Non Destructive Failure Analysis Technique With a Laboratory Based 3D X-ray Nanotomography System

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ABSTRACT

X-ray computed tomography (CT) is a powerful nondestructive 3D imaging technique, which enables the visualization of the three dimensional internal structure of opaque materials such as semiconductor devices. Reports of high resolution CT research on life science, materials and semiconductor has mainly been confined to synchrotron radiation centers. This severely limits the availability and accessibility of x-ray microscopes and the wide proliferation of this methodology. We describe a sub-50nm resolution nanoCT system operating at 8 keV in Zernike phase contrast mode based on a commercially available laboratory x-ray source. The system utilizes high-efficiency Fresnel zone plates with an outermost zone width of 35nm resulting in spatial resolution better than 50 nm. The technical description of the system and failure analysis applications notably in visualizing voids, residues in metal interconnects, and competitive analysis in semiconductor devices will be discussed.

Keywords: x-ray microscopy, computed tomography, nanotomography, Fresnel zone plate, failure analysis, non-destructive inspection, competitive analysis.

1. BACKGROUND

Computer tomography (CT) has been used for several years in the medical community for non invasive x-ray imaging of the human anatomy. The same technique has been applied for non destructive inspections of parts and components where the object can be viewed in 3D using virtual slices (cross sections) of internal structures instead of destructive physical cross sectioning. While conventional microCTs are used for a number of bio-medical[1], material, industrial research[2] and microelectronic[3] pcb and package inspections, the reported spatial resolution typically ranges from a few microns to tens of microns, which is insufficient to observe die level defects in semiconductor devices.

High resolution x-ray microscopy or nanotomography (nanoCT) has increasingly been used in synchrotron radiation research to characterize biological, composites and nanomaterials [4-6]. Studies on the degradation mechanisms in semiconductor copper interconnect segments has also been reported. [7] While these studies had contributed tremendously to the understanding of fundamental science in several fields, the utilization of x-ray nanotomography by the research community at-large, is limited to the ability to book time on such beamlines, which typically range from a few days to no more than a few weeks in a year.

Large scale adoption of x-ray microscopy techniques in the integrated circuit (IC) failure analysis (FA) and R&D community necessitates the development of laboratory based instruments that provide easy access and reliable operation with performance comparable to synchrotron based instruments. For this purpose we developed a hard x-ray tomographic microscope. The first generation system was commercialized in 2003, using Cr-Kα emission line (5.4 keV) with spatial resolution of 60 nm[7]. This system enables 3D tomographic imaging of Cu interconnects through up to 30 μm thick IC silicon dies. While suitable preparation techniques for thinning the silicon substrate such as dimpling are well established and widely used, it is highly desirable to use a higher x-ray energy to simplify sample preparation and increase penetration for higher angle projections in computed tomography. In this paper, we are reporting our second generation system, nanoXCT, using a commercial x-ray generator with a copper target producing Cu-Kα x-rays with an x-ray energy of 8 keV. Since the absorption contrast diminishes rapidly with x-ray energy ($\sim 1/E^3$), we have equipped the nanoXCT system with Zernike phase contrast optics utilizing the slower drop-off (1/E) of phase shift with increasing x-ray energy.

2. STRUCTURAL IMAGING FOR INTEGRATED CIRCUIT FAILURE ANALYSIS

In IC failure analysis, structural imaging is normally carried out by visible and electron microscopy. Optical and confocal microscopy suffer from diffraction limits due to the wavelength of visible light. Spatial resolution is generally no better than 200 nm in the best case, with many common integrated circuit opaque materials. To obtain higher imaging resolution, scanning or transmission electron microscopy (SEM or TEM) is employed. Electron microscopy can achieve spatial resolution in the nm with lengthscale on the order of angstroms, however, sample preparation for these techniques can be very elaborate. Plan-view analysis using SEM requires complex and potentially disruptive chemical and mechanical removal of overlying films to expose areas or interest to the electron beam. Samples must be compatible with high vacuum and be electrically conductive to achieve the highest resolution. TEM places further restrictions on samples which must meet severe limitations on size and thickness necessitating exacting and tedious structural modification and preparation. Cross-sectional analysis requires additional complexity as enough material must be removed to allow adequate imaging of the region of interest while simultaneously keeping the same region free from damage. As IC defects continue to shrink, the material removal precision of these methods is not keeping pace, exacerbating the above problems significantly.

