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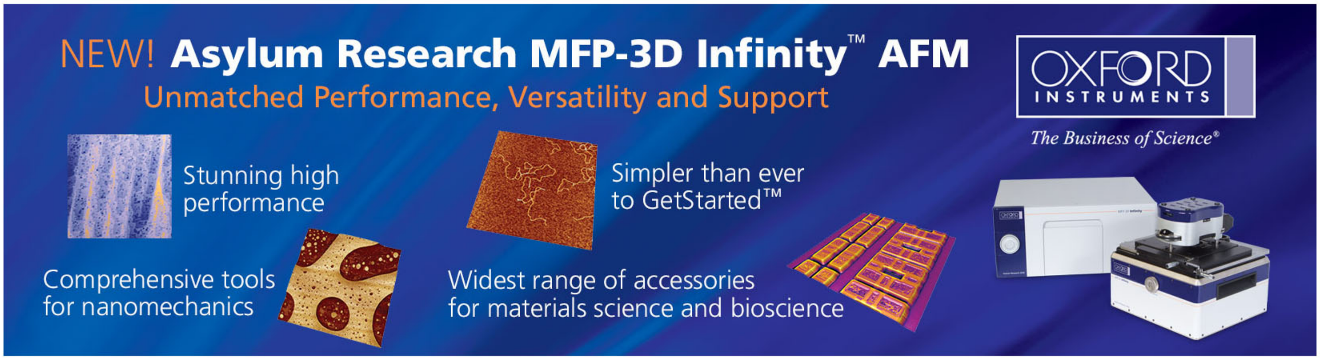

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Characteristics of deep levels in As-implanted GaN films

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Hall, current–voltage and deep level transient spectroscopy measurements were used to characterize the electric properties of n-type GaN films implanted with As atoms. After 800 °C thermal annealing for 60 min, one additional deep level located at $E_C - 0.766$ eV was found in the films. We presume this induced trap is an arsenic-related point defect, most likely antisite in nature. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1499739]

III–V nitrides have been a subject of intensive investigations for applications in optoelectronic devices such as high-temperature transistors,[1] visible and ultraviolet light emitting diodes and laser diodes.[2,3] Due to the lack of a lattice-matched substrate being available for GaN, the epitaxial film is usually comprised of large concentrations of radiative or nonradiative defects, causing degradation of the device performance and lifetime. In order to improve the material quality, varieties of techniques have been employed in preparing GaN film. These have included isoelectric doping, which has been proved to be capable of suppressing the formation of nonradiative centers, deep levels, as well as dislocations.[4] Recent theoretical calculations by Matilla and Zunger,[5] and by Van de Walle and Neugebauer[6] also showed that isovalent doping using As atoms can produce energy levels deep in the band gap of GaN, leading to emission in the desired visible wavelength region. This prediction was confirmed by numbers of authors using primarily optical measurements, including Jadwisienczak and Lozkyowski,[7] Guido *et al.*,[8] Li *et al.*,[9] and Winser and co-workers.[10] They reported that As doping and implanting of GaN could improve the mobility,[9] suppress yellow emission,[11] and, more importantly, enhance the strong blue emissions at peak positions of from 2.60 to 2.73 eV.[7–10] Here, we conduct a series of Hall, current–voltage and deep level transient spectroscopy measurements of As-implanted GaN films. Our results indicate that one additional deep level is generated 0.769 eV below the conduction band, which is most likely to be As related.

The undoped n-type GaN samples were grown on a sapphire substrate using the metalorganic vapor phase epitaxy technique. The corresponding carrier concentration and mobility are about $2\times10^{17}\ \mathrm{cm}^{-3}$ and $318\ \mathrm{cm}^2/\mathrm{V\,s}$, respectively. These samples were subsequently implanted with As^+ ions with 50 keV at 1×10^{14} and $5\times10^{15}\ \mathrm{cm}^{-2}$ dosage levels. They are labeled As14 and As15, respectively. The results of the Hall measurement are depicted in Fig. 1. We see the carrier concentration of the As-implanted film dropped considerably to a value of $\sim1.3\times10^{16}\ \mathrm{cm}^{-3}$, nearly independent of the As ion dosage. However, we do observe a greater difference in the mobility of the two ion dosages. The mobility of As-14 is $275\ \mathrm{cm}^2/\mathrm{V\,s}$, reduced only slightly from its original value. As for As-15, probably because of high implantation damage a highly resistive characteristic was observed, which gives a value of almost zero for the mobility. Nonetheless, the subsequent thermal annealing process did help to improve the film quality as can be seen in Fig. 1. For implanted samples annealed at 800 °C, we find that both the carrier concentration and mobility recover gradually with an increase in annealing time, and reach values nearly identical to those of as-grown one as the annealing time is extended to 60 min.

