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X-ray microscopy in Zernike phase contrast mode at 4 keV photon energy with 60 nm resolution

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Abstract
We report on x-ray microscopy of advanced microelectronic devices imaged in Zernike-type phase contrast mode at 4 keV photon energy. Fresnel zone plates were used as high resolution x-ray objectives providing 60 nm spatial resolution. Integrated circuit copper interconnect structures were imaged in positive as well as negative phase contrast. In both cases the phase contrast in the x-ray images is about five times higher than the pure absorption contrast.

1. Introduction

X-ray imaging in the multi-keV photon energy range permits to penetrate thicker samples which are not accessible by soft x-ray microscopy. However, the absorption contrast decreases with increasing photon energy. To overcome this limitation, phase contrast imaging can be employed. Pioneered in the soft x-ray range at 0.52 keV photon energy [1], Zernike-type phase contrast becomes even more important in the multi-keV regime, where phase shift is dominating over absorption [2, 3]. In this paper, we describe the development of a Zernike phase contrast technique which is used to study defects in buried copper interconnects of advanced microprocessors. Absorption contrast x-ray microscopy on advanced microelectronic structures has been performed recently at 1.8 keV photon energy using 2 μm thick samples [4]. However, high performance integrated circuits consist of an interconnect stack with up to 10 copper layers which require higher photon energies to be penetrated by x-rays [5]. We demonstrate that Zernike phase contrast microscopy at 4 keV photon energy permits to visualize copper interconnect structures buried in dielectrics with high spatial resolution and image contrast.

2. Full-field x-ray microscopy at the ID21 beamline of the ESRF

2.1. Experimental set-up

For full-field x-ray microscopy at the ID21 beamline [6], Fresnel zone plates are employed as high resolution x-ray optics. These are circular diffraction gratings with radially decreasing line spacing. For the first diffraction order, the resolution achievable with such a zone plate is 1.22 × outermost zone width.

The x-ray beam generated by an undulator is monochromatized by a channelcut silicon $\langle 111 \rangle$ monochromator [7] and focused by a 1.4 mm diameter condenser zone plate (CZP) onto the object (figure 1). The CZP increases the photon density on the sample by many orders of magnitude. Furthermore, due to the geometry of the set-up, the coherence of the third generation synchrotron source is significantly decreased and a nearly incoherent illumination of the sample is provided. The CZP is made of gold structures extending 400 nm in height along the

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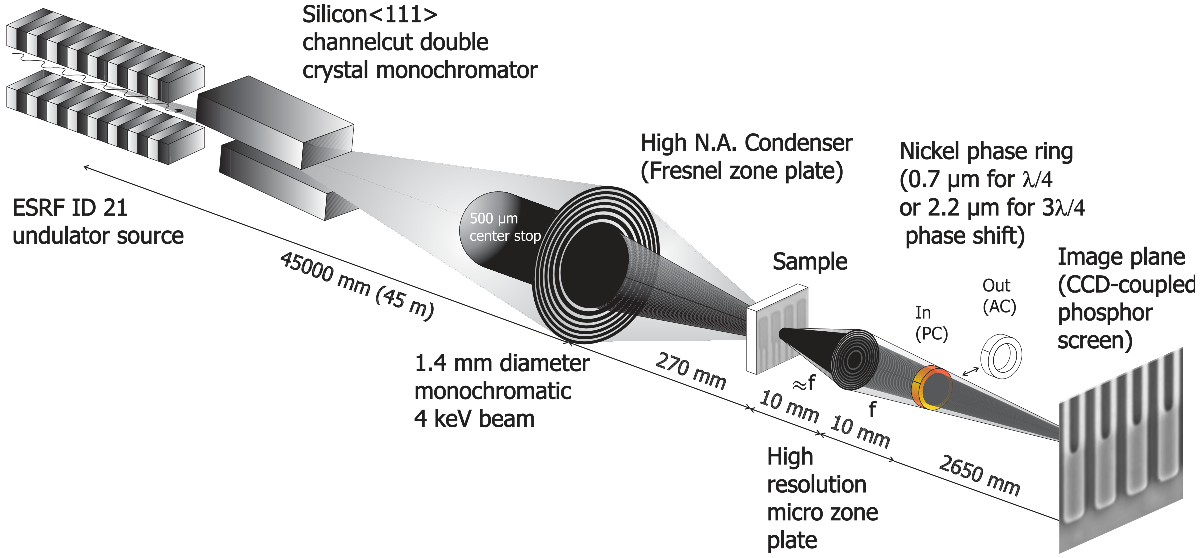

