The Lattice Strain Distribution in Ge_xSn_{1-x} Micro-Disks Investigated at the Sub 100-nm Scale

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Abstract

The local lattice distortion in a crystal, the lattice strain, greatly influences the physical mechanisms underlying the operating principles of semiconductor devices. For example, strain is widely used in the bandgap engineering of group IV-based optoelectronic devices to improve their performance. In the case of GeSn-based light emitters, optimization of the lattice strain allowed the demonstration of optically pumped lasing at room temperature [1] and cw operation in an electrically pumped µ-disk laser [2], thanks to its beneficial effect on the "directness" of the bandgap, leading to increased material gain. It is therefore of paramount importance to characterize the strain with high sensitivity and sub-micron spatial resolution.

Here we show how scanning X-ray diffraction microscopy, a recently developed model-free method based on synchrotron radiation [3,4], can be used to fully determine the landscape of mechanical deformation and stoichiometry fluctuation in a lithographically fabricated $Ge_{1-x}Sn_x$/Ge suspended µ-disk, a structure of the same type as that used to demonstrate the first GeSn laser [5].

The full strain tensor of the entire microstructure, including all normal and shear components, is tomographically reconstructed with a lateral resolution of less than 100 nm and a sensitivity to strain variations of the order of 10^{-4}. By comparing the lattice deformation in different sections of the microdisk, we observe a marked difference between the central pillar region in contact with the virtual Ge substrate and the free-standing outer rim where the Ge layer has been removed. Interestingly, although the misfit dislocation network at the GeSn/Ge relaxed heterointerface in the rim region has been removed during the fabrication process, we observe that a "fossilized" footprint of the dislocations is still present in the strain landscape of the layer. We attribute this to stoichiometric fluctuations that we measure in the $Ge_{1-x}Sn_x$ alloy generated by dislocation-driven strain fields during epitaxial growth, which are unaffected by etching and in turn generate a local strain field.

We then exploit the symmetries of both the microdisk and the Ge1-xSnx material system itself. This allows us, for the first time, to calculate maps of the surface normal stress in an alloyed epitaxial thin film, which is traditionally difficult to impossible to disentangle from stoichiometric fluctuations in diffraction-based data, and is a key piece of information to evaluate in epitaxial layer growth.

We complement the synchrotron experiments with electron microscopy and dedicated finite element method (FEM) simulations of both elastic and plastic relaxation processes in the model system, finding excellent agreement between experiment and theory. Furthermore, the effects of strain on the band structure are predicted in the light of the measured local variations in strain and composition.

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