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Simulation study of Two-dimensional electron gas layer in HEMTs

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Abstract— **Silicon based semiconductor devices are rapidly approaching the theoretical limit of operation and are becoming unsuitable for future military requirements. High electron mobility transistor (HEMT) Two-dimensional electron gas (2DEG) formed at AlGaN/GaN interface is a critical part to tune the characteristic of AlGaN/GaN HEMT devices. Introduction of AlN spacer layer in between AlGaN and GaN layer is one of the ways to improve 2DEG density, mobility, and has effects on quantum well. The influence of AlN spacer layer thickness on the properties of Al0.185Ga0.815N/AlN/GaN and Al0.3Ga0.7N/AlN/GaN hetero-structures has been investigated. The models takes into account both piezoelectric and spontaneous polarization effects at the all interfaces of AlGaN/AlN/GaN structure, Contrary to AlGaN/GaN HEMTs, the insertion of the very thin AlN interfacial layer maintains high mobility by increasing the effective and decreasing alloy scattering Devices based on this structure exhibited good RF performance.**

Index Terms— **High Electron Mobility Transistor, AlN Spacer layer, Two-dimensional electron gas, band gap.**

I. INTRODUCTION

Power electronics as a means to control electrical energy is showing increasing importance in refining and innovating the social infrastructure in the new century. To break through the material limits of Silicon and to realize the drastic performance improvement needed to meet the severe requirements nowadays wide band gap semiconductors such as SiC and GaN have attracted much attention because of their superior physical prosperities. This dissertation focuses on high voltage AlGaN/GaN HEMTs Al composition and layer thickness of barrier layer in HEMT structure and inserting of AlN spacer layer between AlGaN and GaN layer are the two of ways to improve 2DEG density, mobility and has effects on quantum well .The main source of the electrons in 2DEG are the donor-type surface states and ionized donors in the barrier layer [5, 6]. Because III-nitrides are strongly piezoelectric, polarization--induced charges additionally enhance the confinement of the electrons in a transistor channel. From this point of view, the 2DEG concentration can be controlled by the doping and Al mole fraction of the AlGaN barrier layer.

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Electron mobility of 2DEG is limited by several scattering mechanisms occurring in AlGaN/GaN hetero-structures [7, 8]. The most significant scattering mechanism at room temperature is the optical phonon scattering, whereas at low temperatures alloy disorder and interface roughness scattering are the dominating factors reducing mobility. Alloy disorder scattering becomes significant at room temperatures for relatively high carrier concentration [9].

II. SIMULATION METHEDOLOGY

This work investigates the methodology of modeling and model calibration of the AlGaN/GaN HEMTs with the AlN spacer against transfer characteristics of the device as a function of the percent of the effect of Al layer on the operational behavior of the HEMT [1]. The commercial simulation tool ATLAS by Silvaco Clara [2] was employed to simulate and calibrate simulations against two models of HEMTs results Fig. 2, 3, 4. In comparison to the AlGaN/GaN interface [3], a higher sheet charge density is generated at the AlN/GaN interface due to both the larger strain–induced (piezoelectric) and the built–in (spontaneous) polarization fields. The polarization sheet charge density at the AlN/GaN interface can be expressed as:

$$\sigma = -\left(P_{AlN}^{total} - P_{GaN}^{total}\right) C/m^2 \qquad (1)$$

The ability to achieve a high carrier concentration at the 2DEG is determined by the ability of the structure to confine carriers through the polarization effects. To achieve a high carrier confinement, the polarization directions should be the same. The polarization induced sheet charge density (σ) in Equation (1) should be positive. This positive sheet charge attracts electrons and forms the 2DEG [4].

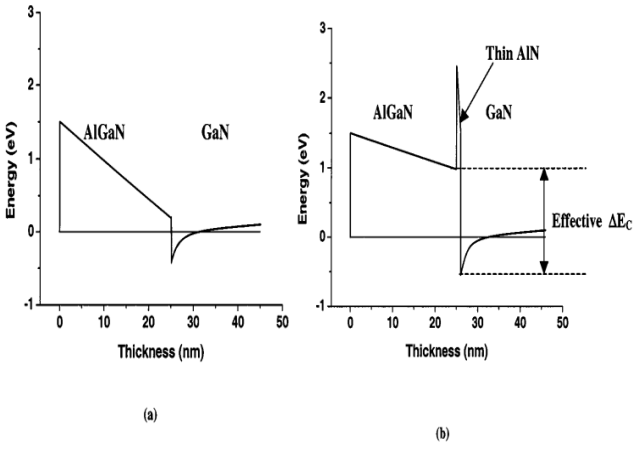

Fig 1. Schematic Energy band diagram of (a) conventional AlGaN/GaN HEMT (b) novel AlGaN/AlN/GaN HEMT.