X-rays, having shorter electromagnetic wavelengths, extend the theoretical resolution limit for imaging from hundreds of nm for visible light to the sub-nm regime. In addition, multi-keV x-rays interact weakly with matter compared to electrons, which allows them to penetrate deep into samples to derive buried structural information intact and artifact-free, without invasive sample preparation. Furthermore, x-ray microscopy does not require extremely thin samples as is the case for transmission electron microscopy, and cross-sectional analysis is performed non-invasively and non-destructively, as will be later shown.

With sub-100 nm resolution capability, x-ray microscopy combined with tomographic methods, provides new perspectives for application to failure localization in micro- and nanoelectronic structures and products, notably in the visualization of voids and residuals in metal interconnects. One of the most powerful advantages against other currently used approaches is that failures or defects can be localized without deprocessing, i.e. without physical modification of the active area of the chip.

3. DESIGN AND PERFORMANCE OF FULL FIELD X-RAY MICROSCOPE

In the last two decades significant progress has been made in the field of x-ray microscopy utilizing Fresnel zone-plates as objective lenses, now achieving better than 15 nm resolution at synchrotron light sources[5]. Zone-plate x-ray microscopes both in scanning and full-field imaging geometry now exist at more than twenty international synchrotron facilities and new ones are being constructed or in the planning phase.

Unlike most of the x-ray microscopes installed at synchrotron facilities which use soft x-ray energies[4-7], the Xradia nanoXCT laboratory system uses hard x-ray energies from a laboratory source. Conventional laboratory x-ray tubes, with target materials such as Rh, Cr and Cu, generate photon energies at 2.7, 5.4 and 8.0 KeV respectively, have currently been used in this setup.

High resolution x-ray microscopy at multi-keV x-ray energies opens up new avenues to nondestructively explore the internal structure of optically opaque solids with submicron resolution previously inaccessible by other analytical techniques. Some of the advantages of using x-rays with higher energies are to provide greater penetrating power and depth of focus, making it possible to image thicker specimens which are advantageous for inorganic materials, such as semiconductor devices. For example, the sample thickness requirement for tomography using soft x-rays is typically 1 to 2 μm for most materials, but at the higher x-ray energy, say at 8 keV, the sample thickness requirement can be relaxed to 100 μm. The imaging optics of our x-ray microscope are Fresnel zone plates[9] (Figure 1) and x-ray optical components fabricated by Xradia.

Fresnel zone plates are diffractive optical elements which focus x-rays by means of diffraction. Spatial resolution, δ is determined by the width of the outermost zone width Δr_n, Resolution of the ZP is $\delta = 1.22\Delta r_n$ while the efficiency is a function of the zone plate thickness. Depth of field is a function of Δr_n and x-ray energy. Ultimately, the main challenge for hard x-ray microscope is to develop zone plates with highest possible aspect ratio between the thickness and the outermost zone width of the zone plate.

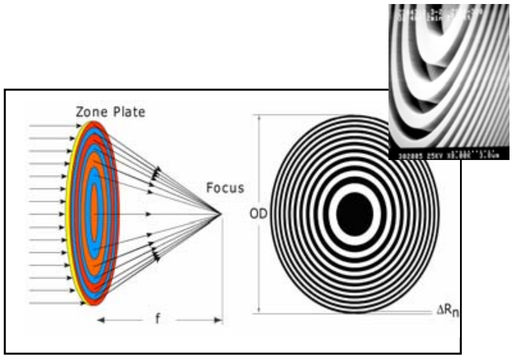

Figure 1: Fresnel Zone plates as focusing optics for x-rays. The Rayleigh resolution δ of a x-ray microscope is proportional to the outermost zone width Δr_n of the zone plate: $\delta = 1.22\Delta r_n$

