

## **PECULIARITIES OF LOW VOLTAGE CATHODOLUMINESCENCE**

Michael Nazarov, Sergey Bukesov, Jong Hyuk Kang, Duk Young Jeon  
*Dept. of Mat'ls Sci. & Eng., KAIST, 373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701,  
Korea*

### **ABSTRACT**

Displays operating at low (<1 kV) voltages have a number of peculiarities. Low voltage cathodoluminescence measurements were carried out on the series of red phosphors to better understand all the phenomena around low voltage measurements. Estimation of potential errors and improvement of luminescence properties at low voltage CL are discussed. The dynamic electrophysical characteristics of vacuum displays are proposed to be described by a three dimensional (3D) diagram involving its equivalent circuit. Topological analysis of such a diagram has allowed us to explain an interesting phenomenon: a hysteresis and breaks on the volt-ampere curves, which were earlier observed experimentally. The approach is intended to be taken as a basis for FPD simulation.

### **INTRODUCTION**

There are some peculiarities in low voltage cathodoluminescence (CL) in comparison with high voltage CL. It should be noted at least two main problems in low voltage CL. One of them concerns the phosphors.

Phosphors are the light-emitting components used in flat panel displays (FPD) based on electroluminescent, plasma or field emission excitation technologies. Unlike cathode ray tube (CRT) displays, which use highly energetic electrons and substantial beam currents to excite phosphor emission, design constraints in FPD severely limit the amount of excitation power available to excite phosphors. Consequently, the emission efficiency of phosphor materials becomes an issue of major concern in the design of FPD. Basic flat panel display technologies consist of essentially four types: LCDs, plasma display panels (PDPs), field-emission displays (FEDs), and electroluminescent displays. By far the most pressing materials challenge for FEDs — as well as for PDPs, electro-luminescent displays, and certain CRT projection displays — is the development of low voltage phosphors. The ones currently in use function reasonably well in higher-voltage displays but lose brightness as voltage decreases. The efficiency of these phosphors optimized for CRTs drops rapidly as the excitation voltage is lowered below 4 kV. The decreased efficiency is thought to be a result of the reduction in the electron penetration depth as the excitation potential is decreased. For example, the penetration depth for ZnS has been found to drop from 0.5-1.5  $\mu\text{m}$  to 17-27 nm as the voltage is lowered from 10 to 1 kV [1]. The major problem may be from the low penetration of electrons into the phosphor lattice, which leads to Coulombic aging. To overcome this problem, a conductive coating on the phosphor surface has been tried and was partially successful [2]. In these points, excellent work on the charging in low-voltage phosphors was reported by Seager et al.[3,4] and mechanisms of degradation of FED phosphors by Holloway et al.[5]. The best TV display phosphors are about 15% efficient, according to Carl Seager of Sandia National Laboratories, and are even less efficient at the lower energies (400-500 V) ultimately desired for FEDs. An exception is zinc oxide, one of the few phosphors that

conduct electricity well. This property makes it possible to build up electric fields inside the phosphor, which are crucial to preventing the loss of surface charges and hence maintaining brightness. However, zinc oxide emits light at a wavelength somewhere between green and blue. Thus it is not useful for the commercial manufacture of three-color displays, as it requires complicated filtering processes that would negate any energy-efficiency advantages. Low voltage FPDs require the development of phosphors that are bright and efficient under low energy excitation, are stable at high currents, and have good saturation characteristics [1, 6]. More in detail this problem will be considered in one of our future articles.

In this paper our investigations are mainly focused on another low voltage CL problem – measurement problem. Displays operating at low (<1 kV) voltages have a number of peculiarities among which there is the necessity to remove charge from the screen immediately through the phosphor layer whose own conductivity is usually quite low. As a result, the voltage drop over such a layer may reach, by our estimations, 70-80% of the applied voltage. Some peculiarities of low voltage CL measurements and estimation of some possible errors are discussed. In this work we explore two issues that might become important for many materials: surface charging during electron beam exposure and degradation of the luminescence due to Coulomb loading. Most phosphors are wide band gap insulators with low conductivities. During e-beam irradiation electron-hole pairs are produced in great numbers, so some photoconductivity must be present, at least near the surface. Exactly how the material responds to achieve this condition is a question of considerable complexity; however, several of the experimental parameters measured in this study give us some insight into this problem.

The available literature reports the characteristics of real displays with no voltage drop over the phosphor layer taken into account, that, in our opinion, cannot give an appropriate pattern of display functioning. That is why we propose a 3D diagrammatic representation of the display performance, which enables the electrophysical properties of the phosphor to be considered and the real modes of display operation to be described.

