Journal of Ovonic Research Vol. 18, No. 2, March - April 2022, p. 159 - 165

Electrical characterization of AlGaN/GaN/Si high electron mobility transistors

H. Mosbahi[a], M. Gassoumi[b,*], A. Guesmi[c], N. Ben Hamadi[c], M.A. Zaidi[d]
[a] *University of Sousse, Department of Transport Technology and Engineering, Higher Institute of Transport and Logistics, , Tunisia*
[b] *University of Monastir, Faculty of Sciences, Laboratory of Condensed Matter and Nanosciences, Monastir 5019, Tunisia*
[c] *Chemistry Department, College of Science, IMSIU (Imam Mohammad Ibn Saud Islamic University), P.O. Box 5701, Riyadh 11432, Saudi Arabia.*
[d] *University of Monastir, Department of Physics, Faculty of Sciences of Monastir, Tunisia.*

AlGaN/GaN/Si HEMTs have been investigated using current-voltage-temperature and CDLTS measurements.As has been found from current voltage measurements, parasitic effects were revealed indicating the presence of traps in HEMT device. As a result, the origins of traps are determined from CDLTS experiments.

(Received December 26, 2021; Accepted March 15, 2022)

Keywords: AlGaN/GaN/Si HEMTs, CDLTS, Current-voltage, Traps

1. Introduction

AlGaN/GaN high electron mobility transistors are outstanding candidates for high-power, high-temperature, high-frequency, high-voltage, medical detection, and environmental monitoring applications.[1-7]III-V nitride materials have attract attention due to the wide band gaps, high breakdown voltages, high electron saturation velocity, strong radiation resistance, and stable chemical properties. [8-13]In addition, the AlGaN/GaN HEMT devices have high power densities, an efficient carrier transport as well as a strong spontaneous and piezoelectric polarization fields.[13,14] Owing the latter feature,a two-dimensional electron gas is formed at the AlGaN/GaN heterointerface with a high charge density, high mobility and sensitive to the change of surface charges.[15,16]However, due to etched the AlGaN barrier layer, electron transport characteristics have affected by interface states in HEMT devices. [17,18] But there remain problems will affect the device reliability and performance such as current collapse, [19,20] leakage current [21,22] and defects. [23-25]

Surface passivation is solution to reduce the limitation of HEMT transistors like SiO_2/SiN, Si_3N_4, Al2O3, SiN_x, MgO or Sc_2O_3 and SiO_2. [23,26-29] For instance, passivation SiO_2/SiN with pretreatment reduces the electron traps, gate-lag, drain-lag and improves the electron transport as well. [23]Also, N_2 plasma treatment improves the ohmic contacts and surface morphology by reducing the N_2 vacancies. [30]

In the present work reports on a study of passivated AlGaN/GaN/Si HEMTs using conductance deep-level transient spectroscopy. The nature and location of the observed traps will be presented. For the same HEMT structure, we have also investigated the static characteristics at output. In order to explain the origin of the traps, an attempt to correlate all of the results.

2. Experiments

The AlGaN/GaN HEMTs under investigation are grown on silicon (111) substrate by using molecular beam epitaxy (MBE). The active layers consist in a 500 nm thick of undoped

[*] Corresponding author: malek.gassoumi@gmail.com
https://doi.org/10.15251/JOR.2022.182.159

AlN/AlGaN buffer, a 1.8 µm undoped GaN channel, a 23 nm thick of undoped $Al_{0.26}Ga_{0.74}N$ barrier and a 1 nm n^+- GaN cap layer. The ohmic contact pads are patterned using e-beam lithography. Hereafter, the metallization by means of evaporated 12/200/40/100 nm Ti/Al/Ni/Au is deposited at 900°C during 30s. The Schottky gate is realized using 100/150 nm Mo/Au layers. On the other hand, the AlGaN/GaN/Si HEMTs are passivated by 100 nm SiO_2. Static and transfer characteristics of the AlGaN/GaN/Si HEMTs is carried out by (I-V-T) measurements with use of an HP 4156. Conductance deep-level transient spectroscopy has been used as a technique to characterize the traps in the device. Measurements were recorded in the 77 – 600 K temperature range from liquid N_2. CDLTS under gate pulse is more suitable for study of the AlGaN/GaN/Si heterostructures because it allows to investigate the deep levels in the buffer layer and the gate area. [31]

