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Realtime observation of "spring fracture" like AlGaN/GaN HEMT failure under bias

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The AlGaN/GaN HEMTs have been considered promising candidates for high-frequency and high-power applications, while the reliability issues greatly limit the commercialization of AlGaN/GaN HEMTs. In the past, the research on the reliability of devices was often based on Raman spectroscopy, cathodoluminescence, and TEM after failure of the devices, which is often considered to be the laborious and complicated "archaeological" kind of analysis [1]. For TEM in particular, this analytical approach does not realize the true potential of TEM for failure characterization. In recent years, researchers have gradually adopted in-situ TEM to investigate the reliability issues, because in-situ TEM can establish a direct connection between the degradation of device electrical property and the damage of material microstructure in real time, which is very helpful to identify the failure location and mechanisms [2]. In-situ TEM research on thin films or nanowires has been carried out, while there is little research on transistors. In 2017, Wang et al. [3] analyzed the real-time failure process of GaN thin film by in-situ TEM. However, the in-situ TEM research on AlGaN/GaN HEMTs is challenging [4, 5], due to the high requirements and difficulty of in-situ device preparation (machining accuracy, electrode connection at the nanoscale, electrostatic protection, etc.).

In this work, the electron transparent sections of AlGaN/GaN HEMT structures were prepared and characterized in TEM chamber in the high vacuum environment with low electron beam dose. The Joule heat during the in-situ electrical test was extremely damaging to the electrodes and semiconductors. The movement of bending contours indicated that Joule heat induced mechanical deformation of the electron-transparent device and was the direct cause of device burnout like spring fracture.

Experiment. The electron-transparent AlGaN/GaN HEMT was prepared by focus ion beam (FIB) and mounted on a micro-electron-mechanical system (MEMS) chip loaded onto DENSolution D9+ holder and inserted into JEM 2100F TEM chamber. The details of the preparation of devices and characterization process were presented in the supplementary materials.

Results and discussion. The electrical test was between the gate and source, with the drain floating, as shown in Figure 1(b). The gate current of the in-situ specimen was much higher than that of the device on die, due to the damage of Schottky contact during the sample preparation process. When a gate voltage of −4 V was applied to the device, part of the gate metal melted and disappeared instantly. Pt particles with different sizes appeared instantaneously in the Pt protective layer. The bending contours appeared in the layers, part of which disappeared after half an hour without any bias and irradiation in the TEM chamber, due to the partial recovery of thermal and mechanical stresses induced by gate damage. Although the gate metal was severely damaged, the heterostructure under the gate and in other areas of the device did not change much in morphology (Figure S5(a)). The AlGaN/GaN layer was photographed by electron diffraction, illustrating the invariant of the crystal structure of GaN, as shown in Figure S5(b), which ensured that the device still had current conduction capability between source and drain under gateless conditions. Therefore, the next electrical characterization was measured between the source and drain, with the gate floating.

The curves of drain current vs. drain voltage were swept multiple times, with the increased sweep range of drain voltage sequentially, as shown in Figure 1(c). The larger current density of electrical-transparent device was induced by the nanoscale size effects on the piezoelectric coefficients [3] and the additional mechanical stress induced by the preparation of electrical-transparent device. The drain current degraded significantly as the drain voltage increased and the device burned out as soon as the drain voltage was swept to 3.5 V. Electron transparent device generated higher heat flux at the same voltage level than the device on die and the heat dissipation path was greatly reduced due to a very thin layer of material retained in vacuum, resulting in a decrease in carrier mobility and current degradation, as well as the thermal burnout of the device.

When the drain bias was applied, the bending contours near the drain moved towards the drain and those near the source moved towards the source, as shown in the video. The typical movement of bending contours under a drain bias of 0–3 V is shown in Figure 1(d). Taking changes of

