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ELECTRO-OPTICAL PROPERTIES OF A SCINTILLATION DETECTOR IN SEM

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ABSTRACT
Possibilities of sensitivity increase of a scintillation detector of electrons are discussed on the basis of analysis of its optical properties. Light signal losses due to imperfect guiding of light from luminescent centres of a scintillator to photoemissive centres of a photocathode of a photomultiplier are analysed. From this point of view different types of scintillators and light-guides are compared. A special attention is paid to a new fast transparent single-crystal scintillator of yttrium aluminium garnet activated by cerium (YAG:Ce^{3+}). Different surface finishes of this scintillator are investigated and a solution in the form of a disc with matted base is presented. Optimum choice of a photomultiplier tube with respect to the emission spectrum of the scintillator is also discussed and experimentally verified.

INTRODUCTION

For detection of backscattered and secondary electrons in a scanning electron microscope (SEM) a scintillator-photomultiplier system (1) is mostly used. It must meet the requirements of high efficiency, low noise, high bandwidth, large dynamic range, long lifetime and must not contaminate vacuum medium. If some of the given requirements is not fulfilled, the image quality is decreased. Parameters of commercially produced photomultipliers make it possible to meet all the above mentioned requirements. Less favourable is, however, the situation in the case of a highly efficient scintillator. Plastic scintillators are burdened with a short lifetime (2,3), lithium activated glass possesses both low efficiency and a short lifetime (3,4), a singlecrystal of sodium iodide is not suitable because it is very hygroscopic (5,6), anthracene can hardly be used in vacuum due to high vapour pressure at room temperature (7), a single crystal of calcium fluoride has a long decay time (3), yttrium silicate powder possesses a limited lifetime (3) and efforts to grow a sufficiently large single crystal of cerium pentaphosphate have not yet been successful(8). The newly developed single crystal of yttrium aluminium garnet activated by cerium (9) appears to be the most promising scintillation material. It has high quantum efficiency, physically unlimited lifetime and fast decay time and it satisfies ultra-high vacuum conditions.

It is true, that high efficiency of the scintillation material is the basic and most necessary condition for good performance of the scintillation detector, but it is not sufficient. Photons emitted by scintillation centres must be guided with minimum losses to the photocathode of the photomultiplier and here transformed with maximum quantum efficiency into photoelectrons. These photoelectrons determine the value of the resulting electric signal. Scintillation detector current sensitivity F_{sd} (defined as the photocurrent from the photomultiplier photocathode per unit current of electrons striking the scintillator surface with energy E_e) can be written:

$$F_{sd} = \frac{E_e - \Delta E_e}{e} \int_{\substack{\text{all} \\ \text{wavelengths}}} C_{sc}(\lambda)\ C_{lg}(\lambda)\ F_{pc}(\lambda)\ d\lambda\ , \tag{1}$$

or assuming that the light emitted by the scintillator is monochromatic (with wavelength λ_0), then eq. (1) takes the form

$$F_{sd} = \frac{E_e - \Delta E_e}{e} C_{sc}(\lambda_0)\ C_{lg}(\lambda_0)\ F_{pc}(\lambda_0). \tag{2}$$

In eqs. (1) and (2) e is the elementary electric charge, ΔE_e is the energy absorbed during the passage of electrons through the scintillator metallic film, $C_{sc}(\lambda)$ is the scintillator energy efficiency (i.e. ratio of the total energy of photons with wavelength λ leaving the scintillator on the light-guide side and of the total energy of electrons absorbed in the scintillation material), $C_{lg}(\lambda)$ is the spectral efficiency of the photon transport through the light-guide and $F_{pc}(\lambda)$ is the photocathode radiant spectral sensitivity $[AW^{-1}]$. The value of the scintillation detector current sensitivity depends on a great many of opto-electrical and optical properties which may either favourably or unfavourably affect the result of the detection and are given by the parameters of three basic parts of the detector, i.e. scintillator, light-guide and photomultiplier, and by the coupling of each other.

The aim of this paper is to analyse problems connected with the choice of individual parts of the detector, with optimum surface finish of the scintillator and of the light-guide to attain the most advantageous optical and opto-electrical properties, with the coupling of the three detector parts so as to achieve the maximum possible sensitivity of the whole system.

