Vol. 90 (1996) *ACTA PHYSICA POLONICA A* No. 5

Proceedings of the XXV International School of Semiconducting Compounds, Jaszowiec 1996

DEEP LEVEL TRANSIENT SPECTROSCOPIC STUDIES OF MOCVD GaN LAYERS GROWN ON SAPPHIRE

A.A. Śliwiński, K.P. Korona, K. Pakuła and J.M. Baranowski

Institute of Experimental Physics, Warsaw University, Hoża 69, 00-681 Warsaw, Poland

The deep level transient spectroscopy of GaN heteroepitaxial layers grown on sapphire was studied. The samples were Mg doped during the growth. The as-grown material is n-type. It becomes p-type after annealing. The samples were measured in the temperature range from 77 K to 420 K. In n-type GaN, one peak (EG1) with activation energy 0.75 eV was detected. In p-type, at least three peaks were observed: AS1 at temperature about 300 K and AS2, AS3 at about 400 K. The dominating one is AS3. It has an activation energy about 1.1 eV.

PACS numbers: 71.55.Eq, 73.61.Ey

Gallium nitride has recently become a very promising material for fabrication of short-wavelength light emitters (light emitting diodes and lasers) [1, 2] and for high temperature electronics. This new material gives a possibility to produce semiconductor full-colour panel displays or high density storage systems. To realise such devices, it is essential to grow high quality GaN layers and to control the defect and impurity concentration. Deep defects could act as extra recombination centers leading to a decrease in laser's efficiency.

The GaN heteroepitaxial layers were grown in a horizontal metal-organic chemical vapour epitaxy (MOCVD) Epigress system adopted by us for the growth of nitrides. Trimethylogallium (TMG) and NH_3 were used as sources of Ga and N, respectively, in addition to H_2 as a carrier gas. Since the lattice mismatch between GaN and Al_2O_3 is 12.5%, it was necessary to grow a low temperature buffer layer. The GaN growth temperature was close to 1000°C and the growth parameters were adjusted in such a way that the crystalline GaN layers of about 2 μm thick were obtained. Pure undoped GaN crystals are highly n-type, probably due to a great number of nitrogen vacancies. In order to obtain p-type samples, it is necessary to dope them with Mg and to anneal them in at least 700°C. The p-type doping was realised using cyclopentadienyl magnesium (Cp_2Mg) as a precursor.

After the growth, the samples were cut and a part of the sample was annealed at temperature 700°C or 1000°C, in order to activate Mg acceptors [3]. The samples were annealed in vacuum or in nitrogen atmosphere. The best results were obtained

for samples annealed in vacuum at 700°C. One sample was successfully activated by the rapid thermal annealing (RTA). The efficiency of the acceptor activation was controlled by measurements of the conductivity reached by the sample after the annealing. The best samples have conductivity of the order of 0.1 Ω^{-1} cm^{-1}. Such low conductivity is due to very low mobility (below 10 $cm^2/(Vs)$) [4].

Aluminium or indium were used for ohmic contacts to the n-type and Au for the p-type samples. The Schottky barriers on the n-type material were formed by evaporating Au. There is no information about the Schottky barrier preparation on the p-type GaN. In this work, diodes were fabricated by Al evaporation. Prior to evaporation, the samples were etched in hot aqua regia.

The samples were studied using Semitrap DLS-82E Deep Level Spectrometer. The construction of a sample holder enabled us to perform measurements up to 440 K. This was unusually high temperature for deep level transient spectroscopy (DLTS) measurements but it was still too low for studying some of the deep defects in GaN. Since the energy gap of this material is very wide ($E_g = 3.44$ eV [5]), activation energies of defects equal to even 2 eV could be expected.

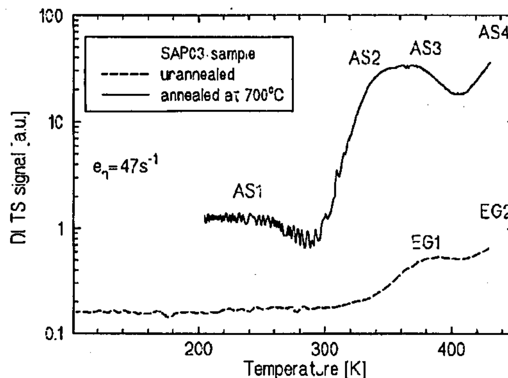

Fig. 1. DLTS spectra measured on as-grown and annealed GaN:Mg samples.

