Femtosecond Studies of High-Field Transient Electron Transport in GaN

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We present an optically-detected time-of-flight technique with femtosecond resolution that monitors the change in the electroabsorption due to charge transport in a III-N *p-i-n* diode, and show how it may be used to determine the electron transit time, electron velocity overshoot, and electron velocity-field characteristics in GaN at room temperature. The samples under study were grown by MOCVD. The experiments were performed using frequency doubled ultrashort pulses derived from a 250 kHz regenerative amplifier-pumped optical parametric amplifier. For a GaN homojunction *p-i-n* diode, the experimentally obtained peak steady-state electron velocity of 1.9×10^7 cm/sec, corresponding to a transit time of ~2.5 ps across the 0.53 μm depletion region, occurs at 225 kV/cm. While the shape of the electron velocity-field characteristic is in qualitative agreement with theoretical predictions, the peak velocity is lower than expected. Moreover, no transient electron velocity overshoot was observed in this device, a phenomenon that may be attributed to the photo-excitation of the electron-hole pairs in the *p*-layer near the interface of the *p*- and *i*-layers, where they may be influenced by both the electric field nonuniformity associated with the "optical dead space" in the *p*-layer and the nonuniform field at the *p-i* junction on the short time scale during which velocity overshoot is expected to occur (< 0.5 ps).

These issues have been addressed by performing measurements on an AlGaN/GaN heterojunction *p-i-n* diode. In this structure the *p*-layer is an $Al_{0.1}Ga_{0.9}N$ window that allows the electron-hole pairs to be excited directly in the *i*-region of the diode, where the electric field E is expected to be more uniform. It has been found that electron velocity overshoot occurs at electric fields as low as 105 kV/cm, with the peak transient velocity increasing with E up to ~320 kV/cm, at which field a peak velocity of 7.25×10^7 cm/s is attained within the first 200 fs after photoexcitation. At higher fields, the measurement of the peak velocity is limited by the 80 fs duration of the pulses, but the increase in transit time with increasing field suggests the onset of negative differential resistance. Velocity overshoot is a phenomenon often associated with the onset of intervalley transfer in other III-V materials. However, theoretical Monte Carlo calculations incorporating a GaN full-zone band structure show that although the peak steady-state velocity occurs at ~200 kV/cm, the ensuing negative differential resistance region of the velocity-field curve is not initially associated with intervalley transfer, as the majority of electrons do not attain sufficient energy to effect this transfer until they are subjected to much higher fields (>325kV/cm). Insight into this behavior can be gleaned from the band nonparabolicity deduced from the constant energy surfaces in the Γ valley, which shows that the effective mass in the c-direction can be viewed as becoming larger at high k-values. This larger effective mass may play a role in velocity overshoot by inhibiting energy gain and reducing the momentum relaxation time at high k-values in the Γ valley. It is important to note that the transit time measurements suggest that the steady-state velocity in this heterojunction device is more than 1.5 times higher than that observed in the homojunction device at comparable fields in the high field regime. Although the material quality in the heterojunction diode is probably better than that of the previously fabricated homojunction diode, a more important factor in attaining the high steady-state velocity may be the improved lateral uniformity of the electric field in the *i*-region resulting from the use of a semitransparent *p*-contact metal covering the entire excitation area.