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doi:10.1017/S1431927617008236
Microsc. Microanal. 23 (Suppl 1), 2017

Analysis of Amorphous-to-crystalline Germanium Stack with Cs-corrected Analytical STEM

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In recent yeas, various avenues are being explored to increase the efficiency of photovoltiacs devices [1]. In this regard amorphous germanium (a-Ge), a semiconducting material, has excellent optical and electronic properties which make it an excellent candidate for solar cell applications [2]. Moreover a-Ge is a better "selective absorber" than amorphous silicon (a-Si) because the former has lower optical band gap (0. 7 eV) than the latter (1.1 eV) [3]. Given the fact that it has excellent properties, a little attention is paid to its characterization with techniques capable of discerning information at nanometer scale spatial resolutions e.g. with transmission electron microscopy (TEM). Consequently, for a-Ge material, there is dearth of studies showing the structure-property relationships established by using such techaniques. That is why a study, completed by using a TEM of model Titan 80-300 ST from FEI Company in the scanning TEM (STEM) mode, is presented in this paper. The microscope was also equipped with a shperical aberration corrector (Cs-corrector) from CEOS for making a finer probe and Gatan Image Filter (model GIF-Quantum 966) so that Cs-corrected STEM and electron energy loss spectroscopy (EELS) analyses can be used to anlayze these samples. In this study, the [001] oriented crytsalline Ge (c-Ge) samples were grown in a metal organic chemical vapor deposition (MOCVD) system of ASM Epsilon 2000 model. The a-Ge layer, with a target thickess of ~ 30 nanomters was then created via gallium (Ga) implantation (at a dose of ~10^{16} atoms/cm^2) into c-Ge with a 30 keV Ga-beam in a focused ion beam (FIB) system of model Helios 450 from FEI Company. The same FIB system was then utilized later on to prepare [110] oriented cross-section specimen to perform the STEM-EELS analysis of stacks.

An high-angle annular dark-field (HAADF) STEM image of the above mentioned a-Ge/c-Ge stack is shown in Figure 1 A and it reveals the presence of a diffuse interface region (~ 10 nm) along with expected a-Ge and c-Ge layers. The interface region exhibited a lighter contrast than can be attributed to either the presence of high-density Ge regions or the damaged regions created by Ga implantation. High resolution STEM (HRSTEM) image taken from that region (shown in Figure 1B) reveals that the crystal structure of Ge was in fact retained in the region. Geometrical phas analysis (GPA) was applied as well to investigate in-plane and out-of-plane strains (Figure 2 A-B) in the implantated region. Strain maps demonstrated that the amorphousization of Ge took place via the process of creating the network of dislocations. STEM-EELS spectrum image (coreloss EELS from continous-rectangular area and lowloss EELS from dashed-region in Figure 1A) datasets were acquired to generate elemental and chemical maps. Elemental map (Figure 2D) revealed the presence of a ~2 nm oxidized layer on a-Ge. It also ruled out the presence of high-density Ge regions at the interface. While in the chemical map (Figure 2 E), the a-Ge and c-Ge regions were separated because the plasmon peaks in those regions had different full-width at half-maximum values. The micro-probe STEM in conjunction of energy filtered (with 10 eV GIF slit width) nanobeam diffratcion (NBD) was applied for the acquisition of STEM-Diffraction datasets to investigate the structral properties of a-Ge and c-Ge regions (Figure 2C & Figure 2F). The radial-distribution functional (RDF) analysis was then applied to those NBD patterns and the obtained results showed the presence of shor-range-order (SRO) in the a-Ge layer (results are not shown herein). In summary, a comprehensive anlaysis of a-Ge/c-Ge stack with fully-loaded TEM instrument allowed determining the various properties of a-Ge at nanoscale dimensions with great ease and accuracy.

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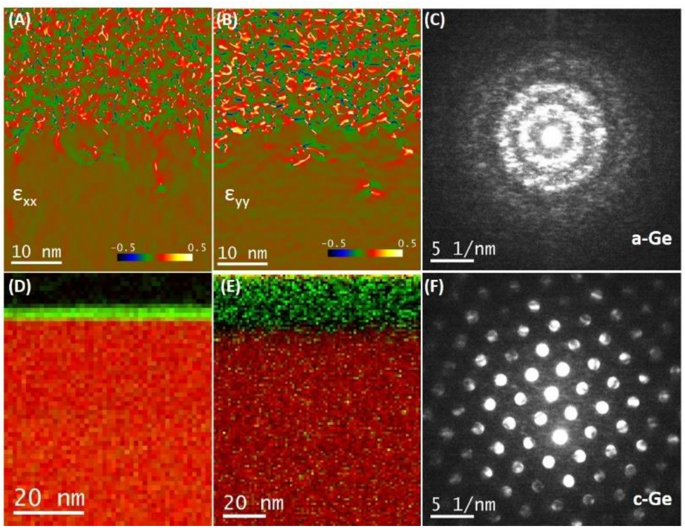

Figure 2

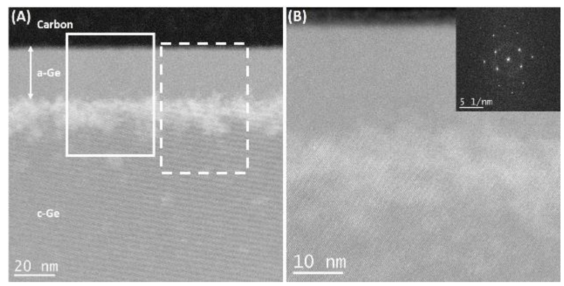

Figure 1

Figure 1. HAADF-STEM imaging of a-Ge/c-Ge stack. (A): STEM image showing the entire layer stack. (B): Image acquired at a higher magnification showing the crystal structure of stack.

Figure 2. Analysis of a-Ge/c-Ge stack. (A-B): In-plane (ε_{xx}) and out-of-plane (ε_{yy}) strain maps generated from image given in Figure 1 (B). (C): Energy-filtered NBD pattern from a-Ge region. (D): Oxygen (green) and Ge (red) elemental map from the rectangular region drawn with continuous line in Figure 1 (A). (E): The map of a-Ge (green) and c-Ge (red) from the rectangular region drawn with dotted line in Figure 1 (A). (F): Energy-filtered NBD pattern from c-Ge region.

https://doi.org/10.1017/S1431927617008236 Published online by Cambridge University Press