3. Direct-current characteristics

Static measurements (I_{ds}-V_{ds}-T) have been performed on the samples prepared at different temperature. Figure 1 shows the drain-currentas a function of drain-to-source voltage at different bias voltageV_{gs}. It is found that the drain-current decreases going from 0.014 A at 100 K to 0.002 A at 500 K. In addition, degradation of drain-current is given in figure 1a, b and c. the decrease of the drain-current may be due a thermally activated effect. This proposal of explanation agrees well with the presence of deep level in the surface states and the barrier layer. [31,32] On the other hand, we have noted the presence of the hysteresis effect (see figure 1 a), the kink effect (see figure 1 b) and leakage current (see figure 1 c). It is found that the hysteresis effect reveal a decreased current in order to pinch-off the channel.

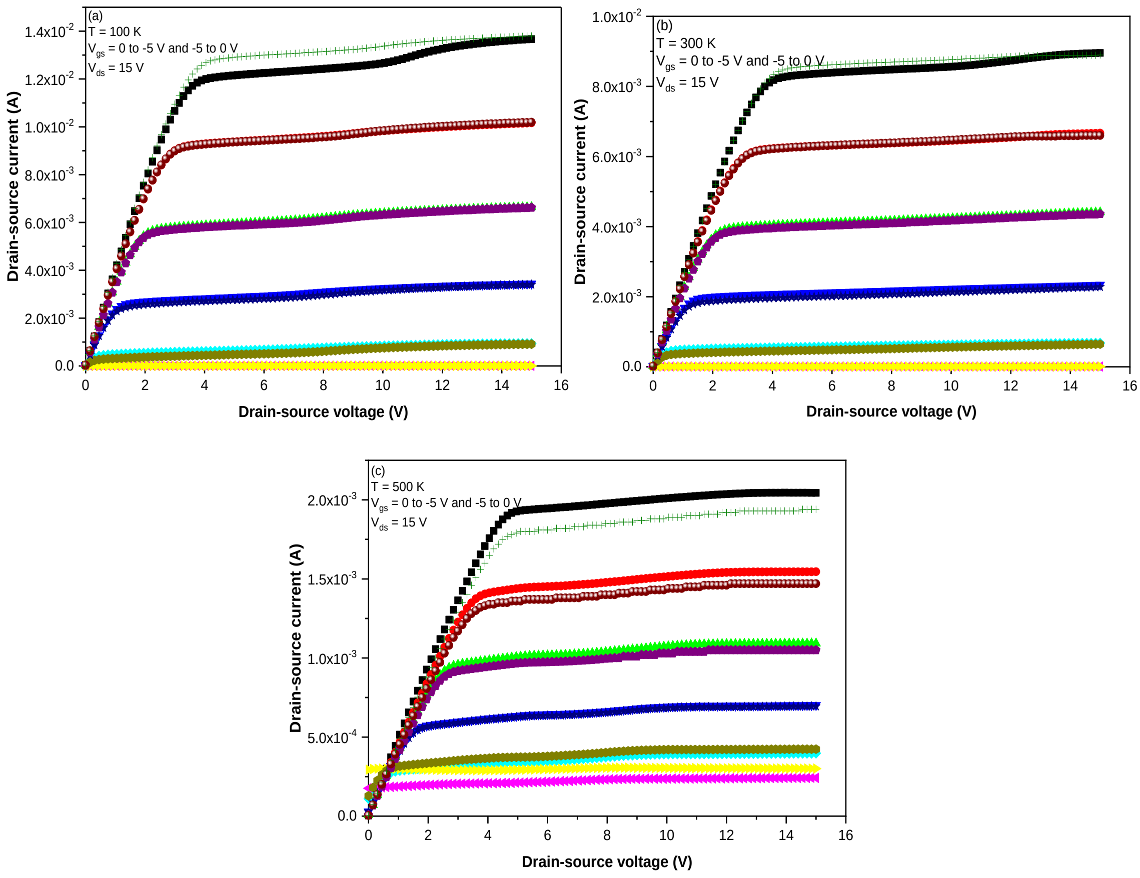

Fig. 1.Direct-current characteristics of the AlGaN/GaN/Si HEMTs at different V_{gs} and various temperature.

The latter behavior is due to the charge accumulation at the AlGaN/GaN heterointerface. It can be seen that the built-in negative charge increases either in the GaN layer or in the AlGaN barrier. In addition, the negative accumulated charge is assigned to the electron injection from the gate into the AlGaN barrier layer through a trap-assisted tunnelling mechanism. [33-35]As also shown (see figure 1 a and b), a spectacular variation of the output conductance, named