

A theoretical model for the cathodoluminescence of granular phosphor screens

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A theoretical model for the cathodoluminescence of a phosphor screen is presented. The model takes into account the granular structure of the screen and the random deposition of the phosphor grains on the screen substrate. It gives reliable predictions even in the case of the low thickness screens where the Hamaker-Ludwig [H. C. Hamaker, *Philips Res. Rep.* **2**, 55 (1947); G. W. Ludwig, *J. Electrochem. Soc.* **118**, 1152 (1971)] model is not applicable. Using this model we obtained results concerning the dependence of the screen efficiency on various parameters. These results are in close agreement with the experimental data already known for the cathodoluminescence of phosphor screens.

INTRODUCTION

All theoretical calculations and predictions concerning the efficiency of fluorescent screens have been based until now on the Hamaker-Ludwig model,^{1,2} according to which a phosphor screen is assumed to be a homogeneous and uniform layer of phosphor material. As a result this model is suitable for nongranular phosphor screens (as the ones prepared by evaporation) and for high thickness granular phosphor screens (as the ones used in fluoroscopy³), but it is almost useless for the low thickness granular phosphor screens used in cathodoluminescence applications.

In a previous paper,⁴ commenting on the shape of the efficiency versus voltage curves for a ZnCdS:Ag cathodoluminescent screen we noted that the existence of successive peaks could qualitatively be explained by taking into account the structure of the phosphor grain and the penetration depth of the electron beam in the phosphor mass, but we did not support that claim by any further detailed calculations. We now present a theoretical model suitable for quantitative calculations even in the case of the low thickness (low weight) screens, which takes into account the granular structure of the screen and the random distribution of the phosphor grains on the screen substrate. This model can be applied in the case of screens excited either by electrons or (after a few minor modifications) by x rays. In this paper, however, we restrict our study only to the case of screens excited by an electron beam.

DESCRIPTION OF THE MODEL

In the vast majority of applications the phosphor screens are prepared of granular phosphors by sedimentation from an aqueous solution. As a result, the transparent substrate of the screen is covered by phosphor grains that are randomly deposited on its surface and the screen structure has the form shown in Fig. 1(a). The phosphor grains have, in general, irregular shapes but are all about the same size. Every grain is surrounded by a phosphor layer that is not fluorescent and is called the "dead layer."⁵ It is obvious that some regions of the screen are not covered by the phosphor grains, other regions are singly covered, others are doubly covered, etc. One expects, as the number of phosphor grains

is increased (which is equivalent to an increase of the screen's weight) the size of the low coverage regions to be reduced. Let us consider a flat substrate and a number of fluorescent particles on it. All particles are rectangular in shape and equal to each other. Every particle is surrounded by a dead layer as it is shown in Fig. 1(b). The particles can overlap with each other and are randomly distributed over the substrate. In this way there appear regions on the substrate that are not covered by particles, singly covered, doubly covered, etc. Let us consider now A to be the total area of the substrate, S to be the base area of each particle, and N to be the total number of the particles on the screen substrate. We designate the mean area of the covered regions of the substrate by $D_k^{(N)}$, where $k = 0, 1, 2, \dots, N$ denotes the order of coverage of the substrate region under consideration. A trivial relation among these quantities is

$$A = \sum_{k=1}^N D_k^{(N)}. \quad (1)$$

The mean area of the region with order of coverage k , for a total of $N + 1$ particles is, given by the following recursion relations:

$$D_k^{(N+1)} = D_k^{(N)} + \langle v \rangle_{N,k-1} - \langle v \rangle_{N,k} \quad k = 1, 2, \dots, N$$

and

$$D_0^{(N+1)} = D_0^{(N)} - \langle v \rangle_{(N,0)}.$$

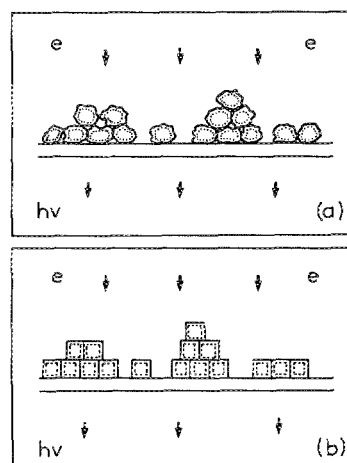


FIG. 1. Cross sections of a phosphor screen: (a) real structure and (b) modeled structure.

