Digital darkfield decompositions

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Lattice imaging facilitates *digital* implementation of optical darkfield strategies that have for decades played a key role in the conventional electron microscopy of materials. Applications to the microscopy of periodic structures are described in the context of recent developments in the mathematical harmonic analysis community, with hopes of inspiring further development along these lines. Applications here, which push present day limits using sharp-edged Fourier windows alone, include the location of weak periodicities in images by virtue of their spatial correlations, and the quantitative mapping of projected strain in a variety of nanostructures.

Figure 1 illustrates the "sinc windowlet" transition between direct and reciprocal space for a pair of two dimensional crystals. This is similar to the way this transition between direct and reciprocal is done in electron optical systems, because it's natural with electrons to build "sharp-edged" apertures. In digitized high-resolution electron phase or z-contrast images, however, many other functional decompositions are possible for making this transition e.g. [1,2]. Moreover, because high resolution electron images often contain specimen-relevant phase information not found in stand-alone diffraction images, the complex darkfield images that one encounters during the transition between direct and reciprocal allow one to quantitatively map lattice displacements and strains, as well as to digitally search for hidden patterns.

In Figure 2, we illustrate with a number of applications. The four panels in the upper left corner of the figure represent complex color darkfield images using two different diffraction spots from an icosahedral twin, oriented down it's 5-fold axis, with the corresponding coordinate color phase gradient (strain) maps to the right of each. More recent work (to be published separately) shows that for randomly-oriented icosahedral twins, the tiling of reciprocal space with a 32×32 array of tiny darkfield images often allows one to confirm their icosahedral nature via sighting of these characteristic "bowtie" and "butterfly" patterns somewhere in the frequency space of that image.

The bottom left of Fig. 2 illustrates a different problem: The mapping of columnar growth in epitaxial Cu_2O on Si. The brightfield image is in green, while a darkfield image formed from substrate Si reflections is in blue. A darkfield image using periodicites in a single Cu_2O column whose planes run about 4° off the growth axis allows one to track the column from bottom to top.

The last example illustrates the mapping of picometer-scale strains in a specimen of strained silicon on silicon-germanium. One begins with a lattice image. A periodicity in the Fourier transform of this image is (using a strategy recommended to us in a note by Owen Saxton) then "translated to the origin" and inverse transformed. This action in effect chooses the reference periodicity of interest. The gradient of Fourier phase in the resulting complex darkfield image is then separated into isotropic strain components (parallel to the operating reflection) and shear strain components (perpendicular to the operating reflection). These are shown in the images below.

References

[1] A. G. Flesia, H. Hel-Or, A. Averbuch, E. J. Candes, R. R. Coifman, and D. L. Donoho, *Digital implementation of ridgelet packets* (Academic Press, New York, 2001).

[2] F. G. Meyer and R. R. Coifman, *Applied and Computational Harmonic Analysis* **4** (1997) 147.

