Inst. Phys. Conf. Ser. No 138: Section 5
Paper presented at the Electron Microscopy and Analysis Group Conf. EMAG93, Liverpool, 1993

Applications of the optical moiré technique in HREM

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ABSTRACT: The optical moiré technique is used in high resolution electron microscopy to investigate small displacements in lattice images. Rigid body shifts of a silicon lattice, extra half planes at dislocations, and distortions in the electron microscope are examined. Reciprocal space vectors of the lattice and moiré fringes help to interpret the patterns.

1. INTRODUCTION

In the optical moiré technique of Dahmen et al. (1990) and Hetherington (1990), an artificial array of dots (also referred to as a "reference lattice") is overlaid onto a lattice image in order to generate a moiré pattern. The resulting patterns are similar but distinct from the standard moiré patterns of crystals that overlap within the thin foil in the microscope (see for example Hirsch et al. 1977). The optical moiré fringes provide a clear and amplified display of small distortions or displacements in the experimental lattice image. The patterns may be understood by considering the reciprocal vectors of the moiré and lattice fringes as explained in Hetherington and Dahmen (1992). In particular, displacements such as rigid body shifts or extra half planes are displayed in the moiré pattern in the same sense as in the original image if the moiré is of the so-called positive parallel type.

2. EXTENDED DEFECTS IN SILICON

Fig. 1a) shows two dissociated dislocation-like defects lying on $(11\bar{1})$ planes. They were encountered in a SiGe/Si (001) sample which had bowed dislocations into the substrate as part of the relaxation mechanism. The moiré pattern of fig. 1b) was formed using the fringes associated with the other, non-parallel set of (111) planes and the reciprocal vectors are shown approximately to scale, in fig. 1c). Away from the defects, the moiré fringes run parallel to the experimental lattice fringes and the reference lattice fringes; in reciprocal space the vectors are collinear. Bending of moiré fringes implies a bending of the (111) fringes in the experimental image. At *A*, this is due to actual bending of the lattice planes around the defect. At *B* however, it is thought to be due mainly to a distortion of the image near to the edge of the microscope plate (see section 4). The orientation of the (111) fringes in the original image, and hence the magnitude of the bending, are found by drawing the reciprocal vectors of the reference lattice and of the moiré fringe, then completing the triangle to obtain the reciprocal vector of the silicon (111) fringe. At region *B* in fig. 1c), the rotation of 20(±2)° of the moiré fringe corresponds to a rotation of 1.05(±0.18)° of the silicon lattice fringe.

The precise nature of the defects *C* and *D* is not yet clear, but the moiré pattern does reveal a single inserted half plane at defect *C* and two inserted half planes at defect *D*. The termination of one of the half planes at *D* appears from the moiré pattern to lie about 16 planar spacings above the $(11\bar{1})$ plane of the stacking fault in the defect, indicating the occurrence of a climb

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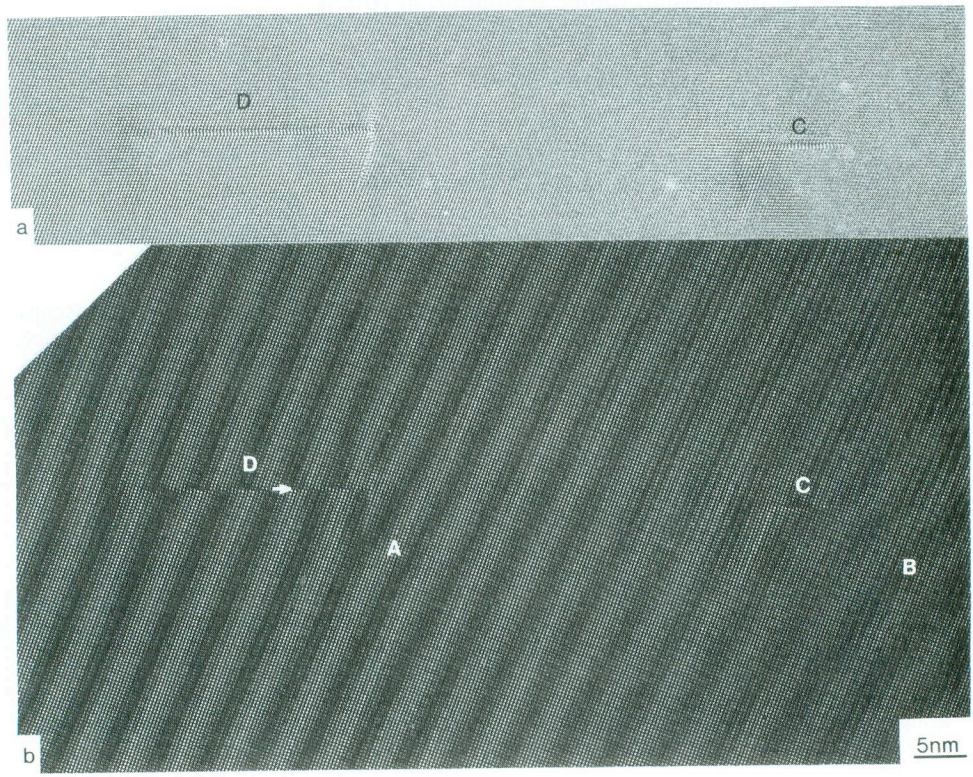
process. The relative displacement of the moiré fringes across the stacking fault, which is by definition the same as the relative displacement of the (111) fringes, is easily measured. The displacement of one third of the fringe spacing (see arrow) indicates an intrinsic stacking fault.



