Phys. Status Solidi C **7**, No. 10, 2386–2389 (2010) / **DOI** 10.1002/pssc.200983868

physica status solidi pss c
www.pss-c.com
current topics in solid state physics

Short-period AlN/GaN p-type superlattices: hole transport use in p-n junctions

John Simon*, **Yu Cao, and Debdeep Jena**

Department of Electrical Engineering, University of Notre Dame, 275 Fitzpatrick Hall, Notre Dame, IN 46556, USA

Received 2 September 2009, revised 15 April 2010, accepted 19 April 2010
Published online 21 June 2010

Keywords AlN/GaN, MBE, superlattices, doping levels, p-n junctions, electrical properties

* Corresponding author: e-mail jsimon@alumni.nd.edu

Hole transport properties of short-period Mg-doped AlN/GaN superlattices are compared with bulk Mg-doped GaN layers. Due to polarization-induced reduction in acceptor ionization energy, the superlattice structures are observed to result in a nearly temperature-independent in-plane p-type conductivity as opposed to a 100-fold decrease in bulk p-type GaN as temperature drops from 300 K to 100 K. Moreover, significant vertical p-type conductivity is facilitated by the ultrathin AlN barriers due to possible hole tunneling & miniband formation: p-n junctions are demonstrated by replacing the p-type GaN layer by a superlattice. The results indicate the feasibility of enhancement of both vertical and lateral p-type conductivity in bipolar transistors and deep-UV optical devices.

1 Introduction III-V nitride semiconductors have attracted a lot of interest for their applications in high-speed high-power electronics and visible and short wavelength optoelectronics. However, the performance of III-V nitride bipolar semiconductor devices is limited by low p-type conductivity owing to a large acceptor activation energy of Mg ($\sim$ 120-200 meV) [1–5], the commonly used p-type dopant. The large bandgaps of high Al-containing nitrides offer a feasible route to very short wavelength optical devices. A pressing problem at present is that with increase of Al composition in AlGaN, the Mg acceptor level moves deeper into the bandgap, degrading the room-temperature (RT) p-type conductivity. Mg acceptor ionization energy increases from $\sim$120-200 meV for GaN to $\sim$500-630 meV for AlN [13, 14, 10]. Additionally, n-type doping also becomes less efficient as Si donor levels move away from the conduction band edge, varying from 20 meV for GaN to 282 meV for AlN [12, 10]. This 'deep dopant problem' of high-Al containing nitrides poses a severe problem in the form of high resistive losses in high-efficiency wide-bandgap bipolar devices, be it bipolar transistors or optical emitters & detectors [15].

Previous studies have shown that by polarization induced periodic modulation of the valence band edge, improvements in the p-type conductivity can be obtained [11]. Improved p-type conductivity in the growth plane in AlGaN/GaN superlattices (SL) has been demonstrated [6, 7]. In addition, it has been demonstrated that with increasing Al content in the AlGaN barriers the Mg effective activation energy in the wells is reduced [8]. This is attributed to an increase in the polarization charges induced at the interfaces, causing larger band bending in the wells and consequently higher ionization of the acceptor atoms. If AlN barriers are used in place of the AlGaN, more conductive p-type layers can be obtained [16]. These conductive sheets of carriers will be spatially separated, meaning vertical transport can be limited. For this reason, ultrathin AlN barriers have been investigated in this work to achieve tunneling assisted high p-type conductivity in the vertical direction. Usage of these Mg doped AlN/GaN SLs in the p-type layer of a p-n junction is demonstrated. This technique is a feasible route for enhancing both p-type and n-type conductivity in high Al-containing UV-emitters and HBTs. Furthermore, miniband formation in the SL will create an

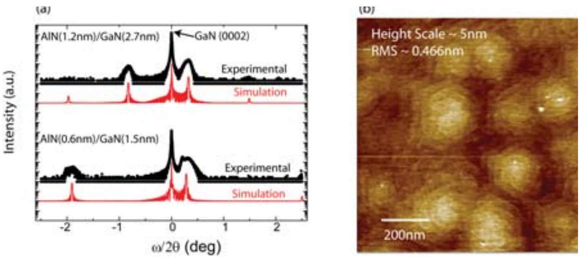

Figure 1 X-ray diffraction measurements (a) performed on S.L. with 2 and 4 nm periods. S.L. period and thickness was verified by simulation. AFM scans (b) show atomic layer steps as evidence of step like growth.

