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Deep centers in a free-standing GaN layer

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Schottky barrier diodes, on both Ga and N faces of a ~300-μm-thick free-standing GaN layer, grown by hydride vapor phase epitaxy (HVPE) on Al_2O_3 followed by laser separation, were studied by capacitance–voltage and deep level transient spectroscopy (DLTS) measurements. From a $1/C^2$ vs V analysis, the barrier heights of Ni/Au Schottky contacts were determined to be different for the two polar faces: 1.27 eV for the Ga face, and 0.75 eV for the N face. In addition to the four common DLTS traps observed previously in other epitaxial GaN including HVPE-grown GaN a new trap B' with activation energy $E_T = 0.53$ eV was found in the Ga-face sample. Also, trap E_1 ($E_T = 0.18$ eV), believed to be related to the N vacancy, was found in the N-face sample, and trap C ($E_T = 0.35$ eV) was in the Ga-face sample. Trap C may have arisen from reactive-ion-etching damage. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1361273]

Hydride vapor phase epitaxy (HVPE) is a promising technique for growing thick GaN films because of the high growth rates attainable.[1] Recently, a process to separate HVPE GaN layers from Al_2O_3 substrates has been developed[2] and it has been proposed that the separated templates can themselves be used as substrates for further GaN growth. It is known that HVPE GaN layers grown on the (0001) plane of sapphire assume Ga polarity. In other words, the surface of the GaN layer is terminated by the Ga plane. Such material is highly defected near the GaN/Al_2O_3 interface, but is of very good quality a few μm from the interface.[3–5] Separated (''free-standing'') layers permit growth on either the Ga or N face, and thus the dependencies of various properties on the particular growth face must be studied. For our free-standing layer, we find that (1) the Schottky barrier height is lower on the N face; (2) a surface-damage-related trap at $E_C - 0.35$ eV, and a new trap at $E_C - 0.53$ eV are found in the Ga-face sample; and (3) a trap at $E_C - 0.18$ eV, which has previously been assigned to an N-vacancy-related defect, is observed in the N-face sample.

The GaN layer used in this study was grown to be about 300 μm thick, and had been separated from its Al_2O_3 substrate by a laser decomposition process.[2] The top (Ga) surface was mechanically polished, and then the polishing damage was partially removed by a Cl_2-based reactive-ion-etching (RIE) process. The bottom (N) surface, which had been next to the Al_2O_3 substrate, originally contained a thin, highly degenerate region, which is present in all HVPE layers grown on Al_2O_3.[5] Thus, about 30 μm of material was removed by mechanical polishing and wet-chemical etching prior to Schottky barrier deposition, without which the Schottky barrier diodes (SBDs) were very leaky and could not be used. After cutting the layer into two pieces, several Ni/Au Schottky barriers, each of 250 μm diameter, were fabricated on the Ga face of one piece, and on the N face of the other piece. Ti/Al/Ti/Au ohmic contacts were then fabricated on the opposite face, respectively, of each piece. Electron-beam evaporation was used for the Ti and Ni metals and thermal evaporation for the Al and Au metals. These SBDs were then mounted on carriers by silver epoxy, and wire bonded for capacitance–voltage (C–V) and deep level transient spectroscopy (DLTS) measurements. Both the C–V and DLTS measurements were carried out in a BioRad DL4600 system, using a 100 mV test signal at 1 MHz. The apparent activation energies (E_T's) and capture cross sections (σ_T's) of the various traps were determined from an Arrhenius plot, using rate windows (e_n's) from 4 to 1000 s^{-1}.

The SBDs formed on the Ga face showed very good I–V characteristics at 300 K, with ideality factors of about 1.04 and leakage currents in the 10^{-10}–10^{-9} A range at a reverse bias $V_b = -15$ V. On the other hand, the SBDs formed on the N face were quite leaky, with leakage currents in the 10^{-4}–10^{-3} A range at $V_b = -5$ V. To investigate the respective Schottky barrier heights on the two faces and to determine the near-surface carrier concentrations, we carried out $1/C^2$ vs V analyses.[6] Plots of $1/C^2$ vs V at 300 K are shown in Fig. 1. For comparative purposes, a typical result for a SBD fabricated on a 68-μm-thick HVPE-GaN film (Ga face up[7]), still on its Al_2O_3 substrate, is also presented in Fig. 1. For both the separated and unseparated Ga-face-up films, the intercepts at $1/C^2 = 0$ are about 1.1 V, while the intercept

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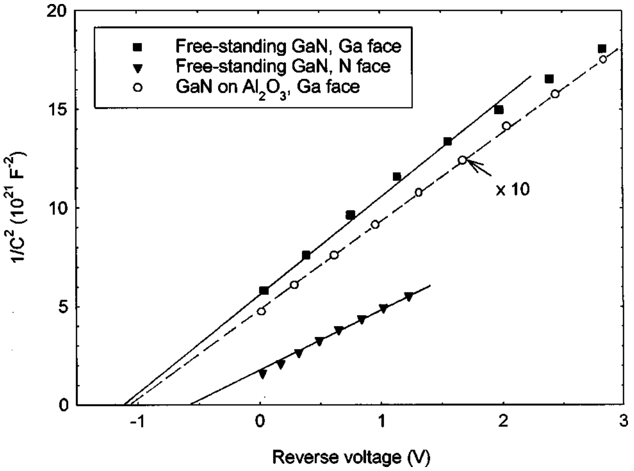

