In scanning transmission electron microscopy (STEM) differential phase contrast (DPC) imaging, the lateral deflection of electrons by fields enables electromagnetic field structure within materials to be mapped and measured. DPC imaging has been used to examine magnetic structure at the micron scale [1] and to map electric field structure in polar materials [2], ferroelectric materials [3] and devices [4]. Recent work has demonstrated the potential for DPC analysis at atomic resolution by examining the electric fields of individual atomic columns [5].

Neglecting dynamic scattering (channeling), a uniform long-range field should rigidly shift the diffraction pattern intensity across the detector in proportion to the field strength. For non-uniform fields, the intensity redistribution is more complex. However, in the phase object approximation the centre of mass (COM) of the diffraction pattern is directly related to the electric field strength. Fast electron pixel detectors promise precise COM determination, but any position sensitive detector can approximate this quantity. We explore the prospects of quantitative DPC imaging using the Segmented Area All Field (SAAF) detector [3], an extension of established STEM detector technology with 16 segments. We consider its application to examining long-range fields in ferroelectrics and to imaging atomic electric fields.

Domain mapping in ferroelectrics involves thick samples where fine electron probes experience significant channeling. The plot in Fig. 1 compares the COM as a function of thickness for BaTiO₃ between the phase object approximation (no channeling), and with channeling as measured by a pixel detector and a SAAF detector. Channeling reduces the COM shift relative to the idealized phase object case. Because of its finite detector segment size, the SAAF detector yields a still smaller value. The mosaic in Fig. 1 shows that both tilt and field lead to asymmetric diffraction patterns, meaning tilt alone could lead to a DPC signal which may be incorrectly attributed to an electric field.

At atomic resolution, channeling is even more restrictive [6]. However, relatively weak scattering materials like graphene are ideal candidates for atomic-resolution reconstruction of the phase and, by extension, the atomic electrostatic potential. Fig. 2(a) and (b) show COM images of a monolayer graphene sample constructed from SAAF signals. Fig. 2(c) shows the DPC reconstruction of the electrostatic potential [7] using these images, which compares favourably to the annular dark field image in Fig. 2(d). Figs. 2(e) and (f) show the DPC reconstructed potential and the annular dark field image, respectively, in the vicinity of a hole in the same sample.

In both the low and high magnification regimes, we use simulation to explore the extent to which DPC imaging with SAAF can be used to visualize and quantify electric fields in materials.
References

[8] This research was supported under the Australian Research Councils Discovery Projects funding scheme (Project DP110101570). N.S. acknowledges support from SENTAN, JST and JSPS KAKENHI Grant number 26289234. R.I. acknowledges support from JSPS KAKENHI grant no. 893986.

FIG. 1. Low magnification DPC. Left: plot of the centre-of-mass shift (COMx) along the [001] direction in BaTiO3 as a function of sample thickness comparing the phase objection approximation (no channeling) with the channeling results for a pixel detector and a SAAF detector. The SAAF detector configuration is inset, with the yellow shading indicating the size of the bright field disk. The BaTiO3 structure is also inset. Right: mosaic of diffraction patterns for varying tilt and internal field values for BaTiO3 at a thickness of 800 Å.

FIG. 2. Atomic resolution DPC. COM images along a) y and b) x based on the SAAF detector, together with the c) DPC phase reconstruction and d) ADF image for monolayer graphene. e) DPC phase reconstruction and f) ADF image from a different region of the sample, which includes a hole with adatoms present at the edges.