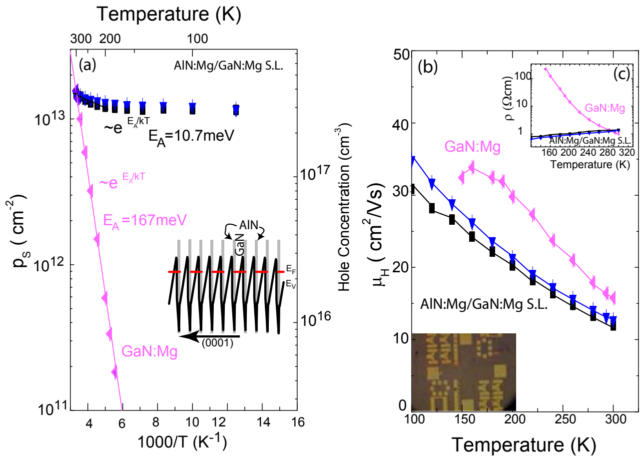

Figure 2 Temperature dependent Hall-effect measurements for Mg doped AlN(1.2nm)/GaN(2.8nm) S.L. grown under Mg BEP of 5.76×10^{-10} (■), and 8.61×10^{-10} (▼) Torr, as well as a Mg bulk doped GaN sample for comparison (◄). Results for a Mg doped GaN sample are shown for comparison. (a)Sheet and volume carrier densities show no carrier freeze out at lower temperatures. (b) Hall mobilities as high as 12 cm^2/Vs are obtained for S.L. samples at room temperature.(c) Sample resistivities at room temperature are comparable to those of Mg doped GaN, and there is no significant with changing Mg BEP.

effectively larger bandgap than that of GaN, which is necessary for short wavelength optical devices.

2 Experiment

Mg doped AlN/GaN SL structures were grown by plasma-assisted Molecular Beam Epitaxy (PA-MBE) on commercially available Fe-doped semi-insulating (SI) GaN templates on sapphire. The growth conditions used were a substrate thermocouple temperature $T_{TC} \sim$ 600°C, N_2 RF plasma power of 275 W, Ga beam equivalent pressure (BEP) of 1.33×10^{-7} Torr, and Al BEP of 1.31×10^{-7} Torr. The measured growth rate was 243 nm/hr. The first set of samples (A) consisted of 100 periods of 1.2 nm/2.8 nm thick AlN/GaN SLs with Mg BEP varying from $\sim 5.8 - 8.7 \times 10^{-10}$ Torr between different samples. In a second set of samples (B), the GaN to AlN layer thickness ratio in the SL was kept constant (same as A), and the SL period was varied from 2 to 8 nm to study the effect of different well thicknesses on the p-type conductivity. The total number of periods was varied so as to keep the total SL thickness constant at 400 nm. A Mg BEP of $\sim 8.6 \times 10^{-10}$ Torr was used for set B. Low resistivity Mg-doped GaN samples, grown under the same growth conditions were used as control samples [9]. SL layer thicknesses were verified by X-ray diffraction measurements (Fig. 1a) performed after growth. Atomic Force Microscopy (AFM) measurements showed atomic steps on the surface with no discernible cracks (Fig. 1b), indicating successful pseudomorphic SL growth.

