Non-destructive 3D Imaging of Nano-structures with Multi-scale X-ray Microscopy

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ABSTRACT

X-ray microscopy offers a unique combination of large penetration depth, high resolution, and high sensitivity to elemental composition. When combined with computed tomography (CT) techniques, the full three-dimensional structure of a sample can be obtained non-destructively and often with little sample preparation. With Xradia's high-resolution x-ray optics technology, we have pushed the imaging resolution to 40 nm in our nanoXCT™ system. This product has been applied to a wide range of applications including single-cell level biological microscopy, failure analysis of integrated circuits, and fuel cell development. By further integrating this high-resolution system with a projection-type x-ray micro-CT system, we have developed a multi-scale x-ray CT system with variable resolution between 40 nm to 40 μm, and field of view from 20 μm to 40 mm. This system offers unprecedented non-destructive imaging capabilities for structures ranging from tens of nm to tens of μm size scale – a three orders of magnitude "zoom" range.

Keywords: x-ray microscopy, CT, nanoXCT, microXCT.

1 INTRODUCTION

X-ray imaging offers several unique capabilities that are favorable for non-destruction imaging and analysis: (1) very large penetration depth; (2) ability to image exact 3D structure with the use of computed tomography (CT) technique [1]; (3) high elemental sensitivity; and (4) no charging effect and very low radiation damage. For example, Fig.1 shows the $1/e$ attenuation length of several materials commonly used the fabrication of nano-structures as a function of x-ray energy [2]. Multi-keV x-rays can penetrate tens to hundreds of um of light metal and semiconductor materials, and many millimeters of organic materials, such as photo-resist or soft tissue. Furthermore, this length scale is increased by an order of magnitude for x-rays with tens of keV energy. In contrast, the penetration depth of other commonly used imaging techniques based on visible light and electrons is limited to no more than several microns by absorption and multiple scattering. *Therefore, x-ray radiation is fundamentally better suited for probing internal structures in a non-invasive and non-destructive fashion.*

This key advantage of x-ray radiation has been recognized since its discovery and is widely used in medical imaging and industrial inspection applications, typically at mm-scale resolution. However, recent developments in x-ray optics and detector technology have lead imaging resolution to micron to nm scale. As a result, x-ray imaging technology has become increasingly more common used for studying micro-structure.

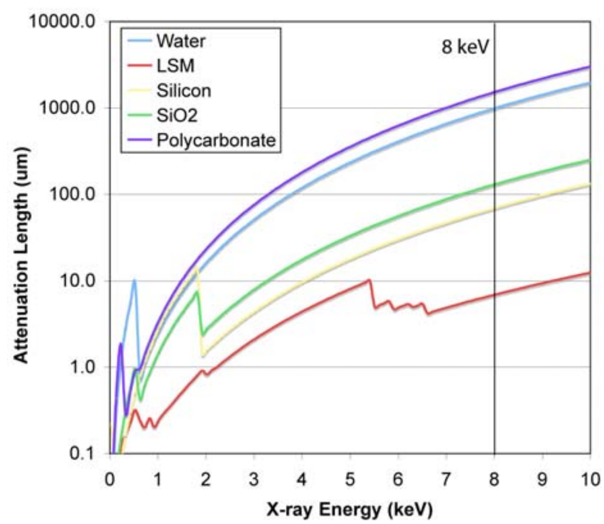

Figure 1. Attenuation length of several materials as a function of x-ray energy.

X-ray imaging is traditionally performed in a direct-projection scheme where a spatially resolved detector is placed behind the subject to record its shadow radiograph. This technique can achieve up sub-micron resolution in 2D imaging and several micron resolution in 3D imaging.

