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The spatial characteristics of electron-and photon-induced secondary electron cascades in CsI

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Abstract

Our microscopic model for electron transport in alkali halides was used for the calculation of the spatial characteristics of secondary electron cascades induced by X-rays and electrons in an infinite CsI volume, in the energy range of 5-50 keV. The results show that the shape of the cascade cloud preserves the features of the primary interactions only at the core, where the cascade has an elongated, forward peaked shape for incident electrons and is spherically symmetric for photons. At the periphery the cloud is practically spherical, and of very low electron density. The maximal cascade dimensions do not exceed $10\mu\text{m}$ at the highest considered energy. The impact of these characteristics on secondary electron emission from finite-thickness CsI layers is discussed.

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1. Introduction

A well known property of insulators in general, and alkali-halides in particular, is their efficient secondary electron emission following their irradiation by charged particles or photon quanta¹. This is due to a sequence of elastic and inelastic interactions occurring in the solid, by which the primary energy is transferred to the atomic electrons, leading to ionizations. The energetic secondary electrons are losing their energy by the same type of interactions, producing an increasing number of low-energy secondary electrons (SE). This cascading process is growing in size until the energy of the electron is reduced to values below the gap energy of the solid. At this stage a large cloud, of hundreds of low-energy SEs, has been produced and it is diffusing within the solid. At these low energies the diffusing electrons can only lose energy by interacting with the lattice phonons, with a very small energy transfer per interaction, but cannot produce further ionizations. Thus the solid becomes rather transparent to these electrons. In alkali halides the large gap energy (e.g. 6.2 eV for CsI) and the low work function (0.1-0.3 eV)² lead to a large number of SEs with a high probability of escape from the surface.

The above properties make alkali halides very good X-ray convertors. Indeed CsI, which is relatively air-stable and easy to produce, has been used for many years as a coating layer on MCPs³, to increase their sensitivity to X-ray detection. We have demonstrated that CsI X-ray convertors may be coupled to gaseous electron multipliers, providing efficient, ultra-fast, large area X-ray imaging devices, with a wide range of potential applications⁴.

During the past few years we have studied in detail CsI film X-ray convertors, both experimentally and theoretically. Timing and localization properties of X-ray imaging detectors were studied, as well as their quantum efficiency and stability at high photon flux⁵⁻⁷. A theoretical model, describing the X-ray conversion and the secondary electron cascading and escape processes in alkali halides, was developed. The model, described in details in our previous works^{8,9}, is using the microscopic

cross-sections of elastic and all inelastic interactions of electrons in the solid, without any adjustable parameters. A Monte Carlo simulation code based on the model was developed. It permits to follow the trajectory of all primary and secondary electrons produced within the convertor volume and to calculate electron escape yields. The details of the Monte Carlo calculations, and results for CsI and KCl irradiated with electrons and photons at energies reaching 100 keV, are given elsewhere ^{9,10}. There is good agreement between experimental and calculated data. Integral characteristics, such as the total electron yield from the convertor as function of its thickness and the incident energy, fit well our measured values of detectors quantum efficiency. The saturation of the yield as function of thickness, which was observed experimentally, is also well reproduced by the model. The model also provides the yields of primary and secondary electrons escaping the solid as function of the incident energy, and the energy distribution of the secondary electrons ¹¹. This information not only broadens our understanding of the SE emission process but also permits to optimize the X-ray convertor according to the particular experimental application.

We have recently expanded our calculational code, which permits now to perform three-dimensional calculations, thus providing the geometrical distributions of the SE cascades within the convertor volume. In this work we report on the cascade development in CsI following an irradiation by electrons and photons, at energies reaching 50 keV. These secondary electron distributions were found to be different in shape for electrons and photons, but in all cases most of the charge is confined within a radius of a few μm .

The impact of these results on the localization resolution of secondary emission X-ray imaging detectors, and their possible relation to the enhanced secondary electron emission of porous CsI convertors ^{12,13} are discussed.

