Finding (point) defects in (nitride-based) device structures using TEM imaging techniques

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Abstract

Within the last five years material characterization through transmission electron microscopy (TEM) imaging has advanced to a point where identification of single defects is attainable. Novel capabilities of device structure characterization is demonstrated here. The degradation of AlGaN/GaN:Si HEMTs is investigated, defects identified and contamination elements localized.

INTRODUCTION

When aberration-corrected TEM became available new experiments were developed which focused on the novel "single atom sensitivity" those advanced microscopes exhibited [1-3]. Simultaneously, 2D materials became a focus area in research. Characterization of device structures, however, remained largely untouched and TEM techniques were mostly used to produce low magnification overview images, in either TEM or STEM mode.

At Berkeley an all ion-mill sample preparation technique was developed which allows for lifting out device areas in a standard focused ion beam (FIB) system and thinning the lamella at low energies to thicknesses suitable for ultra-high resolution. By applying low electron doses at electron energies between 50kV and 300kV most materials and material combinations can be imaged with minimal damage at atomic resolution [4]. These operation conditions allow for taking series of images, producing exit wave reconstructions (EWR) and reconstructing parts of devices in 3D, in atomic resolution. Complementary experiments provide chemical analysis, for example by EDS; structural analysis is used to locally identify strain and local electronic analysis utilizing low EELS can provide information about the presence of additional energy levels such as defect levels. These techniques can be applied to fresh or operated / stressed devices or devices which underwent treatment in extreme conditions such as irradiation or other harsh environments and/or high temperatures. In our current project it is our goal to distinguish growth- and process-induced defects in nitride-based HEMTs from operation- and radiation-induced defects.

Figure 1 shows schematically (not to scale) the epilayer structure, metal contacts and passivation layer of the AlGaN/GaN:Si HEMT structure which is subject of our investigation. The approximate thicknesses of various layers is given in the graphic, the actual metal contact layers are simplified. Our initial focus area is the gate edge.

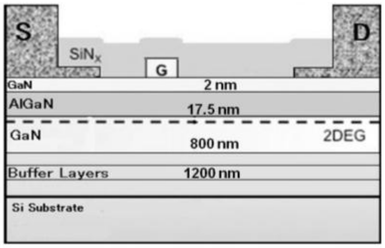

Fig. 1: AlGaN/GaN:Si HEMT structure

RESULTS

FIB sample preparation: From an IC area a 1 μm thick cross-section across the gate finger of a transistor was cut, lifted out and mounted onto a copper TEM grid. It was then pre-thinned to (200-300) nm. For this procedure a 30 kV gallium beam is used. In a low voltage ion mill, "Nanomill" (Fischione), the lamella is further thinned at 900 eV and then cleaned at 500 eV using an argon ion beam.

A variety of samples were imaged: newly processed devices (fresh), devices degraded after operation, devices failed during operation and unprocessed epilayers. Gamma irradiated devices did not show significant degradation, proton irradiated device investigations are in progress. Devices with two different gate contacts are included in the study: The bottom layer is either nickel or platinum, the top layer is gold. All device parts were imaged in high resolution TEM mode at 300kV using a monochromated electron beam and spherical aberration correction.

The TEM samples contain two typical defects close to the gate edge: The edge itself has a gold "foot" area as shown in Fig. 2. The Au top layer covers the side of the Ni bottom layer and even part of the epilayer,it is assumed that it was "flowing over" during the deposition of the passivation layer. Where the gold directly covers the epilayer the crystalline structure underneath is very electron beam sensitive. During the process of imaging part of this area became amorphous ("defective area under foot"). Next to this defect (to the left of Fig. 2) the epilayer exhibits a crater-like "dip" which extends into the AlGaN layer (Fig. 3). In the PtAu gated device this "dip" is much deeper and wider than in the NiAu gated device (as seen in Fig. 4). These defects are seen in all samples, on both sides of the gate and always next to each other. It is therefore concluded that they are likely connected and both process-induced. As the top of those defects is still covered by the SiN_x passivation layer and therefore protected, a sample preparation induced defect can be excluded.