In the past two decades, advances in x-ray optics have lead to the ability to directly magnify x-ray images. Pioneered at synchrotron radiation facilities in Germany and US, x-ray microscopes based on this technology have demonstrated better than 30 nm resolution [3]. Xradia has developed table-top x-ray lens-based imaging system, nanoXCT™, that is able to routinely perform 3D imaging operations at 40 nm resolution in a highly automated fashion [4]. The multi-scale system described in this paper combines the nanoXCT™ system with a direct-projection system to produce a highly versatile x-ray imaging system capable of variable resolution between 40 nm to 40 um, with field of view ranging from 20 um to 40 mm. This large 3 orders of magnitude length scale is unique among imaging technologies and provides unprecedented non-destructive imaging capabilities for a diverse range of applications in biotechnology, nanotechnology, energy research, and advanced materials, *etc*.

2 MULTI-SCALE IMAIGN SYSTEM

The multi-scale x-ray imaging system consists of a nanoXCT™ module for imaging at 40 nm resolution and 20 um field of view, and a microXCT™ direct-projection module for imaging at 1 um or coarser resolution and field of view larger than 0.5 mm. These two modules share a sample positioning system that is able to co-register a sample's region of interest with an accuracy of 1 um.

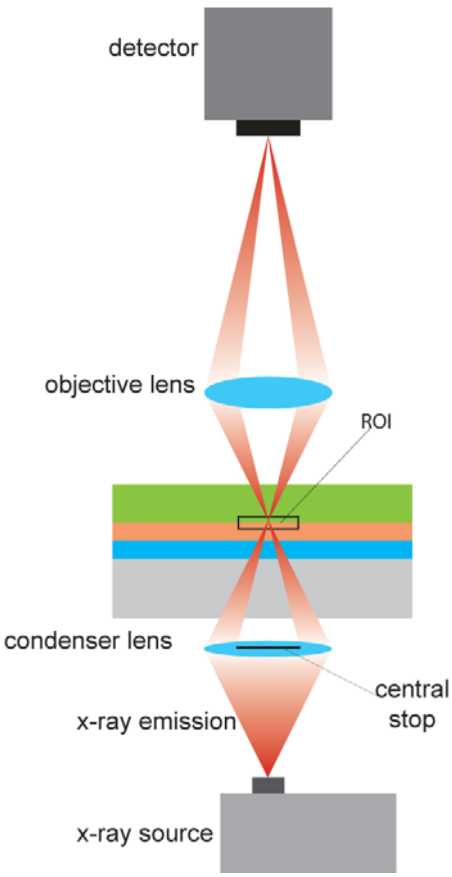

Figure 2. Schematic illustration of the nanoXCT™ system.

The nanoXCT™ is the world's only table-top x-ray CT system with tens of nm resolution. As illustrated schematically in Fig. 2, it resembles a conventional light microscope, consisting of an x-ray source, a condenser lens, an objective lens and a CCD detector. The key features of nanoXCT™ include: (1) penetration depths in the mm range for organic samples and in the 100-um range for light metal and semiconductors, (2) 50 nm resolution that is uniform in 3D, (3) multiple imaging modalities including absorption or Zernike phase contrast to optimize image contrast, and (3) automated data acquisition and analysis.

The nanoXCT™ uses rotating anode x-ray generator and a Fresnel zone plate lens as the objective lens. By using different target material, characteristic x-ray emission at energies between 5 keV and 20 keV can be generated. For example, at a typical 8 keV emission energy from Cu target, organic materials have over 1 mm attenuation length, indicating that tissues or small organs of several mm thickness can be examined without sectioning. For example, single cells within a specimen, such as engineered tissue, can be imaged at 50 nm resolution in 3D. This provides a completely new way to study biological systems near its native state. Similarly, for nanotechnology and materials research applications, the x-ray beam penetrates over 100 um of most solid semiconductor materials such as silicon. This allows fully functional multi-level nano-electronic, MEMS or NEMS devices, or fuel cell devices to be examined with minimal modification, and also possibly while the device is in live operation.

