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DEVELOPMENT OF LIGHT EMITTING ELECTROLUMINESCENT DEVICE BY MEANS OF MATERIAL PRINTING
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DOCTORAL THESIS
DIZERTAČNÍ PRÁCE

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ABSTRACT

The topic of this thesis is development of a printed alternating current powder-based phosphor electroluminescent (ACPEL) light source. It is the only present technology suitable for fabrication of large area, flexible and patterned light sources by the means of material printing and so it represents a promising alternative to some traditional light sources. Emphasis is placed on introduction and investigation of some red brick wall problems associated with this technology. These are a limited hue of colors of emitted electroluminescent light and an operation lifetime of panels exposed to environment.

The first part of this thesis is focused on identification of suitable deposition techniques and their operation conditions leading to reproducible preparation of panels followed by determination of appropriate physical parameters suitable to characterize large area light sources. Therefore relevant coating and printing techniques are introduced along with their practical advantages and disadvantages with respect to preparation of the ACPEL panels.

A photometric quantity luminance L_V together with electric energy consumption P was evaluated to determine driving conditions for a suitable application of ACPEL panels. The maximum luminance $L_V = 133\ \mathrm{cd \cdot m^{-2}}$ was achieved on a blue panel driven by $U_{pp} = 500$ V and $f = 1000$ Hz. Achieved values of power consumption per unit area are (7 ± 3) mW make the light sources based on this technology interesting for practical applications.

The effect of driving conditions on stability of panels together with means to improve a long term stability of ACPEL panels is important topic this thesis deals with. Parameters L_{50} and L_{75} were established from the values of spectral irradiance. It was found that increasing the frequency has a negative effect on the long term stability of panels. A panel driven by 3 times higher frequency with the same voltage showed almost 3 times less values of L_{50} and L_{75} with the same type of lamination while a panel encapsulated by glass showed almost 7 times higher stability than the laminated panel. Optimal stability conditions were achieved when the driving frequency was set between 400 Hz and 800 Hz with robust encapsulation between two glass panels.

Limited hue of colors of light emitted by ACPEL panels is one of the known problems this thesis addresses. This work investigates a promising method, an addition of a color conversion material (CCM) with suitable spectral characteristics. A derivative of diketopyrrolopyrrole (DPP) was found to be a suitable novel CCM for blue phosphor. Using this CCM a 7-times increase of spectral irradiance of a blue panel at 580 nm was easily achieved.

An ease of fabrication, very low power consumption and long life time of the developed ACPEL panels together with developed possibility to modify a hue of emitted light, make them potentially ideal light sources for low-light background illumination for example in automotive industry, safety signs in public buildings, indoor decorative illumination or “branding”etc.

KEYWORDS

Printed Electronics, Phosphor, Alternating Current Powder-based Electroluminescence, Electroluminescent panel, Screen-printing, Large Area Light Source, Material printing, Luminance

ABSTRAKT

Cílem této práce je vývoj světelného zdroje založeného na technologii tlustostěnného elektroluminiscenčního panelu napájeného střídavým napětím (ACPEL). V současné době se jedná se o jedinou technologii založenou na metodách materiálového tisku vhodnou pro přípravu velkoplošných, flexibilních a vzorovaných zdrojů světla. Důraz je v této práci kladen na představení, prozkoumání a odstranění typických problémů, které jsou spojovány s touto technologií. Tyto problémy jsou omezený odstín barvy emitovaného světla a dlouhodobá stabilita elektroluminiscenčního prvku, který je vystaven vlivům prostředí.

Rešeršní část dizertační práce je zaměřena na představení a identifikaci depozičních technik, vhodných pro reprodukovatelnou přípravu ACPEL panelů. Dalším cílem je identifikace fyzikálních parametrů, vhodných pro charakterizaci velkoplošných zdrojů světla.

Praktickým cílem práce je nalezení vhodné metodologie pro popis a charakterizaci panelů, jakožto plošných světelných zdrojů. Fotometrická veličina jas L_V a spotřeba elektrické energie P byly vyhodnoceny jako vhodné parametry, určující aplikaci ACPEL panelů. Na modrém panelu bylo dosaženo maximální hodnoty jasu $L_V = 133\ \mathrm{cd{\cdot}m^{-2}}$ při napětí $U_{pp} = 500$ V a frekvenci $f = 1000$ Hz. Hodnoty spotřeby elektrické energie, vztažené na jednotkovou plochu panelů zkoumaných v této práci, jsou (7±3) mW. Tyto dosažené hodnoty dělají ze světelných zdrojů založených na ACPEL technologii zajímavé kandidáty pro různé aplikace.

Vlivu rostoucí amplitudy a frekvence budícího napětí na dlouhodobou stabilitu panelů je důležitým cílem této práce. Pro popis stability byly zavedeny parametry L_{50} and L_{75}. Bylo zjištěno, že rostoucí frekvence budícího napětí zkracuje životnost panelů. Laminovaný panel napájený napětím s přibližně trojnásobně vyšší frekvencí vykazoval přibližně třetinové hodnoty parametrů L_{50} a L_{75}. Nejvyšších hodnot stabilitních parametrů dosahoval panel enkapsulován mezi skleněné pláty – přibližně sedminásobnou hodnotu oproti laminovanému panelu s trojnásobnou frekvencí. Optimální stability panelů lze dosáhnout při nastavení frekvence v rozmezí 400–800 Hz a zapouzdřením mezi sklo.

Úzká paleta odstínů barev emitovaného světla je jeden z typických problémů, který dále zkoumán v dizertační práci. Tato práce zkoumá nadějnou metodu, přídavek vhodného materiálu pro konverzi barvy (CCM). Nový derivát diketopyrrolopyrrolu (DPP), absorbující v modré oblasti, byl přidán k modrému fosforu a byl pozorován sedminásobný narůst hodnot absolutního spektrálního ozáření v oblasti vlnových délek odpovídajících maximální emisi CCM materiálu.

Jednoduchost přípravy vyvinutých zdrojů světla spolu s velmi nízkou spotřebou a vysokou dobou života dělají z ACPEL panelů zajímavé kandidáty pro podsvícení prvků například v automobilovém průmyslu, pro dekorativní osvětlení, pro „branding“ – zvýraznění reklamních značek

KLÍČOVÁ SLOVA

Elektroluminiscenční panel, sítotisk, fosfor, zdroj světla, materiálový tisk, tištěná elektronika, střídavé napětí

CONTENT

1 AIM OF DISSERTATION THESIS

The first goal of this dissertation thesis is to find a methodology of reproducible preparation of alternating current powder-based panels (ACPEL) and identification of typical problems connected with the procedure. Therefore the first step is an introduction of possible deposition techniques with respect to their suitability to print patterned and homogenous films from very viscous printing formulation. A need to identify parameters and operating conditions of the chosen printing technique leading to reproducible production of panels exhibiting the best optoelectronic properties results from the first aim.

In the view of the fact that electroluminescent panel is a large area light source, identification and implementation of suitable methodology for measurement and evaluation of relevant parameters describing the suitability of the light source for a specific application is one of the main goal of this thesis. This work also deals with further determining of optimal optoelectronic performance under different driving conditions. An increase of both an amplitude and frequency of harmonic alternating voltage leads to a higher luminance but is one of the causes decreasing lifetime. Lifetime of ACPEL panels has been a well-known limit speaking against their mass-production in the field of printed electronics.

Since a narrow palette of emitted light hues is a known deep throat of this technology, another aim of this dissertation thesis is to investigate possible ways leading to extending the color palette. The study and identification of the main factors decreasing the lifetime of panels, together with evaluation of stability parameters under different driving conditions lead to the most important goal of this thesis – a removal of well-known red brick wall problems preventing the ACPEL panels to find broader use in applications.

2 INTRODUCTION

Organic and printed electronics (sometimes also called emerging and many other names) is a novel type of electronics which is beyond the classical approach based on silicon. This new technology offers a way of producing thin film, light-weight, flexible and environmentally friendly products and also a production of printable electrical components that can be integrated into the classical microelectronic systems. Flexible OLED displays electroluminescent panels, smart clothing, solar cells, printed batteries, supracapacitors, memory or label-protection tags are just few examples of promising application of such systems. These electrical devices are built by stacking of multiple thin layers (usually in the order of nanometers and microns) with specific properties atop each other. These materials are soluble in suitable organic solvents and therefore a mass-volume production of specific devices is achievable by various printing techniques. This is a key fact for deployment of printed electronic devices in various applications since their preparation is much more cost-effective then the inorganic devices prepared by traditional techniques. This technology leads to the development of brand new concepts such as wearable electronics, Internet of Things and smart labels.

Organic and printed electronics is based on the combination of new materials and cost-effective large area deposition techniques. These materials were at the beginning almost exclusively of organic origin, hence the name *organic electronics*. Diketopyrrolopyrrole (DPP), poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), TIPS pentacene and poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV) are just few examples. The amount of organic materials exhibiting interesting properties such as electrical conductivity, magnetic properties and excellent durability and so on has been steeply rising for more than 40 years. The fact that Heeger, MacDiarmid and Shirakawa were awarded Nobel Prize in chemistry in the year 2000 for: "*The discovery and development of conductive polymers.*" may serve as a convincing fact. Recently however more and more inorganic and hybrid materials started to be deployed because of the overall development of technology. Printable inorganic formulations of silicon, silver, ZnS, TiO_2, perovskites, carbon nanotubes etc. have been developed as well. Advantage of inorganic materials is their better stability which results in better processability during manufacturing

The whole field of printed electronics has been divided by the experts of Organic and Printed Electronics Association (OE-A) into 5 subcategories such as OLED lightning, organic photovoltaics, flexible displays, electronic components and integrated smart systems. The up to date state is described for all the categories and visions for further short term and long term (2023+) development are introduced together with a list of key technology parameters and so called red brick walls for each of the five subcategories. These red brick problems represent technological problems and difficulties that need to be overcome in order to incorporate organic electronic devices into everyday life. Each subcategory will be rendered technologically useless without successful solving of the below mentioned problems. Some of these problems concerning the lighting industry are:

- Substrate sizes – the production cost decreases with larger deposited areas. This fact indicates that currently well-established evaporation techniques will have to make a way for material printing techniques

- Development of new flexible substrates (improvement of a bending radius) – at the moment only glass substrates are being deployed which are difficult to process by means of material printing

- Development of barrier films – environmental stability of OLED panels is poor and without proper barrier films a lifetime is unacceptably low

Display and lightning technology are very important areas. While OE-A predictions are focused mainly on OLED technology, it is still far from solving all its problems. Mainly poor environment stability is problem for displays because a contact with molecules of water destroys the display permanently. Another problem is that criteria for processing conditions are difficult to meet because the deposition needs to be conducted under highly controlled atmosphere. Also the lifetime of OLED displays is not as high as lifetime of other, more traditional (such as LED and LCD). All these factors make the OLED displays and lighting sources very expensive at present.