The proposed modeling has allowed us to consider the conditions for appearance of a hysteresis on the volt-ampere (and therefore the volt-luminance) curves (observed in [7]) and to give their mathematical description.

## EXPERIMENT

Some samples such as  $\text{YVO}_4:\text{Eu}$  and  $(\text{Y,Gd})\text{VO}_4:\text{Eu}$ , as well as  $\text{Y}_2\text{O}_3:\text{Eu}$ , prepared by different methods were chosen in our experiments. All of them are good candidates as red phosphors for FPD devices. We especially select different phosphors with various particle sizes and synthesis techniques for demonstration of the general regularity in low voltage CL measurements.

To prepare  $\text{YVO}_4:\text{Eu}$  phosphors, solid state reaction (SSR) and precipitation (PM) methods were used. The mean size of the phosphor particles prepared by PM was about 200 nm and about 2  $\mu\text{m}$  by SSR, which were confirmed by SEM analysis.  $\text{Y}_2\text{O}_3:\text{Eu}$  powders were prepared by ceramic techniques and hydrothermal method (similar to sol-gel (SG)) with mean particle size about 1  $\mu\text{m}$ . For the low voltage CL measurement, a Kimball Physics FRA2X-2/EGPS-2X1 electron gun system was used. The e-gun system was installed in a demountable ultrahigh-vacuum chamber combined with a CL spectrophotometer. The vacuum level of  $1 \times 10^{-7}$  Torr was maintained during the experiments. The CL spectra were registered at accelerating voltages 500 and 1000 V for all phosphors. The excitation current density of 20-100  $\mu\text{A}/\text{cm}^2$  was applied. Under these conditions the dependence of the luminescence properties on electron beam current and accelerating voltage was investigated.

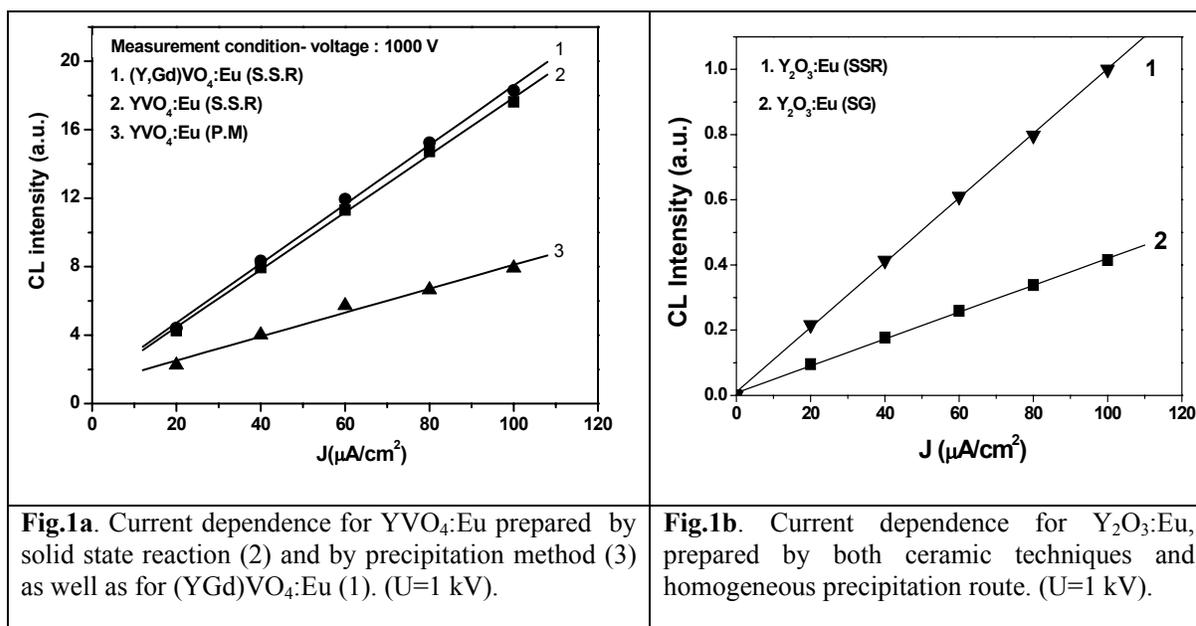
In general case the CL intensity does not depend only on investigated sample but is also an unknown function of emission current and accelerating voltage.

$$I_{CL} = K f_1(J)f_2(U) \quad (1)$$

where K is a certain constant depending on the sample, J is density of emission current and U is accelerating voltage between cathode and anode in CL installation.