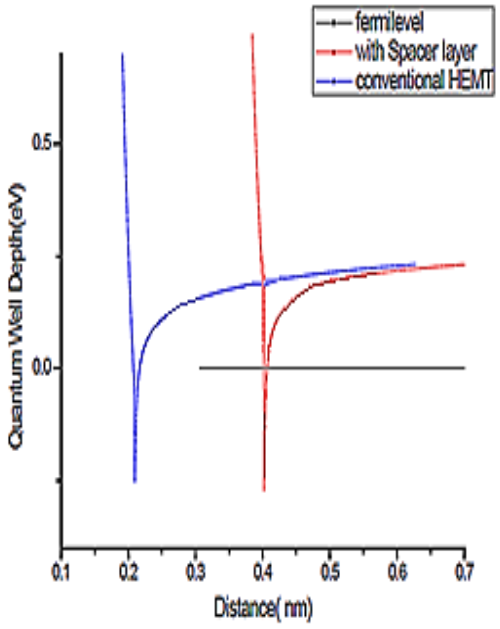

Fig 2.The calculated quantum well depth for the device with and without AlN spacer layers.

$$n_s = \frac{\sigma_{AlGaN} t_{AlGaN} - \frac{\varepsilon\varepsilon_0}{q}\phi_B + \frac{\varepsilon\varepsilon_0}{q^2}\Delta E_{C,AlGaN}}{t_{AlGaN} + d_0} \quad (2)$$

$$n_s = \frac{\sigma_{AlGaN} t_{AlGaN} - \frac{\varepsilon\varepsilon_0}{q}\phi_B + \frac{\varepsilon\varepsilon_0}{q^2}(\Delta E_{C,AlGaN} + \frac{q^2}{\varepsilon\varepsilon_0}\sigma_{AlN} t_{AlN})}{t_{AlGaN} + t_{AlN} + d_0} \quad (3)$$

It is apparent from Equation (2) and (3) that the variation of conventional HEMT and HEMTs with AlN spacer layer with respect to is making differences between AlGaN/GaN and AlGaN/AlN/GaN's amount of sheet carrier concentration. At the equations of (2) and (3), where t is the thicknesses of layer, the dielectric constant, the distance, the gate Schottky-barrier height, q charge of an electron.

I. RESULT AND DISCUSSION

Fig. 1 shows the energy band diagrams of two forms of mentioned HEMTs and fig. 3 shows result of conduction band diagram of conventional AlGaN/GaN HEMT and novel AlGaN/AlN/GaN HEMT which is designed in Silvaco software. The density of 2DEG is based on polarization and μ the mobility is dependent upon the lattice temperature and the ionized impurity concentration for undoped AlGaN/AlN/GaN. The primary advantage of the AlN spacer is the reduction in alloy-disorder scattering at the interface of AlN/GaN leading to an increase of mobility by around 20%. This is owing to the Coulomb scattering between 2DEG carriers when very thick spacer layer is used. As AlN spacer thickness is up to 0.5nm Coulomb force between ions and with lattice is lower, which reduce the scattering and mobility. However, as the thickness further increase beyond 0.5nm width of quantum well Fig. 2 is small enough and coulomb scattering between carriers become dominant. As a result, Carrier sheet resistance is increased as fig. 4.