The quantity $\langle v \rangle_{(N,k)}$ denotes the expected value for the $D_k^{(N)}$ part of the substrate area to be covered, when one more particle is deposited randomly on it. A reasonably accurate estimation for it is given by

$$\langle v \rangle_{(N,k)} = (S/A)D_k^{(N)}. \quad (3)$$

The above estimation is subject only to small statistical fluctuations, due mainly to the different shapes the particles may actually have. Solving the recursion relation (2) with the aid of (1) and (3) we obtain

$$D_k^{(N)}/A = \binom{N}{k} a^k (1-a)^{N-k}, \quad (4)$$

where $a = S/A$.

Let us consider now that the screen shown in Fig. 1(b) is excited to fluorescence by a constant energy electron beam. Every phosphor grain consists, in respect to the electron beam trajectory, of three sublayers. The upper and lower ones correspond to dead layers, which do not emit light, and the central one corresponds to active phosphor material, which emits light.

Let ϵ be the energy loss of the electron beam in the dead layer (upper or lower) and E_{ph} its energy loss in the fluorescent part (active sublayer) of the phosphor grain. The light flux emitted per unit area from every phosphor grain layer as a function of the energy of the electron beam incident on it, is given by the relation

$$\Phi(E) = \begin{cases} 0 & \text{if } E < \epsilon \\ \lambda(E - \epsilon) & \text{if } \epsilon < E < \epsilon + E_{ph} \\ \lambda E_{ph} & \text{if } E > \epsilon + E_{ph}, \end{cases}$$

where λ is the conversion factor of the electron beam power to light flux, a quantity that is directly proportional to the intrinsic efficiency coefficient of the phosphor.

If we consider a region of the screen where there exist k phosphor grains overlapping with each other and suppose for simplicity that each grain is nontransparent to the light of the others, the total light flux emitted per unit area is given by the relation

$$\Phi_k(E) = \begin{cases} 0 & \text{if } E < \epsilon_k \\ \lambda(E - \epsilon_k) & \text{if } \epsilon_k < E < \epsilon_k + E_{ph} \\ \lambda E_{ph} & \text{if } E > \epsilon_k + E_{ph}, \end{cases}$$

where

$$\epsilon_k = \epsilon + (k-1)(2\epsilon + E_{ph}).$$

The total amount of light flux Φ_{tot} coming out from a screen of N fluorescent particles per unit area will be

$$\Phi_{tot} = \sum_{k=0}^N \Phi_k(E) \frac{D_k^{(N)}}{A} = \sum_{k=0}^N \Phi_k(E) \binom{N}{k} a^k (1-a)^{N-k}.$$

If we consider a more general case where every phosphor grain is partially transparent to the light of the superimposed grains, the quantity $\Phi_k(E)$ in the above relation must be replaced by the quantity

$$\sum_{i=1}^k \beta^{k-i} \Phi_i(E),$$

where β is the transparency of the phosphor grain.

In that case the total amount of light flux coming out from the screen will be

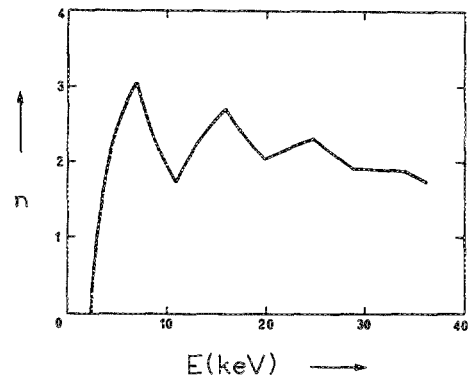


FIG. 2. Calculated cathodoluminescence efficiency of a phosphor screen vs electron beam energy.

$$\Phi_{tot} = \sum_{k=0}^N \sum_{i=1}^k \beta^{k-i} \Phi_i(E) \binom{N}{k} a^k (1-a)^{N-k}.$$

RESULTS and DISCUSSION

Following the model described and using the relations derived above we have calculated the dependence of the efficiency of a cathodoluminescent screen on the two most important parameters: the energy of the exciting electron beam and the screen's weight (number of phosphor grains on the substrate).

