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Advances in heteroepitaxial integration of III-V and IV-VI semiconductors with electron channeling contrast imaging

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Understanding the behavior of crystal defects like dislocations remains key to successfully integrating dissimilar semiconductors for new paradigms in electronics and photonics. Dissimilarities in compound semiconductors arise not only from a mismatch in the lattice parameter but also thermal expansion, crystal structure, or bonding and these differences must be mediated effectively to control the formation of crystal defects. Dislocations degrade the properties of semiconductors and have thwarted attempts to directly grow III-V telecom lasers on silicon CMOS circuits as they facilitate rapid degradation. [1] Likewise, dislocations reduce the efficiency and performance of infrared detectors grown on highly mismatched substrates. [2] Yet, thanks to an improved understanding of dislocations through microscopy, we continue to learn about their unique properties and uncover new ways to manage them to realize the vision of heterogeneous integration. We describe three examples from our work where non-destructive electron channeling contrast imaging (ECCI), a technique refined more than two decades ago [3,4], has yielded unique insight into the materials science of heteroepitaxial integration of compound semiconductors, pointing the way to high quality materials and devices.

The reliability of 1.3 µm wavelength InAs quantum dot (QD) lasers on silicon remains limited by dislocations [5]. While reducing the threading dislocation density has long dominated efforts in the field, recent evidence shows misfit dislocations next to the QDs may be to blame. We verify using ECCI that misfit dislocations form due to thermal expansion mismatch and lattice hardening, as opposed previously suspected lattice-constant mismatch [6]. Electron-hole pairs generated by the primary SEM beam facilitate recombination-enhanced dislocation glide and we identify the driving force of thermal strain in situ via observations of growing misfit dislocations via ECCI. These findings have led to new laser designs on silicon that displace the misfit dislocations away from the active region, resulting in record performance and reliability in the field of silicon photonics [6].

Moving from in-situ observations to site-selective approaches, ECCI has played a pivotal role in identifying pipe-diffusion operating along threading dislocations in lattice-mismatched InGaAs/Ge/Si structures by guiding atom probe tomography [7]. The density of threading dislocations in device-quality III-V semiconductors is typically much lower than worked-metals, so traditional atom probe tomography of randomly extracted sites fails to capture dislocations. We use ECCI to locate clusters of threading dislocations to direct the preparation of atom probe tips. Such an approach has successfully revealed rich physics of pipe diffusion, simultaneously transporting and intermixing indium from InGaAs and germanium atoms from the buffer. At the same time, we see limited solubility at the dislocation core of these atoms even for fully miscible alloys such as InAs in GaAs; we suspect this is likely limited by coherency strain. Such atmospheres are distinct from Cottrell atmospheres predicted to form via segregation in bulk semiconductors and may play a key role in determining the electronic properties of dislocations in real devices.

In the integration of even more dissimilar materials, we use ECCI to reveal the dislocation structure formed during Volmer-Weber island growth of rocksalt-structured narrow bandgap IV-VI semiconductor

PbSe grown epitaxially on InAs and related substrates [8,9]. We find that the 2×1 surface reconstruction of the (001)-InAs surface templates PbSe into tall rectangular islands, yielding highly asymmetric dislocations at the interface and nearly uniaxial strain in these films. In addition to misfit dislocations, ECCI and the related orientation contrast method shows how the coalescence is slowest along low-angle misoriented grain boundaries and at threading dislocations and yields insight into the growth mechanism.

The non-destructive nature and ease of use of ECCI has the potential to transform lattice-mismatched growth of semiconductors, in both traditional semiconductors as well as emerging ones. We anticipate ECCI continuing to play a leading role not only in routine metrology and defect characterization but also in uncovering structure-property relationships of dislocations at length and time scales and in device geometries that nicely complement more detailed microscopy and microanalyses.

