Avalanche Multiplication in p-GaAs/n-GaN Heterojunctions

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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 p-GaAs/n-GaN heterojunctions which have much larger breakdown voltage (~ 360 V) than p-GaAs/n-GaAs homojunctions (~ 13 V). It is essential to optimize the thickness of the setback layer inserted to alleviate the electron blocking effect at the GaAs/GaN interface due to the conduction band misalignment. The thicker the setback layer, the more the interface electron barrier can be reduced, but the lower the breakdown voltage is. The impact ionization has negligible dependence on the setback dopant type.

I. Introduction

The AlGaN/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 p-GaAs/n-GaN base-collector heterojunctions 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

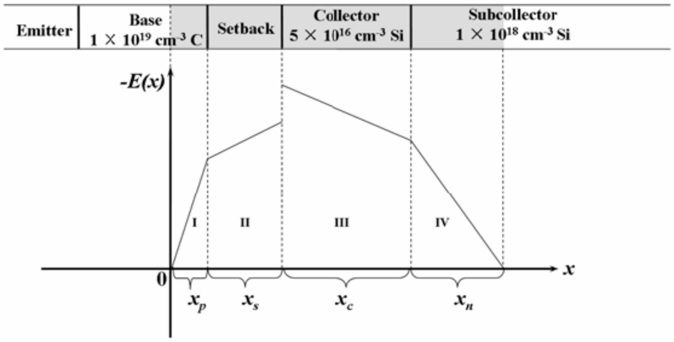


Fig. 1. Electric field profile in the base-collector depletion region. Region I, II, III and IV represent the depletion region in the base layer, the p- setback layer, the GaN collector and GaN subcollector respectively

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 μm) are assumed to be completely depleted. Charge neutrality requires:

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

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:

$$\frac{dE(x)}{dx} = \frac{q}{\varepsilon_0 \varepsilon_s}(N_d - N_a) \tag{2}$$

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:

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

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:

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

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:

$$\begin{aligned} \alpha(x) &= A_e \exp[-\frac{B_e}{E(x)}]^k \\ \beta(x) &= A_h \exp[-\frac{B_h}{E(x)}]^l \end{aligned} \qquad (5)$$

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]:

$$E_{eff}(x) = \frac{\Delta W(x)}{q v_s \tau} \qquad (6)$$

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:

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

The solution to (7) is:

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

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

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

III. Results and Discussions

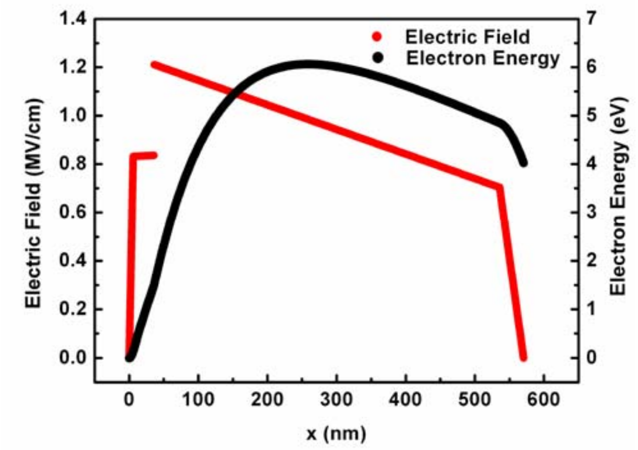
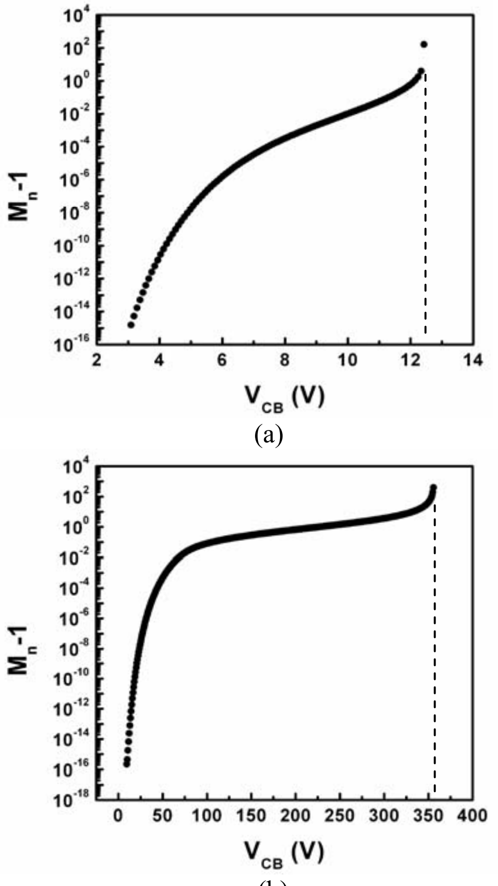


Fig. 2. Electric field and electron energy distributions in the depletion regions of the heterostructure shown in Fig. 1 with 30 nm p-GaAs setback at the reverse external bias of 50 V

Fig. 2 displays the calculated electric field and electron energy distributions in the depletion regions of the sample structures shown in Fig. 1 with 30 nm p-GaAs setback at the reverse bias of 50 V. It clearly indicates a lag between the maximum electron energy and the peak electric field. The calculated electron multiplication of a p-GaAs/n-GaAs homojunction and p-GaAs/n-GaN heterojunction is plotted in Fig. 3 (a) and (b), respectively.



