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Quantitative observation and discrimination of AlGaN- and GaN-related deep levels in AlGaN/GaN heterostructures using capacitance deep level optical spectroscopy

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Deep levels were observed using capacitance deep level optical spectroscopy (DLOS) in an AlGaN/GaN heterostructure equivalent to that of a heterojunction field effect transistor. Band gap states were assigned to either the AlGaN or GaN regions by comparing the DLOS spectra in accumulation and pinch-off modes, where the former reflects both AlGaN- and GaN-related defects, and the latter emphasizes defects residing in the GaN. A band gap state at $E_c$=3.85 eV was unambiguously identified with the AlGaN region, and deep levels at $E_c$=2.64 eV and $E_c$=3.30 eV were associated with the GaN layers. Both the AlGaN and GaN layers exhibited additional deep levels with large lattice relaxation. The influence of deep levels on the two-dimensional electron gas (2DEG) sheet charge was estimated using a lighted capacitance-voltage method. © 2006 American Institute of Physics. [DOI: 10.1063/1.2424670]

Power amplifiers based on AlGaN/GaN heterojunction field effect transistors (HFETs) are hampered by defects attributed to the AlGaN surface and the GaN buffer that exert detrimental influence upon device performance. Thus, quantitative observation of band gap states in AlGaN/GaN heterostructures provides an important metric for optimizing material growth and minimizing the impact of defects. Previous investigations pragmatically used HFETs themselves as a vehicle to study deep levels in AlGaN/GaN heterostructures, primarily focusing on the influence that pulsing of the gate-source bias or drain-source bias has on deep level activity and consequent degradation of pulsed versus dc $I$-$V$ characteristics due to diminished two-dimensional electron gas (2DEG) sheet charge $n_s$. Beyond those deep levels made apparent with bias modulation, additional band gap states can exist that affect $n_s$ and thereby device performance equally for both steady-state, pulsed, and rf operation and thus might not be observed using pulsing-based spectroscopy techniques such as drain current deep level transient spectroscopy (DLO3, I-DLTS) or photoionization induced transient current spectroscopy (PICTS). Moreover, current-based techniques offer limited direct information regarding the location of defects within the heterostructure.

Here, we applied capacitance deep level optical spectroscopy (C-DLOS) to probe deep levels in Schottky diodes formed from an AlGaN/GaN heterostructure equivalent to that of a HFET. C-DLOS provides an advantage over drain current spectroscopy because the depth sensitivity inherent to capacitance measurements can discern deep levels associated with the AlGaN region from those of the underlying GaN layers through choice of the diode bias $V_G$. With the heterostructure biased at $V_G$=0 V (accumulation), C-DLOS readily detects deep levels located within both the AlGaN and GaN regions. Further, the availability of 2DEG electrons for capture suppresses deep level photoemission at the heterointerface. Conversely, when performed at $V_G$ less than the threshold voltage ($V_{th}$) such that the 2DEG is depleted (pinch-off), the heterostructure behaves as a bulk depletion region constituted mainly by GaN, and the photocapacitance of band gap states in the AlGaN region and heterointerface is strongly diminished compared to those in the GaN. It is notable that the role of any surface states at the unmetallized AlGaN surface is negligible since the semitransparent Schottky contact defines the region responsive to C-DLOS under these conditions. Thus, using C-DLOS it is possible both to observe and to distinguish among deep levels associated with the AlGaN region and those corresponding to the underlying GaN.

Optical excitation is necessary to probe the AlGaN cap in capacitance mode, whereas the applicability of traditional DLTS is limited to regions where the Fermi level ($E_F$) position can be modulated with bias, which excludes the AlGaN layer. In accumulation charge control of the 2DEG senses change in deep level occupancy. Deep levels given to electron photoemission increase $n_s$ and are referenced to the conduction band minimum $E_c$. Likewise, a decrease in the photocapacitance indicates hole emission referenced to the valence band maximum $E_v$. In addition to photoemission, electron-hole pair creation also can increase $n_s$, so one must distinguish between these mechanisms. The Franz-Keldysh effect due to the bias and polarization-induced electric fields in the AlGaN generates an effective “redshift” of the optically sensed band gap energy in C-DLOS but is expected to have little influence on deep level photoemission.