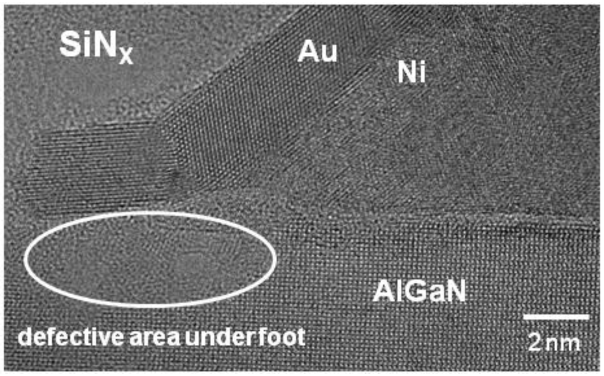

Fig. 2: Ni/Au gate edge in high resolution

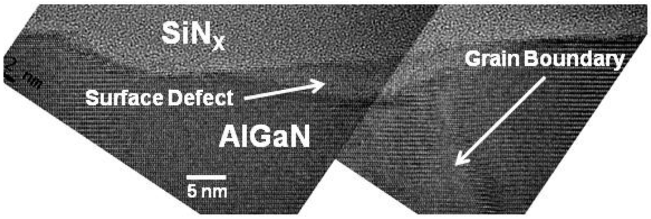

Fig. 3: Defective epilayer structure ("dip") next to the gate edge in high resolution; here: Ni/Au gate.

The defective areas are then imaged in STEM mode at 300kV. Figure 4 shows such a STEM image, also called HAADF image, with the above described two defects, here from a fresh Pt/Au gated device. When the focused electron beam scans over the chosen sample area chemically sensitive X-rays are produced as some electrons are in-elastically scattered and EDS maps can be taken in addition to STEM maps. From those EDS maps line scans across the defects are produced which show the distribution of different elements across the device structure. In these experiments a novel four EDS detector arrangement is used (Bruker, incorporated in an FEI TITAN microscope) which has increased sensitivity for light mass elements such as oxygen, nitrogen or carbon. Therefore, the distribution of metals can be determined simultaneously with the distribution of light elements, in high spatial resolution.

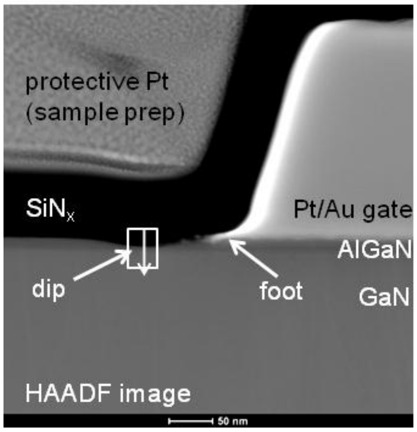

Fig. 4: Overview of the area around the gate edge in low resolution STEM. White rectangle: approx. area where line scans were taken. The thin darker stripe between the gate metal and the GaN is the AlGaN layer

Figure 5 shows typical EDS line scans, taken for fresh Ni/Au (segmented lines) and Pt/Au (straight lines) gated devices. All line scans are taken across the epilayer structure, starting in the passivation layer and ending in the GaN layer (see white box in Fig. 4). When comparing line scans of different devices they are aligned so that the areas of the 2DEG, or the right sides of the Al peaks, are at the same position. Parallel to the epilayer interfaces the EDS signal is integrated, broad lines (width of white box) provide better signals through data accumulation. Scans are also repeated multiple times to increase the signal.