The aim of this work is focused on the study and development of light sources based on an alternative technology – powder-based electroluminescent. This type of devices is interesting from multiple facts. There is no need of new exotic, extremely complicated and expensive molecules and can be fabricated with basic equipment accessible to many manufacturers and relatively large well patterned panels can be produced in short time. The overall concept is very easy and cost-effective in contrast to some of the devices mentioned above. The typical luminance of electroluminescent panel is usually in the range of 100–200 $\mathrm{cd \cdot m^{-2}}$ while average modern TV (either OLED or LCD) ranges between 500–1000 $\mathrm{cd \cdot m^{-2}}$. ACPEL panel is not as effective as other devices but for some applications (back light, interior decoration etc.) it could represent serious alternative to the above mentioned technology.

3 THEORETICAL PART

Electroluminescence (EL) is a conversion of electrical energy to optical by the electronic conversion process. It is nowadays considered as a process of non-thermal (which excludes incandescence – generation of light by heating) generation of light in materials by application of high intensity electric field. The material can be both of organic or inorganic origin.

The electroluminescence in inorganic materials is divided into two distinctive branches: injection EL and high-field EL. The latter is further divided into thin-film EL (TFACEL) and powder-based phosphor EL (ACPEL) which is topical for this thesis. A summary of EL types with respect to the devices that operate on the mentioned principles of electroluminescence is depicted in **Fig. 1**.

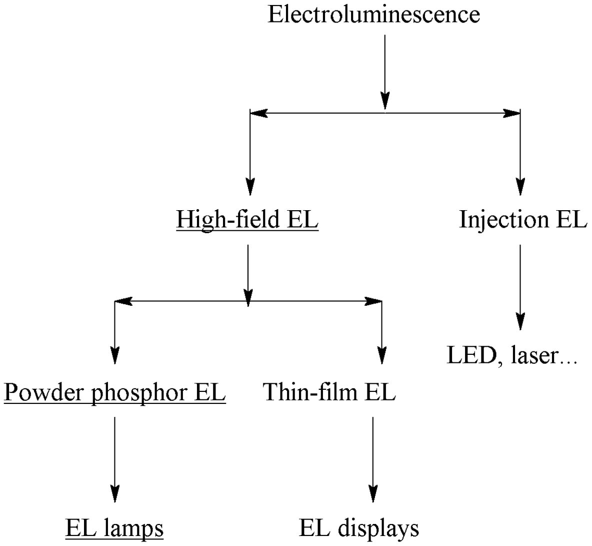

Fig. 1 *Various categories of EL types with typical devices. Under script notes the type which is topical for this thesis.*

The effect of alternating-current electroluminescence (ACEL) in ZnS was first observed by Georges Destriau in 1936 [1]. The lighting devices based on ACEL were at first considered as very promising new sources of light. This first generation of devices didn't show sufficient light output and also the life-time of original materials was very limited. All these factors ensured that ACEL light sources didn't become commercially interesting at late thirties. It took almost 20 years to form basic concepts and first theoretical background of electroluminescence [2, 3] the search for better performing device, new types of electroluminescence based devices have been discovered in following time. Namely DC (direct-current) thin film electroluminescence, DC powder luminescence, AC thin film electroluminescence (ACTFEL) with sputtered or evaporated phosphor layer. A comprehensive review with specific advantages/disadvantages of various approaches was given here [4].

The ACPEL based light-emitting devices have a potential to be very interesting for industry since the preparation can be done by material printing on various substrates including flexible foils [5, 6]. Material printing is well established simple method for deposition of large areas which brings economical advantage among others compared to classical evaporation or sputtering deposition which is typical for ACTFEL. A disadvantage of ACPEL is a very low efficiency and radiance output when compared to other types of lightning sources (LED, fluorescent tubes…). It could be commercially utilized as a source of background lightning or as a lamp in dark rooms. On the other hand it bears the benefits from the material printing.

Pioneering work in the field of electroluminescence has been conducted by Fischer who first clarified the process of generation of electroluminescence in doped ZnS phosphor devices. He later presented improved models that remain valid until today [7]. A comprehensive review on ACPEL was published by [4] where the process of generation of electroluminescence is described from a physical point of view in depth. Smet [8] introduced extensive overview of differently doped phosphors with respect to the emitted light color. Winscom et al 2015 [9] introduced a review on ACPEL devices (materials, mechanism of operation and life time of devices), comparison of ACPEL and other plane light sources and introduction to different approaches of utilizing color conversion materials (CCM) for tuning of emitted light color. And finally the operation of EL devices, especially the study of micro-regions both on and in the phosphor grains where the electroluminescence is generated was introduced by Harris [10].

3.1 MECHANISM OF LIGHT EMISSION IN THE POWDER-BASED EL DEVICE

All the phosphor materials are based on zinc sulfide (ZnS) doped with various metal or transition element cations (Cu^{2+}, Mn^{2+} Al^{3+}, etc.). A study was conducted by Fischer (7) where a ZnS:Cu, Cl grain was observed under optical microscope and light-emitting region in a form of needle-like precipitate of $Cu_{2-x}S$ inside the bulk of a grain. Fischer proposed a model that these $Cu_{2-x}S$ needles are formed on structural defects that occur thanks to the phase transition of ZnS from hexagonal wurtzite which is formed by preparation of zinc blend under high temperature (>1000 °C) to cubic form by subsequent cooling of zinc powder. The precipitate $Cu_{2-x}S$ is a known p-type semiconductor with high conductivity. Microscopic hetero-junctions are formed between ZnS and the copper-based precipitates which are shown in **Fig. 2**.

The total thickness of phosphor and dielectric layers is usually around 50 μm. When this structure is sandwiched between bottom and rear electrode and relatively high voltage (in the order of hundreds of volts) is applied on the electrodes the electric field with large intensity **E**, usually in the order of $10^6 – 10^7$ $V \cdot m^{-1}$ is generated. The intensity of homogenous electric field with respect to distance of electrodes follows **Eq. 1**

$$E = \frac{U}{d} \tag{1}$$

Where E is the magnitude of intensity of electric field ($V \cdot m^{-1}$), U is voltage (V) and d is the distance between electrodes (m).

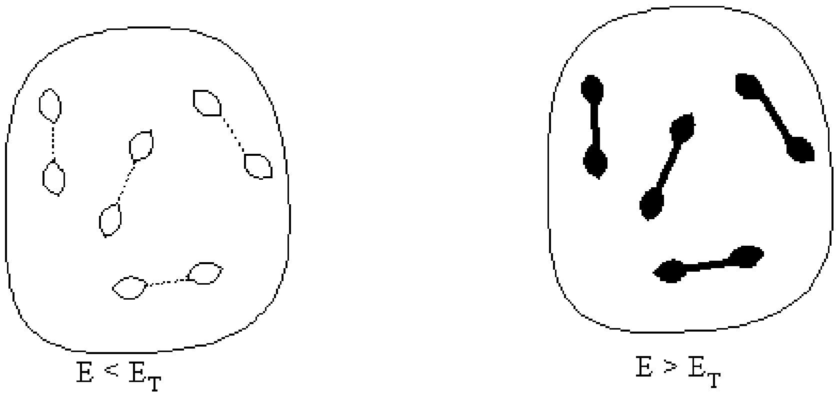

Fig. 2 *Schematic view of typical ZnS particle with light-emitting regions with the needle-like shapes. When the applied electric field has higher intensity than the threshold intensity the impurities start to glow. Adapted from [7].*

Moreover a very strong electric field is further "concentrated" on the sharp tips of $Cu_{2-x}S$ needles reaching the intensity of local electric field up to 10^8 $V \cdot m^{-1}$ since the radius of tips is typically in the order of hundreds of nanometers. Such strong local electric field induces tunneling of electrons and holes from $Cu_{2-x}S$ conductive needles into the phosphor lattice. Here electrons are trapped by shallow traps at Cl while holes are captured by Cu acceptor sites in the lattice. Trapped charge carriers are forced to move in opposite direction with the reversion of polarity of electric field. Electrons radiatively recombine with holes upon the contact and the light is emitted by the grain. This process established by Fischer is called bipolar field emission model and is schematically shown in **Fig. 3** [11]. When applying insufficient voltage on the electrodes the intensity of electric field (E) is less than threshold intensity (E_T) the luminescence does not occur because electrons and holes don't have enough energy to tunnel from the conductor to the bulk of the crystal. On the other hand when the applied voltage exceeds some critical value, the intensity of field is higher than the threshold intensity E_T and the above mentioned process of generation of light takes place.