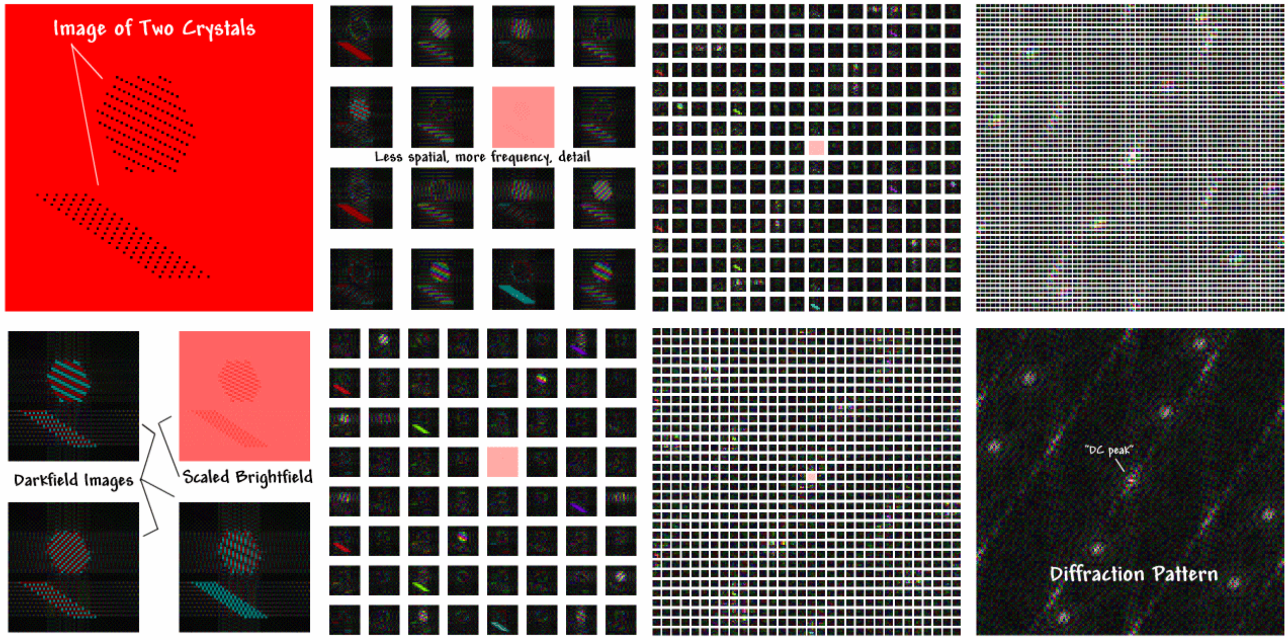

FIG. 1. Series of n×n square Fourier window decompositions running from a real direct space image to the Fourier transform. Hue denotes the Fourier phase of each pixel, with red positive real.

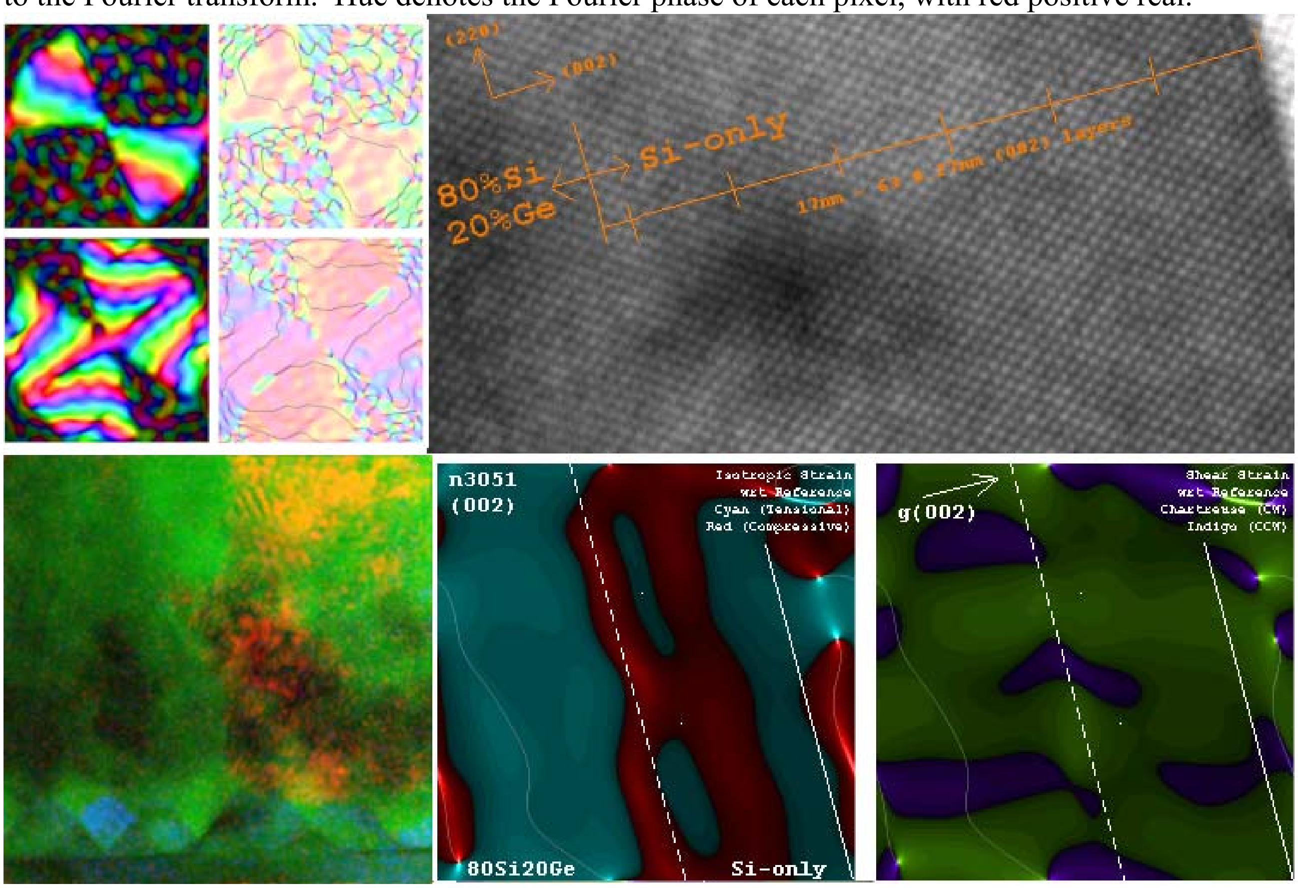

FIG. 2. Top left: complex darkfield images of an icosahedral twin; Bottom left: Cu_2O epi on Si (blue) showing column w/4° tilt (orange); Top right: sSi/SiGe lattice, with strain maps beneath.