kink effect. The kink effect is due to the presence of traps in the structure, the pinch-off voltage shifts and the increase carrier density in the 2DEG. [32,36]Figure 1c shows a large leakage current at T = 500 K. It is worth noticing that the leakage current may be explained by the channel temperature changes due to the self-heating of the AlGaN/GaN/Si HEMTs. However, the leakage current origin is found to be edge leakage currents or deep level impurities. [37,38] It should be noted that the leakage current are dominated by the electron trap state emission near the AlGaN/GaN interface.[37] This implies that this leakage current is related to the presence of dislocations in the GaN layer grown by MBE.[22,38]

The transfer characteristics (I_{ds}-V_{gs}-T) of the AlGaN/GaN/Si HEMTs are found to study the threshold voltage. Figure 2 shows the drain-current as a function of gate-source voltage at 300 K. The transfer characteristics at different temperature as illustrated in the inset of Figure 2. The threshold voltage shift is determined from linear extrapolation of the drain-current versus gate-source-voltage to zero current. The relevant values are listed in Table 1. As can be seen, the threshold voltage variation of AlGaN/GaN/Si HEMTs are found to cause by deep levels associated with electrically active defects in the AlGaN/GaN heterostructures.[38]

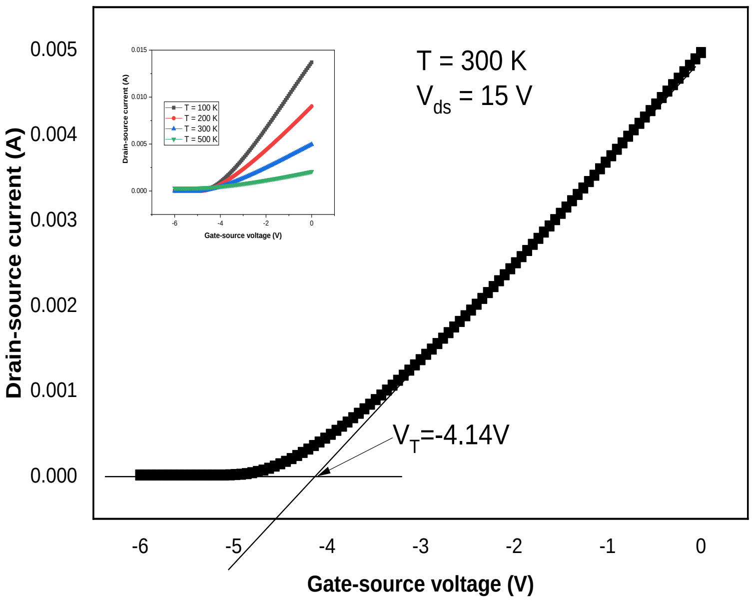

Fig. 2. Transfer characteristics of the AlGaN/GaN/Si HEMT devices.