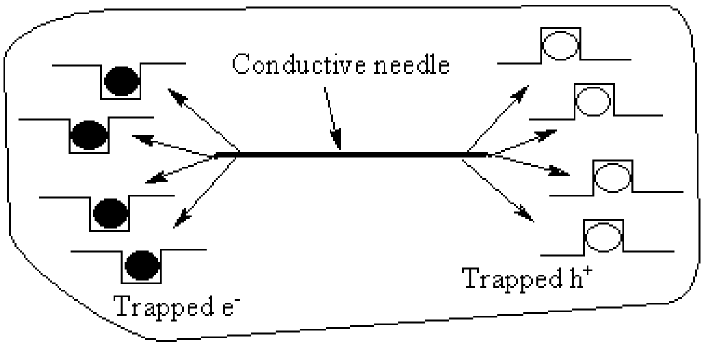

Fig. 3 *Schema of bipolar field emission model proposed by Fischer. Adapted from [7].*

4 EXPERIMENTAL PART

The complete panel consists of flexible substrate with fully transparent electrode (ITO), active phosphor film, dielectric film and top metal electrode. With the exception of transparent electrode all the films are prepared by screen-printing technique. All the printing formulations are commercially available and were purchased from GWENT GROUP Advanced Material System. The fully printed panel based on these pastes serves as a reference panel for determining of optimal printing parameters, operating conditions such as driving voltage and frequency, stability and power consumption. These parameters serve for further optimization of the optoelectronic properties and further improvement of performance of the commercially successful panels. All the layers as fulfill very different roles and different parameters need to be evaluated in order to ensure the optimal behavior of the whole device.

The experimental part of dissertation thesis is focused on optimization of processing conditions for reproducible preparation of fully printed ACPEL panels and their optoelectronic characterization. Optimal thickness of dielectric and phosphor film and surface homogeneity together with printing conditions leading to their reproducible preparation were found. ACPEL panels printed under these optimized conditions were subjects for further optimization of optoelectronic performance of these ACPEL panels.

Chapter 4.1 is focused on photometric characterization of panels as sources of light and on estimation of their electrical power consumption. **Chapter 4.2** deals with a stability of the shining panels, description of specific factors decreasing its lifetime and encapsulation of the printed source of light. Estimation of specific time constants L_{50} and L_{75} is the aim of this chapter. The stability of printed electroluminescent devices is one of the red brick problems for this technology. The topic of **Chapter 4.3** is a modification of a color of the emitted light. A limited portfolio of colors emitted by printed ACPEL panels is also one of deep throats preventing this technology to achieve its full potential.

A schematic of typical powder-based electroluminescence panel and all the layers forming it (left image) with a photo of fully printed device in off-mode (in the middle) and on-mode (on the right) are presented as a **Fig. 4.** A SEM image of an ACPEL panel with typical dimensions of the layers can be seen in **Fig. 5**.

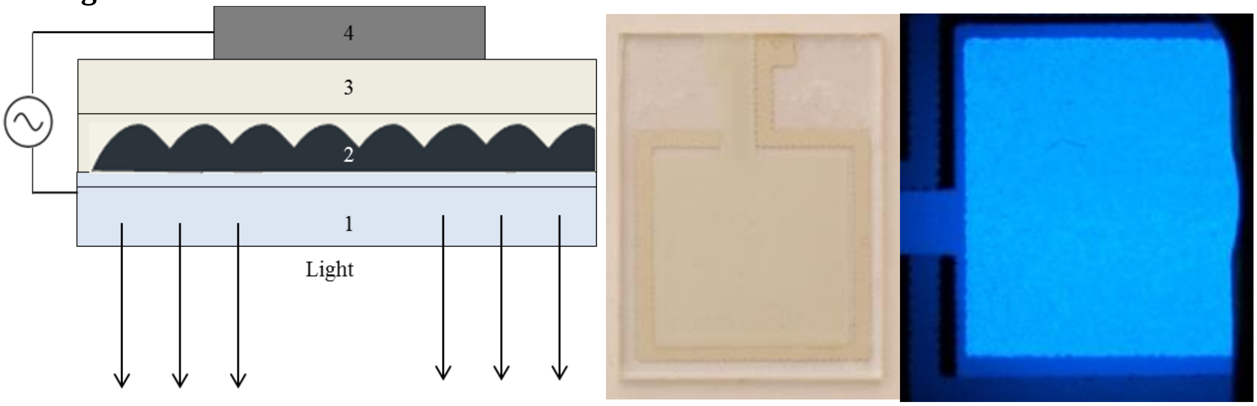

Fig. 4 *Schematics of ACPEL. 1 – PET/glass substrate with ITO electrode/ 2 – phosphor/ 3 – double layer of dielectrics/4 top metal electrode (on the left). Printed (in the middle) and emitting panel (on the right) under 250 V_{pp} and 4 kHz can be seen on the right.*

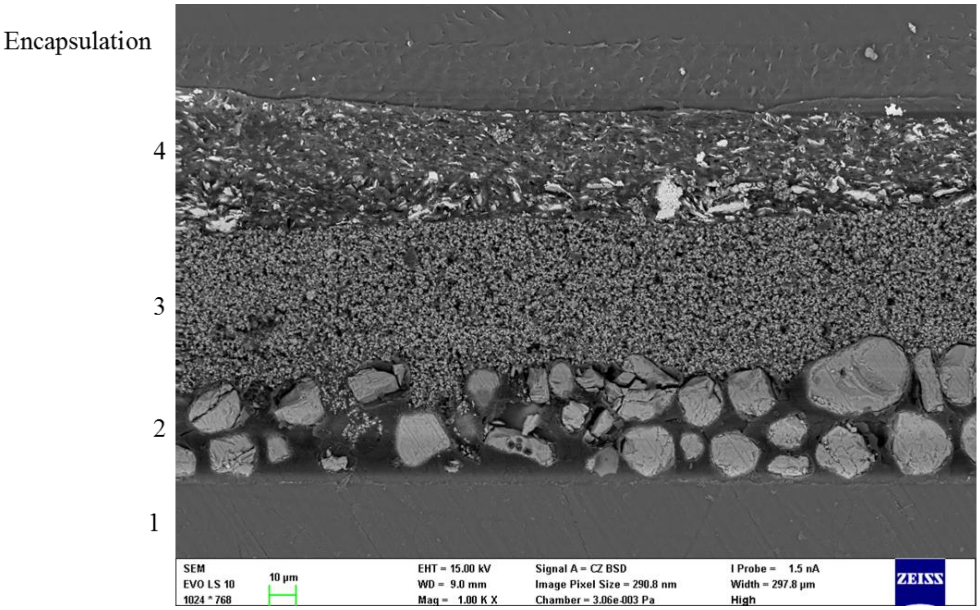

***Fig. 5** A SEM image showing cross-section of fully printed ACPEL device with labeled layers: 1 – ITO substrate; 2 – phosphor; 3 – double dielectric layer; 4 – top metal electrode*

4.1 Optoelectronic properties of developed ACPEL panels

The task of this chapter is to define and evaluate suitable parameters for characterization of large area light sources. Both luminance and power consumption – how much electrical energy will be wasted by operation of the panel – were found to be important parameters from the technological point of view. Another goal, directly resulting from the first one is to determine the optimal driving conditions leading to the radiation of panels based on different phosphors.

A picture taken by optical microscopy of different phosphors (B – blue; O – orange; G – green and Mix) emitting light of different wavelengths is shown in **Fig. 6**. Figure *a* shows that the layer is formed by large individual grains where each grain acts as an individual point source of light. However the placing of grains is so dense that the whole panel exhibits properties of a plane source of light. Figure *c* shows a mixture which consists of blue green and orange phosphor mixed in the ratio 1:1:1. Figures *b*, *d* and *e* show phosphors emitting green, orange and blue light respectively.

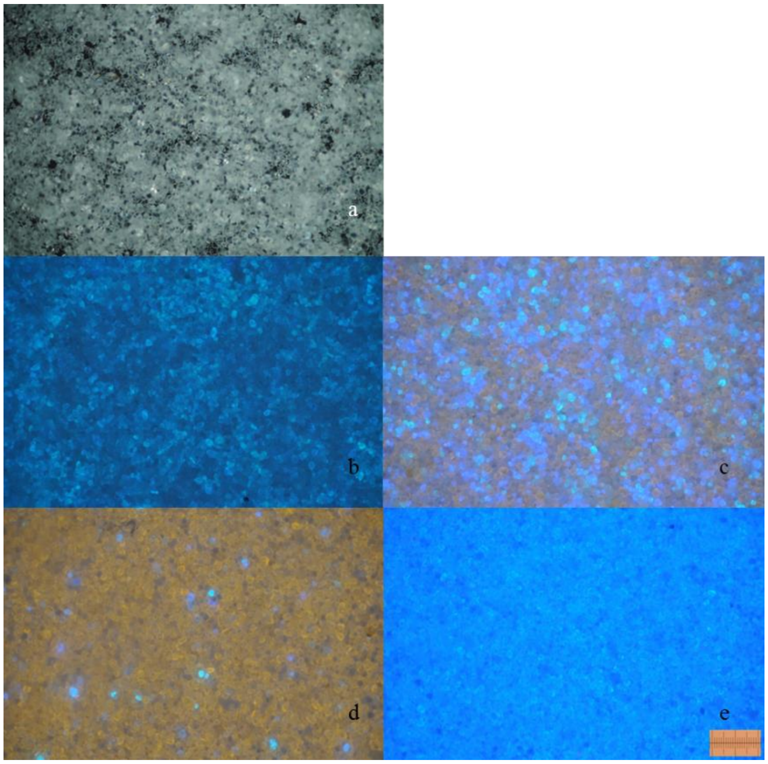

Fig. 6 *A microscopic photography of various emitting phosphor films with 1 micron scale.*

Absolute spectral irradiance of the emitting panels with various standard phosphors was measured with spectrophotometer with optical fiber at 3 different driving conditions for determination of the influence of both increasing voltage amplitude and frequency.

Driving conditions are following:

- U_{pp} = 200 V; f = 1000 Hz
- U_{pp} = 200 V; f = 450 Hz
- U_{pp} = 400 V; f = 450 Hz

The sample B1 therefore means that the absolute spectral irradiance of the blue panel under driving voltage 200 V and frequency 1000 Hz was measured. Irradiance gives the amount of radiant flux that is incident on a surface in given distance and is a relevant quantity to characterize how much area will be irradiated. But the problem is that it is a radiometric quantity so it provides only a little information about how strongly the human eye will be sensitive to the light impulse. So the spectral illuminance as a photometric quantity was calculated and compared to the curve of absolute spectral irradiance as **Fig. 7**.

