Integrated Circuits Investigated by an Energy-Tunable Hard X-ray Microscope

Non-destructive methods for the structure analysis and elemental mapping of integrated circuit (IC) have been a vigorous pursuit among IC manufactures and equipment vendors. However, most of the research tools, such as scanning probe microscopy (SPM), secondary electron microscopy (SEM), and transmission electron microscopy (TEM), are destructive, time-consuming, and requiring great skill in preparing samples. Transmission X-ray microscope (TXM) offers a viable alternative in studying the defects in ICs. Thanks to the high brightness of X-rays generated by the wavelength shifter at NSRRC, the microscope can produce images of 15 μm × 15 μm field of view at 60 nm spatial resolution in several seconds. Moreover, the energy tunability of X-ray from 8 to 11 keV can be further exploited by performing imaging of metallic materials at below and above the X-ray absorption edge energies of the investigated elements. In this so-called differential absorption contrast method, the difference of two images provides a spatial map of the element of interest. A differential absorption contrast imaging of copper interconnect as well as their data set comparison in 3D are presented in this article.

X-ray microscopy has become a promising technique to investigate the structures of integrated circuits. Despite its lower resolution as compared to those afforded by electron microscopies, the high penetration depth and elemental selectivity have rendered the X-ray microscope a competitive tool in investigating IC packaging. Thanks to the tremendous progress made in X-ray optics, detectors, and brighter photon sources generated by synchrotron, the spatial resolution is approaching several tens of nanometers with exposure time of several seconds. Combined with a large depth of focus, the present-day hard X-ray microscope is capable of performing high resolution 3D tomography in several hours. With this instrument, element mapping in 3D which needs large data sets and precise alignment can be realized.

The present hard X-ray microscope is a custom-designed, full-field transmission X-ray microscope (TXM) constructed by Xradia Inc. The microscope is designed to operate in the photon energy range between 8~11 keV utilizing a zone plate optical system to achieve tomographic images at 60 nm resolution with a 15 μm × 15 μm field of view and a depth of field of 50 μm. Silicon-based samples with thicknesses up to 100 μm can be imaged non-destructively. Elements with absorption edges falling within this photon energy range can be detected using the technique of differential absorption contrast imaging. The detectable elements that are of particular interest to IC industry include Cu, Ta, W, Ga, As, and Ge. With a high brilliance synchrotron source, the microscope can generate signals rate up to 100 counts/pixel/sec. The general exposure time for one by one binning is 15 sec, and it can be further reduced by means of a better beamline and improved X-ray microscope optics.

The energy tunability of the X-ray microscope is assisted by utilizing three zone plates. Each zone plate is designed to be optimized for a certain energy range. The diameters of the three zone plates are 85 μm, 75 μm and 70 μm, respectively, aiming at the same focal length for different energies. The calculated magnification factor for the microscope ranges from 780 to 880 for the 8-11 keV energy range, with its overall variation of about 12% with the X-ray energy presented in Fig. 1. With this design, the samples can be imaged at different photon energies but of the similar magnification if the two energies are chosen judiciously. For an energy difference of 100 eV, the variation of magnification is about 1%. Nonetheless, it is still possible to keep the same magnification factor by using two different zone plates, a point to be illustrated later.

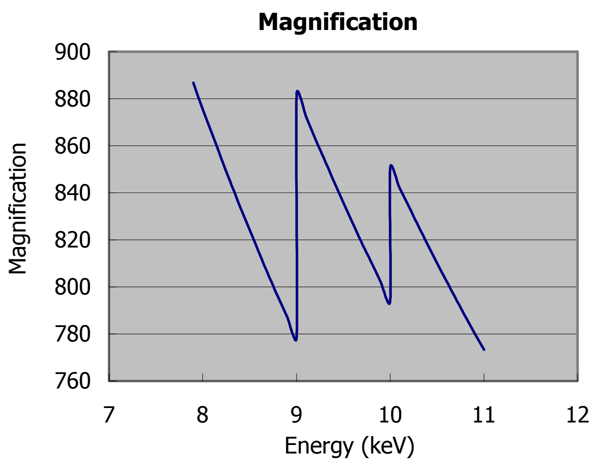

Fig. 1: The calculated magnification versus energy.