The AlGaN/GaN heterostructure was grown on a SiC substrate by metal-organic chemical vapor deposition

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GaAs and confirms sensitivity to the AlGaN cap. Positive inflection points in the spectrum near \(h\nu=1.5, 2.7, 3.3, \) and 3.9 eV indicate electron emission from deep levels, and the latter can be immediately ascribed to the AlGaN since this energy exceeds the GaN band gap. The origins of the other three defect levels were yet ambiguous, so additional measurements were performed at pinch-off to distinguish between GaN- and AlGaN-related band gap states.

At \(V_G=-3.6\) and \(-4\) V the 2DEG is dissipated as seen from the dark C-V curve in Fig. 2, and the depletion depth extends into the GaN. In this case the relative thicknesses of the AlGaN (22 nm), UID-GaN (1700 nm), and GaN:Fe (700 nm) layers weight their contribution to the total photocapacitance. Thus, for \(V_G<V_d\), spectral features arising from the GaN region are strongly emphasized over those associated with the AlGaN. Indeed, appearance of the 3.44 eV GaN band edge peak confirms ascendency of the photoreponse from the GaN layer. As expected, the distinctly AlGaN-related features, i.e., the 4.05 eV band edge peak and the 3.9 eV onset, quench. The lack of the AlGaN band edge in the SSCP spectra at pinch-off implies that AlGaN-related deep levels do not contribute to these spectra either, suggesting that the deep level onsets near 1.5, 2.7, and 3.3 eV occurring at both accumulation and pinch-off derive from the GaN region.

Precise deep level energies were obtained from C-DLOS. Figure 1(b) compares the C-DLOS spectra for \(V_G=0\) and \(-3.6\) V bias conditions, which are offset for clarity. The spectrum corresponding to \(V_G=-4\) V (not shown) was similar to that of \(V_G=-3.6\) V. The solid lines are theoretical fits determining the relevant parameters \(E^o\) and \(d_{FC}\). The model of Lucovsky was used to fit the sharper inflection points in the spectrum near \(h\nu=1.5, 2.7, 3.3, \) and 3.9 eV, respectively, suggesting that these band gap states are identical. The discrepancy in \(E^o\) is attributed to the uncertainty in the data and the fitting procedure. Such arguments can also be made concerning the \(E^o=3.30\) eV and \(E^o=3.31\) eV levels associated with the

FIG. 1. (a) AlGaN/GaN SSCP spectra in accumulation (\(V_G=0\) V) and pinch-off (\(V_G=-3.6, -4\) V). Note the AlGaN band edge in accumulation and the GaN band edge at pinch-off. (b) DLOS spectra at \(V_G=0\) and \(-3.6\) V.

FIG. 2. Lighted capacitance-voltage scan for \(h\nu=3.36\) eV denoting an increase in \(n_s\). The inset shows the increase in capacitance \(\Delta C\) with illumination as a function of \(V_G\).
thus is attributed to the AlGaN cap. The Ec primarily due to photoemission from the semiconductor field effect transistor reported a deep level at 3.3 eV. In a MOCVD-grown GaN metal-semiconductor field effect transistor, a 2DEG, band gap states also contribute. From charge control of the 2DEG, an Ec state is assigned at 3.3 eV. DLOS analysis reveals that the 1.5 eV SSPC onsets apparent for Ec=0 and −3.6 V actually arise from different band gap states at Ec=−2.00 eV with dEc=1.2 eV (0 V) and Ec=−2.42 eV with dEc=1.3 eV (−3.6 V). The discrepancies between the SSPC threshold and Ec energies of these deep levels are a consequence of significant lattice relaxation as indicated by their large dEc.

