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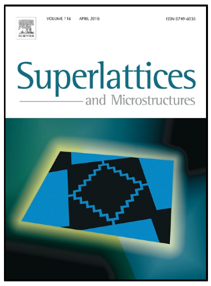

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Nanocrack Formation Due to Inverse Piezoelectric Effect in AlGaN/GaN HEMT

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Abstract

In AlGaN/GaN HEMTs, electrical degradation occurs due to high-voltage stress operation which can be described by a critical voltage operation by which degradation starts to take place which is irreversible. Our investigation is on how electrical degradation occurs due to physical degradation in the device. In this work using Griffith's Equation and inverse piezo electric effect we have shown how physical degradation affects electrical properties of the device and we have also shown how cracks are generated in AlGaN epitaxial layer of the device.
Keywords: Griffith's equation, Inverse piezoelectric effect, Physical degradation, Electrical degradation, Nanocrack formation.

1. Introduction

After Silicon (Si) and Gallium Arsenide (GaAs), Gallium Nitride (GaN) is the most important material in Electronics and material physics. The key property of GaN is that it has wide band gap energy i.e. 3.4eV which is a major reason for its usage in high frequency and high power transistors. In Power electronics applications Aluminum Gallium Nitride/Gallium Nitride (AlGaN/GaN) based High Electron Mobility Transistors (HEMT) are the most implementable devices. But there are some material challenges which are to be investigated. Reliability of these devices is a very crucial issue [1].

This work is on improvement of reliability issue of AlGaN/GaN based HEMT under high voltage application. Under application of high voltage AlGaN/GaN face stress and strain as it is a piezoelectric crystal and these forces can cause nanocrack formation in it. The presence of these nanocracks leads to high undesirable parasitic resistance [2], reduction in electron mobility, and increment in gate current.

2. Role of Inverse Piezoelectric effect and Griffith's Equation

AlGaN/GaN are very good piezoelectric materials hence if we apply high voltage there will be large stress in AlGaN/GaN based HEMT. Under high voltage operation large electric field appears at the gate edge of the transistor which cause high mechanical stress in it, as shown in **Fig.1**. Because of lattice mismatch of AlGaN on GaN, they experiences high tensile strain after application of high voltage which stores some elastic energy in these crystal at rest. If the stored energy exceeds critical value, mechanical deformation will be there in the crystal. Then the defects present in the HEMT will change the device characteristics.

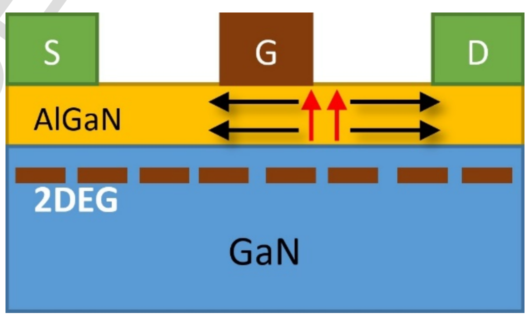

Fig.1. After application of high electrical stress a high-field appears under the edge of the gate, on the drain side of the device (red vertical arrow) which shows large lateral tensile stress in the same region (black horizontal arrows).

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Formation of cracks can be described by Griffith's theory of brittle fracture. According to Griffith crack formation takes place when the released elastic strain energy is equivalent to the energy required to generate new crack. Stress required to produce new crack is given by equation (1)

$$\sigma = \left(\frac{2E\gamma_s}{\pi a}\right)^{\frac{1}{2}} \qquad (1)$$

And plane stress is given by equation (2)

$$\sigma = \left(\frac{2E\gamma_s}{(1-\vartheta^2)\pi a}\right)^{\frac{1}{2}} \qquad (2)$$

Where 'σ' is the tensile stress, 'E' is the Young's Modulus, 'γ_s' is the surface energy density, 'a' is the crack length and 'ϑ' is the Poison's ratio. In **Fig.2.** we have shown how plane stress is acting on AlGaN layer and plane strain equation is described by equation (2)

