

## Investigating Defect Contrast in $\text{Ge}_x\text{Si}_{1-x}/\text{Si}$ Epitaxial Structures Using Electron Channeling Contrast Imaging

Joseph Tessmer<sup>1</sup>, Marc DeGraef<sup>1</sup>, Yoosuf N. Picard<sup>1</sup>

<sup>1</sup> Dept. of Materials Science and Engineering, Carnegie Mellon University, Pittsburgh PA, USA

Defects in crystalline materials can have a large impact on performance and properties. These defects, including misfit dislocations that emerge during epitaxial growth, have traditionally been imaged and characterized in the TEM, where multiple imaging modes can reveal information about dislocation type and location. However, sample preparation for TEM is both time-consuming and destructive. Additionally, the area of the sample available for imaging is small, making investigation of large sample areas unfeasible. Electron Channeling Contrast Imaging (ECCI), an imaging technique in the SEM utilizing strain contrast, has significant upsides when compared to TEM. Firstly, samples for use in the SEM require little to no preparation, saving significant time and effort compared to TEM. Additionally, the ability of the SEM to accommodate large samples means that imaging over large areas is not significantly harder than imaging over small areas. Electron Channeling Patterns (ECPs) are an integral part of ECCI observations. By rocking the beam, the angle of incidence relative to the plane normal can be changed. This angular change reveals contrast bands resulting from Kikuchi diffraction. The positions, sizes, and angles of these bands depend on the structure and orientation of the sample [1].

The strain contrast in ECCI responds to changes in multiple different imaging parameters. Accelerating voltage, beam current, and sample tilt and rotation can all affect the contrast of the image. Once an ECP has been acquired, tilting and rotating the stage to select a channeling condition is similar to selecting a  $\mathbf{g}$  vector in the TEM. Defect contrast depends strongly on the value of  $\mathbf{g} \cdot \mathbf{b}$  for each particular defect. Contrast inversion for prismatic defects can be observed by selecting opposite  $\mathbf{g}$  vectors. By selecting several different channeling conditions, it is possible to not only image the density of crystalline defects, but to determine the allowed directions of their associated Burgers vectors  $\mathbf{b}$  [2].

$\text{Si}_x\text{Ge}_{1-x}/\text{Si}$  has misfit defects that lie at the epitaxial interface. Upon initial investigation, these appear to be long, straight defects in a crosshatch pattern. However, upon further imaging, these contrast features are revealed to have a fine structure of prismatic features of varying type. By selecting multiple different  $hkl$  values for  $\mathbf{g}$  from the ECP, possible  $\mathbf{b}$  vectors for each of these interfacial defects can be identified (Fig. 1). Additionally, shifts in the appearance of the composite contrast features can provide further information as to the nature of the dislocations present at the interface [2].

