Coherent Diffractive Imaging for Extended Samples with a Pre-defined Illumination Pattern

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This project is to detect buried deviant structures in state-of-the-art integrated circuits (IC's) with sub-50nm resolution. X-ray diffraction imaging is one of the most promising candidates, offering good penetration and high resolution for non-periodic structures[1]. Imaging extended samples such as an IC however is more challenging, because conventional phase retrieval methods are limited to small, isolated samples. To reconstruct extended objects, keyhole diffractive imaging[2] and ptychography[3] have been developed. Those two methods, however, still rely on focusing optics to concentrate the illumination. In this paper, we demonstrate another approach that can image extended objects without using focusing optics.

Based on Fienup's work[4], if we illuminate a large object with a coherent beam that has a predefined shape, we can use the illumination shape itself as a support constraint for a phase retrieval algorithm to reconstruct the sample image. As illustrated in the computer simulation (Fig. 1), the sample, which comprises copper wires *50* nm wide and *100* nm high buried beneath *1* um silicon dioxide, is illuminated with unfocused *7* KeV coherent x-rays of triangle shape (Fig. 1(a)). The illuminated area is shown in Fig. 1(b). We choose the triangular shape because its asymmetry is very favorable to phase retrieval[4]. Using the hybrid-input-output (HIO) algorithm[5] with the triangle as the support, we can reconstruct the exit surface wave of the sample. Fig. 1(c) shows the reconstructed image, including the effect of shot noise, for an average intensity of *10,000* photons per pixel at the diffraction image.

We further demonstrate this technique using a scaled-up optical experiment (Fig. 2). The wavelength ratio is *632*nm/*0.18*nm (using *7* KeV x-rays), i.e., a scaling factor of *~3500*. The triangle-shaped illumination is defined by placing a binary mask on the sample. The illuminated area is shown in Fig. 3(b). The side of the triangle is *2* mm while the field of view[6] is 9.1 x 8.8 mm^2, so the oversampling requirement is satisfied. Multiple exposures are recorded by the CCD and are combined to obtain a diffraction pattern of higher dynamic range (Fig. 3(c)). The HIO algorithm is then used to reconstruct the image, as shown in Fig. 3(d). The minimum feature size in the illuminated region is *100* um, corresponding to *~30* nm resolution for the x-ray experiment.

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[4] J. Fienup, Lensless coherent imaging by phase retrieval with an illumination pattern constraint, *Opt. Expr.,* **14**, 498-508 (2006)

[5] J. Fienup, Phase retrieval algorithms: a comparison, *Appl. Opt.*, **21** (15), 2758-2769 (1982)

[6] The field of view (FOV) is defined by: resolution times the number of CCD pixels in each direction. The resolution is set by the maximum diffraction angle the CCD can record, and it is 11.7/15.8 um in x-/y- direction in this setup.

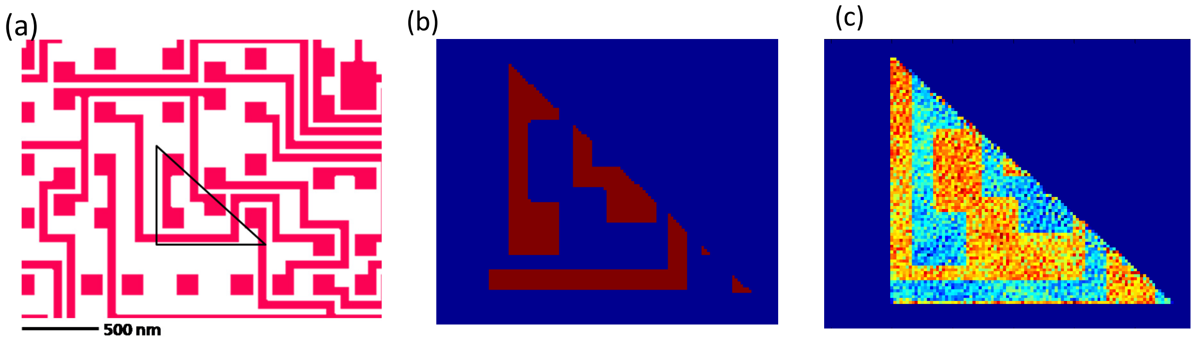

Fig. 1: (a) Top view of the sample used in computer simulation; (b) illuminated area; (c) reconstructed image with 10,000 photons/pixel (10^{10} photons total)

