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Strain analysis for advanced semiconductor devices

Scanning X-ray diffraction microscopy (SXDM) provides a quantitative picture of the materials homogeneity in silicon–germanium substrates and other advanced semiconductor device architectures.

Context

Silicon, the workhorse of the semiconductor industry for half a century, is coming up against its physical limitations. To continue driving the increased speed, miniaturization and functionality of microelectronics, manufacturers are pairing silicon with other materials in order to enhance its properties. This “More than Moore” approach demands sophisticated characterization techniques that can probe complex nanoscale structures embedded in semiconductor devices.

A powerful non-destructive technique developed at ESRF beamline ID01 called scanning X-ray diffraction microscopy (SXDM) allows industry researchers to detect the slightest imperfections in the crystalline structure of heterogeneous structures and thin films, even deep within a stack of different layers. Offering an unprecedented strain resolution of a few parts per million and a spatial resolution of 100nm, the technique is being trialed by IRT Nanoelec partners to forge the next generation of micro- and nano-electronics.

The challenge

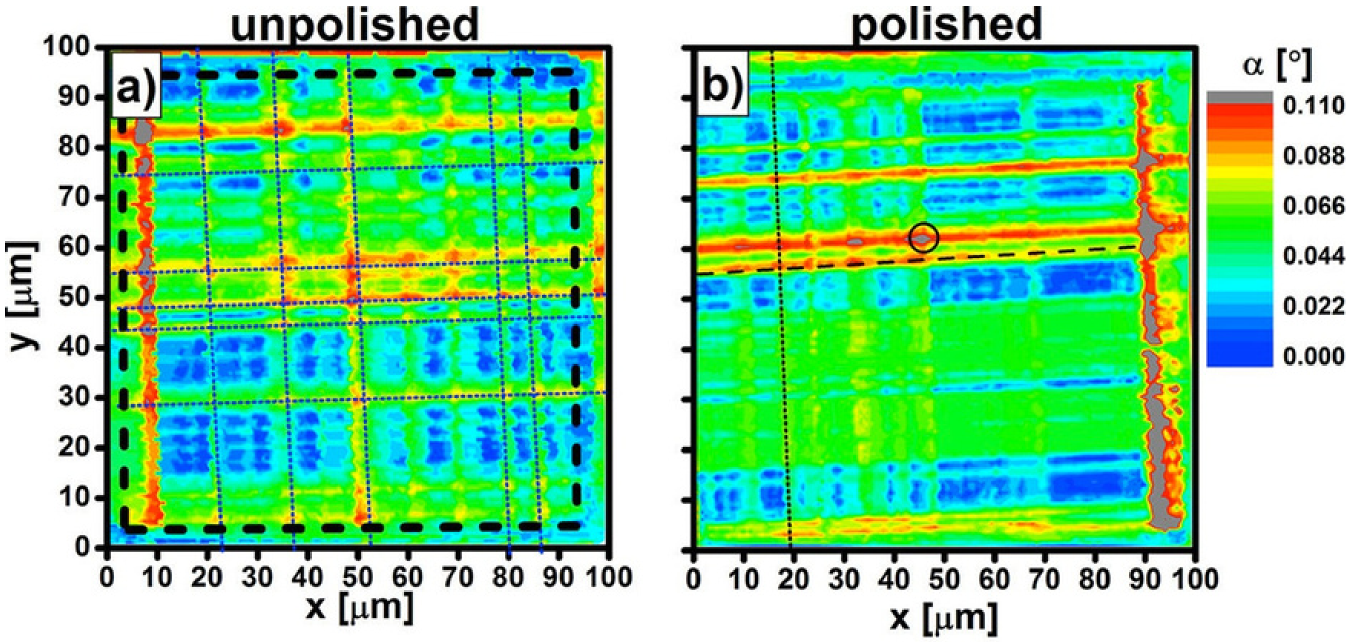
Any imperfections in the microscopic structure of materials, such as defects or variations in the orientations of the crystal lattice, can severely affect the growth and thus performance of semiconductor devices. This is critical when matching silicon with another material such as germanium to create new chip architectures, since it creates greater structural complexity and new interactions that must be understood.

In conjunction with ESRF staff, wafer manufacturer Siltronic investigated a sample comprising step-graded silicon-germanium layers on 300mm silicon wafers, which is a promising substrate for sub-20nm CMOS transistors and other advanced architectures. The aim was to measure the lateral distribution of tilt and strain across the system, as well as its composition, and to compare these parameters when the wafer was treated with and without chemical−mechanical polishing.

The results

The high penetration depth and small spot size of the ESRF X-ray beam allowed the team, in conjunction with laboratory based AFM and Raman techniques, to establish a partial correlation between real-space morphology and structural properties of the sample at the micrometre scale. The results show a strong local correlation between the strain field and composition distribution, indicating that the adatom surface diffusion during growth is driven by strain field fluctuations induced by the underlying dislocation network.

The data also revealed that superficial chemical−mechanical polishing of surfaces does not lead to any significant change of tilt, composition or strain variation compared to that of as-grown samples -- even for very different surface morphologies (see figure).



Maps showing the absolute lattice tilt in as-grown (left) and polished (right) Si0.3Ge0.7 layers, revealing the well-known crosshatch pattern caused by surface undulation of lattice-mismatched surfaces. The similarity between the two panels demonstrates that polishing does not affect lattice orientation, which is important during the growth of semiconductor structures. [Ref. ACS Appl. Mater. Interfaces ***7*** *9031].*

Conclusion

SXDM provides a model free, nondestructive and quantitative method for rapidly extracting key parameters in silicon-germanium films - such as strain, lattice tilt and fluctuations in composition - without any surface or morphological limitations. Its exceptional strain sensitivity and resolution can be applied to any crystalline object, even polycrystalline thin films, and is relevant for ferroelectrics, MEMS and 3D integration of chips.

The technique is therefore of great value to device engineers when evaluating variations in state-of-the-art CMOS and other advanced technologies that cannot be achieved with any other existing method.

The technique

- Scanning X-ray diffraction microscopy (SXDM) is a unique synchrotron X-ray technique that allows rapid and continuous mapping of lattice strain and tilt with sub-micrometre resolution.
- Samples can be semiconductor devices, homogenous materials, thin films and beyond, and can be up to 400mm² in area and 20mm thick.
- X-rays are aligned around the nominal Bragg conditions of the sample and a 2D detector monitors the diffraction signal while the sample is moved using an x-y piezo stage.
- Five-dimensional datasets built from millions of detector images are automatically processed to generate 2D maps of tilt and strain, using in-house software that allows preliminary results to be extracted during an experiment.
- The application of such fast scanning methods offers the possibility of performing *in operando* studies at high temperatures or in gas or liquid environments.