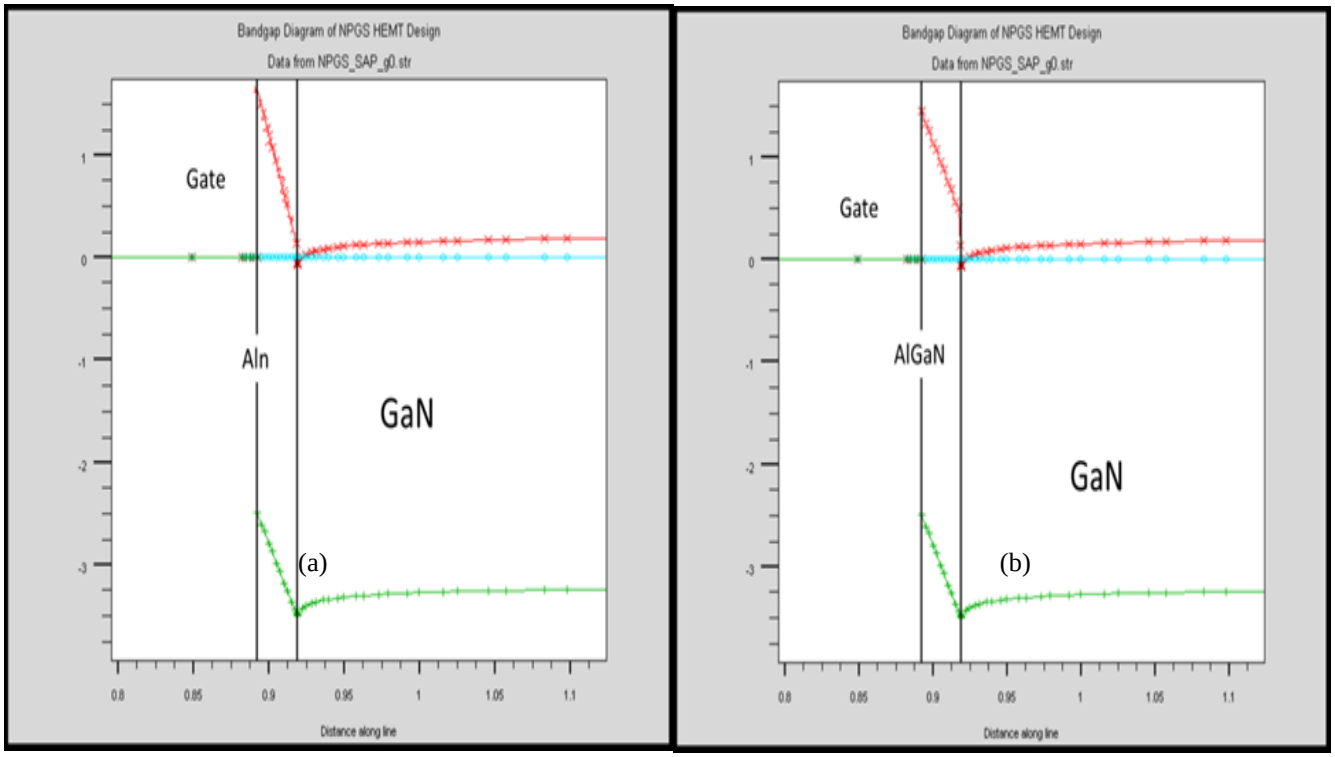

Fig 3. Conduction Band diagram of (a) AlGaN/GaN HEMT and (b)AlGaN/AlN/GaN

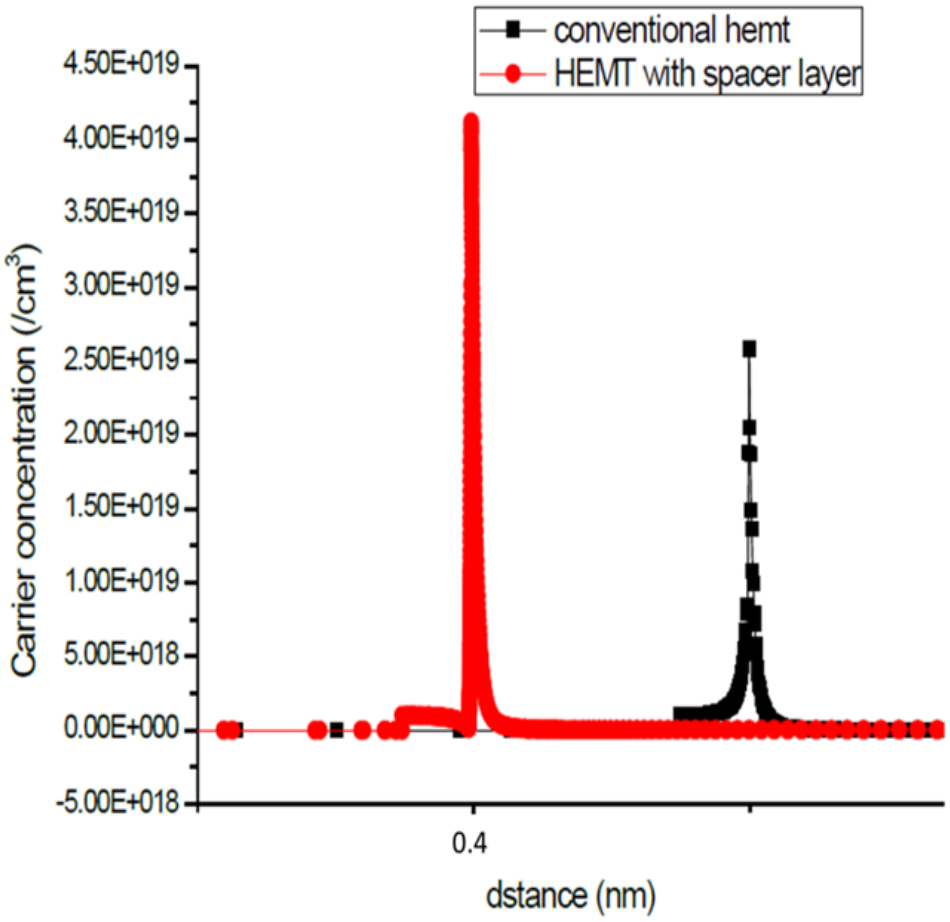

Fig 4.The electron concentration for the device with and without AlN spacer layers.

The spacer based AlGaN/AlN/GaN device's exhibit improvement in electrical properties over AlGaN/GaN devices. Achieved enhanced mobility by the addition of spacer layer AlN and it does not degrade the radiation tolerance. The highest mobility (1700 cm2Vs) was observed for the sample with the 1.2 nm thick AlN spacer in Al0.185Ga0.815N/AlN/GaN and (1625 cm2Vs) was observed for Al0.3Ga0.7N/AlN/GaN with the 1 nm thick AlN spacer fig. 