9-17-2001

Indium-Silicon Co-Doping of High-Aluminum-Content AlGaN for Solar Blind Photodetectors

V. Adivarahan

Grigory Simin
University of South Carolina - Columbia, simin@engr.sc.edu

G. Tamulaitis

R. Srinivasan

J. Yang

See next page for additional authors

Publication Info

Published in *Applied Physics Letters*, Volume 79, Issue 12, 2001, pages 1903-1905.

Adivarahan ,V., Simin, G., Tamulaitis, G., Srinivasan, R., Yang, J., Khan, M. A., Shur, M. S., & Gaska, R. (17 September 2001). Indium-Silicon Co-Doping of High-Aluminum-Content AlGaN for Solar Blind Photodetectors. Applied Physics Letters, 79 (12), 1903-1905. http://dx.doi.org/10.1063/1.1402159

Indium–silicon co-doping of high-aluminum-content AlGaN for solar blind photodetectors

V. Adivarahan, G. Simin, G. Tamulaitis, R. Srinivasan, J. Yang, M. Asif Khan, M. S. Shur, and R. Gaska

Citation: Applied Physics Letters **79**, 1903 (2001); doi: 10.1063/1.1402159
View online: http://dx.doi.org/10.1063/1.1402159
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/79/12?ver=pdfcov
Published by the AIP Publishing

Indium–silicon co-doping of high-aluminum-content AlGaN for solar blind photodetectors

V. Adivarahan,[a] G. Simin,[b] G. Tamulaitis, R. Srinivasan, J. Yang, and M. Asif Khan
Department of Electrical Engineering, University of South Carolina, Columbia, South Carolina 29028

M. S. Shur and R. Gaska
Sensor Electronic Technology, Incorporated, 21 Cavalier Way, Latham, New York 12110

(Received 5 March 2001; accepted for publication 13 July 2001)

We report on an indium–silicon co-doping approach for high-Al-content AlGaN layers. Using this approach, very smooth crack-free n-type AlGaN films as thick as 0.5 μm with Al mole fraction up to 40% were grown over sapphire substrates. The maximum electron concentration in the layers, as determined by Hall measurements, was as high as 8×10^{17} cm^{-3} and the Hall mobility was up to 40 cm^2/Vs. We used this doping technique to demonstrate solar-blind transparent Schottky barrier photodetectors with the cut-off wavelength of 278 nm.
[DOI: 10.1063/1.1402159]

Due to their direct band gap $Al_xGa_{1-x}N$ layers with $x\geqslant0.4$ exhibit a sharp transmission cutoff at $\lambda<280$ nm, thereby offering unique opportunities for the development of intrinsic solar-blind photodetectors for space communications, missile detection, and flame and heat sensing. In past, several groups[1–3] have reported on AlGaN based photoconductive and photovoltaic detectors. The reported photoconductive devices had a large gain but their response times were in excess of several minutes, making them unsuitable for such applications. Since these devices can not operate at zero bias they also have an extra noise coming from the dark current. Recently, AlGaN p–i–n photodiodes were reported.[4,5–7] The p–i–n device geometry for solar-blind AlGaN detectors has several shortcomings. First, p-type doping of AlGaN layers with a high-Al content remains a difficult problem.[5] The resistance of ohmic contacts to p-type AlGaN layers is quite high. This resistance can be avoided by using p GaN and or both p GaN and n GaN as the contact layers[4,6,7] with i $Al_xGa_{1-x}N$ ($x>0.4$) as the active layer. However, the contact GaN layers absorb a significant fraction of the optical beam thereby reducing the device responsivity and deteriorating UV/visible selectivity. Further, to avoid cracking, the i AlGaN active layer thickness has to be restricted to the values well below 2000 Å.

A metal–semiconductor–metal (MSM) design[8] does not require ohmic contacts. The MSM devices however, cannot operate at zero bias, which increases the noise. Since the space charge width and hence the width of the high-field region in the AlGaN layer is usually much smaller than the electrode spacing at moderate bias values, the photoresponse of the MSM diode has a significant slow component. Lateral geometry transparent Schottky barrier photodetectors avoid most of these problems.[9] However, this design requires a n-doped $Al_{0.4}Ga_{0.6}N$ layer, and, to date, all such doping attempts using Si have resulted in insulating material.