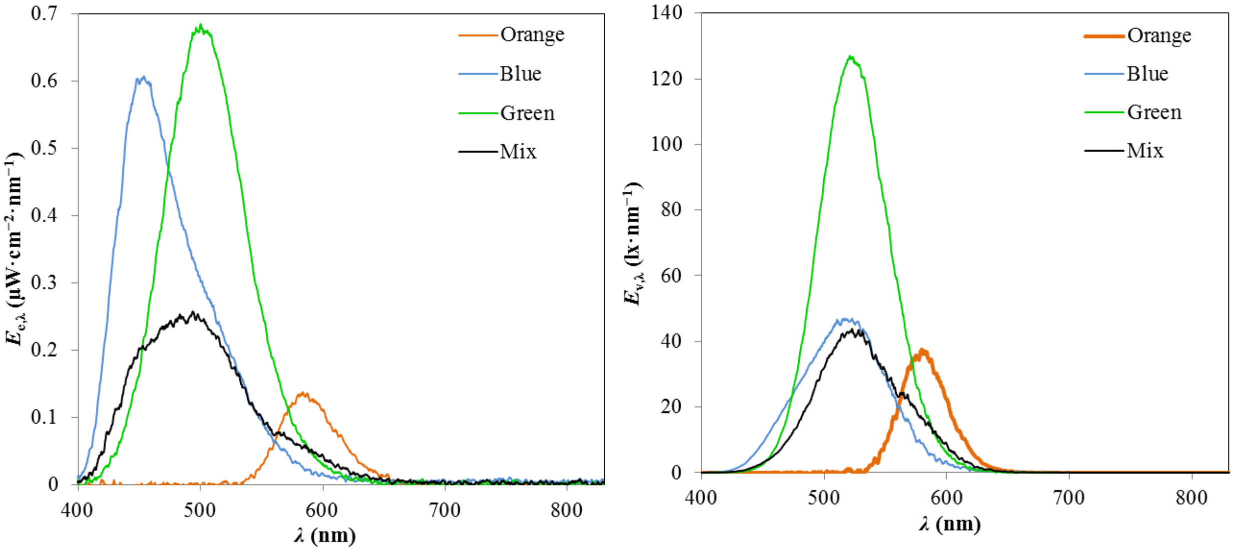

Fig. 7 *Spectral irradiance of panels (on the left) and spectral illuminance (on the right) taken under 250 V and 1000 Hz.*

It is clear that while the irradiance (the left spectrum in **Fig. 7**) of blue panel is much stronger than both orange and mixed phosphor panels the difference in perception of the emitted light is almost the same. The luminance of flat panels was calculated for determination of how bright the panels would appear to the observer. An illuminance E_v represents the luminous flux incident on an area in a fixed distance (d ~ 10 mm). A luminance L_v describes luminous flux emitted in a solid angle and characterizes a panel as a source of light. The active film of a panel itself is formed by homogenously spread crystals of phosphor – point sources of light that behave in a macroscopic scale as an extended source of light. In this case the calculation of luminance from the illuminance is given by **Eq. 2**

$$L_{e,\lambda} = \frac{E_{e,\lambda}}{\pi \cdot \sin^2\left(\frac{\theta}{2}\right)} \tag{2}$$

Where ϑ is the angle of view of the sampling optics. In the case of bare optical fiber the angle is $\vartheta \sim 25°$ and $\vartheta \sim 180°$ with use of a cosine corrector. The values of irradiance E_e, illuminance E_v and luminance L_v of all the test subjects are summarized in the **Tab. 1**. Measurement of the irradiance shows that the orange panel emits only 20 % of radiation compared to blue and green panels and 30 % of radiation compared to mixed phosphor panel. The resulting photopic response to the human eye is therefore very low and the orange panel is relatively a poor light source. Green panel is by far the most promising light source because of two facts. Firstly the light is generated with higher efficiency compared to the other panels and secondly standard observer's eye is by definition most sensitive to green color.

***Tab. 1** Radiometric and photometric properties characterizing the panels as extended sources of light. The first column "Conditions" describe which type of phosphor was subjected to which driving conditions.*

Conditions	Irradiance, E_e (W·m^{-2})	Illuminance, E_v (lm·m^{-2})	Luminance, L_v (cd·m^{-2})
O1	$9.50\cdot10^{-4}$	$4.39\cdot10^{-1}$	**2.98**
O2	$5.22\cdot10^{-4}$	$2.61\cdot10^{-1}$	**1.77**
O3	$2.97\cdot10^{-3}$	1.39	**9.48**
B1	$4.81\cdot10^{-3}$	$8.62\cdot10^{-1}$	**5.85**
B2	$2.69\cdot10^{-3}$	$5.81\cdot10^{-1}$	**3.95**
B3	$1.31\cdot10^{-2}$	2.85	**19.30**
G1	$6.07\cdot10^{-3}$	2.09	**14.20**
G2	$3.22\cdot10^{-3}$	1.14	**7.78**
G3	$1.45\cdot10^{-2}$	5.31	**36.10**
Mix1	$3.20\cdot10^{-3}$	$9.11\cdot10^{-1}$	**6.19**
Mix2	$2.06\cdot10^{-3}$	$6.05\cdot10^{-1}$	**4.11**
Mix3	$9.76\cdot10^{-3}$	3.04	**20.60**

Another important parameter for characterization of a light source beside its luminance is the power consumption. It was estimated by a serial connection of a known resistor (R = 326 Ω) to the electroluminescent panel and a measurement of a voltage generated on the resistor (U_R – V); a current flowing through both the panel and the resistor (I – A) and a phase shift (φ – rad) between the driving voltage and a flowing current since the ACPEL panel exhibits capacitive load. All the measurements were conducted by an oscilloscope Tektronix TBS 2000. The power consumption (P –watt) is calculated by **Eq. 3.**

$$P = \frac{(U_{\mathrm{pp}} - U_{\mathrm{R}})}{2\sqrt{2}} \cdot \frac{U_{\mathrm{R}}}{2R \cdot \sqrt{2}} \cdot \cos\varphi = \frac{(U_{\mathrm{pp}} - U_{\mathrm{R}}) \cdot U_{\mathrm{R}}}{8R} \cdot \cos\varphi \qquad (3)$$

Tab. 2 shows estimated power consumption of printed panels with various active areas under different driving conditions together with calculated power consumption given per cm^2 of samples with an increasing area.

***Tab. 2** An estimated power consumption of samples with an increasing active area A driven under different conditions.*

A (cm^2)	U_{pp} (V)	f (Hz)	P (mW)	P/A (mW·cm^{-2})
78	200	370	103	1
78	200	1000	225	3
78	400	370	504	6
9	200	370	10	1
9	200	1000	23	3
9	400	370	44	5
1	200	370	1	1
1	200	1000	3	3
1	400	370	10	10

4.2 Effect of driving conditions on optoelectronic performance and stability of panels

From the theory of electroluminescence is clear that both increasing driving voltage amplitude and frequency increase luminous performance of the panel. But the increasing values of driving conditions have a detrimental effect on the stability of panels which is a bottleneck for an application of electroluminescent devices. This chapter aims to investigate this effect and determine optimal driving conditions from both the optoelectronic and stability point of view. A test was conducted on a blue sample with increasing voltage at a fixed driving frequency and vice versa on increasing frequency at one fixed voltage. Absolute spectral irradiance of the blue panel was measured and plotted in **Fig. 8** and luminance was calculated for characterization of the panel.

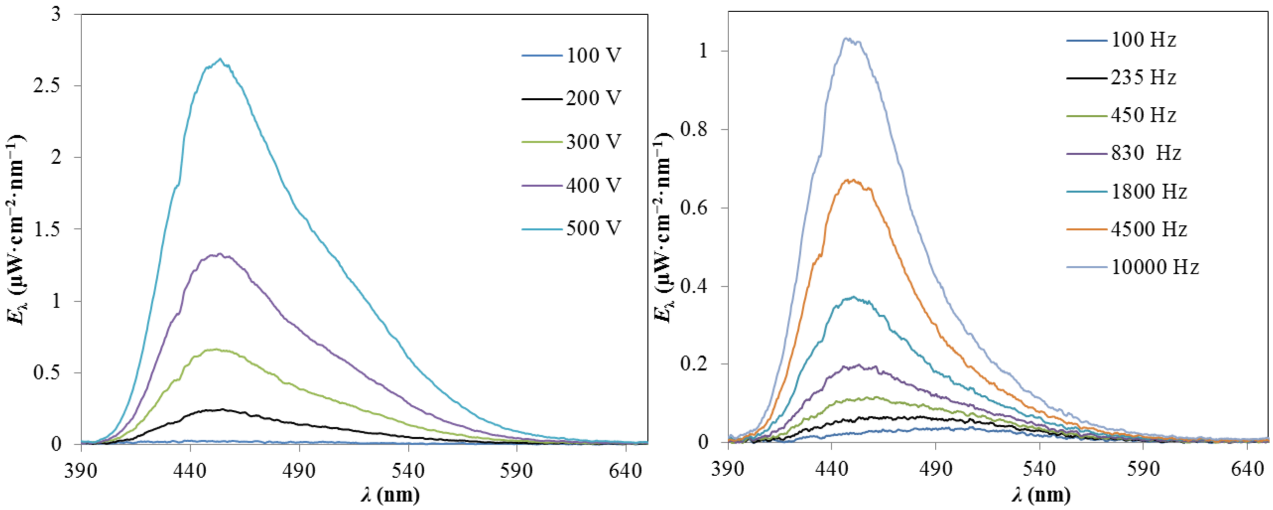

***Fig. 8** The left figure shows spectral irradiance of panel measured as a function of the driving frequency at a constant voltage 200 V$_{pp}$ with increasing driving frequency* (Hz) *and the right figure represents the effect of increasing the voltage (*V*) at a constant frequency 1000 Hz.*

Fig. 8 and **Tab. 3** clearly show that high voltage has higher impact on the overall optoelectronic properties than very high driving frequency. It was also found that the increasing frequency decreases the dominant wavelength λ_D of the emitted light (which shall be further discussed in **Chapter 4.3**).

