Atomic resolved EELS analysis across interfaces in III-V MOSFET high-k dielectric gate stacks

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Introduction

N-type III-V materials are one of the potential candidates to replace Si MOSFET technology. In particular n-type GaAs shows carrier mobility 5 times higher than that of Si [1]. Until recently, the realization of GaAs based MOSFET devices has been limited by the difficulties of making a good dielectric oxide layer in terms of leakage current and unpinned Fermi level. However, it has been shown that the evaporation of O_2 onto a GaAs surface leads to the formation of a pinned Fermi level at the interface. The O_2 initially displaces surface As atoms and then bonds to the Ga atoms in the second layer. When two O atoms are bonded to a central Ga atom, they withdraw charge from the second Ga atom determining the state formation within the gap. The presence of this central atom between two O atoms is the main reason why the Fermi level results to be pinned by direct oxidation. On the other hand, when Ga_2O is absorbed onto the GaAs surface, it appears to insert into As dimer pairs. Once it has been fully absorbed, a surface reconstruction occurs leaving the surface with 2x2 periodicity. This new surface appears to passivate the surface and change the charge on the initial As surface atoms towards more bulk like value. The new Ga atoms in the chemisorbed Ga_2O layer as well as the second layer Ga atoms in the substrate have no states in the band gap. The presence of this Ga_2O monolayer bonded to the GaAs surface determines the Fermi level to be unpinned. Deposition of an amorphous GdGaO layer is needed in order to keep the leakage current to a low value [2]. Thus, the performance of the entire transistor is largely influenced by the morphology and chemistry across the interface. Scanning Transmission Electron Microscopy ((S)TEM) related techniques are particularly suited to investigate the structure and the chemistry of this interface. In particular the combination of electron energy loss spectroscopy (EELS) and STEM enables spectrum imaging (SI) which is the acquisition of one or more spectra at each point of the scanned image. With the development of aberration corrected microscopes, EELS SI is now routinely used to study the chemistry across interfaces at atomic resolution. However when the sample is electron beam sensitive, atomic resolution level analysis becomes more challenging unless fast spectrometers are used. This is the case of the GaAs/Ga_2O_3 interface where the amorphous oxide layer tends to crystalize under the electron beam. The GIF Quantum® [3] with its spectral rate of 1000 spectra per second allows the acquisition of atomic EELS maps at a speed fast enough that beam damage is avoided. In addition the lens system present in the GIF Quantum® with the capability to correct the aberration up to the 5th order, leads to the possibility to use large collection angles allowing more signal to enter the spectrometer whilst maintaining the energy resolution.

Methods and Materials

We applied the EELS SI approach to the characterization of the GaAs/Ga_2O_3 interface with a spatial resolution of just over 1Å. According to [4] the chemistry across the interface region largely influences the electrical properties of the dielectric stack and more importantly is the reason why the Fermi level is unpinned. The material was grown by MBE on a semi-insulating GaAs substrate using a dual chamber system as schematically reported in Figure 1. 5nm of AlAs was grown in order to locate the position of the As with respect to the Ga in the GaAs region. The As is much heavier than the Al and therefore much easier to distinguish. The position will be the same in the GaAs layer. 30nm of amorphous Ga_2O_3 was grown on the GaAs substrate. 40nm of Pt was electron beam evaporated onto the Ga_2O_3. This layer is important in order to protect and preserve the quality of the sample from the damage that might occur during the specimen preparation process. TEM specimens were prepared using conventional cross-sectioning involving at the final stage ion-milling using a Gatan PIPS®. EELS data were acquired using the STEM-EELS system at Florida State University which is composed of a probe-corrected ARM 200 equipped with cold-FEG and a fully upgraded GIF Quantum® as EELS spectrometer.