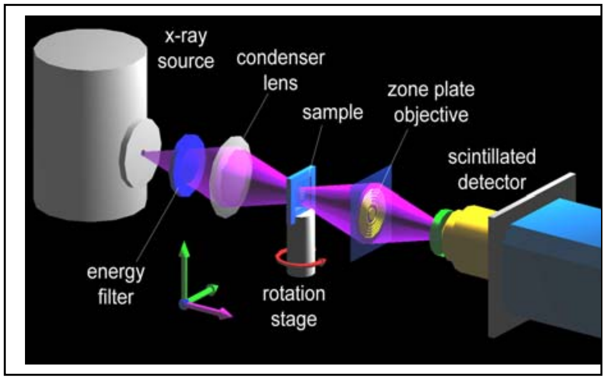

Figure 2: Schematic of nanoXCT 3D X-ray microscope with specialized Fresnel Zone plate optics, condensers for high resolution applications with a nano-precision sample stage.

The Xradia x-ray microscope is configured like a typical full field microscope incorporating a source, condenser and objective optics as shown in (Figure 2).

Contrast in transmission x-ray imaging is mainly based on attenuation length/absorption differences between different materials within the sample. For semiconductor materials, the lower Z materials such as Si and dielectrics, and the higher Z conducting materials such as Cu and Ta, provide a natural absorption contrast (Figure 3). This intrinsic property coupled with the fact that x-rays do not have charged particles that could radically alter the structural properties of ultra low k porous dielectric materials, makes x-ray nanotomography a good candidate for FA structural characterization of next generation interconnects.

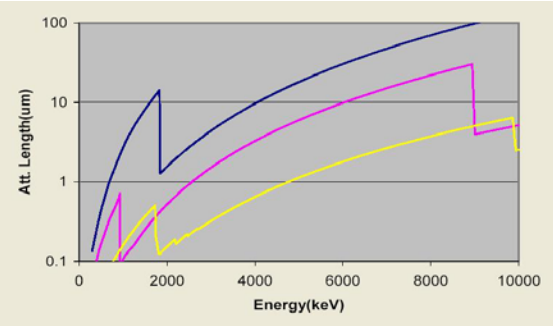

Figure 3: x-ray interaction lengths in Si, Cu and Ta (from top to bottom).Attenuation length refers to the thickness required to absorb 1/e or about 37 % of incident x-ray

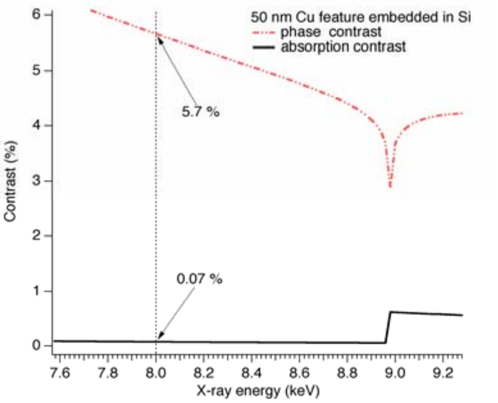

Figure 4: Calculated absorption and the contrast boost for a 50 nm thick Cu feature embedded in Si with phase contrast imaging mode

Further contrast boost can be realized for Cu interconnect material when the Xradia x-ray microscope operates in the Zernike phase contrast mode. This is done by incorporating a phase ring in the back focal plane of the zone plate[10-11]. The phase ring phase-shifts the rays of the undiffracted beam, while the phase of the rays diffracted by the sample remain unchanged. Zernike phase contrast imaging can significantly improve contrast for most materials. The absorption and phase contrast of 50 nm thick Cu features imbedded into Si was calculated and presented in Fig. 4. It can be seen that at 8 keV x-ray energy, the contrast is increased by a factor greater than 80 times. 1% contrast is typically sufficient for tomographic reconstruction algorithms to clearly resolve features.