We now report on an In–Si co-doping approach to obtain n $Al_{0.4}Ga_{0.6}N$ active layers with resistivity as low as 0.16 ohm cm. In addition to significantly increasing the doping efficiency, the introduction of a small concentration of In also allows for the direct deposition of a crack-free 0.5 μm thick Si-doped $Al_{0.4}Ga_{0.6}N$ layer over a 200 Å thick AlN buffer layer on basal plane sapphire substrates. We also demonstrate the potential of using these In–Si co-doped layers for a lateral geometry, true solar-blind Schottky barrier detector (λ cutoff at 278 nm). The epilayer structures of this study were grown using low-pressure metalorganic chemical vapor deposition. The active AlGaN layer and the 200 Å thick AlN buffer layer were deposited at a pressure of 76 Torr and growth temperatures of 950 °C and 600 °C, respectively. Triethylgallium, trimethylaluminum, trimethylindium (TMI), and ammonia were used as the precursors, with hydrogen as the carrier gas. The active AlGaN layer was co-doped using disilane (Si_2H_4) and TMI. The secondary ion mass spectometry analysis shows that this co-doping procedure introduces a trace amount (about 0.5%) of In in the active layer.

Standard Van Der Pauw measurements showed the sheet resistivity of the In–Si co-doped AlGaN layers of 0.08...0.3 ohm cm depending on the TMI flux. From Hall measurements, the carrier concentration and electron mobility of these layers were found to be $n\approx2$ to 8×10^{17} cm^{-3} and $\mu_n\approx40$ cm^2/V s. Similar values of electron concentration was also extracted from capacitance–voltage (C–V) measurements. AlGaN layers deposited without the TMI flux were highly insulating and thus unusable for Schottky detector fabrication. These layers were completely depleted at zero bias as shown by the C–V measurements.

The increased n-type doping due to the addition of In can result from the introduction of a shallow impurity level. Indium incorporation might also reduce the defect formation as indicated by the improved structural quality and morphology of the grown films.[10] Further, indium might counteract the incorporation of defects responsible for the self-compensation of high-Al mole fraction AlGaN layers, such as DX centers and cation vacancies.[11] More detailed studies

[a]Also with Sensor Electronic Tech. Inc.
[b]Electronic mail: simin@engr.sc.edu

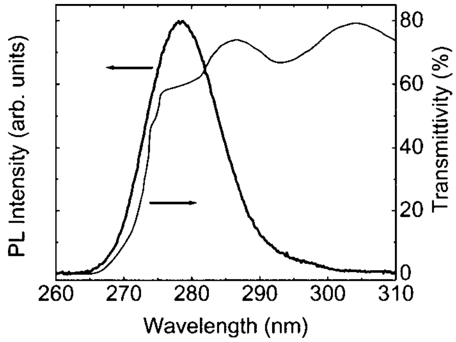

FIG. 1. Spectra of optical transmission and PL of the In co-doped AlGaN epilayer with approximately 40% of Al are shown.

are underway to determine the exact mechanism, and the results will be reported elsewhere.

In Fig. 1, we include the room temperature optical transmission and photoluminescence spectra of In co-doped AlGaN layer. The photoluminescence (PL) spectrum was measured by using a TRIAX-550 spectrometer with a liquid-nitrogen-cooled charge coupled device and a 230 nm pump from a frequency doubled dye laser. The dye laser was pumped using 600 ps long pulses from a nitrogen laser. As can be seen from Fig. 1, both the optical transmission cutoff and the peak PL occur at 278.5 nm. From the optical characteristics, we extracted the Al mole fraction in the AlGaN to be approximately 40%. The PL linewidth full width at half maximum is 12 nm. This narrow PL linewidth and a coincidence of the optical transmission cutoff with the PL peak position indicate a good structural quality of the $Al_{0.4}Ga_{0.6}N$ layers, which can serve as the active layers for transparent Schottky barrier photodetectors.