Table 1.Threshold voltage of the AlGaN/GaN/Si HEMTs.

Temperature (K)	100	200	300	400	500
V_{th} (V)	-4.55	-4.34	-4.14	-3.93	-3.73

4. CDLTS measurements

Conductance deep-level transient spectroscopy measurements have been performed on AlGaN/GaN HEMTs. Figure 3 shows the CDLTS signal of AlGaN/GaN/Si HEMTs. As can be noticed, the spectrum is composed of three defects, labeled A1-A3. The signatures of these defects are determined from the Arrhenius plot and illustrated in the inset of Figure 3.

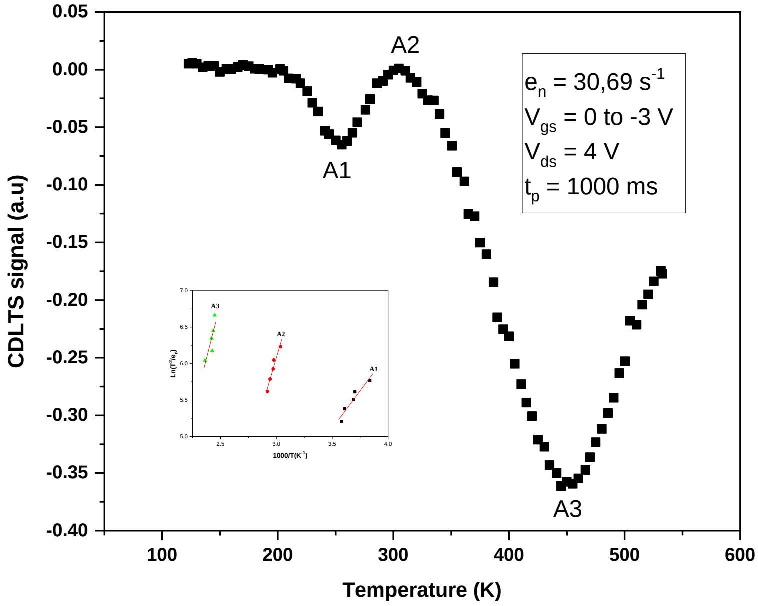

Fig. 3.CDLTS spectra of the AlGaN/GaN/Si HEMTs. The inset shows the signatures of the traps.

The trap A1 is found to have an energy level at 0.24 eV and a capture cross section of 8.3 x 10^{-16} cm^2.It is worth noticing that this trap is similar to that reported by Fang et al. [40] in n-GaN grown by hydride vapor phase epitaxy (HVPE) using deep-level transient spectroscopy (DLTS) measurements. The same trap is also observed by Mosbahi et al.[23,41] in a previous works for an MBE grown AlGaN/GaN/Si. This trap is expected to be a complex involving a pair of Ga- and N–vacancies and located at the AlGaN/GaNheterointerface.

The trap named A2 has an energy located at 0.31 eV and a capture cross section of 5.89 x 10^{-17} cm^2. To our knowledge, it seems that this trapping is observed for the first time in our CDLTS measurements after gate pulse. This trap can be attributed to dislocation localized in the AlGaN barrier. [42]

