Multiscale differential phase contrast analysis with
a unitary detector

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A new approach to generate differential phase contrast (DPC) images for the visualization and quantification of local magnetic fields in a wide range of modern nano materials is reported. In contrast to conventional DPC methods our technique utilizes the idea of a unitary detector under bright field conditions, making it immediately usable by a majority of modern transmission electron microscopes. The approach is put on test to characterize the local magnetization of cylindrical nanowires and their 3D ordered arrays, revealing high sensitivity of our method in a combination with nanometer-scale spatial resolution.

Keywords: DPC, TEM, magnetization, nanomaterials, nanowires, virtual detector

Highlights:

- New approach for differential phase contrast imaging is proposed
- New DPC approach is based on a unitary detector under bright field conditions
- High sensitivity and nanometer spatial resolution is demonstrated
- Magnetization of cobalt-nickel nanowires and their 3D ordered arrays is characterized

To move forward with creating novel nano-electronic devices we need to understand electrons behavior in a wide range of materials which dimensions have been greatly reduced down to the nanometer scale. This is a common task for electronics industry dealing with transistors [1], electronic or magnetic memories [2,3], light-emitting, photovoltaic or multiferroic devices [4-6]. A key role for development and production of such devices is the nanoscale characterization of the local magnetic fields in the materials [7-11]. Such characterization is also of paramount importance for biomedical applications like hyperthermia treatment or local drug delivery [12,13]. Other examples are paleomagnetism, environmental magnetism or biomagnetism [14-17].

In terms of resolution and sensitivity the best tool for the local magnetic fields characterization is the Transmission Electron Microscopy (TEM). Several methods within TEM such as Lorenz microscopy [18-20], Electron Holography [21-23] (EH) and Differential Phase Contrast [24-29] (DPC) have been developed and successfully used for visualization and quantification of the nanoscale magnetic fields. While being complimentary to each other all these methods have their intrinsic constraints, like limited field of view or low resolution, and all of them depend on the presence of complex equipment (Lorentz lens, biprism) additional to a conventional TEM systems.

Out of the above three the DPC method is the most useful for fast switching between studying of objects of about 10 μ m down to a few nm in size (multiscale imaging). However, the conventional DPC also requires specially designed position sensitive detector(s) (split, segmented, multi-sectored, etc) and costly hardware solutions [26], thus significantly limiting the wide use of the method.

Here we report for the first time a simple generalization of the DPC imaging method to extend the capabilities of the majority of existing TEM systems (without modifications) towards multiscale characterization of local magnetic properties of nanomaterials. We prove the usability of our method both at micro- and nano- scale by applying it for the investigation of 2 materials: a) cylindrical Co/Ni nanowires with a high length to diameter ratio; b) ordered arrays of Co/Ni nanowires – promising candidates for 3D magnetic memory devices.

2. **The main idea: LM-STEM, DPC and a unitary detector**

The Low Magnification Scanning TEM (LM-STEM) is a mode of a typical TEM system at which the current in the objective lens (OL) is significantly lowered or even switched off completely. The major reason to lower the OL value is to allow a wide scanning range (low magnification), thus giving a big field of view (1-2mm) of a specimen. With the OL completely switched off this mode can be used to study magnetic samples, since it provides a field free environment and does not alter the magnetization of the materials. Following the reciprocity principle, even though it is scanning mode, when realized with Bright Field (BF) detector LM-STEM is completely analogous to the conventional Lorentz TEM (Fresnel imaging), with the exception, that it does not require an additional Lorentz lens, and thus can be exploited with a big number of modern TEM microscopes without modifications or upgrades. It is LM-STEM we use for our new, generalized DPC approach.

The detailed description of DPC principles can be found elsewhere [24-29]. The main idea of conventional DPC with a dark field four-quadrant detector is illustrated in Fig.1a, b. In scanning mode the displacement of a diffraction disc (due to a magnetic field in the plane of the sample) results in a set of 4 different signals (DPC images) simultaneously recorded by individual quadrants A, B, C, D.

A single detector divided into quadrants is equivalent to 4 unitary (non-segmented) detectors in positions A-B-C-D (Fig.1c). Alternatively we can use just one unitary detector but physically move it in a circle (with consecutive steps of 90°) to four positions (A-B-C-D) equidistant from the zero-field diffraction disc: Fig.1c, d. Recording a signal at each position we can collect (in series) the same set of DPC images.

