Research Article

MgZnO spacer thickness dependence of 2DEG concentration and I-V characteristics of MgZnO/ZnO hetero structure

Kyunghan Chun[a]

[a]Department of Electronic Engineering, Daegu Catholic University, Gyeongbuk, Korea
[a]kchun@cu.ac.kr

Abstract: In this paper, we investigate that the spacer layer thickness affects the polarization effect on thetwo-dimensional electron gas (2DEG) concentration and current-voltage properties in an MgZnO/ZnO hetero structure. In the conduction band edge profile, MgZnO/ZnO hetero structure with athick layer of spacer shows sharper bending. As a result, the MgZnO/ZnO hetero structure witha relatively thick layer of spacer is expected to surpass the MgZnO/ZnO hetero structure with athin layer of spacer in the carrier confinement. However, if the spacer layer thickness exceeds 30nm, the carrier concentration will no longer increase. The drain current and pinch-off voltage havebeen shown to be proportional to the spacer layer thickness from the addition in electron densitydue to the increased spacer layer thickness.

Keywords: 2-DEG, ZnO, MgZnO, HEMT, heterostructure,

1. Introduction

Recently, high-electron mobility transistors (HEMTs) have been studied for high-voltageand high-power operation at microwave frequencies [1-4]. The performance of hetero structure is attributed to the two-dimensional electronic gas (2DEG) at the heterointerface. TheMgZnO/ZnO hetero structure exhibits a high 2DEG density of 10^{13}cm^{-2}, which is due toa strong piezoelectric and spontaneous polarization effect [5]. High 2DEG density induceshigh carrier density and good mobility characteristics, which can result in high current performance. Therefore, it is required to further improve the mobility and density of 2DEGon the channel. [6] has been studied the density of carriers on the channel due to the Mgcomposition and the result shows that the carrier density is proportional to the Mg composition. And the effect of inserted spacer layer on 2DEG concentrations has also beenstudied by several authors, such as improving alloy disorder scattering problem using undoped spacer layers in GaN-based AlGaN / GaN HEMT [7, 8]. However, for ZnO-basedMgZnO/ZnO HEMT, there is little research on the MgZnO spacer thickness dependenceand current-voltage characteristics of 2DEG concentrations.

In this paper, we theoretically investigate the characteristics of the MgZnO/ZnOheterostructure with several spacer layer thicknesses in view of 2DEG concentration and current-voltage characteristics. Self-consistent (SC) band structures and wave functions can beobtained by repeatedly solving the Schrödinger and Poison equations for electrons [9]. Silvaco simulation is used to get the numerical results. Figure 1 shows the structure of MgZnO/ZnO HEMT and as moving from gate contact to substrate, the HEMT structure is layeredby an n-doped ($n = 1.0\times10^{18}$cm^{-3}) MgZnO layers, an undopedMgZnO spacers, and a thickZnO substrates. The n-doped MgZnO layer was used with 25nm thickness and the spacerlayer has a thickness from 10nm to 50nm in 10nm increments. The fabrication processassumes that the layer grows on the ZnO substrate.

2. Results and Discussion

Figure 2 shows the conduction band and the electron densities of the MgZnO/ZnO HEMTstructure. The conduction band edge profiles were shown in Figure 2 (a) according to thefive thicknesses (10nm-50nm) of the undopedMgZnO spacers in the HEMT structure,and Figure 2 (b) indicated the changes in the electron density due to the effect of thesethickness changes. In the HEMT structure, the n-doped $Mg_xZn_{1-x}O$ layer has a thicknessof 25nm and the Mg content is fixed at x=0.25. The Self-Consistent solution is obtainedat V=0V. In the conduction band plot of Figure 2 (a), it is seen that the bending of theconduction band occurs in the intersection between the MgZnO spacer and ZnO, and thedegree of this bending indicates that the thickness of the spacer increases. However, if thethickness of the MgZnO spacer is more than 30nm, the increase in the thickness no longeraffects the depth of the bending, so it can be assumed that there is a limit to the bendingcaused by the changes in the thickness of the spacer. Therefore, within the limit range, wecan predict that there is a difference in the HEMT performance due to the thickness changeof the spacer, which can be found in the electron density plot Figure 2 (b). For example,we show a value approximately four times greater in terms of electron density for MgZnOspacers with d_{sp}=10nm and 30nm. Similarly with Figure 2 (a), for the thickness of thespacer over 30nm, electron density in Figure 2 (b) also shows that there is no significantdifference in the electron density due to the increase in the thickness of the MgZnO spacer.