After Hall measurements, Schottky diodes were fabricated on the 60 min annealed samples (labeled As14-60 and As15-60) to study As implanting effects on GaN. Using the procedure published in the literature,[4,12] the results of current–voltage and Hall characteristics are summarized in Table I. It is interesting to note that the annealed arsenic-implanted GaN film performed even better than the as-grown one. Not only is the ideality factor reduced from 1.387 to 1.227, but the Schottky barrier height and reverse current density are also improved substantially from 0.744 eV and

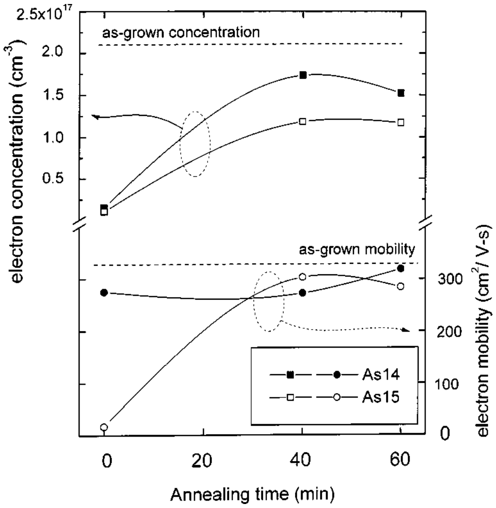

FIG. 1. Carrier mobility and concentration of various samples vs the annealing time.

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TABLE I. Parameters of Hall and current–voltage properties for as-grown, As14, As14-60, As15, and As15-60 samples.

Sample	Dosage (cm^{-2})	Mobility ($cm^2/V\,s$)	Concentration (cm^{-3})	Ideality factor	J_s (A/cm^2)	Φ_{bn} (eV)
As grown		318	2.14×10^{17}	1.387	4.90×10^{-7}	0.744
As14	1×10^{14}	275	1.55×10^{16}	⋯	Poorly rectified	⋯
As14-60	1×10^{14}	319	1.74×10^{17}	1.227	3.77×10^{-10}	0.927
As15	5×10^{15}	16	1.10×10^{16}	⋯	Poorly rectified	⋯
As15-60	5×10^{15}	284	9.76×10^{16}	1.293	7.56×10^{-10}	0.909

4.90×10^{-7} A/cm^2 to 0.927 eV and 3.77×10^{-10} A/cm^2, respectively.

To investigate whether there are electrically active As-induced defects generated in the band gap, we performed deep level transient spectroscopy (DLTS) measurements. The results of As14-60 and As15-60 are shown in Fig. 2. For comparison, that of the as-grown sample is also included. The measurements were conducted at a bias of -1 V, pulsed periodically to 0 V for trap filling. Transient capacitance signals were acquired by using a test ac signal of 100 kHz and 100 meV over the temperature range from 370 to 100 K. It is seen there is only one prominent deep level in the as-grown GaN that is peaked at 340 K. Together with the Arrhenius plots in Fig. 3, we could determine the activation energy and the trap concentration of this 340 K point defect to be $E_C-0.879$ eV (labeled E_4) and 7.09×10^{15} cm^{-3}, respectively. Two additional deep levels, $E_C-0.600$ (labeled E_2) and -0.766 eV (labeled E_{As}), showed up in As14-60. On the other hand, for As15-60, the E_4 deep level diminished almost completely, and instead a shallower deep level $E_C-0.157$ eV (labeled E_1) showed up. For convenience, all of the trap parameters of these samples are listed in Table II.

Although there are numbers of deep levels that appear in the diodes, E_1, E_2 and E_4 defects were observed in a variety of GaN samples grown by different methods, including metalorganic vapor phase epitaxy,[4,12–14] hydride vapor phase epitaxy[15] and molecular beam epitaxy.[16] Accordingly, E_1, E_2 and E_4 defects are commonly thought to be native defects and have been assigned to the nitrogen vacancy related complex, nitrogen antisite and nitrogen interstitial, respectively. Since ion implantation is known to create native defects,[14] we attribute the E_1 and E_2 traps found in our As-implanted films to this effect. On the other hand, the concentration of an additional E_{As} level increase with an increase in arsenic doping suggests the formation of this deep level is closely related to the arsenic ions. A tentative explanation for this particular trap is described as follows.

