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NanoMilling and STEM Imaging of Sub-50 nm InP HEMT

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Abstract

The sub-50 nm Indium Arsenide Composite Channel (IACC) High Electron Mobility Transistors (HEMTs) are fabricated on 100 mm Indium Phosphide (InP) substrates. This technology offers the best performance for low-noise and high-frequency, space and military applications. Typical failure mechanisms are observed in III-V HEMT technologies, including gate sinking, impact ionization and electromigration. Experiments were conducted to understand failure mechanisms of the IACC HEMTs by life testing devices at accelerated temperatures and biases; their electrical characteristics were measured at each stress interval. In order to determine which devices and where any defects occurred after the accelerated life tests, an additional test was completed, a Low-Noise Amplifier (LNA) Circuit assessment. The Low-Noise Amplifier (LNA) Circuit assessment determines which HEMT device is the weakest amongst the LNA circuit. Since many of the known III-V semiconductor failure mechanisms physically degrade or damage HEMTs, cross-sections are important to prepare to detect these mechanisms. In this presentation, advanced microscopy techniques with sub-nanometer resolutions, will examine physical characteristics of the HEMT at the atomic scale. The microscopy techniques will include a Focused Ion Beam/Scanning Electron Microscope (FIB/SEM), Nanomill and a Transmission Electron Microscope (TEM) along with Energy Dispersive Spectroscopy (EDS).

Introduction

The Indium Arsenide Composite Channel (IACC) High Electron Mobility Transistor (HEMT) is manufactured on a 100 mm Indium Phosphide (InP) substrate. The IACC has inherent material properties such as 25% higher electron mobility than indium/gallium/arsenide (InGaAs), high saturation velocity and high sheet carrier density. These properties provide maximum cutoff frequencies in the THz range [1] with sub-50 nm gates and transconductances up to 2000 to 2500 mS/mm. Figure 1A shows a top view SEM image of an IACC HEMT and 1B displays the cross-section of a 35 nm InP HEMT T-gate [2].

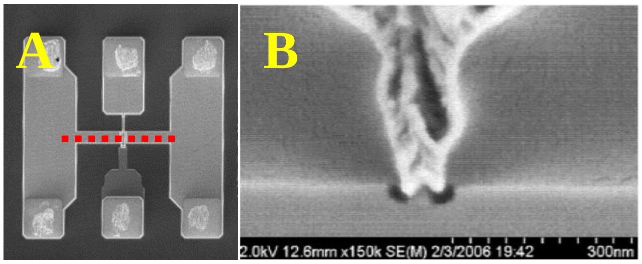

Figure 1: (A) Top view SEM image of an InP HEMT device (red dashes indicates the cross-sectioning area); (B) SEM cross-section image of a 35 nm InP HEMT T-gate [2]

Since Indium Phosphide (InP)-based High Electron Mobility Transistors (HEMTs) were developed, they have significantly decreased in size. With the smaller devices and, therefore, smaller gate lengths, additional failure mechanisms have been discovered. State-of-the-art microscopy tools must be used in order to see these atomic-range physical and chemical degradations. Therefore, the Scanning Electron Microscope/Focused Ion Beam (SEM/FIB), Nanomill and Scanning Transmission Electron Microscope (STEM) are utilized to understand the physical characteristics.

The DualBeam SEM/FIB used in this presentation is an FEI Quanta 3D. It uses a gallium liquid-metal ion source to remove material to create a cross-section of the HEMT. The FIB can make cross-sections at specific target areas within a few nanometers. While there are many pros to the FIB, there are some limitations. For example, gallium ions are usually residual on the analytical surface and the gallium ion beam may damage the surface and limit image resolution. Therefore, when trying to see atomic-scale features in a cross-section of the HEMT, the additional, unwanted layers, make it difficult to discern the failure mechanisms. This is where the Nanomill instrument comes in. The Nanomill is an instrument which utilizes an argon gas ion source targeted to a specific area of interest. It removes damaged and amorphous layers left behind by the FIB. The Nanomill is a Fischione 1040 which utilizes an inert argon gas to remove specimen damage. The beam is scanned over the specimen's surface and has a beam size as small as 1 µm [3]. The STEM used here is a STEM detector in the JEOL 2800 TEM. When formatting your paper, do not use Ventura or Corel Draw files.

Experimentation

Methods

Accelerated Life Test

In order to try to induce impact ionization, the HEMT was DC biased at 215°C, current density was fixed at 100 mA and the drain voltage was stepped from 1.3 V to 2.0 V with 0.1 V intervals for 48 hours at each interval.

Microscopy Techniques

As previously mentioned, a DualBeam SEM/FIB and STEM are used to determine the physical features of the HEMT. Light and dark field STEM images were taken at an accelerating voltage of 200 kV of cross-sectioned and thinned HEMT samples. The cross-sections were prepared using a DualBeam SEM/FIB at accelerating voltages from 30 kV during bulk material removal, to 5 kV during polishing.

