

A Novel X-ray Microtomography System with High Resolution and Throughput

Yuxin Wang, Fred Duewer, Shashidhar Kamath, David Scott, and Wenbing Yun

Xradia, Inc., 4075A Sprig Dr., Concord, CA 94520

ABSTRACT

The large penetration depth and rich contrast mechanisms of x rays makes it ideal for non-destructive or non-invasive imaging applications. Projection-type x-ray micro-imaging systems are widely used in micro- and nano-technology industries to study the internal structures of manufactured components such as micro-electro-mechanical (MEM) or semiconductor devices. The resolution of these system is typically determined by the size of the x-ray source. As a consequence, a small x-ray source size and high magnification are required to achieve high resolution. Since both factors reduce the detectable flux, a compromise between the resolution and the throughput must be made. Based on its innovative high-resolution detector, Xradia has developed a new system, the microXCT, that solves this problem by using a unique optical design. It is able to acquire images with 1-micrometer resolution in an exposure time of a few seconds. This instrument includes a fully automated tomographic data acquisition and reconstruction capability for an user to study the 3D structure of a sample at micrometer three-dimensional resolution. This system's unique capability of imaging at high-resolution with minimal compromise in the throughput makes it a valuable tool in non-destructive imaging applications in microtechnology and biotechnology.

1 INTRODUCTION

Since its discovery, the ability of x rays to see through material has been exploited extensively in non-invasive and non-destructive imaging applications in medical and industrial applications. For nano-technology, in particular, x-ray imaging systems provide the ability to non-destructively image the internal structures of devices with tens of nm to a few μm resolution. To date, laboratory x-ray microscopes that employ x-ray optical elements have achieved 60 nm resolution [1]. They are typically used in failure analysis applications in semiconductor industries. The more widely used systems are projection-type x-ray microscopes that use no x-ray optics, but only uses a scintillated x-ray detector to record the projected shadow image through a sample (see Fig. 1). A number of manufacturers offer commercial systems with resolution ranging from tens of μm to sub-micron. These instruments are widely deployed in a wide spectrum of industrial and scientific applications including semiconductor and electronics testing, biomedical research, archeology, and geology.

Besides commercial system, many such systems have been developed using synchrotron radiation sources. They typically offer much higher throughput to allow real-time study of dynamic events, and continuously tunable x-ray energy, which greatly enhances the material analysis capabilities.

In most commercial system, very high magnification is required to achieve the high resolution. The resolution with these designs is approximately the size of the x-ray source. Many manufacturers have develop nano-focused x-ray sources in order to achieve sub- μm resolution. The reduction of source size, combined with the high magnification, have severely limited the throughput of these systems. To overcome this limitation, Xradia has developed a new system using an unique optical design based on its innovative high-resolution detector system. It is able to acquire images with 1-micrometer resolution in an exposure time of a few seconds. This throughput approaches that of synchrotron-based instruments.

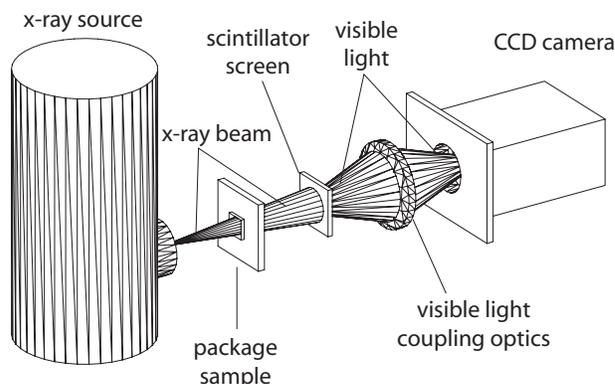


Figure 1. Illustration of a typical projection-type x-ray microscope.

2 IMAGING SYSTEM GEOMETRY

We first look at the imaging properties of the projection type microscopes. As illustrated in Fig. 1, the imaging system consists of a x-ray source, a sample position system, and a detector system, which simply records the shadow of the sample. We first look at the resolution limit of this system. Fig. 2 shows the geometry of such a system with a

x-ray source with size s , two point objects separated by distance δ , and their shadow on the detector plane. The source to sample distance is l_s , and the sample to detector distance is l_d . In this geometry, Each point casts a shadow on the detector plane with the size $(l_d/l_s)s$. This is essentially the point spread function. The magnification is:

$$M = \frac{l_s + l_d}{l_s}$$

Ignoring the diffraction effect, we can use the criteria that the two point objects are resolved if the center of the object does not fall into the shadow of the other. That is:

$$\left(\frac{l_s + l_d}{l_d}\right)\delta \geq \frac{l_d}{l_s}s$$

Therefore the resolution limit determined by the imaging geometry is:

$$\delta \geq \frac{M-1}{M}s$$

A couple of special cases can be observed from this expression:

1. *Contact printing mode*: $M \approx 1$, then $\delta = 0$. That is, infinitely high resolution can be achieved in contact printing mode, where the sample is placed very close to the detector. In practice the system resolution is primarily determined by the detector resolution.
2. *Projection imaging mode*: $l_d \gg l_s$, and $M \geq 1$, then $\delta \approx s$. In this mode, the system resolution is determined primarily the source size. The detector resolution is relaxed because the features are magnified by the diverging x-ray beam. If the detector has sufficiently high resolution to sample the image, the system resolution is approximately that of the source size. Note that the resolution is never worse than the source size.

These are basically the two ways to achieve high resolution: one can use either a very high resolution detector or a x-ray source with very fine spot size. The trade-off is then to build a high resolution detector with high efficiency versus a source with high flux.

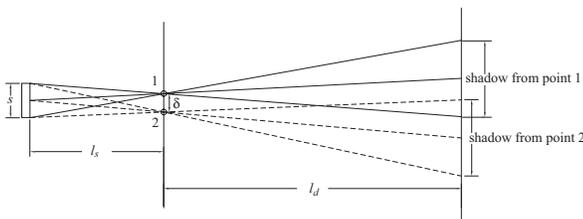


Figure 2. Imaging geometry of projection-type x-ray microscopes.

How much compromise must be made in each case with practical systems? Non-destructive imaging requires x rays with sufficient energy to penetrate through a complete device with a few mm to centimeter in size. X ray sources with more than 50-150 keV electron bombardment energy are used in most commercial systems. With the projection mode, to achieve 1 um resolution, the detector can be of coarse resolution with good efficiency, but the x-ray source spot size must be kept less than 1 um. The mean range of electrons in a bombardment target can be estimated with these empirical formulae:

$$\text{lateral} = \frac{0.1E^{1.5}(\text{keV})}{\rho(\text{g/cm}^3)}$$

$$\text{depth} = \frac{0.077E^{1.5}(\text{keV})}{\rho(\text{g/cm}^3)}$$

For example, with 150 keV electrons, the range is about 10 um in tungsten. The dimension of the x-ray generation volume is slightly larger. As illustrated in Fig. 3, the x-ray generation volume of a target is approximately that of the electron focal spot near the surface, but balloons to tens of um deeper into the target. To keep the spot size to 1 um, one must either lower the electron acceleration voltage, or use a thin film target with less than 1 um thickness instead of a solid target. Lowering the acceleration voltage makes the x rays less penetrating and is only acceptable for imaging small or partially destructed samples. Using a thin film target allows x rays to be generated only near the surface and avoid most of the x-ray generation volume. This clearly causes an severe efficiency loss since at 150 keV, no more than a few percent of the x rays are generated near the surface.

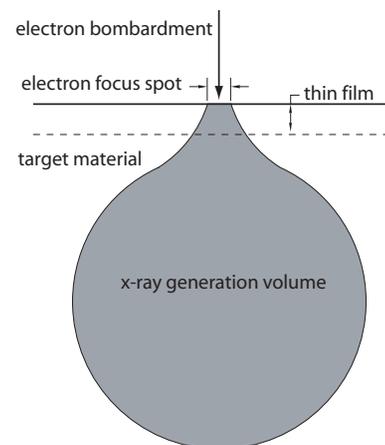


Figure 3. Illustration of the x-ray generation volume of an electron-bombardment target.

With contact printing mode, on the other hand, a moderate sized x-ray source can be used to take advantage of its full x-ray generation volume, but a scintillated detector with microscope objective coupling is needed. The x-ray shadow of the sample is converted to a visible light image detected by a single crystal scintillator. The visible light image is then imaged to a CCD camera by an objective lens. To reach 1- μm scale resolution, the objective lens must have sufficiently high numerical aperture of at least 0.25. This high numerical aperture restricts the depth of field to tens of μm . Therefore, the scintillator must be made thinner than tens of μm in order to achieve the desired resolution. This thin scintillator typically absorbs only about 10-20% of the incoming radiation, therefore reducing

the efficiency and the throughput. With current designs, the detector efficiency loss with contact printing mode is not as severe as the output loss with the projection mode. As a result, ones using contact mode can provide about tens times better throughput than projection mode systems at 1- μm level resolution. If the resolution is relaxed to tens of μm , the two system configurations are essentially similar and their throughput becomes comparable. Besides the throughput considerations, the long magnification beam path required in projection systems also have negative consequences on the system's footprint and image artifacts resulting from diffraction effects.

