane (HPLC grade) was purchased from Merck.

3.2. Devices

OLED devices with FIrpic were prepared by Philips Research Aachen. The organic layers were deposited using thermal evaporation on indium–tin-oxide (ITO) covered glass substrates. The light blue emitting device consists of a 50-nm α -NPD layer, followed by 10 nm TCTA. As host 100 nm TCTA was used that



Fig. 9. Chemical reaction (I) shows the possibilities of the cleavage of naphthyl from hole transport material α -NPD. One of those occurs already in a tiny amount in unstressed device (a). In stressed device both isomers occurs in greater amount which is shown in chemical reaction (II).

was doped with 8% of the blue turquoise phosphorescent emitter FIrpic. As electron transport layer (ETL) BAlq was employed in layer thickness of 50 nm. Electrons were injected from 100 nm Al cathode which was deposited on the top of the BAlq. As cathode, 1 nm LiF and 100 nm Al was deposited on top of the organic layers. These devices were aged under glove box conditions (<0.1 ppm H_2O and O_2 each) for 24 h at 10 V and 100 mA/cm².

3.3. Sample preparation

For LC/ESI/MS analysis devices were prepared in the following way. Active areas of the devices were cut out with a diamond cutting tool. Using the cut-off technique, the organic thin films of the devices were carefully separated from the non-active areas. For the analysis 1 cm \times 1 cm area of the device were used for the further process. Unstressed and aged active area pieces were extracted separately in 5 ml dioxane. The cathode and anode materials were removed from the organic extract, by filtration through a 4-µm nylon microdisc filter. Afterwards the filtrate was evaporated with a N₂ stream and dissolved with 500 µl dioxane.

3.4. LC/ESI/MS measurements

For LC/ESI/MS analysis the injection volume was 10 μ l extract. The analytes and the device extracts were analyzed using a Merck Hitachi HPLC system (Darmstadt, Germany). Consisting of a smash pump (Model L-2100) including a degaser, an oven (Model L-2300), an automated injector and an UV (Model L-2400) detector. MS analyses were carried using a Bruker Daltonics esquire 4000 (Bremen, Germany) instrument. The ion trap octapole mass spectrometer with electron spray ionization (ESI), which was operated in positive ionization mode.

All HPLC separations were carried out using a polar Chromolith Si 100 column with 100% acetonitrile as eluent and a flow rate of 0.3 ml/min.

Acknowledgment

This work has been supported by BMBF (Bundesministerium für Bildung und Forschung)-funded project 13N8669 (OPAL). The authors wish to thank Philips Technologie GmbH-Philips Research (Aachen, Germany) for their financial support.

- References
- S.A. Van Slyke, C.H. Chen, C.W. Tang, Applied Physics Letters 69 (1996) 2160-2162.
- [2] B.K. Crone, P.S. Davids, I.H. Campbell, D.L. Smith, Journal of Applied Physics 87 (2000) 1974–1982.
- [3] S. Tokito, Y. Taga, Applied Physics Letters 66 (1995) 673-675.
- [4] R.H. Jordan, L.J. Rothberg, A. Dodabalapur, R.E. Slusher, Applied Physics Letters 69 (1996) 1997–1999.
- [5] V. Bulovic, P. Tian, P.E. Burrows, M.R. Gokhale, S.R. Forrest, M.E. Thompson, Applied Physics Letters 70 (1997) 2954–2956.
- [6] R. Antony, A. Moliton, B. Lucas, Applied Physics A: Materials Science & Processing 70 (2000) 185–195.
- [7] C. Adachi, R.C. Kwong, P. Djurovich, V. Adamovich, M.A. Baldo, M.E. Thompson, S.R. Forrest, Applied Physics Letters 79 (2001) 2082–2084.
- [8] M.A. Baldo, D.F. O'Brien, Y. You, A. Shoustikov, S. Sibley, M.E. Thompson, S.R. Forrest, Nature (London) 395 (1998) 151–154.
- [9] M.A. Baldo, S. Lamansky, P.E. Burrows, M.E. Thompson, S.R. Forrest, Applied Physics Letters 75 (1999) 4–6.
- [10] K.H. Tomoyuki Nakayama, K. Furukawa, H. Ohtani, Konica Minolta Technology Report, 2006, 5, 115–120.
- [11] L. Yan, Y. Gao, Thin Solid Films 417 (2002) 101-106.
- [12] M. Carrard, S. Goncalves-Conto, L. Si-Ahmed, D. Ade, A. Siove, Thin Solid Films 352 (1999) 189-194.
- [13] À. Delcorte, S. Hermans, M. Devillers, N. Lourette, F. Aubriet, J.F. Muller, P. Bertrand, Applied Surface Science 231–232 (2004) 131–135.
- [14] S.T. Lee, Z.Q. Gao, L.S. Hung, Applied Physics Letters 75 (1999) 1404-1406.
- [15] A.R. Schlatmann, D.W. Floet, A. Hilberer, F. Garten, J.M. Smulders, T.M. Klapwijk, G. Hadziioannou, Applied Physics Letters 69 (1996) 1764–1766.
- [16] D.Y. Kondakov, W.C. Lenhart, W.F. Nichols, Journal of Applied Physics 101 (2007), 024512/024511-024512/024517.
- [17] D.Y. Kondakov, W.C. Lenhart, W.F. Nichols, Abstracts of Papers, 232nd ACS National Meeting, San Francisco, CA, United States, September 10–14, 2006 Journal Title: Abstracts of Papers, 232nd ACS National Meeting, San Francisco, CA, United States, September 10–14, 2006, 2006, ORGN-095.
- [18] V. Goldberg, M. Kaplan, L. Soltzberg, J. Genevich, R. Berry, A. Bukhari, S. Chan, M. Damour, L. Friguglietti, E. Gunn, K. Ho, A. Johnson, Y.Y. Lin, A. Lowenthal, S. Suth, R. To, R. Yopak, J.D. Slinker, G.G. Malliaras, S. Flores-Torres, H.D. Abruna, Materials Research Society Symposium Proceedings 846 (2005) 301–306.
- [19] S. Scholz, K. Walzer, K. Leo, Advanced Functional Materials 18 (2008) 2541– 2547.
- [20] E. Baranoff, S. Suarez, P. Bugnon, C. Barolo, R. Buscaino, R. Scopelliti, L. Zuppiroli, M. Graetzel, M.K. Nazeeruddin, Inorganic Chemistry, vol. 47, American Chemical Society (ACS), Washington, DC, United States, 2008, pp. 6575–6577.