Atomic resolution HR(S)TEM and EDXS analyses of GaInAs/GaSb and GaInP/GaSb bond interfaces for high-efficiency solar cells

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The use of direct wafer bonding to combine semiconductor materials that have a large lattice mismatch is especially beneficial for high efficiency multi-junction solar cells. Multi-junction solar cells that have been fabricated by wafer bonding are of particular interest since efficiencies of up to 46% have been obtained [1] and efficiencies of up to 50% are within reach for concentrator solar cells based on III-V compound semiconductors. Fast atom beam activation is used as a pre-treatment to remove oxides and contamination before bonding [2]. Aberration-corrected transmission electron microsocpy (TEM) analyses of GaAs/Si interfaces have previously been applied successfully to support the implementation of bonding concepts for the development of high-efficiency solar cells [3].

Here, we investigate cross-sectional specimens of GaInAs/GaSb and GaInP/GaSb bond interfaces in wafer-bonded multi-junction solar cells, in order to obtain an improved understanding of their interface structures and thermal stability, by combining aberration-corrected high-resolution TEM (HRTEM), high-angle annular dark-field scanning TEM (HAADF STEM), energy-dispersive X-ray spectroscopy (EDXS) in the STEM and *in situ* TEM heating experiments.

Figures 1a-e shows results obtained from the GaInP/GaSb bond interface. Fig.1a shows the interface at low magnification. Figure 1b shows an HRTEM image, which reveals an amorphous interface layer (~1 nm thick). Figure 1c shows an atomic resolution HAADF STEM image of the bond interface structure and a digital diffractogram (inset), revealing a nearly perfect structural orientation relationship between the two crystalline layers. When correctly positioned with respect to the HAADF image, elemental maps extracted from EDXS spectrum images (Figs 1d and 1e) reveal that a high level of Ga is present at the interface. The Ga can be attributed to the pre-treatment procedure and bonding conditions. *I situ* thermal treatment of this interface results in pronounced interdiffusion for temperatures above 225°C (not shown here).

Figures 2a-c show the GaInAs/GaSb bond interface, which is decorated by pores and cavities that extend along the interface by more than 10 nm. As a result of the use of misoriented wafers for bonding, the crystal lattices are rotated with respect to each other by a few degrees (Figs 2b and 2c).

Our results confirm that the advanced imaging and spectroscopic methods of aberration-corrected (S)TEM are advantageous for characterizing the morphology, elemental distribution and structure of layers and bond interfaces for the monitoring, control and optimization of different concepts used for fabricating high-efficiency solar cells. Out results are also of interest for assessing electrical conductivity phenomena at these interfaces.

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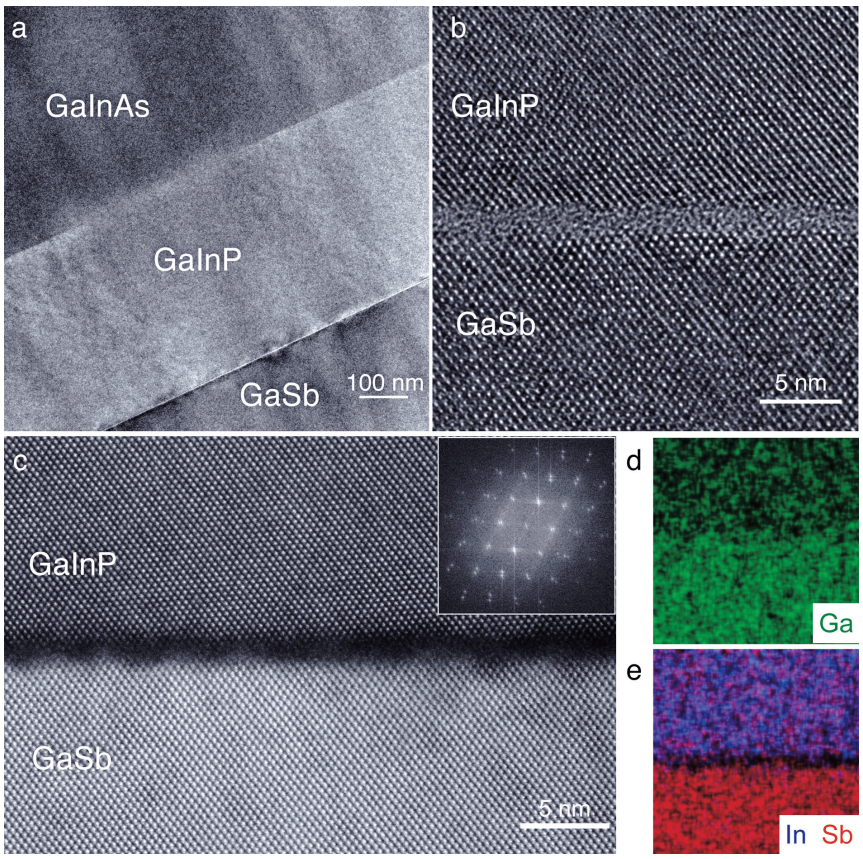

