3-D Tour of Integrated Circuits at the Nanometer Scale

High-resolution non-destructive three-dimensional imaging of integrated circuits

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Non-destructive imaging at the one to a few nanometer length scale has broad implications for science and technology. In a short note, D. Sayre [1] presaged the development of coherent diffraction imaging postulating that by ‘oversampling’ one can retrieve the phase from a diffraction measurement that at the outset yields only the amplitudes of the complex structure factors needed to determine the electron density by Fourier methods. This idea was fleshed out by Fienup [2]. The concept is based on an iteration using the starting amplitudes from the measured diffraction pattern and a random set of phases. To begin, Fourier transform a guess of the object. Replace the amplitudes by the measured amplitudes to form an estimate of the Fourier transform of the object; inverse Fourier transform the estimate and apply the constraints; Fourier transform the constrained image of the object and continue around the loop until the algorithm converges.

This is a very attractive concept that can yield nanometer resolution electron densities using x-rays. X-rays have the penetrating power to study thick samples but lack the optics for direct imaging. This approach, inversion of the scattering pattern and a phase retrieval algorithm has been at the forefront of developments using accelerator based x-ray sources. The first realization waited almost 50 years. Sayre [3] and collaborators successfully inverted a measured diffraction pattern in 1999 and the field exploded. One of the challenges is the inversion and the possibility of the phase retrieval not converging. This issue has been addressed by the development of ptychography where the object is translated a fraction of the size of the illumination and multiple diffraction patterns collected (see J.M. Rodenburg [4]).

These approaches require coherent illumination and thus the source requirements are quite demanding. Fortunately, in parallel with the development of algorithms there has been a parallel development of x-ray sources. The source brightness determines the coherent flux. Until the completion and commissioning of the MAX IV storage ring [5] storage ring sources often had near diffraction limited beams in the vertical direction at x-ray wavelengths, but orders of magnitude away in the horizontal plane. Eriksson and his team began to address this issue and there has been a rush to implement these concepts as retrofits to existing machines, in particular the ESRF in Grenoble, France, the Advanced Photon source in Argonne, USA and the SPRing-8 facility in Harima, Japan and most recently the Advanced Light Source in Berkeley, USA and the Swiss Light source in Villigen, Switzerland. These upgrades will approach the diffraction limit in both planes at wavelengths approaching 1 nanometer thus increasing the coherent flux by several orders of magnitude. This will not suffice if one wants to collect sufficient data to use ptychogaphic tomography to image a full integrated circuit at 10 nanometer length scale. One will also need improvements in optics. There are a variety of nanofocusing optics for hard x-rays ranging from mirrors that have achieved 25 nm foci [6], Fresnel zone plates with foci below 10 nm [7], multilayer Laue lens achieving 8 nm [8] and refractive lens with 43 x 18 nm^2 by Schroer and collaborators [9]. These developments when combined with the source developments will make the concept described by Holler at al. a reality.

But wait, the paper describes cutting out a 10 micronpillar from both a known and an unknown integrated circuit. This isn't non-destructive. It leaves open the question of how does one image an intact integrated circuit. Helfen et al.[10] discuss an approach for 3-dimensional imaging of flat devices. In the 'conventional' tomographic approach one would ideally want a cylindrical specimen as was the case for the ptychographic study of Holler et al. where a 10 micron pillar was used and for the tomographic study the sample was rotated about the cylinder axis. If one did a similar thing with an integrated circuit, rotating either about the long or short dimension the absorption would change dramatically rendering high resolution impossible. In the paper by Helfen and collaborators they 'eliminate' the absorption variation by rotating the 'flat sample' about the normal the flat specimen in a way which removes the constraint of a cylindrical specimen.

We're there: the ptychographic approach address the issues of convergence of the phase retrieval algorithm and most importantly a sample that has an extent far exceeding the illumination area of the coherent beam, the laminography approach to tomographic studies permits reconstruction of flat specimens without resolution degradation and lastly the advances in sources, optics and detectors make the possibility of non-destructive imaging of complete integrated circuits with resolution of order 10 nm a reality in just a few short years. Not only will this open up possibilities for materials problems but also extensions of imaging in their infancy in catalysis and biology are waiting for the combination of sources, optics and detectors that are almost upon us.

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