Performance of detector elements for electron microscopes

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Summary: Signal processing in scanning and transmission electron microscopes is analysed in this paper. Distinguished are criteria of principal and commercial significance, and problematic parameters of different systems are highlighted. The most important properties of scintillation detection systems and imaging screens are discussed more in detail. For the scintillation detector, the analysis of conversion of the signal to photons, their transport from emission centres to PMT photocathode, and their conversion to photoelectrons is carried out. For the imaging screen, attention is focussed on the spectral matching and spatial resolution.

1. Introduction

As for the time sequence, we distinguish several kinds of image processing systems. In the scanning electron microscope (SEM), the point by point imaging system processes only one pixel of the image, whereas in the transmission electron microscope (TEM), the whole matrix of image points is processed at the same moment. Each kind of image processing systems can be also characterized according to the processing mechanism. Direct detection systems process the image information without signal transformation, while indirect detection systems utilise optical coupling, which is very advantageous if electric potential separation is necessary.

Single P-N or PIN diodes, channel multipliers and CCD elements are used as direct detector elements for point imaging in various electronic devices. In SEM, semiconductor detectors [1] as well as channel multipliers [2] have been examined as early as more than 30 years ago. The scintillation detection system utilising a scintillator, light-guide and photomultiplier is the widespread used indirect detection system for point by point imaging in SEM. It was introduced to the SEM from the field of radiation detection by Everhart and Thornley as early as in 1960 [3]. However long, its performance has been developed all the time. The oldest direct detector element for area imaging is photographic emulsion on a substrate, the only imaging system available at the beginning of TEM. At present, the PIN diode array, channel plates and especially CCD chips are extensively used as direct detection systems for area imaging in electronic devices. In TEM, indirect imaging systems are more often used, in particular cathodoluminescent imaging screens transferring the image to the TV or CCD camera through some fibre or lens optical system.

2. Performance criteria

It is necessary to study a lot of properties for the evaluation of the detection system performance. Of course, the influence of the individual parameters onto the performance is different. Various attributes of and troubles in scintillation or solid state detection systems are listed in Table. 1. The most important parameters are those affecting the detective quantum efficiency (DQE). With them, the energy conversion efficiency, intrinsic noise and decay time are the most important quantities. DQE of a detector is reduced for a very low as well as for a very high signal. For the low signal the background noise comes in harmfulness, while for the very high signal saturation effects decrease DQE. Unfortunately, saturation effects appear at much lower doses in solid state systems. Homogeneity and spatial resolution are significant attributes primarily for area imaging systems. Some parameters (for example construction simplicity or price) are important mainly from the commercial point of view. If we have

Table 1: Influence of individual attributes on the electron detector performance. [1]Valid only for plastic scintillators, [2]only for plastic and powder scintillators, [3]only for some systems.

parameter/property	principal significance	significant for DQE	significant only for area systems	significant for commerce	problematic in system: scintillation	problematic in system: solid state
efficiency	●	●		●		
intrinsic noise	●	●		●		●
bandwidth / decay time	●	●		●		●
dynamic range / linearity		●		●		●
self absorption		●		●	●	
radiation resistance / lifetime		●		●	●[1]	●
homogeneity			●	●	●	
spatial resolution			●	●		●
construction simplicity				●		
use simplicity				●		
high vacuum applicability				●	●[2]	●[3]
reliability				●		
price				●	●	

to compare advantages and disadvantages of scintillation and solid state systems, the scintillation one possesses much lower intrinsic noise and higher bandwidth, dynamic range and lifetime. On the other hand, the solid state system has no self absorption, possesses better homogeneity, and last but not least its cost is lower.

3. Scintillation detection system

Simply expressed, any detector is valuable if it doesn't waste the collected signal, if it doesn't introduce noise, and if its response is sufficiently fast. To find the neck of a detection system, one must examine the whole detection path step by step. An outline of such a trail for a scintillation detector is in Figure 1.

3.1. Conversion to photons

Passing the first step of signal electron collection unnoticed, the energy conversion from electrons to photons is the basic detection process. For this purpose cerium activated yttrium aluminium garnet (YAG:Ce) and (more expensive) yttrium aluminium perovskite (YAP:Ce) single crystal scintillators with well defined properties are usually utilised. Much attention has been paid to the examination of their conversion efficiency as well as of time response or of spectral characteristics [4]. Theoretical limits of conversion efficiency are about 23 and 25 photons per 1 kV electron (p/kV) for YAG:Ce and YAP:Ce, respectively. There is no great chance for improvement in the conversion efficiency, if values of 19 and 18 p/kV were obtained for YAG:Ce and YAP:Ce, respec-