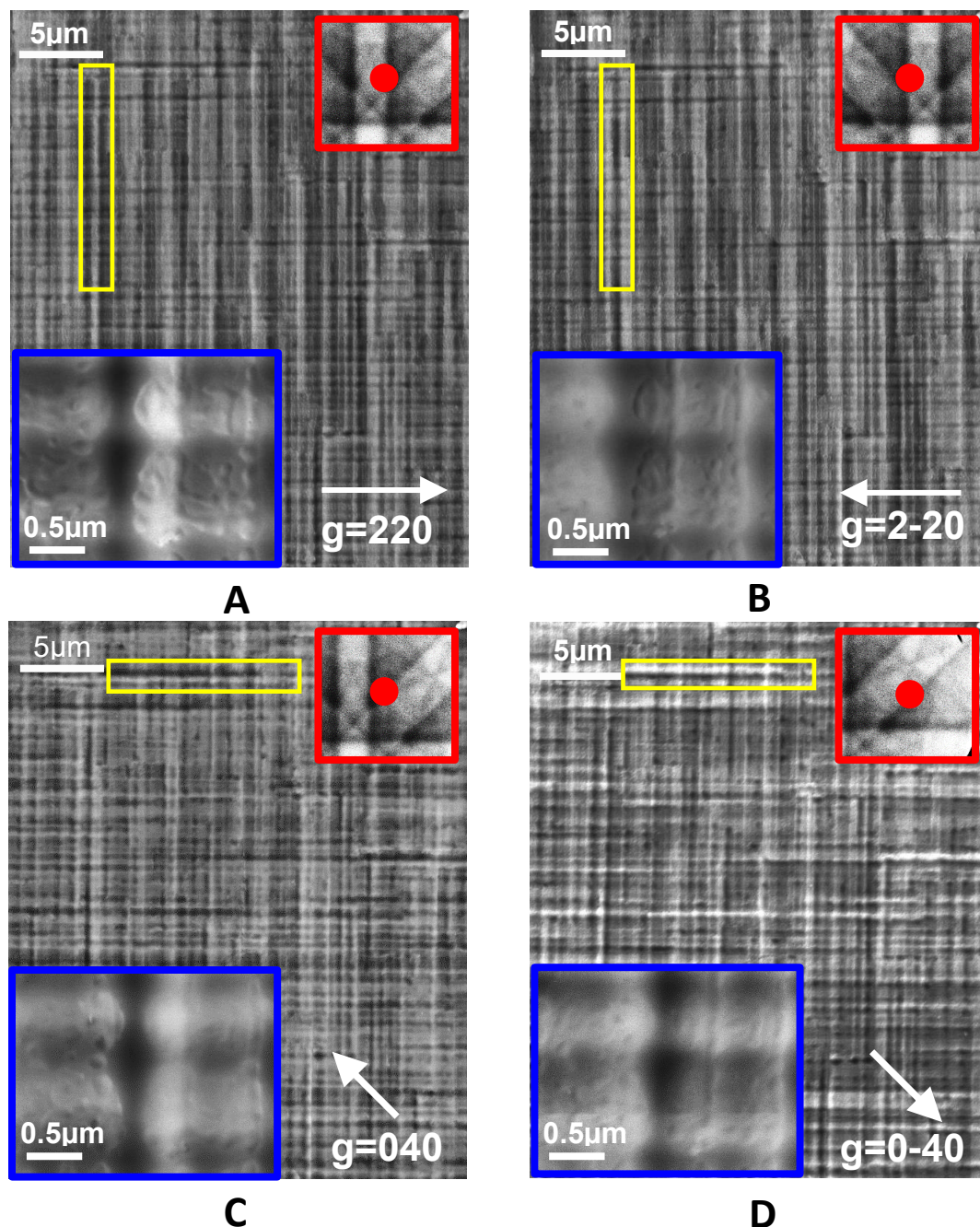
Based on visibility changes for different selected  $\mathbf{g}$ , the crosshatch dislocations appear to have  $\mathbf{b} = a/2 \langle 110 \rangle$ . The perpendicular  $\mathbf{b}$  vectors are responsible for shifts in the highlighted dislocations between horizontal and vertical when selecting  $\mathbf{g} = \langle 220 \rangle$ . Additionally, this explains the visibility of both horizontal and vertical dislocations for  $\mathbf{g} = \langle 400 \rangle$ . The fine prismatic dislocations also show contrast inversion, though they are expected to have  $60^\circ$  character rather than pure edge character [3] [4].

### References:

- [1] Picard, Yoosuf N., and Mark E. Twigg, *Journal of Applied Physics* **104.12** (2008): p.124906.
- [2] Carnevale, Santino D., *et al*, *Applied Physics Letters* **104.23** (2014): p. 232111.

[3] Kvam, E. P. *et al*, Journal of Materials Research **5.09** (1990): p.1900.

[4] Research supported by an ONR grant, # N00014-16-1-2821. The authors acknowledge use of the Materials Characterization Facility at Carnegie Mellon University supported by grant MCF-677785.



**Figure 1.** ECCI SEM micrographs of SiGe misfit defects imaged at 20kV and 10mm working distance with a BSE detector at A)  $g=220$ , B)  $g=2-20$ , C)  $g=040$ , D)  $g=0-40$ . Contrast inversion is visible in overlaid boxes from A-B and C-D. Upper right inset: ECP micrograph denoting selected  $g$ . Lower left inset: Higher magnification ECCI micrographs showing fine structure.