Nanomilling

The Nanomill was used twice after the FIB with a couple different milling conditions. The first round of the Nanomill used a voltage of 700 eV for 20 minutes; all Nanomilling was done at + and -10 degree tilts to cross-section and polish both sides of the sample. The sample was then polished at 300 eV for 10 minutes. The sample was looked at in the STEM after the first Nanomill round and since the features under the gate were still not improved enough to see them, another round of the Nanomill was used. The second round of Nanomilling was again used at 700 eV, but only for 15 minutes and then polished at 300 eV for 10 minutes.

Results

There were varying degrees of degrading devices, but one with a gradual degradation was chosen to cross-section because we wanted to see if we could catch the beginning of the failure mechanism and understand how it behaves. The SEM/FIB was first used to cross-section the device. In order to prepare a cross-section, a very careful technique must be used in order to get the most out of our STEM images. First, a protective layer must be placed over the area of choice. The SEM/FIB is equipped with a platinum gas which protects the sample surface. However, these devices have a gold airbridge that cover the gate fingers, which makes for an inherently good protective layer. Figure 2A is a top view SEM image of the HEMT at 0 deg tilt and a 52 deg tilt is shown in Figure 2B; the airbridge is clearly shown in both figures covering all four gate fingers. Two trenches are then made at a eucentric height where the electron and ion beam intersect at a 52 deg tilt around the airbridge with the gallium ion source, Figure 2C. Figure 2D shows a J-shape cut created under the sample in order to lift it out with a probe. The sample is then welded to a copper grid with a platinum gas to thin and polish until about a 100 nm thickness for STEM imaging; Figure 2E shows the sample welded to the copper grid and 2F is a top view of the sample thickness.

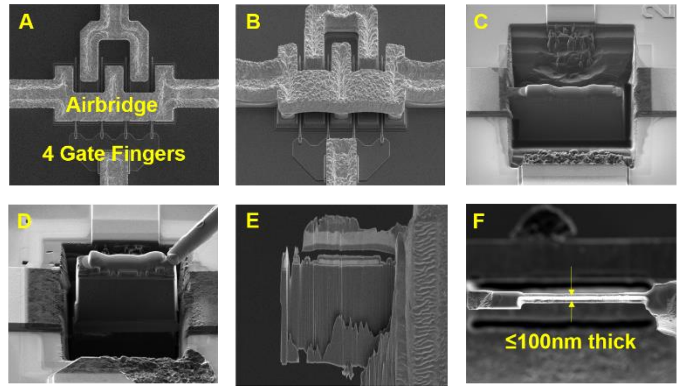

Figure 2: FIB steps to create cross-section of HEMT

The Nanomill is then used to continue thinning and polishing the FIB lamella. Figure 3 below shows the Nanomill display which allows the user to watch the operation in real time.

Figure 3: Nanomill displays operating status in real time. The red rectangle is positioned over the FIB lamella [3]

The FIB lamella was then taken to the TEM to use the STEM detector. Figure 4A is a STEM image taken before Nanomilling. This was used as a baseline to compare after Nanomilling was complete. Figure 4B was then taken after the first round of Nanomilling. Comparing images A and B, we can see a clear layer under the gate that we could not see in A. The Nanomill was then used a second time, Figure 4C, and there is a higher resolution of the materials under the gate, including the channel.

