X-ray Spectra Calculations for Inspection of Semiconductors with Different Target/Filter Combinations Using MCNPX

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Abstract: X-rays are commonly used for inspecting semiconductors. However, excessive radiation dose could damage semiconductors. Therefore, unnecessary exposure needs to be reduced. The ray quality, which is influenced by the tube voltage and filter, determines the exposure. We designed an X-ray tube for inspecting semiconductors with different target/filter combinations and calculated X-ray spectra using the MCNPX (Monte Carlo n-particle extended) code. The target material was W, and the filters were made of Mo, W, and Zr. The W/W combination showed the lowest flux. The MCNPX code can reduce the development time and cost of the target/filter combination for inspecting semiconductors.

Key words: Inspection, semiconductor, damage, filter, MCNPX.

1. Introduction

Semiconductor manufacturing technologies are continually being researched to improve the performance and degree of integration and to reduce the size of semiconductors. Semiconductors are often very small, and therefore, inspection cannot be performed using the naked eye below a certain size. To overcome this problem, X-rays are used as a nondestructive defect inspection method. For example, X-ray laminography, a technique that captures tomographic photos of a sample multilayer by using the data obtained from X-rays and a detector, is used for nondestructive inspection. However, recent studies on the damage caused to semiconductors by the TID (total ionizing dose) effect of BJTs (bipolar junction transistors) raised the issue of low-energy X-rays causing damage to semiconductors [1]. TID is mostly caused by charge trapping when electron holes form between silicon and silicon dioxide in semiconductors.

Threshold voltage changes and leakage current increases when TID occurs and MOSFET is used [2]. Therefore, methods to reduce damage need to be studied. Generally, the ray quality in radiation imaging is an important factor that determines the amount of radiation exposure; it is affected by the tube voltage and added filter [3]. The inverse proportionality of the photoelectric effect to the cube of the energy of incident photons means that if a photon's energy is increased slightly, the photoelectric effect will decrease sharply. Therefore, to minimize the dose, a high kVp technique that increases the X-ray energy is recommended. However, this technique leads to another problem: the Compton scattering interaction increases when photoelectric absorption decreases, and the scattered photons deteriorate the image quality. This is because when a large photoelectric effect occurs, attenuation is severe, and when a large Compton reaction occurs, attenuation decreases [4]. In general, various types of added filters that can effectively reduce the

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unnecessary energy region must be developed. However, fabricating an added filter and evaluating its properties incurs considerable time and cost. The MCNPX (Monte Carlo n-particle extended) code is a powerful tool for studying and optimizing ionizing radiation systems. In this study, the X-ray spectra for different target-filter combinations were calculated by the Monte Carlo method using the MCNPX code.

2. Experimental Setup

Fig. 1 shows the simplified geometry configuration of the X-ray tube used for inspection. The X-ray tube used lead as a shielding material, and its length and diameter were 60 and 15 cm, respectively. The outside of the X-ray tube was set to be air and the inside, vacuum. The target material used was W. The filter was made from Mo, W, and Zr. The position at which the target and electrons collide was set to be the origin point (0, 0, 0). The distance between the target and the filter was 76 cm. The target had a diameter and thickness of 8 cm and 25 μm , respectively. Table 1 lists the characteristics of the target and filter materials.

Mo has a similar K-absorption edge as Zr. W has a higher-energy K-absorption edge compared to the

other materials. The maximum tube voltage was set as 50, 80, 10, and 120 keV ($\text{erg} = 0.028$), and the tube current was 100 mA. Because MCNPX outputs a value corresponding to one electron, the tube current was coded using Eq. (1) ($\text{fm } 2.250\text{e}21$). The mode was e and p (mode e p). The particle number was 3 (electron, $\text{par} = 3$). The distance between the target and the electron was 5 cm ($\text{pos} = 5\ 0\ 0$). Tally cards were used to specify the type of information that the user wanted to obtain from the Monte Carlo calculation. The information included the current across a surface, flux at a point, and heating in a region [5]. Table 2 shows a description of the tally card. To find the value of the flux averaged over a cell, we used *F4 tally (*F4:p 6). Further, to calculate the X-ray spectra, we used the e code ($\text{e}4\ 1\text{e}-10\ 999\text{i}\ 0.2$); in this case, the energy of the desired region can be divided into the desired number. NPS denotes the number of runs. To reduce the error ($< 3\%$), NPS was set to $1\text{e}8$.

$$\text{fm code at } 100\ \text{mA} = \text{Tube current} \times \text{Number of electrons per } 1\ \text{A} \times 3600 = 100\ \text{mA} \times 6.250 \times 10^{18}/\text{A} \times 3600 = 2.250 \times 10^{21} \quad (1)$$

Fig. 2 shows the Cd-Te X-ray spectrometer used for X-ray spectrum measurement in this study. Because

Fig. 1 Geometry configuration of X-ray tube.

