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On the achievable field sensitivity of a segmented annular detector for differential phase contrast measurements

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A R T I C L E I N F O

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A B S T R A C T

Differential phase contrast microscopy measures minute deflections of the electron probe due to electric and/or magnetic fields, using a position sensitive device. Although recently, pixelated detectors have become available which also serve as a position sensitive device, the most frequently used detector is a four-segmented annular semiconducting detector ring (or variations thereof), where the difference signals of opposing detector elements represent the components of the deflection vector. This deflection vector can be used directly to quantitatively determine the deflecting field, provided the specimen's thickness is known. While there exist many measurements of both electric and magnetic fields, even at an atomic level, until now the question of the smallest clearly resolvable field value for this detector has not yet been answered. This paper treats the problem theoretically first, leading to a calibration factor κ which depends solely on simple, experimentally accessible parameters and relates the deflecting field to the measured deflection vector. In a second step, the calibration factor for our combination of microscope and detector is determined experimentally for various combinations of camera length, condenser aperture and spot size to determine the optimum setup. From this optimized condition we determine the minimum change in field which leads to a clearly measurable signal change for both HMSTEM and LMSTEM operation. A strategy is described which allows the experimenter to choose the setup giving the highest field sensitivity. Quantification problems due to scattering processes in the specimen are addressed and ways are shown to choose a setup which is less sensitive to these artefacts.

1. Introduction

The foundation for modern differential phase contrast microscopy was laid in the early 70s of the last century by Rose [1] who described the possibility of phase contrast imaging in a STEM using a concentrically arranged array of annular detectors. Dekkers and de Lang [2] were the first who suggested to use a split detector to measure the modulated phase of an electron beam. The first experimental realization of DPC in a STEM was carried out by Chapman in 1978 [3], using a circular split detector to measure the movement of the STEM diffraction disk, caused by the Lorentz deflection of the electron beam when it passes through a specimen with a magnetic domain wall structure. With the shifts of the diffraction disk being directly proportional to the product of the strength of the local magnetic induction and specimen thickness he was able to directly image the field distribution within the specimen. Continuous improvement of the technique showed that it is not only possible to image magnetic [4–7] but also electric field distributions [8–10] with down to atomic scale spatial resolution [11–13]. The most common detector layout used for DPC measurements is the segmented annular ring detector introduced by Chapman in 1990 [14]. Recently, pixelated detectors like a fast CCD or MOSFET based TEM camera have been used more frequently [15–21]. This paper, however, will exclusively deal with the properties of an annular four quadrant detector as it is an established and nowadays commercially available part of modern STEMs. With this detector geometry it is possible to combine the signals of individual segments as needed, e.g. by taking the sum of all signals one obtains, depending on the radius r of the central hole, an (annular) bright field STEM (smaller r) or an annular dark field image (larger r). Even a split segment configuration [2] can easily be accomplished.

Although DPC has recently been gaining more attention as a tool to image microscopic electric and magnetic field distributions with a STEM, there are comparably few papers which focus on the question which parameters influence the measured signal, primarily from the point of view of the detector geometry and the microscope's settings [3,22–24], rather than considering the electron-specimen interaction. Hence, this work will deal with the identi-

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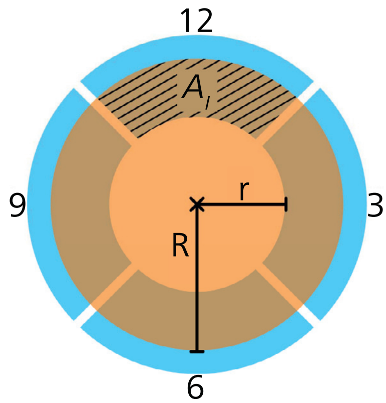

Fig. 1. Annular DPC detector (inner (hole) radius r) centricaly illuminated with the electron diffraction disk (radius R). The hatched area A_I represents the overlap of the beam with one segment. The individual segments are named after the numerals on a clock face.

fication and characterization of measurement parameters influencing the sensitivity of DPC imaging for our specific DPC setup. In the next chapter we will present theoretical considerations on the signal formation to derive formulae which identify and describe the influence of these parameters and further allow the calibration of any other real setup. Some of these considerations are based on former theoretical work performed by Zweck [23] who estimated the achievable sensitivity of annular four quadrant DPC detectors regarding small shifts of the diffraction disk. Next we will present the results of an experimental calibration of our DPC setup relating the measurement signals acquired in arbitrary analog-to-digital converter units to absolute values of the deflecting field strength and deflection angle via setup dependent conversion factors. This has been done for all reasonable combinations of microscope settings affecting the responsivity of the detector. In this context one of our main interests was to evaluate the achievable sensitivity for beam deflections in standard high magnification STEM and low magnification STEM modes. We will conclude this work with an evaluation of the influence of camera length, diffraction disk radius and detector geometry on the calibration. All of the experiments were performed on a FEI Tecnai F30 instrument equipped with two concentric annular DPC detectors.