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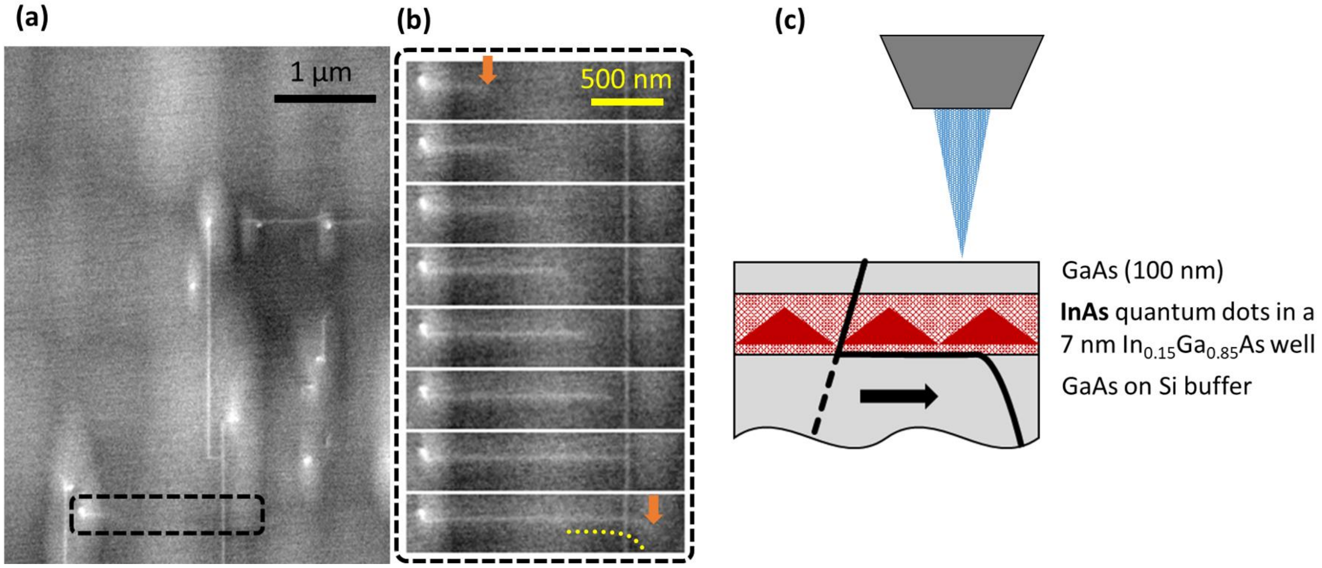

Figure 1. Electron channeling contrast image (ECCI) of a single InAs QD layer in a 7 nm In0.15Ga0.85As quantum well capped with a 100 nm GaAs layer synthesized on a GaAs/Si template. (a) A number of misfit dislocations are seen despite the QD layer being below critical thickness with respect to GaAs. (b) Irradiation by the primary beam of the SEM results in recombination-enhanced dislocation glide which leads to misfit dislocation growth, seen in-situ over a 500 s time lapse using a 30 kV beam with an (400)/(220) channeling condition. (c) Examination of the fixed and moving threading dislocation segments reveals dislocation glide only in the lower GaAs layer, not the InAs QD layer due to lattice hardening in the InAs QDs. This implicates the thermal expansion mismatch between the III-V layers and silicon in providing the driving force to form misfit dislocations.

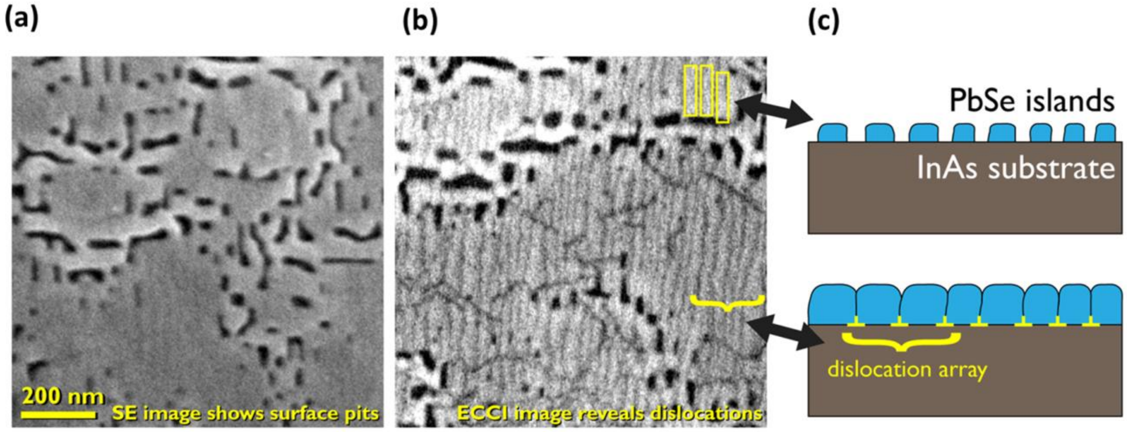

Figure 2. Secondary electron and electron channeling contrast image (30 kV, (400)/(220) channeling) of two separate areas of partially coalesced films comprising 15 monolayers (~ 5 nm) of PbSe on (001)-InAs prepared with a 2x1 surface reconstruction. A series of misfit dislocations along the [110] form due to coalescence of elognated PbSe islands. The coalescence is slowest around misoriented grains seen via orientation contrast.

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