Enhancing the Performance of Gallium Nitride Devices by Using Polarization Effect

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Abstract

In GaN p-n junction diode the spontaneous polarization is zero at the interface of p-GaN and n-GaN layers but dominant across the outer surfaces. This surface electric field degrades the performance of gallium nitride homo-junction devices by increasing the required value of the operating voltage (forward bias voltage). In this paper a new technique has been reported to minimize the polarization induced surface electric field across the p-n junction diode. In this technique a layer of InGaN is grown on the p-GaN layer and a simple mathematical expression has been derived in terms of the thickness of InGaN layer (d) and indium composition (x) at which resultant surface electric field across the device is zero. This technique provides the dual advantages; one is to reduce the surface electric field across the GaN p-n junction diode and second is to reduce the resistance of p-GaN metal contact. This technique may be useful for improving the performance of GaN based devices such as laser diode, light emitting diode, photo-detector, solar cell etc.

Keywords

GaN/InGaN heterostructure, Ga-face gallium nitride layer, metal contact, Piezoelectric polarization, Spontaneous polarization,.

1. Introduction

The polarization (spontaneous and piezoelectric polarization) effect is dominant in III-nitride semiconductor materials due to non-centrosymmetry of wurtzite structure and large ionicity (for InN=0.578, GaN=0.5, AlN=0.449) between In/Ga/Al and N atoms [1]. The spontaneous polarization is the inherent property of the GaN material. This spontaneous polarization is constant and periodic throughout in the bulk of GaN material. This polarization field generates an electric field in the GaN layer. The magnitude of spontaneous electric field is free from the thickness of the GaN layer. When a GaN p-n junction diode is formed; the surface electric field is develop across the device due to the spontaneous polarization. The orientation of spontaneous polarization in GaN p-n junction diode is shown in figure 1.

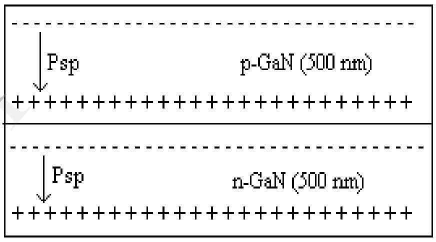

Fig 1. Orientation of spontaneous polarization in p-n junction diode.

Figure 1. shows that the spontaneous electric fields of p-GaN and n-GaN layer cancels each other at the interface of two layers so the net polarization induced charges in the depletion region is zero but develops an electric field across the outer surfaces. This electric field is called the surface electric field which increases the operating voltage (forward bias voltage) of the GaN p-n junction diode. In this work we have grown an InGaN layer on the top of the p-GaN layer and optimize the InGaN layer thickness (d) and indium composition (x) by using self derived mathematical expression for achieving zero surface electric field across the p-n junction diode.

2. Methodology

In this method of reducing the surface electric field across the GaN p-n junction diode we grown an InGaN layer on the top of the p-GaN layer. The piezoelectric polarization charges are generated in the InGaN layer due to lattice mismatch between p-GaN and InGaN layers. This is because of the magnitude of the piezoelectric polarization depends on the strain between the p-GaN and InGaN layers and distance from the p-GaN/InGaN interface layer. The strain between the p-GaN and InGaN layer is proportional to the indium composition (x) of the InGaN layer. Thus the number of piezoelectric polarization charges at the top surface of the InGaN layer is depend on the indium composition (x) in InGaN layer and thickness of the InGaN layer. The direction of spontaneous polarization and piezoelectric polarization is opposite for Ga-face p-GaN/InGaN heterostructure as shown in figure 2.

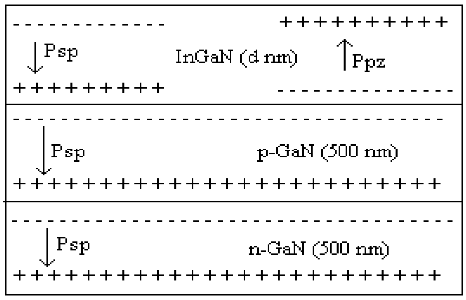

Fig 2. Orientation of polarization in InGaN layer

From above discussion it is clear that the number of piezoelectric polarization charges on the top surface of the InGaN layer is controlled by the two parameters; first is the indium composition (x) in InGaN layer and second is the thickness (d) of the InGaN layer. In this work our objective is to optimize the value of InGaN layer thickness (d) for different values of indium composition (x), for which the net polarization electric field across the p-n junction diode is zero. The percentage reduction of piezoelectric polarization with increase in distance from the GaN/InGaN interface layer is shown in figure 3, [2].

