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doi:10.15199/48.2021.12.11

# Embedded system for supply voltage converter of organic light-emitting diode with extended functionality

***Abstract**. The work is dealing with the problem of developing an embedded system for supply voltage converter of Organic Light-Emitting Diode (OLED) with advanced functionality, namely - with an embedded ability to measure the Volt-Ampere (V – A) characteristics of structures directly during their operation. The measurement of the V – A characteristics of OLED structures is performed on the transient processes of voltage generation in the drivers boost circuits. Model researches show the operating conditions of the boost OLED power driver with in-situ measurement of its V – A characteristics. In accordance with the results of model researches and requirements for the implementation of modern electronics devices, an embedded system of voltage converter for OLED structure has been developed. The basis of the developed converter is a programmable system on chip PSoC of 5LP Family Cypress Semiconductor Corporation.*

***Streszczenie.** Praca dotyczy problemu opracowania wbudowanego systemu przetwornika napięcia zasilania organicznej diody elektroluminescencyjnej (OLED) z zaawansowaną funkcjonalnością, mianowicie - z wbudowaną możliwością bezpośredniego pomiaru charakterystyk woltoamperowych (W – A) struktur. podczas ich eksploatacji. Pomiar charakterystyki W – A struktur OLED wykonywany jest na przejściowych procesach generowania napięcia w obwodach doładowania sterowników. Badania modelowe pokazują warunki pracy zasilacza boost OLED z pomiarem in-situ jego charakterystyk W – A. Zgodnie z wynikami badań modelowych oraz wymaganiami dla implementacji nowoczesnych urządzeń elektronicznych, opracowano wbudowany system przetwornika napięcia dla struktury OLED. Podstawą opracowanego konwertera jest układ programowalny na chipie rodziny PSoC 5LP Cypress Semiconductor Corporation. (**Wbudowany system przetwornicy napięcia zasilającego organicznych diod elektrycznych o rozszerzonej funkcjonalności)***

**Keywords:** Embedded System, Supply voltage converter, OLED driver
**Słowa kluczowe:** System wbudowany, konwerter napięcia zasilania, sterownik OLED.

## Introduction

In its development, the electronics industry and one of its main scientific and technical areas - microcircuitry, constantly puts up new and increasingly stringent requirements for the products. The defining requirements for the microcircuitry of devices of modern electronics are their compliance with the concept of hardware and software embedded systems, in particular, Programmable System on Chip (PSoC) [1-2]. This concept ensures high efficiency of implementation and operational modification of microelectronic devices. Embedded systems are the basis for the implementation of a wide range of hardware and software solutions for reconfigured circuit nodes and functionally completed control systems. The main requirements are: operation at low supply voltages, minimum power consumption, rail-to-rail modes etc.

This work is devoted to the problem of developing an embedded management system for organic LEDs (OLED, Organic Light-Emitting Diode) with advanced functionality, specifically with embedded ability to measure the drift characteristics of OLED structures directly during their operation. In modern literature, this functionality is characterized by the term "in-situ", which literally means "inside" the body or system [3]. Currently, projects in the field of organic LED technology and power management are of topical relevance. This control is performed by specialized power controllers of OLED structures.

## Literature analysis

The main purpose of LED controllers is to stabilize their power supply modes, for the implementation of which mainly the voltage boost circuits are use. The use of such circuits is necessitated by the need to convert the voltage of low-voltage sources, in particular, electrochemical cells (mostly up to 3 V) or USB, Wi-Fi, Bluetooth interfaces (voltage from 3 to 5 V) into the supply voltage of LEDs over 5 V ( depending on the type of LED). Such a boost conversion is especially relevant in the development of controllers of OLED structures, the supply voltage of which can reach 10..15 V. The circuits that stabilize the power supply of LEDs have been named as Boost LED Driver [4], Boost Converter [5], Buck-Boost Converter [6].

The subject of research in this area is an increase in the conversion factor of the supply voltage [4], parallel operating modes of integrated converters [5], an efficiency increase in conversion with a combination of switching inductive and capacitive components [6], operation of converters at extremely low supply voltages [7], implementation of LED controllers for the telecommunication standard Visible Light Communication (IEEE 802.15.7) [8], conversion modes in boost converters with self-oscillation [9] and balancing [10], features of converters for street lighting tasks in modular configuration [11]. Problems and implementation of the power converter of OLED structures are presented in [12]. The problem of instability and degradation of OLED parameters in the process of their operation is presented in [13], and the issue of modelling the characteristics of OLED structures taking into account their instabilities - in [14]. The correction of power modes and the development of drift compensation circuit for OLED structures are considered in [15]. The implementation of the OLED driver using the feedback circuit is the subject of research in [16]. Consequently, the analysis of modern literature indicates the significant relevance of the tasks of further development of power controllers for organic LEDs.

