Electron irradiation of AlGaN/GaN and AlN/GaN heterojunctions

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The effects of 10 MeV electron irradiation on AlGaN/GaN and AlN/GaN heterojunctions grown by molecular beam epitaxy are reported. The irradiation increases the resistivity of the GaN buffer due to compensation by radiation defects with levels near E_c-1 eV and decreases the mobility of the two-dimensional electron gas (2DEG) near the AlGaN/GaN (or AlN/GaN) interface. The bulk carrier removal rate in the GaN buffer is the same for both types of structures and similar to carrier removal rates for undoped *n*-GaN films. In structures with a density of residual donors of $\sim 10^{15}$ cm^{-3}, irradiation with electron doses of $\sim 5\times 10^{15}$ cm^{-2} renders the buffer semi-insulating. The 50% degradation of the 2DEG conductivity happens at several times higher doses (close to 3×10^{16} cm^{-2} versus 6.5×10^{15} cm^{-2}) for AlN/GaN than for AlGaN/GaN structures, most likely because of the lower thickness of the AlN barrier.
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High electron mobility transistor (HEMT) structures based on AlGaN/GaN and AlN/GaN are of interest for high-power microwave applications.[1–5] One of the issues in such structures is the need for highly resistive GaN buffers for proper channel pinch-off, good interdevice isolation, and low microwave power losses. Several groups have demonstrated semi-insulating undoped GaN buffers in which conductivity is compensated by a high dislocation density or by native point defects,[6,7] but reproducible fabrication of undoped SI GaN buffers is challenging. Another approach is doping with transition metals such as Fe[8–14] and this can produce semi-insulating buffers in HEMT structures grown by molecular beam epitaxy (MBE).[15,16] To improve two-dimensional gas (2DEG) mobility, separation of the HEMT channel from the Fe doped region of the buffer is achieved by growing on top of the GaN(Fe) an unintentionally doped GaN (uid-GaN) layer. To preserve the high resistivity of the combined buffer without compromising the 2DEG mobility requires optimizing the Fe concentration and the thickness of the uid-GaN portion of the buffer.[17,18]

In this letter we show electron irradiation can produce high resistivity buffers. This compensates the conductivity of *n*-GaN by introduction of nitrogen interstitial-related compensating acceptors near E_c-1 eV with a carrier removal rate in undoped *n*-GaN of ~ 0.5 cm^{-1}.[16–18] In combined GaN(Fe)/uid-GaN buffers, the main compensating center is at $\sim E_c-0.5$ eV and electron irradiation pins the Fermi level in conducting buffers to this trap. The associated increase in resistivity of the 2DEG has been studied for proton and neutron irradiation HEMT structures and the decrease of the 2DEG mobility was found to be the major issue.[19–21]

The structures were grown by MBE on (0001) sapphire substrates using a thin (20 nm) high temperature AlN nucleation layer. Two structures were studied. Both consisted of GaN(Fe) subbuffer (0.7 μm thick), uid-GaN layer, AlGaN (Al composition $x=0.28$), or AlN barrier and a thin (1–2 nm) undoped GaN cap layer. Sample 902 used a 2.2 μm thick uid layer and the 2DEG sheet concentration was 1.3×10^{13} cm^{-2} with mobility of 1410 cm^2/V s. Sample 102 used a 4.1 μm thick uid layer and the 2DEG sheet concentration was 1.9×10^{13} cm^{-2} with mobility of 1360 cm^2/V s. The concentration of residual electrons in the buffers was determined by capacitance-voltage (*C-V*) measurements with the AlGaN (or AlN) barriers removed by etching.[14,15] In both cases the residual donor concentration in the buffer was $\sim 10^{15}$ cm^{-3}. The structures were irradiated at 300 K by 10 MeV electrons with doses of 5×10^{15}, 1×10^{16}, or 3×10^{16} cm^{-2}. Before and after irradiation the films were characterized by Hall/van der Pauw, *C-V* with Au Schottky diodes, current-voltage (*I-V*), and deep level transient spectroscopy (DLTS).

