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Nanoscale 3-dimensional characterization of wide bandgap power and microdevices

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Abstract

Depth-resolved cathodoluminescence spectroscopy (DRCLS) using an ultrahigh vacuum scanning electron microscope can characterize temperature, mechanical stress, and native point defect densities on a nanometer scale in three dimensions inside operating high power devices. These measurements can identify physical mechanisms that alter device properties and degrade lifetime.

1. Introduction

As microelectronics shrinks below the sub-micron regime, technologists require techniques to characterize physical properties on a nanometer scale that can impact macroscopic performance and ultimately lifetime. Electron beam excitation and recombination of electron-hole pairs inside semiconductor devices produces cathodoluminescence features whose energies provide temperature, strain, and defect information. With increasing incident electron beam energies E_B from 0.1 to several keV, excitation depths increase on a scale of tens to hundreds of nm while beam spot diameters of 5-10 nm define lateral resolution resulting in nanometer-scale localized excitation in 3 dimensions. Probing inside operating devices, particularly wide bandgap power and micro-devices reveals local regions of high temperature and strain that create native point defects that contribute to electrical and mechanical failure. Depth-resolved cathodoluminescence spectroscopy (DRCLS) [1] of operating AlGaN/GaN high electron mobility transistors (HEMTs) describe drain-side gate foot regions at the 2DEG interface that correlate spatially localized temperature and strain with native point defects at the same location [2]. Hyperspectral imaging maps show how applied electrical bias can move defects across micron distances at metal-ZnO diodes even near room temperature. Nanoscale DRCLS of ZnO nano- and micro-wires displays analogous defect diffusion that controls electronic changes in Schottky barriers and ohmic contacts both in the same nanostructure.

2. High power, wide bandgap transistors

Several features of cathodoluminescence spectra can characterize physical properties of semiconductor devices under high power operation. The peak energy E_G of electron-hole recombination from conduction to valence band is sensitive to both temperature and mechanical stress. For GaN, E_G from 100 to 900ºC decreases with temperature T as 3.365 – 5.98$\pm$0.12x10^{-4} eV T(ºC). Mechanical stress also decreases E_G, reported as -26 meV/GPa. Emission features at energies below the band gap include excitons, phonon replicas and, critical for semiconductor devices, native point defect and impurity levels at energies well within the band gap. The 3-dimensional capability of DRCLS enables correlations of temperature, stress, and defect densities on a near-nm scale to be correlated with macroscopic electronic measurements. Figure 1(a) illustrates how incident electron beams can be positioned across the source-gate-drain surface area of an AlGaN/GaN HEMT as well as above, at, and below the 2DEG interface. Band gap measurements between gate and drain and versus depth from the surface to nearly 2 microns below yield a temperature map in Fig. 1(b) that includes the buried 2DEG, a 50 nm thick, strained AlGaN overlayer, and the GaN buffer layer below. The expanded region near the

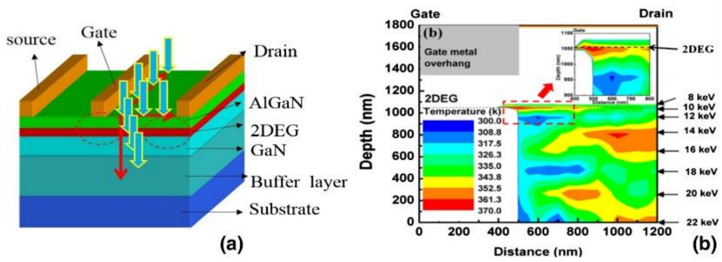

Fig. 1 (a) Schematic illustration of AlGa/GaN HEMT structure with arrows indicating probe locations both laterally and in depth. (b) Corresponding cross sectional map versus depth through the 2DEG of temperature between indicated gate overhang and drain.

drain-side gate foot shows the 2DEG hot spot, consistent with theoretical models. Note the presence of elevated temperature regions 100's of nm within the GaN buffer layer. Figure 2 shows an analogous drain-side gate foot cross section, the Monte Carlo simulations of electron-hole pair creation rate vs. E_B, and depth profiles of three specific GaN and AlGaN

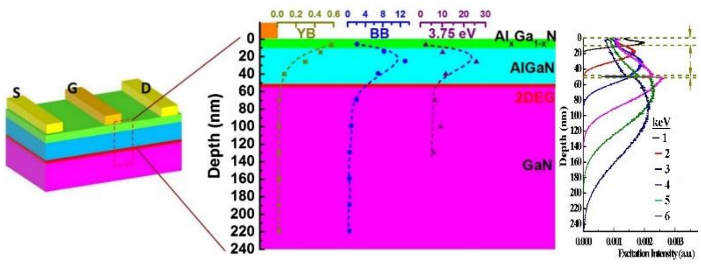

Fig. 2. Schematic HEMT structure with cross section (dotted), three defect depth profiles, and Monte Carlo e-h pair creation rates vs E_B.