Figure 1. Schematic of the x-ray microscope (TXM) in Zernike phase contrast mode installed at ID21 at the European synchrotron radiation facility (ESRF). In the ray diagram, only the radiation passing directly through the sample is shown, diffracted light is omitted for simplicity.

beam direction with an outermost zone width of 60 nm, providing a numerical aperture of the sample illumination that is well matched to the aperture of the objective lens (micro-zone plate, MZP) with an outermost zone width of 50 nm [2]. Therefore, the full resolution provided by the MZP is achieved, which would be not the case if the sample was illuminated with parallel light. Since the CZP demagnifies the x-ray source only to a few microns vertically, it is scanned perpendicular to the beam axis so as to increase the illuminated field to $20 \times 20\ \mu\mathrm{m}^2$. The MZP forms a 265× magnified image of the sample onto a phosphor screen, where the x-rays are converted to visible light and magnified by an objective onto a CCD camera. This optical set-up can be used in phase contrast mode with the phase ring in the Fourier plane of the MZP as well as in amplitude contrast without the phase ring.

2.2. *Principle of Zernike-type phase contrast microscopy*

The interaction of x-rays with structures in a sample leads to the generation of diffracted light besides the direct (undiffracted) radiation passing through the sample. According to Abbe theory, diffracted light from an object is required for image formation in a microscope. For an absorption sample, the phase shift between undiffracted (U) and diffracted (D) light is 180°, resulting in a high absorption contrast when superimposing the wave vectors of U and D (figure 2(*a*)). However, the condition is different for a phase sample where the phase relation between direct and diffracted light is in good approximation 90° (assuming a phase shift δ much smaller than the wavelength, which is met for kiloelectronvolt radiation and sample thickness of the sample under study) resulting in a sum wave vector (S) in the image plane having almost the same amount as the direct light vector thus showing very weak contrast for the sample structure (figure 2(*b*)). To use the phase information to generate a visible intensity modulation (i.e. contrast) in the image plane, it is required according to Zernike to phase shift the undiffracted light [8]. This can be accomplished with a phase shifting optical element in the back focal plane of the objective that is matched in its geometry to the distribution of the undiffracted light (here phase ring geometry corresponding to the ring shaped hollow cone illumination, see figure 1). By these means, the undiffracted light (U) can be phase shifted either by 90° (figure 2(*c*)) or 270° (figure 2(*d*)) in respect to the diffracted light (D) and U is in addition reduced in its amplitude by absorption in the phase ring material, thus better matching the intensity level of D. Consequently, U and D can be superimposed in the image plane as parallel or antiparallel vectors, giving high contrast [9].

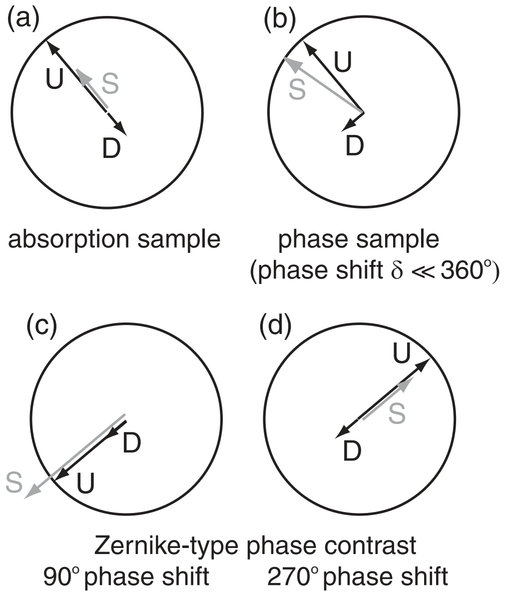

Figure 2. Vector diagrams (the full circle of 360° corresponds to the wavelength λ) describing the amplitude and phase relations between undiffracted (U), diffracted light (D) and their superimposition (S) as measured in the image plane. (*a*) and (*b*) Show the situation for an absorption and a phase sample. (*c*) and (*d*) Illustration of phase shifting the wave vector of the undiffracted light (U), shown in (*b*), by 90° (*c*) or 270° (*d*). The attenuation of the undiffracted light by absorption in the phase ring material is neglected in this consideration.

