Methods and facilities of the automated control for thin film indicators

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Abstract. The algorithms, methods for measuring the structure parameters of thin-film electroluminescent indicators are studied. The algorithm for determining threshold voltage and plotting current – brightness characteristics was created. Realization of this algorithm accelerates process of monitoring of parameters by production known and development of new exemplars of indicator technique on the basis of thin-film electroluminescent indicators. The main aspects of a comprehensive approach to problem solving of automation of process of measurement of values of parameters of structures of thin-film electroluminescent indicators were designated, features of functioning of thin-film electroluminescent indicators as a basis of formation of structure of the device of the automated testing are considered, automation of processing of results of an experiment at the level of the software is described. Key parameters of indicators are determined, problems of automation of measuring processes are formulated, and the algorithm of determination of the threshold voltage and creation of voltage-brightness characteristic of the thin-film electroluminescent indicators in the automated mode is developed. The ideas explained in this article allow formulating the requirement specification on development of the device of the automated measurement of parameters of thin-film electroluminescent elements and also its constituents and the software.

1. Introduction

Thin-film electroluminescent indicator (TFELI) devices currently can be one of the most popular elements for the creation of microelectronic means for displaying information, especially in the development of special equipment. Their advantages include: completely solid construction, reliability, high brightness and speed, wide viewing angle, resistance to ionizing radiation, as well as temperature stability.

The disadvantages of these TFEL devices include the need to use an alternating voltage with a sufficiently large amplitude. But there are modern highly efficient inverters that allow converting a constant voltage (from 2 V) into an alternating voltage with the required parameters [1].

To-date, there have been developed automation tools for the design of TFELIs, methods for automating the design of technological processes for the production of these devices [2]. It is also
necessary to take into account current trends in increasing the speed and quality of control procedures for displaying information and their components [3]. Therefore, diagnostic methods for thin-film indicators should be automated.

2. Description of the TFEL structure

To develop an algorithm for determining the threshold voltage and constructing the voltage-brightness characteristics of indicator devices in an automated mode, it is necessary to consider the properties of TFEL capacitors as elements that are part of the electrical circuit, which includes the emitter and the control system.

TFEL structures of the MDLDM type (metal-dielectric-luminophore-dielectric-metal) usually consist of five layers successively deposited on a glass substrate using thin-film technology.

This structure is shown in Figure 1.

Fig. 1. Structure of the TFELI

Zinc sulfide doped with manganese or rare-earth fluorides is usually used as the luminescent layer. Strontium and calcium sulfides doped with rare-earth metal fluorides have proved to be promising phosphors.

Plates of alkali-free heat-resistant glass 2 - 3 mm thick with a deposited layer of a transparent electrode, for the creation of which heavily doped indium or tin oxides, which are degenerate wide-gap semiconductors, are used as substrates for the fabrication of structures. To obtain opaque electrodes, aluminum, indium, tin, and refractory metals are used.

To create dielectric films in electroluminescent structures, oxides of silicon, aluminum, yttrium and rare earth metals, silicon nitride, etc., their compositions, ferroelectric materials are used [1].

The main role of dielectric layers is to limit the charge passing through the phosphor in operating conditions. The need to use such layers is due to the properties of the charge transfer process in a luminescent film. Electroluminescence in thin layers of zinc sulfide and other materials is associated with electrical breakdown of the semiconductor.

Two dielectric layers separating the phosphor film from the electrodes make it possible to represent this device as an electroluminescent capacitor, which forces the use of an alternating voltage to provide electroluminescence [4].
3. Description of volt-brightness characteristics of TFEL
Since a person receives most of the information with the help of vision, and TFELI are intended primarily for visualizing digital data, therefore, the main characteristic of these indicators is the voltage-brightness.
Figure 2 shows a typical I/V characteristic of a TFEL structure based on zinc sulfide doped with manganese.

![Typical I/V characteristic](image)

**Fig. 2.** Typical I/V characteristic of the TFEL capacitor in linear and semi-logarithmic coordinates (f = 1 kHz (1); 5 kHz (2) and 20 kHz (3))

In Figure 2, one can see that this dependence is linear at low voltages and frequencies, with an increase in these parameters, the dependence graph is sublinear. It is customary to depict the graphs of the volt-brightness characteristics in a semi-logarithmic scale, that is, on the abscissa axis, the voltage is indicated in a linear scale, and on the ordinate axis, the brightness is shown in logarithmic coordinates.