Knowledge of these functions  $f_1$  and  $f_2$  could help us in modeling emission process and energy transfer in investigated sample. They can be obtained from direct experiments changing J and U.

For fixed accelerating voltage  $U=1$  kV the current dependences for some investigated samples are shown in Fig. 1.



**Fig.1a.** Current dependence for  $YVO_4:Eu$  prepared by solid state reaction (2) and by precipitation method (3) as well as for  $(Y,Gd)VO_4:Eu$  (1). ( $U=1$  kV).

**Fig.1b.** Current dependence for  $Y_2O_3:Eu$ , prepared by both ceramic techniques and homogeneous precipitation route. ( $U=1$  kV).

One can see the linear intensity dependence for all the powders

$$I_{CL}=KJ \quad (2)$$

Coefficient K depends on materials and differs for different powders and synthesis conditions.

Voltage dependences for the same samples are presented in Fig. 2.

All experimental curves in Fig. 2a and 2b are well described mathematically by the polynomial functions

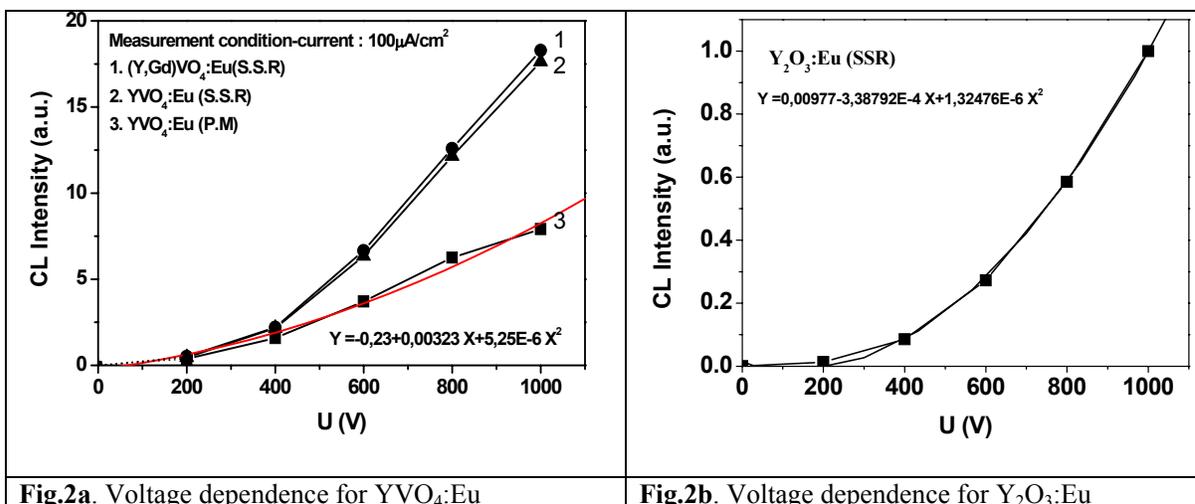
$$Y= A+BU+CU^2 \quad (3)$$

where A,B,C are experimental constants various for different samples or used techniques.

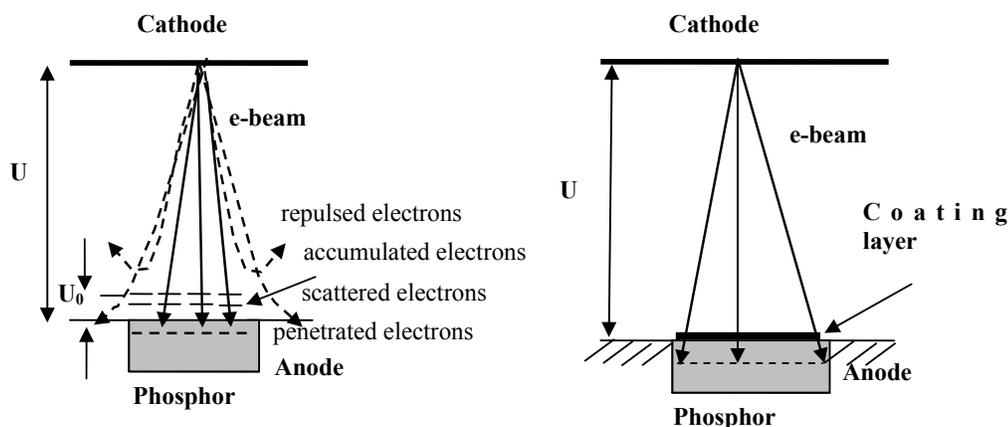
The equation (2) can be presented as a power function

$$I_{CL} = K(U-U_0)^\alpha \quad (4)$$

where  $\alpha$  can take for different phosphors the values 1,2,3. In our cases, as we can see from experimental data (fig.2),  $\alpha=2$ .  $U_0$  is a “dead layer voltage” which is formed because of negative electrical charge near the anode surface.