Figure 1. GaInP/ GaSb bond interface. <110> zone axis orientation.

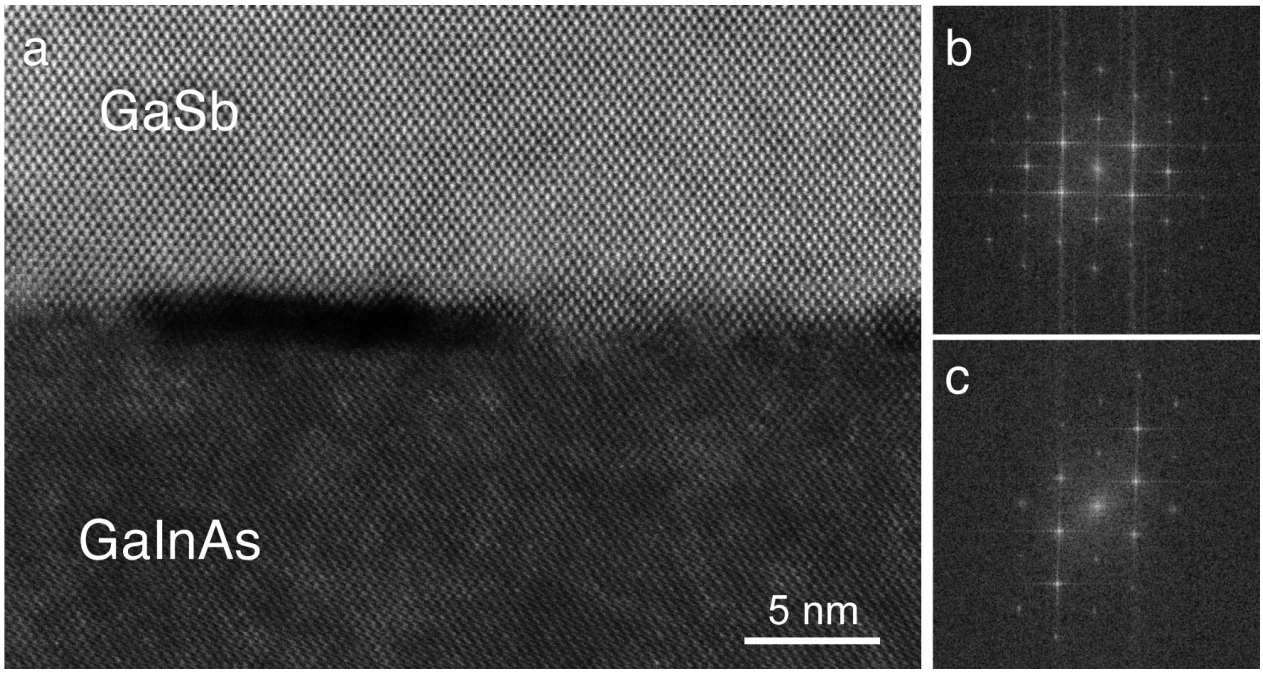

Figure 2. GaInAs/GaSb bond interface. <110> zone axis orientation.