The use of the logarithmic scale for such a parameter as the brightness of radiation is associated with the subjectivity of a person's perception of its magnitude; an increase in the brightness of a light source by an order of magnitude is perceived by a person as a twofold increase.

As can be seen from the figure, the voltage-brightness characteristic has a threshold character, i.e., a sharp increase in brightness occurs when a certain voltage is applied to the TFEL.

The magnitude of the threshold voltage is primarily determined by the properties of the phosphor material: the threshold electric field strength, the magnitude and ratio of the capacities of the luminescent and dielectric layers. The value of the threshold electric field strength in phosphor films isolated from the electrodes is determined by the mechanism of generation of free charge carriers $10^5 \sim 10^6$ V/cm [1].

4. Features of a sinusoidal signal
The main type of used alternating signal is sinusoidal. Let's consider its parameters.
The effective value of an alternating current or voltage is called the value that is taken in calculating the released heat or power. For a direct current, the effective value is equal to the amplitude, average and instantaneous, for an alternating signal, these are all different values.

The instantaneous value of the alternating voltage is the absolute level of the voltage at a particular moment in time. The peak value is the largest value of a sinusoid (or another curve for a non-sinusoidal waveform) over a period. The amplitude value is taken modulo. The average is the sum of all instantaneous values for the period, divided by the number of samples. Mathematically, it is the integral of the instantaneous values over the period. Obviously, for a sinusoidal form, the average value over the period will be zero. If the waveform is distorted, the average value over the period may turn out to be non-zero - then it is called the constant component of the alternating voltage. The effective or effective voltage value is a value numerically equal to:

$$ U = \frac{1}{T} \int_{0}^{T} u^2 \, dt, $$

(1)

where $U$ is the effective value, $T$ is the time of one period, $u$ is the instantaneous value of the voltage.

Active and amplitude ($U_m$) voltages are related as follows:

$$ U = \frac{U_m}{\sqrt{2}}. $$

(2)

Often, instead of the effective one, another value of the alternating voltage is measured - the average rectified (the constant component of the unsmoothed ripple voltage at the output of the full-wave rectifier). It is equal to $2 / \pi \approx 0.637$ of the sinusoid amplitude which is 1.11 times less than its effective value. The overwhelming majority of universal low-frequency measuring instruments (multimeters) show not the effective, but the average rectified value of the alternating voltage, multiplied by this correction factor [5].

5. Algorithm for constructing the volt-brightness characteristic of TFEL in an automated mode

For the analysis of electrical characteristics, it is more correct to determine the threshold voltage by measuring the charge or power, but from the user’s point of view, it is preferable to determine the threshold voltage by measuring the brightness, that is, to actually build the voltage-brightness characteristic. 

As a result of the analysis of modern measurement systems, the necessary requirements for these systems and their algorithms were formulated:

- the possibility of conducting an experiment at the physical level using full-scale TFELI samples;
- high reliability, clarity and information content of the data obtained;
- the ability to store and transfer measurement information to a PC;
- high speed of data processing and reporting;
- ease of use;
- the possibility of upgrading the system, expanding its functionality.

Based on the foregoing, the main parameters determined by the algorithm are the brightness of the TFELI and the effective value of the sinusoidal voltage, measured at the same time. The implemented algorithm must determine the threshold voltage of the TFEL by detecting the moment when the brightness increases with the photosensor and measuring the value of the sinusoidal voltage applied to the TFEL at this moment, then the device must measure the brightness and voltage values, and also be able to transmit data to the PC.

Figure 3 shows a block diagram of the algorithm. First, all counters are reset to zero, etc. Then the system waits for a signal from the photosensor to appear, that is, the moment the TFEL starts to glow. The beginning of emission of radiation is recorded by the system by reading data from the photosensor, as well as transmitting information about the voltage applied at that moment to the TFEL. Thus, the threshold voltage of the indicator is determined. Next, there is a sequential determination of the brightness and voltage values, the transfer of these data to the PC in order to build the voltage-brightness characteristics of the TFEL and display it on the computer monitor in a user-friendly form (table, graph, histogram, etc.).
6. Description of the device implementing this program
To implement the above actions, as well as to process the measurement results and the possibility of interaction of the developed measuring device with a personal computer, it was decided to use a microcontroller (MC).