5. This result gives the effect of Al-mole fraction in AlGaN barrier fig. 6. However, after exceeding a critical thickness of the AlN spacer may cause an increase in dipole scattering due to strong polarization effect [10] and therefore deteriorate 2DEG's mobility. Below this critical thickness, the AlN spacer enhances the conduction band offset what effectively reduces the penetration of the wave-function into AlGaN barrier and thus reduces the effect of alloy disorder scattering. This is consistent with theoretical calculations.

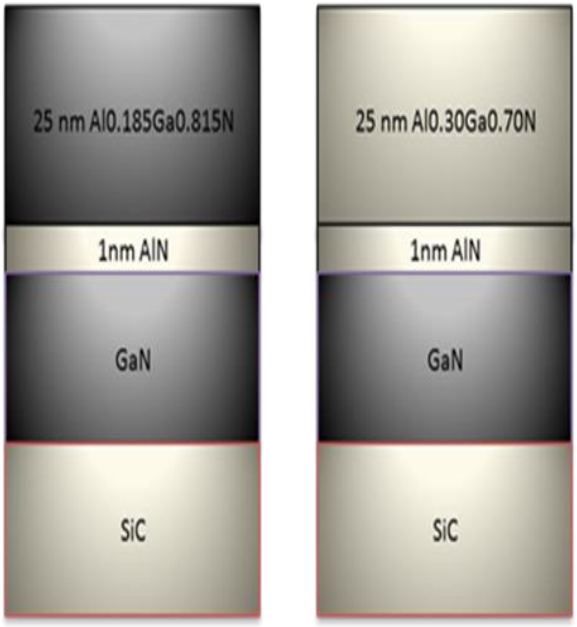

Fig 5. A cross-section of the simulated Al0.185Ga0.815N/AlN/GaN and Al0.3Ga0.7N/AlN/GaN HEMTs