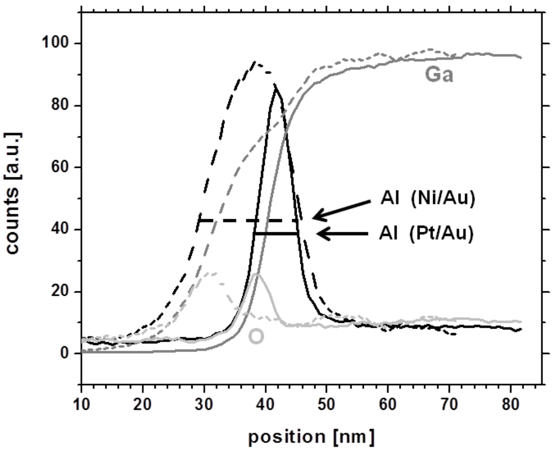

Fig. 5: EDS line scans across "dip" areas in fresh Ni/Au (segmented lines) and Pt/Au (straight lines) HEMTs. Black - Al profile / Grey - Ga profile / Light gray - O profile

In Fig. 5 one clearly sees that the epilayer defect is deeper in the Pt/Au gated device; the residual AlGaN layer is thinner as shown in the Al profile (black line). Astonishingly, the Ga profiles (grey lines) trail the Al profiles although we expect a 2 nm thick GaN cover layer in the epilayer stacking. This cover layer is absent in all processed devices. We did, however, find it in the unprocessed epilayer. Again, this is a processed-induced structure change. At the surface of the AlGaN layer an accumulation of oxygen is observed (light grey lines). Simultaneously, the corresponding nitrogen profiles (not shown here for better visibility) show a decrease at the AlGaN surface. The AlGaN surface area is oxidized.

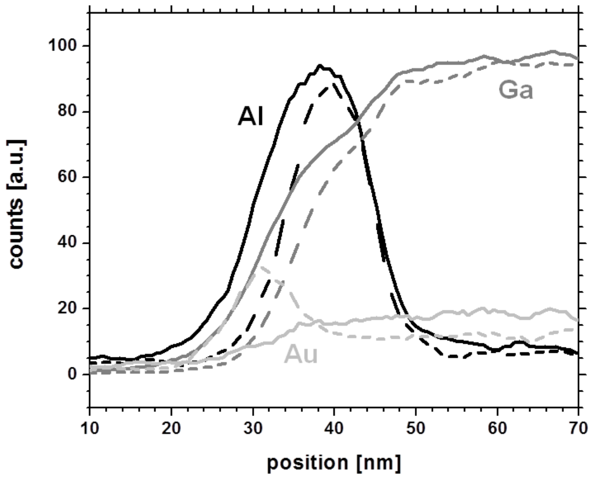

Fig. 5: EDS line scans across "dip" areas in fresh (straight lines) and degraded (segmented lines) Ni/Au gated HEMTs. Black - Al profile / Grey - Ga profile / Light grey - Au profile

When the epilayer defect of a fresh device is compared with one of a degraded device an additional thickness reduction of the AlGaN layer is observed (black lines in Fig. 6). The "dip" defect becomes deeper. At the same time an accumulation of gold at the AlGaN surface is detected in the Ni/Au gated degraded device (light gray lines). In the corresponding fresh device a small increase in the gold profile may be present but no surface accumulation was observed.

Gold is known to occupy the substitutional spaces in the Ga/Al sub-lattice [5,6]. When it accumulates in the AlGaN lattice it locally replaces Al and Ga and eventually will destroy the lattice structure completely. It is possible that the electron beam sensitivity of the AlGaN as observed only under the "foot" area is also caused by Au incorporation. Because Au is a high mass element it is expected to appear as larger phase contrast in a phase image of an exit wave reconstruction (EWR) in such defective areas.

An EWR reproduces the exit wave of the elastically scattered electron beam from an image series. The single images are taken at different foci which recovers information loss caused by the imperfections of the magnifying objective lens system. In other words, if the (aberration) parameters of your microscope are known it can be calculated how the electron beam is affected by those parameters. The aberration parameters can be subtracted and an undisturbed exit wave can be calculated if a focal series is available.