4. FAILURE ANALYSIS APPLICATIONS

Failure localization applications in complex nano- and microelectronic structures and products make hard X-rays of great interest since multi-keV photons are able to penetrate the whole interconnect stacks on thinned Si substrates up to about 100 μm thick[7]. Consequently, nanotomography can be applied to image not only one segment of a metal interconnect test structure but the whole interconnect stack of memories or processors simultaneously. The technique is nondestructive, i.e. no destructive sample preparation like layer deprocessing or cross-sectioning with FIB is needed. However, the Si substrates usually have to be thinned down to 100 μm and less. If the region of interest that should be imaged is known, the substrate can be thinned locally utilizing simple sample preparation techniques like dimpling.

We describe examples where the nanoXCT system is used in physical failure analysis and localization.

The first example involves imaging a Pentium 4 Chip. Figure 5 shows a 2D full field transmission image through the IC chip with nine Cu metallization layers embedded into the Si die. The image was taken with a Cu laboratory source (8 keV x-ray energy) in Zernike phase contrast mode. The size of the smallest Copper feature in the image is 90 nm and the Si die was backside thinned down to ~70 um thickness to increase the x-ray transmission. In 2D mode, the collapse of all metal layers into a single projection image makes it very difficult to discern the geometrical structure of the Cu lines and vias connecting the individual layers from a single image. However, with tomography technique, the 3D volume reconstruction and the whole interconnect 9 metal layer stack can be virtually sliced/delayed for individual layer inspection. A series of such projections was taken with a rotation range of +/-70 degrees (limited by sample holder shadowing). Figure 6 shows a volume rendering of the computer-reconstructed data from 140 projection images.

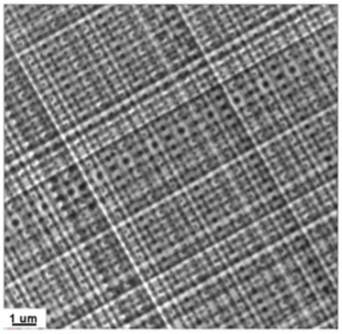

Figure 5: 2D projection image of a 70 um thick Si integrated circuit (IC) with 9 Cu metallization layers at normal incidence (0 degree).
(Sample courtesy: I. Kato, Noah Corporation)

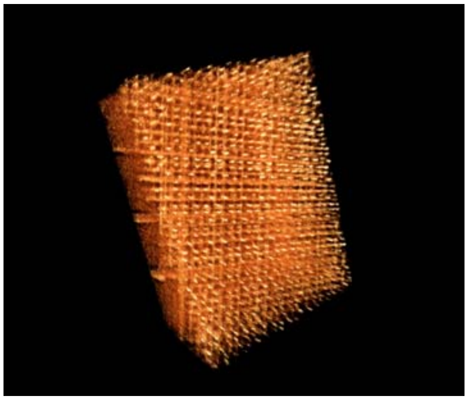

Figure 6: 3D Volume rendering of an IC chip with 9 Cu layers from 140 2D projections.

The reconstructed 3D dataset of the Copper interconnect stack of the IC subsequently can be “virtually delayered” and individual layers were extracted as shown in Figure 7.

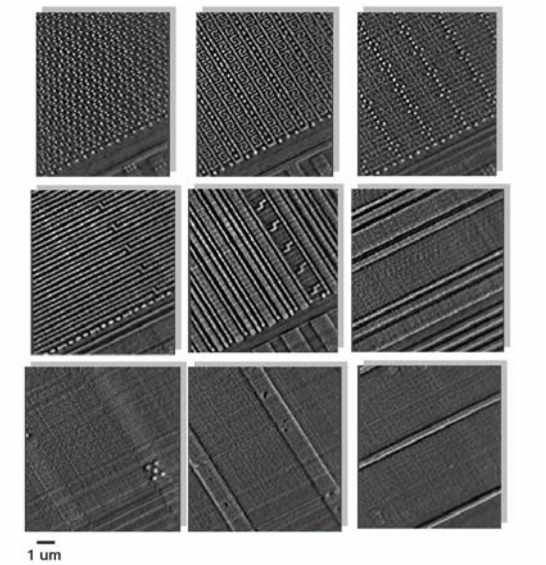

Figure 7: Virtual delayering of nine Cu metallization layers from M1 (top row left image) to M9 (bottom row right image). Sub-100 nm voids in broad Cu lines (bottom row center image) are clearly observed.