By acquiring a series of 2D images with the sample rotated stepwise, 3D tomographic images can thus be reconstructed. The theoretically voxel resolution is 60 nm × 60 nm × 60 nm for full angle. For the limited angle, the spatial resolution depends on the availability of high angle data, the number of projection data, and the alignment of the data. The resolution test has been performed by using a spoke pattern and the 3D resolution is determined to be better than 100 nm.

The preparation of an IC sample for TXM measurement is much easier than that for TEM. The thickness can be up to 50 µm but the thinner sample is better. During the sample preparation, the back of the IC chip is thinned down by a grinder, dimpled at the center and then the thickness is further reduced from the central part of the sample down to the desired dimension. After this treatment, the IC chip is still mechanically strong and will not crack when clamped to the sample holder.

Key hole in the tungsten plug is used to ensure an accurate alignment of multi-layer interconnects. If the key hole is too big, the circuit connection can be open and the IC will fail. The investigation of the key hole with TEM requires an ultra thin slice of the IC sample in order to allow the penetration of the electrons. This practice takes time and also destroys the sample; moreover, one can only measure one key hole per sample. TXM data set, comprising of 141 images from –70 to +70 degrees, are taken at 10.5 keV, above the L_{III} absorption edge of tungsten at 10.2 keV. The data sets are then aligned and processed, and the resulting image is shown in Fig. 2. The diameter of the tungsten plug is 0.35 µm and the diameters of key holes are determined to be between 0.1 µm and 0.15 µm.

The multi-layered Cu interconnected IC structure has been imaged with different photon energies. The image contrast can be enhanced due to different absorption factors. The experiment demonstrates the contrast differential method for the IC sample in two dimensions. The absorption coefficient for Cu at 9.5 keV is only four times larger than that at 8.4 keV. However, the reason for choosing the two said energies is that they give rises to the similar magnification of about 830, as inferred from Fig. 1. Figures 3(a) and 3(b) shows the two images taken at 8.4 keV and 9.5 keV with two different zone plates.

After correcting for the image drift problem with the software, an image subtraction is next performed. The difference image is given by subtracting the signal count acquired with 8.4 keV X-ray from the corresponding count obtained with 9.5 keV X-ray in a pixel-to-pixel manner. Figure 4 presents an as-treated image for Cu interconnect and the bright regions indicate more abundant areas of Cu in the chip.

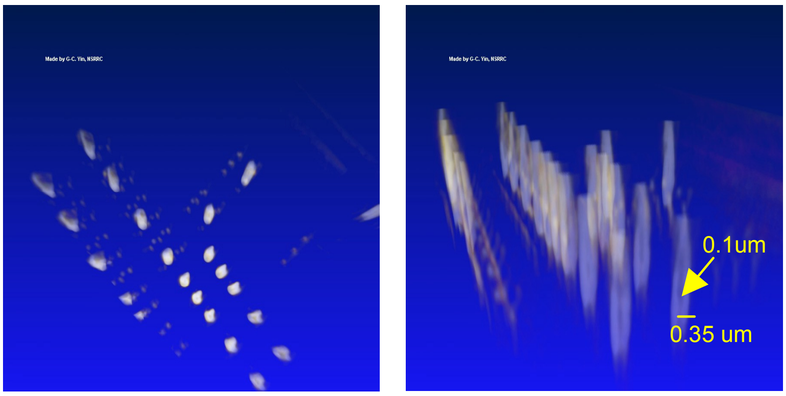

Fig. 2: The 3D display of tungsten plugs. The "key holes" can be easily observed, the tungsten plug is 0.35 µm in diameter and the hole size is 0.1 µm in diameter.