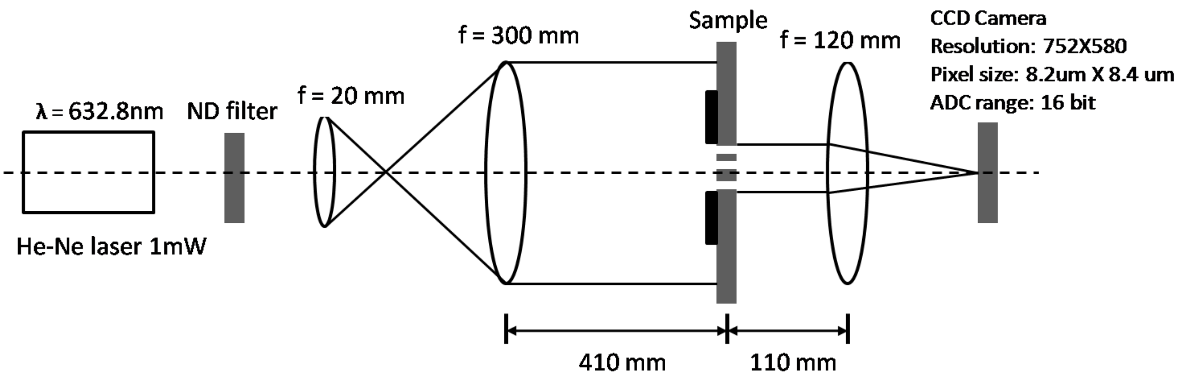

Fig. 2: Scaled optical experiment setup. He-Ne laser with 632nm wavelength passes through a neutral density filter to attenuate the light as needed. The beam is expanded to 9mm diameter by two lenses. A triangular aperture is placed in front of the sample thus gives a pre-defined illumination area on the sample. The far-field diffraction pattern is imaged by the objective lens onto the CCD.

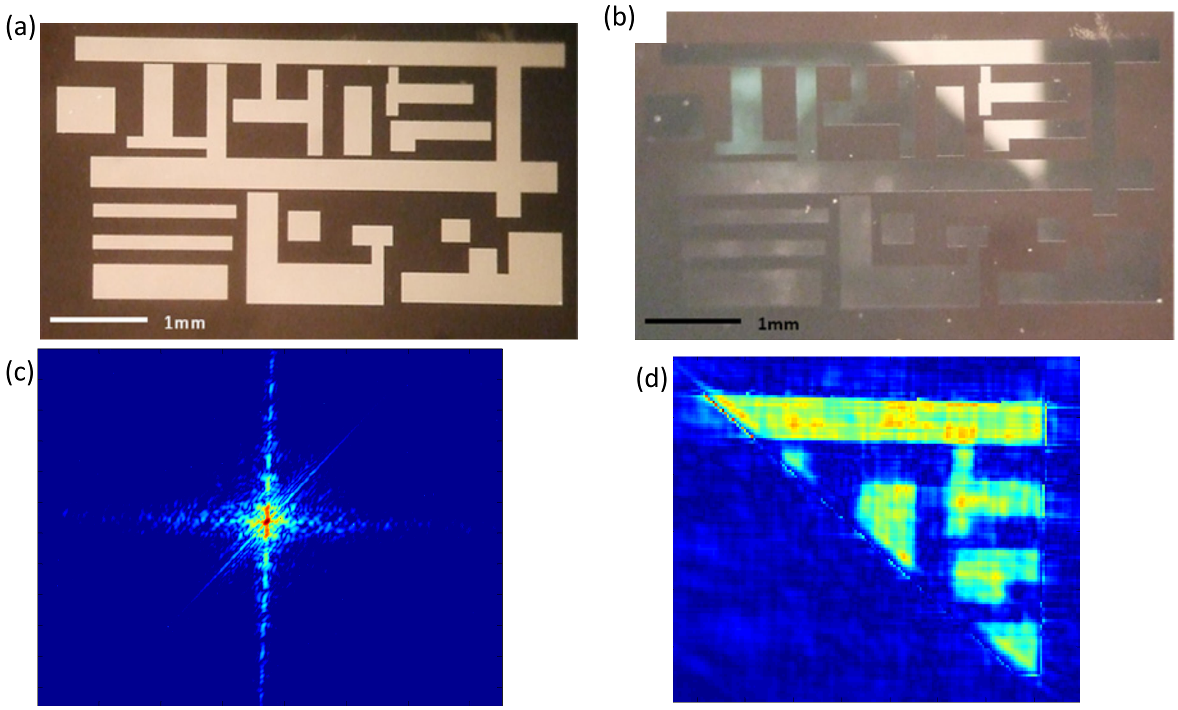

Fig. 3: (a) The objects are patterns etched in 200nm thick chromium on a quartz substrate; (b) illuminated region; (c) diffraction pattern of the illuminated area; (d) the reconstructed image.