We then fabricated lateral geometry transparent Schottky barrier detectors using the In–Si co-doped *n* AlGaN layers. The layer with electron concentration $n \approx 4\times10^{17}$ cm^{-3} was chosen for this experiment as it provides both low ohmic contact resistance, low Schottky barrier leakage current and large enough zero bias depletion in the space charge region. The design was similar to our prior work.[10] First, ohmic contacts consisting of Ti(200 Å)/Al(600 Å)/Ti(200 Å)/Au(1000 Å) were deposited using electron beam (e-beam) evaporation. We also deposited a transmission line model (TLM) patterns. The as-deposited ohmic contacts were nonlinear. The linearity was significantly improved by an 850 °C anneal for 1 min in flowing N_2. Using TLM measurements, the sheet resistivity of the n^+ AlGaN layer was found to be 0.16 ohm cm, in good agreement with the van der Pauw data. In Fig. 2(a), we show the current–voltage ($I-V$) characteristics measured between two 50 μm×150 μm TLM pads separated by a 2 μm gap. Note, the $I-V$ characteristics are linear due to the low sheet resistivity of the AlGaN layer. The TLM measurements yielded the specific contact resistivity to be 2.5×10^{-3} ohm cm^2. Connotation of novelty is not permitted.

Transparent Schottky barriers were then formed using e-beam deposited 50 Å thick 300 μm×300 μm Pd Schottky contacts and a Ti (200 Å)/Au (3000 Å) probe pads. The probe pads were deposited only on a small portion of the Schottky contact. In Fig. 2(b), we show the dark $I-V$ characteristics for the transparent Schottky barriers fabricated as

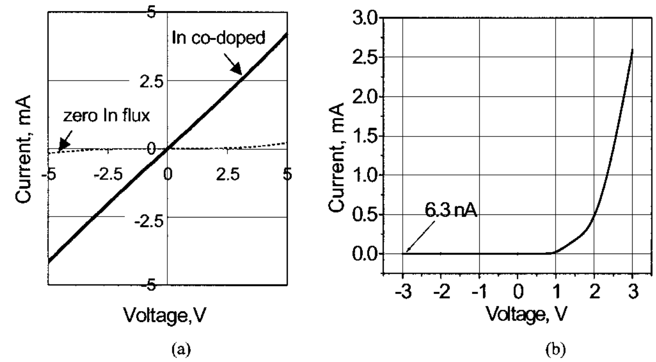

FIG. 2. $I-V$ characteristics of the ohmic contacts to In co-doped AlGaN (a) and of the AlGaN Schottky photodiode (b) are shown. Dashed line in the left-hand side shows the $I-V$ curve for the AlGaN layer with zero flow of TMI (no In co-doping).

just described. As seen, the turn-on voltage and the forward differential resistance were approximately 1.2 V and 500 ohm, and the reverse leakage current at a bias of −3 V was as low as 6 nA. In order to extract the barrier height for these Schottky barriers, we also measured the temperature dependence of the forward current at small forward voltages. These measurements yielded an effective barrier height of 0.64 V [see Fig. 3(a)]. We also measured the ideality factor for our transparent Schottky barriers to be $n=2.34$ [see Fig. 3(b)]. We explain this relatively low Schottky barrier height by the effect of barrier lowering due to high impurity concentration in our In-co-doped AlGaN layers.

The Schottky barrier spectral photoresponse was then measured using a light from a xenon lamp and a monochromator as pump beam, which was focused to illuminate the active surface of the device. A UV-enhanced calibrated Si detector was used to measure the input pump beam power. The spectral photoresponsivity signal for the 300 μm×300 μm transparent Schottky detector on *n* $Al_{0.4}Ga_{0.6}N$ is shown in Fig. 4. As seen, the device has a peak photoresponsivity of about 0.033 A/W at 275 nm, and the photoresponse falls by more than three orders of magnitude within 30 nm. $C-V$ measurements indicate a zero-bias depletion width of 0.05 μm with a carrier concentration of 4×10^{17} cm^{-3}. This depletion region thickness is not large enough to ensure the full light absorbtion in the space charge region of the Schottky barrier and thus reduces the maximum achievable value of the photoresponsivity. More than two times higher

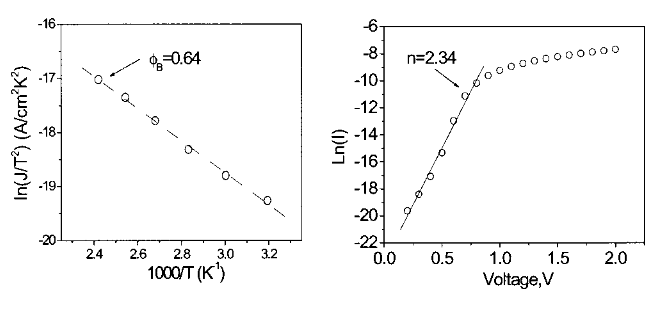

FIG. 3. (a) Dependence of the current density, J/T^2 on temperature, $1000/T$ and (b) forward current dependence on forward bias for AlGaN photodiode are shown.