After As implantation, our GaN film is generally believed to hold large quantities of native defects, most likely in the form of nitrogen and gallium vacancies and arsenic interstitials. Due to their unstable nature, these arsenic interstitials have a great tendency to incorporate either on Ga and form isovalent arsenic substitutes (As_N) or on N sites and form an arsenic antisite (As_{Ga}) during the subsequent thermal annealing process. Calculation showed both of these levels are types of donor defects with energies positioned 0.11–0.33 eV above the valence band and 2.6–2.7 eV above the valance band for As_N and As_{Ga},[5,6] respectively. The As_N

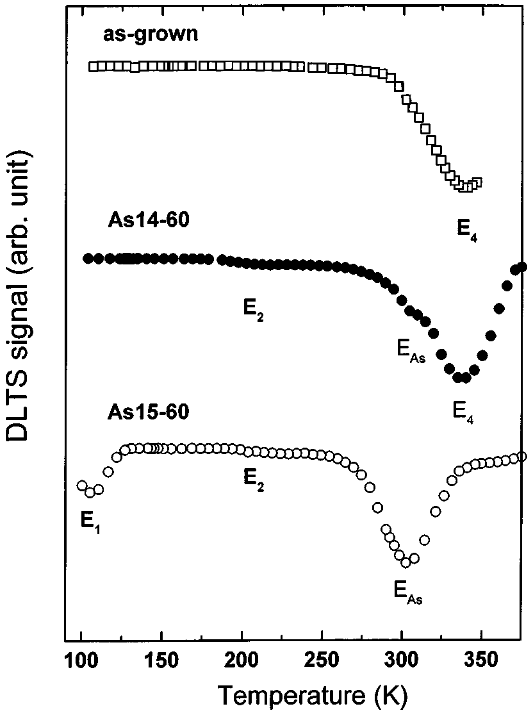

FIG. 2. DLTS spectra of the as-grown, As14-60, and As15-60 samples.

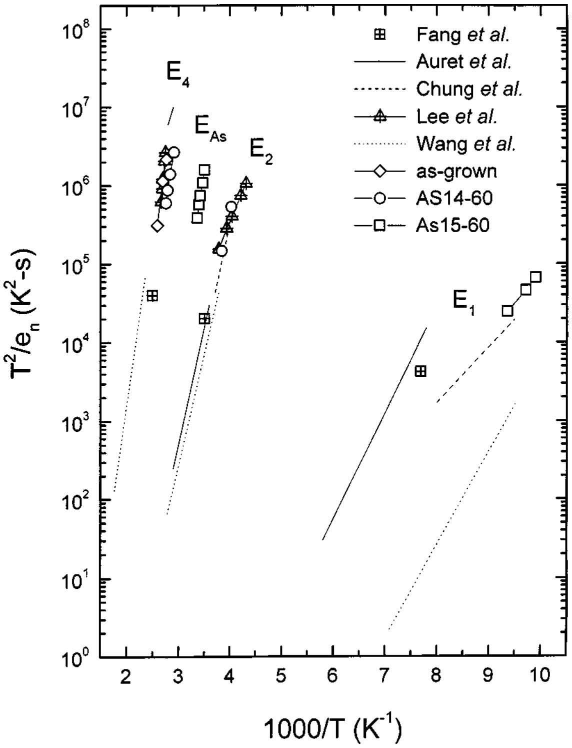

FIG. 3. Arrhenius plot of DLTS signals for as-grown, As14-60, and As15-60 samples. Similar deep levels published in the literature are also included.

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TABLE II. Parameters of DLTS signals for as-grown, As14-60, and As15-60 samples.

Sample number	ΔE_1 (eV)	N_1 (cm^{-3})	ΔE_2 (eV)	N_2 (cm^{-3})	ΔE_{As} (eV)	N_{As} (cm^{-3})	ΔE_4 (eV)	N_4 (cm^{-3})
As grown							0.879	7.09×10^{15}
As14-60			0.600	2.77×10^{14}	0.766	9.24×10^{14}	0.920	5.92×10^{15}
As15-60	0.157	1.03×10^{15}	0.600	3.09×10^{14}	0.769	7.37×10^{15}		

level therefore is too deep to account for the data observed and leads us to believe the E_{As} deep level is the arsenic antisite defect. This is supported by the sum of 0.766 and 2.6–2.7 eV being equal to approximately 3.4 eV, the GaN band gap,[17] and by the much lower formation energy of the arsenic antisite than that of the isovalent arsenic substitute (-0.37 vs 4.2 eV).[6] More interestingly, our DLTS results agreed with photoluminescence (PL) data of As-doped GaN films reported to date,[7–10] in which, a strong, broad blue emission with energy of approximately 2.6–2.73 eV (Refs. 7–10) was found in As-doped GaN films, irrespective of being ion-implantated or epitaxial samples.

In summary, we have performed a DLTS study of arsenic-implanted GaN films. After 60 min annealing at 800 °C, we found a deep level lying ~0.766 eV below the conduction band of the As-implanted GaN samples. We tentatively assign this trap to an arsenic antisite since its energy coincides well with the result predicted by theoretical calculation. Our DLTS results also agreed with data from PL measurements fairly well. This suggests that arsenic ions in GaN induce deep levels that are active in both electrical and optical transition processes.

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