Fig. 7 demonstrates the data evaluation from an exit wave reconstruction. The phase of an exit wave (Fig. 7a) shows the positions of atom columns as bright spots. The grey value at the peak positions of those atom columns is a measure of the phase contrast of the respective atom column. The contrast, however, is taken at an averaged focus value for the whole image, the exit plane of the exit wave. At present, the EWR software is unable to determine local focus values. Because the actual sample is not atomically flat an average focus is not accurate over the whole image and a procedure, called wave propagation, has to be applied to correct for this inaccuracy of the phase contrast. The resulting "column mass" which describes the number of atoms in one column and their respective chemical nature is plotted in Fig. 7b in a color-coded plot. Darker contrast represents lighter (or fewer) atoms and brighter contrast represents heavier (or more) atoms.

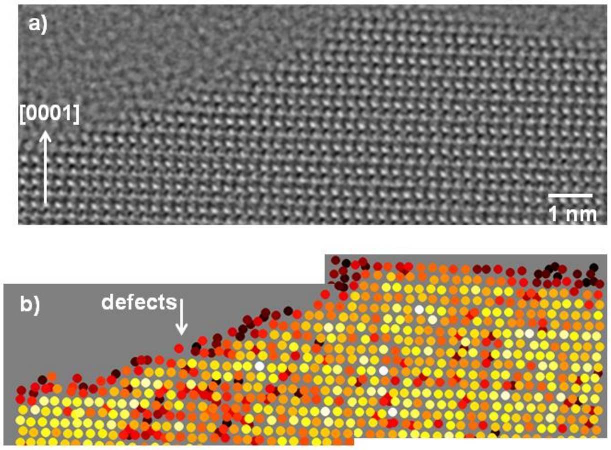

Fig. 7: Exit wave reconstruction (a) and corresponding column mass value after wave propagation (b) showing part of an epilayer defect in a Ni/Au gated fresh device.

In Fig. 7 mostly the Ga/Al sub-lattice is shown, with wurtzite lattices typical A-B-A-B stacking along the c-axis ([0001] in Fig. 7a). Some nitrogen columns are also visible (darker colors due to lower mass and in between (0001) Ga/Al planes). The surface of the epilayer shows exclusively dark colors because that's the thinnest sample area, with only one or two atoms per atom column.

Interestingly, an increased number of atom columns also have dark contrast around an area with line defects (white arrow in Fig. 7b). EDS maps taken in atomic resolution at such areas will show if this area is indeed oxygen rich and where in the lattice the oxygen atoms are located. Some of the bright atom columns, about one percent of the Al/Ga sublattice places, show an unusually large contrast (white dots in the color image, invisible in the black / white color coding). Those are the prime locations for gold presence, to be confirmed by either high resolution EDS maps or STEM imaging in atomic resolution.

CONCLUSIONS

Complete electronic device structures can nowadays be investigated in atomic resolution as sample preparation techniques and TEM imaging have advanced to a technological standard where single atom sensitivity is achieved. In the current investigation we find two extended defects, one gold containing gate edge feature (foot) followed by a crater-like defect of the epilayer itself (dip). The relative location to each other indicates that both defects are process induced. Additionally, a 2 nm GaN cover layer is absent in processed devices. Oxygen is present at the epilayer surface in all devices investigated, and even in the unprocessed epilayer. The GaN cover layer does not effectively suppress oxygen diffusion.

EDS analysis showed that gold contamination is present in the "dip" defect. The gold likely diffused from the gate contact. In degraded devices gold is found accumulated at the surface of a "dip". The remaining AlGaN layer is thinner, a larger, gold-containing amorphous layer forms at its surface. The exact position determination of gold atoms is in progress. Oxygen is likely accumulated around line defects and its location will be atomically resolved in future high resolution EDS maps.

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ACRONYMS

EDS: Energy Dispersive (x-ray) Spectroscopy
EELS: Electron Energy Loss Spectroscopy
EWR: Exit Wave Reconstruction
FIB: Focused Ion Beam
HAADF: High Angle Annular Dark Field
HEMT: High Electron Mobility Transistor
IC: Integrated Circuit
TEM: Transmission Electron Microscopy
STEM: Scanning TEM