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Application of Bare Surface Barrier Height to Assess Reliability in AlGaN/GaN Heterostructures

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GaN heterostructures based devices exhibit high two-dimensional electron gas (2DEG) densities even in undoped heterostructures due to presence of strong piezoelectric polarization (see Fig. 1). The lattice mismatch between AlGaN and GaN is the key effect producing strong piezoelectric charges. This mismatch creates strain energy that increases with increasing Al content as well as the thickness of the AlGaN barrier.

Over the last few years, the bare surface barrier height (SBH), i.e., the energy difference between the Fermi level and the conduction band minimum (see Fig. 2), has been an active area of research [1-4]. The reason for this interest is its coupling to the low density distributed surface donor states that reside in the forbidden gap of the top AlGaN surface. These surface states are considered to be the source of the electrons that form the 2DEG at the AlGaN/GaN interface. Different groups in the last decade have used Kelvin probe microscopy and Kelvin force microscopy to measure the surface barrier height in the AlGaN/GaN heterostructures [1, 4]. Recently, results from capacitance voltage characteristics were applied for the calculation of the surface barrier height in different GaN based heterostructures [2]. To our knowledge, the application of surface barrier height has till now only been used for calculation of surface potential for studies related to current collapse [1]. However, since the surface barrier height is a function of the density and distribution of the surface donor states, it can be used as signature for the characterization of GaN based devices. Due to a lack of a viable model, this feature has previously not been exploited to the full extent.

In this paper, based on our previous work, we propose a procedure to model the structural and electrical reliability of these devices prior to and at post stress conditions.The bare SBH of the AlGaN layer depends on the effective total polarization charge as shown in our earlier work [3]. The polarization depends on the strain energy and the total effective residual strain in the AlGaN layer. Any change in the residual strain after mechanical, electrical, radiation or high temperature stress changes the SBH correspondingly. Hence, measurements of the SBH will contain information about the internal structural state of the barrier layer, which relates closely to its structural and electrical reliability.

Understanding the physical mechanisms related to device degradation is essential for reliable device design. SBH provides an accurate estimate of the initial residual strain, the total effective polarization, and the total internal field in the barrier [3]. During the off-state of AlGaN/GaN HEMTs, the gate is negatively biased and a very high electric field is applied across the AlGaN layer. This field can lead to device degradation by producing additional strain through the so-called inverse piezoelectric effect.

Based on our model for bare SBH in the AlGaN layers [3], we can divide the effects of barrier thickness into two regions – the unrelaxed region and partially relaxed region for each given Al content. Using this model, the effective reduction in strain present in the AlGaN layer can be calculated, as indicated in Fig. 3. This is a direct measure of the degradation of piezoelectric effect and the number of dislocations forming. The resultant reduction in total polarization versus the barrier thickness can also be calculated as shown in Fig.4. which is again a measure of device degradation.

As demonstrated above, measurements of the SBH will contain information about the internal structural state of the barrier layer, which relates closely to its structural reliability. Hence, SBH can be used as a performance metric for the reliability of AlGaN/GaN heterostructures, providing a quantitative measure of the structure degradation in the barrier layer. SBH can also be used as potentially, an important tool for characterization and assessment of device reliability following various stress conditions, such as after application of high electric fields and, in fresh devices, just after the growth of the barrier layer or after exposure of the device to extreme high temperatures extreme conditions, where SBH measurements can be used to search for signatures related to changes in effective polarization and residual strain.Likewise, the dependence of the surface donor level and surface donor density on temperature can be characterized this way to enable an enhanced power of predictability in our model.

In conclusion, we have presented a new modeling and characterization framework for assessing structural reliability in AlGaN/GaN heterostructures is presented, relying on measurements of the bare surface barrier height. Specifically, we have demonstrated how this framework can be utilized, together with experimental data, as a diagnostic and predictive tool for reliability assessment of these structures to characterize the post stress effects (both electrical and high temperature) for harsh environment conditions.

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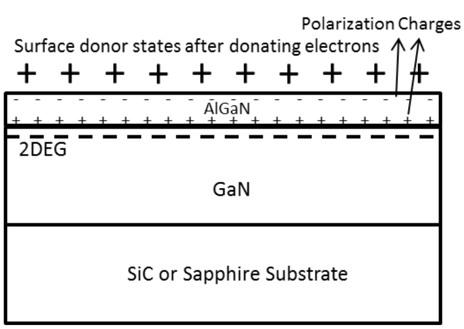

Figure 1 Typical structure of a AlGaN/GaN HEMT showing various charges at the different interfaces and illustrating the formation of 2DEG with electrons supplied by surface donor states.

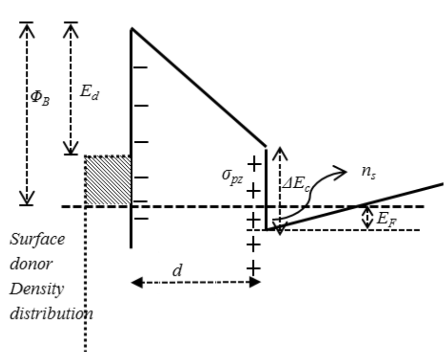

Figure 2 Band diagram of typical structure of a AlGaN/GaN HEMT. Φ_b is the surface barrier height (SBH).

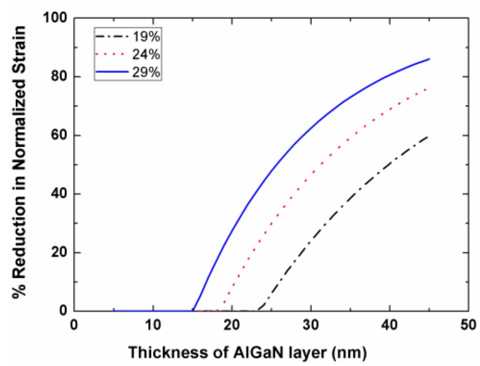

Figure 3 Calculated % reduction in normalized strain present in AlGaN layer for three different Al compositions. At large Al content, strain relaxation occurs at lower thickness and dislocations form to reduce strain energy

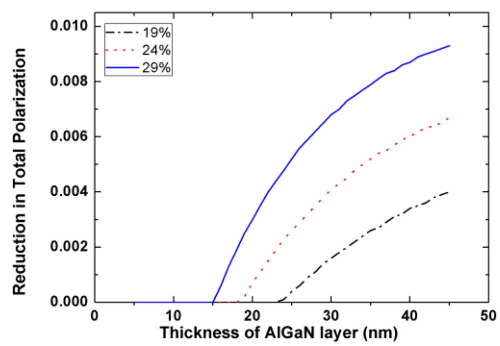

Figure 4 Reduction in effective total polarization in AlGaN layer versus thickness for different Al contents. Beyond the critical thickness, the piezoelectric polarization weakens owing to strain relaxation and the total polarization tends towards the spontaneous polarization value.