2. Methodology

The geometrical dimensions of electron- and photon-induced cascades in CsI were calculated using the Monte Carlo code described above. The interaction cross section of X-rays were taken from the extended tabulations in ref. 14. The

photoelectron and Auger electron energies were estimated, using the binding energies in Xe. Auger cascades and fluorescence emission have been calculated according to their probabilities for the relaxation of excited electron shells. The cross sections characterizing the various interactions of primary and secondary electrons in the solid, have been calculated from the theory as described in detail in ref 9. The Monte Carlo code simulates the cascade development in three dimensions, using the “direct scheme” described elsewhere^{15,16}. All trajectories of primary (incident electrons, photo- and Auger electrons) and secondary electrons are followed until the electron energy drops below the gap energy, where the ionization process stops. We assume an infinite CsI medium and define the primary conversion point as the origin of the coordinates frame (0,0). The incident particle direction is along the z-axis. When the cascading process stops, after several hundreds of SEs have been produced, we record their coordinates. Due to the azimuthal symmetry of the process we use cylindrical, z and r, coordinates. All results presented below are average parameters, obtained with a large number of simulated trajectories. For every variant (type of particle and energy) several hundreds of thousands of primary trajectories were followed, providing a statistical uncertainty below 10%.

3. Results

The cascade development may be presented in terms of three-dimensional density maps or their projections. Due to the azimuthal symmetry we have chosen to present the three-dimensional SE density (i.e. number electrons per nm³) as function of the longitudinal distance z from the (0,0) point and the lateral distance r from the z axis. Fig. 1 is a three-dimensional plot of the SE density distribution as function of z and r, for the case of 20 keV incident electrons. Fig. 2 shows density maps, in form of contour plots, of cascades generated by 10, 20 and 40 keV electrons. The plots cover only the cascade core, down to densities of about $2 \cdot 10^{-5}$ electron/nm³. In fact, the cascade cloud extends much farther with a monotonically decreasing density as is evident from Fig. 1. The initially elongated cascade shape becomes more

and more spherical at increasing distances. The maximal electron density is upstream the incident electron location.

The downstream contours (situated at the left side of the starting point (0,0)) result from cascades initiated by Auger and backscattered energetic electrons. In Figs. 3,4 we show the integrated electron density distributions projected on the longitudinal and lateral cascade axis. The number of SEs, given per unit length for the longitudinal distribution, was obtained by integrating the electron density over discs of a given z . The density distribution in the lateral direction, given per unit area was obtained by integrating the electron density over cylindrical shells of a given radius r . Each distribution may be characterized by the dimension within which 50% or 90% of the cascade electrons are confined. It should be noted that due to the increasing integration volume at increasing distances, the projected distributions are in fact much broader than could be expected from looking at Fig. 2. Fig. 5 shows the energy dependence of the characteristics of the longitudinal and lateral SE distributions. It can be seen that the maximal dimensions of the cascades i.e. the distance enclosing 90% of the cascade electrons, at the highest incident electron energy ($E=50$ keV), do not exceed $10\mu\text{m}$.

In the case of incident X-rays (see Fig.6) the SE density contours are practically isotropic, hence the longitudinal and lateral spreads are almost the same. This is due to the relatively low anisotropy of the photoelectron emission and to the isotropic distribution of Auger electrons. In Fig. 7 the integrated one- dimensional longitudinal density distributions for X-rays of different energies are shown. In all cases the peak position is at the cascade starting point. The distributions have two components: a narrow, high-density, peak and long extending shoulders. The relative intensity under the shoulders depends on the photon energy. This is due to the existence of two types of primary electrons initiating the cascade: photoelectrons and Auger electrons. At the shell energy there is a drastic change in the energy partition between the photoelectrons and the Auger electrons. The core of the distribution is related to the less energetic primary electrons, which loses all its energy within a small volume. The shoulders are related to the more energetic partners. Thus for example, at 20 keV the photoelectron emitted from the L-shell ($E_L = 5$ keV), has 15

keV, and is contributing mainly to the shoulders, while the Auger electron, having 2-5 keV, is leading to the peaked core of the distribution. Above the K-shell, ($E_K - 35.5$ keV) the role of the Auger electrons decreases due to the increasing rate of fluorescent radiation, which is not absorbed within the volume where the cascade develops. The contributions from Auger- and photo-electrons are shown separately in Fig. 7, for 20 and 40 keV.

Table I summarizes the total number of SEs produced in the cascade for incident electrons and photons of 10-50 keV. In the case of photons we separated the contributions from Auger- and photo-electrons, demonstrating the effect of energy loss due to fluorescence, leading to a reduction in the cascade charge, and the relative importance of Auger cascades in the SE production. In the case of electrons the number of secondary electrons upstream the incident electron location is also provided in the table.