The samples thus grown on SI substrates were processed into Van der Pauw patterns (shown in Fig. 2 insert) for transport measurements. Mesa patterns were defined by vertical etching in a Reactive Ion Etcher (RIE) using Cl_2 plasma, and as-deposited Ni/Au contacts were used as ohmic contacts. Temperature-dependent Hall-effect measurements (120-300 K) were performed on all the samples in a 0.5 Tesla magnetic field.

3 Results

Figure 2 shows the measured results for the temperature dependent Hall-effect measurements performed for AlN/GaN SL series A grown under different Mg BEP. The measured results for the Mg doped bulk GaN

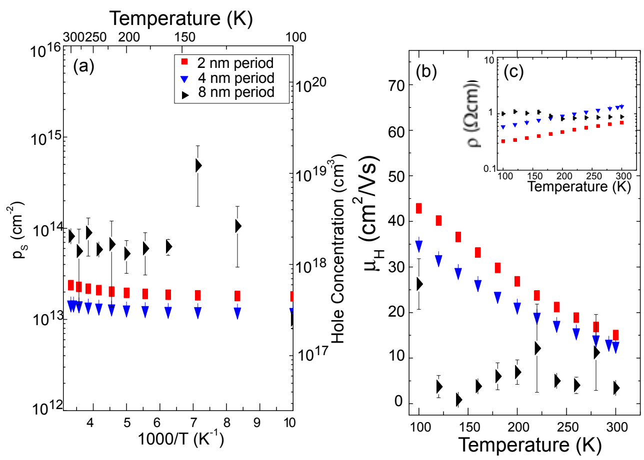

Figure 3 Hole carrier concentration (a), mobility (b), and resistivity (c) with changing S.L. periods of 2 (■), 4 (▼), and 8 nm (►). As the S.L. period increases the polarization fields decrease, which result in a decrease in the carrier mobility and an increase in the p-type resistivity.

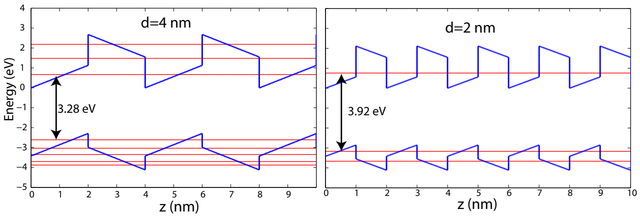

Figure 4 Airy function calculations of mini-band formation in AlN-GaN superlattices for period thickness of 4 (left) and 2 nm (right). As the period thickness is decreased the effective bandgap is increased.

control sample is also shown for comparison. Mobilities as high as 35 cm^2/Vs at 100 K were obtained for the SL doped samples. Hole concentrations showed no carrier freeze out at low temperatures. A small (∼10meV) acceptor activation energy was extracted from the measurements between 300-200 K, while the control GaN sample shows a sharp carrier freeze-out with an activation energy of E_A ∼167 meV. Insertion of thin AlN layers result in large polarization fields across the SL causing an effective reduction in the acceptor activation energy. The polarization fields cause the valence band to bend (as seen in Fig. 2a insert) causing the valence band edge in the well regions to come closer to the fermi level and activate the Mg acceptor atoms.

In series B, resistivities as low as 0.32 Ωcm were found in the Mg doped S.L. samples with a period of 2 nm (Fig. 3) and a mobility of 45 cm^2/Vs at 100 K. By reducing the barrier thickness in the SL, the band bending is reduced and causing a reduction in the number of carriers generated. A thinner barrier will also allow for enhanced vertical transport by tunneling assisted current through the SL, as well as an increased effective energy bandgap. This is confirmed by Airy function calculations of the SL structures (Fig. 4) showing an increase in the energy gap with decreasing SL period thickness. For this reason a compromise must be made in order to enhance both vertical (thinner SL period) and lateral (thicker SL period) hole transport across the SL, while still maintaining a large bandgap needed for short wavelength optoelectronic devices.

