Quantitative coherent diffractive imaging of an integrated circuit at a spatial resolution of 20 nm

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The complex transmission function of an integrated circuit is reconstructed at 20 nm spatial resolution using coherent diffractive imaging. A quantitative map is made of the exit surface wave emerging from void defects within the circuit interconnect. Assuming a known index of refraction for the substrate allows the volume of these voids to be estimated from the phase retardation in this region. Sample scanning and tomography of extended objects using coherent diffractive imaging is demonstrated. © 2008 American Institute of Physics. [DOI: 10.1063/1.3025819]

Coherent diffractive imaging (CDI) is a technique whereby a nonperiodic object is iteratively reconstructed from its Nyquist-sampled far-field diffraction pattern.1,2 Reconstructions obtained using CDI have very high spatial resolution and, in contrast to traditional x-ray microscopy images, contain information about the complex exit surface wave (ESW). Sampling requirements preclude plane-wave CDI on extended objects. However, two methods have recently been reported that permit the reconstruction of arbitrary sized samples from their measured diffraction.3,4 Here, we use Fresnel CDI (FCDI) to image and characterize an IBM integrated circuit at very high spatial resolution. We demonstrate that this method allows the sample to be “scanned,” with each beam position giving a high-resolution independently reconstructed field of view. We reconstruct and separately analyze several projections of a part of the sample, showing that the three-dimensional (3D) tomographic reconstruction of an extended object is possible. Finally, using low-resolution elemental data from scanning transmission x-ray microscopy (STXM) and fluorescence measurements, we quantitate voids and defects within the circuit. Hence, our data show that CDI can be applied as a quantitative high-resolution technique, with flexibility comparable to that of conventional optical or electron microscopy.

Figure 1(a) shows a schematic of the FCDI arrangement, allowing rotation and translation in the plane perpendicular to the beam direction. The x-ray measurements were made at beamline 2-ID-B of the Advanced Photon Source. Data were collected at two energies 1.8 keV (Fig. 1) and 2.15 keV (Figs. 2 and 3). A Fresnel zone plate (FZP) with a nominal outer zone width of 50 nm and a focal length of 12 mm at 1.8 keV was used to generate the incident illumination. A 28 μm central stop upstream of the FZP and a 20 μm order sorting aperture remove the direct beam and higher-order contributions from the FZP. The 160 μm FZP was almost fully coherently illuminated in both directions. The detector was a direct-read charge coupled device with 2048 × 2048 pixels, each 13.5 μm square, placed 0.55 m from the focal plane. Further details of the experimental setup may be found in Refs. 4, 6, and 8.

We treat the sample as an object of thickness t(\vec{r}) with a spatially dependent complex index of refraction n(\vec{r})=1−\delta(\vec{r})−i\beta(\vec{r}). For a given wavenumber k, and provided \delta(\vec{r})k\delta r and −\beta(\vec{r})k\delta r are small, the transmission function is

\[ T(\vec{r}) = \exp[-\beta(\vec{r})k\delta r] \exp[i\delta(\vec{r})k\delta r] \].

(1)

The sample thickness can be directly related to the arguments of the exponentials in Eq. (1), whereby the amplitude is reduced by the first exponential and the phase advance through the object is \delta(\vec{r})k\delta r. Figure 1(b) shows the amplitude of the reconstructed sample transmission function obtained using CDI. The reconstruction contains both a thinned area and an untreated part of the sample (the boundary is indicated by the arrow). Of particular interest is the region containing the W fuses and integrated circuit interconnects, which were Ta lined and contained both Cu and W components. On the top right-hand side of the circuit, most of the interconnect, fuse, and surrounding area is missing, leaving only part of the Ta liner and a partially evaporated Cu wire between the missing fuse and the remaining fuse.