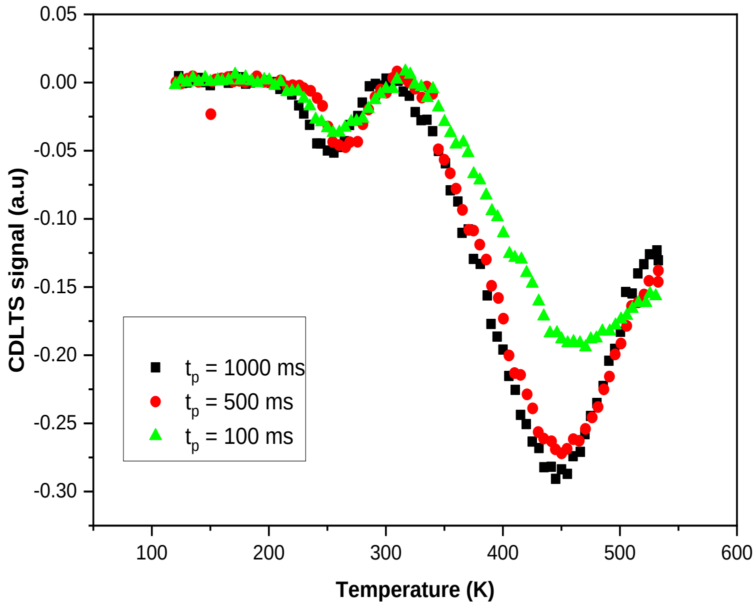

Fig. 4.CDLTS spectra of the AlGaN/GaN/Si HEMTs at different t_p.

The deep trap A3 is characterized by an ionization energy of 0.51 eV and a capture cross section of 4.07 x 10^{-17} cm^2. This trap was detected by Gassoumi et al.[43] in AlGaN/GaN heterointerface, also by Mosbahi et al.[23]. The same trap is observed by Sin et al.[44] in AlGaNSchottky diodes. As has been advanced, this traps is assigned to an N-antisite from AlGaN barrier.

To determine the traps nature, we have carried CDLTS measurements as function of pulse time. Figure 4 shows the CDLTS signal at different t_p. In addition, we have noticed the presence of the same traps. It is worth noticing that the traps A1 and A2 are punctual defects. Then, trap A3 is an extended defect.

5. Conclusion

In the present work, we have investigated the transport properties of AlGaN/GaN/Si HEMTs. The electrical behavior of the structure is characterized by using current-voltage and CDLTS measurements. As has been shown, parasitic effects explainsby the presence of deep levels in the transistor device. As a consequence, CDLTS is used to characterize deep levels. This leads to show the relationship between the anomalies in the I-V-T characteristics and CDLTS measurements have been estabilished.

Acknowledgements

The authors extend their appreciation to the Deanship of Scientific Research at Imam Mohammad Ibn Saud Islamic University for funding this work through Research Group no. RG-21-09-66.

References

[1] V. Kumar, A. Kuliev, R. Schwindt, M. Muir, G. Simin, J. Yang, M.A. Khan, I. Adesida, Solid-State Electron. 2003, 47, 1577; https://doi.org/10.1016/S0038-1101(03)00078-9
[2] M.J. Manfra, N. Weimann, Y. Baeyens, P. Roux, D.M. Tennant, Electron. Lett. 2003, 39, 694 https://doi.org/10.1049/el:20030451
[3] S.J. Pearton, F. Ren, Y.-L. Wang, B.H. Chu, K.H. Chen, C.Y. Chang, W. Lim, J. Lin, D.P. Norton, Prog. Mater. Sci. 2010, 55, 1-59; https://doi.org/10.1016/j.pmatsci.2009.08.003
[4] F. Ren, S.J. Pearton, Phys. Status Solidi C. 2012, 9, 393;https://doi.org/10.1002/pssc.201100296
[5]V.K.J.F. Khanna, Front. Sens. 2013, 1, 38; https://doi.org/10.1177/0256090920130111
[6] V. Cimalla, Label-Free Biosens. 2017, 59; https://doi.org/10.1007/5346_2017_20
[7] U.K. Mishra, L. Shen, T.E. Kazior, Y.F. Wu, Proc. IEEE. 2008, 96, 287 https://doi.org/10.1109/JPROC.2007.911060
[8] S. Strite, H. Morkoç, J. Vac. Sci. Technol. B. 1992, 10, 1237 https://doi.org/10.1116/1.585897
[9] N. Chaniotakis, N. Sofkiti, Anal. Chim.Acta. 2008, 615, 1https://doi.org/10.1016/j.aca.2008.03.046
[10] A. Ould-Abbas, O. Zeggai, M. Bouchaour, H. Zeggai, N. Sahouane, M. Madani, D. Trari, M. Boukais, N. Chabane-Sari, J. Optoelectron. Adv. Mater.**2013**, 15, 1323.
[11]M. Rais-Zadeh, V.J. Gokhale, A. Ansari, M. Faucher, D. Theron, Y. Cordier, L. Buchaillot, J. Microelectromech. Syst. 2014, 23, 1252; https://doi.org/10.1109/JMEMS.2014.2352617
[12]S. Kargarrazi, A.S. Yalamarthy, P.F. Satterthwaite, S.W. Blankenberg, C. Chapin, D. G. Senesky, IEEE J. Electron Devices Soc. 2019, 7, 931; https://doi.org/10.1109/JEDS.2019.2937008