2. Theory on signal formation

2.1. Relation between deflection angle and DPC signal

The signal S^{seg} obtained from one detector segment, being partly illuminated by a homogeneously filled diffraction disk, (see Fig. 1) can be written as

$$S^{seg}\,[\mathrm{SU}] = A_I[\mathrm{m}^2]\cdot j\left[\frac{\mathrm{A}}{\mathrm{m}^2}\right]\cdot\gamma\left[\frac{\mathrm{SU}}{\mathrm{A}}\right] \tag{1}$$

with A_I being the illuminated area on the detector, j the beam current density and γ a constant, system dependent factor describing the conversion of the incident electron current to digital signal units (SU) obtained from the read out electronics of the DPC setup. It contains the detection quantum efficiency of the detector as well as influences of the signal amplification and AD conversion. The segments of the detector are named after the numerals on a clock face. Starting with a centred diffraction disk, illuminating areas of identical size on each segment, as shown in Fig. 1, we get a base signal S_0 defined as

$$\begin{aligned} S_0 &:= S_0^3 = S_0^6 = S_0^9 = S_0^{12} \\ &= j\cdot\gamma\cdot A = j\cdot\gamma\cdot\frac{1}{4}\left(R^2\pi - r^2\pi\right) \end{aligned} \tag{2}$$

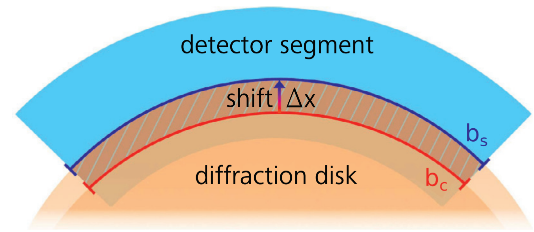

Fig. 2. Schematic to describe the change of the illuminated area (dashed area) of a single segment when the diffraction disk gets shifted further onto the detector by a distance Δx. The change of the arc length while shifting the disk can be neglected ($b_s \approx b_c$) because Δx is small compared to the disk radius R.

R and r are the radii of the diffraction disk and the detector hole as marked in Fig. 1. In Fig. 2 the diffraction disk is shifted by a distance Δx towards segment 12 leading to an increase of the illuminated area A_I (hatched area) by

$$\Delta A_I \approx \underbrace{\frac{1}{4}\cdot 2\pi R}_{\text{arc length}}\cdot\Delta x \tag{3}$$

In this equation we used that the arc length of the centred disk b_c is in good approximation equal to the arc length of the shifted disk b_s, leading to the linear increase of A_I with Δx. This approximation can safely be made because usually the convergence angle α is large (mrad range) compared to the deflection angle β (µrad range) and hence R is large (millimetre range) compared to the typical shifts of the diffraction disk on the detector (micrometre range). Zweck et al. [23] demonstrated the linear dependence between signal and small ($\Delta x \lesssim 0.6R$) beam displacements. Based on this we can derive the signal δS contributed by the additional illuminated detector area ΔA_I as

$$\delta S = j\cdot\gamma\cdot\Delta A_I = j\cdot\gamma\cdot\frac{1}{2}\cdot\Delta x\cdot\pi\cdot R \tag{4}$$

The total signal of a segment when the disk is shifted either on (summation in Eq. (5)) or off (subtraction in Eq. (5)) can thus be described as

$$S^{seg}_{total} = \underbrace{j\cdot\gamma\cdot\frac{1}{4}(R^2\pi - r^2\pi)}_{S_0} \pm \underbrace{j\cdot\gamma\cdot\frac{1}{2}\cdot\Delta x\cdot\pi\cdot R}_{\delta S} \tag{5}$$

When we consider two opposing segments, the signal of the one where the beam is shifted onto it obviously increases ($S_0+\delta S$) by the same amount as the signal of the other one decreases ($S_0-\delta S$). With this in mind the signal difference S_{dif} is

$$\begin{aligned} S_{dif}(\Delta x) &= S_0 \pm \delta S - (S_0 \mp \delta S) \\ &= 2\delta S \\ &= \pi\cdot R\cdot j\cdot\gamma\cdot\Delta x \end{aligned} \tag{6}$$

Hence, the base signal S_0 has no direct influence on the result of DPC measurements as only the signal δS caused by a shift Δx of the diffraction disk contributes to difference signal S_{dif}. Eq. (6) shows that S_{dif} has a linear dependence on the diffraction disk shift. This is a direct implication of the approximation made above (see Eq. (3)) and calculations done by Zweck et al. [23] further justify the detector linearity in standard DPC imaging for small deflections Δx.

Based on these considerations we can define two orthogonal vectors describing the signal difference for each detector axis

$$\begin{aligned} \vec{S}^{\,3-9}_{dif} &= \pi\cdot R\cdot j\cdot\gamma\cdot\Delta x\cdot\hat{e}_x \\ \vec{S}^{\,12-6}_{dif} &= \pi\cdot R\cdot j\cdot\gamma\cdot\Delta y\cdot\hat{e}_y \end{aligned} \tag{7}$$

where Δx and Δy describe the disk's shift along the directions connecting sectors $(3-9)$ or $(12-6)$, respectively. By adding up