To demonstrate vertical hole conduction through the SL structures, 200 nm thick Mg doped AlN/GaN S.L. with short period thicknesses of 2 and 4 nm were grown on top of n-type GaN substrates. Mesas were etched in a Cl_2 plasma in a RIE, and Ni/Au and Al/Au contacts were used for the ohmic contacts to the p-type and n-type layers respectively. Current voltage characteristics were measured across the junction to study the vertical transport through these p-n junctions.

The thinner AlN barrier result in enhancement in the vertical transport through the SL. This is verified by measuring the current through the p-n junctions with different period thickness shown in Fig. 5. ON/OFF ratios measured at -5/5V increased from 12 to 1180 when changing the period thickness from 4nm to 2nm. Ideality factors between 2-3 were extracted from the current -voltage measurements for the 2 nm period junction. Leakage currents of the SL doped samples were over one order of magnitude smaller as compared to the Mg bulk doped sample. This can be attributed to the larger barriers to electron flow imposed by the SL.

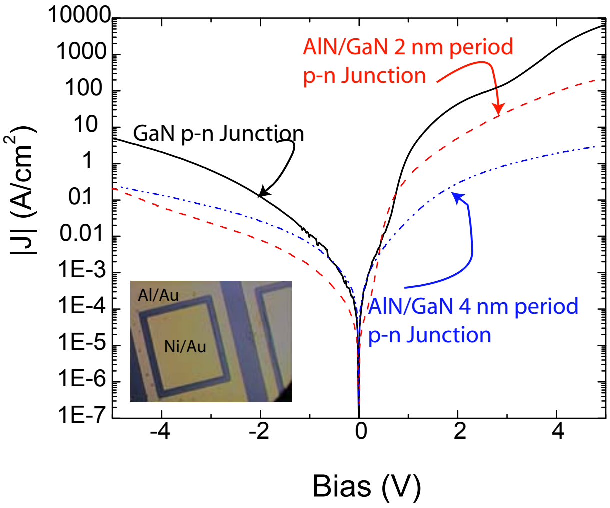

Figure 5 p-n current voltage characteristics for 2 and 4 nm p-type S.L. as well as a bulk doped GaN sample. The ON current increases with decreasing barrier thickness resulting in a larger ON/OFF ratio for the S.L. samples.

To further investigate the vertical transport properties of the Mg doped SL structures, vertical resistance measurements were extracted from etched pillars connected to each other by a conductive p-type GaN layer (as seen in the inset of Fig. 6). The contact resistance (R_C) and sheet resistance (R_{SH}) of the top and bottom GaN layers were extracted from TLM measurements of a control bulk doped GaN sample with no etched pillars. The equivalent circuit diagram is shown in the bottom insert of Fig. 6. The vertical resistance of the SL doped structures have a much weaker temperature dependence (86 meV) than compared to the bulk doped structure (134 meV). The constant carrier concentration found in the SL structures (as seen in Fig. 2) also results in a lower temperature dependence of the vertical transport across the SL structures.

4 Conclusion Substitution of SL structures in the p-type layer of optical and electronic bipolar devices will lead to more conductive layers, reducing resistive losses. These layers must be carefully designed to optimize both lateral transport (thicker SL periods) and vertical transport (thinner SL periods), as well as maintaining a large optical transparency window. This doping technique can be applied to the enhancement of both n- and p-type carriers, which makes it particularly attractive to short-wavelength

