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Photoionisation spectroscopy of traps in AlGaIn/GaN high electron mobility transistors grown by molecular beam epitaxy

P.B. Klein, J.A. Mittereder, S.C. Binari, J.A. Roussos, D.S. Katzer and D.F. Storm

Photoionisation spectroscopy has been carried out in bias-stressed AlGaIn/GaN high electron mobility transistors grown by MBE in order to probe the nature of the deep trapping centres responsible for stress-induced current collapse in these devices. The results indicate that a GaN buffer layer trap previously associated with current collapse in devices grown by MOCVD is responsible for induced collapse in MBE-grown structures.

Introduction: Owing to the physical characteristics of the group-III nitrides, nitride-based electronic devices offer great potential for operation at high power, high frequency, high temperature and in adverse environments. However, trapping effects are now one of the main problem areas that prevent the integration of these devices into mainstream applications [1]. A trap-related phenomenon of particular concern is current collapse. Current collapse is manifested as a significant drop in the DC drain current as the result of the application of a high drain-source voltage. The collapse results [2] from the injection of hot carriers from the conducting channel to an adjacent region of the device that contains a high concentration of deep trapping centres. The subsequent trapping of these carriers leads to the reduced drain current.

A technique that has been introduced recently to investigate the nature of the traps that cause current collapse is photoionisation spectroscopy [3]. In these measurements, a fully collapsed device, in which the deep traps have been filled, is illuminated with below-bandgap light. When the incident photon energy is greater than the absorption threshold for releasing the trapped carriers, the carriers can escape from the trap and drift back to the conducting channel, thus restoring the drain current. The dependence of the drain current increase on the incident photon energy maps out a photoionisation spectrum, which is an absorption spectrum that is characteristic of the deep defect and may be used to identify or 'tag' the defect. Previous photoionisation studies of nitride-based metal-semiconductor field effect transistors (MESFETs) [3–5] and high electron mobility transistors (HEMTs) [6] grown by metal organic chemical vapour deposition (MOCVD) have shown that two deep traps residing in the high-resistivity (HR) GaN buffer layer are responsible for collapse in these devices. The two traps, labelled trap1 and trap2, introduce two broad, below-gap absorptions into the spectrum with photoionisation thresholds at 1.8 and 2.85 eV, respectively. Both traps have also been associated with persistent photoconductivity in GaN. Trap1 appears to be a strongly lattice-coupled deep donor [3, 7] and trap2 has been identified [8] as a carbon-related defect.

These studies have been made in MOCVD-grown devices, as similar structures grown by MBE in our laboratory have not exhibited a large enough collapse to carry out these measurements. Recently, however, it has been shown [9] that the application of a high drain bias stress for several hours has the effect of inducing current collapse in HEMT structures. The effect of the stress must be to generate defects (or change the charge state of existing defects), most probably by hot carrier damage [10], such that after the stress is removed, empty deep defects are present and available to trap carriers when a high voltage is later applied to the device. We have observed that significant current collapse was induced in several MBE-grown wafers [9] after the application of stress. The defects introduced by stress represent a potential reliability issue for these devices. In this Letter we investigate the nature of the traps that are responsible for current collapse in stressed MBE-grown structures through photoionisation spectroscopy measurements.

Results: Typical DC I - V curves ($V_{GS}=0$ V) are shown in Fig. 1 for an MBE-grown HEMT both before and after 16 h of stress at $V_{DS}=30$ V and $I_{DS}=200$ mA/mm [9]. Each set of data consists of three I - V sweeps taken sequentially. The first of the three I - V sweeps exposes the device to a high bias at the end of the sweep, thus leading to hot carrier injection and trapping. The subsequent two sweeps

reflect the trapped carrier concentration through the amount of observed collapse—i.e. the amount of reduction in the drain current. Before stress, very little loss in drain current is observed, as the last two sweeps (almost identical) exhibit only a slightly reduced drain current. After stress, a large drop in drain current is observed in the last two sweeps, indicating that significant current collapse has been induced through the applied stress.