***Tab. 3** Luminance of a panel with various driving conditions.*

Sample	Luminance ($cd \cdot m^{-2}$)
100 Hz	3.8
1800 Hz	14.6
10 kHz	30.6
100 V	2.6
300 V	32.4
500 V	133.0

Phosphor panels show several promising properties, namely the power consumption and flexibility, making them potentially interesting for the market. However one of their most prominent red brick wall is their environmental and overall stability. Unfortunately the exact process of phosphor degradation is up to now not clarified, although Klassen et al [11] did a study on degradation of different phosphors with an aim to match ongoing physical processes in the phosphor to the drop of luminance. Detailed study was conducted by Swart et al [12] where the degradation of ZnS was conducted by electron bombardment in environment of residual gas (H_2O, H_2 and CH_4) with pressure $1.5 \cdot 10^{-6}$ Pa and oxygen $1.3 \cdot 10^{-4}$ Pa. A direct correlation between morphological changes of the phosphor and decrease of luminescence was found.

The possible degradation processes of ZnS can be summed up with the following **Eq**. **23–25**

$$2H_2O \rightleftharpoons 2H_2 + O_2 \tag{4}$$

$$ZnS + 2O_2 \rightleftharpoons ZnSO_4 \tag{5}$$

$$2ZnS + 3O_2 \rightleftharpoons 2ZnO + 2SO_2 \tag{6}$$

Molecules of water and some other residual gases are degraded by strong electron beam or strong electrical field to hydrogen and oxygen atoms **Eq. 4** which undergo further reactions to form non luminescent ZnO or $ZnSO_4$ **Eq. 5** and **Eq.** 6. Both reactions are thermodynamically possible and preferred because their $\Delta H < 0$ kcal·mol^{-1}.

From the information given above results that setting of extremely high driving conditions will induce generation of light with increased brightness at the cost of decreased stability of a panel. The more intense electric field will create more non luminescent defects and the active luminescence centers in the bulk near the surface of the material will be depleted at higher speed. Furthermore humid environment has downright detrimental effect on the panels based on active phosphor layer.

A test of stability was conducted on various panels under different conditions and different type of protection against the humid air. The parameters describing the stability L_{75} and L_{50} (the time after which the luminance drops to 75 % respectively 50 % of the original value) were calculated from the fit and are summarized in **Tab. 4**.

Three different driving conditions were chosen to estimate an influence of voltage and frequency and encapsulation.

i $U_{pp} = 200$ V; $f = 1000$ Hz laminated

ii $U_{pp} = 200$ V; $f = 370$ Hz laminated

iii $U_{pp} = 400$ V; $f = 370$ Hz encapsulated between two glass plates with EVA foil

The drop of the luminance over time of sample *i*. showed trend given by empirical **Eq. 7** [13].

$$\frac{E_e}{E_{e,0}} = (1 + \mathrm{K}t)^{-1} \tag{7}$$

Where E_e is absolute irradiance of sample in a given time t (hours), $E_{e,0}$ absolute irradiance at the beginning of the measurement and K is a time constant (h^{-1}).

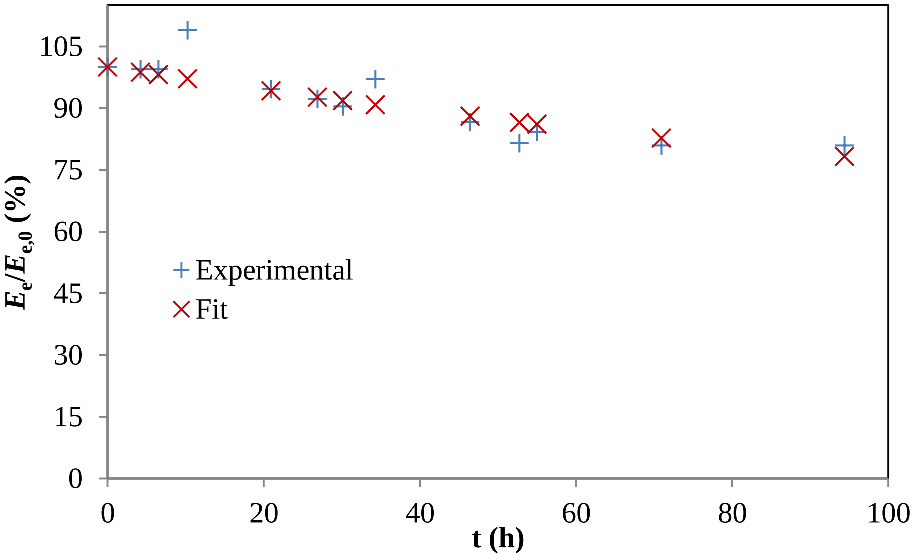

***Fig. 9** Drop of the luminance of panel **i** over 100 hours (blue crosses) and data fitted by **Eq.6** (red crosses).*

Fig. 9 shows very nice match between experimental and fitted data for the panel ***i***. The degradation of panel ***ii*** was measured over 80 hours and the measured decay was shallower. Parameters L_{50} and L_{75} show almost 3 times higher values than those of sample ***i***. confirming that too high driving frequency has detrimental effect on the stability of the panel and should be set below 1000 Hz.

The last tested sample ***iii*** was driven by the highest voltage of all the samples and was fully encapsulated by EVA foil between two flat glass panels. Its degradation over time showed the most gradual behavior with the values of both stability parameters almost 7 times higher compared to the sample ***i***.

Tab. 4 *A summary of stability of all the tested devices with varying driving conditions and type of protection.*

Driving conditions	**Encapsulation**	**$K \cdot 10^{-3}$ (h^{-1})**	**L_{75} (h)**	**L_{50} (h)**
i.	Lamination	2.94	113	340
ii.	Lamination	1.06	316	948
iii.	Encapsulation	0.44	754	2261

4.3 TUNING OF LIGHT EMITTED BY ACPEL PANELS

Phosphors showing emission from blue to red wavelengths are well known but the ability to tune the color of emitted light is limited. Therefore a study to broaden a palette of emitted light colors was conducted in this work. Extensive review of variously doped phosphors was given by [10]. Although the range of potential materials is large only a few of them turned out to be commercially suitable phosphors. For instance ZnS:Cu, Cl emits at 450 nm, ZnS:Cu, Al at 540 nm, ZnS:Cu,Mn,Al at 590 nm and ZnS:Cu at 690 nm.

There exist several ways how to change the color of emitted light. One is to change the driving frequency. Another approach is to prepare phosphor powders based on ZnS with various dopants based on rare earth metals (Eu^{+3}, Sm^{+3}, In^{+3}, Tb^{+3} etc.) [14, 15]. This way of modification is economically problematic because of the price of the above mentioned materials. Interesting approach is the introduction of quantum dots with defined dimensions to modify the color of emission [16]. Quantum dots are however often based on very toxic elements such as lead or cadmium which renders them practically useless for large scale applications.

Very promising approach appears to be the modification of emitted color by addition of specific color conversion material (CCM). The light emitted by a phosphor is reabsorbed by the CCM and the light of different wavelength is obtained. Rhodamine dyes have been successfully used as a CCM material [17] since they show solid state fluorescence with solid quantum yields and good stability. The maximal absorbance of Rhodamine B is at ~550 nm and emission at 570 nm. This approach is somewhat problematic because not many materials absorb at the desired wavelengths where a specific phosphor emits and show good solid state fluorescence. Another issue is with the stability of the new mixture of phosphor and fluorophore since the latter materials tend to be easily photodegradable compared to the phosphor. Also the color of the phosphor under no voltage can be somewhat shifted from the default white which doesn’t need to be desirable.

The last mentioned approach is topical for this dissertation thesis. Rhodamine B was used as a CCM for commercial orange paste because of the good compatibility between phosphor emission and Rhodamine absorption wavelengths. Potentially very interesting group of substances could be diketopyrrolopyrrole (DPP) derivatives because of their stability [18], solid state fluorescence [19] and a possibility to tune their fluorescence spectra by molecular tailoring [20].

4.3.1 Influence of driving frequency on the electroluminescence spectra

From the results in **Tab. 1** can be seen that both increasing voltage and frequency increase the total radiation given by ACPEL panels. The influence of higher voltage is quite clear (comparison of samples 2 and 3) and contributes to the increased luminance of the light source more significantly than the increase in frequency. It was also shown that the increasing values of driving frequency shift the emitted light toward shorter wavelengths.

Tab. 5 summarizes the change of emitted dominant wavelength on the driving frequency of all tested phosphors. The dominant wavelength is determined from the CIE color coordinates space. A straight line connecting the measured point with white point is extrapolated and the intersection of the line with a closer boundary of the color space is called the dominant wavelength. It is defined as a monochromatic light that would evoke the same perception of a hue as is caused by the studied illuminant with a spectral light characteristic. It is a good parameter for characterization of a light mixture. The intersection on the opposite end is called the complementary wavelength. The orange phosphor emission is almost constant with the increasing frequency. The *x* and *y* coordinates were measured and plotted in the CIE 1931 chromaticity diagram as **Fig. 10** to visualize the change of emitted color.