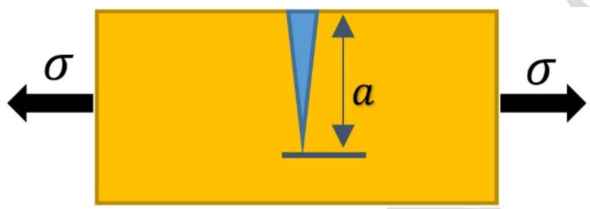

Fig.2. Formation of brittle crack of length 'a' due to plane stress 'σ' which is actually tensile stress applied on AlGaN layer in AlGaN/GaN based HEMT

Generation of charge in a crystal is proportional to the force applied to the crystal and as it is a piezoelectric crystal the vice versa phenomenon is also true i.e. mechanical force is proportional to the charge applied on the crystal which is given by equation (3) where 'F' is the force, 'Q' is the charge applied on the crystal and 'd' is the charge constant of the crystal

$$F = \frac{Q}{d} \qquad (3)$$

Furthermore if we derive equation (3) we can find out that change in length of the crystal is proportional to the charge applied on the crystal which is mentioned in equation (4) where 'W_G' is the width, 't' is the thickness, 'L_G' is the gate length, 'L' is source to drain spacing of the HEMT as described in **Fig.3.**

$$\Delta L = \frac{QL}{dwtE} \qquad (4)$$

$$\Delta L = \frac{CVL}{dwtE} \qquad (5)$$

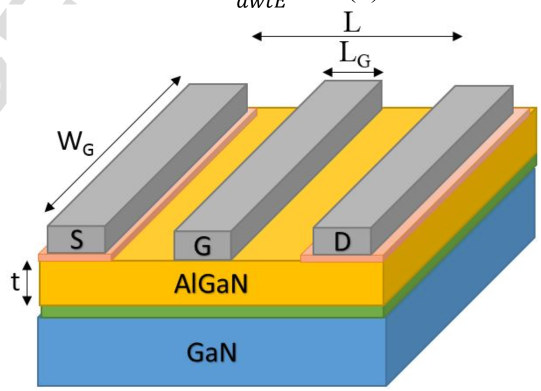

Fig.3. Device Dimensions for our experiment. These dimensions are used in equation (4) and (5)

3. Experiment

This work is on theoretical analysis of crack formation. The device we have considered here has gate length (L_G) 0.25 µm, gate width (W_G) 400 µm, source to drain spacing (L) 4 µm, thickness of AlGaN layer (t) 15nm on epitaxial GaN layer, carrier concentration is $1.06 \times 10^{13} cm^{-2}$, sheet resistance is 310 Ω/sq and mobility of electron is 1900 cm^{-2}/V-s [3]. Ohmic contact layer consists of Ti/Al/Ni/Au.

The device we have analyzed here did undergo electrical stressing. As piezoelectric crystal do not respond to constant force so we have applied stepped stressing i.e. we are increasing the stress over time in the step manner which leads to degradation in the device [5]. On the other hand in step stress recovery experiment device is kept into rest after step stress experiment. These process continues one after another. Considering the range of V_{DS} from 0V to 14V [6] we have observed I_{DS} curves of the device for V_{GS} ranging from -4V to 1V in 1 V increment before and after applying stress as described in **Fig.4.** In V_{DS} = 0V equal amount of high electric-field is applied to the source side and drain side for the device under test.