It is important to implement the advanced functionality of these controllers, which is based on the operational correction of power modes. As it will be shown in this paper, an important component of this correction is the embedded function of periodic measurement of Volt-Ampere (V – A) characteristics of OLED structures, which solves the problem of in-situ tracking of drift of their parameters.

## Operating principle and model research

A new solution for an OLED controller designing, the novelty of which is a combination of the process of increasing the voltage in the driver circuit and simultaneous in-situ measurement of OLED characteristics during the increase and decrease of this voltage pulses is presented in this paper. This feature is crucial in the development of a new generation of intelligent OLED controllers, which in relation to known solutions, are characterized by reduced power consumption and increased speed of periodic or continuous measurement of the current–voltage characteristics of OLED structures. On the basis of such measurement, the drift of OLED structures characteristics is predicted during their operation, and therefore, the possibility of operative correction of their power supply modes is provided.

The measurement of the V – A characteristics of OLED structures is performed on the transient processes of voltage formation in the boost circuits of the drivers. In order to ensure the requirements for such measurements, the parameters of the pulses of transient processes must meet certain criteria. The pulse amplitude should be sufficient to scan the V – A characteristics of OLED structures in the whole range of their possible functioning, and the shape and increasing time should be optimal from the point of view of further detection of regularities of these V – A characteristics, in particular, regarding their drift in temperature modulation or OLED structure degradation. It is a question of providing compromise requirements. In a number of scanning and measurement tasks, the V – A characteristics must be fast enough to prevent heating, but acceptable for high-precision analog-to-digital conversion, but acceptable for high-precision analog-to-digital conversion. In other tasks, the parameters of the pulses should make it possible to investigate the thermal parameters, for example, the thermal resistance and its relationship to the heating time. The subject of such studies may be the degradation of OLED parameters, in which data sets of multiple measurements are formed.

Summarizing the possible solutions to such supply and measurement modes, let us consider the forms of impulses in the increasing or decreasing phases of which the V – A characteristics of OLED structures are measured. The measurement can be performed during the increasing or decreasing pulses, and if necessary, both during the increasing and decreasing pulses.

The shape of such pulses, in particular the time dependence of voltage $U(t)$, is described by analytical expressions:

$$U(t)=E\left(1-e^{-\frac{t}{\tau}}\right),\quad U(t)=U_0 e^{-\frac{t}{\tau}}, \tag{1}$$

where: $E$ is the supply voltage, $U_0$ is the initial voltage level, $\tau$ is the time constant.

More complex pulse shapes are formed at the RCL circuit, which can be implemented in OLED power driver boost circuits. In particular, fig. 1 presents the results of model SPICE (Simulation Program with Integrated Circuit Emphasis) studies of circuits containing the charge circuit of the capacitor *C1 (VE, R1, C1)* and the inductance *L1*, which is connected to the load resistor *R2* by the *S1* switch. In this example: *R1* = 100 Ohm, *R2* = 10 Ohm, *L1* = 0.001 H, **C1**= 1E-5 F (1), 1E-4 F (2), 1E-3 F (3).

Two processes are combined in this pulse generation circuit: a continuous charge of *C1* through *R1* and a periodic discharge of *C1* through *L1, R2*. The first of these processes is slow and is determined by the time constant $\tau_1 = R_1C_1$, including the energy characteristics of the circuit power supply. Instead, the second process is fast and is determined by the time constant $\tau_2 = R_2L_1$ and the switching frequency of *S1*. The obtained plots of the signals demonstrate the characteristic of transient processes for the transmission of reactive energy which under certain conditions turn into damped oscillations. It can be seen that the signal shapes of these processes are different from pulse to pulse, which indicates the incomplete transmission of energy during the period of switching pulses. This effect must be taken into account when optimizing the operating modes of both the power driver and the signal converter for measuring the V – A characteristics of OLED structures.