Figure 1 shows the 300 K *C-V* characteristics measured on the 902 AlGaN/GaN (solid curves 1–3) and the 102 AlN/GaN (dashed curves 1′–3′) HEMTs before and after irradiation with fluences of 5×10^{15} and 1×10^{16} cm^{-2}. For virgin *C-V* characteristics (curves 1 and 1′) one observes flat regions at high reverse voltages with capacitance higher than the parasitic capacitance (~10 pF in our case). This is an indication that the buffers before irradiation were conducting. After irradiation, the capacitance in depletion dropped below 10 pF, proving that the buffer became semi-insulating. This is confirmed by conductivity measurements on the irradiated (fluence of 3×10^{16} cm^{-2}) samples with the AlGaN or AlN barriers removed by etching in phosphoric acid. These structures showed 300 K sheet resistivity $>10^{10}$ Ω/sq, with activation energy of conductivity ~0.6 eV. Electron irradiation causes a decrease in the buffer conductivity by compensating the residual donors with radiation induced acceptors.

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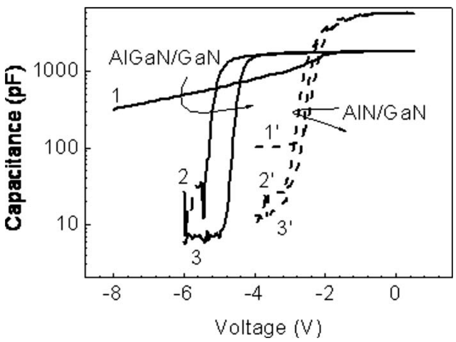

FIG. 1. 300 K 1 kHz *C-V* characteristics measured for the AlGaN/GaN sample 902 (solid curves) and the AlN/GaN sample 102 (dashed curves); curves 1 and 1′ correspond to the virgin samples, curves 2 and 2′ were taken after irradiation with the dose of 5×10^{15} cm^{-2}, curves 3 and 3′ after irradiation with the dose of 10^{16} cm^{-2}.

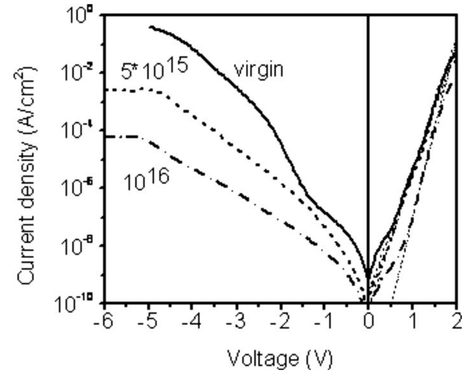

FIG. 3. 300 K *I-V* characteristics from AlGaN/GaN structure before (curve 1) and after irradiation with 10 MeV electron doses of 5×10^{15} cm^{-2} (curve 2) and 1×10^{16} cm^{-2} (curve 3).

Figure 2 shows the changes in the 300 K sheet resistivity ρ_s and electron mobility μ with irradiation for the two samples, normalized to the preirradiation values. The sheet resistivity changes with dose are slow for the AlN/GaN structure 102. For the AlGaN/GaN sample 902, a measurable increase was detected at much lower doses: the resistance increased by about 14% after a dose of 5×10^{15} cm^{-2} and by about six times after irradiation with a dose of 3×10^{16} cm^{-2}. The 2DEG concentrations were not affected by irradiation in both cases so that the entire increase in sheet resistivity comes from the decrease in mobility. Figure 3 shows the variation of the room temperature *I-V* characteristics of a Schottky diode on the AlGaN/GaN structure after electron irradiation. Irradiation strongly decreases the leakage current of the structure, but also, after irradiation with the electron dose of 10^{16} cm^{-2}, leads to about an order of magnitude increase in the series resistance. For the AlN/GaN structure a similar decrease in the leakage is observed, but the series resistance increase was lower.