C-DLOS offers insight into the location of the observed deep levels. The Ec=−3.85 eV band gap state is likely associated with either the Ni–AlGaN interface or the AlGaN barrier region. A distinction between these possibilities might be made by changing the Schottky metal. An AlGaN-related trap lying near Ec has been suggested by Meneghesso et al., based on DLTS investigation of an AlGaN/GaN HFET, although in that case the defect was attributed to the bare AlGaN surface. Observation of the Ec=−2.42, 2.64, and 3.30 eV deep levels at Ec=−3.6 V strongly implies that they are associated with either the UID-GaN or GaN:Fe regions, or both. Ascribing the Ec=−2.64 eV level with MOCVD GaN agrees with a previous C-DLOS and DLTS study of n-type GaN grown by MOCVD that observed a band gap state at Ec=0.87 eV/Ec=−2.64 eV,11 for which gallium vacancy-related defects were identified as a likely source. Similarly, the PICTS of a MOCD-grown GaN metal-semiconductor field effect transistor reported a deep level at Ec=−2.67 eV.9 As with the Ec=−3.85 eV state, the Ec=−2.00 eV deep level was observed only for VGe=0 V and thus is attributed to the AlGaN cap. The Ec=−2.42 eV state likely arises from the GaN region because it was evident only for VGe=−3.6 V, and its apparent absence at VGe=0 V can be explained by the overwhelming photoresponse of the Ec=−2.00 eV deep level.

The increase of nEc due to deep level photoemission was estimated from lighted capacitance-voltage (LCV) curves. The LCV curves were recorded by illuminating the diode with monochromatic light until the photocapacitance reached a steady state and then performing a Ec-V scan while maintaining illumination. As is evident from the LCV scan in Fig. 2, at hν=3.6 eV photoemission increases nEc and thereby the capacitance, shifting Vth to a more negative value. In the same manner that C-V scans can determine nD, the integrated increase in capacitance with illumination ΔC(VG) (shown in the inset of Fig. 2) yields ΔnEc=8.8×1010 cm−2, which is primarily due to photoemission from the Ec=−2.64 and 3.30 eV deep levels, though the Ec=−2.0 eV and Ec=−2.4 eV band gap states also contribute. From charge control of the 2DEG, ΔnEc=Dt only if the defects reside at the AlGaN surface or heterointerface, otherwise ΔnEc<Dt. Here, the distribution of AlGaN and GaN defects are unknown, so ΔnEc must be considered to underestimate Dt. Also, optical excitation with hν>Ec/2 provides a lower bound for ΔnEc because competing electron and hole photoemission from the same state is possible.13 Determining ΔnEc for the Ec=−3.85 eV deep level proved problematic because the enhanced electric field in the AlGaN layer at reverse bias necessary for LCV caused additional redshifting of the AlGaN band edge via the Franz-Keldysh effect such that electron-hole pair creation became indistinct from photoemission from the Ec=−3.85 eV deep level. This could be remedied with a simple test structure requiring low applied bias such as Ohmic pads separated by a semitransparent Ni field, where the proportional increase with illumination of the conductance between the pads and that of nEc are approximately equal. In any case, this result suggests that deep levels in the GaN buffer would appreciably diminish the maximum drain current in a HFET device since ΔnEc(hν=3.6 eV) is, at minimum, −1.5% of nEc=6.2×1012 cm−2. Due to their deep position relative to Ec, the deep levels attributed to the GaN region are unlikely to be involved in high frequency dispersion; however, the Ec=−3.85 eV AlGaN level could induce dispersion in cases where EF approaches Ec.

In summary, deep levels observed via C-DLOS in an AlGaN/GaN heterostructure equivalent to a HFET were associated with either AlGaN or GaN regions by comparing C-DLOS spectra at both accumulation and pinch-off. This effectively accomplishes trap depth profiling from the AlGaN barrier through the GaN bulk regions under the “gate” contact. Using LCV the influence of deep levels in the GaN on nEc was estimated.

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