Considering the dependence of the efficiency n on the electron beam energy E , we give in Fig. 2 a typical plot for the relation $n = f(E)$. The exact position, magnitude, and number of the peaks can be affected by changing the various physical parameters of the model.

The number of peaks in the curves is mainly affected by the number of particles on the substrate, as it is shown in Fig. 3. For screens of very low weight the relation $n = f(E)$ takes the form of the curve (a), which shows practically only one peak. Increasing the number of the particles, a second peak appears (curve b) and after that a third one, etc. In very thick screens the high-order peaks are greater than the low-order ones.

The peak positions in respect to the energy (voltage) of the electron beam is mainly affected by the size of the phosphor grain. As this size is increased the peaks move towards

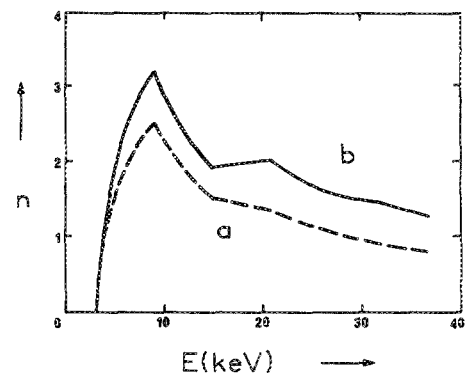


FIG. 3. Calculated cathodoluminescence efficiency vs electron beam energy for two screens of different weights. Curve a: low weight screen. Curve b: heavy weight screen.

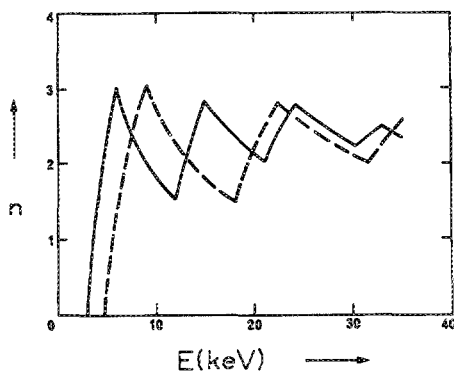


FIG. 4. Calculated cathodoluminescence efficiency vs electron beam energy for two screens of different grain size. Continuous line: small grain screen. Broken line: large grain screen. Grain diameter ratio: 1.5.

higher-energy values, as it is shown in Fig. 4. The depth of the minima between the peaks and the electron energy necessary for the appearance of luminescence in the screen are mainly affected by the ratio of the dead to the active layer ($m_{\text{dead}}/m_{\text{active}}$) in each grain. In Figs. 2–4, the efficiency is plotted in arbitrary units; to be quantitative it is necessary to estimate and take into account the appropriate values of the intrinsic efficiency coefficient, the grain size, the relative thickness of the dead layer in respect to the grain size, the transparency of the phosphor grains, etc., for the specific screen under consideration.

In order to show the suitability of the model for carrying out reliable predictions for the efficiency of a screen we give as an example (Fig. 5) the experimental data concerning the relation $n = f(E)$ for two ZnCdS:Ag phosphor screens, which have been measured in the past,⁴ and the corresponding theoretical curves based on the presented model. The

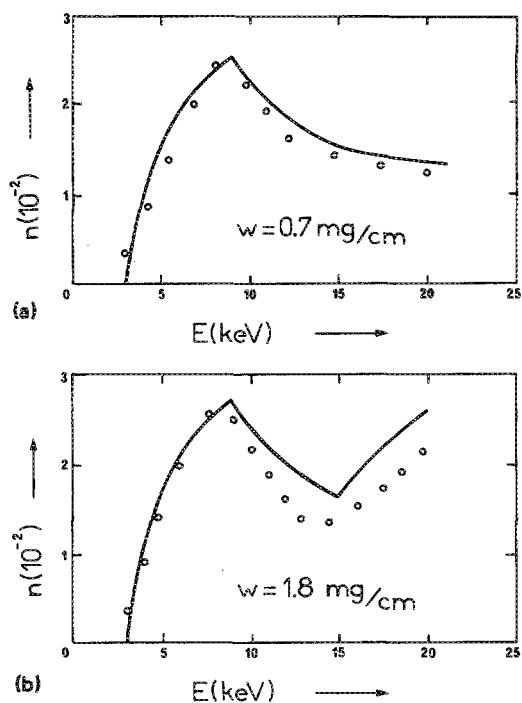


FIG. 5. Calculated and experimental cathodoluminescence efficiency vs electron beam energy for two ZnCdS:Ag phosphor screens of different weights.