Table 1 Characteristics of the target and filter materials.

	Atomic number	Density (g/cm^3)	K-edge (keV)
Tungsten	74	19.25	69.51
Molybdenum	42	10.28	20.00
Zirconium	40	6.52	17.99

Table 2 Description of tally card.

Tally type	Tally description	Fn units	*Fn units
F1 (n, p, e)	Current integrated over a surface	particles	MeV
F2 (n, p, e)	Flux averaged over a surface	particles/cm ²	MeV/cm ²
F4 (n, p, e)	Flux averaged over a cell	particles/cm ²	MeV/cm ²
F5 (n, p)	Flux at a point or ring detector	particles/cm ²	MeV/cm ²
F6 (n, p)	Energy deposition averaged over a cell	MeV/g	Jerks/g
F7 (n)	Fission energy deposition averaged over a cell	MeV/g	Jerks/g
F8 (p)	Energy distribution of pulses created in a detector by radiation	Pulse	MeV

Fig. 2 Cd-Te X-ray spectrometer.

this spectrometer works at room temperature and has high mass absorption coefficient when exposed to the X-rays of a sample, as a semiconductor detector, it affords greater advantages than other Si and Ge semiconductor detectors, which have different photoelectric absorption probabilities.

3. Experimental Results

Fig. 3 shows the X-ray spectra without the filter for energies of 50, 80, 100, and 120 keV. The characteristic X-ray peaks of W are very clear in these spectra. The maximum energy of the X-ray spectrum was confirmed to be 50, 80, 100, and 120 keV.

Fig. 4 shows the X-ray spectrum of the inspected equipment for tube voltage of 120 keV and another X-ray spectrum with a filter to reduce the dose. The characteristic peaks of W and of each filter were observed in all spectra. Compared to the case without a filter, the absorbed dose in air decreased by ~25.9%, 24.9%, and 26.9% when Mo, Zr, and W filters were used. Furthermore, compared to the case without a filter in the energy range below 40 keV, the absorbed

dose in air decreased by ~35.4%, 33.2%, and 38.0% when Mo, Zr, and W filters were used. Fig. 5 shows the MCNPX value at 50 keV as well as the values measured using the real inspection equipment. The computer simulation results show that the absorbed dose in air decreased by ~47.3% with the Mo filter

Fig. 3 X-ray spectra without filter for 50, 80, 100, 120 keV. **Fig. 4 X-ray spectrum (120 keV) of the inspection equipment designed using MCNPX.**

Fig. 5 X-ray spectrum (50 keV) of the inspection equipment designed with MCNPX and that of the actual inspection equipment.

Fig. 6 Relative dose distribution for each filter.

compared to the case without the Mo filter. The values measured with Cd-Te show that the absorbed dose in air decreased by $\sim 40.1\%$ with the Mo filter compared to the case without the Mo filter.

Fig. 6 shows the absorbed dose when Mo, Zr, and W filters were used at energies of 50, 80, 100, and 120 keV. The results confirmed that the absorbed dose was the lowest at every tube voltage when the W filter was used.

4. Conclusions

This research used MCNPX to design various filters. The MCNPX values were compared with the

measured values with the aim of reducing the damage caused to semiconductors during inspection. The results showed that the inspection equipment using a W filter absorbed the most dose at tube voltages of 50, 80, 100, and 120 keV. Furthermore, the MCNPX values showed 47.3% decay rate at 50 keV; in comparison, the measured values which showed 40.1% decay rate, indicating an error of 7.2%. Based on this study, equipment that reduces damage caused to semiconductors while enabling better imaging can be developed if more various filters are designed and manufactured to evaluate the resulting doses and images.

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