A typical unitary detector in a conventional TEM system, however, is not flexible to shift around routinely (only “in” and “out” hardware fixed positions). The diffraction plane of the microscope, on the other hand, is electronically adjustable (diffraction shift). Using the diffraction shift we can consecutively reposition the diffraction disc, this time going in a circle around a fixed unitary detector: Fig.1e, f. With the same equidistance between the zero-field diffraction disc and the detector (Fig.1e), the positions A*-B*-C*-D* in both Fig.1e and Fig.1f are equivalent to positions A-B-C-D in Fig.1c

and Fig1.d respectively. Thus, recording a signal at positions $A^*-B^*-C^*-D^*$ results in the same set of images as A-B-C-D and the conventional DPC method.

Figure 1. Transition from a conventional four-quadrant detector to a unitary detector DPC imaging. **a, b,** Diffraction disc positions with respect to the four-quadrant detector without and with magnetic field in plane of the sample. **c, d,** Four unitary detectors or one detector repositioning around diffraction disc. **e, f,** Diffraction disc shift around the unitary detector

For the convenience hereinafter we can treat $A^*-B^*-C^*-D^*$ as the unitary detector positions (rather than diffraction shift). The operation of moving around $A^*-B^*-C^*-D^*$ (Fig.1e, f) and subsequent image acquisition can be performed manually or under the software control. It is this procedure we suggest as a generalized DPC approach.

The drawback of the scheme $A^*..D^*$ in comparison to a conventional DPC is that 4 images are acquired not simultaneously but in series. Not only it takes longer, but it also requires post realignment of the images if there is a sample drift during the acquisition.

On the other hand, the advantage of the scheme is that the detectors positions are controlled electronically by diffraction shift of the microscope. These positions can be voluntarily chosen in such a way that axis A^*-C^* or B^*-D^* is in line with a preferential direction of the sample (if any). This is

especially important when the sample is flipped (as normally required for magnetic field visualization). In this case we can simply redefine detector positions in line with TEM sample instead of repositioning the sample in a holder (see below). The biggest advantage, though, is that the scheme $A^*.D^*$ requires only one, unitary detector and, in principle, any STEM detector physically present on the microscope can be used.

It is also essential that our experiments demonstrate the maximum sensitivity to the magnetic signal of the suggested DPC scheme under the BF conditions, i.e. when the zero-field diffraction disc in $A^*.D^*$ positions is overlapping with the detector. This leads to the need of a BF detector.

BF detectors are typically semiconductor detectors, characterized by a large dark current and rather poor detective quantum efficiency (DQE) at low signals due to inherent noise. They are also not easy in controlling contrast and brightness levels. At the same time typical scintillator-photomultiplier detectors are characterized by very high gain with DQE close to 0.9, and low noise level compared to semiconductor detectors [30].

Scintillator-photomultiplier detectors are normally produced in a round shape with a hole in the center to be used as angular or high angle angular dark field (HAADF) detectors with straight forward settings of contrast and brightness. While not suitable as a BF detector directly, a HAADF detector can be turned into a Virtual Bright Field (VBF) detector.

To create a VBF detector we use a selected area (SA) aperture, which in LM-STEM mode can effectively shadow the HAADF detector. As schematically shown in Fig.2, the SA aperture (when introduced) blocks almost the entire active surface of the HAADF detector, leaving only a small area (SA aperture hole) to collect electrons. This limited area of the HAADF detector can be used as a VBF detector. The size of this detector in terms of the collection semi-angle β is defined by the size of the SA apertures available on the microscope.

Figure 2. VBF detector principle. The optimum position of the SA aperture is on the side closest to the photomultiplier (not shown here), to prevent a shadowing effect of the HAADF detector hole.

By combining the VBF detector with the DPC scheme based on the diffraction shifts ($A^*-B^*-C^*-D^*$) we end up with the VBF-DPC method. We complete it with a conventional way to differentiate signals coming from the magnetic field and from the electrostatic potential due to the change of the mean inner potential of the sample (different material, thickness etc.) [22,23]. This is achieved by a mechanical sample flipping over (in a sample holder) and schematically shown in Fig.3.

A flip around an arbitrary axis can always be represented as a flip around a fixed (given) axis and a rotation (in the plane of the sample) by a double angle between arbitrary and fixed axes. The double angle between axes can be produced by the rotation (redefinition) of detector positions (owing to the VBF-DPC flexibility). As a result any general case of a sample flipping can be reduced to a particular flipping around a fixed axis, which we consider below.