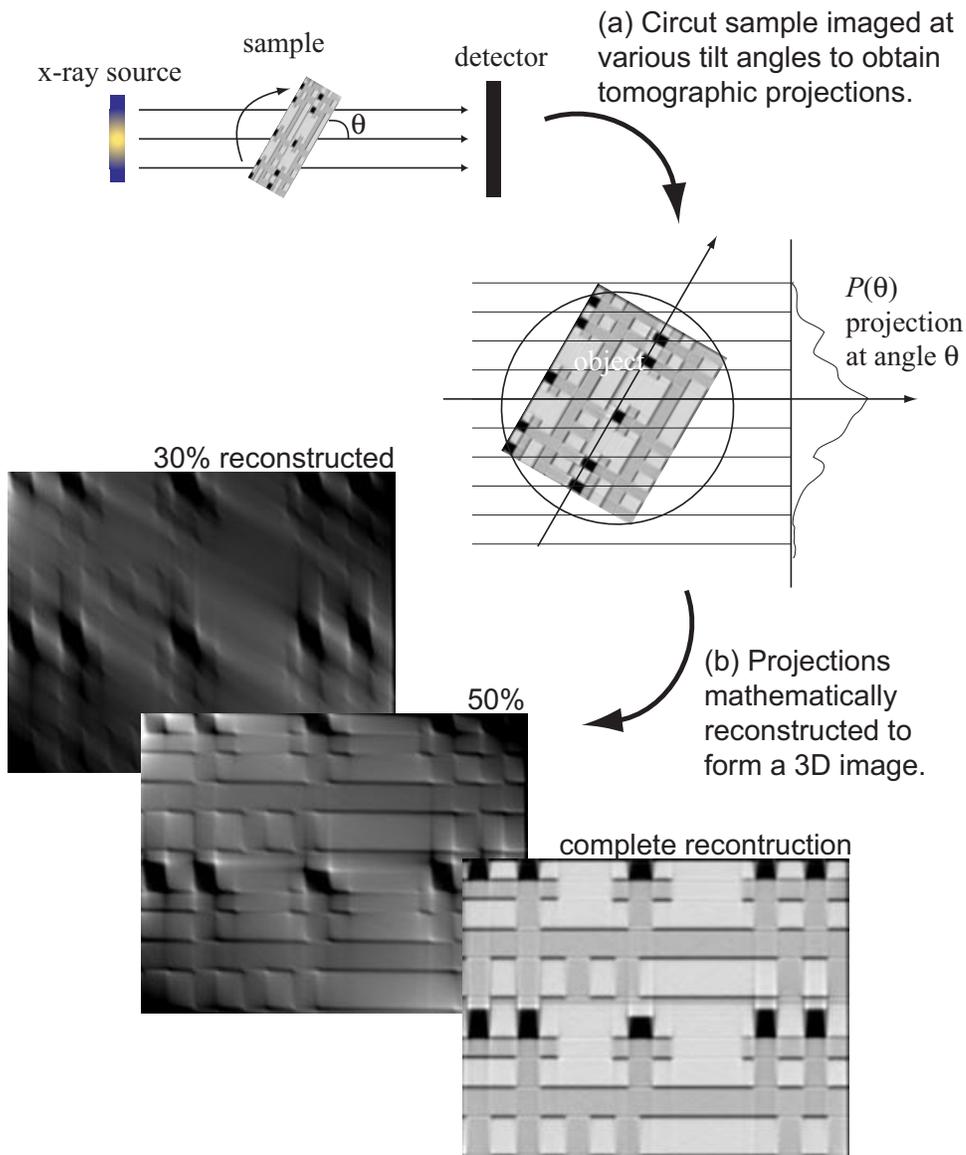


Figure 4. Illustration of the tomographic imaging process: The sample is first imaged at different tilt angles from the x-ray beam to obtain a series of *tomographic projections*. These projections are then recombined mathematically to form a 3D image representing the 3D structure of the sample.