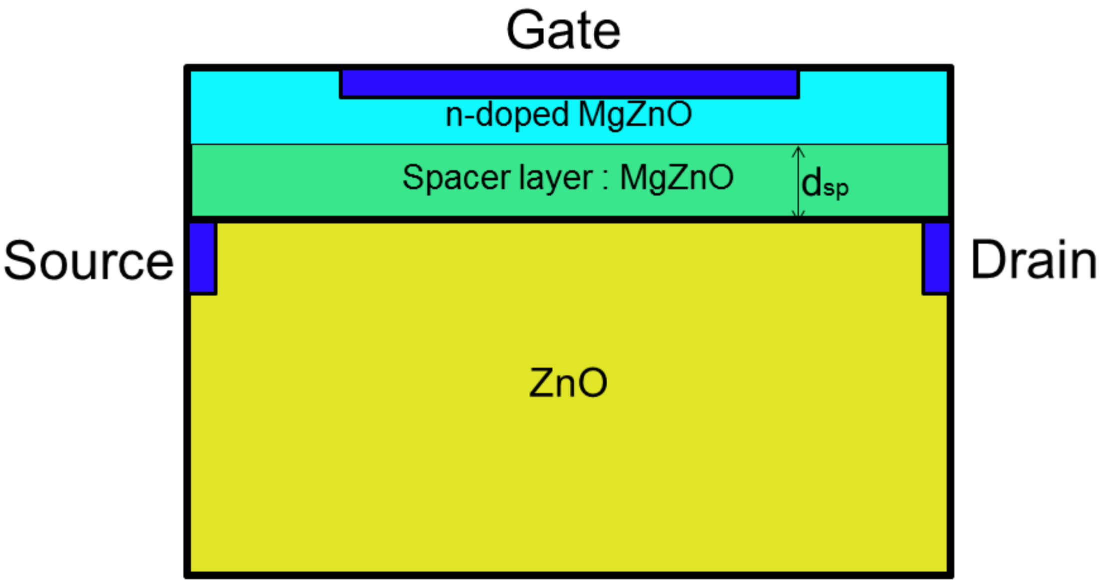

Figure 1. Structure of the MgZnO/ZnO HEMT. The HEMT structure consists (moving from the gate contact to the substrate) of an n-doped (n=1.0×10^{18} cm^{-3}) MgZnO layer, an undopedMgZnO spacer, and a thick ZnO substrate