FIG. 1. Plots of $1/C^2$ vs V at 300 K for Ni/Au SBDs fabricated on the Ga and N faces of free-standing GaN and the Ga face of HVPE-GaN on Al_2O_3.

for the N-face-up film is much smaller, only about 0.6 V. Thus, we believe that the Schottky barrier asymmetry is related to the surface polarity. The barrier heights of Ni on GaN are then determined to be 1.27 eV on the Ga face and 0.75 eV on the N face. The value 1.27 eV is very close to that published for Ni on GaN;[8,9] however, the lower barrier height found here for the N face has not been reported before. The latter result may imply Fermi level pinning on the N surface. The different Schottky barriers on the two faces may also depend on details of the surface reconstruction. More investigations are needed to confirm the present observations. From the slopes of the $1/C^2$ vs V plots, the near-surface carrier concentrations for the samples with the Ga face and the N face up, respectively, are calculated to be 1.2×10^{16} and 1.8×10^{16} cm^{-3}. These values are among the lowest ever reported for conductive GaN. Since the mobility is also very high, $\sim$1100 cm^2/V s at 300 K,[10] this material clearly has unusually low densities of residual donors and acceptors.

Typical DLTS spectra for a SBD obtained from the Ga-face sample, measured as a function of filling pulse width (W_f), are shown in Fig. 2. We see that (i) there exist six deep traps (labeled A_1, A, B, B', C, and D) in the temperature range of 80–450 K and (ii) three of these traps, A_1, A, and B', show significant increases in peak height as W_f increases from 0.2 to 20 ms. The ‘‘fingerprints’’ of these traps, i.e., E_T and σ_T, determined from the Arrhenius plots of T^2/e_n vs $1/T$, are $E_T=0.70$ eV and $\sigma_T=1.7\times10^{-15}$ cm^2 for A; $E_T=0.58$ eV and $\sigma_T=2.4\times10^{-15}$ cm^2 for B; $E_T=0.53$ eV and $\sigma_T=1.5\times10^{-15}$ cm^2 for B'; $E_T=0.35$ eV and $\sigma_T=1.6\times10^{-15}$ cm^2 for C; and $E_T=0.25$ eV and $\sigma_T=1.2\times10^{-15}$ cm^2 for D. Traps A_1, A, B, and D are commonly observed in epitaxial GaN grown by various techniques, including metalorganic chemical vapor deposition (MOCVD), reactive molecular beam epitaxy (RMBE), and HVPE.[11] A significant increase in a DLTS signal as a function of W_f, as found for traps A_1, A, and B', usually suggests a small capture cross section; however, similar behavior can be found if the trap behaves like a ‘‘line defect,’’ which is typically associated with threading dislocations. For example, we have discussed such behavior in connection with traps C_1 and A_1 in thin RMBE-GaN layers.[11] Further investigations of the capture kinetics of traps A_1, A, and B' are needed. We also measured DLTS spectra as a function of forward filling pulse height V_f (not shown here). The prominence of trap C found in the Ga-face sample appears to be related to the surface damage caused by RIE, since this center can be detected only in the top 0.4 μm, and cannot be found at all in the N-face sample (see below), which was processed by polishing followed by chemical etching and not by RIE. Interestingly, the behavior of trap C found here is very similar to that of a sputter-deposition-induced trap $ES3$ in MOCVD-grown n-GaN reported by Auret *et al.*[12] Unlike the case for trap C, the new trap B' is found not only near the surface, but also in the deeper region. From the results of Fig. 2, it appears that B' has a small capture cross section, but B' also seems to be affected by the strength of the electric field in the depletion region. For example, in Fig. 3, trap B' can be more clearly observed in the spectrum with $V_b=-8.0$ V, as compared to that with $V_b=-1.0$ V. Also, a significant reduction of the peak height of trap C was observed at $V_b=-8.0$ V. This unusual phenomenon, i.e., a decrease of peak height with more negative V_b, occurs for a trap which exists only in the top-surface region. A full report will be published elsewhere.