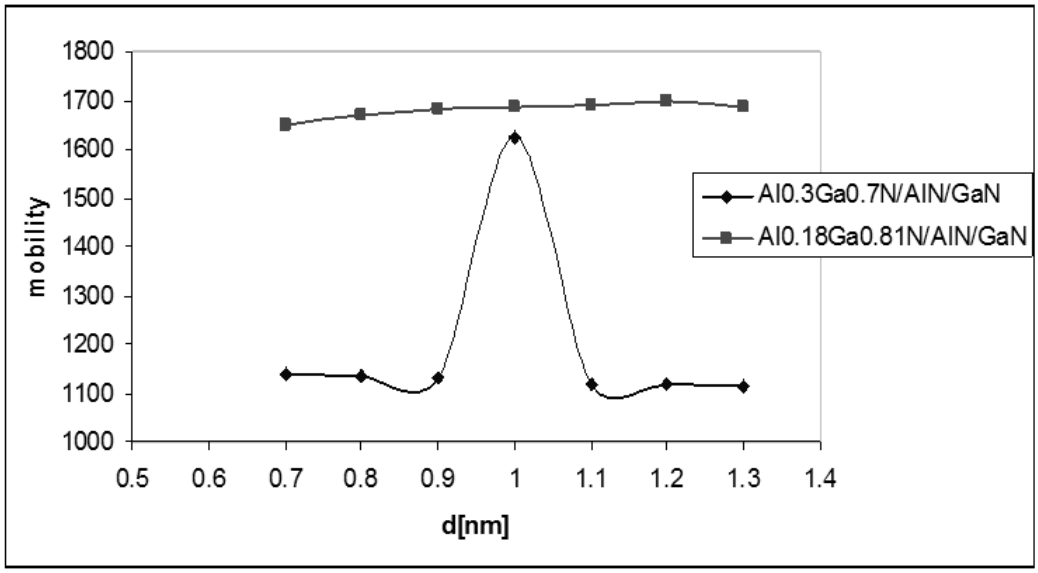

Fig 6. Mobility of 2DEG as a function of AlN spacer thickness in Al0.18Ga0.82N/AlN/GaN and Al0.3Ga0.7N/AlN/GaN heterostructures.

III. CONCLUSION

Based on theoretical calculations, the influence of AlN spacer layer thickness on the properties of Al0.185Ga0.815N/AlN/GaN and Al0.3Ga0.7N/AlN/GaN heterostructures has been investigated. The increase in 2DEG Hall mobility in the samples with AlN spacer can be associated with alloy disorder scattering suppression due to a decrease in the penetration of electron wave-function into AlGaN barrier. The mobility depends on AlN spacer thicknesses and the percent of the Al in AlGaN layer so it can cause an increase in the polarization induced dipole scattering mechanism. Because alloy disorder scattering suppression by the AlN spacer layer is strongly dependent on the sharpness of AlN/GaN interfaces.

REFERENCES

[1] O. Ambacher, B. Foutz, J. Smart, J. R. Shealy, N. G. Weimann, K. Chu, M. Murphy, A. J. Sierakowski, W. J. Schaff, L. F. Eastman, R. Dimitrov, A. Mitchell, and M. Stutzmann, "Two dimensional electron gases induced by spontaneous and piezoelectric polarization in un-doped and doped AlGaN/GaNheterostructures", J. Appl. Phys. vol. 87, 2000 pp. 334-344.

[2] Santa Clara, "Atlas User's Manual, Device Simulation Software", SILVACO Inc., CA, USA, 2013, pp. 264–268.

[3] R. Quay, "Gallium Nitride Electronics", Springer, 2008.

[4] O. Ambacher, J. Smart, J. R. Shealy, N. G. Weimann, K. Chu, M. Murphy, W. J. Schaff, L. F. Eastman, R. Dimitrov, L. Wittmer, M. Stutzmann, W. Rieger, and J. Hilsenbeck, "Two-dimensional electron gases by spontaneous and piezoelectric polarization charges in N- and Ga-face AlGaN/GaN heterostructures", J. Appl. Phys., vol. 85, 1999, pp. 3222–3233.

[5] J.P.ibbetson, P.T.fini, K.D.ness, S.P.denbaars, J.S. speck, U.K.mishra, "Polarization effects,surface states, and the source of electrons in AlGaN/GaNheterostructure field effect transistors",Applied Physics Letters 77(2), 2000, pp. 250–252.

[6] YIFEI Zhang, SINGH J, "Charge control andmobility studies for an AlGaN/GaN high electron mobility transistor", Journal of Applied Physics 85(1), 1999, pp. 587–594.

[7] S. syed, J. manfram, Y.J.wang, R.J.molnar, H.L.stolmar, "Electron scattering in AlGaN/GaNstructures", Applied Physics Letters 84(9), 2004, pp. 1507–1509.

[8] O.katz, A.horn, G.bahir, J.salzman, "Electron mobility in an AlGaN/GaN two-dimensionalelectron gas. I. Carrier concentrationdependent mobility", IEEE Transactions on ElectronDevices 50(10), 2003, pp. 2002–2008.

[9] Y. zhang, I.P.smorchkova, C.R. elsass, S. keller, J.P. ibbetson, S.denbaars, U.K. mishra,J.singh, "Charge control and mobility in AlGaN/GaN transistors: experimental and theoretical Studies", Journal of Applied Physics 87(11), 2000, pp. 7981- 7987.

[10] ZHAO.wei, D.jena, "Dipole scattering in highly polar semiconductor alloys", Journal of Applied Physics 96(4), 2004, pp. 2095–2101.

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