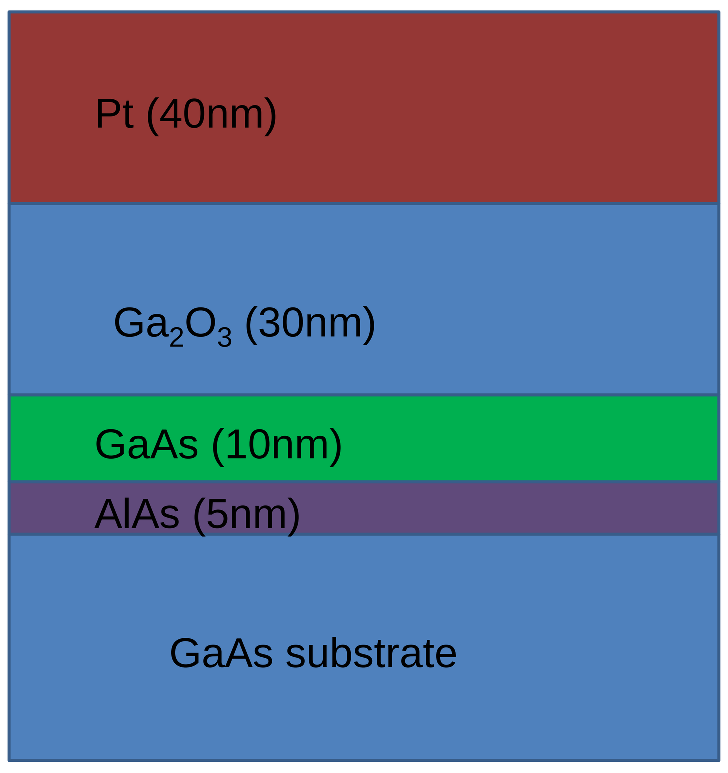
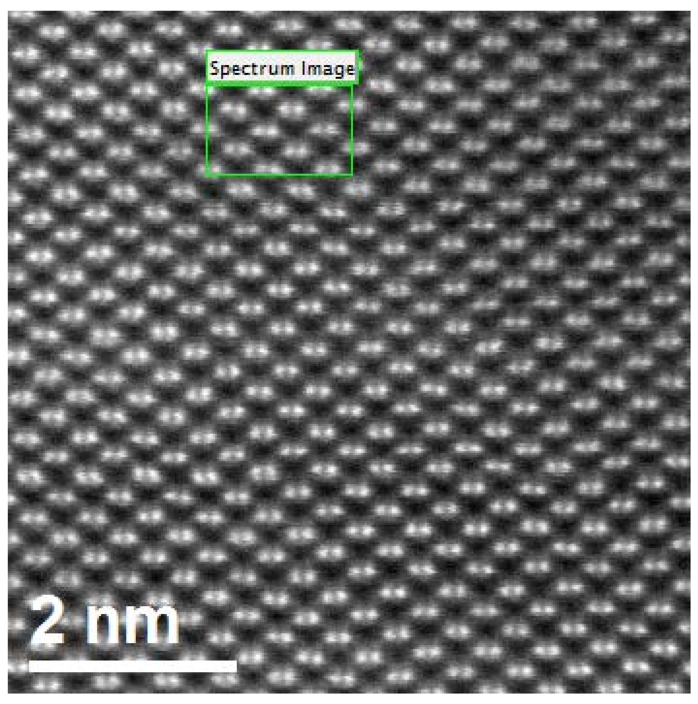


Figure 1: As grown structure. The 5nm AlAs layer is added in order help locate the position of the As in the dumbbell. As is much heavier than Al and as result it will generate more scattering that will make his signal much stronger. Its position in the AlAs will be the same in the GaAs as well. 40nm of Pt was electron beam deposited in order to prevent the surface of the damage that might occur during specimen preparation

Acquiring EELS data from GaAs.

The experimental conditions set for the EELS SI experiment were first tested across a region in the GaAs substrate shown in Figure 2a. Here the Ga $L_{2,3}$-edges at 1115eV and the As $L_{2,3}$ at 1323eV were extracted using an exposure time of 10ms per pixel, mapped out and shown in the colorized EELS elemental map in Figure 2b. Maps were obtained using means multiple linear least square fitting (MLLS) routine [5,6]. These maps show high contrast and more importantly the resolution needed to resolve the dumbbell in the crystalline GaAs [110]. Here the Ga is sitting on the left hand side of the dumbbell whereas the As on the right.



