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Holographic Setup for 2D-Dopant Profiling using the Lorentz-Lens

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In semiconductor devices like MOSFETs produced with present technology, the gate length is on the scale of about 100 nm. Small deviations from the designed structure of the electric potential distributions resulting from dopant implantation may significantly change the electric properties of the device. Off-axis electron holography at medium resolution is currently the only microscopic technique for investigations of electric potentials and magnetic fields on this scale. An electron microscope equipped with field emission gun, Möllenstedt biprism, and Lorentz-lens has proven to be a most favorable machine due to the large field of view for holography. However, the special properties of the Lorentz-lens force the user to rethink the proper setup for holography.

At the Philips CM200FEG ST/Lorentz electron microscope, the Lorentz-lens has a spherical aberration of about 8 m, which results in a point resolution of about 2.2 nm at Scherzer defocus of $D_z = -5.375$ µm. Since the envelope due to the illumination aperture strongly damps the contrast transfer function, the information limit is only slightly better than the point resolution. However, the lateral resolution resolved by holography is mainly given by the total magnification of the electron microscope, which is about 50 kX. Having a slow-scan CCD camera with 24 µm pixel size and a sampling of at least four pixels per interference fringe, the resulting fringe spacing related to the object plane is about 2 nm. In order to clearly separate in Fourier space the sidebands from the centerband, the spatial frequencies within the object should not extent beyond 1/(4 nm), even less for strong objects. Especially, when speaking about resolution of non-periodic samples, not only the structure size is important but also the gradient at structure edges with correspondingly higher spatial frequencies involved has to be considered (fig. 2). Here, one should always bear in mind that spatial frequency contributions larger than five-times the point-resolution cause strong delocalization hence may be misinterpreted. This has to be taken into account when aiming at high accuracy at lateral resolution better than e.g. 20 nm. In any case, the Gabor defocus $D_z = -3$ µm should be used, which allows a direct interpretation of the large area phase contrast in terms of potential distribution without correction of wave aberration.

Besides lateral resolution, the phase resolution can be even more important in 2D-dopant profiling since the desired aim is the quantitative measurement of electric potentials with high accuracy. The phase detection limit is inverse proportional to the interference fringe contrast and to the square root of the number of recorded electrons. Therefore, the fringe spacing should be as broad as possible resulting in a significantly improved interference fringe contrast. Unfortunately, due to the limited brightness of the gun, only extending the exposure time can increase the number of electrons. Exposure time is, however, limited due to instabilities of the microscope, its environment, the biprism, and the sample. In conclusion, the experimental setup is a tradeoff between stability, lateral resolution, and phase detection limit.

Fig. 3 shows reconstructed phase images of FIB-prepared n-MOS and p-MOS field effect transistors. Recording parameters are optimized with respect to field of view, lateral resolution, and phase detection limit resulting in the combination of magnification $M = 19$ kX, fringe spacing

$s = 3.8$ nm at a biprism voltage of $U_F = 160$ V, aperture radius in Fourier space for isolation of sideband $q_a = 1/(8\text{ nm})$, and exposure time $t_{exp} = 8$ s. The field of view of 860 nm is large enough to image a complete MOSFET. Recent experiments have shown that increasing the fringe contrast by a factor of two significantly improves the signal/noise ration in the reconstructed phase image.