EXPERIMENTAL TECHNIQUES

The efficiency measurement of scintillators was made in an adapted electron microscope. In order to ensure better defined conditions, the beam of primary electrons, not secondary electrons as in SEM, was used to the excitation of luminescence in the scintillator. The electrons were incident on the scintillator surface with 10 keV energy and current density of 4.10^{-8} Acm^{-2}. The electron beam diameter was 3 mm. The anode current of the photomultiplier at constant voltage was the measure of the sensitivity F_{sd} of the scintillation detector (10). The spectral optical transmittance of the light-guiding and scintillation materials was measured with the spectrophotometer SPECORD UV VIS (VEB Carl Zeiss Jena). We studied and measured various kinds of scintillation materials, various kinds, shapes and ways of finishing of scintillator substrates as well as various kinds of light-guides using the same photomultiplier or replacing it by another one.

SCINTILLATOR

The scintillator is the most important element of the electron detector in the SEM. For detection of ionizing radiation there exists a number of scintillators with high efficiency but only a few of them satisfy a very important condition of short decay time and long lifetime. The comparison of efficiency and lifetime of different scintillation materials which have decay time shorter than 100 ns and come into consideration for the intended application was made elswere (3,9,10). It follows from the comparison that the best parameters obtained are those of the newly developed scintillator: a single crystal of yttrium aluminium garnet activated by cerium ($YAG:Ce^{3+}$) which can be used for detection of fast electrons and has nearly unlimited lifetime. We have found, that with the same scintillation material, scintillator efficiency differs considerably according to the shape of specimen used. These effects are probably associated with optical properties of individual specimens of YAG:Ce^{3+} and it is the aim of this paper to give their possible explanation.

Scintillator efficiency C_{sc} as introduced in equation (1) or (2) depends both on the quantity of light emitted by luminescent centres and on the perfectness of light guiding in the desired direction. The quantity of light emitted by luminescent centres is given by energy-conversion efficiency C_{ec} of the material. Perfect guiding of light depends on the optical transmittance T_2 of the boundary of the scintillator on the light-guide side, furthermore on the internal reflectance R_1 of the scintillator surface coated by a metallic film and on the optical absorptance A_{sc} of the volume of the scintillation material and its substrate. (The substrate is considered only with specimens prepared by powder technology and plastic film technology respectively). The dependence of scintillator efficiency on all described parameters can be expressed by

$$C_{sc} = \frac{1+R_1}{2} T_2 (1-A_{sc}) C_{ec} \; . \qquad (3)$$

Quantities R_1, T_2 and A_{sc} are integrated over all directions. Provided the same scintillation material is used, energy-conversion efficiency may be considered the constant. However, this cannot be said about the other terms of equation (3), because transmittance and reflectance of the scintillator surface as well as optical absorptance within its volume may change according to the shape, size and surface finish of the specimen.

Output Boundary Effect

Measurement results in Fig. 1 illustrate the dependence of scintillator efficiency on the type of the scintillator surface. Discs of 0,5 mm thickness and 9,6 mm diameter were prepared from the YAG:Ce^{3+} single crystal having plane surfaces polished or matted by fine diamond. In this way discs of different surface finish combinations were made and coupled without any optical cement to the light-guide and measured under the above mentioned conditions. As evident from the diagram, it is not the perfectly polished speci-

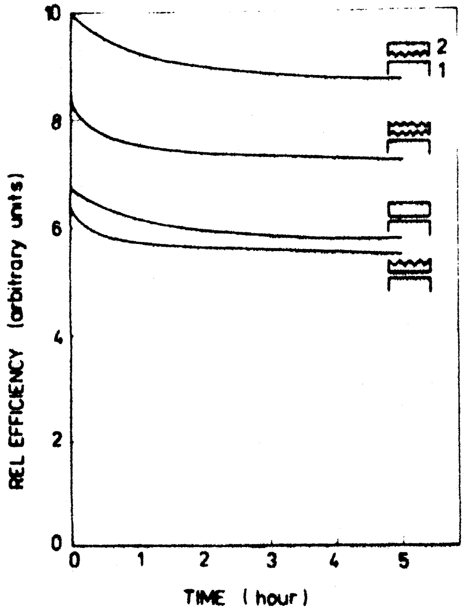

FIG. 1
Influence of surface finish of YAG:Ce^{3+} single crystal scintillator on the efficiency and the lifetime of the scintillator. 1 - light-guide; 2 - scintillator; ——— polished surface, ∿∿∿∿ matted surface.

