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Ferroelectric Electron Holography

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Conventional TEM-investigation of ferroelectric structures has been a difficult task since decades. To assess the facilities of electron holography for the determination of the electric polarisation in ferroelectrics, a simple dipole model was set up [1]. It turns out that by interaction of the electron wave with an array of equally oriented dipoles – like in a ferroelectric domain – the electron phase is modulated in two aspects: First, each dipole modulates the wave microscopically according to the positive and negative charges in each unit cell; second, there is a mesoscopic phase shift nearly linearly increasing in direction of the polarisation (fig.1). These phase shifts arise only from the "in-plane"-components of polarisation perpendicular to the electron beam, whereas the electron wave is not affected by the "out-of-plane" components along the electron beam; Spence et al. already showed this theoretically [2]. The mesoscopic phase modulation can be computed as

$$\varphi(\vec{r}) = \frac{\sigma}{\varepsilon} \int_t \left[\int_{\vec{0}}^{\vec{r}} \vec{P}_{ip} d\vec{r} \right] dz$$

with σ the interaction constant of the microscope, $\varepsilon = \varepsilon_0 \varepsilon_r$ the dielectric constant, and t the object thickness; $\vec{P}_{ip}$ is the in-plane component of polarisation. Assuming constant polarisation over thickness t, this amounts to

$$\varphi(\vec{r}) = \frac{\sigma\, t}{\varepsilon} \int_{\vec{0}}^{\vec{r}} \vec{P}_{ip} d\vec{r}$$

Consequently, the in-plane component $\vec{P}_{ip}$ can be determined from the phase image by means of

$$\vec{P}_{ip} = \frac{\varepsilon}{\sigma\, t} grad\left[\varphi(\vec{r})\right].$$

Using our CM200FEG-ST/Lorentz electron microscope with $\sigma = 0.0073/(V\,nm)$, we took holograms of $BaTiO_3$ with Lorentz–lens covering a field of view of about 800nm in square. Assuming an object thickness of $t = 50nm$, for $BaTiO_3$ ($\vec{P}_{ip} = \vec{P} = 26\mu C/cm^2$, $\varepsilon_r \approx 1{,}700$) a phase gradient of the order of $2\pi/1{,}000\,rad/nm$ can be expected. In the phase images, we found significant phase modulations over domains (fig.2); the surface plot of the phase image allows visual inspection in terms of polarisation; the phase gradient is more accurately displayed as an arrow plot. To determine also the out-of plane components, one has to tilt the specimen around a well-known, arbitrary in-plane axis; from these two phase images the distribution of total polarisation $\vec{P}$ can be determined in strength and orientation.

References
[1] H. Lichte, Cryst.Res.Technol. 35(2000), 887
[2] J.C.H. Spence, J.M. Cowley and J.M. Zuo, Appl.Phys.Lett 62(19), 2446
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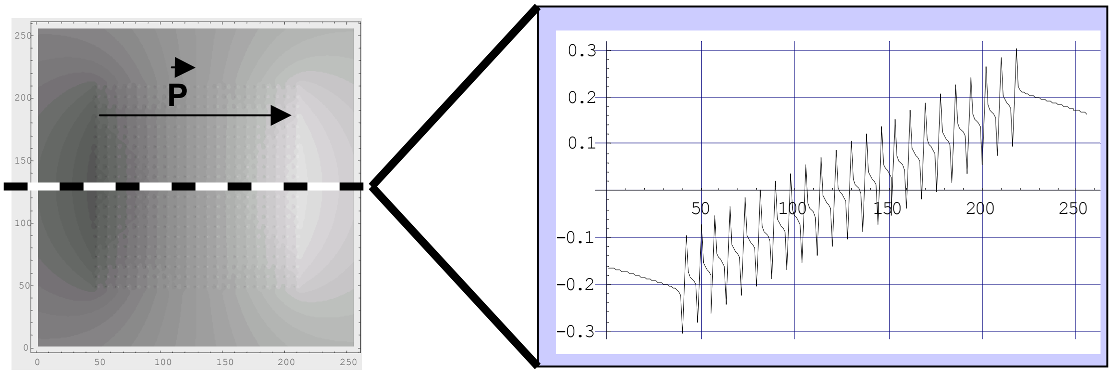

Fig.1 Phase shift produced by a 2D-model of a ferroelectric domain made up by a mono-layer of 21*21 dipoles (left); the line scan (right) shows that - in addition to the modulation by the single dipoles - a far-reaching phase slope of the electron wave over the whole domain is found.

