Nanoscale Temperature Distribution, Defect Mapping and Evolution Inside Active AlGaN/GaN High Electron Mobility Transistors

Chung-Han Lin[1], T.A. Merz[2], D. R. Doutt[2], M. J. Hetzer[2], Jungwoo Joh[3], Jesús A. del Alamo[3], U. K. Mishra[4] and L. J. Brillson[5]

[1]Dept. Electrical & Computer Engineering, The Ohio State University, Columbus, OH 43210, USA

[2]Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA

[3]Microsystems Technology Laboratories, MIT, Cambridge MA 02139, USA

[4]Depts. Electrical & Computer Eng. and Mat's, UC-Santa Barbara, Santa Barbara, CA 93106 USA

[5]Depts. Electrical & Computer Eng., Physics, and Center for Materials Research, The Ohio State University, Columbus, OH 43210, USA

Because of its inherent material properties, GaN-based high electron mobility transistors (HEMTs) are very suitable for high power operation. However, under these conditions, Joule heating and high electric fields inside the device may generate defects that adversely affect device properties. In this study, we use depth-resolved cathodoluminescence spectroscopy (DRCLS), atomic force microscopy (AFM) and Kelvin probe force microscopy (KPFM) to investigate the temperature distribution and defect generation inside state-of-the-art AlGaN/GaN-based HEMTs on a scale of tens of nanometers.

Using DRCLS to monitor temperature-dependent near band edge (NBE) energies during actual device operation, we found continuous and significant temperature increases from drain to gate over the ~ 600 nm gate - drain spacing even under low power operation (Fig.1). DRCLS also provided maps across the HEMT's source-gate-drain regions of NBE emission intensities, which decrease with the formation of deep level defects (Fig. 2). Indeed, such maps reveal inhomogeneous NBE darkening by defects inside the channels and under the gates that may be sites of increased carrier scattering, decreased thermal conductivity and heating. KPFM maps indicate a correlation between higher surface potential and darkened regions. Also DRCLS spectra vs. position inside channels and along/under gates reveal deep level "yellow band" (YB) (i.e., Ga vacancy-related) and "blue band" (BB) emissions that increase over 12 hours device operation (e.g., Fig.3). DRCLS spectra from both the "extrinsic drain" and "under gate", show defect generation after 12 hour operation. The averaged YB/NBE ratio vs. position shows that YB under the gate on the drain side increases by 3.5x compared with ~2.2x under the gate on the source side and very little in the extrinsic drain region. Furthermore, YB emission exhibits much larger changes than BB with operation and location, indicating a link between this defect and device degradation. Thus DRCLS with ~50 nm spatial resolution laterally and tens of nm vertically provides detailed correlations between temperature under actual state-of-the-art device operation, defect distribution and specific defect evolution laterally and depth-wise with device operation. The results obtained with this combination of techniques can be used to reveal and in principle predict physical mechanisms of AlGaN/GaN HEMT degradation under realistic conditions.

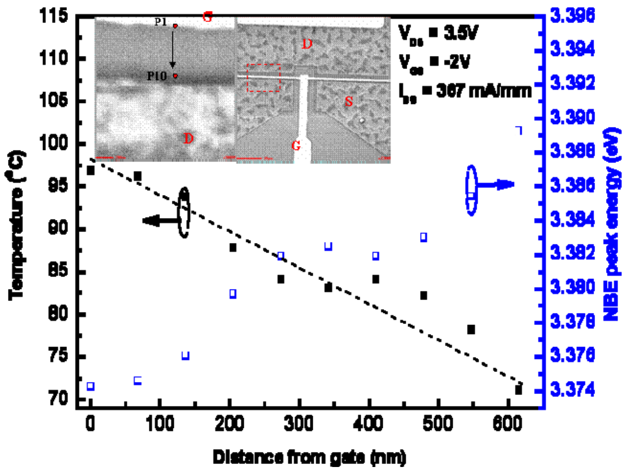

Figure 1. The temperature distribution of a HEMT operated at V_{DS} = 3.5V and V_{GS} = -2V. The inset photo shows the SEM image of region from which data was measured.

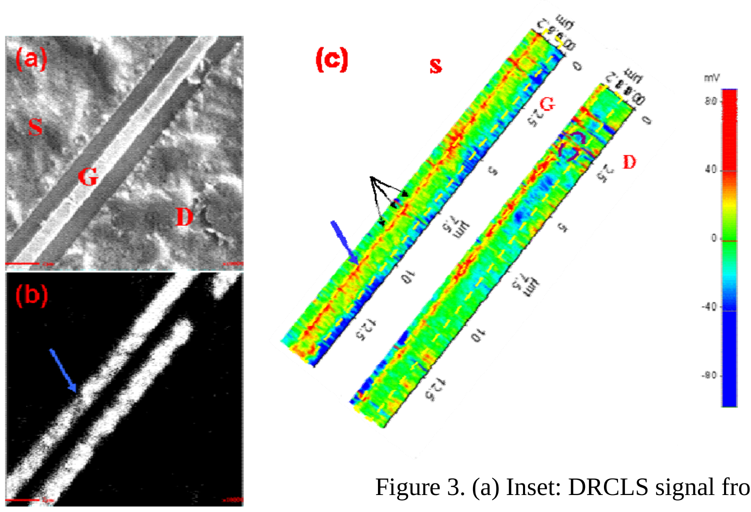

Figure 2 (a) SEM image shows the Source (S), Gate (G) and Drain (D) region. (b) Corresponding CL map of band gap emission with (a). (c) KPFM result taken simultaneously in the same (a) region. Blue arrows show the same region in Figs. 2 (b) and 2 (c), where devices degrade faster.

Figure 3. (a) Inset: DRCLS signal from region under gate before and after (also main figure) 12 hours, V_D= 10V, V_G=-2V,20 mA operation, the 2.2 eV YB signal increased. (b) SEM image of the device under test (DUT) and (c) corresponding reference device. Boxes indicate DRCLS regions probed. (d) the average YB/NBE ratio showing largest YB increase in Region 2. The inset shows smaller changes in the blue band (BB)/NBE ratio vs. position.