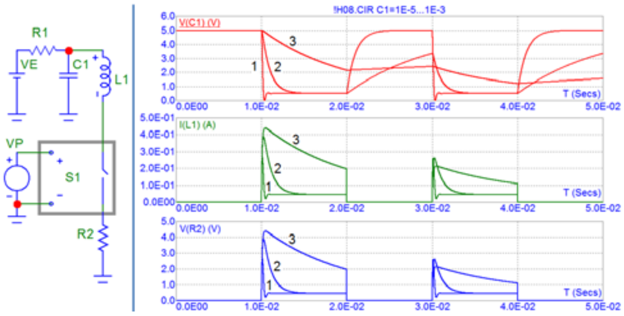
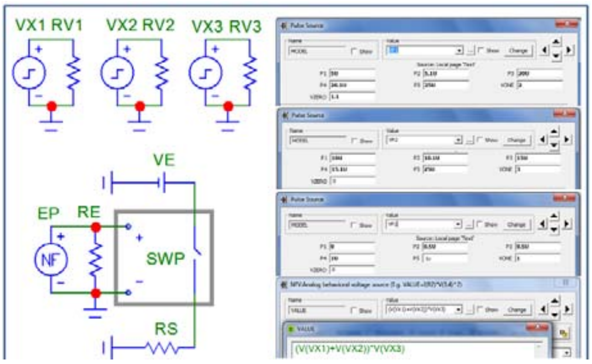


Fig.1. Switching scheme of the RC LC circuit and signal shapes

In accordance with the problem of combining the functions of voltage increase by the power driver and measuring the V – A characteristics of OLED structures by the signal converter, we consider the regularities of output voltage formation using the macromodel of pulse-width modulator control. The macromodel (Fig. 2) contains an analog SWP key with a controlled transmission characteristic. Therefore, the EP source, the output voltage of which is determined by a set of other DC and pulse sources VX1, VX2, VX3, is used.



(V(VX1)+V(VX2))*V(VX3)

Fig. 2. Macromodel of pulse-width control

The switch control voltage is set by a functionally controlled source EP containing several components, in particular several additive and one multiplicative component of modulation. Additive components can be represented by rectangular (trapezoidal) pulses of a certain amplitude and duration, and the multiplicative component - triangular pulses, the frequency of which ultimately represents the frequency of pulse-width modulation.

This example uses two levels of the additive component represented by trapezoidal pulses *V (VX1), V (VX2),* and one level of the multiplicative component represented by triangular pulses *V (VX3)*. Shapes of the signals of these sources are presented in Fig. 3. The result of the synthesis of controlled pulse-width modulation, which is formed by a switch of type *S (V-Swich)* is presented in in Fig. 4.

SPICE model of the driver control circuit is presented in fig. 5, and examples of its research are presented in fig.6 (*f* = 10 kHz, *L1* = 3E-3 H, *C1*=1E-8 F). It can be seen that the operation conditions of the OLED power-boosting driver with in-situ tracking of its V – A characteristics are fulfilled, namely:

- the supply voltage of the OLED structure V (DOLE) exceeds the input supply voltage of the driver circuit several times from 2 to 5 times depending on the I (DOLE), operating mode and component parameters;

- the shapes of the received pulses correspond to the requirements of the procedure for measuring the V – A characteristics, in particular the formation of the areas of smooth (quasi-linear) increase and decrease.

Therefore, the results of the research show the possibility of forming boost OLED power driver with the pulses of form, which allows carrying out cyclic scanning of the V – A characteristics of these structures.