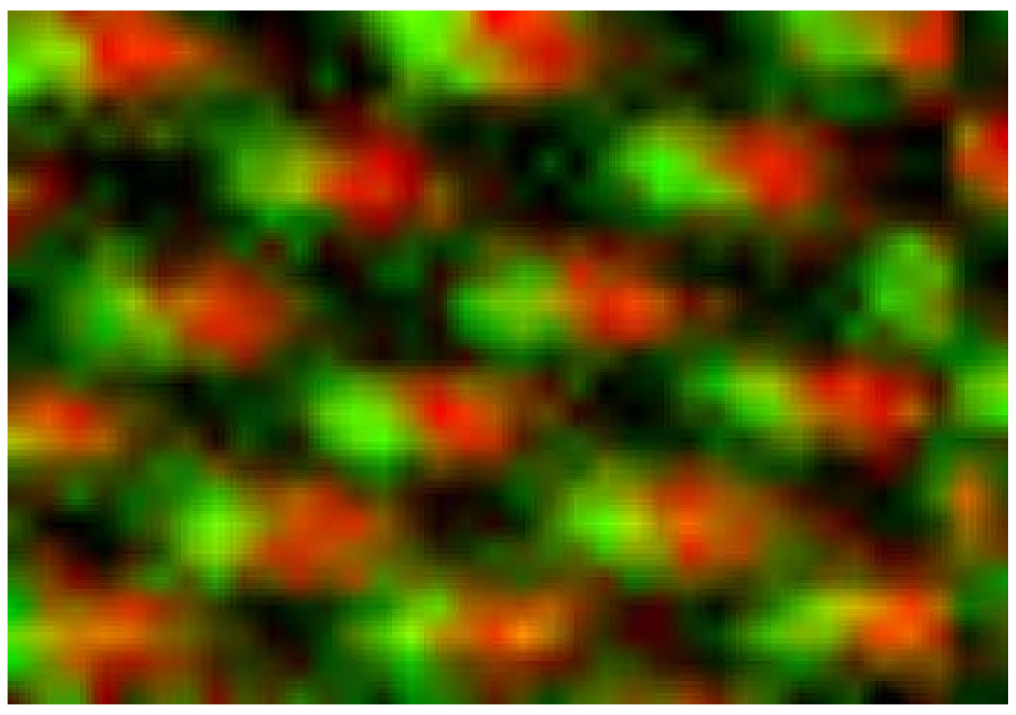


Figure 2a: High-resolution ADF STEM image. The green box is the area where the beam was scanned during the acquisition of the EELS SI. *Figure 2b*: Colorized EELS elemental map of As $L_{2,3}$-edges at 1323 in red color and Ga $L_{2,3}$-edges at 1115eV in green. The resolution and the contrast shown by these EELS maps are very high.

EELS from the GaAs/Ga_2O_3 interface.

After the promising results from the region across the GaAs crystalline area that prove the high level of spatial resolution achievable by EELS SI, the area across the GaAs/Ga_2O_3 interface was analyzed. The area in the green box shown in Figure 5 was scanned by the electron beam during the acquisition of the EELS SI which took just about 30 seconds. The high-resolution ADF STEM image in Figure 3 does not show many details and yet the elemental distribution at the interface appears to be unknown. However, as reported in the colorized EELS elemental map of the O K-edge at 532eV in blue, the Ga $L_{2,3}$-edges at 1115eV in green and the As at 1323eV in red shown in Figure 4, it is possible to tell that the last dumbbell in the interface is less populated and contains both Ga and As. The region between the GaAs and the Ga_2O_3seems to be amorphous and enriched in Ga. This can also be seen in the extracted line profiles from the Ga, As and O elemental maps shown in Figure 5. All the lines are normalized to the same maximum. The Ga and the O lines in the Ga_2O_3 area do not seem to overlap at the interface and the Ga line is slightly shifted to the left towards the GaAs region. This is in agreement with Hale et al. [4] where the presence of a Ga_2O monolayer at the interface it is reported.

