

Avalanche Multiplication in GaAs/GaN Heterostructures

- Problem Definition

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A non-local model by solving the simplified hydrodynamic energy-balance equation has been utilized to calculate the electron multiplication in GaAs/GaN heterostructures (*to be expanded*).

I. Introduction

The AlGaIn/GaN npn heterojunction bipolar transistors (HBT) are promising for high-power microwave applications due to the large bandgap energies of III-nitrides. But such HBTs suffer from the highly resistive p-GaN base layers and the difficulty in obtaining high-quality ohmic contacts on p-GaN. The AlGaAs/GaAs HBTs, on the other hand, have demonstrated excellent high-speed, high-current performance, thanks to the mature techniques of achieving both high-quality epitaxial materials and ohmic contacts. But they are limited by the low breakdown voltage due to the smaller bandgap energies and higher impact ionization rates of GaAs. Combining the advantages of both GaAs and GaN systems, the HBTs fabricated on AlGaAs(emitter)/GaAs(base)/GaN(collector) are expected to exhibit high-speed, high-power characteristics. Despite the almost impossible epitaxial growth of the entire device structures due to the large lattice constant mismatch between GaAs and GaN, n-AlGaAs/p-GaAs/n-GaN HBTs, formed by direct wafer fusion, have been demonstrated [1]. The conduction band discontinuity between the GaAs base and GaN collector forms a spike barrier blocking the electrons transporting into the collector. A setback layer of lightly doped GaAs inserted between the GaAs base and GaN collector will help pull down the electron barrier and as a result, increase the current gain. It has been recently reported that wafer fused AlGaAs/GaAs/GaN HBTs with 30 nm p-GaAs setback layers exhibit DC current gains of ~ 6-9 [2].

In HBTs operating at the forward active regime, avalanche breakdown is mainly attributed to the high electric field in the base-collector depletion region. If an electron has negligible energy before entering the depletion region from the base side, it needs to travel a certain distance, called dead space distance, to reach the threshold energy to induce impact ionization. In an AlGaAs/GaAs/GaN HBT without the setback layer, the depletion region in the heavily doped GaAs is so small that the electron can not have enough energy to induce impact ionization in GaAs and as a result the avalanche multiplication will be totally determined by the impact ionization in the GaN collector. The breakdown voltage will be improved greatly due to the low impact ionization rates of GaN. With a thin GaAs setback layer which is usually fully depleted, however, the electron can travel a longer distance and gain more energy before leaving GaAs and the probability of inducing impact ionization in GaAs is enhanced, reducing the avalanche breakdown voltage. Therefore, theoretical investigation

of the avalanche multiplication in GaAs/GaN base-collector regions is critical for optimizing the device structures.

This paper presents the theoretical calculation of the electron avalanche multiplication in GaAs/GaN base-collector heterostructures with/without setback layers of different dopant types and thicknesses. A non-local impact ionization model based on solving the simplified electron energy-balance equation is utilized to characterize the avalanche multiplication.

II. Model Description

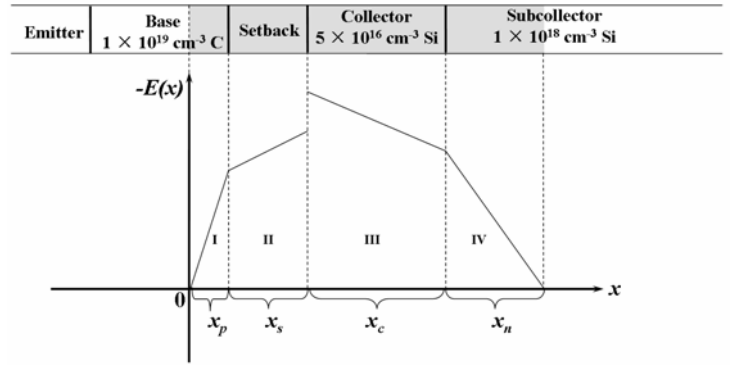


Fig. 1. Electric field profile in the base-collector depletion region. Region I, II, III and IV represent the depletion region in the base layer, the p- setback layer, the GaN collector and GaN subcollector respectively.