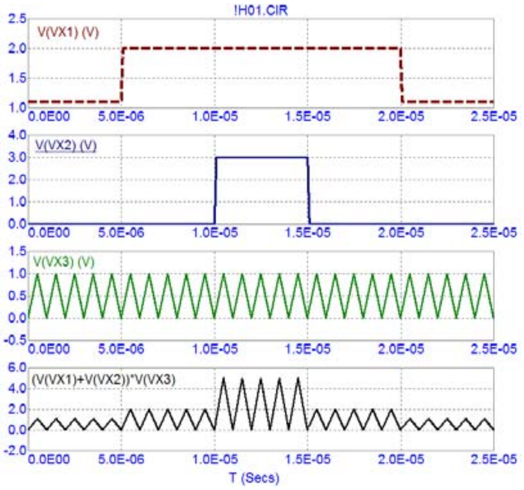


Fig. 3. Shapes of signals *VX1, VX2, VX3, EP*

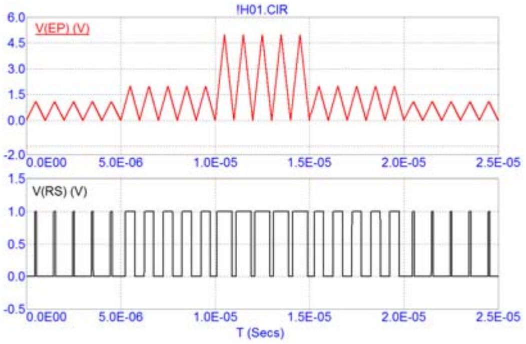


Fig. 4. Shapes of signals *V(EP)* and output voltage *V(RS)*

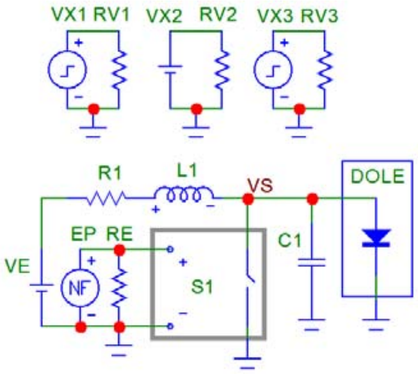


Fig. 5. Schematic diagram of a functionally integrated driver

In a number of tasks of parametric analysis of OLED structures, especially when it comes to the high accuracy of the process of measuring their emitting and thermal characteristics, the shape of the power pulses of OLED structures must be strictly controlled. In solving such problems, preference is given to linear increase or decrease of fronts, which ensures uniform distribution of points throughout the V – A characteristics and high flexibility (adaptability) of the research process.

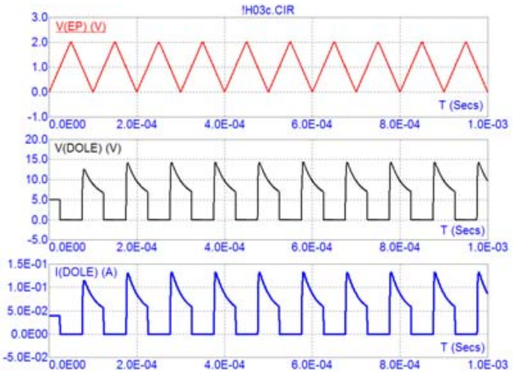
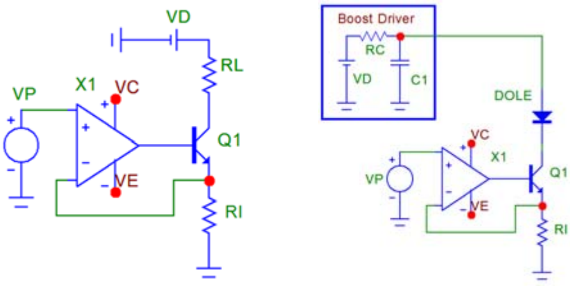


Fig. 6. Shapes of signals at $f$ = 10 kHz, $L1$ = 3E-3 H, $C1$=1E-8 F

The implementation of such researches involves the use of the current feedback circuit in the OLED power supply. The basic circuit with current feedback (Fig. 7, a) contains: master pulse source $V_P$, operational amplifier $X_1$, transistor $Q_1$ for output circuit control, current measuring resistor $R_I$, power supply $V_D$ of output circuit and load $R_L$, as the investigated OLED structure. The operation of the current feedback circuit is based on the stabilization of the current of the output circuit with the condition $I_{OUT}(t) = V_{IN}(t) / R_I$, where $V_{IN}$ (t) is the shape of the voltage pulse, specified by the input source $V_P$. Fulfilling this condition is provided by a feedback circuit on the operational amplifier $X1$.



a) b)

Fig. 7. Control schemes of OLED V – A characteristics measurement processes

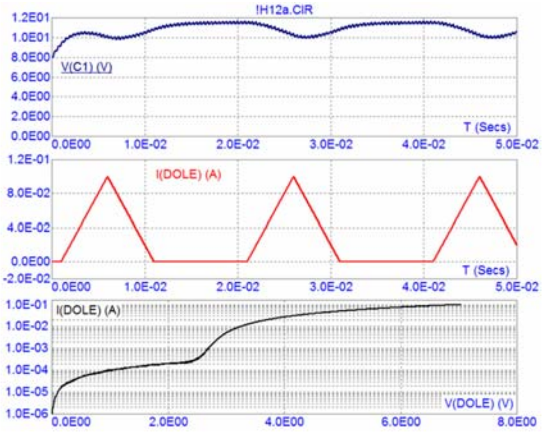


Fig. 8. Shapes of signals and the result of measuring the V – A characteristic of the OLED structure: I(DOLE) = f(V(DOLE))