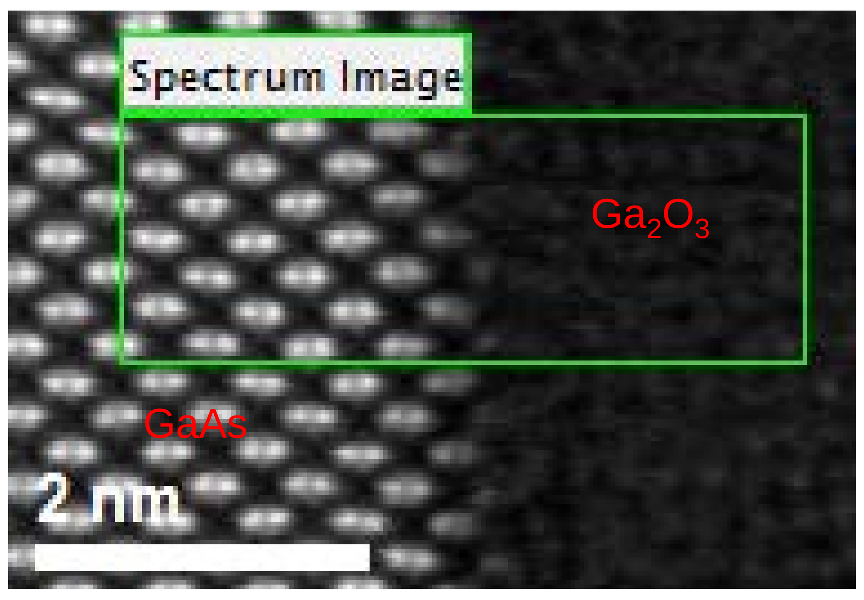


Figure 3: High-resolution ADF STEM image of the GaAs/Ga_2O_3 interface region. The green box is the area where the beam was scanned during the acquisition of the EELS SI.

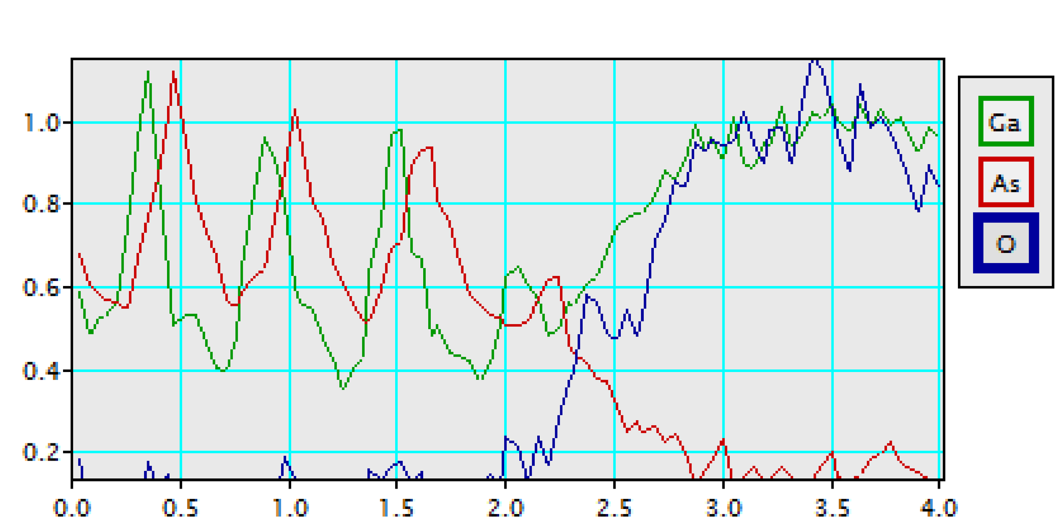


Figure 5: extracted line intensity profiles from the Ga, As and O elemental maps in Figure 4. All the lines are normalized to the same maximum and show how the elements are distributed across the interface region.