(a)

(b)

Fig. 3. Calculated electron multiplication in (a) p-GaAs/n-GaAs homojunction and (b) p-GaAs/n-GaN heterojunction

By replacing the GaAs collector with GaN, the avalanche breakdown voltage is greatly improved, from ~ 13 V to ~ 360 V, due to the much smaller impact ionization rates of wider bandgap materials. However, an electron barrier appears at the GaAs/GaN interface produced by the conduction band misalignment. This barrier will block the electrons transporting into the collector and thus result in current gain reduction. By inserting a lightly doped setback layer between the highly doped p-GaAs base and n-GaN collector, the electron barrier is supposed to be pulled down and therefore more electrons are able to flow into the collector contributing to the collector current. Fig. 4 shows the simulated conduction band through the p-GaAs/n-GaN heterostructure without (black) /with (red) a 30 nm lightly doped p-GaAs setback layer.

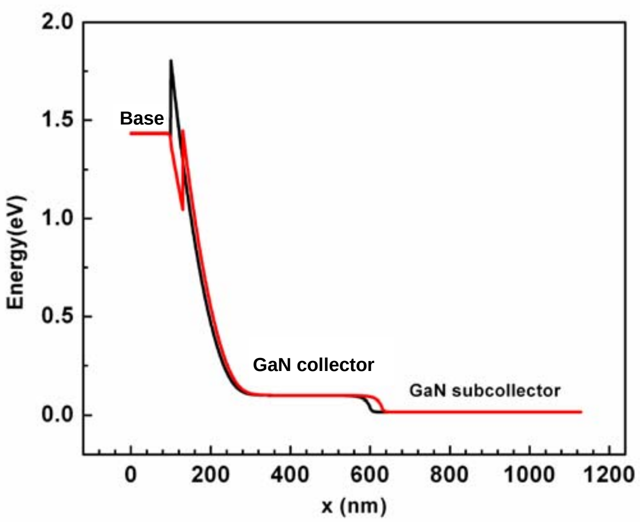


Fig. 4. Conduction band through the p-GaAs/n-GaN heterostructure without (black) /with (red) a 30 nm lightly doped p-GaAs setback layer

Though the current gain can be improved by insertion of a setback layer, the electrons within the depletion region now need to go through a longer distance in GaAs before reaching GaN. As a result, the probability of inducing impact ionization is enhanced which is dependent on the thickness of the setback layer since it can be fully depleted given the much lower dopant concentration (~ 10^{16} cm^{-3}) compared with the base (~ 10^{19} cm^{-3}). The thicker the setback layer is, the higher the chance of impact ionization is. On the other hand, the band diagram simulation indicates that the thicker the setback layer is, the more the interface electron blocking barrier can be pulled down. So a trade-off between breakdown and current gain must be satisfied. Fig. 5 plots the electron multiplication of p-GaAs/n-GaN with lightly doped p-GaAs setback of different layer thicknesses. It is seen that a setback of only 10 nm can reduce the breakdown voltage by a factor of 3. But such a thin setback layer can not yet efficiently remove the electron blocking effect at the GaAs/GaN interface. The band diagram simulation indicates that a setback layer of about 20 nm to 30 nm is needed to pull the interface energy spike peak down to the same level as the conduction band of the heavily doped p-GaAs base. Thorough experimental work is required to find the optimized device layer structure to obtain high breakdown voltage without largely decreasing the current gain. The dopant type of the setback layer does not matter in either the breakdown or current gain improvement, demonstrated at least by the theoretical analysis. Electron multiplication calculation has been carried out on the p-GaAs/n-GaN heteojunction with lightly doped n-GaAs setback of different layer thicknesses and shows the same breakdown condition as that with p-GaAs setback layers.

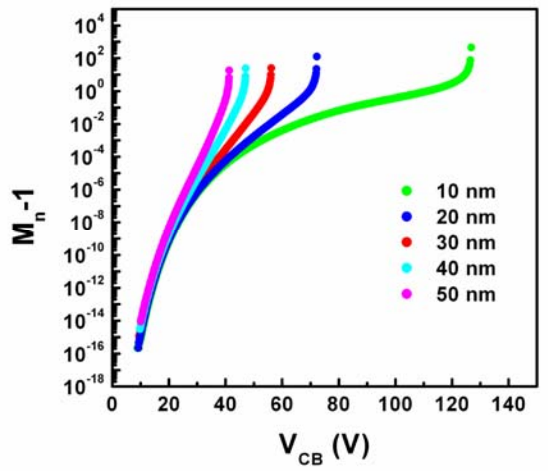


Fig. 5. Electron multiplication of p-GaAs/n-GaN with lightly doped p-GaAs setback of different layer thicknesses

IV. Conclusions

The electron multiplication of both p-GaAs/n-GaAs homojunctions and p-GaAs/n-GaN heterojunctions has been calculated using a non-local model. The avalanche breakdown voltage of AlGaAs/GaAs HBTs can be greatly improved by replacing the GaAs collector with GaN. The insertion of setback layers to remove the electron blocking barrier at the interface can increase the probability of inducting impact ionization and the thicker the setback layer, the higher the probability. The dopant type of the setback layer has negligible effects on the breakdown condition.

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