The control scheme of the measuring process of the V – A characteristics of the OLED structure with a boost driver power supply is shown in Fig. 7, b. The investigated OLED structure is represented by the DOLE SPICE model. Measurements are performed both during the increase and decrease of the pulses (Up & Down), which makes it possible to observe the regularities of such a study (Fig. 8). Pulsations of the output voltage of the boost driver, the parameters of which are described by the macromodel

Boost Driver, are represented by the voltage on the capacitor *V (C1)*. The investigated V – A characteristic of the OLED structure is represented by the function *f* of the current *I (DOLE)* from the voltage *V (DOLE)*.

**Implementation of the embedded OLED controller**

In accordance with the above results of model research and requirements for the implementation of modern electronics devices, an embedded power management system for OLED structures has been developed, which provides: one- or two-stage increase in supply voltage; software control of the power mode of OLED structures; multi-mode measurement of V – A characteristics of OLED structures; control of OLED structures operating modes by contactless capacitive sensor; transmission of control commands and measurement results via the universal USB interface bus.

The controller is implemented on the basis of programmable systems on the chip, namely on the PSoC family 5LP Family Cypress Semiconductor Corporation [17] (Fig. 9).

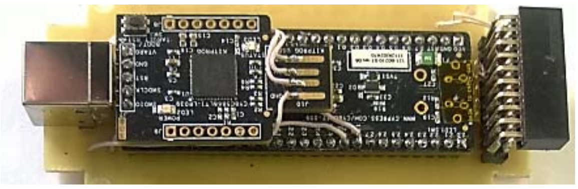


Fig. 9. Photo of the OLED controller on PSoC

The hardware and software implementation of the intelligent controller of OLED structures is carried out in the integrated development environment of PSoC Creator. The PSoC structure includes a control microprocessor, digital and analog system nodes, volatile and non-volatile memory matrices, system resources, IP blocks of interfaces and signal converters of sensor devices, as well as programming and power management units. The basis of digital nodes and IP blocks is a matrix of universal and specialized blocks, in particular for the implementation of interfaces, timers, pulse-width modulators and more. Analog nodes of PSoC are blocks on switching capacitors and blocks with continuous signal conversion, in particular: operational amplifiers, comparators, reference voltage sources on the principle of a forbidden zone, analog multiplexers, etc. The nodes are connected by a software-configured network of signal lines.

The block diagram of the developed power controller and OLED structure control with in-situ tracking of drift of their characteristics is presented in fig. 10.

In order to implement the above mentioned functionalities in the structure of the developed intelligent controller of OLED structures the following built-in PSoC 5LP hardware and software components and IP units (the list shows only the main components) are used: Boost Conv (Boost Converter) – PSoC supply voltage generation unit based on boost converter; Timer – controlled timer; WaveDAC (Wave Digit-Analog Converter) – pulse shaper unit; Control_Reg – Control Register; PWM - Pulse Width Modulator unit; Opamp (Operational Amplifier) – operational amplifier with programmable power supply; PGA (Programmable Gain Amplifier) – amplifier with programmable gain; ADC_SAR (Successive Approximation Register ADC) – odes of two ADC of SAR type; CapSense (Capacitive Sensing) – node signal conversion capacitive sensor control modes of operation of the embedded system; UART (Universal Asynchronous Receiver Transmitter) – communication node based on UART interface; I2C (I2C Bus Interface) – communication node based on I2C interface.

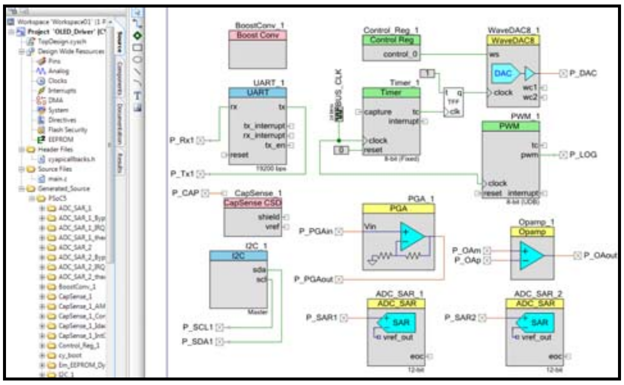


Fig .10. Scheme of a universal OLED controller in the PSoC Creator environment

On the basis of the developed universal controller various algorithms of power supply and measurement of V – A characteristics of OLED structures are realized, in particular: formation of high supply voltage; radiation intensity control; measurement of V – A characteristics on transient processes of power pulses; measurement of V – A characteristics with negative current feedback; contactless capacitive control of power modes, etc.