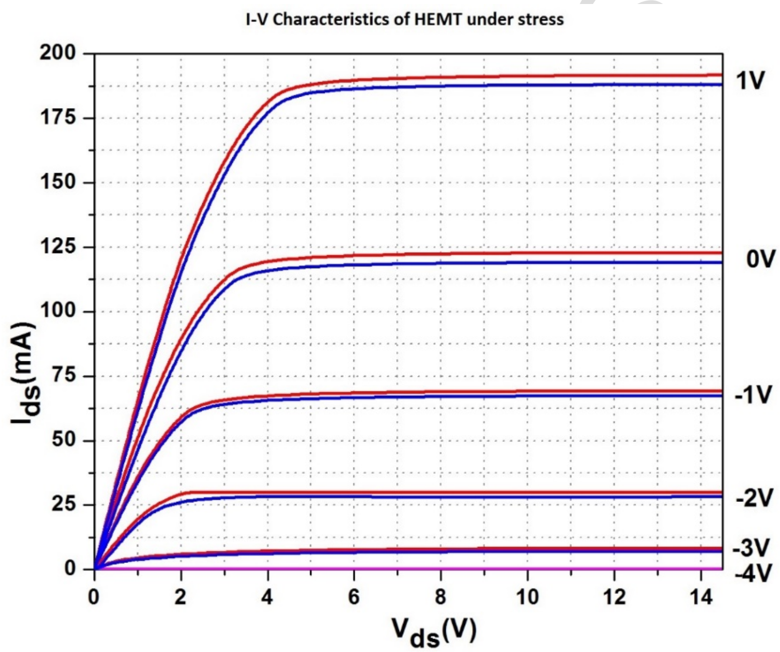

Fig.4. Characteristics of Drain current degradation vs Drain voltage due to tensile stress in AlGaN/GaN material. V_{ds} is ranging from 0 to 14 volt and V_{GS} is taken from -4 volt to -1 volt I_{ds} is in mA. Blue color shows I_{ds} vs V_{ds} characteristics after stress and red color shows I_{ds} vs V_{ds} characteristics before stress.

4. Results and Discussion

In this experiment V_{GS} is ranging from -4V to 1V with step stressing of 1V in every minute with V_{DS} 0V to 14V. This stress mechanism causes reduction in drain current which results in increase in gate leakage current. Due to increase in gate leakage current ON resistance of HEMT increases. So off-state current enhances large gate current, particularly in reverse bias condition [7].

The maximum of the length distribution for nanocracks present within the channel region of the device yields an estimate of 780 MPa for the stress in the AlGaN film required for additional crack growth. This is approximately 40% of the calculated theoretical tensile stress in the film for Al0.28Ga0.72N present on top of pure GaN (1.94 GPa), so it seems feasible that the residual stress in the AlGaN film of the channel, due to pseudomorphic mismatch as well as due to the conditions associated with the deposition of the passivation layer, could be just barely lower than this value of 780 MPa.

The effect described above can be modeled by a modified form of Griffith's Equation, expressed below in Eq. (6). In this equation, $'K'$ is the fracture toughness of the film (in $Pa - m^{\frac{1}{2}}$), $'a'$ is the crack length (in m), and the tensile stress acting on the film required for additional crack growth is 'σ' (in N-m) [3]. Including channel region of AlGaN, crack length is related to stress state of the device, and we should take geometry of the epitaxial layer into account. In our experiment, a modifier $'Z'$ is used to describe the geometry of a crack, forms in an epitaxial film on top of a much thicker substrate. The value of the constant for 2D channeling crack is 1.976 but for thinner film (i.e. the ratio of AlGaN thickness to GaN thickness is more than 1:10) the value of this constant is indistinguishable, which is certainly the approximate case for the AlGaN epitaxial layer on top of GaN.

$$\sigma = \frac{K}{(Z\pi a)^{\frac{1}{2}}} \qquad (6)$$

To calculate the generation of stress in the film from a given crack length, the fracture toughness can be calculated which is given by Eq. (7).Which calculates the fracture toughness in the plane strain state. In this equation, 'γ' is the surface energy of the crack (equal to twice the surface energy of a [11–20] prism plane, or $157 eV/Å^2$, estimated by linear interpolation between the theoretically calculated surface energies of the GaN [11–20] and the AlN [11–20] planes) [8]. The Young's Modulus 'E' is assumed to be equal to 309 GPa and the Poisson Ratio $'\vartheta'$ is assumed to be equal to 0.51 [4].