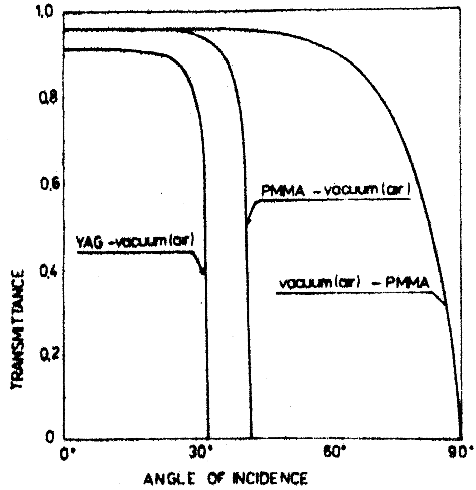

FIG. 2
Directional dependence of light transmittance between different media. PMMA = polymethyl methacrylate; YAG = yttrium aluminium garnet (evaluted for indeces of refraction n_{YAG} = 1,84; n_{PMMA} = 1,49).

men, i.e. specimen with the surface finish commonly used in scintillation detectors, that gives the highest efficiency. The specimen with matted surface on the light-guide side yields efficiency higher by 30% at least. Some conclusions for the explanation of the obtained results follow from the laws of geometrical optics (see e.g. (11)).

Light incident on a smooth surface of a transparent medium is partly refracted, partly reflected and the ratio of both parts is determined by Fresnel's formulae from which for transmittance T of unpolarized light through the boundary of two transparent media the following relation holds true:

$$T = 1 - \frac{1}{2}\left[\frac{\sin^2(\varepsilon-\varepsilon')}{\sin^2(\varepsilon+\varepsilon')} + \frac{\tan^2(\varepsilon-\varepsilon')}{\tan^2(\varepsilon+\varepsilon')}\right] . \tag{4}$$

Here, ε and ε' are angles of incidence and refraction, respectively, for which Snell's law $n' \sin \varepsilon' = n \sin \varepsilon$ is valid, where n and n' are indeces of refraction of relevant media.

Graphical representation of equation (4) showing the dependence of transmitted light on the angle of incidence is given in Fig. 2. The curves correspond to the transmission of light through the boundary between different media considered for the scintillation detector of electrons.

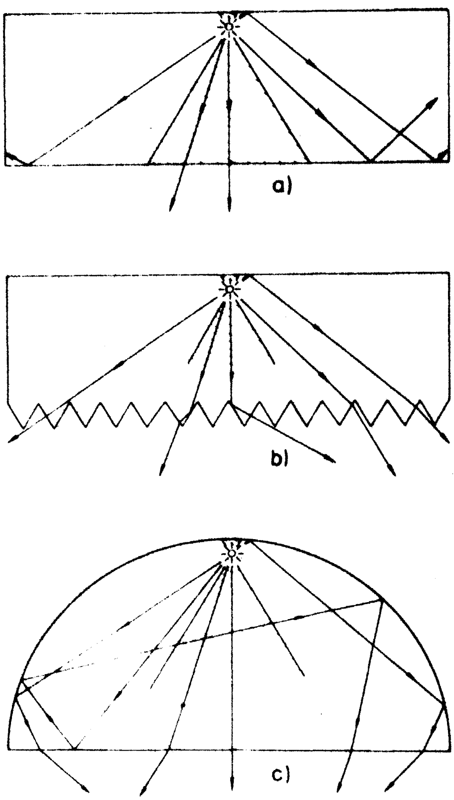

FIG. 3
Model of light propagation from a luminescent centre of a scintillator having the index of refraction $n = 1{,}84$.
a) polished disc specimen,
b) disc specimen matted on the light-guide side, c) hemispherical polished specimen

Let us now return to the discussion of measurement results given in Fig. 1. We may suppose that light emitted by luminescent centres of the single crystal propagates in all directions (Fig. 3a). It means it is incident at different angles onto the boundary of the scintillator and vacuum. (With respect to unevennes of surfaces of the scintillator and the light-guide it is not possible to consider the boundary between the scintillator and the light-guide.)