Accordingly, the digital part should include:
1. Analog-to-digital converter (ADC) for working with brightness and voltage sensors;
2. Device for interaction of MC with USB;
3. Display or indicator for displaying the measurement results and a decoder for the latter;
4. MK with a sufficient number of inputs and outputs;
5. Connector for downloading programs to the MC; Arduino tools and their analogs can be used to meet the above requirements. A photodiode, photoresistor, etc., as well as circuits with the ability to suppress light interference can be used as a photosensor. For voltage monitoring, a rectifier with a voltage division function can be used. The indication can be carried out using three seven-segment indicators and the corresponding register microcircuits. It makes sense to exchange register and microcontroller data using the SPI interface. The documentation for seven-segment indicators contains a table with information about which logic level must be applied to the input in order for this or that digit to light up. For indicators with a common cathode, the table looks like this:

**Indication table**

The column on the far right with the name HEX is a byte representation of a digit for transferring it using a register. To work with several indicators, you must use either a serial connection of devices to the bus, or parallel.

When connected in parallel (Fig. 4), several slaves share the SCLK, MOSI and MISO wires, with each slave having its own CS (SS) line. The master determines the device with which the exchange is carried out by generating a low signal at his CS (SS) input.

|   | A | B | C | D | E | F | G | DP | HEX |
|---|---|---|---|---|---|---|---|----|-----|
| 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 3F  |
| 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 06  |
| 2 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 5B  |
| 3 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 4F  |
| 4 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 66  |
| 5 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 6D  |
| 6 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 7D  |
| 7 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 07  |
| 8 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 7F  |
| 9 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 6F  |
To connect n devices, n CS (SS) lines are required, that is, for the SPI environment to function with n slaves, n + 3 microcontroller pins must be allocated for this.

When connecting devices in series (Fig. 5), they use the common SCLK and CS wires, and the output of one is connected to the input of the other. The MOSI of the master is connected to the first device and the MISO to the last.

![Fig. 5. Serial connection](image)

This connection allows you to build one 16-bit shift register from two 8-bit shift registers. The circuitry of the device on indicators with a common cathode determines the following order of information transmission via SPI: the first is the byte that is responsible for which digit will be displayed (anode byte), and the second is the byte that is responsible for the position of the digit (cathode byte) [6].

The anode byte during the SPI transfer session is transferred through the DD2 register to DD3. The cathode byte is placed in DD3 and remains there. As a result, the numbers are displayed on the indicators:

```cpp
#include <SPI.h>
// connect CS wire to pin 8 of Arduino
enum {reg = 8};
void setup ()
{

  // Set the reference voltage to 2.56 V
  analogReference (INTERNAL);
  // initialize SPI
  SPI.begin ();
  // define pin 8 of Arduino as output
  pinMode (reg, OUTPUT);
  // Open the last. port and set the baud rate
  Serial.begin (9600);
}
```

To display three digits, a dynamic indication is used, that is, the image of each digit turns on for a short time, then turns off, and the procedure is repeated for subsequent digits.

It has been experimentally established that when the digit is switched every 8 milliseconds, the flicker is distinguishable, but at a value of 7 milliseconds, the eye no longer sees the sampling. The cathode
byte is calculated so that 00011000 ignites the left bit, 00010100 - the middle one, 00001100 - the right one. That is, the one in bits 2, 3 and 4 is responsible for the ignition of the corresponding bit:

```c
// Variables to display hundreds, tens, units
int hundreds = 0, tens = 0, ones = 0;
// display time for each digit
int delayTime = 1;
// codes of numbers on a seven-segment indicator (0-9 and empty)
static uint8_t digit[11] = {0x3F, 0x06,0x5B, 0x4F, 0x66,0x6D, 0x7D, 0x07,0x7F, 0x6F, 0x00};
// position codes of the lit indicator (left, center, right)
static uint8_t pos[3] = {0x18,0x14,0x0C};
```

