CHARGE CONTROL ANALYSIS OF GALLIUM NITRIDE SEMICONDUCTOR HETEROSTRUCTURES AND COMPARISON WITH GaAs HFET FAILURE MECHANISMS

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ABSTRACT

Conventional high electron mobility transistors (HFETs) based on AlGaN/GaN heterostructures have been accurately modeled and the results are described in this paper. The Schroedinger's equation and the Poisson's equation have been solved self-consistently in order to obtain a relationship between the sheet carrier density and the applied gate voltage. The relationship is treated using a non-linear exponential fit that enables a more accurate analysis of the saturation region compared to other models used hitherto.
Key words: charge control, transistors, gallium nitride, numerical simulation

1. INTRODUCTION

There are two important issues that govern the AlGaN/GaN high electron mobility transistors (HEMTs) which are significantly different from HEMTs made from structures such as AlGaAs/GaAs or InAlAs/InGaAs. The first has to do with the very strong piezoelectric effect present due to the lattice mismatch between AlGaN and GaN. It is known that group III nitrides have large piezoelectric constants along the (0001) direction. When (0001)-oriented thin AlGaN layers are grown pseudomorphically on a thick GaN, the biaxial strain induces a piezoelectric field in the material. As a result, there is a strong interface charge at the HEMT interface. The second effect has to do with interface roughness. Although this effect is present in other HEMT structures as well, the larger band discontinuity combined with larger effective mass in the channel makes interface roughness much more important in controlling the channel mobility. Additionally, the combination of interface roughness and piezoelectric effect can cause the charges at the interface to be distributed nonuniformly.

In fact, a unique feature of AlGaN/GaN material system is the high sheet carrier concentration (in the order of 1 x 10^{13} cm), which can be achieved in the channel not only due to the large bandgap discontinuity at the interface, but also due to the piezoelectric and spontaneous polarization effects without intentionally doping the barrier layer. Theoretical and experimental studies carried out by many researchers showed the effect of both spontaneous and piezoelectric polarizations on the carrier distribution at the hetero-interface, and the importance of proper inclusion of these effects in the analysis of III nitride structures.

In the area of device modeling, several theoretical models have been reported in the literature. One group of these models solves Poisson's equation coupled with Schrodinger's wave equation self-consistently using trial wave functions [1]. However, the treatment of the 2DEG was carried out in a similar way like that in AIGaAs/GaAs HEMTs, and the obtained results reflected only the difference in material systems of the two devices. Another group of models gives simple analytical formula for the sheet carrier density n_s versus the Al mole fraction x, for normally undoped HEMT structures including piezoelectric polarization effect. This formula was further modified to include the effect of both spontaneous and piezoelectric polarizations and doping of the barrier layer [2, 3]. In another attempt, an analytical expression for the Fermi-level versus ns and interpolation formulae for calculation of the polarization sheet charge density are given. Non-linear formulae for the polarization effects were incorporated into a quasi-2D model presented in, instead of the linear interpolations used before [4].

2. CHARGE CONTROL

A simplified numerical model to characterize the charge control in AlGaN/GaN HEMTs is given by using the basic phenomena of spontaneous and piezoelectric polarization as well as the ones used for estimation of their values. The model could explain the effect of spontaneous and piezoelectric polarization, the 3 -D free carriers, and the neutralized donors in the doped layer in the sheet charge calculations [1].

Numerical formulas have been developed to study the charge control and transport of AlGaN/GaN-based HEMT device. The charge control model is based on a self consistent solution of the Poisson equation and Schrodinger equation. Piezoelectric effect due to strain is modeled by including a polarization field. In examining transport in the two-dimensional channel, much of present understanding of transport in semiconductor devices depends upon the use of Born approximation and the independence of various scattering mechanisms. Scattering mechanisms such as ionized impurity scattering, interface roughness scattering, alloy scattering, etc. are handled within the Born approximation and are assumed to act independently. In many problems of interest, it is known that Born approximation is not valid but it is still used because of the complexity of the problem.

For the AlGaN/GaN system, our simulations show that there is considerable localization of low lying electronic states. While Born approximation becomes invalid under these conditions, the Kubo formula is used to study transport. The breakdown of Born approximation reflects itself in mobility increasing with temperature—a signature of hopping conductivity. At high temperatures, the Kubo formula and Born approximation give similar results. The temperature at which the two formalisms become equally valid depends on the interface roughness parameters. A very high sheet charge density can be produced due to the strong piezoelectric effect at the interface. The sheet charge density increases with increase in Al fraction in the barrier. The increase is primarily due to the higher piezoelectric charge. Solving the three- dimensional Schrodinger equation for the HEMT in presence of interface roughness shows that even a small amount of interface roughness causes localization of low lying electron levels. To study transport in such a system, the Kubo formula is used. The results of this model show that for strong interface roughness the mobility around 77 K is essentially independent of temperature and even shows a region where it increases with temperature.

3. PHYSICS OF FAILURE

High electron mobility transistors fabricated from nitride semiconductors utilizing the AlGaN/GaN heterojunction demonstrate excellent performance in RF range. However, the nitride devices demonstrate reliability problems where the dc current and RF output power continually decrease as a function of time. One of the reliability problems is related to the conduction characteristics of the gate electrode and an electron tunneling mechanism where electrons leak from the gate to the surface of the semiconductor. Although the degree of performance degradation varies with the design, processing steps, and device manufacturer, all high voltage AlGaN/GaN transistors are affected and the problem is more severe as operating frequency is increased. However, the more detailed study considers trap generations, trapping behaviors (regarding long-term and temporary recovery), and correlation between damage and trap density. The degradation mechanism also includes issues such as piezoelectric effects, tensile strain, and electron trapping, defect formation, aimed to predict electrical behavior of the device (Current Collapse, Power soak, DC and RF degradation). In the present work, the Poisson's and the Schroedinger's equations are solved self-consistently to obtain the wave functions, the eigenenergies and the carrier distribution at the hetero-interface. Calculations are performed for different gate biases to obtain a relationship between the carrier density and the applied gate voltage, in order to understand the above outlined failure mechanisms.

It should be noted that some investigations focus on showing the implementation of the deep-level effects in the device models. Therefore the charge control model provides a good physical understanding of HEMT operation and is easily applied to a wide variety of HEMT structures including pHEMT and multichannel HEMT. However, the conventional charge-control models are inadequate in characterizing the DX centers and substrate related phenomena. The new self-consistent charge-control models incorporating deep level effects can take into account DX centers, substrate trapping and strain in GaN HFETs. The conventional charge-control models are also insufficient to describe HFET's operation in a depletion-mode and near pinch-off.

4. REFERENCES

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