Schematic diagrams of charging phosphor by accumulated electrons and model, explaining the negative role of  $U_0$  are shown in Fig.3.



**Fig. 3.** Schematic diagrams of charging phosphor by accumulated electrons and improving CL intensity with coating layer.

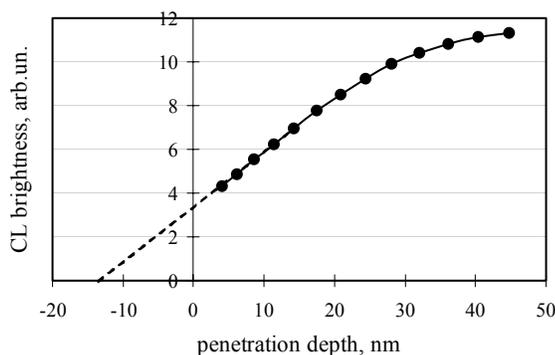
It should be noted that in general case  $U_0$  strongly depends on studied material and is a function of accelerating voltage, excited current and electrical conductivity of sample. When an investigated sample is dielectric with resistivity  $R$  about  $10^{10} \Omega$  (such as Y<sub>2</sub>O<sub>3</sub>:Eu, for example), this charged layer is significant and  $U_0$  can reach about 100-200 V and need to be taken into account at low voltage measurements. There are two negative effects related with forming of this “dead layer voltage”  $U_0$ . The electrons injected into the phosphor powder or near the surface may be scattered outward from the excited area by repulsion of a potential barrier due to the accumulated electrons near the phosphor surface. Some of primary electrons in electron beam can be repulsed by this accumulated layer, decreasing the excited current and as consequence the brightness. Secondly, the penetration depth of excited electrons also diminishes that decreases the CL intensity. Fig. 3 represents this charging phenomenon on dielectric phosphors.

To estimate the influence of delayed layer on the brightness of phosphor let us

calculate the penetration depth of primary electrons especially at low voltages, because a systematic error in calculating values is possible and it depends on the chosen formula. The majorities of the known formulas are obtained for high-energy electrons, and their approximations for low energy ones are not correct sometimes. In our calculations we selected a simple equation, which well describes the penetration depth of electrons in a wide range of their energies:

$$\rho z_0 = 10^{-5} U^{3/2},$$

where  $\rho$  is the density of matter (g/cm<sup>3</sup>),  $U$  is accelerating voltage of electrons in (kV) and  $Z_0$  is penetration depth in cm. For many phosphors including above-named the penetration depth at accelerating voltage  $U=1$  kV is in range 15-20 nm (Fig.4) [8].



**Fig.4.** The intensity of integral CL vs the penetration depth of primary electrons for ZnS:Ag,Cl phosphor. The power of electron excitation was  $P=15$  mW/cm<sup>2</sup>.

For investigated samples in this region the brightness and CL intensity are also directly proportionate to the penetration depth

$$I_{CL} \sim Z_0 \text{ and } \Delta I_{CL} \sim \Delta Z_0$$

So, taking into account the potential barrier  $U_0$  due to the accumulated electrons near the phosphor surface, we can find the variation of penetration depth:

$$\Delta Z_0 = C U^{3/2} - C (U - U_0)^{3/2}, \text{ where } C = 10^{-5} / \rho$$

If we take in Taylor's series only the first two terms for this function, the variation of comparative CL intensity  $\Delta I_{CL} / I_{CL}$  due to presence of dead layer voltage could be estimated as:

$$\varepsilon = \Delta I_{CL} / I_{CL} = (\Delta Z_0 / Z_0) \cdot 100\% = (3/2)(U_0 / U) \cdot 100\%$$

At low voltages about 1 kV the decrease of brightness due to  $U_0$  may run up to 40% and more.