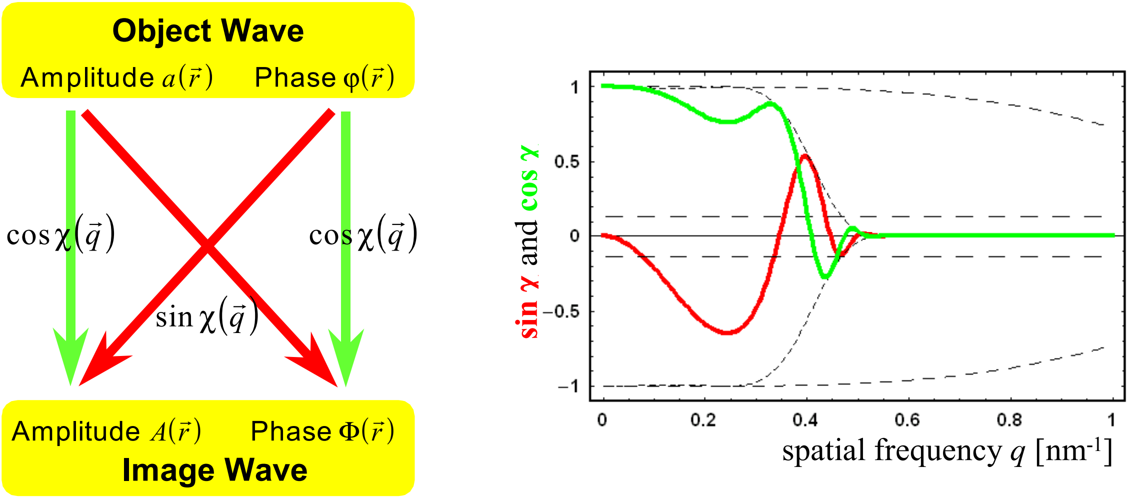

Fig. 1: Contrast transfer properties of Lorentz-lens. The Gabor defocus amplifies the direct transfer of information (marked in green) and suppresses the cross-talk for lower spatial frequencies. In the contrast transfer function plot, the spatial frequencies, which are used for phase reconstruction in fig. 3, are marked in yellow.

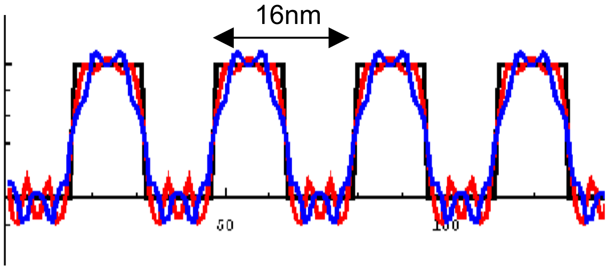

Fig. 2: Linescan of phase across periodically arranged rectangular stripes of 16 nm period, holographically recorded using the Lorentz-lens. Black: object phase; red: image phase at Gabor defocus; blue: image phase at Scherzer defocus. This simulation shows considerable falsifications.

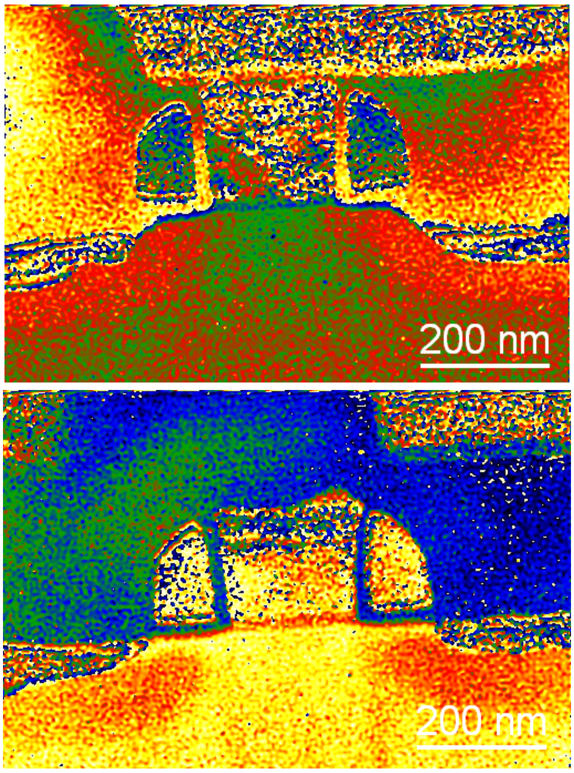

Fig. 3: Reconstructed phase images of n-MOSFET (top) and p-MOSFET (bottom).

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