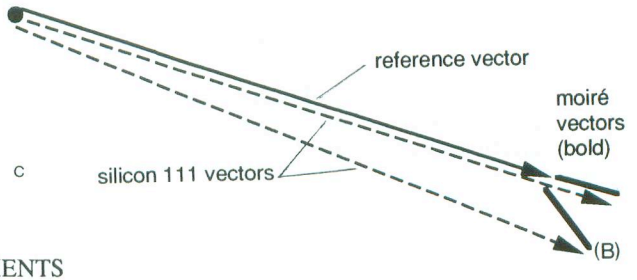


Fig 1a) HREM [1$\bar{1}$0] image of defects in silicon, b) moiré pattern (shown at same scale), c) reciprocal space vectors from general region and from area *B*.

3. RIGID BODY DISPLACEMENTS

The ability of the optical moiré technique to examine lattice fringes across a wide area of an image make it a useful technique for the detection and measurement of rigid body displacements. In the case shown here, the possible contraction of a silicon lattice across a delta-doped layer of boron is investigated. Delta doping is the introduction of a very thin layer of a dopant during the growth process. The resultant small structural modification has been investigated through a Fresnel Contrast Analysis by Dunin-Borkowski et al. (1993), although by that method, measurement of the rigid body displacement would be indirect. Accurate measurement of rigid body displacements by HREM is often hindered by buckling of the specimen, random thickness variations due to uneven surfaces on the specimen, and specimen or microscope misalignments. These factors can cause a shift of the image dots even when there is no shift in the specimen lattice. However, the technique of preparing a cross section

by cleaving (as described by Hetherington, 1988) was possible in this case and the resulting wedge shaped specimen helped to minimise the problem.

Figure 2a) shows the cross section aligned at a [100] zone with (022) and (02$\bar{2}$) fringes forming the lattice image. The boron layer, arrowed, was located from the image in slightly thicker crystal. Any contraction along the normal to the layer would result in a "dogleg" in the silicon {022} planes. The moiré pattern in fig 2b) was generated by a square array of dots and hence consists of two sets of moiré fringes, arising from interference with (0$\bar{2}$2) and (02$\bar{2}$) fringes. A particular problem occurs with the {022} fringes moving into the wedge since the image character changes with the rapid thickness increase. In order to overcome this, the experimental lattice was rotated anti-clockwise in order to align the moiré fringes normal and parallel to the wedge edge as shown in fig. 2c). Figs. 2d, e and f) show schematically (and not to scale) the origin of the moiré patterns in reciprocal space.

In fact, no "dogleg" is seen in the vertical moiré of fig 2c) which means that any contraction is below the detection limits of this technique, estimated here to be 0.02nm (corresponding to a displacement of 10% of the fringe spacing). An alternative strategy is to use the regression analysis technique of Wood et al. (1984) which measured the contraction to be 0.006nm.