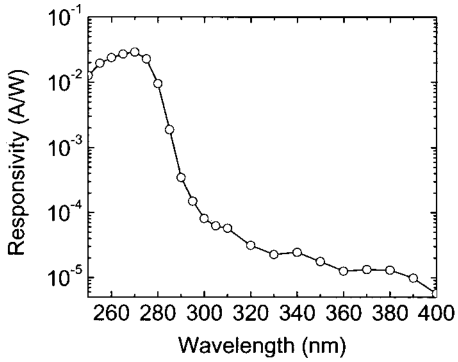

FIG. 4. Photoresponsivity spectrum of the AlGaN photodiode is shown.

peak responsivity was measured on the device with optimized epilayer design. The detailed report on these results will be published elsewhere.

In conclusion, we have demonstrated that ternary AlGaN layers with Al mole fraction as high as 40% can be *n* doped up to 8×10^{17} cm^{-3} using an In–Si co-doping approach. This enables the fabrication of transparent Pd-Schottky barriers and Ti/Al/Ti/Au ohmic contacts with specific contact resistivity of 2.5×10^{-3} $ohm\,cm^2$. These transparent Schottky barriers serve as excellent solar-blind UV photodetectors with a zero-bias peak responsivity of 0.033 A/W at a wavelength of 275 nm and more than three orders of magnitude of UV/visible rejection ratio.

The work at USC was supported by the Ballistic Missile Defense Organization (BMDO) under Army SMDC Contract No. DASG60-98-1-0004, monitored by Mr. Tarry Bauer, Dr. Brian Strickland, and Dr. Kepi Wu. The work at SET, Inc. was supported by BMDO under the Small Business Innovation Research Program and was monitored by Dr. Lewis Cohn and Dr. Thomas Grycewicz of the Defense Threat Reduction Agency (DTRA).

[1] M. A. Khan, J. N. Kuznia, D. T. Olson, M. Blasinghame, and A. R. Bhattarai, Appl. Phys. Lett. **63**, 2455 (1993).
[2] M. A. Khan, Q. Chen, C. J. Sun, M. S. Shur, M. F. Macmillan, R. P. Devaty, and J. Chyke, Proc. SPIE **2397**, 283 (1995).
[3] A. Osinsky, S. Gangopadhyay, B. W. Lim, M. Z. Anwar, M. A. Khan, D. V. Kuksenkov, and H. Temkin, Appl. Phys. Lett. **72**, 742 (1998).
[4] D. Walker, V. Kumar, K. Mi, P. Sandvik, P. Kung, X. H. Zhang, and M. Razeghi, Appl. Phys. Lett. **76**, 403 (2000).
[5] S. C. Jain, M. Willander, J. Narayan, and R. Van Overstraeten, Journ. Appl. Phys. V **87**, 965 (2000).
[6] G. B. Parish, S. Keller, P. Kozodoy, J. P. Ibbetson, H. Marchand, P. T. Fini, S. B. Fleischer, S. P. DenBaars, U. K. Mishra, and E. J. Tarsa, Appl. Phys. Lett. **75**, 247 (1999).
[7] E. J. Tarsa, P. Kozodoy, J. Ibbetson, and B. P. Keller, G. Parish, and U. Mishra, Appl. Phys. Lett. **77**, 316 (2000).
[8] T. Li, D. J. H. Lambert, A. L. Beck, C. J. Collins, B. Yang, M. H. Wong, U. Chowdhury, R. D. Dupuis, and J. C. Campbell, Electron. Lett. **36**, 1581 (2000).
[9] V. Adivarahan, G. Simin, J. W. Yang, A. Lunev, M. Asif Khan, N. Pala, M. Shur, and R. Gaska, Appl. Phys. Lett. **77**, 863 (2000).
[10] G. Tamulaitis, K. Kazlauskas, S. Juršėnas, A. Žukauskas, M. A. Khan, J. W. Yang, J. Zhang, G. Simin, R. Gaska, and M. S. Shur, Appl. Phys. Lett. **77**, 2136 (2000).
[11] C. Stampfl and Chris G. Van de Walle, Appl. Phys. Lett. **72**, 459 (1998).