3 THE MICROXCT SYSTEM

The microXCT is a high-performance x-ray imaging system with many innovative conceptual and engineering designs. Its resolution and field of view are adjustable from a few settings according to the sample size and the required resolution. In the high-resolution mode, a resolution of 1 μm can be achieved with 1 mm field of view. In the survey mode, it provides 10 mm field of view, with 10 μm resolution. An intermediate resolution setting can also be used. The system is based on a commercial x-ray source with a moderate spot size that makes use of the full x-ray generation volume of the target, and a proprietary detector system developed by Xradia. This system provides very high throughput, particularly for the high resolution modes, where images with 1- μm resolution can be acquired with second-scale exposure times. Images can be acquired in real-time in the survey mode. The sample is mounted on a rotation stage to provide full 360 degree sample tilting, thus allowing 3D tomographic data acquisition. The process of tomographic imaging is illustrated in Fig. 4: a series of images are acquired as the sample is rotated to different tilt angles. These images are then assembled mathematically to produce a 3D image of the sample. With this method, the internal structure of the sample is obtained without physical modification [2].

In operation, it offers user-friendly graphical user interface with fully automated data acquisition to acquire the tomographic projections, perform the image processing procedures, reconstruct the 3D structure, and provides the user with a 3D view of the result. Operator attention is needed only for loading the sample and analyzing the data. One to a few hours is required for acquiring and reconstructing a 3D tomographic data set.

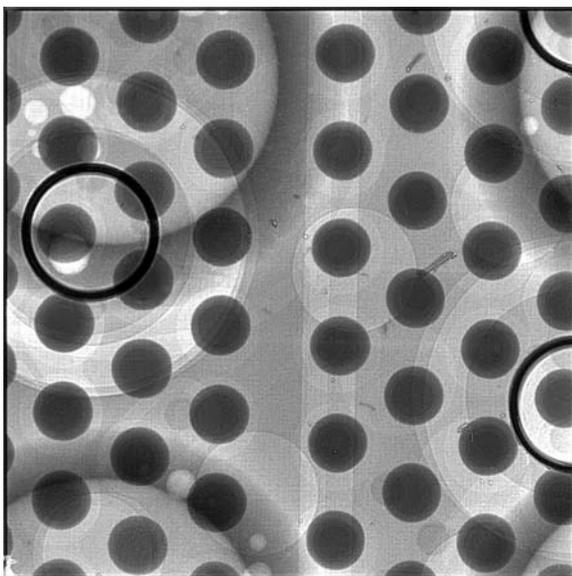


Figure 5. An AMD Athlon chip packaging imaged with the microXCT.

Because this system operates in the contact printing mode, it has a very small footprint of 2.5 ft x 4 ft. It has very modest power consumption and does not require any special facility preparations such as cooling water or special gas connections.

4 PRACTICAL APPLICATIONS

As a non-destructive micro-imaging instrument, the microXCT is a valuable tool in a wide range of scientific and industrial applications. Its strength is imaging the internal structures of samples of 1 mm to tens of mm in size at 1 μm to tens of μm resolution. Most samples can be mounted in the microscope for imaging without any preparations. We will list a couple of examples of failure analysis with integrated circuits packaging and inspection of MEM devices.

4.1 Semiconductor Packaging Failure Analysis

The feature size of IC packaging have decrease to μm -level in the past few years while the complexity have increased drastically. The traditional 2-D x-ray inspection are becoming increasingly inadequate for imaging them because the resolution of these system are typically tens of μm , and without quantitative 3D imaging capability, 2D images contain too many overlapping features for the operator to interpret, making fault identification very difficult.

The solution is a high-resolution 3D system with integrated 3D imaging capability that is automated well enough for an operator to use routinely. Fig. 4 shows the image of an AMD Athlon processor packaging taken at an angle normal to the chip surface with the microXCT system. It is clear

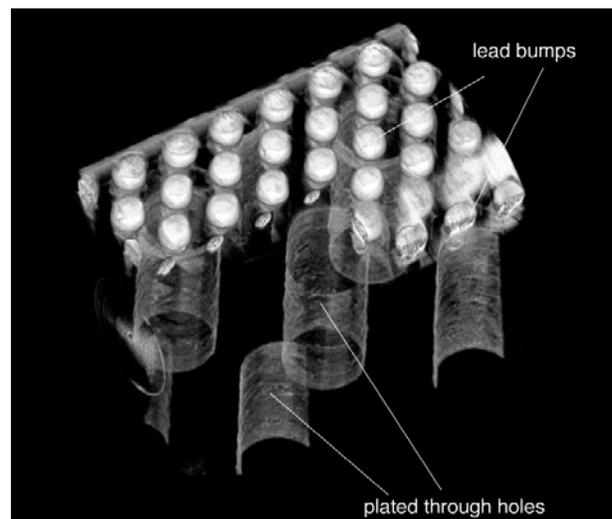


Figure 6. Volume rendering of the reconstructed 3D image of the AMD packaging .

the system has high enough resolution to resolve most features in the sample, but since many features are overlapping, its structure is very difficult to determine from this 2D image. A 3D tomographic reconstruction is able to resolve the features in depth. Figure 6 shows a rendering of the reconstructed 3D image. Features such as solder bumps, copper lines, plated through holes are clearly visible. Figure 7 shows one section of the reconstruction in the plane perpendicular to the chip surface which clearly reveals the depth structures of the device. This cross-sectional view is usually obtained by physically cutting the sample. Using the microXCT, however, internal defects of the packaging can be found without the destructive process.