$$K = \left(\frac{2E\gamma}{1-\vartheta^2}\right)^{\frac{1}{2}} \qquad (7)$$

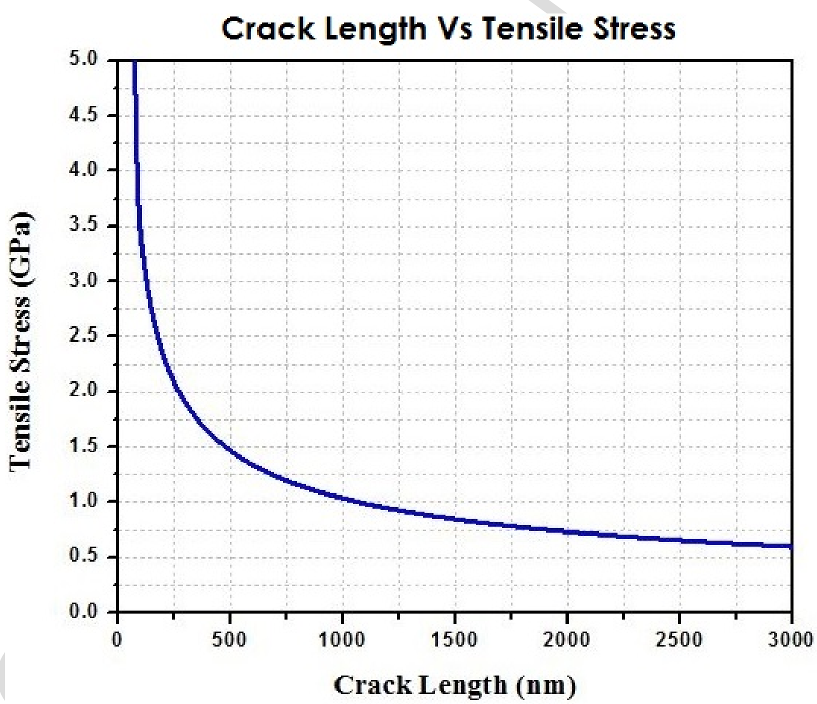

Fig.5. Plot for Tensile stress vs crack length generated in epitaxial layer of AlGaN/GaN based HEMT as described by the Griffith's equation.

Using equation (6) and equation (7) we can theoretically calculate crack length in AlGaN layer under stress and **Fig.5.** is the explanation of this theoretical approach. According to **Fig.5.** when there is no crack in AlGaN layer the stress was maximum, but when the crack is generated, surface energy released and stress decreases. Hence crack length increases through the AlGaN layer. The relation between crack length and tensile stress gives exponential results. According to the curve (**Fig.5.**) at 1.5GPa of stress the crack length is 500 nm, at 1GPa of stress the crack length is 1000nm and then at 0.5GPa of stress the crack length is about 3000nm.

5. Conclusion

We have observed that due to stressing the I_{ds} curve family face electrical degradation. At V_{GS}=1V the degradation is maximum and at V_{GS}=-3V the degradation is minimum. Generation of crack results in generation of parasitic resistance which is also a major reason for electrical degradation. Not only this, crystalline defects results in gate leakage current.

Acknowledgement

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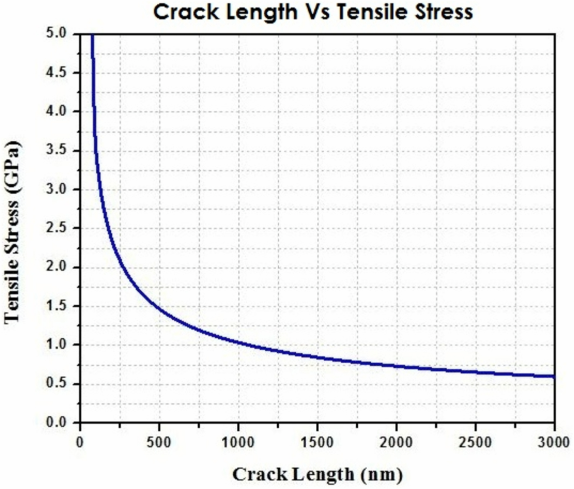
HIGHLIGHTS

- Electrical stress applied on AlGaN/GaN HEMT.
- Because of electrical stress physical degradation takes place after the critical voltage of material degradation.
- As material degradation takes place as a result electrical degradation occurs.



Crack Length Vs Tensile Stress
Tensile Stress (GPa)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
500
1000
1500
2000
2500
3000
Crack Length (nm)