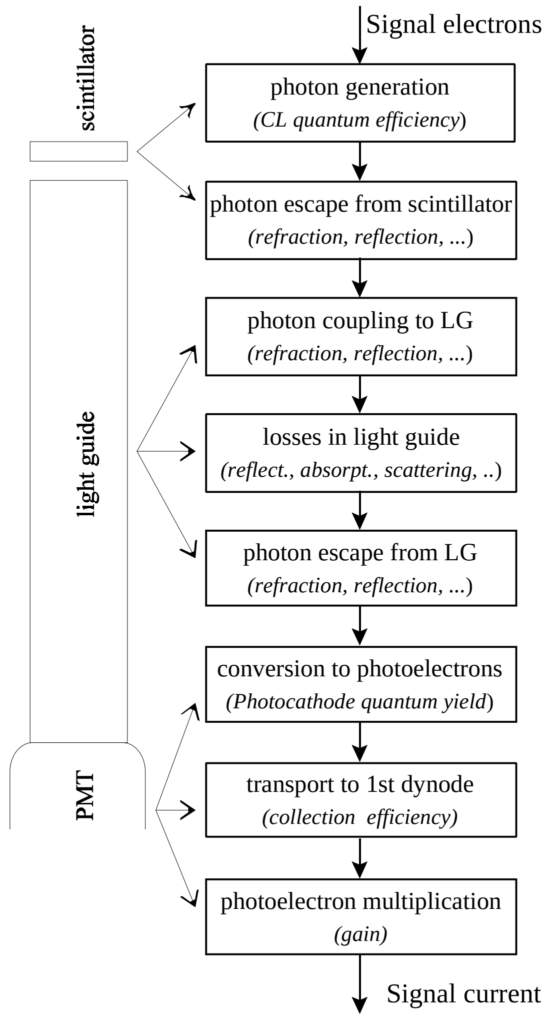

Figure 1: Analysis of signal transport in the scintillation detector in SEM. Asserting quantities of individual steps are in italic.

tively. Rather, improvement in the decay characteristics of YAG:Ce single crystals can be expected.

3.2. Photon collection

Photons generated at luminescent centres of a scintillator must be efficiently guided toward the photocathode of the photomultiplier tube (PMT). During this stage of signal processing, significant losses can occur when photons escape from the scintillator, are coupled to and transported through the light guide (LG), and finally when photons escape from LG and enter the entrance window of the PMT (see Fig. 1). An optimal design of the light guiding system (often limited by the space available in the microscope chamber) can hardly be made without an optical analysis.

To determine the photon collection efficiency, the Monte Carlo (MC) simulation method has been developed [5]. The MC method (making use of the random direction of photon emission and describing the trajectory of photon transport) can analyse nearly any scintillation system, whatever surface treatment is used. Simulation includes Fresnel passage through the boundary of different parts of the system, as well as mirror and Fresnel reflections on coated and uncoated surfaces. Optical absorption, diffusion reflection and passage through a matted surface are also included.

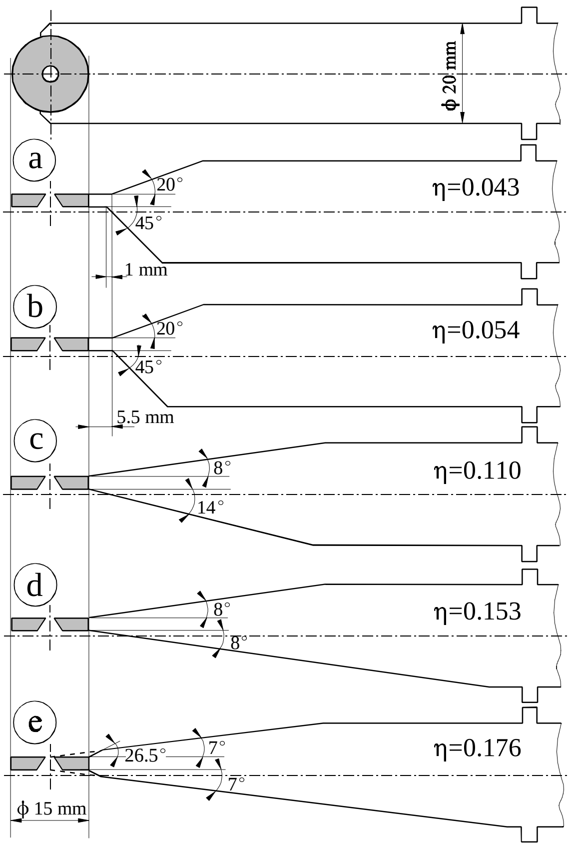

Figure 2: Schematic drawing of the geometry of key configurations during optimization of the BSE scintillation detector S 4000 (Hitachi). η denotes photon transport efficiency.

Table 2: Spectral characteristics and matching of single crystal scintillators and scintillator-photocathode systems, respectively . [1]Peak position (λ_{max}) and full width of the half maximum (FWHM) of the main emission band. [2]Spectral matching of the system related to that with an ideal photocathode.

scintillator	**emission spectra[1] (nm)**		**scintillator-photo-cathode matching[2] (%)**		
	λ_{max}	FWHM	S20	S11	GaAs:Cs
YAP:Ce	366	52	71	66	90
YAG:Ce	560	122	78	46	98
P47	420	77	92	84	95

Significance of photon transport simulation can be demonstrated by presenting the step by step improvement of the BSE scintillation detector (S 4000 Hitachi SEM). The final optimized design (e) in Figure 2 has been accomplished by integrating low angle widening planes and especially a conical light guiding ring close to the scintillator. The resulting photon collection efficiency is about 400 %, compared with the initial one calculated for design (a) in Figure 2.

