Quantitative materials analysis of micro devices using absorption-based thickness measurements

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Abstract. Preliminary work in designing an X-ray inspection machine with the capability of providing quantitative thickness analysis based on absorption measurements has been demonstrated. This study attempts to use the grey levels data to investigate the nature and thickness of occluded features and materials within devices. The investigation focused on metallic materials essential to semiconductor and MEMS technologies such as tin, aluminium, copper, silver, iron and zinc. The materials were arranged to simulate different feature thicknesses and sample geometries. The X-ray parameters were varied in order to modify the X-ray energy spectrum with the aim of optimising the measurement conditions for each sample. The capability of the method to resolve differences in thicknesses was found to be highly dependent on the material. The thickness resolution with aluminium was the poorest due to its low radiographic density. The thickness resolutions achievable for silver and tin were significantly better and of the order of 0.015 mm and 0.025 mm respectively. From the linear relationship between the X-ray attenuation and sample thickness established, the energy dependent linear attenuation coefficient for each material was determined for a series of specific energy spectra. A decrease in the linear attenuation coefficient was observed as the applied voltage and thickness of the material increased. The results provide a platform for the development of a novel absorption-based thickness measurement system that can be optimised for a range of industrial applications.

1. Introduction
The merciless decrease in size and parallel increase in complexity of advanced manufactured devices presents a number of challenges for materials characterisation and quality inspection. The problems are amplified in high volume production environments and when the critical features are occluded. The continual industrial technology demands from manufacturers are driving the development of new metrology techniques. Many non-destructive techniques such as ultrasound and eddy currents have been widely used to inspect occluded features. However, the process of sample preparation, needs for coupling

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media, low speed and/or limited resolution of these techniques are frequent barriers for these techniques to be more widespread for in-situ industrial applications [1]. In addition, many alternative measurement systems do not provide the real time imaging data necessary for determining the cause and precise location of defects. Conventionally, X-ray imaging allows defects in devices to be imaged based on the difference in absorption characteristics, however, quantitative measurements are generally not carried out.

The degree of absorption is largely governed by the nature of the material and the characteristics of the incident X-rays. The incident X-rays are influenced by three primary factors: the target material, the energy distribution, and the number of incident electrons. Manipulation of these three factors can thus be used to tailor the spectral characteristics of the emitted X-rays. The accelerating voltage and applied tube current are the easiest of the three variables to modify and will be used to optimise the system resolution in this work [2,3]. Varying the tube voltage primarily changes the X-ray energy distribution and therefore the penetrating power. Higher accelerating voltage would provide stronger penetrating power. The applied current primarily influences the number of electrons and consequently the X-ray flux. This study attempts to correlate the gray level data from the detector against material thickness.

2. Methodology
A nanofocus Fein Focus FOX 160.25 X-ray imaging system equipped with a 16-bit Varian Direct Digital Detector (DDD) was used in this study. Thin and pinhole free 99.99% pure foils of tin, aluminium, copper, silver, zinc and iron of different thicknesses were used. These foils were placed on a tray for support and were positioned at the centre of a light cone, at an equidistant position between the tube and detector to limit the effect of the geometric unsharpness and difference in path length associated with the cone beam. The accelerating voltage and applied current of the X-ray tube were varied accordingly to determine the optimum instrument configuration for each material. 16-bit images were captured after integrating 15 frames and the gray levels statistics were extracted from a 2*2cm area of the images. The experimental procedures were repeated three times to ensure reproducibility and repeatability.

The reduction in the intensity of monochromatic X-rays can be expressed by an exponential relation which is known as Beer’s Law, as given by Eq. (1) [4]

$$\ln \left( \frac{I}{I_o} \right) = -\mu x$$

where $I$ is the intensity of transmitted beam $I_o$ after passing through a thickness, $x$ and $\mu$ is the linear absorption coefficient which is dependent on the material considered, its density and the wavelength. The function on the left hand side of Eq. (1) was correlated against the actual thickness to optimise the system and to generate calibration data for each material.

3. Results and Discussion
At a fixed accelerating voltage and applied current, the six materials showed a similar trend in gray value statistics. The highest average gray value was observed in the absence of any sample, as the material thickness increased, the gray value decreased due to higher absorption of the incident X-rays. Here, it was found that the aluminium foil which had a thickness of 0.025 mm was transparent to the x-ray radiation though within the resolution limits of the system configuration. This limitation can be attributed to the relatively high energy of the X-ray spectrum generated from the tungsten target. Further investigations with lower atomic number targets such as molybdenum are in progress to improve the resolution. The thinnest copper foil of thickness 0.02 mm, figure 1 had adequate differential contrast from the background and was therefore resolvable using the selected instrument configuration. Similar observations were made.
for silver, tin, iron and zinc in which the minimum thickness detectable for each material is given by figure 2(a). The results here also seemed to suggest that the minimum thickness resolution for a material were not affected as thickness of that material increased within the limits of the experiments carried out.

Figure 1. Gray values distribution of copper foils at different thickness at 90kV

When comparing different materials, we can observed that the intensity transmitted through aluminium is the highest and least for silver and tin as would be expected, as shown in figure 2(b).

Figure 2(a). The minimum detectable thickness for each material at 66kV

Figure 2(b). Variation of gray values with thickness for different materials at 66kV

The corresponding gray value for a specific thickness increases with the accelerating voltage, as shown in figure 3(a). The gray values were shown to decreases exponentially with increase in thickness for all materials. This is an important observation and indicates that the use of gray values combined with Beer’s Law can be used as a traceable technique for quantifiable absorption based measurements. By plotting ln (I/I_o) vs. thickness, the linear absorption coefficient can be obtained from the slope of the graph. The linear absorption coefficient decreases in a 3rd order polynomial with accelerating voltage, as shown in figure 3(b). These results served as an important indicative parameter for the selection of energy range in achieving optimum thickness resolution. When the applied current is increased similar trends were observed, figure 3(c). The accuracy of these measurements varied from 0.1% to 6.9% of the actual thickness.
4. Conclusion

This study has demonstrated the capability of providing quantitative material thickness analysis using absorption-based measurements from gray values. The thickness resolution that was measured varied between 0.005-0.125 mm is highly dependent on the material type due to their difference in absorption characteristics. As the thickness of the material increases for a fixed voltage and current, the degree of absorption increases according to Beer’s Law, therefore the system setup can be tailored to specific materials. This preliminary work had proven that the gray level data from a DDD can be used for quantitative absorption based measurements. The next step is to focus on measuring thickness of features in multimaterial structures which are realistic models of semiconductor and MEMS systems.

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