Microcathodoluminescence Characterization of III-V Nitride Heterojunctions and Devices

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INTRODUCTION

The III-V nitride semiconductors provide the basis for some of the most advanced micro- and optoelectronic devices today. These materials are particularly advantaged for high frequency and power applications due to their high sheet carrier concentrations and mobilities, a result of the large piezoelectric effects near their lattice-mismatched heterointerfaces. Nevertheless, measurement of electronic structure properties in stacks of active III-nitride layers can be challenging because of their nanometer-scale thicknesses and hence the difficulty of probing with electrostatic techniques. These challenges are compounded in characterizing electronic structure in real device structures, where basic physical measurements must be made on a sub-micron lateral scale.

HETEROJUNCTION AND DEVICE CHARACTERIZATION

We have used depth and laterally-resolved cathodo-luminescence spectroscopy (CLS) to characterize electronic properties of III-V nitride heterojunctions and device structures on a nanometer scale and localized to individual micron-scale transistor devices. We have correlated these microscopic electronic properties to the optical and electrical features on a macroscopic scale. Our results for quantum wells, GaN/sapphire growth templates, and AlGaN/GaN high electron mobility transistor (HEMT) devices reveal clear evidence for the effects of chemical interdiffusion and resultant defect formation on the microscopic electronic structure. Indeed, for state-of-the-art device structures, they demonstrate well-defined correlations between the defect features observed via CLS versus both the contact and sheet resistances of the transistors. These results show that spatially-resolved spectral features can provide physical explanations for the observed optoelectronic and microelectronic properties.

RESULTS

We used a near-surface variant of CLS, termed low energy electron-excited nanoluminescence (LEEN) spectroscopy to probe the multilayers comprising GaN/InGaN/GaN double heterojunctions in laser diode structures (1). LEEN features reveal the formation of new electronic states localized near the quantum well interfaces under relatively In-rich conditions. These states are due to formation of a cubic GaN region comparable to the quantum well layer in thickness rather than the bulk native defects typically associated with growth quality. The nanoscale depth dependence of the non-contact, non-destructive LEEN technique enables detection of this competitive recombination channel within a few nanometers of the "buried" heterojunction interfaces.

We used low-temperature (10K) CLS with a submicron electron beam in an ultrahigh vacuum scanning electron microscope (SEM) to probe the spatial distribution and energies of electronic defects near GaN/Al_2O_3 interfaces grown by hydride vapor phase epitaxy (HVPE) (2). Cross-sectional secondary electron microscopy CLS show systematic variations in impurity/defect emissions over a wide range of HVPE GaN/sapphire electronic properties. These data, along with electrochemical capacitance-voltage profiling and secondary ion mass spectrometry, provide a consistent picture of near-interface doping by O diffusion from Al_2O_3 into GaN, over a range 100-200 nm.

LEEN reveals spatially localized point defects that strongly affect two dimensional electron gas (2DEG) densities and mobilities at AlGaN/GaN HEMTs (3). Auger electron spectroscopy (AES) shows that stoichiometry varies radially across the growth wafer both at the near-surface GaN/AlGaN interface and at the 2DEG AlGaN/GaN junction. The AlGaN band gap and defects vary across the wafer and correlate with AlGaN/GaN interdiffusion measured by AES depth profiling. The spatial variations of interface diffusion and stoichiometry indicate optimal radii for high 2DEG densities and mobilities.

The optical characterization of AlGaN/GaN device layers can be used to predict contact and device performance. LEEN spectra of individual transistors can be associated with individual device performance, in contrast to the averaged characterization of large surface areas. Changes in localized defects can be measured from device to device separated by less than 100 microns on the same wafer that manifest themselves in different electrical performance. Such defects can also be associated with specific layers of the device. Sheet resistance can be correlated with AlGaN band edge emission energy. Contact resistance can be correlated with both donor-acceptor pair and "yellow" luminescence (4). These correlations are consistent with the physical and chemical origins of the CLS spectral features.

Overall, these results demonstrate that localized electronic states and band structure can be probed using depth-resolved and spatially-localized luminescence techniques. These studies reveal that chemical interdiffusion, reaction, and morphological change on a nanometer scale can form localized defects that can influence micro- and optoelectronic performance. The ability to locate defects in nanoscale structures provides opportunities to optimize heterojunction growth and ultimate device performance.

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REFERENCES

1. L.J. Brillson, T.M. Levin, G.H. Jessen, and F.A. Ponce, Appl. Phys. Lett., 75, 3835 (1999).
2. S.T. Bradley, A.P. Young, L.J. Brillson, M.J. Murphy, W.J. Schaff, and L.F. Eastman, IEEE Trans. Electron. Dev., **48**, 412 (2001).
3. S.H. Goss, X.L. Sun, A.P. Young, L.J. Brillson, D.C. Look, and R.J. Molnar, Appl. Phys. Lett., **78**, 3630 (2001).
4. G.H. Jessen, B.D. White, S.T. Bradley, P.E. Smith, L.J. Brillson, J.E. Van Nostrand, R. Fitch, G.D. Via, J.K. Gillespie, R.W. Dettmer, and J. S. Sewell, Solid-State Electron., **46**, 1427 (2002) and to be published.