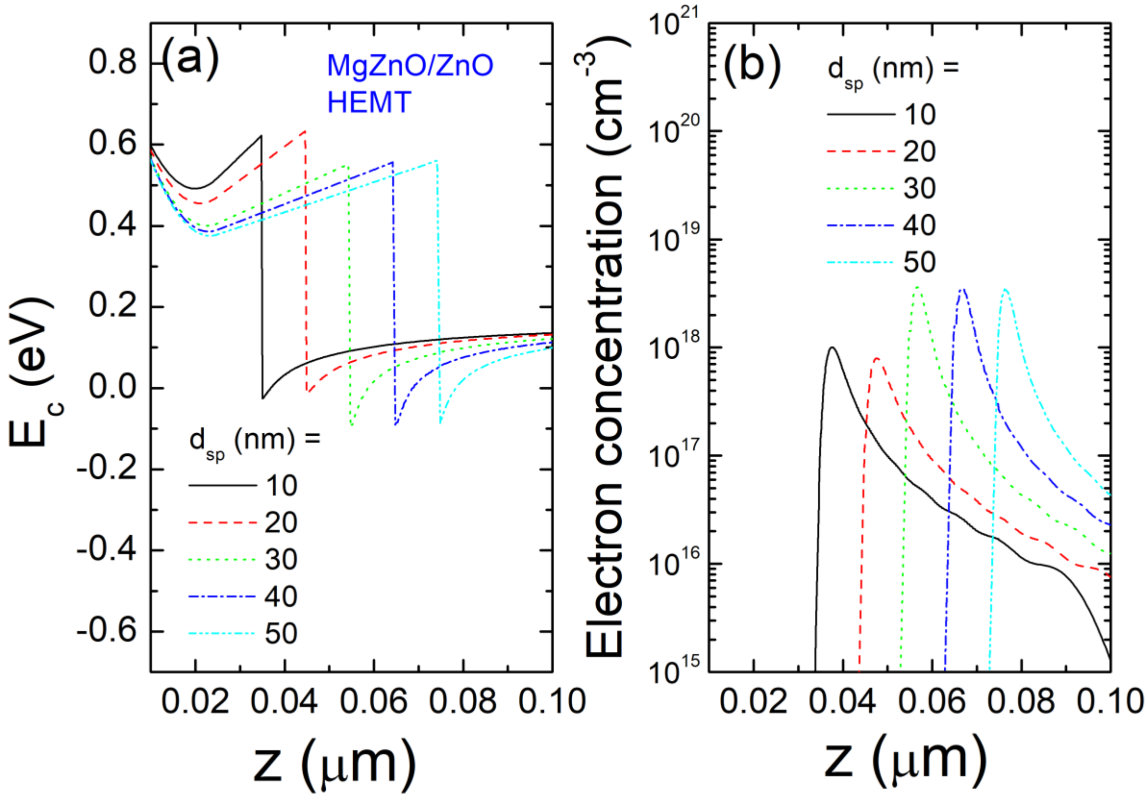

Figure 2.(a) Conduction band edge profiles and (b) the electron densities of the MgZnO/ZnO HEMT structures with several spacer layer thicknesses (d_{sp})

Figure 3 shows the wave function of the MgZnO/ZnO HEMT structure. Only the first fourof the nth-order subbands of the wave function were considered, and these of the normalizedwave function squares can be seen as probability density functions in which particles existin a particular location. To verify the spacer thickness effect on the wave function easily,the total value of the sum of squares is also displayed. In order to compare the variationof the wave function according to the thickness of the MgZnO spacer, the wave functionsof (a) d_{sp}=10nm and (b) d_{sp}=30nm are shown, because the wave functions of larger thand_{sp}=30nm did not differ from the wave functions of d_{sp}=30nm. Depending on the thickness,we show high probability densities near the interface of *z*=35nm in Figure 3 (a) and nearthe interface of *z*=55nm in Figure 3 (b). This is due to the difference in piezoelectric andspontaneous polarizations in the intersection between the MgZnO and ZnO layers, in whichpositive charges are induced and electrons are drawn together by this positive charge. Inparticular, considering Figure 2, where the deeper the bend of the conduction band, thehigher the electron density, the probability density is greater in the MgZnO/ZnO HEMTstructure of the d_{sp}=35nm MgZnO spacer than that of less than d_{sp}=35nm.