The microXCT™ module uses a direct-project x-ray imaging scheme, but has a unique design that uses a very high-resolution detector system [5]. In a projection system, the geometrical magnification is:

$$M = \frac{L_s + L_d}{L_s}, \tag{1}$$

where, L_s is the source to sample distance and the L_d is the sample to detector distance. We can then derive from a geometric argument that the achievable resolution of this system is:

$$\delta \geq \max\left(\frac{M-1}{M}s, \frac{\delta_{\det}}{M}\right), \tag{2}$$

where s is the size of the x-ray source spot and $\delta_{\det}$ is the detector resolution. From this simple relationship, we see that in order to achieve high resolution, one can make M close to 1. In this case, the sample plane overlaps the detector plane, and we arrive at the geometry of *proximity (or contact-printing) mode*, where the system resolution depends entirely on that of the detector. Traditional film-based radiography operates in this mode to take advantage of high-resolution of the recording medium. An alternative imaging mode is to let $M >> 1$, that is, increase the magnification so that the features in the sample are magnified sufficiently to be sampled even with a detector with coarse resolution. This lead to the *projection mode*, where the resolution is roughly the source size. A high resolution imaging system can be based on either projection or proximity mode. The trade-offs, or the challenges, are that with the proximity mode, one must have a detector with high resolution while with the projection mode, one must have a source with very small spot size.

Traditional industrial high-resolution imaging systems typically operate in the projection mode. In order to achieve highest resolution, the sample must be placed very close the source, often within millimeters distance. This requirement is acceptable for 2D imaging but presents a severe limitation on the sample size for 3D imaging. Xradia's microXCT™, however, uses a unique combination of moderate x-ray source size and high detector resolution to overcome this restriction and achieve a 1-um resolution for both 2D and 3D imaging with large samples. This is the highest resolution achieved in the industry. At this highest resolution, the nanoXCT™ provides a 0.5 mm field of view, but wider field of view of up to 40 mm can be achieved by different magnification settings in the detector optics. Furthermore, operating at x-ray energy of 100-150 kVp, the microXCT™ is able to image many millimeters to centimeters thick samples of organic and semiconductor material or light metal, such as complete semiconductor packaging, circuit boards, and bones.

3 APPLICATION EXAMPLES

We illustrate the capabilities of the multi-scale system with an application in analyzing integrated circuit devices. Modern microprocessors die contain multiple layers of interconnects with line width ranging from 45 nm to microns and a thickness of up to 10 um. The die is typically mounted on a packaging that contains multi-level structure with micron-sized conductors and a total thickness of several mm. They contain a wide range of feature sizes that is well suited for the multi-scale x-ray imaging system. Furthermore, the analysis can be performed non-destructively in most cases with little sample preparation.

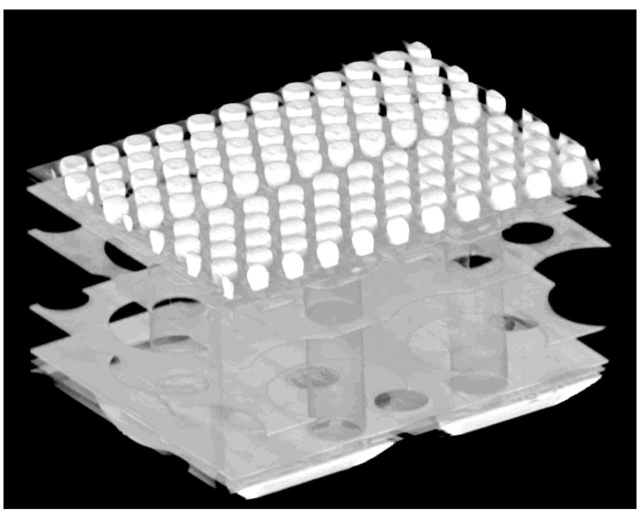

Figure 3. A microprocessor packaging imaged by the microXCT™ module.

Fig. 3 shows a typical flip-chip packaging imaged with the microXCT™ module. The 3D image is obtained by taking a series of projection image at different view angles and then mathematically reconstruct the sample's 3D structure. This 3D image is then generated with iso-surface volume rendering. Key features of the sample such as the μBGA contacts and through holes can be identified from the 3D image, but we can also examine detailed features by studying the cross-sectional images of the 3D volume data, as shown in Fig. 4. This is commonly referred to as *virtual cross-sectioning*. In this example, a μBGA ball containing foreign particles can be identified from both the "layer plane" and the "cross-sectional plane".