Through a perfectly polished scintillator-vacuum boundary only that part of light can penetrate with low losses, that is characterized by the angle of incidence of 30°max. Results obtained with YAG:Ce^{3+} scintillator and presented in Fig. 1 prove this fact correct. The remainder of light is reflected back into the scintillator and leaves it through its side walls or it is absorbed after repeated reflections. Using specimens with the surface polished on the light-guide side, the transmittance of light T_2 introduced in equation (3) cannot take a higher value than approximately 1/3 which is a very low value. Somewhat different results were obtained with specimens having their surfaces on the light-guide side matted. An idealized representation of this situation is shown in Fig. 3b. Transmittance for that part of light which passed the boundary of the above mentioned polished specimens without losses will be this time somewhat lower by losses caused by multiple reflection of light on the mat surface. However at the same time conditions for transmission of the remaining 2/3 of light unutilized in the case of polished boundary will be favourably changed. Specimens with their matted surfaces on the light-guide side present therefore expressively higher relative efficiency than those with surfaces polished, Fig. 1.

Shape Effect

The increase in transmittance T_2 of light through the scintillator boundary on the light-guide side can be achieved in another way, too. As already mentioned transmittance of this boundary is maximum for that part of light which is incident perpendicularly or at a low angle of incidence. This can also be achieved by a change of geometry of the scintillator surface at the side of impact of electrons. If the scintillator has the shape shown in Fig. 3c, then by single or multiple reflection from the internal wall of the spherical surface light propagates in the desired direction. Nowadays one makes use of this effect in preparation of "fish eye" scintillators where powder scintillator is deposited on a hemispherical substrate. If the scintillator is to be made from a single crystal as in the case of YAG:Ce^{3+} the formation of the hemispherical shape necessitates complicated technology of grinding and it is rather expensive. Moreover, the hemispherical single crystal scintillator is too bulky in comparison with the discs so that the path of light inside it is many times longer. This fact may result in a higher absorption of light inside the scintillator.

Scintillators made of powder materials have not these disadvantages. Scintillation powder is deposited on substrates of different shapes out of which the hemispherical shape appears to be the most advantageous one. For substrates such materials are used which possess good optical properties, sufficient adhesion for scintillation powder and which are easy to shape. Fig. 4 gives measure-

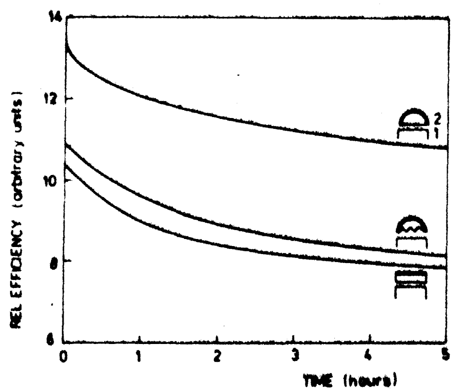

FIG. 4
Comparison of the efficiency and the lifetime of the powdered YAG:Ce^{3+} scintillator, deposited on the polymethyl methacrylate substrates of different shapes and surface finishes. 1 - light-guide; 2- substrate with scintillation material; —— polished surface; ∿∿∿ matted surface.

ment results of time dependence of relative efficiency of powder scintillators obtained by deposition of YAG:Ce^{3+} powder on polymethyl methacrylate (PMMA) substrates of different shapes with matted and polished surfaces, respectively, on the light-guide side. The obtained results favour the model shown in Fig. 3c. It is evident that hemispherical specimens with matted surfaces on the light--guide side give lower efficiency than the same specimens with polished surfaces. This confirms that in the case of hemispherical specimens the substantial part of light is incident on the boundary of the light-guide side perpendicularly or nearly perpendicularly.

The Application of Optical Cement

Some manufacturers of SEMs recommend to reduce losses of light leaving the scintillator by using an optical cement between the scintillator and the light-guide. The cement (e.g. Canada balsam) must have the index of refraction close to that of the scintillator and the light-guide. However, the suggested solution has numerous disadvantages. These optical cements cannot be used in ultra-high vacuum SEMs because all of them worsen the ultra-high vacuum medium.The choice of cements suitable for normal vacuum conditions is not great, too. Moreover, it is difficult to deposit the cement over the whole boundary surface homogeneously. It must be deposited in a very thin film and cover only the boundary not the lateral area of the light-guide or the scintillator.

Some experiments were made with a single crystal scintillator disc optically coupled to the light-guide by the Canada balsam having the index of refraction 1,54. Low increase in relative efficiency (about 10%) was noted only with specimens having their coupled surfaces polished whereas those with matted surfaces showed no change at all.