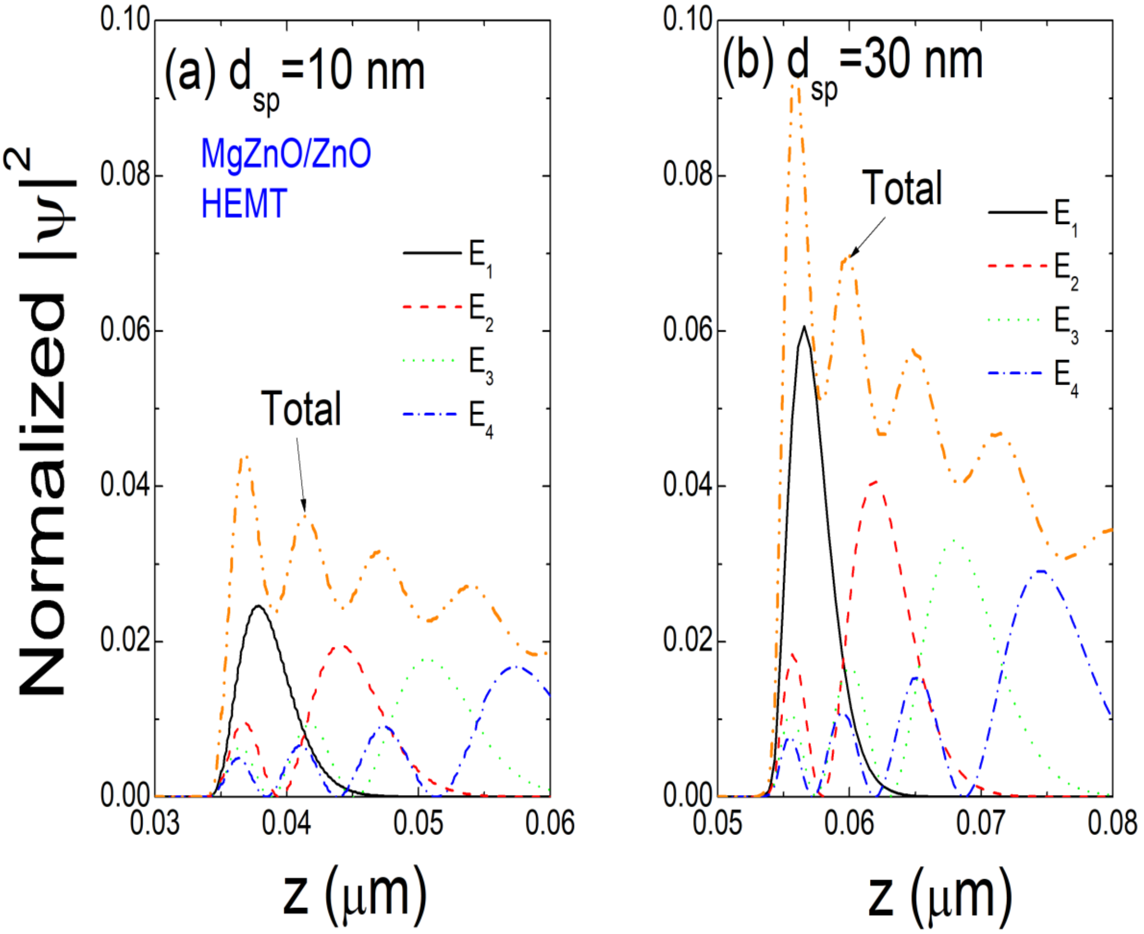

Figure 3.(a) Squares of normalized wave functions for the first four subbands of the MgZnO/ZnO HEMT structure with the undopedMgZnO spacer layer thicknessd_{sp}=10nm and (b) d_{sp}=30nm

Figure 4 shows the I-V characteristics of MgZnO/ZnO HEMT. Figure 4 (a) shows draincurrent (I_{DS}) versus gate voltage (V_{GS}) at 1V fixed drain voltage (V_{DS}) to verify current change in the channel enlargement by the gate voltage and Figure 4 (b) shows draincurrent(I_{DS}) versus drain voltage (V_{DS}) at 0V fixed gate voltage (V_{GS}). The drain currentshows a proportional result that increases with the thickness change of the MgZnO spacerin both Figure 4 (a) and (b). For example, at V_{GS}=5V in Figure 4 (a), for d_{sp}=30nm,the drain current is increased by 25% to $I_{DS}=5\times10^{-4}$A while for d_{sp}=10nm, the draincurrent is $I_{DS}=4\times10^{-4}$A. As a result, if the gate voltage is greater than 5V, the increasein the thickness of the MgZnO spacer leads to an increase in drain current. At Figure 4(b), you can check the pinch off voltage, which also increases as the thickness of the MgZnOspacer increases. The increasing bias voltage causes this result from changes in the electrondensity