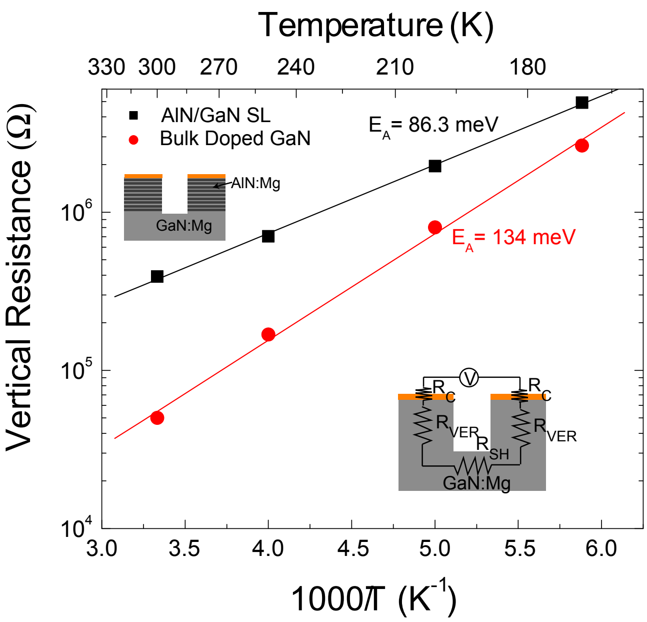

Figure 6 Vertical current resistance extracted from etched structures for both SL doped structures with 2 nm period (■), and Mg doped GaN (●). Contact resistance (R_C), and lateral sheet resistance (R_{SH})were extracted from an un-etched bulk doped GaN sample. Temperature dependent measurements of the vertical resistance show that the SL doped structures have a much smaller dependence on temperature than the bulk Mg doped GaN structures.

optoelectronic devices, where doping of high Al containing AlGaN is a challenge. The method demonstrated in this paper also allows for enhancement of the p-type conductivity in bipolar transistors were both vertical and lateral conduction is necessary.

References

[1] T. Tanaka, A. Watanabe, H. Amano, Y. Kobayashi, I. Akasaki, S. Yamazaki, and M. Koike, Appl. Phy. Lett. **65**, 593 (1994).

[2] W. Kim, A. Salvador,A. E. Botchkarev, O. Aktas, S. N. Mohammad, and H. Morcoç, Appl. Phy. Lett. **69**, 559 (1996).

[3] W. Götz, N. M. Johnson, J. Walker, D. P. Bour, and R. A. Street, Appl. Phy. Lett. **68**, 667 (1996).

[4] H. Nakayama, P. Hacke, M. R. Huque Khan, T. Detchprohm, K. Hiramatsu, and N. Sawaki, Jpn. J. Appl. Phys. **35**, L282 (1996).

[5] C.J. Eiting, P.A. Grudowski, and R.D. Dupuis, Electron. Lett. **3**, 1987 (1997).

[6] I.D. Goepfert, E.F. Schubert, A. Osinsky, and P.E. Norris, Electron. Lett. **35**, 1109 (1999).

[7] P. Kozodoy, M. Hansen, S.P. DenBaars, and U.K. Mishra, Appl. Phys. Lett. **74**, 3681 (1999).

[8] K. Kumakura, T. Makimoto, and N. Kobayashi, Jpn. Appl. Phys. **39**, 2428 (2000).

[9] J. Simon and D. Jena, Phys. Status Solidi A **205**, 1074 (2008).

[10] Y. Taniyasu, M. Kasu, and T. Makimoto, Nature **441**, 325 (2006).

[11] E. F. Schubert, W. Grieshaber, and I. D. Goepfert, Appl. Phys. Lett. **69**, 3737 (1996).

[12] B. Borisov, V. Kuryatkov, Yu. Kudryavtsev, R. Asomoza, S. Nikishin, D. Y. Song, M. Holtz, and H. Temkin, Appl. Phys. Lett. **87**, 132106 (2005).

[13] K. B. Nam, M. L. Nakarmi, J. Li, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **83**, 878 (2003).

[14] M. L. Nakarmi, N. Nepal, C. Ugolini, T. M. Altahtamouni, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **89**, 152120 (2006).

[15] A. Khan, K. Balakrishnan, and T. Katona, Nature Photonics **2**, 77 (2008).

[16] M. Iwaya, S. Terao, S. Takanami, A. Miyazaki, S. Kamiyama, H. Amano, and I. Akasaki, Phys. Status Solidi C **1**, 34 (2002).