Let us choose the coordinate system to be aligned with a sample (for example $\mathbf{x}$ goes with a long axis of the sample, see Fig.3a) and we align (define) detectors in such a way that A^*-C^* axis is parallel to $\mathbf{x}$ direction and B^*-D^* goes along $\mathbf{y}$.

Figure 3. Configuration of the sample with respect to VBF detectors. a, Directions of diffraction shifts (signal increase) due to electrostatic $\mathbf{E}$ and magnetic $\mathbf{B}$ fields before flipping of the sample. **b,** Detectors realigned according to the flipped sample and corresponding signal directions.

The magnetic field $\mathbf{B}$ generates a signal in the direction orthogonal to the field itself. Assume, for example, the detector A^* receives a signal $\mathbf{S}(\mathbf{By})$ due to the y component of the magnetic field. Under the sample flipping around the fixed B^*-D^* axis (after a proper detectors rotation), the axis $A_f^*-C_f^*$ stays parallel to x direction (Fig.3b). In this case the y component of the magnetic field is not changed, thus the detector A_f^* receives the same signal $\mathbf{S}(\mathbf{By})$.

The electrostatic field $\mathbf{E}$, on the other hand, generates a signal in the direction parallel to itself, and the x component of the electrostatic field is reversed in direction after the specimen's flipping around the B^*-D^* axis. So, if the detector A^* receives the signal $\mathbf{S}(\mathbf{Ex})$ then the detector A_f^* (after flipping) receives $-\mathbf{S}(\mathbf{Ex})$.

Following the same approach we obtain the meaning of signals generated by each detector in case of the initial and flipped over sample. Individual components of magnetic and electrostatic fields are derived by a simple combinatorics of signals coming from corresponding detectors.

We also need to take into account that each detector receives first of all a bright field signal ($\mathbf{BFs}$), whereas magnetic $\mathbf{S}(\mathbf{B})$ or electrostatic $\mathbf{S}(\mathbf{E})$ signals are essentially modulations for $\mathbf{BFs}$. Assuming that $\mathbf{BFs}$ has no directional dependence (i.e. all detectors receive identical $\mathbf{BFs}$), “pure” magnetic or

electrostatic components can be obtained by a normalization (division) with **BFs**. The results are summarized in Table1.

Table 1. Electrostatic, magnetic and BFs signals on VBF detectors and their combinations

$A^* := [S(E_x) + S(B_y) + 1] * BFs$	$A_f^* := [-S(E_x) + S(B_y) + 1] * BFs$
$B^* := [-S(E_y) + S(B_x) + 1] * BFs$	$B_f^* := [-S(E_y) - S(B_x) + 1] * BFs$
$C^* := [-S(E_x) - S(B_y) + 1] * BFs$	$C_f^* := [S(E_x) - S(B_y) + 1] * BFs$
$D^* := [S(E_y) - S(B_x) + 1] * BFs$	$D_f^* := [S(E_y) + S(B_x) + 1] * BFs$
$(A^* + A_f^*) - (C^* + C_f^*) := 4 * S(B_y) * BFs$	$(B^* - B_f^*) - (D^* - D_f^*) := 4 * S(B_x) * BFs$
$(A^* - A_f^*) - (C^* - C_f^*) := 4 * S(E_x) * BFs$	$(B^* + B_f^*) - (D^* + D_f^*) := -4 * S(E_y) * BFs$
$A^* + B^* + C^* + D^* := 4 * BFs$	$A_f^* + B_f^* + C_f^* + D_f^* := 4 * BFs$

3. Results and discussion

Experimental conditions

LM-STEM images for the VBF-DPC were acquired on a Titan 60-300 electron microscope (FEI Co) equipped with a high brightness electron gun (x-FEG), and Fischione HAADF STEM detector. The microscope was operated at 200 keV acceleration voltage. The LM-STEM was intentionally tuned for OL=0% condition to allow zero magnetic field environment. To confirm that the magnetic field from the objective or condenser lenses did not influence the initial magnetic state of the materials during experiments the specimens were rotated horizontally in the specimen holder and flipped over.

For highest sensitivity of the VBF-DPC method in case of the semi-convergence angle $\alpha \geq \beta$ geometrical considerations suggest to apply the overlapping between the zero-field diffraction disc and VBF detector such that $\gamma = \beta$ (see Fig.2) i.e. the edge of the diffraction goes through the center of VBF detector.