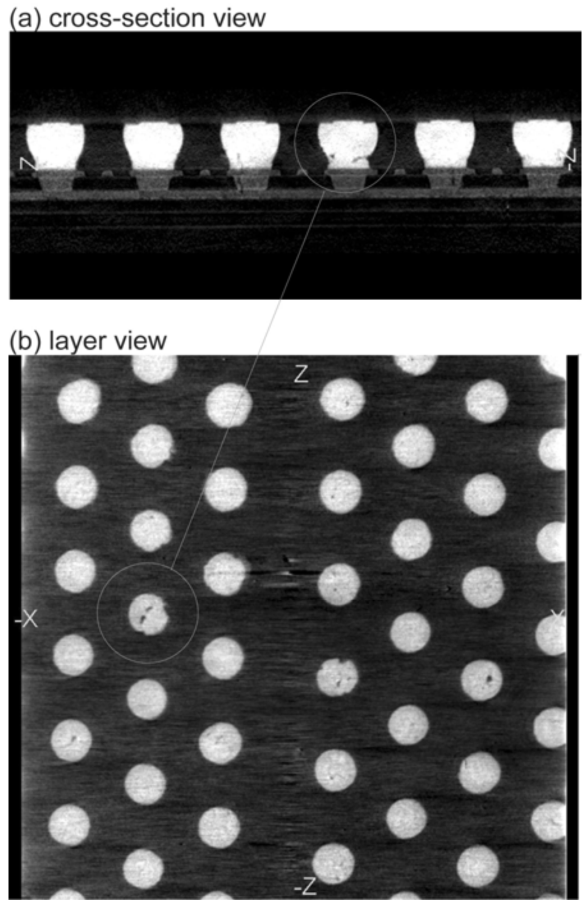

Figure 4. Virtual cross-sectioning images that allows one to view the 3D internal structure without physically sectioning the sample. One μBGA ball containing small trapped particles can be identified in both cross-section views.

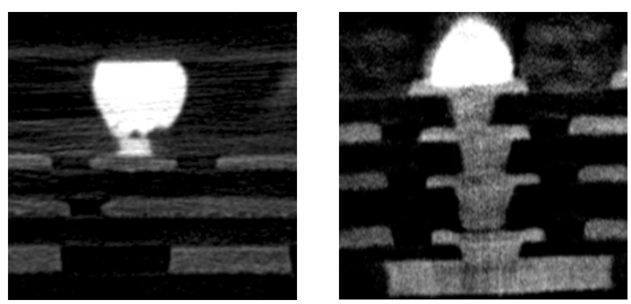

Figure 5. Images of poor contact (left) and delamination (right) defects in a packaging sample.

More difficult micron-sized defect types such as poor wetting and delamination can also be identified from the 3D images as shown in Fig. 5. Traditionally, in order to observe these defects, one must be cut and polish the sample to reach the suspected failure location and use a visible light microscope or scanning electron microscope

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(SEM) to identify the failure. This physical cross-sectioning process is destructive, time-consuming and often prone to introducing new defects.

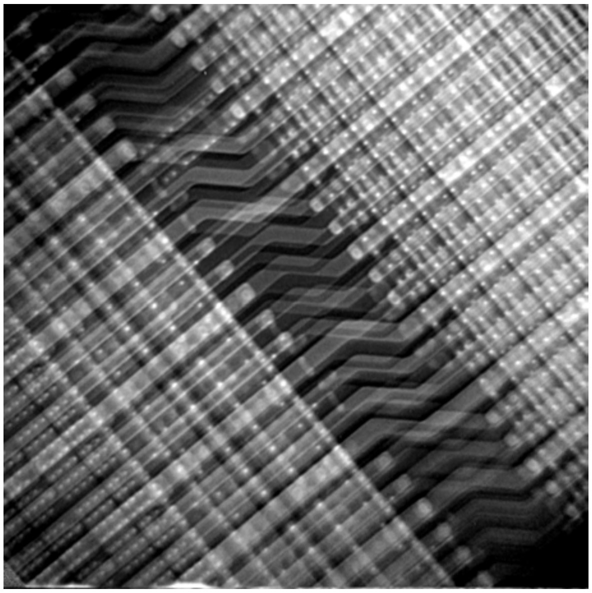

Figure 6. An integrated circuit die imaged with the nanoXCT™ module.