To exclude or diminish the influence of "dead layer voltage"  $U_0$ , it is advisable to decrease the resistance of the powder introducing the conductive nonluminescent powder (for

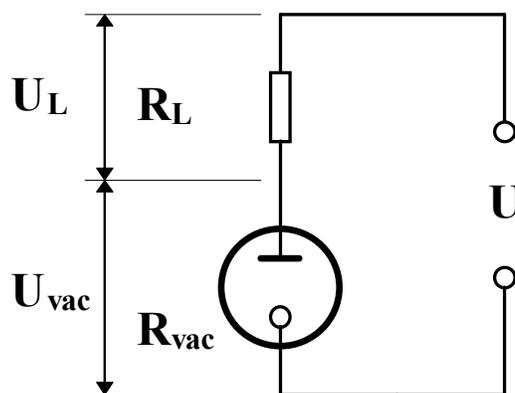
example, such as ZnS, ITO) or use a thin conductive coating. We can expect the increase of CL intensity at low voltage about 50%

There is one else reason that can diminish the “dead layer voltage”. It may be the photoconductivity that is present, at least near the surface. This phenomenon can also explain the hysteresis on the volt-ampere (and therefore the volt-luminance) curves (observed in [7,9]). Bearing this in mind, let us consider the theoretical model and mathematical description of three dimensional diagrammatic representation of vacuum display excited by low energy electrons.

## RESULTS AND DISCUSSION

### THEORETICAL MODEL

The electrical properties of a display can be considered while based on its equivalent circuit (Fig. 5). The justification of representation of a real display in such a manner was discussed and proved experimentally in [10].



**Fig. 5.** Equivalent circuit of the vacuum display.

Here  $R_L$  is a resistor corresponding to the resistance of the phosphor layer,  $R_{vac}$  represents the vacuum cathode-anode gap. Then the overall voltage applied to the display  $U$  will contain the voltage drops over the phosphor layer and the vacuum gap. The currents through the layer  $I_L$  and the vacuum gap  $I_{vac}$  are equal and equal to the total current in the circuit.

Let us first analyze each element separately.  $I_{vac}$  depends on  $U_{vac}$  and is determined by the cathode's volt-ampere characteristics.  $I_L$  is related with  $U_L$  via its differential resistance  $R_L$ , which, in its turn, depends on the energy of bombarding electrons ( $U_{vac}$ ) due to electron-stimulated conduction. So, we write a set of equations:

$$I_{vac} = I_{vac}(U_{vac}) \quad (5)$$

$$I_L = I_L(U_L, U_{vac}) \quad (6)$$

$$U = U_{vac} + U_L \quad (7)$$

To perform their qualitative topological analysis, represent these functions graphically

in 3D space  $\{I, U_L, U_{vac}\}$ , which enables the voltage dependences of currents to be observed.

Take function (1). As  $I_{vac}$  is  $U_L$ -independent, the corresponding surface (name it as  $\sigma_{vac}$ ) is formed by the straight line parallel motion along the volt-ampere curve of the vacuum gap (Fig. 6).

To draw the surface  $\sigma_L$ , let us consider the  $I_L=I_L(U_L)$  dependence at several constant values of  $U_{vac}$ . The differential resistance of the layer is:

$$R_L = \left( \frac{\partial U_L}{\partial I_L} \right)$$

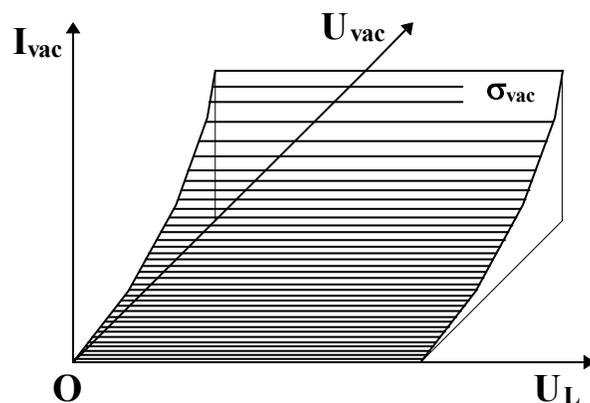


Fig. 6. 3D volt-ampere surface of the vacuum gap.