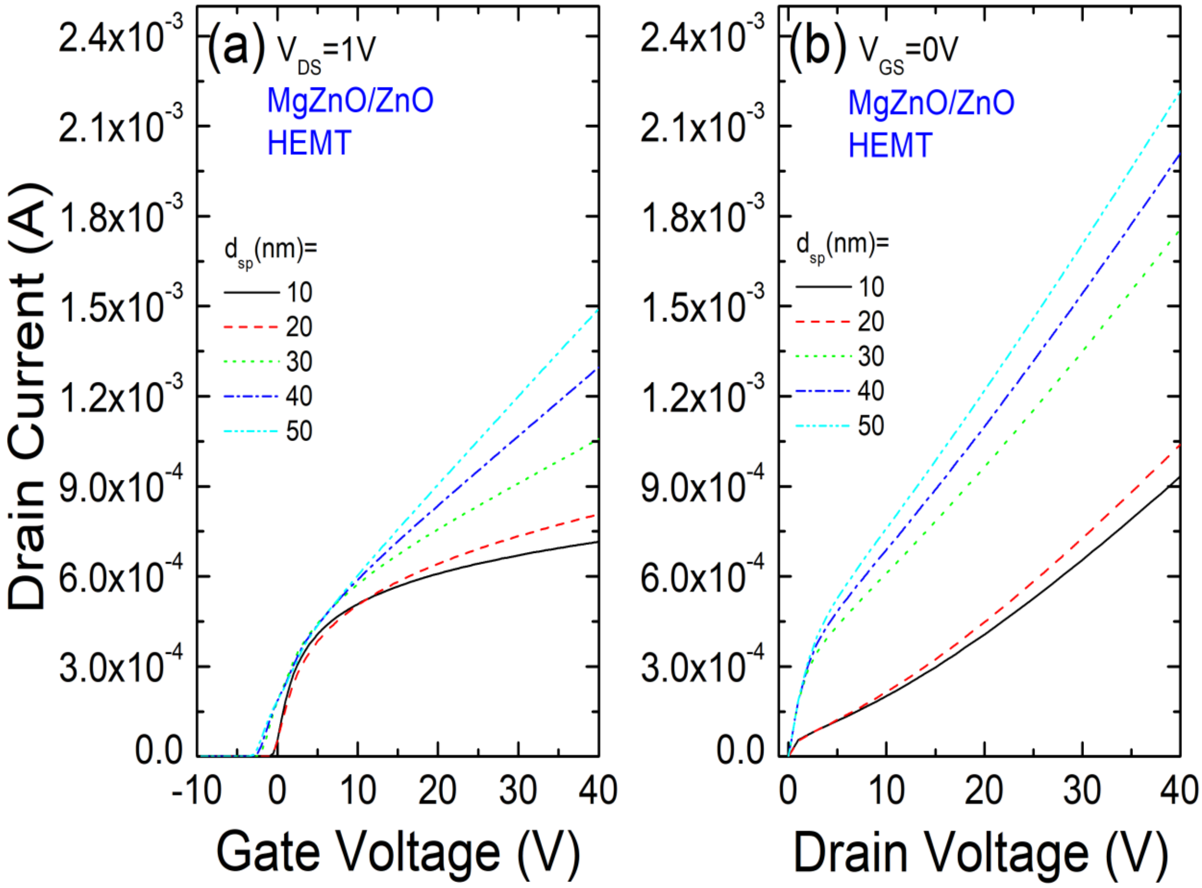

Figure 4.(a) Drain current (I_{DS}) versus the gate voltage (V_{GS}) at a drain voltage (V_{DS}) of 1V and (b) drain current (I_{DS}) versus the drain voltage (V_{DS}) for several gate biases (V_{GS}) for the MgZnO/ZnO HEMT structure

4. Summary

In summary, MgZnO/ZnO hetero structure was theoretically investigated as a function ofa spacer layer thickness in the polarization effect on 2DEG concentration and current-voltagecharacteristics. As the space layer thickness increases, the bending of the conduction bandin the interface between MgZnO and ZnO becomes sharper and the sharp location shiftsright linearly. However, in a range of d_{sp}>30nm, the bending of the conduction band isnearly irrespective of the spacer layer thickness. As a result, the carrier confinement in theMgZnO/ZnO HEMT with a relatively thick spacer layer shows better performance than thatin the MgZnO/ZnO HEMT with a thin spacer layer. The drain current and the pinch-offvoltage also increase with growing spacer layer thickness.

References

[1] V. V. Solovyev and I. V. Kukushkin, Appl. Phys. Express12, 021001 (2019).

[2] P. Kumar, M. A. Khan, G. Siddharth, S. Kumar, R. Singh, and S. Mukherjee, J. Phys. D:App. Phys. 53, 10.1088/1361-6463/ab6467 (2020).

[3] Y. K. Verma, V. Mishra, and S. K. Gupta, Journal of Circuits, Systems and Computers 29,2050009 (2020).

[4] X. Zhou, D. Jiang, M. Zhao, N. Wang, Y. Duan, W. Wang, M. Li, Q. Li, C. Shan, and J. Sun,J. Alloy. Compd. 820, 153416 (2020).

[5] M. Yano, K. Hashimoto, K. Fujimoto, K. Koikea, S. Sasa, M. Inoue, Y. Uetsuji, T. Ohnishiand K. Inaba, J. Cryst. Growth 301-302, 353 (2007).

[6] S.-H. Park, W.-P.Hong, and J.-J. Kim, J. Korean Phys. Soc. 69, 96 (2016).

[7] Nurul Aida Farhana Othman, SharidyaRahman, SharifahFatmadiana Wan MuhamadHatta,NorhayatiSoin, BrahimBenbakhti, Steven Duffy, Microelectronics International 36, 73 (2019).

[8] Madhulika, Jain, N., Kumar, S. et al. Influence of barrier and spacer layer on structural andelectrical properties of AlGaN/GaN HEMT. Int. j. inf. tecnol.12, 119{124 (2020).

[9] S. L. Chuang and C. S. Chang, Phys. Rev. B 54, 2491 (1996).

[10] S. J. Pearton, D. P. Norton, K. Ip, Y. W. Heo and T. Steiner, J. Vac. Sci. Technol. B 22, 932(2004).