The nanoXCT™ module is able to perform 3D CT imaging at 40 nm resolution. As the microXCT™ is intended for studying micron-scale feature such as packaging or engineered tissues, the nanoXCT™ is well-suited for imaging nanometer-scale features such as semiconductor dies or individual biological cells. Fig. 6 shows an integrated circuit die with 5 metal layers imaged with nanoXCT™ module. The finest lines in this sample with 80 nm width are clearly resolved in the image, but the overlapping features make it difficult to distinguish them. These features, however, can be resolved in depth with the CT technique. Fig. 7 shows several virtual cross-sectional images extracted from the reconstructed 3D volume data. The metal structure of the sample can then be analyzed from these images.

In addition to semiconductor applications, the x-ray CT technique can be applied to a wide range of fields such as in biotechnology to examine osteoporotic bone or engineered tissues samples, composite materials, and NEMS or MEMS devices, *etc*. The non-destructive x-ray micro-CT technique is increasingly more accepted as an alternative to physical cross-sectioning in these applications and may in some cases completely replace destructive testing and evaluation procedures.

4 SUMMARY

Multi-scale x-ray microscopy offers a unique combination of large penetration depth, high resolution, and wide scale range. When combined with the CT technique, the full three-dimensional structure of a sample can be obtained non-destructively and often with little sample preparation. This system offers unprecedented analytical and imaging capabilities that will significantly improve the productivity of technologies requiring studies at nanometer to micron scale.

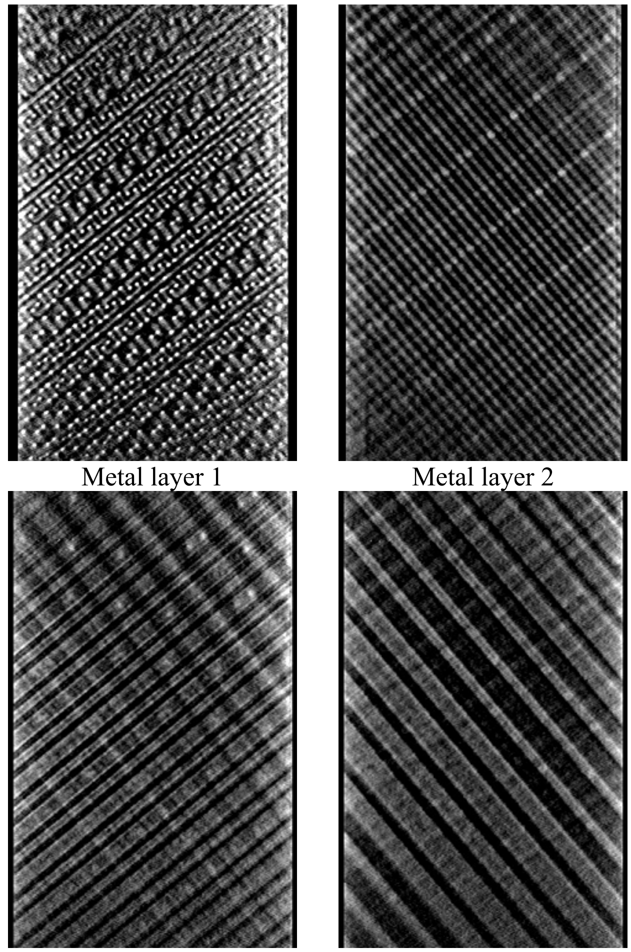

Figure 7. Four lower metal layers from the 3D data.

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