Metal-Coated Surface Design

Internal reflectance R_1 of the boundary on the side of incident electrons (i.e. reflectance for the light incident internally on the scintillator boundary - see eq. (3)) is another parameter affecting the scintillator efficiency C_{so}. If the light is to be delivered to the light-guide with maximum efficiency, reflectance R_1 must be maximum. This can be achieved only with the perfectly polished surface covered with a sufficiently thick film of a suitable metal, e.g. aluminium. Vacuum deposited aluminium will at the same time play an important part in maintaining high electrical potential (7 to 12 kV) on the scintillator surface. From the standpoint of high optical reflectance and electrical conductivity it is necessary that the aluminium film be sufficiently thick. On the other hand, however, the thick film of aluminium must not obstruct the passage of signal electrons. Therefore, it is necessary to choose a certain optimum thickness of the aluminium film.

Energy ΔE_e [eV] lost during the passage of the electron through a film of thickness x [cm] and density ρ [gcm^{-3}] is given by the Thompson-Whiddington law

$$\Delta E_e = E_e - (E_e^2 - b\rho x)^{\frac{1}{2}} , \tag{5}$$

where E_e denotes the initial energy of an electron and b is the constant 4.10^{11} $(eV)^2 cm^2 g^{-1}$.

It follows from equation (5) that power losses of signal electrons utilized in the SEM ($\approx$10 keV) are almost negligible during the passage through an Al film of up to 50 nm thickness whereas during the passage through a 500 nm film they amount nearly to 40% of the total electron energy. During the passage through an aluminium film thicker than 926 nm the energy of signal electrons is absorbed entirely. Thus it is obvious that from the standpoint of minimum power losses during the passage of signal electrons (with 10 keV energy) through an aluminium film the thickness of this film must not exceed 50 nm. This thickness should be, however, also in accordance with the maximum reflectance of light and its perfect guiding to the photocathode of the photomultiplier.

Optical reflectance of metals is almost independent of the angle of incidence of light and for sufficiently thick metal films it is very high in the visible spectrum region (12). It is well known that reflectance of metals is the larger the larger is their electrical conductivity. This is a very good property from the standpoint of demands on the scintillator surface. From the paper by Hass and Waylonis (13) one can conclude that aluminium films thicker than 50 nm show for the visible region of spectrum the same reflectance as specimens of infinite thickness (88,0 to 92,5% according to the wavelength of incident light).

It follows from this analysis that the optimum thickness of the aluminium film on the scintillator surface amounts to about 50 nm. These theoretical presumptions have been verified by the measurement of the efficiency of YAG:Ce^{3+} single crystal scintillators with evaporated aluminium films of different thicknesses. Bril and Klasens (14) obtained similar results using powder phosphors.

The influence of the internal reflectance R_1 on the scintillator efficiency is also proved by measurement results involved in Fig. 1. Surfaces of single crystal scintillator discs (later covered with aluminium films) were either polished or matted and specimens prepared in this way were measured under conditions presented in the foregoing. It can be seen that scintillators with lower reflectance (matted) on the side of incident electrons show lower efficiency than similar specimens with corresponding surfaces polished.

Optical Absorption Effect

Optical absorptance in the scintillator A_{sc} given in eq. (3) is another important factor affecting the efficiency of the scintillation detector. It follows from this equation that a high value of this parameter is undesirable. Therefore, it is necessary to pay more attention to both the size and the technology of preparation of the scintillator.

Scintillation materials may be divided into transparent and opaque ones. Plastic scintillators, glass and some single crystals are the best known transparent scintillators suitable for applications in the SEM. Thicker transparent scintillation materials can be regarded as light-guides. Problems connected with light-guides and transparent scintillators are discussed in the following section.

A group of powder anorganic scintillators prepared by depositing powder phosphor on appropriate substrates is the representative of opaque scintillators suitable for detection of electrons in the SEM. The powder materials find acceptance with specimens of hemispherical or otherwise shaped surfaces. From the point of view of minimum optical absorptance of light emitted from luminescent centres the powder layer should be as thin as possible. On the other hand, if the powder layer is too thin, the energy of incident electrons is not absorbed entirely.

Bril and Klasens (14) investigated the optimum thickness of some powder phosphors deposited on glass substrates by the measurements of light yield both at the side of impact of electrons and at the side of the glass substrate. It follows from their measurements that the optimum thickness of the powder phosphor layer which corresponds to the maximum light yield at the glass side is about four times smaller than the depth of penetration of electrons. Using the optimum thickness of the luminescent material losses due to unsufficient absorption of energy of electrons amount to 10%. Other losses due to absorption and scattering of light within the volume and on both boundaries of the phosphor amount to 45 to 55%. The optimum thickness of powder scintillation layer corresponding to the maximum efficiency of the scintillator differs according to the energy of incident electrons and according to the density of material used. Our experiments have shown that the optimum layer thickness of YAG:Ce^{3+} scintillation powder is 6 mg/cm^2.