Figure 4 compares deep trap spectra measured on the AlN/GaN structure before and after irradiation with a dose of 10^{16} cm^{-2}. These spectra were taken with optical injection from a deuterium lamp pulse at a reverse bias of −3 V. Both electron and hole traps present in the AlN barrier, at the AlN/GaN interface and in the GaN buffer, can be detected. Hole traps manifest themselves as negative peaks corresponding to capacitance decreasing with time during the capacitance decay. Both spectra are dominated by a broad hole trap band extending from 85 to 400 K, likely related to extended defects such as dislocations.[22] This hole trap band is modulated by positive peaks due to electron traps E1, E2, E3 with activation energies 0.2, 0.25, and 0.6 eV, respectively, produced by traps in the GaN buffer.[23] In addition, in the irradiated sample, we observed another electron trap E4 with the activation energy of 1 eV. The Arrhenius plot of this trap is very similar to the Arrhenius plot of the main compensating radiation defect in GaN associated with nitrogen interstitials.[16–18]

The results show the main process occurring in the buffers upon irradiation is compensation of conductivity produced by the radiation induced acceptors with level close to 1 eV and often associated with nitrogen interstitials.[16–18] The carrier removal rate estimated from our data is about 0.4–0.6 cm^{-1}, in good agreement with measurements performed on undoped *n*-GaN films with residual donor density 10^{16} cm^{-3} grown by metal-organic chemical vapor deposition.[18] Our measurements on MOCVD AlGaN/GaN HEMT structures grown on undoped *n*-GaN buffers with residual concentration of $\sim5\times10^{16}$ cm^{-3} give a similar removal rate. The higher the residual donor concentration, the higher the irradiation dose needed to render the material semi-insulating. The important consideration is that this dose does not produce unacceptable changes in the 2DEG conductivity. The main damaging factor of electron irradiation is the 2DEG mobility degradation caused by generation of defects near the AlGaN/GaN interface. This mobility degradation occurs at an order of magnitude lower doses in AlGaN/GaN structures compared to AlN/GaN. The might be due to the difference in the barrier thickness and correspondingly lower lattice damage produced near the interface. This is similar to

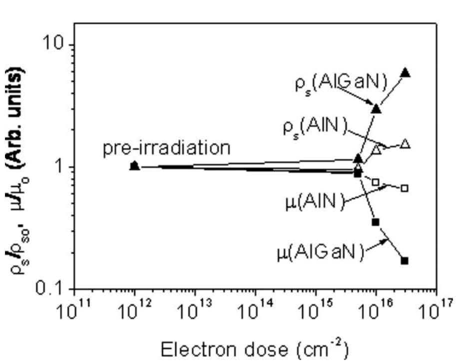

FIG. 2. Dependence of sheet resistivity ρ_s and mobility μ of the AlGaN/GaN and AlN/GaN samples on the dose of 10 MeV electrons.

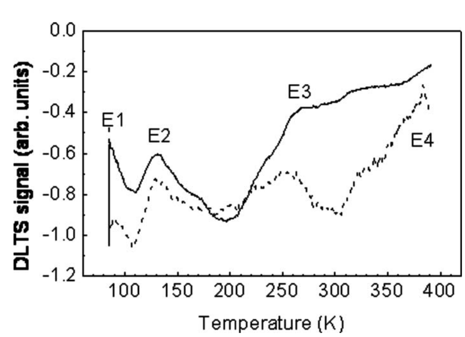

FIG. 4. DLTS spectra with injection pulse from UV deuterium lamp (5 s long) measured for the AlN/GaN structure before (solid line) and after irradiation with 10^{16} cm^{-2} electrons; reverse bias of −3 V, time windows 500/5000 ms.

the observation that increasing proton energy from 1.8 to 40 MeV strongly decreases the amount of damage produced in HEMTs.[24–26]

Another issue is the thermal stability of the radiation induced changes in the buffer resistivity. The main annealing step in proton irradiated GaN occurs near 300 °C where shallow donorlike defects with activation energy 0.2 eV are removed.[25] This should increase the resistivity because the compensating defects at E_c-1 eV are stable even after annealing at 800 °C.[26] Hence, the obvious practical implementation of the process would be electron irradiation of device structures to avoid annealing of radiation defects during Ohmic contact formation.

In conclusion, electron irradiation of HEMTs can be used to increase the GaN buffer resistivity. The radiation hardness of the AlN/GaN HEMT structures is about an order of magnitude higher than for AlGaN/GaN HEMTs.

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