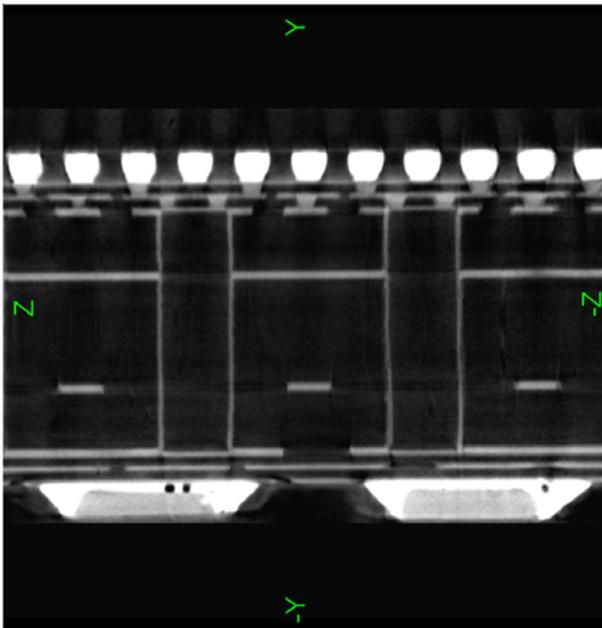


Figure 7. A slice from the reconstructed 3D image of the AMD Athlon package.

4.2 Embedded MEM Structures

Embedded MEM structures can be imaged in a similar way as integrated circuit chip packaging. Figure 8 shows an image of an accelerometer fabricated with MEM technology. Most of today's MEM devices contain embedded um-scale features. The microXCT is able to image these features non-destructively. In many cases, the motion and mechanical properties of a MEM device can be studied dynamically as it is in operation.

5 CONCLUSION

We have developed a projection type x-ray microscope based on a unique optical design. This system's capability of imaging at high-resolution with minimal compromise in the throughput makes it a powerful tool in non-destructive imaging applications in microtechnology and biotechnology, for example, integrated circuits packaging

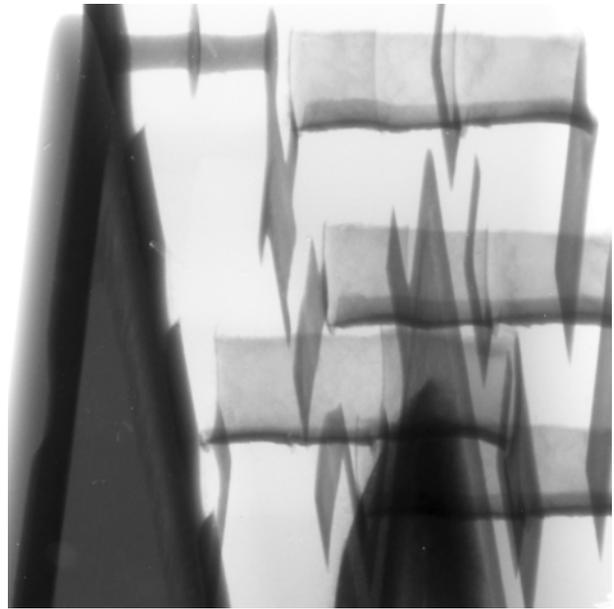


Figure 8. A 2D image of a MEM accelerometer imaged with the microXCT at 60 degree tilt angle..

failure analysis, imaging embedded MEMs structures, material stress failure mode analysis, bone implant interface, etc. Because of its high throughput, quasi-real-time 3D imaging can be performed to study dynamic processes such as formation and propagation of cracks in a bio-mechanical sample or delamination in a integrated circuit packaging.

REFERENCES

- [1] Wang, et. al., "A Transmission X-ray Microscope (TXM) for Non-destructive 3D Imaging of ICs at Sub-100 nm Resolution," *ISTFA Proceeding*, ASM International, 2002
- [2] Rosenfeld and Kak, *Digital Picture Processing*, Vol. 1, Academic Press Inc., 1982.