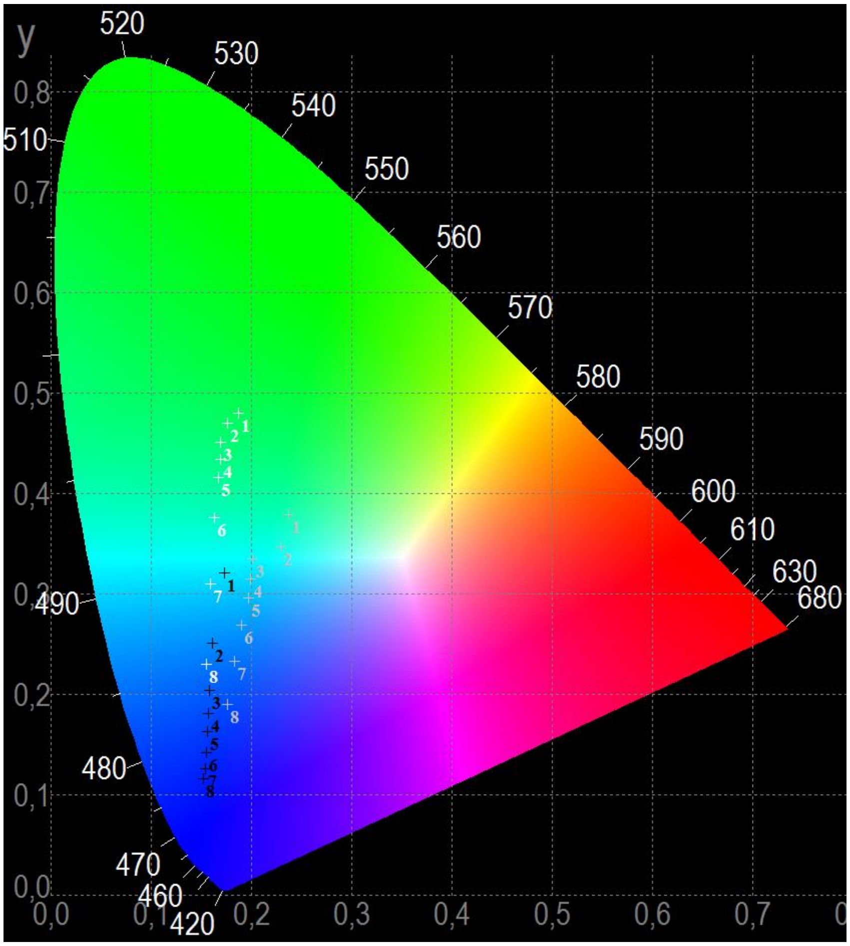

Fig. 10 *CIE 1931 color space where black points represent the change of blue panel, white points represent green panel and silver points represent mixed printing formulation under 250* V_{pp} *and frequencies 100; 235;450; 680; 1000; 1800; 3700 and 10 000 Hz represent samples 1–8 respectively.*

Tab. 5 *Change of dominant wavelength as a function of frequency taken at constant voltage of 250 V_{pp}.*

f (Hz)	$\lambda_{D,Blue}$ (nm)	$\lambda_{D,Green}$ (nm)	$\lambda_{D,Orange}$ (nm)	$\lambda_{D,Mix}$ (nm)
100	490	503	583	495
235	485	502	584	491
450	481	500	584	490
680	479	498	584	489
1000	477	497	584	487
1800	475	494	585	485
3700	473	489	586	482
10000	472	483	587	478

The mechanism of change of emitted light wavelength for blue and green phosphors by the change of frequency was described by Zalm [21]. Two different dopant energy levels (so-called blue and green centers) are present in the structure of ZnS. Upon excitation of electrons into the conduction band the electrons recombine radiatively with the vacant dopant centers. A position of the dopant activation center in a band gap determines the wavelength of emitted light. With increasing frequency the dopant activation center with lower energy is preferred giving rise to the electroluminescent light shifted toward blue region [21]. This process is shown in **Fig. 11**. For an orange phosphor no such a shift of activation center energies was observed and the color of emitted light is not changed.

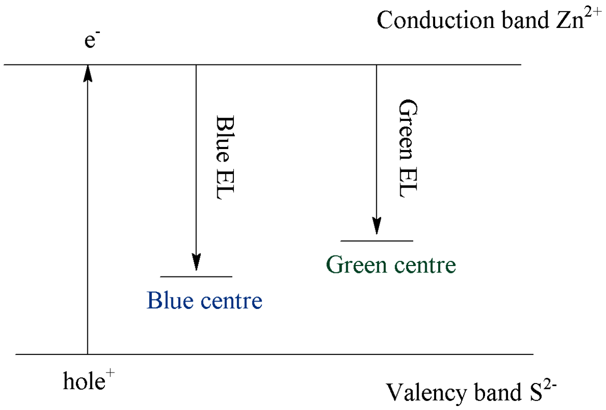

Fig. 11 *The electronic structure of ZnS crystal with dopant activation centers. Adapted from [21].*

4.3.2 DPP as a color conversion material

A novel DPP derivative used for modification of the blue phosphor was prepared by synthetic chemists at the Faculty of Chemical Technology at University of Pardubice. Its UV-Vis absorption spectra in water showed absorption in the region of wavelengths approximately from 450 to 520 nm and its fluorescence emission spectrum showed maximum emission at λ_{em} = 565 nm. Its emission in solid state showed shift to λ_{em} = 600 nm with the parameter full width at half maximum (FWHM) around 80 nm making this DPP an ideal CCM for studied standard blue phosphor. The measured absorption and fluorescence spectra are shown as **Fig. 12**.

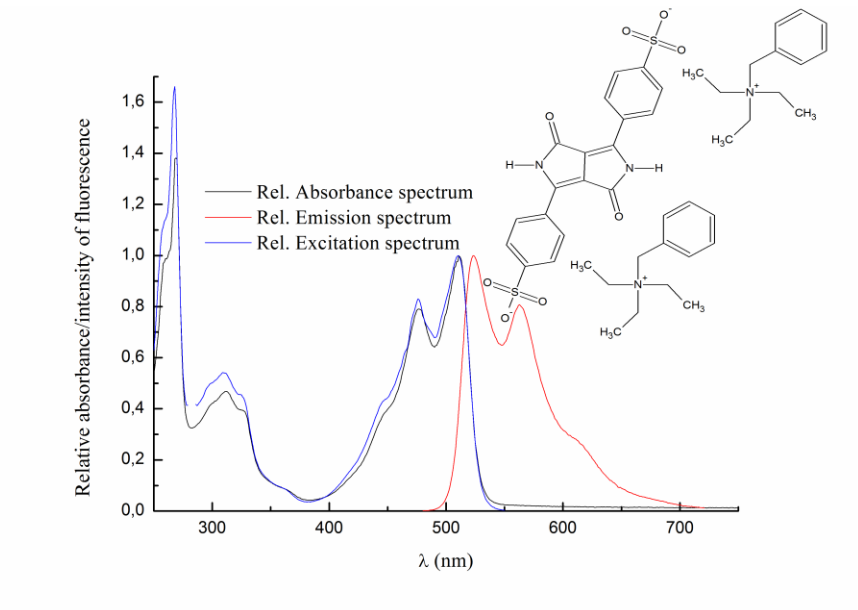

Fig. 12 *Absorption and excitation (black and blue curve respectively) and emission spectrum (red curve) with a structural formula of the studied DPP derivative.*

Two sets of samples were prepared (a) where fluorophore was added directly into the phosphor formulation with increasing concentration and printed via screen-printing: P1 – with mass fraction of fluorophore $w = 0.8$ %; P2 – with mass fraction of fluorophore 2.5 % and samples (b) where fluorophore was added in the form of thin layer between ITO substrate and phosphor layer: P3 – deposition by dip coating and P4 – deposition by spin coating with 2500 rpm. A reference blue phosphor with no added fluorophore was prepared as a sample P5.**Tab. 6** summarizes the conditions of preparation of individual samples.

Tab. 6 *Details on processing conditions of samples.*

Sample	Process
P1	Sample (a) with 0.8 $\%_{\mathrm{W}}$ of DPP
P2	Sample (a) with 2.5 $\%_{\mathrm{W}}$ of DPP
P3	Sample (b) with dip coated DPP layer
P4	Sample (b) with spin coated DPP layer
P5	Reference blue phosphor

The spectra of absolute irradiance of all the samples were taken at fixed voltage U_{pp} = 250 V_{pp} with increasing frequency in the range 100–25 000 Hz and the dominant wavelengths λ_D were plotted against the increasing frequency as **Fig. 13**.

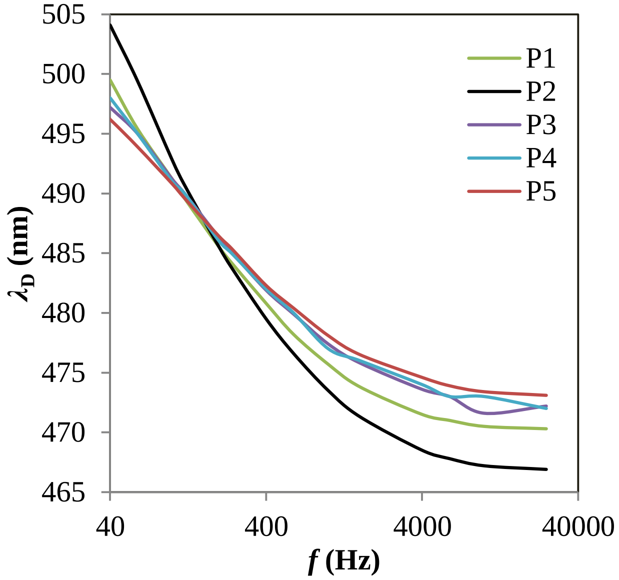

***Fig. 13** The dominant wavelength of emitted electroluminescence as a function of frequency.*

Samples P5 – reference, P4 and P3 with deposited thin layer of fluorophore show very similar light response and it can be concluded that CCM material deposited as a filter layer by coating technique does not show any effect on the conversion of emitted light in this experiment. This can be due to the fact that the spin-coated filter film was too thin to show any difference. Samples P1 and P2 with fluorophore incorporated directly into the printing formulation however show somewhat different behavior. Samples P3 and P4 were excluded from further characterization because of the minimal effect of a fluorophore as a very thin filter layer.

Normalized spectral irradiance of reference sample and both samples with color conversion material can be seen in **Fig. 14**. The presence of fluorophore changes the shape of spectrum in the region of maximal emission of fluorescence. The irradiance of samples P1 and P2 is slightly decreased in the region of wavelengths 480–530 nm (maximum of absorbance of the fluorophore) compared to the reference sample (red line) because the light was reabsorbed by the fluorophore. The rise of spectral irradiance in a region ~ 580–600 nm corresponds with region of emission of the DPP. It is worth noting that reference sample lacks this new peak [22].