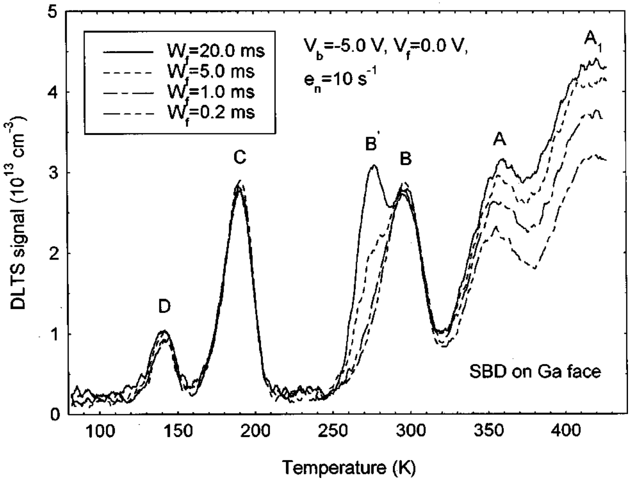

FIG. 2. DLTS spectra for a SBD made on the Ga face, measured as a function of filling pulse width (W_f).

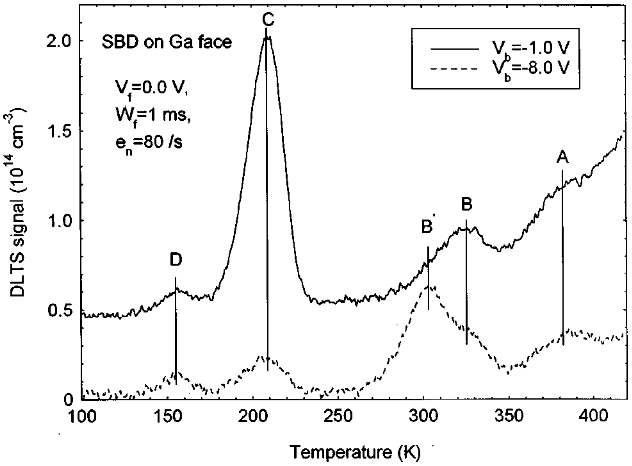

FIG. 3. DLTS spectra for a SBD made on the Ga face, measured at $V_b=-1.0$ and -8.0 V.

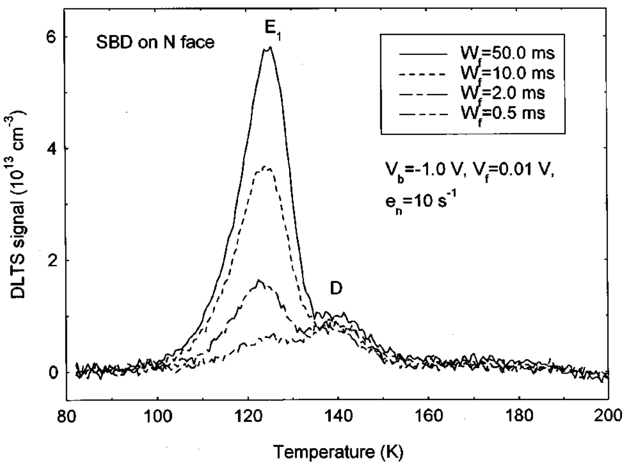

FIG. 4. DLTS spectra for a SBD made on the N face, measured as a function of filling pulse width (W_f).

For several of the N-face SBDs, measured at temperatures below 200 K, we observed trap *D*, but not trap *C*. However, in some of the N-face SBDs, we found trap E_1, which is shown in Fig. 4 as a function of W_f. The E_T and σ_T for trap E_1 were determined to be 0.18 eV and 4×10^{-17} cm^2, respectively. The much lower value of the capture cross section for trap E_1, compared to that of trap *D*, can explain the strong influence of W_f on the peak height of trap E_1. Trap E_1 was also observed in thin GaN films grown at 750 °C by RMBE, as previously reported.[11] Through comparisons of the DLTS spectra in as-grown RMBE GaN and electron-irradiated MOCVD GaN, shown in Figs. 4 and 8 of Ref. 11, trap E_1 is found to be very similar to the electron-irradiation-induced trap *E*, and is thus believed to be a complex involving the N vacancy. This tentative assignment is supported by the fact that ammonia, the N source in RMBE growth, is rather stable at the low growth temperatures employed, and thus N vacancies might be expected. Also, the observation of trap E_1 in the N-face SBDs of this study might be an indication of nitrogen deficiency in the early stages of HVPE growth.

In summary, we have used DLTS to study the deep-center characteristics of both Ga-face and N-face samples from a ~300-μm-thick, free-standing HVPE-grown GaN layer. In addition to four traps commonly observed in various epitaxial GaN layers, a new trap B', with parameters $E_T = 0.53$ eV and $\sigma_T = 1.5 \times 10^{-15}$ cm^2, was found in the Ga-face sample. The B' peak height depends strongly on the filling pulse width and the electric-field strength. For the N-face sample, a N-vacancy related trap E_1, with $E_T = 0.18$ eV and $\sigma_T = 4 \times 10^{-17}$ cm^2, was observed. On the other hand, the Ga-face sample contained trap *C*, with $E_T = 0.35$ eV and $\sigma_T = 1.6 \times 10^{-15}$ cm^2. This trap is thought to be related to surface damage caused by the RIE process employed. By using *C–V* measurements, the barrier heights of Ni/Au Schottky contacts were determined to be 1.27 and 0.75 eV, when fabricated on the Ga face and the N face, respectively.

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