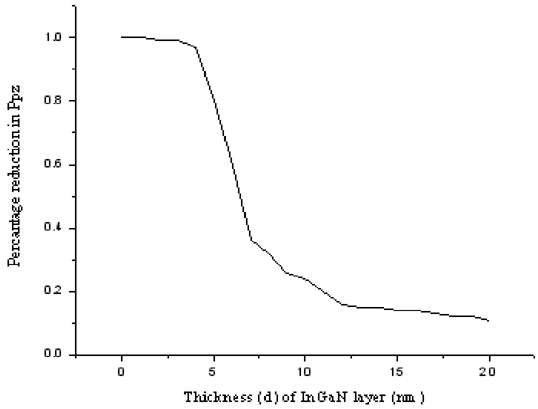

Fig 3. Percentage reduction in piezoelectric polarization with thickness of InGaN layer

The value of spontaneous polarization is fixed for GaN layer and its value is [3]

$P_{sp}^{p\text{-}GaN} = -0.029\ C/m^2$ --------------------- (1)

The value of spontaneous polarization in InGaN layer in terms of indium composition (x) is [4]

$P_{sp}^{InGaN} = -0.003 \times x - 0.029$ -------------- (2)

The value of piezoelectric polarization at the interface of GaN/InGaN heterostructure in terms of indium composition (x) is [5]

$P_{pz}^{InGaN} = 0.176 \times x$ ------------------------- (3)

Figure 2 shows that the positive charges are accumulate at the bottom surface of the n-GaN layer due to spontaneous polarization. Our objective is to generate the same number of positive charges at the top surface of the InGaN layer to eliminate the effect of surface electric field induced by the spontaneous polarization. The number of positive charges required at the top surface of the InGaN layer is equal to the sum of the number of negative charges at the top surface of the InGaN layer and number of positive charges at the bottom surface of the n-GaN layer. Than the required piezoelectric positive charges at the top surface of InGaN layer to eliminate the effect of spontaneous polarization is

$P_{req} = P_{sp}^{InGaN} + P_{sp}^{p\text{-}GaN}$ -------------------- (4)

From equation (1) and (2) we get

$P_{req} = -0.003 \times x - 0.058$ -------------------- (5)

But the number of positive charges at the top surface of the InGaN layer is depend on the thickness (d) of the layer which is shown in figure 3. Because both the polarizations P_{req} and P_{pz}^{InGaN} works in opposite directions thus for zero surface electric field across the p-n junction diode we can write the following equation

$P_{req} + d \times P_{pz}^{InGaN} = 0$ ----------------------- (6)

From equation (3) and (5) we get

$d = (0.003 \times x + 0.058) / (0.176 \times x)$ ------ (7)

Equation (7) shows the relation between the thickness of the InGaN layer (d) and indium composition (x) in the InGaN layer for zero surface electric field across the device induced by the spontaneous polarization.

3. Result and discussion

When a layer of InGaN material is grown on the p-GaN layer; very strong piezoelectric polarization produced in the InGaN layer. This piezoelectric polarization generates the large number of positive charges in the InGaN layer. If the number of positive charges at the top surface of the InGaN layer due to piezoelectric polarization is equal to the positive charges at the bottom surface of the n-GaN layer due to spontaneous polarization than the net surface electric field across the top surface of the InGaN layer and bottom surface of the n-GaN layer is zero. By using equation (7) we have calculate the required thickness (d) of the InGaN layer for different values of indium composition (x) in InGaN layer at which the net surface electric field across the p-n junction diode is zero. The required thickness (d) of the InGaN layer for different values of indium composition (x) is shown in figure 4.

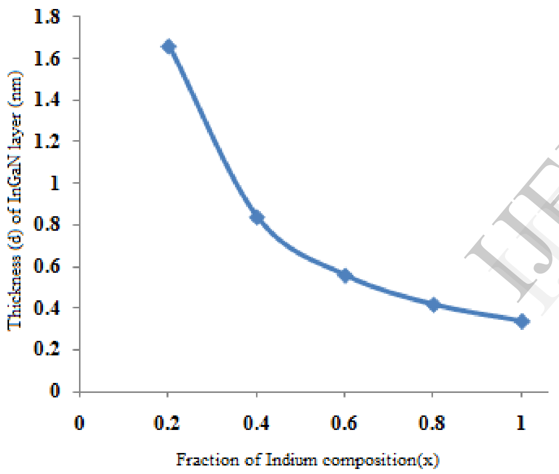

Fig 4. Thickness of InGaN layer vs. Indium composition for zero surface electric field.

Figure 4. shows that the required thickness of InGaN layer for zero surface electric field across the p-n diode is inversely proportional to the indium composition in InGaN layer. The net surface electric field across the p-n junction diode without InGaN layer is fixed. As we increase the indium composition in InGaN layer the piezoelectric polarization is also increases due to increased lattice mismatch with p-GaN layer. But the requirement of positive charges at the top surface of the InGaN layer for zero surface electric field is fixed therefore it is necessary to limit the thickness of the InGaN layer to control the piezoelectric positive charges for maintaining zero surface electric field across the p-n junction diode.

4. Conclusion

From figure 4. it is clear that the very small thickness (less than 2nm) of InGaN layer is required on the top of the p-GaN layer for eliminating the effect of surface electric field across the p-n junction diode. This technique of reducing the effect of spontaneous polarization on operating voltage (forward voltage) of the p-n junction diode provide an extra benefit of developing ohmic contact for p-GaN side. By adjusting the InGaN layer thickness and indium composition we can easily generates the required number of positive charges in InGaN layer at the interface of p-InGaN/metal contact for developing ohmic contact. Therefore this technique is very useful for improving the performance of GaN based devices such as laser diode, light emitting diode, solar cell etc.

5. References

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