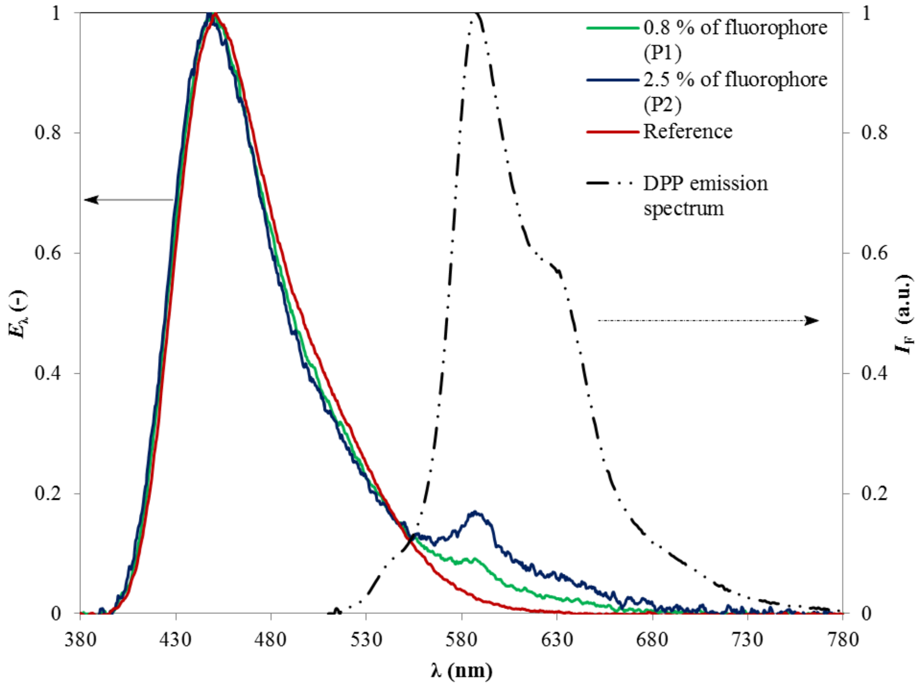

Fig. 14 *Normalized spectral irradiance of reference blue panel and panels with fluorophore. Emission spectrum of fluorophore (dotted line) is added for comparison.*

4.3.3 Rhodamine B as a CCM

A similar test was conducted with standard fluorophore Rhodamine B which shows maximal absorption at approximately 540 nm when dissolved in ethanol and maximal emission at approximately 565 nm [23]. These spectral properties could make Rhodamine B a promising material for modification of orange panel which emits light with small relative intensity compared to the other panels.

A series of 4 samples with varying concentration of Rhodamine B was prepared by addition of Rhodamine B solved in ethanol to the orange phosphor printing formulation. A reference sample (O) without presence of Rhodamine B; sample (R1) with 120 μL/g, sample (R2) with 500 μL/g and sample (R3) with concentration 600 μL/g. Details of the prepared samples together with their optical properties are summarized in **Tab. 7**. Spectra of absolute spectral irradiance were taken at fixed U_{pp} = 200 V and f = 1000 Hz. For determination of the effect of emitted orange light on the human eye the spectra of absolute spectral illuminance were calculated and plotted as **Fig. 15**.

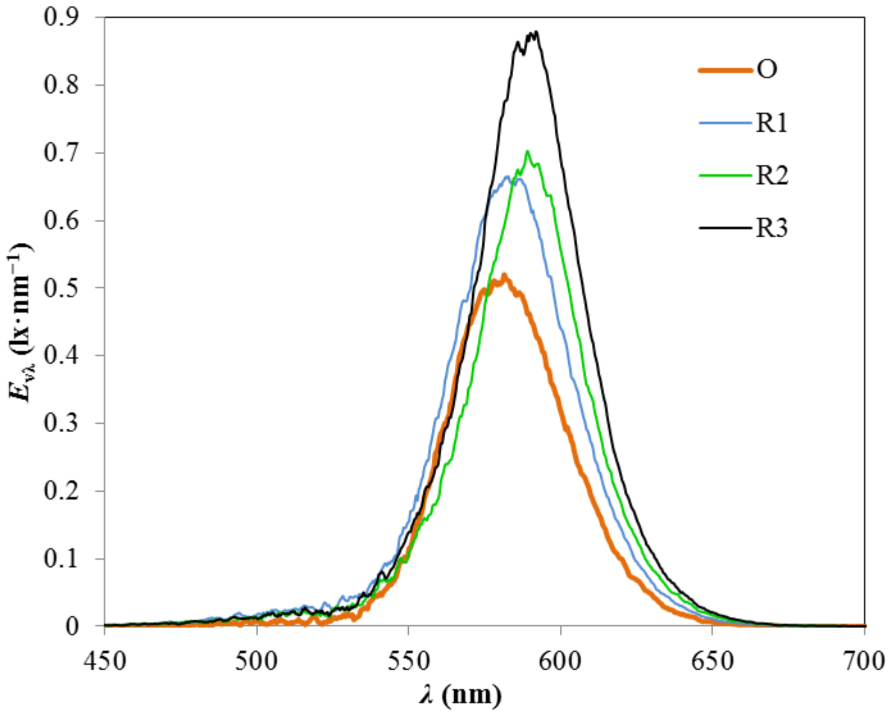

Fig. 15 *Absolute spectral illuminance of samples with increasing concentration of fluorophore.*

Tab. 7 *Concentration of Rhodamine B in tested samples.*

Sample	**Conc. of fluorophore (μL·g^{-1})**	**E_v (lx)**	**L_v (cd·m^{-2})**	**Relative efficiency (%)**
O	0	0.57	3.85	100
R1	120	0.76	5.18	134
R2	500	0.74	5.00	130
R3	600	0.92	6.26	163

The luminance increases with the higher concentration of fluorophore as can be seen in **Tab. 7**. The sample R1 and R2 show very similar behavior although the concentration of the fluorophore is more than 4 times higher. This fact might be given by the insufficient homogeneity of sample P3. The irradiance spectrum was taken by the bare fiber without the cosine corrector and so the angle of view, ϑ of the sampling optics was very narrow. It is 25° for the bare fiber compared to almost 180°for the cosine corrector. A very small area – statistically insufficient – of the shining surface was measured and the results are likely to be a subject to a large margin of error. Another explanation of the increasing luminance might be that addition of fluorophore in a solution is diluting the phosphor paste and the printed phosphor film is thinner. The thinner the film is the higher electric field is generated between the electrodes and the panel radiates more.

5 CONCLUSION

In order to fulfill the main aim of this thesis, development of ACPEL panels and overcoming red brick wall problems associated with this type of technology, the first step was to identify most suitable deposition techniques. Several facts limit a broad portfolio of all the printing techniques suitable for this task. the panels are printed from inherently highly dense and viscous printing pastes, some films forming the whole panel need to be patterned, the height of active layers is typically in the order of tens of microns and of a printing technique should be R2R compatible for high output preparation. All these facts are making screen-printing technique an optimal mean for deposition of the ACPEL panels. Another advantage of the screen-printing is a fact that it is currently the most wide-spread technique in a field of printed electronics.

Determination of influence of driving conditions on the optoelectronic performance of the ACPEL panels together with their electric power consumption is one of the main goals of the whole thesis and was covered in **Chapter 4.1**. Absolute spectral irradiance spectra of panels with different phosphors driven by varying driving conditions were measured and the values of luminance and electric power consumption were evaluated. It was shown that the highest value of luminance was achieved when a panel containing green phosphor was subjected to higher tested amplitude of alternating voltage. It was shown that both increasing the voltage and frequency increase the optoelectronic performance of panels but the effect of the increasing voltage amplitude is more profound. The highest achieved luminance was $L_V = 130\ \mathrm{cd\ m^{-2}}$ on the panels driven at $f = 1000\ \mathrm{Hz}$ and $U_{pp} = 500\ \mathrm{V}$. A power consumption of panels increases with increasing voltage, frequency and an area of the phosphor film. A typical power consumption per unit area (P/A) of panels driven by 400 Vpp and 370 Hz was estimated to be $P/A = (7 \pm 3)\ \mathrm{mW \cdot cm^{-2}}$ and panel with 78 $\mathrm{cm^2}$ showed the total power consumption $P = 0.5\ \mathrm{W}$, which is several order less than other typical light sources. These values make panels based on this technology interesting for practical applications.

Increasing both amplitude of alternating voltage and frequency has negative effect on the lifetime of the panel. The aim of **Chapter 4.2** was to investigate how a lifetime of panels changes under different driving conditions. Parameters L_{75} and L_{50}, describing time after which luminance drops to 75 % respectively 50 % were evaluated for samples differing with driving frequency, driving voltage amplitude and type of encapsulation. It was proved that increasing the values of driving conditions has negative effect on the stability of panels. The best stability with $L_{50} = 2260$ hours was obtained on a panel that was driven by frequency 370 Hz and was encapsulated by polymer foil between two glass panels. Values of both the stability parameters were almost 7 times higher compared to the not encapsulated panel driven by f = 1000 Hz. To ensure the highest possible stability of panels one must take into consideration both driving conditions and the type of encapsulation. The frequency of applied voltage needs to be less than 1000 Hz to ensure high stability but higher than 200 Hz to ensure reasonable optoelectronic performance suitable for the given application of the large area light sources.

Chapter 4.3 addresses possibilities to modify color of light emitted by an electroluminescent panel. One way is a change of a driving frequency. It was shown that the color coordinates of light emitted by a blue phosphor driven with increasing frequency are changed therefore a light of different hue is emitted. This effect was measured on the panels formed by blue, green, orange and mix phosphors for the frequencies in a range $f = (100\text{–}10\ 000)\ \mathrm{Hz}$ and a dominant wavelength of light was measured. It was found that the change of wavelength between 100 Hz and 10 000 Hz is approximately 20 nm for blue, green and mix phosphors and orange phosphor does not change color of emitted light at all. It was concluded that this effect cannot lead to efficient change of color because human eye cannot distinguish colors with so close values of wavelength. Another problem is that frequencies higher than 1000 Hz are destructive for a long time stability of panels as was concluded in **Chapter 4.2**. A more promising way was an addition of color conversion material directly into the phosphor printing formulation and/or deposition of a CCM as a filter covering the phosphor film. A DPP derivative with suitable absorption and emission spectra was chosen as a CCM to change color of light emitted by a blue phosphor panel. An addition of the CCM achieved a 7 times increase of irradiance at wavelengths around 680 nm corresponding to a maximum emission of the CCM.