LIGHT-GUIDE

Light leaving the scintillator placed in vacuum of the specimen chamber of a SEM is guided with a light-guide to the photocathode of the photomultiplier positioned outside the vacuum of the SEM. The shape and size of the light-guide must be designed so as to fit in the arrangement of the SEM. The most frequently used light-guides are those of constant circular section with their front areas perpendicular to the axis. The light-guide makes it possible to transfer the light signal along any path which does not cross in the space. With regard to signal losses the path is to be short and, if possible, straight. The material for the light-guide must be perfectly transparent and have high optical transmittance in axial direction, especially. The surface of the material must be perfectly polished and must not be in contact with a material having a high index of refraction and a high absorption coefficient.

The efficiency C_{lg} of the guiding of light involved in equations(1) and (2), is determined both by surface optical properties and by volume optical properties of the light-guide and it is given by the relation

$$C_{lg} = K\, T_3\, T_4\, (1 - A_{lg}), \tag{6}$$

where T_3 and T_4 are transmittances of the input and output boundary of the light-guide, respectively, and together with the coefficient K they express surface optical properties. The coefficient $K \leq 1$ involves losses due to all internal reflections during the light transport and it depends on the material, size and curvature of the light-guide, on the surface finish of its lateral area and on the material in contact with this area if there is any. A_{lg} is the optical absorptance of the light-guide given by the absorption coefficient of the material used and it expresses volume optical properties of the light-guide. In equation (6) there are not considered losses due to light scattering having their origin in the non-homogeneity of the material. These losses will be neglected.

Surface Optical Properties

Surface optical propeties are determined above all by the index of refraction of the material used. The change of the index of refraction of light-guiding materials is very small in the region of emission spectra of commonly used scintillators. Therefore, surface optical properties of light-guides are nearly independent of the wavelength of the transmitted light. However, their directional dependence is considerably great.

Transmittances T_3 and T_4 of the input and output boundary, respectively, are determined by losses due to Fresnel's reflections. The theoretical directional dependence of these transmittances is shown for the polymethyl methacrylate (PMMA) light-guide having the index of refraction n = 1,502 in Fig. 2. The curves are applicable only for a perfectly polished surface of the light-guide. Similar dependence is valid for other light-guides commonly used (quartz, glass) with regard to near indeces of refraction of these materials. It is evident from Fig. 2 that the transmittance of the output boundary of the light-guide shows a less advantageous directional dependence than that of the input boundary. However, this fact affects unfavourably only a curved light-guide, not a straight one. If considering that the input boundary of the light-guide transmits with acceptable losses only the light characterized by an angle of incidence smaller than 70° (Fig. 2), then according to the law of refraction the angle at which the light is incident onto the output boundary of a straight light-guide cannot be greater than 39°. Thus the light leaves the light-guide with minimum losses. Therefore, on the assumption that a light-guide has perpendicular front areas and a suitable index of refraction, substantial losses may occur only during the transmission of the light through the output boundary of a curved light-guide.

Another advantage of a straight light-guide is the magnitude of the coefficient K. The magnitude of this coefficient is given both by the internal reflectance of the lateral area of the light-guide and by the number of reflections. According to the Snell's law of refraction any light transmitted through the front area, for example of the PMMA light-guide (n = 1,502) cannot be incident on the lateral area of this light-guide at an angle of incidence smaller than 48°. This guarantees the total reflection of light if the surface is perfectly smooth and homogeneous. In the case of a curved light-guide these requirements are not fulfilled and thus further losses of light occur due to non-total reflection from the light-guide lateral area. The conclusions are not also valid in those cases where the light-guide is in contact with another material even if the index of refraction of this material permits the total reflection of light. In this case the light is reflected from the absorbing medium of the material in contact so that from the energy standpoint the reflection is incomplete.