Discussion

The results presented above show that the cascading process of SE generation in CsI develops to dimensions not exceeding $10\mu\text{m}$ for the maximal primary energy considered. The difference between cascades induced by electrons and photons is evident only at the core: elongated, forward-peaked shape for incident electrons and spherically symmetric for photons. At the periphery, after many randomizing interactions, the cloud is practically spherical and of low density.

As was mentioned above we stopped the development of the cascade as soon as all electrons have reached the gap energy. At this point we recorded the electron coordinates, providing a “freezed” snap-shot of the cascade cloud. Indeed the electrons continue to move in a diffused manner introducing an additional spread, but as was previously estimated ⁸, this spread does not exceed a few tens of nanometers. Hence, the transport of the SEs, until their escape from the surface of a finite convertor volume, will not change the cloud size.

We may therefore conclude that the localization resolution measured by us in SE low-pressure avalanche X-ray detectors ⁵⁻⁷ is not dominated by the SE cascade

size but rather by the processes occurring during the gaseous avalanche build up, and its recording by the electronic readout system.

Our experimental studies and previous theoretical calculations have shown that the SE yield as function of the CsI thickness, at a given photon energy, reaches a saturation ^{5,10}. Except for energies near the atomic shells, where irregularities occur, the thickness value at which this saturation occurs increases with the photon energy. The present results explain this effect. It is related to the increase in the longitudinal dimensions of the cascade cloud with increasing photon energy, which implies that cascades induced by photons converted at larger distances from the surface may still have some SEs escaping the surface.

Our results may also be used as a basis for the interpretation of the increased SE emission from porous CsI layers ^{12,13}. If the dimensions of the cascade induced by particles or X-rays are comparable to the dimensions of the “spongy” CsI granules, more SEs in the cascade will be produced close to the surface, with an increased probability of emission. This is of course a very simplified vision. Other effects like changes in the work function and, maybe, presence of high electrical fields, induced by the SE emission process from the porous convertor ^{12,13}, should also be considered. Theoretical and experimental aspects of SE emission from porous solids are presently under investigation.

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Table 1:

Energy dependence of the total number of secondary electrons in cascades induced by 5-50 keV photons and electrons. For photon-induced cascades the photoelectron contribution is also provided, while in electron-induced cascades the forward component (see Fig. 3) is added.

	Photons		electrons	
E[keV]	Total	Photoelectron only	Total	forward component only
5	231	80	323	246
10	618	368	638	490
20	1251	987	1274	985
40	881	627	2479	1860
50	1453	1290	2851	2280

- Fig. 1 A three-dimensional presentation of the secondary electron density distribution in the core of the cascade, induced by 20 keV electrons. The distribution is presented in cylindrical coordinates.
- Fig. 2 Contour plots showing the core of secondary electron density distributions (electrons /nm³), in cascades induced by 10, 20 and 40 keV electrons. The location of the peak and its value are also indicated. The distributions are presented in cylindrical coordinates.
- Fig. 3 The projected secondary electron density distribution on the longitudinal axis of the cascade cloud, induced by 20 keV electrons. Z_{1f} , Z_{1b} and Z_{2f} , Z_{2b} are the respective distances from the origine, in the forward and backward directions, within which 50% and 90% of the cascade electrons are confined.
- Fig. 4 The projected secondary electron density distribution on the lateral dimension of the cascade cloud, induced by 20 keV electrons. R_1 and R_2 are the respective radii which confine 50% and 90% of the cascade electrons.
- Fig. 5 The dependence of the cascade characteristic dimensions, shown in Figs. 3 and 4, on the incident electron energy.
- Fig. 6 Contour plots showing the secondary electron density distribution (electrons/nm³), presented in cylindrical coordinates, in cascades induced by 20 keV photons. The location of the distribution peak and its value are also indicated.
- Fig. 7 The projected secondary electron density distributions on the longitudinal axis, of cascade clouds induced by 10,20,40 and 50 keV photons (a-d). The photoelectron contribution is shown in e-f while that of Auger electrons is shown in g-h, for 20 and 40 keV photons.

Fig. 1

Electrons

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7