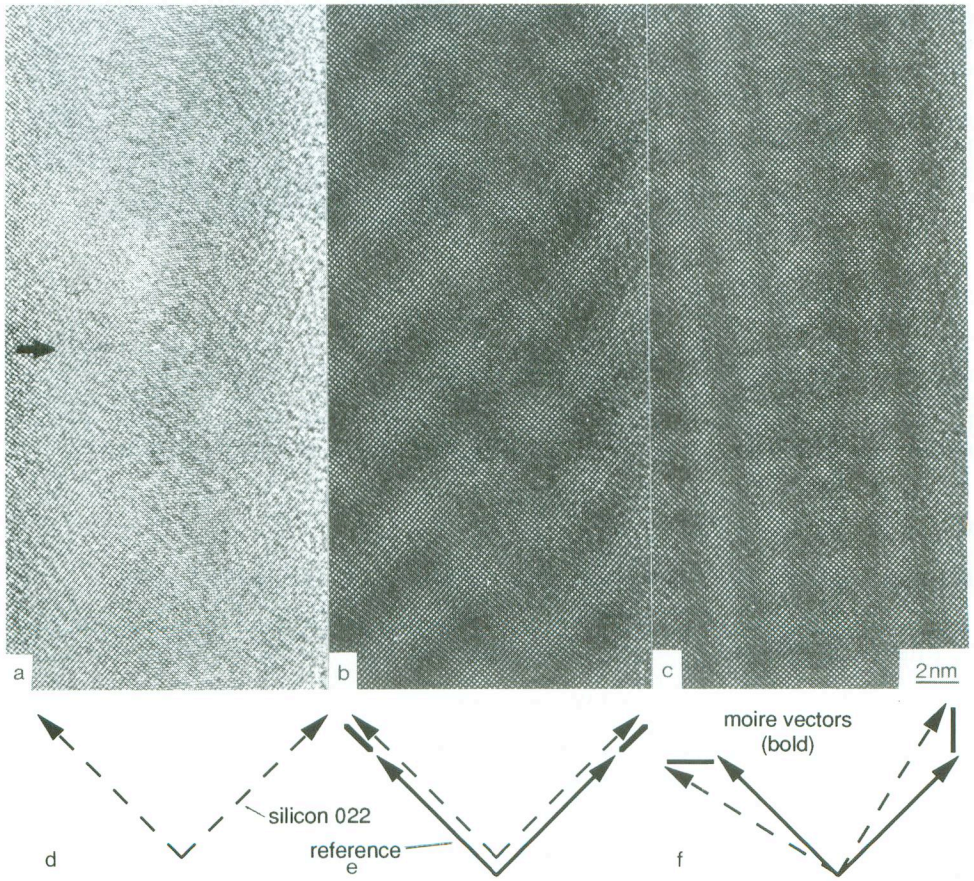


Fig. 2a) Wedge of silicon with boron layer arrowed (edge of specimen on right hand side), b) moiré fringes parallel to the {022} fringes and c) rotated to run (approximately) parallel and perpendicular to the thickness contours. d), e) and f) reciprocal space vectors.

4. MICROSCOPE DISTORTIONS

Imperfections in the imaging lenses lead to distortions in HREM micrographs. In order to investigate this, a specimen with a near perfect lattice (i.e. uniform thickness and no buckling) is preferred. An annealed thin foil of Al_2O_3 comes close to satisfying these requirements and the region used here has only one surface step across an area of 200nm square. Two identical plates were exposed in the microscope at X400k, the [0001] zone giving three sets of fringes of spacing 0.24nm. In this preliminary investigation, one plate was reversed about the vertical axis and aligned on top of the other to form a moiré pattern due to the slight rotation between the lattices (approx. 3° at the centre). A contact print, shown in fig. 3, was made in order to avoid possible distortions from a photographic enlarger. The bending and expansion of the moiré fringes towards the edge of the plates reveal a rotation in the lattice image of the order of 1° relative to the centre; work is now in progress to assess the distortions present in images from different microscopes.

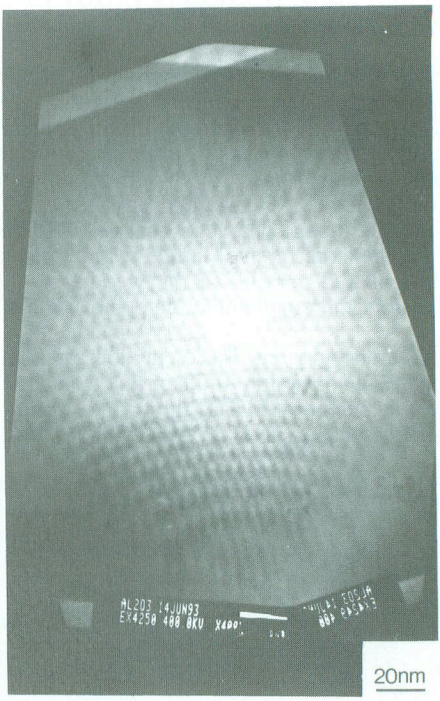


Fig. 3 Distortions from microscope imaging lenses (see text for details).

5. CONCLUSIONS

The optical moiré technique has helped to analyse defects in silicon by displaying the termination of inserted half planes and the displacement of (111) fringes on crossing a stacking fault. A rigid body displacement across a thin boron layer in silicon was investigated but not detected by the technique. Distortions from the imaging lenses at typical magnifications (X400k) may be significant if the full width of the EM film is considered.

6. ACKNOWLEDGEMENTS

R Kubiac and E H C Parker of Warwick Univ. and G Botton are thanked for samples.

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