It is necessary to split the transmitted number into components. Let there be a number int f, which in the decimal system has no more than three digits, that is, a number less than 1000. Algorithm:
1. Divide f by 100, staying within int we get the number of hundreds.
2. Subtract from f the number of hundreds, multiplied by 100, divide the remainder by 10 - determine the number of tens.
3. Subtract from f the number of hundreds multiplied by 100 and the number of tens multiplied by 10 - we get the number of units.
4. If the number of hundreds is zero, then nothing is displayed in the left digit.
5. If the number of hundreds and tens is zero, then nothing is displayed in the left and middle digits:

```c
void OutLED (int f)
{
    int x = 600;
    Serial.println (f);
    do {
        // hundreds are allocated
        hundreds = f / 100;
        // dozens are allocated
        tens = (f-hundreds * 100) / 10;
        // units are allocated
        ones = f-hundreds * 100-tens * 10;
        // if there are no hundreds, nothing is displayed in the 3rd digit
        if (hundreds == 0) hundreds = 10;
        // if there are no hundreds and tens, nothing is displayed in the 2nd digit
        if (hundreds == 10 && tens == 0) tens = 10;
        then a pair of bytes is transmitted via SPI for each bit of our number in turn:
```

```c
    // start SPI transmission
digitalWrite (reg, LOW);
    // transfer the code of the digit corresponding to the place of hundreds
    SPI.transfer (digit [hundreds]);
    // the left indicator is selected
    SPI.transfer (pos [0]);
    // end of transfer
digitalWrite (reg, HIGH);
```
// pause equal to delayTime
delay (delayTime);
// transfer the code of the digit corresponding to the tens place
digitalWrite (reg, LOW);
SPI.transfer (digit [tens]);
// select the central indicator
SPI.transfer (pos [1]);
digitalWrite (reg, HIGH);
delay (delayTime);
// transfer the code of the digit corresponding to the ones place
digitalWrite (reg, LOW);
SPI.transfer (digit [ones]);
// select the right indicator
SPI.transfer (pos [2]);
digitalWrite (reg, HIGH);
delay (delayTime);
x--;}
} while (x> 0);
}

Reading the signal from the photosensor and determining the value of the supply voltage is performed as follows:

void loop ()
{
// Reading information from the light meter output
float L = analogRead (A1);
// Is the light / dark threshold exceeded?
if (L> 10)
// Overcome
{float f = analogRead (A0);
  f = f * 142; // take into account the division ratio and get the amplitude value
  f = f * 0.707; // conversion of amplitude to real value
  f = f * 0.0025; // convert from ADC values to volts
  OutLED (f); }
// Not overcome
else
{float f;
  OutLED (f = 0);}
}

Programming is carried out entirely through its own software shell (IDE), available free of charge from the Arduino website. This shell contains a text editor, a project manager, a preprocessor, an interface for transferring data from a PC to an MC and vice versa (thanks to this, voltage and brightness data are transferred to a computer via USB during the entire time the program is running), a compiler and tools for downloading the program to MK. The shell is written in Java based on the Processing project, runs on Windows, Mac OS X and Linux.

7.  Experiment Results
As samples of indicators for the experiment, we used the standard structures of five layers on a glass base obtained in earlier studies, which are shown in Figure 1. The substrates were plates with a thickness of 1.5 to 3 mm made of alkali-free glass. The phosphor layer, 0.5 to 1.5 microns thick, was
formed from zinc sulfide doped with manganese. In the role of a transparent electrode, tin and indium oxides, 0.2 microns thick, were used. A solid solution of yttrium and zirconium oxides, 0.3 microns thick, was taken as dielectrics. An aluminum layer up to 2 microns thick served as an opaque electrode. TFELI is installed in an opaque box.

A photocell based on cadmium sulfide was used as a receiver of optical radiation, the signal from which is fed through an operational amplifier and filters to the first input of the MC ADC. The voltage from the power generator of the TFEL element is fed through a rectifier with a divider to the second input of the MC ADC.

In the course of the experiment, the brightness of the TFEL was measured depending on the sinusoidal signal applied to it. The volt-brightness characteristics presented in Figure 6 were plotted at a supply voltage frequency of 50 Hz and 1 kHz, the series resistance of the circuit (R) was 30 kOhm and 68 kOhm.

It can be noted that with an increase in the series resistance of the circuit, the brightness of the indicators decreases. This is due to the fact that with a high resistance, the duration of internal transient processes is longer than with a small value of R [1, 7]. Also, an increase in the brightness of the TFEL was determined, associated with an increase in the frequency of the supply voltage with a constant resistance R. Thus, the data obtained as a result of the experiment are consistent with the results of theoretical analysis [8, 9] and previous measurements [1], which confirms the consistency of the above-described method of automated control TFELI.

8. Conclusion
The research carried out in the field of automation of the processes of measuring the brightness functional characteristics of TFELs made it possible to distinguish the following results: developed an algorithm for measuring the lighting parameters of TFELI;
- a software and hardware solution for the implementation of the above-described algorithm has been developed.

Thus, based on the requirements for devices and systems for determining the values of the indicator parameters, the ability to carry out measurement operations in an automated mode with the ability to control this system and process the results (including the formation of databases and their exchange) using a personal computer is realized.
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