A description of the image reconstruction process may be found in Refs. 4, 6, and 9–11. For the method applied in this letter the illumination itself is used to define the reconstructed field of view. The progress and consistency between the reconstructed ESW and measured diffraction were characterized by the error metric defined as

\[ \chi^2 = \sum_{n=0}^{N-1} \left[ |F(n)|^2 - |\mathcal{J} \rho(n)|^2 \right]^2 / \sum_{n=0}^{N-1} |F(n)|^2 \],

(2)

where \( F(n) \) is the measured intensity in the nth pixel and \( \mathcal{J} \) is defined as the propagation operator. Convergence of the algorithm from a random start is usually achieved within a few hundred iterations, although the reconstruction is frequently allowed to progress for several thousand iterations to check that the solution is not underconstrained. Typical values of the error metric for the final reconstructed ESW presented in this paper are \( \sim 10^{-4} \).
Modern microelectronic chips can have up to ten different metal layers, making the interpretation of a single plan-view image difficult. In order to resolve these layers, data were collected at several sample orientations. Taking the position when the sample was nominally perpendicular to the beam to be at $0^\circ$, diffraction patterns were recorded at sample rotations of $\pm 19^\circ$. Figures 2(a) and 2(b) show the phase and amplitude reconstructions from each of the three projections, from Eq. (3) $\Gamma=20$, 25, and 22 nm for $\theta=0^\circ$, $19^\circ$, and $-19^\circ$, respectively. Comparison with earlier data
collected from the same region shows that we reconstruct all of the features present in the electron microscopy and STXM images. The Cu wire provides a reasonably sharp feature against which to test the spatial resolution. Measurements of the change in transmission for \( \theta = 0^\circ \) at the edge of the wire, made at 50 different positions on the CDI reconstruction, yielded experimental values for the edge sharpness that ranged from 19 to 53 nm. This ensemble possesses an average sharpness of 41 nm [see Figs. 2(c) and 2(d)]. A single lineout across one edge of the wire is shown in Fig. 2(d); curve-fitting of this profile demonstrates an experimental resolution of at least 22 nm, consistent with the theoretical value of 20 nm.

One of the most likely locations for failure within the modern integrated circuit is the interconnection between the different metallization layers. These connections are generally made by a small hole, known as a via, through the interlevel dielectric and filled with metal. There are multiple failure modes associated with vias, including voiding, incomplete etching, metal underfilling, and size variation. Most of these modes are driven by process problems and some by failure during operation or stress. The aspect ratio, volume, and composition of these vias are invaluable information, supplementing the electrical data, and useful for assessing the health of the interconnect. Within our sample, the two voids in the Ta liner on either side of the W wire are analogous to heavily depleted vias and can be regarded as a model defect. Unfortunately, in the reconstructed amplitude of the ESW as well as in individual scanning transmission electron microscopy and STXM images, the exact location and size of these voids are not readily apparent; however, the voids can be characterized directly from the reconstructed phase of the ESW where retardation (blue/pink patches) compared to the surrounding Ta liner is apparent. Figure 3 contains an enlargement of this area.

A 3D rendering of the voids in the missing interconnect for the three different projections is also shown in Fig. 3, where the void depth was estimated from the phase shift of the x rays leaving this region. Based on the results from STXM measurements, the analysis assumed that the missing interconnect region was covered by a uniform layer of Ta and that the voids were entirely due to differences in the thickness of silica. Integrating over the area of the two voids yields a total volume of \( 1.56 \times 10^{-2} \) \( \mu m^3 \) (0.93 \( \times 10^{-2} \)) and 0.63 \( \times 10^{-2} \) \( \mu m^2 \) for the left and right void, respectively, for the projection at \( 0^\circ \) tilt.

In this letter we have used CDI to image a semiconductor integrated circuit in a manner that displays a flexibility comparable to conventional optical or electron microscopy. Unlike most other x-ray techniques, the method routinely has a spatial resolution better than that of the imaging optic. We have shown that analysis of the reconstructed complex wave transmitted through the sample allows high-resolution quantitative x-ray microscopy and is amenable to tomographic imaging of extended objects, facilitating the reconstruction of a 3D sample transmission function. This knowledge could provide invaluable information when imaging biological, layered, or buried structures.

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13. See EPAPS Document No. E-APPLAB-93-001847 for additional material supporting the calculated resolution and reproducibility of the final image. For more information on EPAPS, see http://www.aip.org/pubservs/epaps/html.