Fig.1 shows the electric field profile within the base-collector depletion region. Region I, II, III and IV represent the depletion region in the base layer, the p-setback layer, the GaN collector and GaN subcollector respectively. The setback layer and lightly doped GaN collector ($x_c = 0.5 \mu\text{m}$) are assumed to be completely depleted. Charge neutrality requires:

$$N_{ap}x_p + N_{as}x_s = N_{dc}x_c + N_{dsc}x_{sc} \quad (1)$$

Where $N_{ap}(x_p)$, $N_{as}(x_s)$, $N_{dc}(x_c)$ and $N_{dsc}(x_{sc})$ are the doping concentration (thickness) of the base depletion region, p-setback layer, lightly doped collector layer and subcollector depletion region, respectively. The slope of the electric field is determined by:

$$\frac{dE(x)}{dx} = \frac{q}{\epsilon_0 \epsilon_s} (N_d - N_a) \quad (2)$$

Where q is the electron charge, ε_0 is the vacuum dielectric constant and ε_s is the semiconductor dielectric constant which is 12.9 for GaAs and 8.9 for GaN. The sum of area I, II, III and IV is equal to the total potential drop on these regions:

$$-\int_0^{x_{dep}} E(x)dx = V_{in} + V_{BC} \quad (3)$$

Where V_{in} is the built-in voltage and V_{BC} the externally applied base-collector voltage, assuming all the applied voltage falls on the depletion region. The electric fields at the two sides of the GaAs/GaN interface follow the continuity boundary condition:

$$\varepsilon_{GaAs} E_{GaAs} = \varepsilon_{GaN} E_{GaN} \quad (4)$$

where ε_{GaAs} and ε_{GaN} are the dielectric constants of GaAs and GaN, and E_{GaAs} and E_{GaN} the electric field at the GaAs side and GaN side of the GaAs/GaN interface, respectively. By solving Equation (1) – (4), the electric field distribution as well as the thickness of the depletion region in the base and subcollector can be obtained.

In the local-field model, the impact ionization coefficient is related to the local electric field by:

$$\alpha(x) = A_e \exp\left[-\frac{B_e}{E(x)}\right]^k \quad (5)$$

$$\beta(x) = A_h \exp\left[-\frac{B_h}{E(x)}\right]^l$$

where α and β are the electron and hole ionization coefficient, respectively. This model is suitable for a slowly changing electric field. In the situation stated in this paper, however, the electric field varies very fast along x and the electron energy lags the local electric field, resulting in a significant non-local effect [3-7]. An effective electric field $E_{eff}(x)$ should be used to replace the local electric field in (5). $E_{eff}(x)$ can be obtained by [3]:

$$E_{eff}(x) = \frac{\Delta W(x)}{qv_s \tau} \quad (6)$$

where ΔW is the electron non-equilibrium energy. Following two assumptions [3]: the electron kinetic energy is much smaller than the thermal energy and heat flow is negligible, the electron energy-balance equation can be simplified to be:

$$\frac{d\Delta W(x)}{dx} + \frac{3}{5} \frac{\Delta W(x)}{v_s \tau} + \frac{3}{5} qE(x) = 0 \quad (7)$$

The solution to (7) is:

$$\Delta W(x) = \frac{3}{5} q \int_0^x E(\xi) \exp\left[-\frac{3(\xi-x)}{5v_s \tau}\right] d\xi \quad (8)$$

Then the electron multiplication can be calculated using [5]:

$$M_n - 1 = \frac{1}{1 - \int_0^w \alpha(x) \exp\left\{-\int_0^x [\alpha(\xi) - \beta(\xi)] d\xi\right\} dx} - 1 \quad (8)$$

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