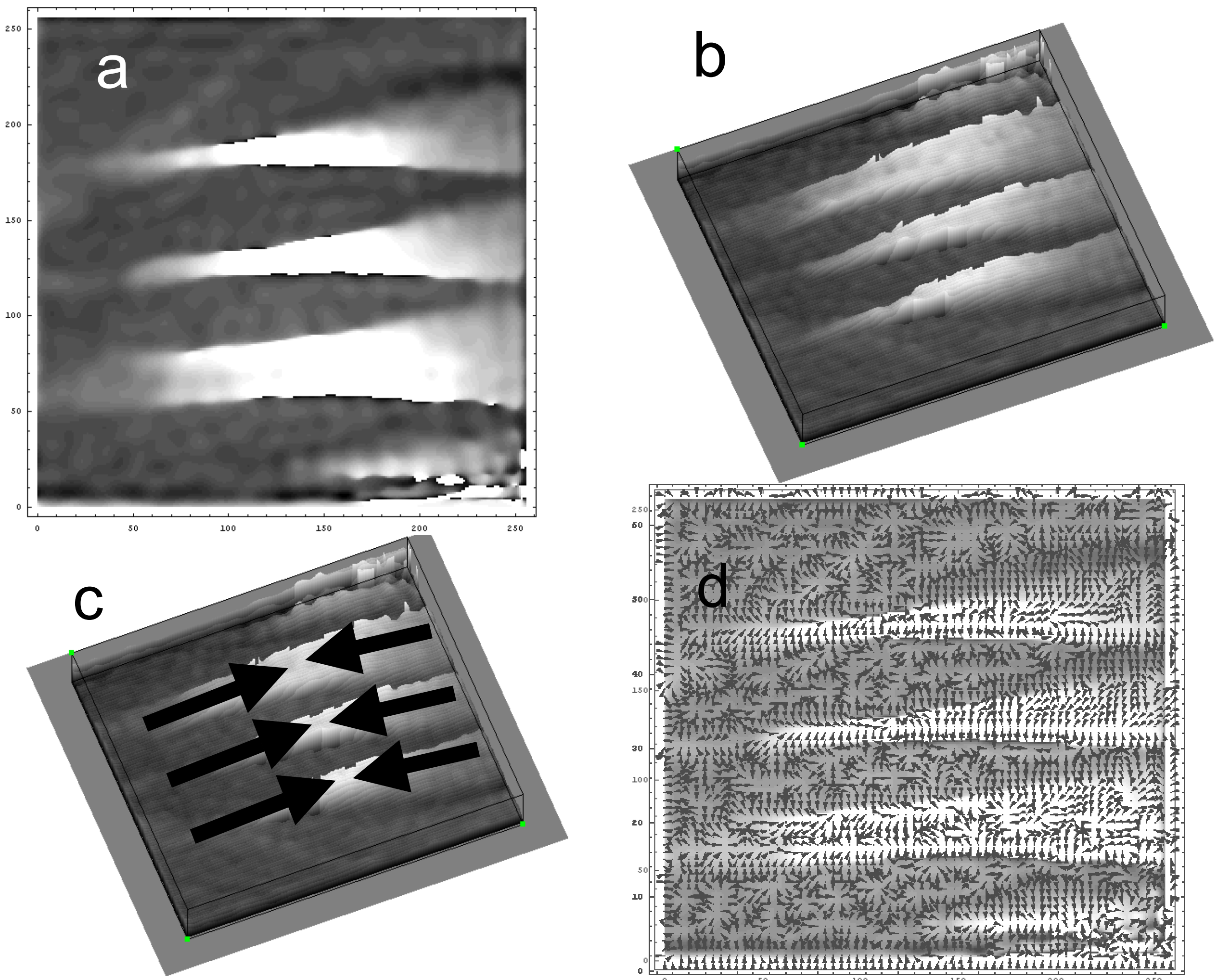

Fig.2 Phase in ferroelectric domains in $BaTiO_3$ (a), phase surface (b) suggesting polarisation (c), and phase gradient as arrow plot showing polarisation distribution. No in-plane polarisation is found in the dark areas which are virtually flat.

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