Multiphysics 3D study of compound semiconductor nano-structures via scanning probes

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While silicon technology dominates the mainstream microelectronics market, compound semiconductors (CS) consisting of two or more elements, such as GaS, InAs, AlN, offer solutions beyond capabilities of Si, in particular as light sources for data communications and lighting, and as platforms for high frequency and power electronics. Combining CS with Si production technology can provide both efficient manufacturing and unique functional capabilities. Unfortunately, the engineering of advanced CS structures remains highly challenging - defects stemming from the interfaces between dissimilar materials, and inhomogeneous strain and incompatible growth conditions of different layers represent just a small part of major obstacles in realising new CS devices. With key elements of new structures usually hidden under surface layers - including single and multiple quantum wells, and/or have a complex geometry of nanowires (NW) and quantum dots (QDs), the capabilities for their study with required nanoscale resolution are quite limited. The best approach to-date of cross-sectional TEM allows to map local defects and to reveal strain, but it does remains highly laborious, provides a view of a very small and not always representative fraction of the sample, and, most essentially, is not capable to measure key mechanical, thermal and electronic properties of these nanostructures - the ones that ultimately define their performance.

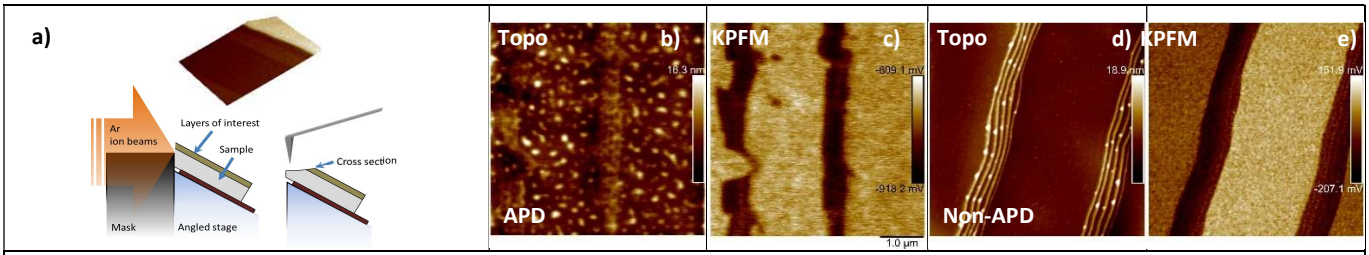

FIG 1. a) Principle of the BEXP™ nano-cross-sectioning with 3D rendering of the sample cut, b), d) – topography and c), d) contact potential of the iii-v multiple quantum wells (MQW) structures grown on Si with (b), c) and without d), e) antiphase domains (APD). A regular non-APD and defects in APD structure revealed in the section, with non-APD structure showing superior electrical potential regularity.

Here we demonstrate a novel methodology for the 3D mapping of the CS nano-structures and devices, which combines the Beam Exit Cross-Sectional Polishing (BEXP™) invented by Lancaster researchers, with materials sensitive measurements of local physical properties via Scanning Probe Microscopy (SPM).[1] The BEXP uses converging Ar ion beams that are shaped in a narrow slit by the tungsten mask that cut the sample surface from the side at a shallow angle. Such geometry allows to preserve the intact top surface of the sample that never faces the beam, and to create an obtuse (170-175 deg) cross-section of the sample. The resulting surface has near-atomic roughness, well below 1nm RMS, and extends from nm under the immediate surface to many um in depth across the sample 3D structure, with the section width on the macroscopic sub-mm range. The key BEXP™ features - low angle cut adjacent to the intact top surface, increased depth sensitivity due to the low angle cut, near-atomic roughness and an absence of surface material modification due to the inert nature of Ar beam, produce a perfect sample for material sensitive SPM studies.

In this work we report 4 physical properties contrast modalities – (i) nanomechanical mapping of sections via Ultrasonic Force Microscopy (UFM) that has superior contrast to mechanical properties of stiff materials[2], (ii) electron affinity via contact potential difference (CPD) that probes Fermi level and doping by using Kelvin Force Probe Microscopy (KPFM)[3, 4], (iii) local electrical conductivity via Scanning Spreading Resistance Microscopy (SSRM), and crystal orientation probed via piezoelectric properties sensitive Piezo Force Microscopy (PFM), as well as a “standard” topographical contrast.

We have studied the growth of GaAs/AlGaAs MQW structures with and without antiphase domains (APD) originating at the Si-GaAs interface[5]. We were able to clearly observe the MQW morphology in the nanomechanical UFM contrast, and in KPFM, as well as modulation of local electrical transport in MQW via SSRM. The disruption of the MQW structure due to the APD presence was very clearly seen, and the new phenomenon that these seem to drastically reduce the electrical potential difference generated in the gap between InAs MQW structures (Fig1).

In order to explore a complex 3D structure of "forest" of GaN nanowires grown on Si (Fig 2a), we used a layer of "dummy" spin-on-glass (NDG-7000) that created a uniform non-interacting layer with GaN and high quality BEXP™ sections. That allowed high quality observation of a nanomechanical contrast across the NW and at NW/Si interface, that also indicated local inhomogeneities in the NW section. The KPFM contact potential showed an equally high quality contrast between NW, Si and spin-on-glass, and can be explained by the large 3.4 eV bandgap of GaN compared to 1.1 eV bandgap of Si. At the same time, the phase PFM contrast unexpectedly showed a surprising features within the NW (Fig 2d). These indicated the different polarity of the growth that can occur within the same NW. This capability to monitor the polarity of iii-v nitride nanostructures can provide a significant impact in the development of new efficient light emitters and shed a light on the nature of the CS growth on Si substrates.

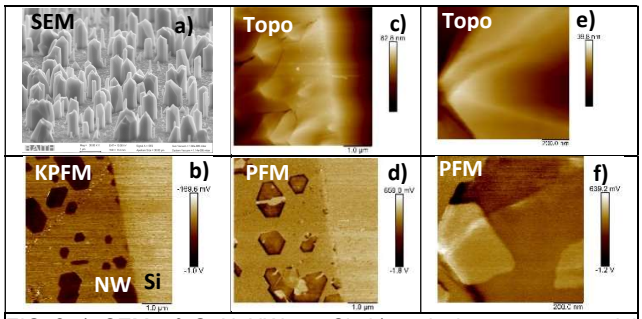

FIG 2.a) SEM of GaN NW on Si, b) typical contact potential difference KPFM map of the GaN-Si at the NW-Si interface, d, f) PFM phase maps (c,d) corresponding – topography images) uniquely showing the polarity of the GaN crystal growth that cannot be observed in the topography or KPFM images.

In conclusion, this work not only proven the feasibility and usefulness of the combination of the BEXP with the material sensitive SPM for studies of 3D structure compound semiconductors, but also demonstrated that it allows to explore both the growth methodology as well as the fundamental electronic and atomistic phenomena in these complex nanostructured materials.

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