At low  $U_{vac}$  ( $<U_0$ , the generation threshold), the electron energy is insufficient to excite extra conduction as well as luminescence. The layer possesses a certain initial resistance  $R_0$ , which almost does not depend on  $U_{vac}$ :

$$R_L \Big|_{U_{vac} < U_0} = \left( \frac{\partial U_L}{\partial I_L} \right) \Big|_{U_{vac} < U_0} = R_0$$

When  $U_{vac}$  reaches the mentioned  $U_0$ , cathodoluminescence and electron-stimulated conduction arise simultaneously, and  $R_L$  starts to fall [10], which makes the volt-ampere curve steeper. Further increasing the steepness is limited by the maximal conductivity due to saturation. Upon this saturation ( $U_{vac} > U_s$ ),  $R_L$  shows a very slight dependence on  $U_{vac}$ . So, we have a region where both luminescence and conductivity are saturated [11].  $I_L$  has a strong dependence on  $U_{vac}$  within  $[U_0, U_s]$  only.

Proceeding from the above, function 2 can be represented in our 3D space somehow like  $\sigma_L$  (Fig. 7).

The region N of this surface corresponds to the range  $[U_0, U_s]$ . The character of the volt-ampere characteristics within this region is determined by the changes in the phosphor layer resistance; in the general case,  $I_L$  depends on  $U_L$  nonlinearly. However, the characteristics shown in Fig.7 are linear, which is let by the qualitative nature of the phenomena under consideration.

For a real display, the behavior of these characteristics will be determined by the family of volt-ampere curves of the phosphor layer recorded for every fixed  $U_{vac}$  value.

Analytically, the above can be written as:

$$\left( \frac{\partial I_L}{\partial U_{vac}} \right) \Big|_{U_0 < U_{vac} < U_S} > 0;$$

$$R_L \Big|_{U_{vac} > U_0} < R_0.$$

When the surfaces  $\sigma_{vac}$  and  $\sigma_L$  are drawn in the common coordinate system, this allows us to determine all the possible modes of display operation (Fig. 8).

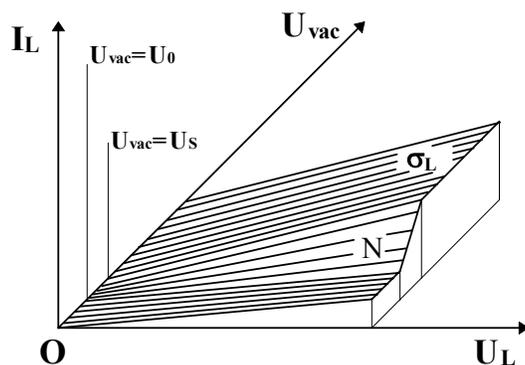


Fig.7. 3D volt-ampere surface of the phosphor layer.

The intersection of these surfaces gives a working curve that follows from the condition:

$$I_L = I_{vac} = I$$

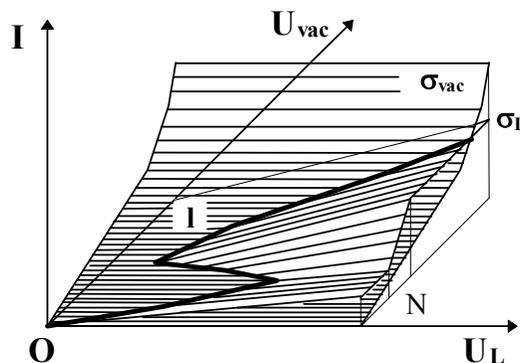


Fig. 8. 3D volt-ampere characteristic of the vacuum display.

As one can see from Fig. 8, the working curve may have a S-like bend related to the presence of the region N (the maximal influence of low-energy electrons on conduction). This bend, under certain circumstances, will cause a hysteresis on the volt-ampere characteristics and volt-luminescence characteristics. Mathematically, this condition is expressed as:

$$\left[ \left( \frac{\partial I_L}{\partial U_{vac}} \right) - \left( \frac{\partial I_{vac}}{\partial U_{va}} \right) \right] \Big|_{U_0 < U_{vac} < U_S} > R^{-1} \Big|_{U_0 < U_{vac} < U_S}$$

i.e. within  $U_0 < U_{vac} < U_S$  the  $U_{vac}$  dependence of the current through the screen must exceed the current dependence through the vacuum gap by a value greater than the layer conductivity at the moment.

We have considered some modes of display operation, when hysteresis may either be absent or play a remarkable role.

## CONCLUSION

Estimation of potential errors and improvement of luminescence properties of some phosphors at low voltage CL are proposed. The dynamic electrophysical properties of vacuum displays are suggested to be described by a 3D diagram involving its equivalent circuit. The proposed 3D diagram will be used to optimize the display performance and to explain some of its features.

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## AUTHOR DETAILS

Dr. M. Nazarov, Department of Material Science and Engineering, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea, e-mail: mvnazarov@mail.ru

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