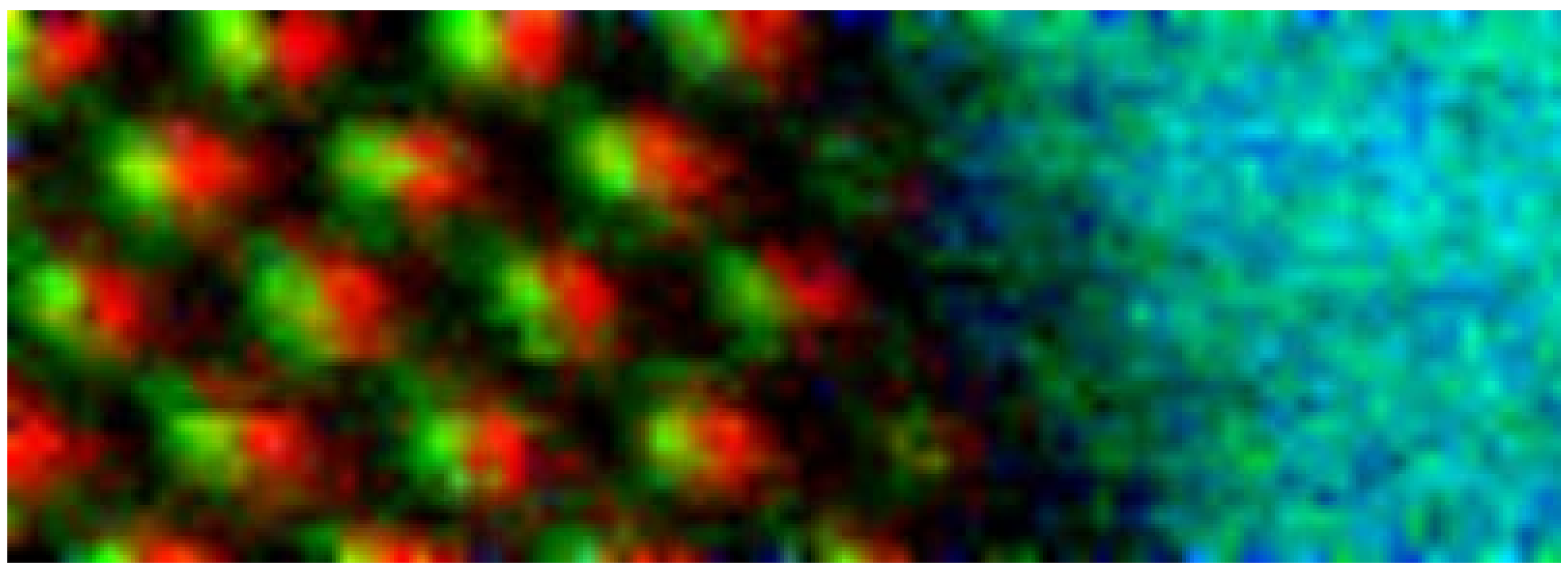


Figure 4: Colorized EELS elemental map of As $L_{2,3}$-edges at 1323 in red color the Ga $L_{2,3}$-edges at 1115eV in green and the O K-edge in blue. The details that this image shows at the interface are not entirely visible in the high-resolution ADF STEM image.

Conclusions

We have shown that EELS SI can reveal the elemental distribution across the interface and variations within one monolayer can be also detected. Light elements such as the O cannot be detected efficiently with high-resolution ADF imaging due to their low scattering power. On the other hand EELS is very efficient towards light elements which can be detected. The next step would be to analyze this interface when oriented along the perpendicular direction [1-10]. This can be accomplished by preparing a TEM specimen with the original wafer cut along the perpendicular direction. In this way, it will be possible to have a specimen with GaAs [1-10] and as result the As will be sitting on the left with respect to the Ga in the dumbbell. This will give a clear and complete understanding of the interface which is not achievable using high-resolution ADF STEM imaging alone.

References

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