The number of reflections in the light-guide is least for the light incident on the input of a straight light-guide in the planes determined by the axis of this light-guide and it is increasing with the distance of the plane of incidence from this axis. On the basis of fundamental laws of geometrical optics it can be derived that a mean number of reflections in a cylindrical PMMA light-guide (n = 1,502) is approximately given by the product $0,44 L_{lg}/D_{lg}$, L_{lg} being the length and D_{lg} the diameter of the light-guide. The coefficient 0,44 holds true only on the assumption of a uniform distribution of planes and angles of incidence of light on the input boundary of the light-guide. If a curved light-guide is used this coefficient increases.

It follows from the analysis, for a scintillation detector such a light-guide can be designed for which losses due to surface optical properties will be very low. If, for constructional reasons, a curved light-guide is to be used this should have a maximum radius of curvature and a minimum diameter of its section. This, no doubt, leads to an increased number of internal reflections but with regard to high internal reflectance of the lateral area of the light-guide has no unfavourable consequences. If it is necessary to guide the light along a path having very little radii of curvature it is more advantageous to use a bundle of fibre light-guides.

Volume Optical Properties

Volume optical properties of the light-guide are determined above all by the optical absorptance A_{lg} of the light guided with the light-guide. Optical absorptance depends on the length of the path of light inside the light-guide and on the coefficient of absorptance of its material. The length of the path of light depends on the diameter D_{lg} of the light-guide only inside a curved light-guide where it is $(1 + D_{lg}/2r)$ times greater than inside a straight one (r being the radius of curvature). In contradistinction to quantities characterizing surface optical properties of a light-guide the coefficient of absorptance of the material of a light-guide shows in certain regions of a spectrum a strong dependence on the wavelength of the passing light. Measurement results of spectral optical transmittance of different light-guiding materials used in a SEM are given in Fig. 5. It becomes evident from the dependence that even spectral absorptances of the same type of material needn't be identical. For example, PMMA used in JEOL microscopes is suitable for the guiding of light of wavelength above 50 nm, whereas PMMA of some other manufacturers can be used neither in the coupling with a plastic scintillator NE 102A (416 nm) nor with some other powder scintillators. Fused quartz which is a general-purpose light-guiding material shows the least optical absorptance as well as low spectral dependence.

As mentioned in the preceding section, some transparent scintillators may be used as light-guides, too. The advantage of this application is the vanishing of the scintillator - light-guide inter-

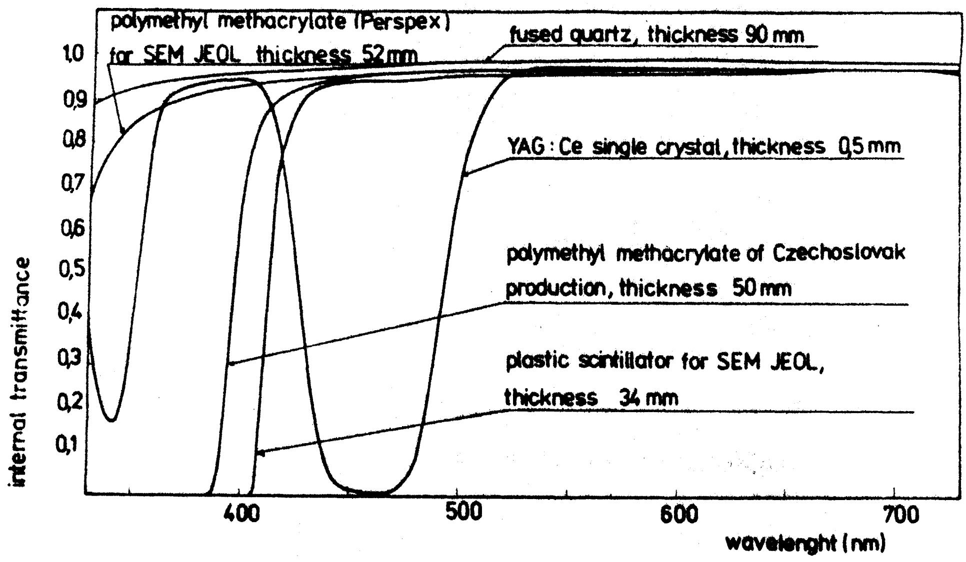

Fig. 5
Spectral optical transmittance of some light-guiding and scintillation materials. The curves are corrected for reflection.

face, which is the source of the processed signal losses. The absorption properties of the plastic scintillator used in JEOL microscopes and of the YAG:Ce^{3+} single crystal scintillator are given in Fig. 5. Thanks to the validity of the Stokes' law of fluorescence (15), transparent scintillators usually don't show high light absorptance in the spectral region of their maximum emission. However, even under these conditions, the absorption of the light from the side of the emission band especially makes mostly a utilization of transparent scintillators as long light-guides impossible. This application is sometimes disadvantageous from the standpoint of the high price, too.