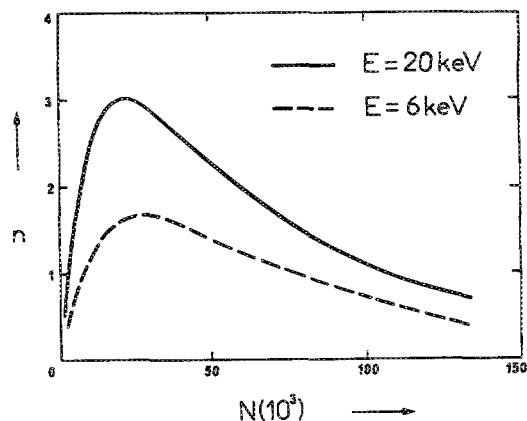


FIG. 6. Calculated cathodoluminescence efficiency of a phosphor screen vs screen weight (number of phosphor grains on the screen's substrate) for two different electron beam energies.

agreement is satisfactory and in all cases much better than that of the uniform screen Hamaker–Ludwig model, that fails to predict or explain the existence of multiple peaks, which is the actual case shown in Fig. 5(b).

The dependence of the efficiency on the screen's thickness is shown in Fig. 6. As expected, there is a peak in the efficiency for a certain screen weight. This peak position is slowly moving towards higher weights as the energy of the electron beam increases. There is also a variety of other calculations concerning the phosphor screens that can be carried out on the basis of this model (e.g., calculations concerning the coverage uniformity of the screen's substrate by the phosphor grains) which we do not present here.

The model presented here has of course a number of inadequacies, which are mainly due to its simplicity and which become obvious when comparing the theoretical results with the corresponding experimental data. These inadequacies are as follows.

(a) According to the model, the electron beam power spent in each phosphor grain sublayer (active or dead) is constant for all the active or dead layers, respectively, regardless of their real order of deposition on the substrate. This is only an approximation of what really happens. As is well known, and can be easily verified by inspecting the Landau equations concerning the energy loss of electrons crossing a material layer,⁶ this power spent is not constant for similar layers but depends on the energy of the electrons when entering each layer; as a result it is different from layer to layer and becomes greater for the deeper ones.

(b) The light created within each phosphor grain is partially absorbed from the material of this very same grain. This self-absorption is not taken into account by the model, however it could be incorporated trivially by discretizing each phosphor grain.

(c) According to the model, all the electrons entering a given grain layer have exactly the same energy. This assumption is not true and is mainly responsible for the discrepancy observed in Fig. 5(b) between the experimental data and the theoretical curve for energies greater than 12 keV. What actually happens is that the electrons enter the various successive phosphor grain layers having slightly different energies,

because the grains of the phosphor have irregular shapes and because the electrons during their pass from one grain to another are partially scattered.

(d) The model neglects the scattering of the light in the screen. Due to the fact that we have a one-dimensional model (propagation of light is important and considered only along the direction perpendicular to the screen's surface) the scattering process can be easily incorporated in the absorption process, provided that the transparency coefficient β depends on the screen's thickness.²

In spite of the above inadequacies the model considerably improves our understanding and our predictive ability for the cathodoluminescence of phosphor screens. This becomes obvious if the model is compared to the Hamaker-Ludwig model used until now. The latter, due to the fact that it is based on the assumption of a uniform screen, is successfully applicable only in the case of the heavy weight screens ($w > 50 \text{ mg/cm}^2$) that are almost completely out of use in cathodoluminescence.

In summary, we would like to make a final remark: The model presented here can be easily improved with respect to all of its shortcomings, however, its simplicity would be sacrificed.

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