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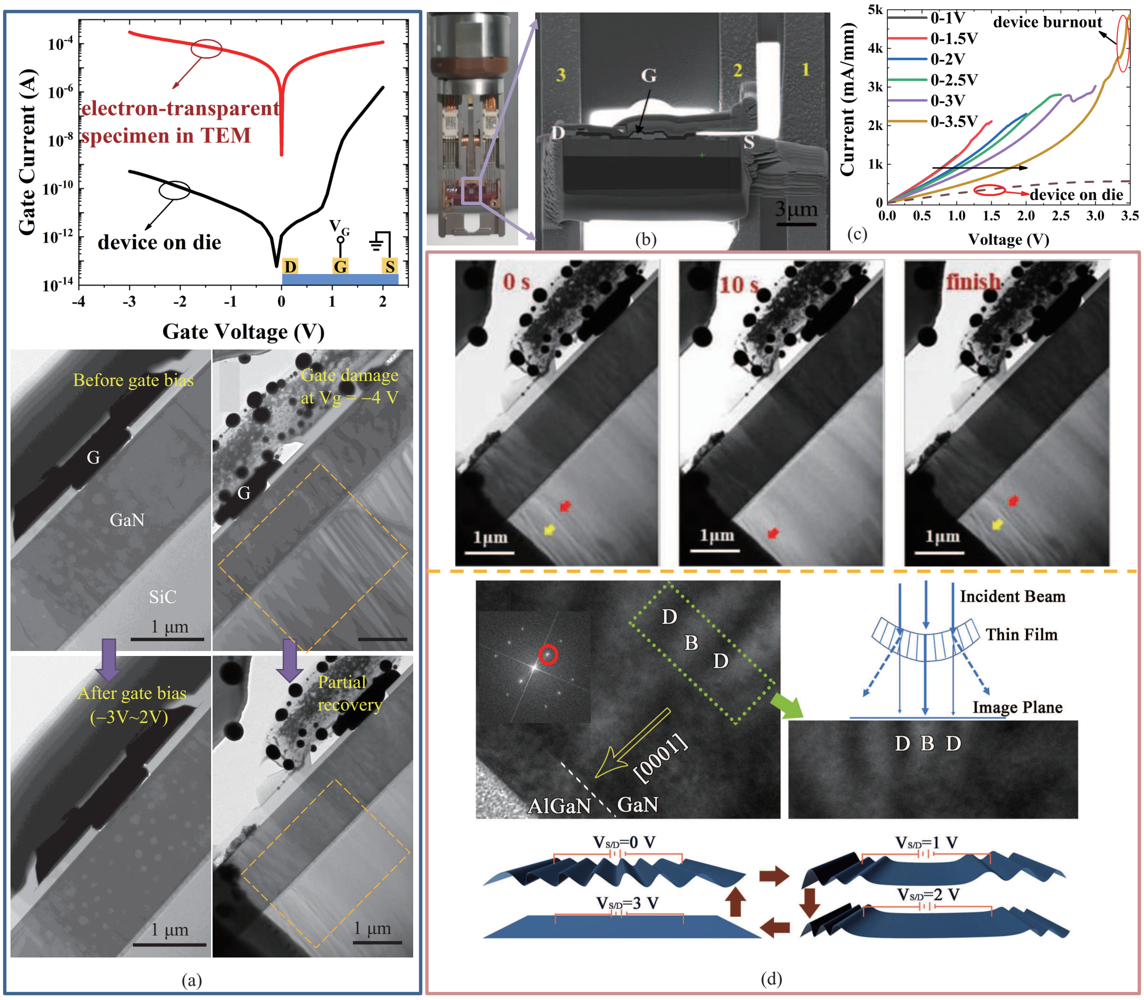

Figure 1 (Color online) (a) Gate current of electron transparent device in TEM and device on die and in-situ TEM characterization between gate and source; (b) device on the MEMS chip with connection of electrodes; (c) drain current vs. drain voltage with gate floating; (d) typical movement of bending contours with drain bias sweeping from 0 to 3 V and analyzing the "spring fracture" mechanism.

the two bending contours marked by yellow and red arrows as reference points under a drain bias of 0–3 V, it was seen that the movement of the bending contours made the originally wrinkled layers become flat. As the drain bias was removed, the device returned to its original morphology and the surface wrinkles appeared again.

Figure 1(d) shows the bright and dark bending contours after magnifying AlGaN/GaN layers. According to the Fourier transform image (FFT) in the upper left corner, it can be calibrated that the bending contours extend along [0001]GaN direction. After enlarging the green dashed area, the bright area marked with B should be upward convex, while the dark area marked with D is downward concave. The movement of bending contours indicates that the in-situ device is stretched similar to a spring under an external force and recovers to the original state as the external force is removed. According to the morphological characteristics of the convex and concave, the schematic diagram of "spring stretching" phenomenon under biasing is drawn in Figure 1(d), which is caused by the thermal expansion of materials along the [0001] direction (the responding plane is C plane) due to Joule heat. As the drain voltage increases, the "spring stretching" phenomenon is more obvious. The device is stretched and flat near 3.5 V and finally burnout due to the high elastic potential energy which exceeds the expansion limit of materials, as shown in the supplementary video.

Conclusion. The electrical characteristics and failure process of AlGaN/GaN HEMTs under gate bias and drain bias were studied in TEM chamber in real time. When gate voltage was applied, the high gate current indicated that the Schottky contact degraded during the preparation of electron-transparent device. The heat accumulation accelerated the damage of the gate metal. Under drain biasing, the drain current density was higher than that of the device on-die due to the enhanced piezoelectric effect. The device showed a "spring stretch" like behavior due to heat accumulation. When the drain voltage rose, the material layers exceeded the thermal expansion limit, the device eventually broke and was damaged through the so-called "spring fracture" failure behavior. The results suggest the great importance of thermal expansion performance to the failure of AlGaN/GaN HEMT devices. At present, research on GaN HEMTs by in-situ TEM is still in its infancy. The preparation process of transparent samples still needs to be continuously optimized. More work is needed to realize a quantitative comparison with conventional HEMT reliability, considering the mechanical, thermal, and electrical boundary conditions. This paper will promote the development of reliability research in GaN-based HEMT by in-situ TEM.

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Supporting information Video and other supplemental document. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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