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The convergence semi-angle of the STEM probe was measured to be $\alpha = 0.6\text{mrad}$. The VBF detector was produced with an SA aperture of $40\mu\text{m}$, resulting in the collection semi-angle $\beta = 0.2\text{mrad}$.

Material a – multisegmented Co/Ni nanowire

3D memory devices should dramatically increase the information record density. Cylindrical magnetic nanowires fabricated in the nanoporous templates [31,32] are potential candidates for such 3D devices. For their realization a controlled positioning or pinning of magnetic domain walls (DWs) within nanowires [33] is required. The first progress in this direction has been made by realizing multisegment Co/Ni nanowires (Fig. 4a). Sharp atomic interfaces between segments with different magnetization and magnetocrystalline anisotropy result in strong stray fields which can effectively pin a DW during its propagation along the nanowire.

We utilized our VBF-DPC method to study the periodic stray fields, magnetization and DW pinning at the interfaces of a $9.4\mu\text{m}$ long multisegment Co/Ni nanowire with a diameter varying from 70 to 80 nm.

Both for the initial and the flipped sample the axis A^*-C^* was aligned with the nanowire's long axis (as suggested in Fig.3 and in **Appendix A**). The components of the magnetic field parallel $\mathbf{B}_x$ and perpendicular $\mathbf{B}_y$ to the nanowire are derived according to Table 1 and shown in Fig. 4b, c correspondingly. The periodic variation of the magnetization amplitude and stray fields from the interfaces directly correlates with the nanowire composition (Fig. 4a) obtained by electron energy loss spectroscopy (EELS). Note, the EELS map was recorded at the same conditions as VBF-DPC i.e. LM-STEM field free environment.

The reconstructed color map of the total magnetic field directions inside and around the nanowire is shown in Fig. 4d. Two magnetic domains (left and right hand sides of the nanowire) with colors corresponding to the magnetization in opposite directions (see color wheel) can be identified on the

map. The point in the middle of the nanowire where the magnetization direction is reversed, defines the position of the domain wall.

For both domains the direction of the nanowire's magnetization mainly follows the long axis due to the strong shape anisotropy. The magnetization magnitude varies from Co to Ni segments since the magnetic moment of Co is 3 times larger than of Ni (Fig. 4b). For the same reason stray fields around Co segments are larger than around Ni. It is remarkable that with the constant direction of magnetization within one domain, the stray fields of the adjacent Co and Ni segments periodically change the direction to the opposite (Fig. 4d). So, the interfaces act as strong periodic magnetic N and S poles (see the model in **Appendix B**).

Figure 4. Characterization of multisegment nanowire. **a**, Periodic variation of Co and Ni composition obtained from EELS. **b**, **c** The magnitude (temperature scheme) of the magnetic field components parallel B_x and perpendicular B_y to the nanowire. **d**, The map of the magnetic field directions reconstructed from **b** and **c**.

Material b – nanowires array

As was recently demonstrated [35] hcp Co nanowires can represent a 3D vortex state. To probe the magnetic states of the ordered array of the Co/Ni nanowires we prepared a plane section of the aluminum oxide template with nanowires embedded inside of it (details see in [35]). With the field of

view much larger than with electron holography and no need for the reference beam in vacuum the VBF-DPC allows to image any part of the sample. The magnetic vortices and interactions between nanowires are observable in real time even with a single image acquired at any position (A^* to D^*) of the VBF detector. Compared to a conventional electron holography the DPC is also in general less sensitive to the charging effects caused by the isolating alumina matrix.

Derived according to Table 1 the components of the magnetic field of the nanowires array are shown in Fig. 5a, b. The color map of the magnetization rotation is shown in Fig. 5c, whereas vortices with the opposite chirality are visualized in Fig. 5d. Note the insignificant cross-talk between adjacent nanowires.

Figure 5. Characterization of the plane section of a nanowires array at the Co segment position. a, b The magnitude of the orthogonal components B_x and B_y of the magnetic field. **c**, The map of the magnetic field directions. **d**, The magnetic field vectors (from the area selected on **c**).

The analysis of resolved features (i.e. vortex core) of the sample provides a direct measure of the spatial resolution of our VBF-DPC method. It is found to be about 4nm (in agreement with a diffraction limit for $\alpha = 0.6\text{mrad}$), which makes it competitive with Lorenz and Electron Holography TEM for magnetic fields investigations.