[13] H. Morkoç, Handbook of Nitride Semiconductors and Devices, vol. I-III, Wiley-VCH, Berlin, 2008; https://doi.org/10.1002/9783527628445
[14] Y.F. Wu, M. Moore, A. Saxler, T. Wisleder, P. Parikh, Proceedings 64th Device Research Conference.State CollegePA USA, 26–28 June **2006**, 151.
[15] T. Oeder, A. Castellazzi, M. Pfost, Proceedings 29th International Symposium on Power Semiconductor Devices and IC's (ISPSD), Sapporo Japan, 28 May–1 June **2017**, 211.
[16] C. Wood, D. Jena, Springer Science & Business Media. **2007**.
[17] K.S. Im, J.B. Ha, K.W. Kim, J.S. Lee, D.S. Kim, H.C. Choi, J.H. Lee, Phys. Status Solidi, 2010, 7, 2013; https://doi.org/10.1002/pssc.200983654
[18]Z. Xu, J. Wang, Y. Cai, J. Liu, C. Jin, Z. Yang, M. Wang, M. Yu, B. Xie, W. Wu, X. Ma, J. Zhang, Y. Hao, IEEE Electron Device Lett. 2014, 35, 1200; https://doi.org/10.1109/LED.2013.2291854
[19]G. Meneghesso, F. Rossi, G. Salviati, M.J. Uren, E. Munoz, E. Zanoni, Appl. Phys. Lett. 2010, 96, 263512; https://doi.org/10.1063/1.3459968
[20] L. Fu, H. Lu, D. Chen, R. Zhang, Y. Zheng, T. Chen, K. Wei, X. Liu, Appl. Phys. Lett. 2011, 98, 173508; https://doi.org/10.1063/1.3584861
[21]F. Iucolano, F. Roccaforte, F. Giannazzo, V. Raineri, J. Appl. Phys. 2008, 104, 093706 https://doi.org/10.1063/1.3006133
[22]S. Huang, B. Shen, F.-J. Xu, F. Lin, Z.-L. Miao, J. Song, L. Lu, L.-B.Cen, L.-W.Sang,Z.-X. Qin, Z.-J.Yang, G.-Y. Zhang, Semicond. Sci. Technol. 2009, 24, 055005; https://doi.org/10.1088/0268-1242/24/5/055005
[23]H. Mosbahi, M. Gassoumi, I. Saidi, H. Mejri, C. Gaquière, M.A. Zaidi, H. Maaref, Current Applied Physics. 2013, 13, 1359; https://doi.org/10.1016/j.cap.2013.04.003
[24] S. Sabuktagin, S. Dogan, A.A. Baski, H. Morkoç, Appl. Phys. Lett. 2005, 86, 083506 https://doi.org/10.1063/1.1867553
[25] H. Kim, J. Lee, D. Liu, W. Lu, Appl. Phys. Lett. 2005, 86, 143505; https://doi.org/10.1063/1.1899255
[26] X.Z. Dang, E.T. Yu, E.J. Piner, B.T. McDermott, J. Appl. Phys. 2001, 90, 1357; https://doi.org/10.1063/1.1383014
[27] B. Luo, J.W. Johnson,B.P.Gila,A.Onstine,C.R.Abernathy, F.Ren, S.J.Pearton,A.G.Baca, A.M. Dabiran, A.M.Wowchack, P.P. Chow, Solid-State Electron. 2002, 46, 467 https://doi.org/10.1016/S0038-1101(01)00314-8
[28] Y. Ohno, T. Nakao, S. Kishimoto, K. Maezawa, T. Mizutani, Appl. Phys. Lett. 2004, 84, 2184; https://doi.org/10.1063/1.1687983
[29] N. Maed, T. Tawara, T. Saitoh, K. Tsubaki, N. Kobayashi, Physica Status Solidi (a). 2003, 200, 168; https://doi.org/10.1002/pssa.200303468
[30] B.J. Min, S. Yoon, K.T. Won, L.J. Lam, Appl. Phys. Lett. 2006, 89, 152113 https://doi.org/10.1063/1.2360890
[31]M. Gassoumi, Semiconductors. 2020, 54, 129647;https://doi.org/10.1134/S1063782620100127
[32] H. Mosbahi, M. Gassoumi, H. Mejri, M.A. Zaidi, C. Gaquiere, H. Maaref, Electron Devices, **2012**, 15, 1225.
[33]L.E. Byrum, G. Ariyawansa, R.C. Jayasinghe, N. Dietz, A.G.U. Perera, S.G. Matsik, I. T. Ferguson, A. Bezinger, H.C. Liu, J. Appl. Phys. 2009, 105, 023709; https://doi.org/10.1063/1.3068179
[34] W. Chikhaoui, J. M Bluet, P. Girad, G. Bremond, C. Bru-Chevallier, C. Dua, R. Aubry, Phys. B Condens. Matter. 2009, 404, 4877; https://doi.org/10.1016/j.physb.2009.08.231
[35]W. Chikhaoui, J.M. Bluet, C. Bru-Chevallier, C. Dua, R. Aubry, Phys. Status Solidi C 2010, 7, 92; https://doi.org/10.1002/pssc.200982634
[36] H. Mosbahi, M. Charfeddine, M. Gassoumi, H. Mejri, C. Gaquiere, B. Grimbert, M.A. Zaidi, H. Maaref, Sensors & Transducers. May 2014, 27, Special Issue, 277.
[37] H. Zhang, E. J. Miller, E. T. Yu, J. Appl. Phys. 2006, 99, 023703; https://doi.org/10.1063/1.2159547
[38] J. W. P. Hsu, M. J. Manfra, R. J. Molnar, B. Heying, J. S. Speck, Appl. Phys. Lett. 2002, 81, 79; https://doi.org/10.1063/1.1490147

