# Novel Base Doping Profile For Improved Speed and Power

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***Abstract* — We have experimentally studied the effect of two new base doping profiles on the base transit time of a GaAs npn heterojunction bipolar transistor. The doping in a region close to the collector is reduced either by a doping grade or a stepwise reduction. Quasi-electric fields resulting from these doping gradients increase the minority carrier velocity and the beta of large area transistors. By focusing these doping changes adjacent to the collector, the amount of low-doped base material and the resulting increase in base sheet resistance can be minimized. For both a step change in doping or graded doping change a 10% decrease in base transit time is achieved while only causing a 4 % increase in base sheet resistance. The impact on base transit time is confirmed with $f_T$ data on small area devices.**

## I. Introduction

The base transit time is an important factor influencing the overall speed of bipolar transistors. One method of decreasing the transit time is to grade the base doping from high at the emitter to low at the collector [1]. This produces a quasi-electric field accelerating the carriers across the base and lowering the base transit time. However, the doping grade has the undesirable effect of decreasing the average doping level of the base and increasing the base sheet resistance.

Several theoretical simulations of GaAs HBTs have identified doping profiles capable of significantly decreasing the base transit time [2]-[4]. Yet after considering the additional constraint of a constant base sheet resistance, it was found that a uniform base doping provides an optimal structure [5]. Two experimental studies have experimentally investigated doping grades in GaAs HBTs, both utilizing exponential doping grades [6]-[7]. The results were consistent with the theoretical work finding decreased transit time with increased base sheet resistance.

In this work, we have examined the impact of doping profiles on the base transport of GaAs HBTs. In particular this work examines concentrating the doping changes near the collector. A first set of samples is grown with a step doping change from $4.0x10^{19}$ $cm^{-3}$ to $2.5x10^{19}$ $cm^{-3}$ with the lowest doping adjacent to the collector. The position of this doping change within the base is varied within the sample set. The second sample set is similar but instead of a stepwise doping change a linear doping grade is used. The impact of these structures on the base sheet resistance and minority carrier velocity is studied.

## II. Experimental

The HBTs were grown by MOCVD. The HBT consists of a 5000 Å subcollector doped to $4x10^{18}cm^{-3}$, a 7000 Å collector doped to $1x10^{16}$ $cm^{-3}$, followed by the carbon doped base layer. A 500 Å InGaP emitter doped to $3x10^{17}cm^{-3}$ was deposited on the base followed by a 1000 Å emitter cap doped to $3x10^{18}cm^{-3}$, and finally a heavily doped InGaAs contact layer. The first sample set having the stepwise change in doping had a total base thickness of 920 Å while the graded doping samples have a thickness of 950 Å. The distance from the stepwise change in doping or the start of the doping grade to the collector is referred to as $X_L$.

Large area device fabrication used wet etching to define 75x75 $\mu m^2$ emitter devices. Current-voltage measurements were performed, and the low frequency gain (β) at a current density of 1 $kA/cm^2$ was measured. This current density is in the region where neutral base recombination limits β [8]. The base sheet resistance was obtained via a Van der Pauw pattern, which is used to evaluate the base doping.

Changes in the average electron velocity across the base layer have been calculated based upon changes in the β of large area devices. In the limit of neutral base recombination typically seen in GaAs HBTs, β can be related to the average electron velocity via:

$$\beta \simeq \frac{v\tau_{rec}}{w} \quad (1)$$

where $v$ is the average minority carrier velocity across the

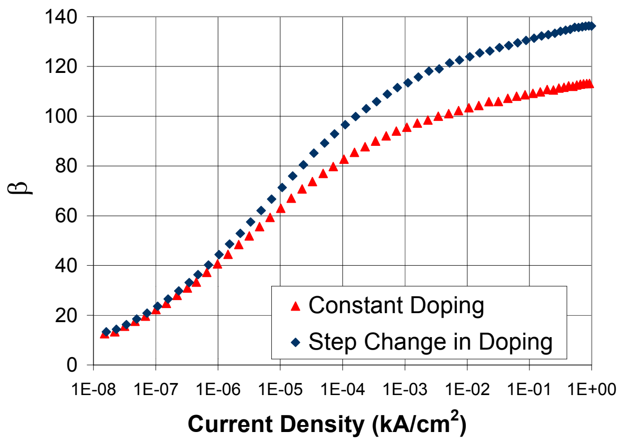


Fig. 1. The shape of the β versus current density curve is the same for uniformly and stepwise doped samples. β for the stepwise doped sample is increased 20% over the uniformly doped sample.