PHOTOMULTIPLIER

The photomultiplier is the last part of the scintillation detection system to be discussed. In order to obtain the electrical signal generated by photoelectrons it is necessary to transform with minimum losses light leaving the light-guide and being incident on the photocathode of the detection system. The resulting electrical signal is further amplified and treated in the multiplying system of the photomultiplier and other electrical circuits and it serves for imaging of the specimen surface examined in the SEM.

The photomultiplier must have (i) high gain, (ii) low noise and (iii)high bandwidth, i.e. short rise and decay time of the anode puls, but the analysis of these parameters exceeds the framework of this paper.

From the standpoint of analysis of optoelectrical properties of the scintillation detection system the properties of the photocathode are of great importance. This is in accordance with eq. (1) and (2) given in the introductory part of this paper. These properties represent the most important criterion for the choice of a suitable photomultiplier and they are determined by the radiant spectral sensitivity F_{pc} of the photocathode. Sensitivity F_{pc} is in fact the ratio of current of photoelectrons emitted by the photocathode and the incident radiant power $[AW^{-1}]$. This sensitivity is strongly dependent on the wavelength and is determined by three basic types of photocathodes (S 1, S 11, S 20, cfr. (16)). Individual modifications of the basic types of photocathodes are given by the type of the entrance window (quartz, quartz glass, glass) and also by certain alterations of technology in photocathode production. If the light signal incident on the entrance window of the photomultiplier is to be treated with minimum losses, one must know the emission spectral characteristic of the scintillator or, better, the spectral characteristic of light leaving the light-guide and accordingly choose the appropriate photomultiplier spectrally matched to this emission characteristic.

According to measurement results of the emission characteristics of scintillators obtained in our laboratory and according to measurements of other authors (17,18,19), scintillators suitable for the use in the SEM show maximum emission of light in the wavelength region from 330 nm ($YPO_4:Ce^{3+}$) to 415 nm ($Y_2SiO_5:Ce^{3+}$), with the exception of powder scintillators used by the firm JEOL (510 nm) and the new single crystal of $YAG:Ce^{3+}$ (9) (550-570 nm). It is evident that for most scintillators photocathodes S 11 and S 20, respectively, will be appropriate, however, with some scintillators a photomultiplier with a quartz entrance window must be used. For the new type of the single crystal scintillator $YAG:Ce^{3+}$ the photocathode S 11 is not convenient; S 20 appears to be more suitable. However, measurement results obtained in our laboratory prove that even with the use of S 11 photocathode the scintillation detector with the single crystal $YAG:Ce^{3+}$ disc shows higher sensitivity than with classical scintillators.

CONCLUSION

The maximum sensitivity of a scintillation detector depends not only on the energy-conversion efficiency in the scintillator and on the quantum efficiency of the photocathode but also on the perfection of light signal guiding from the luminescent centres to the photoemissive centres of the spectrally matched photocathode of the photomultiplier.

On the basis of the foregoing study of different sorts of scintillation materials the single crystal $YAG:Ce^{3+}$ having high radiation damage resistance and other parameters comparable with scintillators used in SEM was chosen for the detection of fast electrons. We found out that with regard to the high index of refraction of $YAG:Ce^{3+}$ and thereby to high losses due to Fresnel's reflections when the light leaves the polished plate scintillator it is suitable to shape the single crystal as a disc with the area on the side of incident electrons polished and covered with aluminium film of about 50 nm thickness and with the matted area touching the light-guide. This treatment permits the maximum transmission of light to the light-guide without using the optical cement between the scintillator and the light-guide.

The maximum efficiency of light-guiding through the light--guide can be achieved by using a straight cylindrical light-guide with a perfectly polished surface. The material used must have a sufficiently high index of refraction and low spectral optical absorptance. The optimum choice of a photomultiplier having suitable spectral sensitivity of the photocathode must be based on the knowledge of the emission spectral characteristic of the scintillator.

A scintillation detector is a convenient detection system not only of electrons but also of other sorts of ionizing radiation if the signal is sufficiently strong. Problems are encountered when weak signals are to be detected. Then the noise becomes competitive to a great extent and it is necessary to process the light from the scintillator without greater losses of the signal. The presented results may contribute to successful solution of this problem.

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