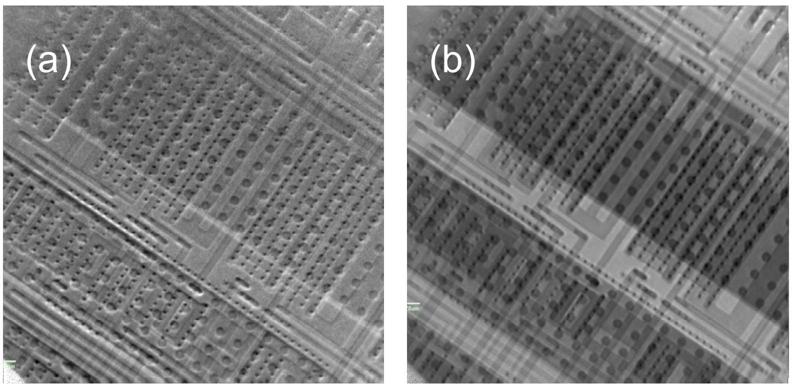

Fig. 3: TXM images are taken at 8.4 keV (a) and 9.5 keV (b) using different zone plates, but of similar spatial magnification.

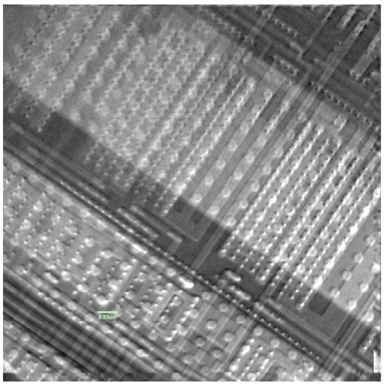

Fig. 4: The contrast difference image that is enhanced by X-ray absorption difference across the Cu K-edge indicates the distribution of Cu in the IC.

We located the same area on the IC sample to perform tomography measurements at two different energies in order to explore the contrast enhancement of Cu. The two tomographic data sets are taken at 8.4 keV and 9.5 keV at reasonably close magnification for data processing. Both data sets are composed of 141 images from –70 deg to +70 deg. The two data sets are reconstructed, rendered and shown in Fig. 5(a) and (b). The data sets are then aligned in three dimensions and processed by simple subtraction (Fig. 5(c)). The 3D image is enhanced by subtracting noise and artifacts of the reconstruction. The enhancement can be seen by comparing image (d), before processing, and (e), after processing. The left edges of two images look the same because there is no subtraction applied.

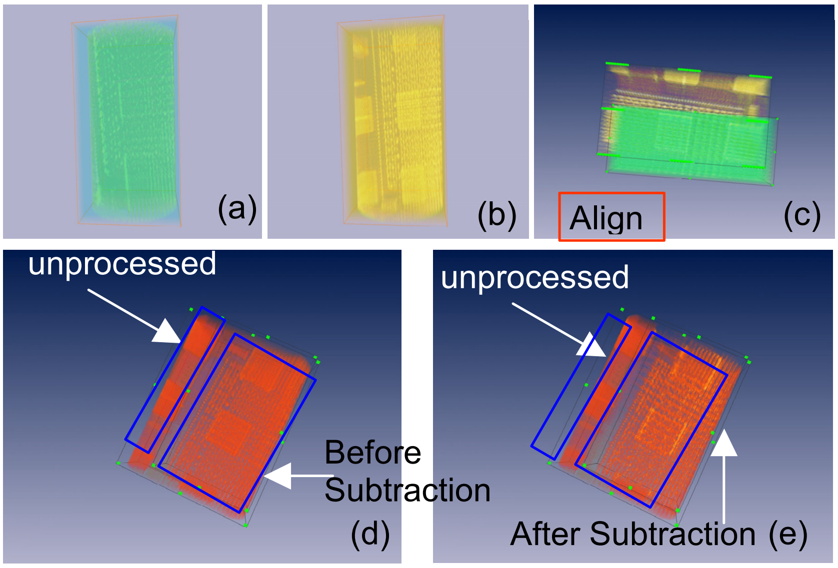

Fig. 5: The 3D TXM images from Cu interconnects in the IC structure; (a) and (b) are taken at 8.4 keV and 9.5 keV respectively. The finest features of Cu in the images are 110 nm. (c) The two image data sets are aligned in 3D. (d) The two data sets before subtraction. (e) The two data sets after subtraction in 3D.

The elemental mapping can be done by the subtraction of the two tomographic data sets. In principle, this method can be applied to any element with two data sets acquired above and below its absorption edge. Thus, a three-dimensional, non-destructive, element-selective investigation of ICs can be realized.

BEAMLINE
01B X-ray Microscope beamline

EXPERIMENTAL STATION
Transmission X-ray Microscopy end station

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PUBLICATIONS

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