An example of the PSoC use in an embedded OLED controller system with advanced functionality is shown in Fig. 11.

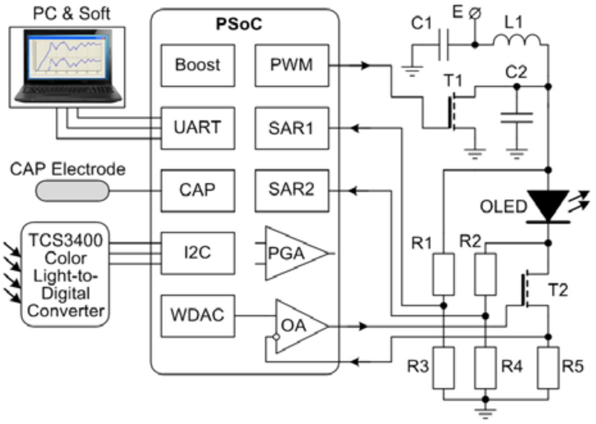


Fig. 11. An example of the PSoC use in the circuit of the OLED controller

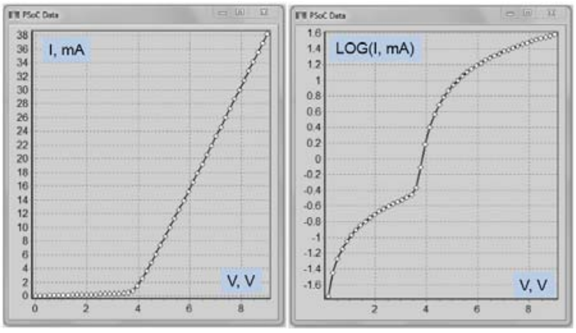


Fig. 12. Example of an OLED structure measurement result

An example of the result of measuring the V –A characteristics of an OLED structure using this controller is presented in Fig. 12.

Power mode control is provided by the transistor T1, and the current of the OLED structure in the process of its V –A characteristics measurement is provided by the transistor T2. Resistors R1, R2, R3, R4 form dividers, the output voltages of which are normalized to the conversion range of SAR1, SAR2. These divisors are fundamentally important, because the voltages on the OLED exceed the supply voltage of PSoC. Therefore, without dividers, the values of the measuring voltage on the OLED not only go beyond the conversion range of the ADC, but can also lead to the failure of the entire signal conversion circuit.

Other applications of controller units are possible, in particular using an amplifier with a programmable PGA factor, which allows you to expand the ranges of measured voltages and programmatically control these ranges. A simple application involves no negative current feedback. A more sophisticated application involves a control algorithm in which the value of the OLED current of the structure is determined by a feedback circuit based on information about the level of light radiation or colour temperature parameters.

## Conclusions

The paper presents a new solution for developing of an OLED controller, the novelty of which is a combination of the process of voltage increasing in the driver circuit and simultaneous in-situ measurement of OLED characteristics during the increase and decrease of this voltage pulses. The measurement of the V – A characteristics of OLED structures is performed on the transient processes of voltage generation in the boost circuits of the drivers.

Model researches show the operating conditions of the boost OLED power driver with in-situ measurement of its V – A characteristics. First of all, the supply voltage of the OLED structure V (DOLE) must exceed the input supply voltage of the driver circuit several times from 2 to 5 times depending on current I (DOLE), operating mode and component parameters. Secondly, the shapes of the received pulses correspond to the requirements of the procedure for measuring the V – A characteristics, in particular the formation of the areas of smooth (quasi-linear) increase and decrease.

In accordance with the results of model researches and requirements for the implementation of modern electronics devices, the embedded management system for OLED structures has been developed, which provides: one- or two-stage increase in supply voltage; software control of power mode of OLED structures; multi-mode measurement of V – A characteristics of OLED structures; control of operating modes of OLED structures by contactless capacitive sensor; transmission of control commands and measurement results via the universal USB interface bus. The controller is implemented on the basis of programmable systems on the chip, namely on the PSoC 5LP Family Cypress Semiconductor Corporation. On the basis of in-situ measurement of V – A characteristics, the drift characteristics of OLED structures during their operation are predicted, and thus, the possibility of operative correction of their power supply modes is provided.

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