native point defects, two of which peak within the AlGaN layer. The energies of these defects can be correlated with energies measured by capacitance-voltage methods. DRCLS also provides energy-specific maps of native defects across the source-gate-drain area as a function of depth, revealing the presence of dislocations with sub-micron separations at specific depths below the active HEMT layers. DRCLS correlates relative defect densities with the negative potential of micron-size regions at the drain-side gate foot measured by Kelvin probe force microscopy (KPFM), regions that are the first to fail with continued voltage stress. Figure 3(a) shows an AlGaN/GaN HEMT top view. DRCLS (Fig. 3(b) middle) into the extrinsic drain and source reveals dark regions of low

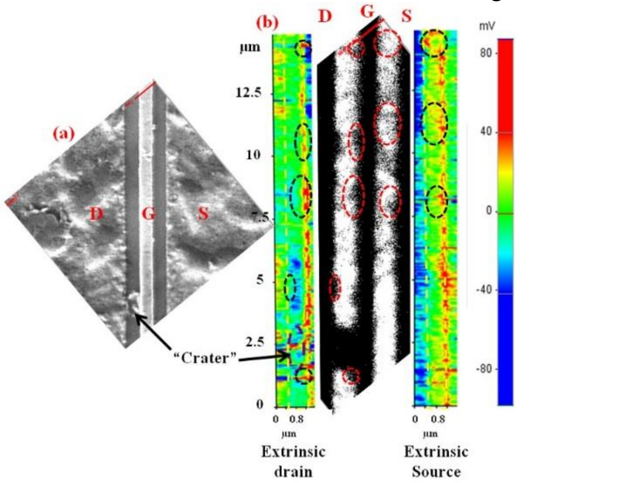

Fig. 3. (a) SEI image of AlGaN/GaN HEMT after failure; (b) corresponding NBE intensity map and extrinsic drain and source KPFM potential maps.

NBE intensity due to high defects densities. Corresponding KPFM maps show regions of high negative potential associated with these higher defect concentrations. The correlation of dramatic stress increase with increased lattice defect formation provides support for the inverse piezoelectric model of critical field degradation of AlGaN/GaN HEMTs [3].

With its nanoscale, 3-dimensional capabilities, DRCL appears able to probe physical mechanisms inside high-power semiconductor devices during their operation.

3. High voltage nanostructure electronics

DRCLS combined with hyperspectral imaging (HSI) provides 3D maps of defects inside ZnO and Ga_2O_3 nanostructures. Besides describing defect distributions that vary both radially and length-wise inside ZnO nano-and microwires, HSI reveals direct evidence for electromigration of charged native point defects at both the nano- and micron scale. Figure 4 shows how applied bias of <1-2x10^5 V/cm from metal-ZnO diode to ground within the outer 50-100 nm depth drives Zn vacancy (V_{Zn}) and Cu_{Zn} acceptors across several microns within tens of minutes near room temperature. DRCLS measures similar defect diffusion normal to the surface for ZnO and other oxide semiconductors. Comparable voltage gradients occur for sub-micron HEMTs, Schottky depletion regions, and semiconductors with dielectric breakdown.

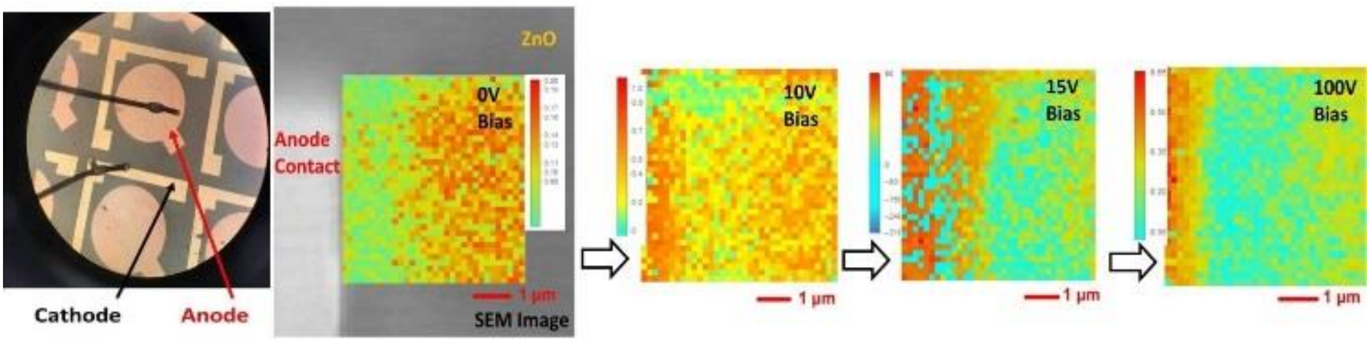

Fig. 4. (a) Secondary electron image (left) and hyperspectral maps (right) of native point defect diffusion between ZnO IrO_x-.anode and Au cathode.100 V applied bias = 2 x 10^5 V/cm.

3. Conclusions

Depth-resolved cathodoluminescence spectroscopy with nanoscale spatial resolution in 3 dimensions can measure and map several physical properties – temperature, mechanical stress, and native point defect densities of wide band gap semiconductors available for high power and nanoscale devices. These measurements inside devices under actual operation provide insight for physical failure mechanisms and possible guidance for design of future devices.

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