[39] H. Mosbahi, M. Gassoumi, C. Gaquiere, M.A. Zaidi, H. Maaref, Optoelectronics and Advanced Materials-Rapid Communication.**2010**, 4, 1783.
[40] Z.Q. Fang, D.C. Look, J. Jasinski, M. Benamara, Z. LilientalWeber, R.J. Molnar, Appl. Phys. Lett. 2001, 7, 332; https://doi.org/10.1063/1.1338970
[41]H. Mosbahi, M. Gassoumi, M. Charfeddine, M.A. Zaidi, C. Gaquiere, H. Maaref, J. Optoelectron. Adv. M.**12**, 2190 (2010).
[42]M. Charfeddine, M. Gassoumi, H. Mosbahi, C. Gaquiere, M.A. Zaidi, H. Maaref, Modern Physics. 2011, 2, 1229; https://doi.org/10.4236/jmp.2011.210152
[43]M. Gassoumi, J.M. Bluet, G. Guillot, C. Gaquière, H. Maaref, Mater. Sci. Eng. C. 2008, 28, 787; https://doi.org/10.1016/j.msec.2007.10.068
[44] S. X. Sun, Y. H. Zhong, H. Y. Mei, R. X. Yao, F. J. Chen, Y. X. Li, Y. F. Hu, Journal of Ovonic Research. 2021, 17-137