A similar test was conducted for orange phosphor with Rhodamine B as a CCM leading to increase of illumination up to 63 %. It was, however, difficult to associate it with the effect of reabsorption of light by the CCM as with the blue CCM. Both inhomogeneity of orange panels or the effect of dilution the printing formulation, thus decreasing a thickness of the film and increasing the intensity of electric field between the electrodes are possible explanation of the measured of increased optoelectronic performance.

This thesis concludes that the red brick walls defined in the introduction can be overcome with careful setting of both the parameters leading to preparation of the panels and driving conditions. Reasonable luminance above 130 $\mathrm{cd \cdot m^{-2}}$, power consumption per unit area 0.5 $\mathrm{mW \cdot cm^{-2}}$ with L_{50} in order of thousands of hours can be obtained. Typical values of the achieved luminance make panels based on the ACPEL technology excellent candidates for various indoor decorative light sources and large area background sources of light. ACPEL panels have already found partial application in automotive and commercial industry and in future it might be expected that they will find more applications.

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2016 - present	Cvičení z Chemické informatiky I a II

Oral lectures at international conferences

6th meeting on student conference Chemie je život 2017 (Brno, Czech Republic)

Posters at international conferences

2014 – 7th International Symposium on Flexible Organic Electronics (Thessaloniki, Greece)

2015 – 11th International Conference on Organic Electronics (Erlangen-Nürnberg, Germany)

2016 – 12th International Conference on Organic Electronics (Bratislava, Slovakia)

2017 – 13th International Conference of Organic Electronics (Sankt Peterburg, Russia)

2017 – Studentská odborná konference Chemie je život (Brno, Czech Republic)

2018 – 7th meeting on Chemistry and Life (Brno, Czech Republic)

2018 – 18th International Symposium on Luminescence Spectrometry (Brest, France)

Consultation of diploma theses and bachelor theses

Bachelor theses

Klára Foldynová	Modifikace inkoustů pro tisk luminiscenčních prvků
Patrícia Guricová	Materiálový tisk luminiscenčního panelu

Diploma theses

Klára Foldynová	Studium vlivu dielektrika na optoelektronické vlastnosti elektroluminiscenčních zařízení
Patrícia Guricová	Možnosti přípravy bíle emitujícího elektroluminiscenčního panelu

Academic criticism

Silvie Hrbková	Studium optických vlastností organických materiálů pro nelineárně optické aplikace
Aneta Bráblíková	Optimalizace tisku organických elektronických struktur pro bioelektroniku

Publication activity

Book chapter

KOVALENKO, Alexander and Michal HRABAL, 2017. Printable solar cells. SANKIR, Nurdan Demirci a Mehmet SANKIR. *Printable solar cells*. Hoboken, NJ: Wiley, 163 - 202. ISBN 9781119283713.

Articles in impacted magazines

HRABAL, M.; ZHIVKOV, I.; OMASTA, L.; FOLDÝNOVÁ, K.; GURICOVÁ, P.; VALA, M.; WEITER, M. Solid-state fluorescence organic materials as a tool for spectral modification of ZnS-based screen-printed thick layer electroluminescence devices. *Chemical Papers*. 2018, 72(7), 1677-1684. DOI: 10.1007/s11696-018-0404-z.

STŘÍTESKÝ, S.; MARKOVÁ, A.; VÍTEČEK J.; ŠAFAŘÍKOVÁ, E.; HRABAL, M.; KUBÁČ, L.; KUBALA, L.; WEITER, M.; VALA, M. Printing inks of electroactive polymer PEDOT:PSS: The study of biocompatibility, stability, and electrical properties. *Journal Of Biomedical Materials Research Part A*. 2018, 106(4), 1121-1128. DOI: 10.1002/jbm.a.36314.

Conference papers indexed in the Web of Science database

HRABAL, M.; ZHIVKOV, I.;TULIEV, N., DOBRIKOV, G., OMASTA, L.; VALA, M. Voltage source for AC electroluminescent measurements. *IEEE Xplore.* Sozopol, Bulgaria: IEEE, 2017. p. 1-4. ISBN: 978-1-5386-1753-3.

ZHIVKOV, I.; TODOROV, I.;HRABAL, M., YORDANOV, R.; VALA, M. Measurement of impedance with computer controlled setup. *IEEE Xplore.* Sozopol, Bulgaria: IEEE, 2018. p. 1-4. DOI: 10.1109/ET.2018.8549594. ISBN: 978-1-5386-6692-0.

HRABAL, M; DZIK, P; OMASTA, L; VALA, M; KALINA, M; FLORIÁN, P; WEITER, M. Improvement of Performance of Electroluminescent Panel by Reducing the Thickness of Dielectric Layer. *Material science forum*. ISSN 1662-9752. accepted.

Conference papers and abstracts

2018

HRABAL, M.; KRATOCHVÍL, M.; VALA, M.; LUŇÁK, S.;PAUK, K.;IMRAMOVSKÝ, A. *Solid state fluorescence of push-pull distyrylbenzenes.* 18th International Symposium on Luminescence Spectrometry: Fundamentals and Applications, 2018. s. 57-57.

2017

OMASTA, L.; SALYK, O.; STŘÍTESKÝ, S.; HRABAL, M.; VALA, M.; WEITER, M. *Screen printing of organic electrochemical transistor for real-time cell culture monitoring.* Sborník abstraktů. 1. Brno: Vysoké učení technické v Brně, Fakulta chemická, Purkyňova 464/118, 612 00 Brno, 2017. s. 88-88. ISBN: 978-80-214-5488-0.

HRABAL, M.; OMASTA, L.; VALA, M.; WEITER, M. *Screen printing and characterization of thick layer electroluminescence panels.* Sborník abstraktů. Brno: Vysoké učení technické v Brně, Fakulta chemická, Purkyňova 464/118, 612 00, 2017. s. 82-82. ISBN: 978-80-214-5488-0.

HRABAL, M.; OMASTA, L.; STŘÍTESKÝ, S.; VALA, M.; WEITER, M. *Organic electrochemical transistors (OECT) prepared via screen printing technique as a tool for biosenssing.* 13th International Conference on Organic Electronics - 2017 - Book of abstracts. Saint Petersburg: 2017. s. 112-112.

OMASTA, L.; SALYK, O.; STŘÍTESKÝ, S.; HRABAL, M.; VALA, M.; WEITER, M. *Organic electrochemical transistors for real-time cell observation.* XVII. Workshop of Physical Chemists and Electrochemists Book of abstracts. 1. Brno: Masaryk University, 2017. s. 41-41. ISBN: 978-80-210-8580-0.

2016

HRABAL, M.; OMASTA, L.; VALA, M.; SALYK, O.; WEITER, M. *Printing of thin films for printed electronics.* Book of Abstracts of The 12th International Conference on Organic Electronics. Bratislava, Slovakia: Slovak University of Technology in Bratislava, 2016. s. 31-31. ISBN: 978-80-227-4571- 0.

OMASTA, L.; HRABAL, M.; SALYK, O.; VALA, M.; WEITER, M. *Printed lateral biosensors based on organic electrochemical transistor.* Book of Abstracts of The 12th International Conference on Organic Electronics. Bratislava, Slovakia: Slovak University of Technology in Bratislava, 2016. s. 57-57. ISBN: 978-80-227-4571- 0.

2015

OMASTA, L.; SALYK, O.; HRABAL, M.; WEITER, M. *PRINTED BIOSENSORS BASED ON ORGANIC ELECTROCHEMICAL TRANSISTORS.* Book of Abstracts 11th International Conference on Organic Electronics. Erlangen-Nurnberg, Germany. Friedrich- Alexander Universität, 2015. s. 58-58.

OMASTA, L.; SALYK, O.; HRABAL, M.; WEITER, M. *Preparation and optimization of printed layers for biosensing.* Chemistry & Life 2015 - Book of Abstracts. first. Brno: Brno University of Technology, Faculty of Chemistry, 2015. s. 140-140. ISBN: 978-80-214-5228- 2.

HRABAL, M.; OMASTA, L.; VALA, M. *Preparation of organic electrochemical transistors via screen printing.* Book of Abstracts 11th International Conference on Organic Electronics. První. Erlangen-Nurnberg, Germany: Friedrich- Alexander Universitat, 2015. s. 25-25.

HRABAL, M.; OMASTA, L.; VALA, M.; WEITER, M. *Optimization of Screen Printing Process for Printed Electronic Devices.* Chemistry and Life Brno 2015. 2015. s. 138-139. ISBN: 978-80-214-5228- 2.

2014

HRABAL, M.; VALA, M.; DZIK, P.; WEITER, M. *Optimization of physical properties of inks for material ink- jet printing.* 2014. s. 162-162.

2013

HONOVÁ, J.; HRABAL, M.; STŘÍTESKÝ, S.; HEINRICHOVÁ, P.; VALA, M.; WEITER, M. *New diketopyrrolopyrrole derivatives for organic photovoltaics.* Studentská konference Chemie je život. Brno: 2013. s. 82-82. ISBN: 978-80-214-4822- 3.

HONOVÁ, J.; VALA, M.; FREBORT, Š.; HEINRICHOVÁ, P.; ŠPÉROVÁ, M.; STŘÍTESKÝ, S.; HRABAL, M.; KUBÁČ, L.; WEITER, M. *New Diketopyrrolopyrrole Derivatives for Organic Photovoltaics.* ECME2013. Imperial College London: ECME 2013, 2013. s. 68-68.

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