Following the known approach (for example [29]) we can measure the shift (difference in position) of diffraction for the electron beam going through the specimen and through the vacuum. Since such a difference is directly proportional to the local magnetic field we can probe the sample to quantify the magnetization profile a specimen. However, just by the principle of the method, the intensity of the VBF-DPC images (Fig.3b,c and Fig.5a,b) is directly proportional to the above shift of the diffraction (see **Appendix C** for the linearity criteria), thus providing an alternative way of the magnetization quantification directly from the DPC images. Estimation of the magnetization of different Co/Ni nanowire's segments is given also in **Appendix C**.

Several artefacts (intrinsic for all DPC methods) might impact the accuracy of the magnetization quantification. One of them is the “vacuum level” alignment. Ideally we want all the VBF-DPC detectors ($A^*.D^*$) result in exactly the same intensity of images taken from the vacuum (no specimen). This requires a perfect centering of the diffraction disc with respect to the detectors. On practice this condition is difficult to realize. Some difference (a few %) in signals is always present, appearing as a systematic error for the quantification.

Another source of errors is a scanning system of a typical TEM. Ideally we expect the scanning electron beam to be exactly parallel to the optical axis of the microscope. On practice there is always a small amount of beam tilt introduced by the scanning system. The effect goes stronger with the increase of the scanning range and it has a directional dependence (slightly different scanning coils in x and y direction). As a result (beam tilt translates into diffraction shift), the DPC image from a uniform specimen area (or vacuum) might have a non-uniform (gradient) intensity distribution, especially in Low Magnification mode.

To treat both issues mentioned above we suggest to record an individual reference image from the vacuum for each detector position ($A^*..D^*$). These 4 reference images then can be used to normalize corresponding VBF-DPC images from a specimen, prior to application of the combinatorics from Table1.

4. Conclusions

We demonstrate for the first time a simple and robust method (VBF-DPC) for probing the magnetic properties of micro- and nano-scale samples. This method implies a usage of a unitary (non-segmented) virtual bright field detector in combination with a modified differential phase contrast approach.

Our method demonstrates high sensitivity to the local magnetic fields, provides a very large field of view, a few nanometers spatial resolution and in-focus condition. As such the method opens new opportunities for studying materials with TEM under external stimulus like magnetic field, electric current, temperature change etc. It allowed us to characterize the magnetic structure of a cylindrical multisegment nanowire and the magnetic vortices in an ordered array of nanowires.

In principle, the idea to use a unitary detector for the DPC imaging is immediately applicable to practically any TEM system which can operate in STEM mode under field free environment and has position insensitive detector (e.g. conventional bright field detector). However, the method benefits the most in a combination with a virtual bright field detector, which can be realized in TEM systems configured with an SA aperture in the plane conjugated to a HAADF detector in LM-STEM mode.

The method exploits all the advantages of previously reported DPC techniques while overcoming old, sometimes artificial limitations. We believe the VBF-DPC method will help moving forward many different research areas like the development of novel nanoelectronic devices as well as materials for biomedical applications.

S.L. conceived the project, designed and performed experiments, performed data analysis, wrote the manuscript; Yu.P.I. produced materials and prepared TEM samples, participated in experiments, performed data analysis, contributed to the manuscript writing; J.K. and A.C. supported the experiments and contributed to the manuscript writing. All authors contributed to the discussions.

Appendix A. Alignment of the sample with respect to the detectors

The orientation of the sample in the diffraction plane can be established by so-called shadow imaging (under strongly defocused probe), when the sample starts to be clearly visible within the diffraction disc (Fig.A.1a). For the magnetic sample with preferential directions of magnetization $\mathbf{B}$, like a long axis of the nanowire, “pure” components $\mathbf{B}_x$ and $\mathbf{B}_y$ (along and perpendicular to the nanowire) can be obtained with DPC imaging without elaborate mathematical transformation. To achieve this in case of conventional DPC, one detector axis (for example A-C) should be exactly in line with the nanowire’s long axis. Normally this requires a very precise specimen orientation in a specimen holder (mechanically).

Figure A.1. Experimental setup for the measurement of the nanowire magnetization. a Shadow image of the nanowire and optimum positions of the detectors for conventional DPC. **b**, Diffraction disc configuration with respect to a unitary detector for VBF-DPC.

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In case of VBF-DPC the alignment of axis A^*-C^* (or B^*-D^*) with respect to the sample can be obtained by a simple repositioning (electronically) of the diffraction disc with respect to the virtual detector as shown in Fig.A.1b.