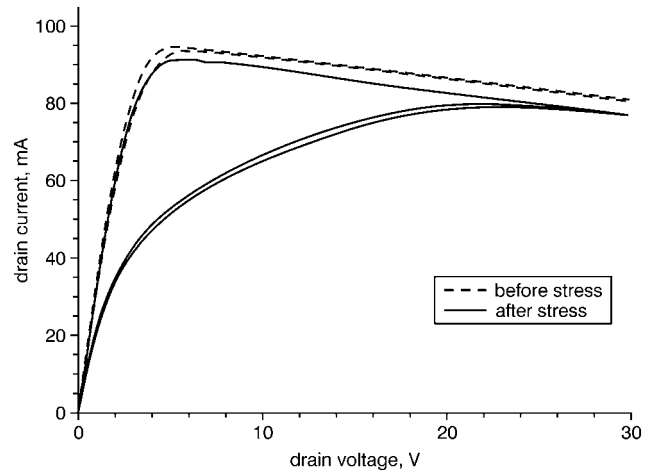


Fig. 1 I - V characteristics ($V_{GS}=0$) of typical MBE-grown HEMT before and after stress

Each set of I - V s consists of three consecutive sweeps

Photoionisation spectra are shown in Fig. 2 for an MBE-grown HEMT after stress has been applied, and compared to a MESFET and a HEMT, both grown by MOCVD. The MOCVD devices both reflect the two broad absorption thresholds associated with trap1 and trap2 [3], as well as the expected rise at the GaN bandgap. The spectrum of the MBE device is quite different, exhibiting a broad trap1 absorption, no visible trap2 absorption threshold near 2.85 eV, and a new absorption threshold near 3.7 eV, above the GaN bandgap. The spectra of the MBE-grown devices are distinctly different from any of the spectra previously obtained from MOCVD structures.

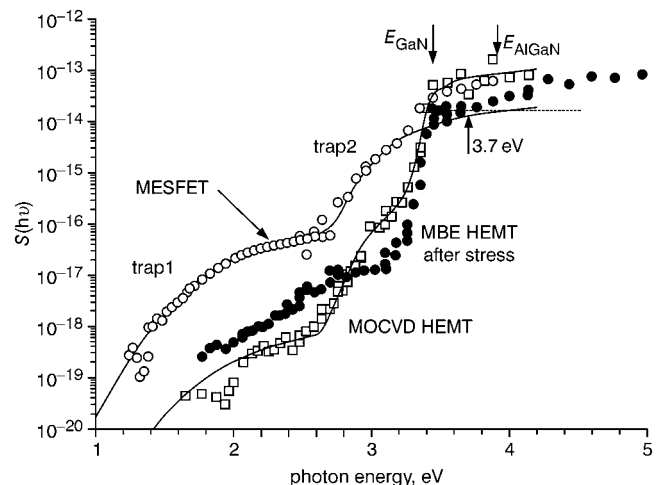


Fig. 2 Photoionisation spectrum of stressed MBE-grown HEMT compared to that of MOCVD-grown MESFET and HEMT structures

- MBE-grown HEMT
- MOCVD-grown MESFET
- MOCVD-grown HEMT

Discussion: The absence of a trap2 feature in the absorption spectrum of MBE-grown devices is consistent with the recent association [8] of this defect with the presence of carbon in MOCVD-grown structures. While carbon is one of the primary unintentional impurities in MOCVD-grown materials as a result of the organic precursors employed in the growth, it is not expected in MBE materials in substantial concentrations. Thus, the carbon-related defect responsible for the trap2 absorption (and current collapse) is absent in the MBE material.

The absorption threshold at 3.7 eV is clearly associated with the AlGa_N layer, as it occurs above the GaN bandgap. The increase in drain current induced by this illumination must be the result of photoexcited electrons that restore some of the 2DEG sheet charge that was lost due to current collapse. However, to excite a conduction band electron in the AlGa_N ($x=0.25$, $E_g \simeq 3.9$ eV) with 3.7 eV photons, the defect level would have to be roughly 0.2 eV above the AlGa_N valence band. This is too shallow to be a deep defect, but is in the same energy range as shallow acceptors in AlGa_N. We must conclude, therefore, that the 3.7 eV threshold does not appear to be associated with a deep centre that could result in current collapse, but instead corresponds to the photoneutralisation of ionised shallow acceptors. Since the trap1 defect and the 3.7 eV threshold were the only features in the photoionisation spectrum that could be associated with the collapse, it appears that the sole trapping centre that is responsible for stress-induced current collapse in MBE-grown HEMTs is trap1, a GaN buffer layer defect [3, 4].

Since trap1 was only able to contribute to current collapse after stress, we must conclude that either (i) the defect was created directly by the stress by hot carrier damage, or (ii) the defect existed previously, but was already filled before the stress and emptied (and thus able to trap charge) as a result of the stress. This could occur, for example, if hot carrier damage resulted in the generation of defects that were lower in the bandgap than trap1, resulting in the emptying of the trap1 carriers into the lower-lying stress-induced defect states.

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