Cu lines are shown with bright contrast while Si and voids appear dark in the images. The results shown in Fig. 7 clearly demonstrate the power of the tomographic imaging of Cu interconnects with 50 nm resolution using hard x-rays for direct visualization of defects in the Copper interconnect stack. As the entire metal layer stack is imaged without physical sample preparation, applications for competitive analysis and patent verification are also possible.

In a typical FA process flow, fault isolation is carried out by a variety of techniques starting from electrical probers, automated testers, and curve tracers to dedicated electrical fault localization FA techniques such as liquid crystal, photon emission and thermal imaging microscopy, magnetic current mapping, laser scanning stimulation (OBIRCH, TIVA, SDL, LIVA) and e-beam testers. Upon localization of the electrical fault to a region of interest, invariably, the next step requires physical destruction of the sample, either through cross section-polishing or a focused ion beam (FIB) cut, followed by SEM or TEM imaging. This process can be time consuming with the distinct possibility that the physical fault may be missed or artifacts created.

Non destructive physical fault localization with this new nanotomography technique offers a new paradigm in failure analysis, with the advantage that the FA file may be closed without a further need for deprocessing. The following is an example of fault isolation of a via contact open and missing after an electromigration test (Figure 8, 9).

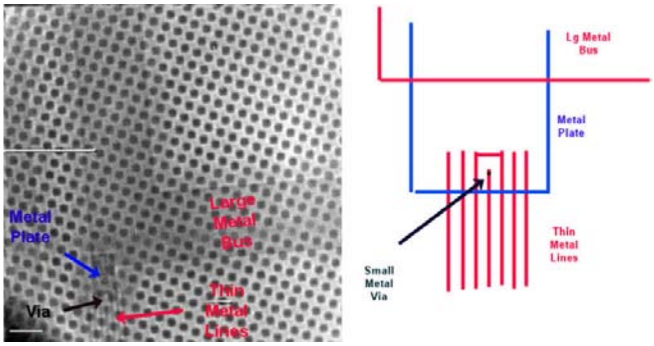

Figure 8: 2D X-ray imaging, of possible region of interest to locate missing via or other defects

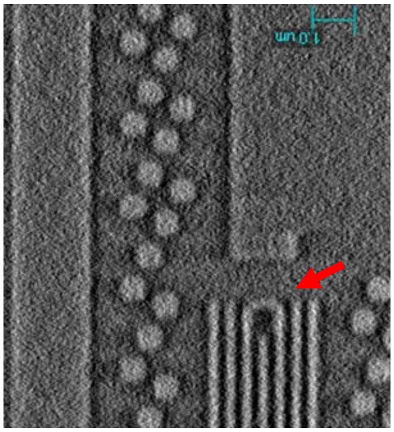

Figure 9: CT slice through the chip localizing the missing via to the correct metal layer

5. CONCLUSIONS AND OUTLOOK

X-ray nanotomography offers a new approach in non destructive characterization of defects in failure analysis, R&D, competitive analysis and patent enforcement. We have demonstrated sub-50nm resolution tomographic 3D imaging for fault localization in multi-level Cu interconnect structures with a hard x-ray nanotomography system based on a laboratory x-ray source, operating at 8 keV x-ray energy in Zernike phase contrast mode. The feasibility of such a laboratory system is based on our development of high performance, high efficiency x-ray optical components, namely the x-ray condenser lens, the x-ray objective zone plate, and the x-ray detector. Virtual delayering of reconstructed data offers a novel approach towards localization of failures in IC without physical deprocessing. In the near future, the continued advancement in zone plate resolution and efficiency in the hard x-ray energy range promises even higher throughput and spatial resolution. It is expected that hard x-ray nanotomography system will proliferate into many areas of R&D and FA applications as a standard nondestructive microscopy technique that bridges the gap between visible light and electron microscopy.

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