Appendix B. Model magnets in comparison with experimental results

To model periodic change of the direction of stray magnetic fields let us consider a long cylinder, composed of 3 segments with the same length. Assume that segments at both ends are strong magnets (e.g. Co) with the same orientation of N and S poles, while the central segment has a much weaker magnetization (Ni). Inside such a structure the magnetization follows everywhere the same direction (see Fig. B.1a). For strong magnetic segments the stray field lines go in the direction opposite to the internal magnetization. However, in a weaker magnetization segment we have a smaller density of the magnetic flux, thus some lines of magnetic field have to go outside (through the interface between segments) and to follow the same direction as internal magnetization (to be continuous). This is what we observe experimentally for the magnetic field directions of Co/Ni nanowire within one magnetic domain (see Fig. B.1b where black arrows denote directions obtained from the color map).

Figure B.1. Periodic variation of magnetic field directions. **a**, Model structure of the magnetic field lines from a composite magnet. **b**, Experimental color map of the magnetic field directions within one domain of a Co/Ni nanowire.

Appendix C. Linearity conditions and magnetization quantification

To confirm a linear dependence between the intensity of VBF-DPC images and the angle of the electron deflection under the local magnetic field of the specimen we calculate the area $A(d)$ of the overlap between the diffraction disc of size α and the round detector of size β as a function of distance d between their edges. In our experiments we use such a configuration that $\alpha = 3\beta$ and the edge of the zero-field diffraction disc goes through the center of the detector, i.e. $d = \beta$ and the initial overlap area is $A(\beta)$.

Geometrically, the VBF-DPC signal can be represented as a difference between the area $A(\beta + \Delta d)$, which is a signal on one of the detectors, and the area $A(\beta - \Delta d)$, i.e. the signal on the opposite detector. The normalization to the sum $A(\beta + \Delta d) + A(\beta - \Delta d)$ physically has the same meaning as the normalization to **BFs** signal (as in Table 1). The value of Δd is essentially the angle θ of the electron deflection under the local magnetic field.

Our calculations demonstrate (Fig. C.1a) that the deviation of VBF-DPC signal from the linear function is less than 1.5% in the range of $\Delta d/\beta$ from -0.35 to 0.35. For the experimental configuration ($d = \beta$) the variation of initial overlapping area $A(\beta)$ as a function of the vertical shift h (Fig.C.1b) is $\leq 1\%$ for $h/\beta \leq 0.2$.

The maximum intensity (signal) detected in our VBF-DPC images corresponds to $\Delta d/\beta = 0.32$ and $h/\beta = 0.06$, which is well within the linear range. Thus, we conclude that in the range of the intensity variation of our experimental data, the VBF-DPC signal is directly proportional to the deflection angle θ (within 1.5% accuracy).

For small values the angle of deflection of an electron traveling perpendicular and through the center of a cylindrical magnet with a diameter D and a uniform magnetization B_r is approximately:

$$\theta = qDB_r/(mV), \quad (\text{C.1})$$

where q is the electron charge, m is the electron mass (relativistic for TEM), V is the electron speed.

For the Ni segment of a Co/Ni nanowire we detected homogeneous magnetization parallel to the nanowire, which allows us to apply Eq.C.1 for magnetization evaluation. The maximum measured deflection angle $\theta = 0.028 \text{ mrad}$ in the middle of Ni segment results in the estimated magnetization value of $0.58 \pm 0.04 \text{ T}$ for $D=80\text{nm}$. Here the accuracy is mainly limited by the calibration of the convergence angle and the detector size as well as the nanowire thickness measurements. This result is in a good agreement with a typical bulk value for Ni [31].

For the Co segment we observed the concentration of the magnetization at the core of the NW which can be attributed to the complex 3D vortex structure due to the strong magnetocrystalline anisotropy of hcp Co [34,35]. In this case Eq.C.1 gives only a rough approximation, since it does not take into account strong magnetic stray fields going outside the Co segment (reaching up to 10% of the field inside). With the measured deflection angle $\theta = 0.064 \text{ mrad}$ we estimate the magnetization in the middle of Co segment as $1.51 \pm 0.2 \text{ T}$ ($D=70\text{nm}$).

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Highlights:

- New approach for differential phase contrast imaging is proposed
- New DPC approach is based on a unitary detector under bright field conditions
- High sensitivity and nanometer spatial resolution is demonstrated
- Magnetization of cobalt-nickel nanowires and their 3D ordered arrays is characterized

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