The results of the DLTS measurements are plotted in Fig. 1. In the as-grown material only two deep defects with a low concentration were observed. The first peak (EG1) appears at about 350 K. The thermal activation energy of EG1 defect $E_a = 0.75 \pm 0.1$ eV and its electron capture cross-section of about 3×10^{-15} cm^2 were determined. This peak is commonly observed in MOCVD and hydride vapor phase epitaxy (HVPE) GaN [6–8] which suggests that it originates from a native defect. The second peak has the maximum well above 400 K. We could not determine its activation energy but comparing with other papers [7, 8] we could conclude that this defect is also often observed in GaN.

Figure 1 also shows the spectrum of a sample annealed in vacuum, at temperature of 700°C for one hour. The AS1 defect has the activation energy of (0.4 ± 0.1) eV and a hole capture cross-section of about 10^{-16} cm^{-2}. The AS1 peak is only visible at higher emission rates. The activation energy of the peak

AS2, appearing at higher temperature, is equal to (0.7 ± 0.1) eV and it has the cross-section of the order of 10^{-15} cm^{-2}. The position of the AS3 peak is very close to AS2. At higher emission rates, the AS2 and AS3 peaks are merged, but at lower emission rates it is possible to separate them and to evaluate the AS3 activation energy $E_a = (1.1 \pm 0.1)$ eV. After analysis of the spectra we can conclude that in higher temperatures a fourth peak (AS4) exists, but it is impossible to perform measurements necessary to evaluate its activation energy.

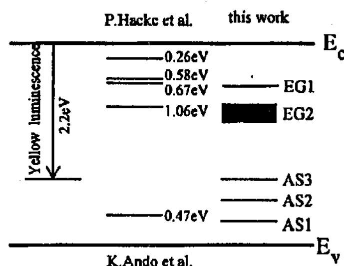

Fig. 2. Scheme of observed deep levels in the energy gap of GaN.

The scheme of deep levels in GaN energy gap is plotted in Fig. 2. On the left-hand side we have marked an expected position of a deep level responsible for the commonly observed yellow luminescence $h\nu = 2.2$ eV [9]. This peak is observed in samples of different origin, therefore it has been postulated [9] that this peak is connected with an intrinsic defect. We can expect the presence of this defect in our layers as well. In fact, its position corresponds to the position of the AS3 level. Taking into account large experimental error, unknown height of a capture barrier and lattice relaxation effects, we cannot conclude that the AS3 is certainly connected with the yellow luminescence, therefore further studies are necessary to resolve this problem. The AS1 peak could be the same as HG1 peak ($E_a = 0.47$ eV) observed by Ando et al. [10] in Mg-doped GaN.

In summary, DLTS spectra measured for the GaN heteroepitaxial layers grown on sapphire were presented. The samples were Mg doped. After annealing, the p-type material was obtained. Three peaks were observed. The dominant one was AS3 with the activation energy $E_a = (1.1 \pm 0.1)$ eV. Further studies are necessary to determine if it is related with commonly observed yellow luminescence in GaN.

We acknowledge the help of Dr. Adam Babiński (actually in Australian National University). This work has been financially supported by the Committee for Scientific Research grant number 7T08 A06110.

References

[1] S. Nakamura, T. Mukai, M. Senoh, *Jpn. J. Appl. Phys.* **30**, L1998 (1991).

[2] S. Nakamura, T. Mukai, M. Senoh, *Appl. Phys. Lett.* **64**, 1687 (1994).

[3] S. Nakamura, N. Iwase, M. Senoh, T. Mukai, *Jpn. J. Appl. Phys.* **31**, 1258 (1992).

[4] B. Suchanek, private communication.

[5] B. Monemar, *Phys. Rev. B* **10**, 676 (1974).

[6] P. Hacke, A. Maekawa, N. Koide, K. Hiramatsu, N. Sawaki, *Jpn. J. Appl. Phys.* **33**, 6443 (1994).

[7] W.I. Lee, T.C. Huang, J.D. Guo, M.S. Feng, *Appl. Phys. Lett.* **67**, 1721 (1995).

[8] P. Hacke, H. Nakayama, T. Detchprohm, K. Hiramatsu, N. Sawaki, in: *Proc. Int. Symp. on Blue Lasers and LEDs, Chiba'96, Japan 1996*, Eds. A. Yoshikawa, K. Kishino, M. Kobayashi, T. Yasuda, Ohmsha, IOS, Tokyo 1996, p. 184.

[9] I. Akasaki, H. Amano, in: *Properties of Group III Nitrides*, Ed. J.H. Edgar, INSPEC, London 1994, p. 222.

[10] K. Ando, K. Koizumi, H. Yoshida, H. Kasada, T. Isu, S. Nakamura, in Ref. [8], p. LN-2.