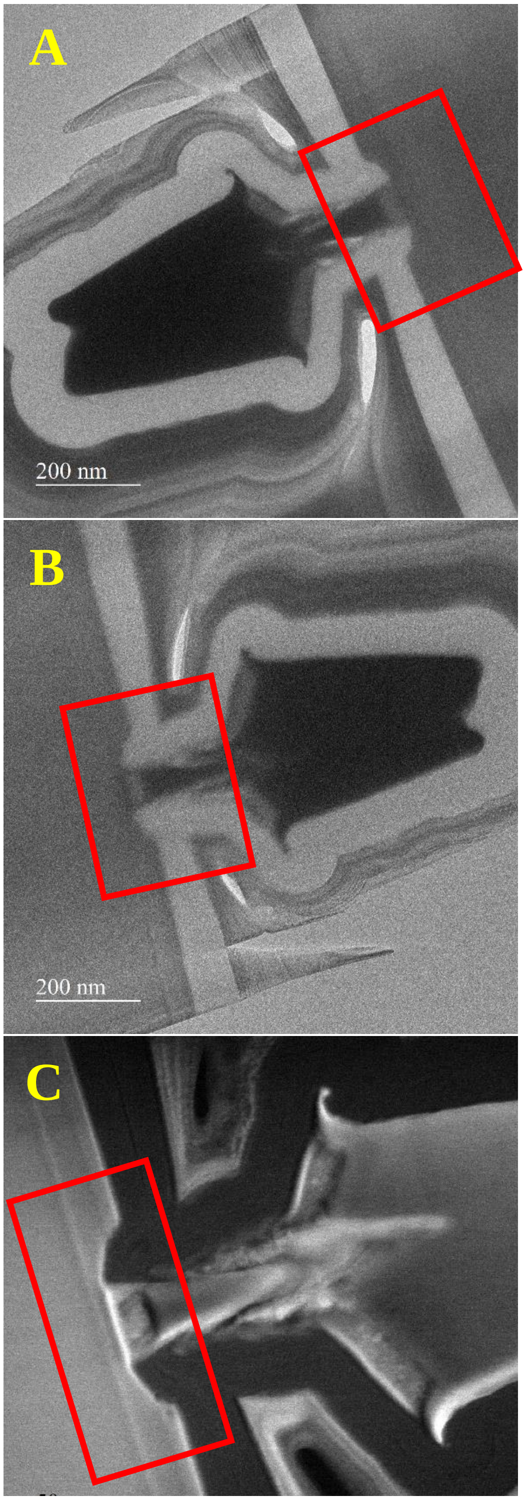

Figure 4: STEM images of HEMT cross-sections: (A) Before Nanomilling; (B) After 1st round of Nanomilling; (C) After 2nd round of Nanomilling. The boxed areas are the regions of concern under the gate finger.

Discussion

The accelerated life test completed was to purposely induce the impact ionization failure mechanism. Impact ionization is a particle generation process where an electron is highly energized by an external electric field in the valence or conduction band and collides with an electron in the valence band. The electron in the valence band gains enough energy to get excited into the conduction band and generates an electron-hole pair [4]. The electron and hole impact ionization rates are proportional to the electric field according to Chynoweth's Law [5] shown in Equation 1:

[1]

$$\propto_{n/p} = A_{n/p} \exp\left(-\frac{B_{n/p}}{E}\right)$$

Where $A_{n/p}$ and $B_{n/p}$ are the ionization rate parameters. Therefore, in order to induce impact ionization, a high electric field acceleration must be applied; drain voltage was stepped up to 2.0 Volts to see whether the devices catastrophically failed or degraded gradually at a continuous rate. Many devices continued to degrade at a gradual rate and some degraded quickly. To understand the impact ionization failure mechanism behavior, we would like to cross-section at both states. This paper only describes the cross-section of a gradually degraded device to show how the Nanomill can help us distinguish failure mechanisms.

The STEM was used to try to identify these features because the STEM has two types of powerful imaging capabilities: bright-field and dark-field imaging. Bright-field imaging is where the aperture is placed in the back focal plane of the objective lens and allows only a direct beam to pass. The heavy atoms will appear with a dark contrast. With dark-field imaging, the direct beam is blocked by the aperture where one or more diffracted beams are allowed to pass the objective aperture. Information such as planar defects, stacking faults and particle size can be gathered by dark-field imaging [6]. Between these two imaging techniques, a great deal of useful information can be gathered for semiconductors. Therefore, both imaging techniques were used to understand what features are displayed. Figure 5 below shows the HEMT gate after the second round of Nanomilling and there is a different feature to the right of the gate than on the left (boxed in red).

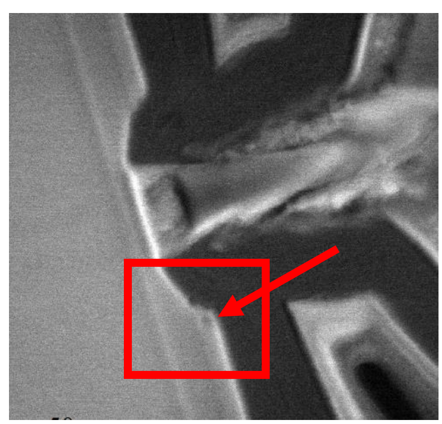
Figure 5: HEMT gate after second round of Nanomilling discovering an unknown feature

There was no physical change under the gate where gate sinking has typically occurred [7], however, something has been altered. To further this investigation, and conclude if this is a result of impact ionization, a few things can be done. First, chemical analysis by Energy Dispersive Spectroscopy (EDS) in the STEM can be used to identify if there is any movement of material. Impact ionization usually does not change the chemical composition of a material. In addition, electroluminescence can be carried out to identify the regions of electron-hole recombination [8]. Additional testing and analysis will reveal whether this is the failure mechanism we were looking for or another one that was not intentionally induced. This feature may be a typical failure mechanism that is seen in III-V semiconductors or a new, unexplored, mechanism.

Conclusions

In conclusion, due to the HEMTs sub-nanometer features, the SEM/FIB and STEM have become essential instruments in understanding the transistors' physical characteristics. Now, the Nanomill is has become just as important to further characterize the HEMTs behavior under critical conditions.

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