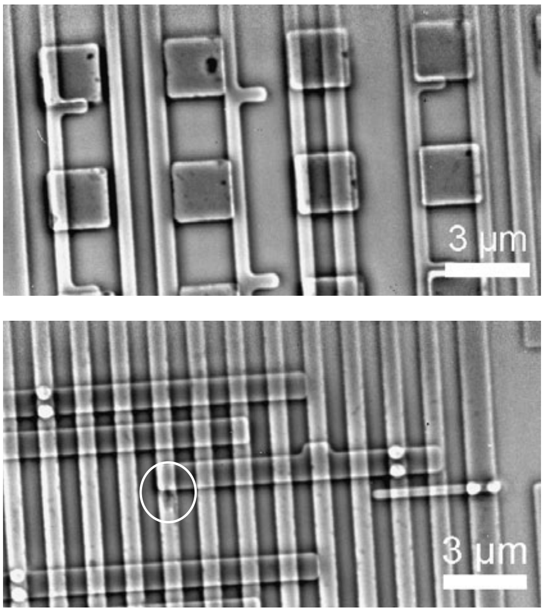

Figure 3. Copper interconnect structures, imaged with the ID21 transmission x-ray microscope in positive phase contrast, i.e. the direct, undiffracted light passing through the sample was phase shifted by 90° using a 0.7 μm thick nickel phase ring. In the left image, irregularities in the square structures can be seen. Furthermore, an irregularity within a conducting copper line that could be a nucleation site for electromigration processes is indicated by the white circle in the right image.

3. High resolution phase contrast imaging of copper interconnects

State of the art microprocessors which operate at frequencies in the gigahertz range require the integration of more than 100 million transistors which have to be connected by metal interconnects with line widths down to 200 nm and below. As the number of devices increase and the feature sizes become smaller, the speed of microprocessors is increasingly determined by interconnect design, technology and materials. In addition, as the dimensions of the interconnects continue to shrink, the formation of voids in interconnects induced by high current densities (electromigration) during integrated circuit operation can cause an open circuit or an increase in resistance, resulting in malfunction or speed degradation. To dectect defects and voids in copper interconnects, phase contrast x-ray microscopy was performed using test structures manufactured by AMD Saxony LLC & Co. KG, Dresden, Germany. Figures 3 and 4 show positive as well as negative phase contrast x-ray micrographs of these samples. No other imaging technique than x-ray microscopy with kiloelectronvolt radiation can provide non-destructively insight on copper lines and vias between layers within the silicon dioxide dielectric of the microprocessor. The spatial resolution of about 60 nm is well adapted to interconnect feature sizes in advanced integrated circuits currently under development in microelectronics industry. In addition, due to the high image contrast, phase contrast x-ray microscopy is a unique tool for the detection of small voids in copper interconnects.

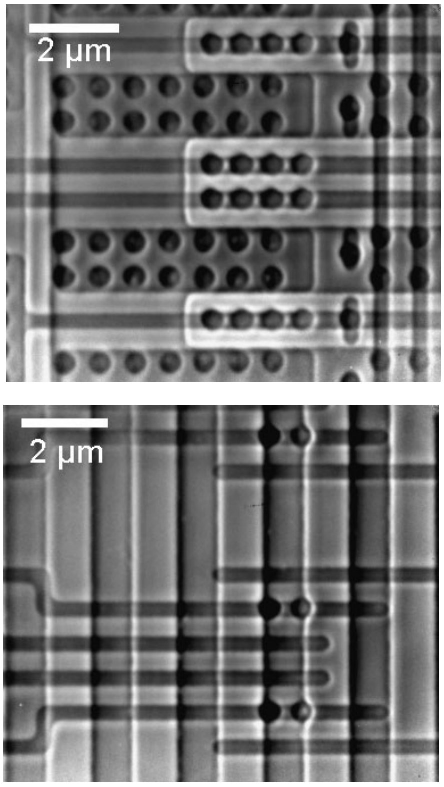

Figure 4. Copper interconnect structures, imaged with the ID21 transmission x-ray microscope in negative phase contrast, i.e. the direct, undiffracted light passing through the sample was phase shifted by 270° using a 2.2 μm thick nickel phase ring.

4. Conclusions and outlook

Phase contrast x-ray microscopy in Zernike mode was successfully demonstrated in the multi-keV regime. The resolution limit of 60 nm provided by the current x-ray optics was reached. Furthermore, the image contrast is in good agreement with theoretical predictions. By choosing optimized phase rings [2], this technique will be applied to other scientific application fields (biology, medicine, materials and environmental science). In addition, due to the large depth of field of x-ray objectives operating in the kiloelectronvolt photon energy range, high resolution tomography based on x-ray microscope images is possible. Recently, at higher photon energies up to 13 keV, Fresnel zone plates [10] used as x-ray objectives have delivered images with about 85 nm resolution [11]. Developing new phase contrast microscopes operating at higher energies is driven by the possibility to study weakly absorbing structures in thick samples with high spatial resolution.

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