3.3. Conversion to photoelectrons

In order to obtain an adequate signal for the electronic processing, it is necessary to transform photons (incident on the entrance window of PMT) to photoelectrons, to collect them at the first dynode and to multiply them to obtain the sufficient gain. From the point of view of the opto-electronic analysis the properties of the PMT photocathode are of great importance. Radiant spectral sensitivity of the photocathode is the most important characteristic for the choice of PMT. This photocathode sensitivity is strongly dependent on the wavelength, and it is characterised by the photocathode type (S1, S11, S20, ..) and modified by the material of the entrance window (glass/quartz) of PMT. To treat the signal photons so that minimum losses occur, one must know their spectral characteristic and choose the photocathode spectrally matched to this characteristic.

It follows from the results summarized in Table 2 [6] that the P47 scintillator shows the best spectral matching to the commonly used S20 and/or S11 photocathodes. The widespread used YAG:Ce single crystal has low spectral matching to the S11 photocathode. For this scintillator, it is necessary to apply the S20 photocathode, although the matching is limited even at such a combination. Matching is also limited for the YAP:Ce single crystal, but both S11 and S20 photocathodes can be used, and matching can be increased by using PMT with a quartz window. Matching of all scintillators can be upgraded to a great extent by using a photocathode with negative electron affinity.

4. Imaging screens

In electron microscopy only grayscale imaging is done, and no demands are put on the colour reproduction. However, the spectrum of the light emitted from the screen should be suitable for the direct observation with human eye as well as for indirect recording using a photoemulsion or CCD camera. Any imaging element has to possess a good signal-to-noise ratio, but with TEM screens the highest demands are put on the spatial resolution. As is shown in Figure 3, the reason is that volumes of electron interactions in the screen can be very large, especially for high energy TEM. Moreover, images on the screen are usually relatively small and have to be magnified by light optics.

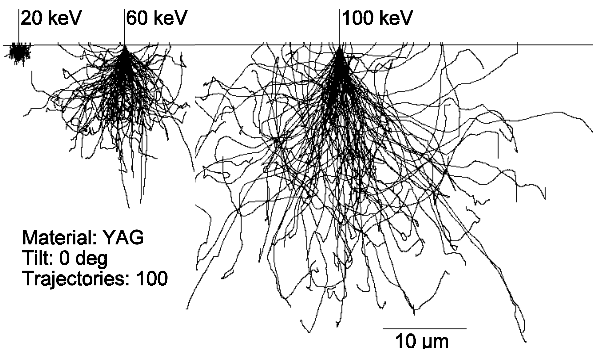

Figure 3: MC simulation of electron interaction volumes in the YAG:Ce single crystal screen.

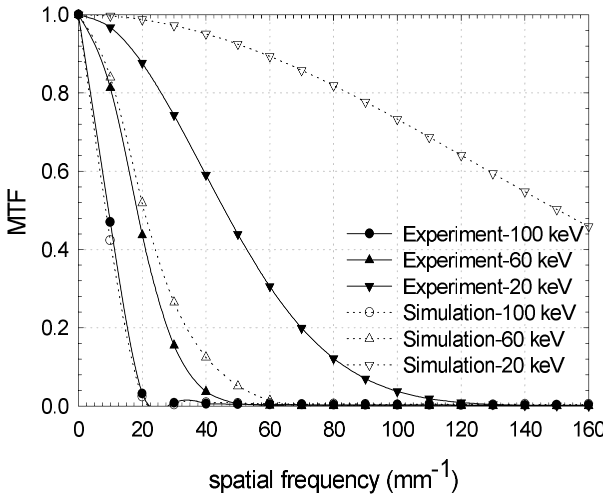

Figure 4: Modulation transfer function of the YAG:Ce single crystal screen for different beam energies. 20 keV experiments are affected by the edge scaling inaccuracy.

On viewing in daylight, the human eye has its maximum sensitivity at approximately 550 nm. It is nearly the same value as the maximum emission of the YAG:Ce single crystal, as shown in Table 2. Considering other optical properties of this single crystal (in particular its optical homogeneity), it is very suitable as an imaging screen in TEM, too. The spatial resolution of screens can be best expressed by the modulation transfer function (MTF) [7], shown for YAG:Ce in Figure 4. The calculated results have been obtained from MC simulation of energy distribution, and experimental ones by Fourier transform of edge spread measurement. For YAG:Ce, the resolutions of 150, 18 and 8 lines per mm have been found for 20, 60 and 100 keV electrons, respectively.

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