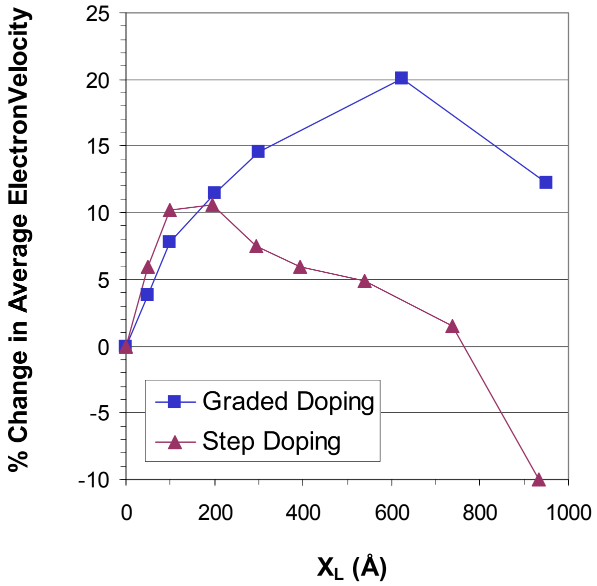


Fig. 2. Both step or graded doping profiles result in an increase in electron velocity. At a distance of 100 Å from the collector the structure with a stepwise change in doping has reached a maximum velocity. The average velocity of the doping grade continues to increase until 600 Å of a 950 Å base layer are graded.

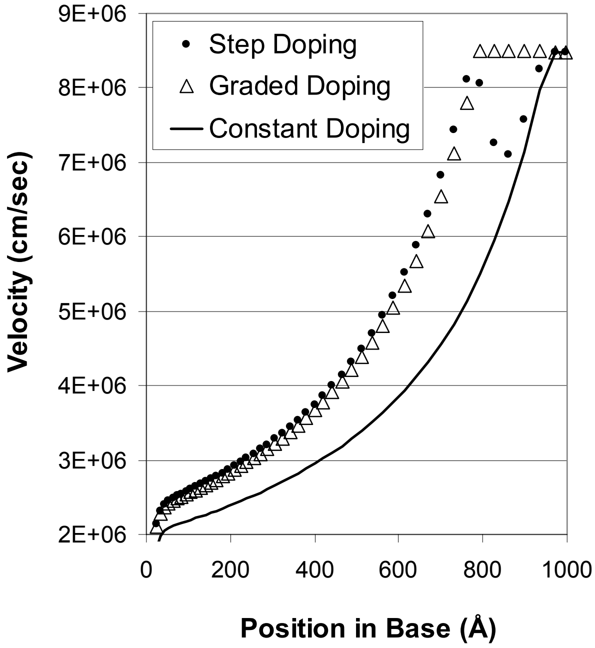


Fig. 3. SEDAN simulation of the minority carrier velocity across the base layer for the different base doping structures. $X_L$ was set to 200 Å with a 1000 Å base thickness in the simulations.

base, $\tau_{rec}$ is the minority carrier lifetime in the base, and $w$ is the base thickness. The recombination lifetime is well known to vary inversely with C-doping in modern GaAs HBTs [9], which is experimentally determined from the base sheet resistance.

## III. Results and Discussion

The result of the doping change is to increase β as shown in Figure 1. The step change in doping with $X_L$=200 Å increases β by 20%. The unchanged shape of the β versus current density curve indicates that only the neutral base recombination is effected. Additionally, Gummel and common emitter curves are unchanged as previously reported [10].

The change in average electron velocity for the two sample sets is plotted in Fig. 2. The initial point where $X_L$=0 Å is the structure with the base uniformly doped at a level of 4.0x10$^{19}$ cm$^{-3}$. The final point of the set with the stepwise doping change has a base uniformly doped at a level of 2.5x10$^{19}$ cm$^{-3}$. Both the step and graded doping profiles result in an increase in average velocity as $X_L$ increases from 0. The stepwise doping change results in a larger velocity than the graded samples for $X_L$ < 200 Å. A maximum velocity is reached when $X_L$ = 100 Å for the step doping change structure. The graded doping samples continue to increase in velocity as $X_L$ increases to 600 Å.

The effect of the change in base doping is to set-up a quasi-electrical field accelerating the carriers. This forms a drift current in addition to the diffusion current already present. Device simulations using SEDAN were used to gauge the effect of the doping changes on the carrier transport [11]. These results are summarized in Fig. 3. The stepwise change in doping and the graded doping accelerate the carriers to the saturation velocity. The stepwise change in doping creates a very localized quasi-electric field and the carriers slow to conventional velocities after the doping change. The graded doping maintains the carriers at the saturation velocity until entering the collector.

The high electron velocity in the presence of the electric field necessitates a low electron carrier concentration due to the continuity equation :

$$J = qnv \tag{2}$$

where q is the electron charge and n is the electron concentration. The doping change lowers the electron concentration locally, increasing the electron gradient prior to the doping change. This increases the velocity of the carriers diffusing from the emitter to the doping change. When $X_L$ is small this factor is particularly important, as the carriers are accelerated over most of the base layer.

To be technologically useful Ref. 4 illustrates how an increase in average velocity needs to be accomplished with a minimal an increase in base sheet resistance. Fig. 4 plots the percent change in average velocity versus the percent change in base sheet resistance. As expected the stepwise change in doping has a larger increase in base sheet resistance than the samples with a graded base doping. By concentrating the doping change into the 200 Å adjacent to the collector the base sheet resistance increases a minimal 5 %, whereas grading the full 1000 Å base width results in a 25 % increase in base sheet resistance. Both structures, however, result in similar increases in average velocity of 12 %. This is the

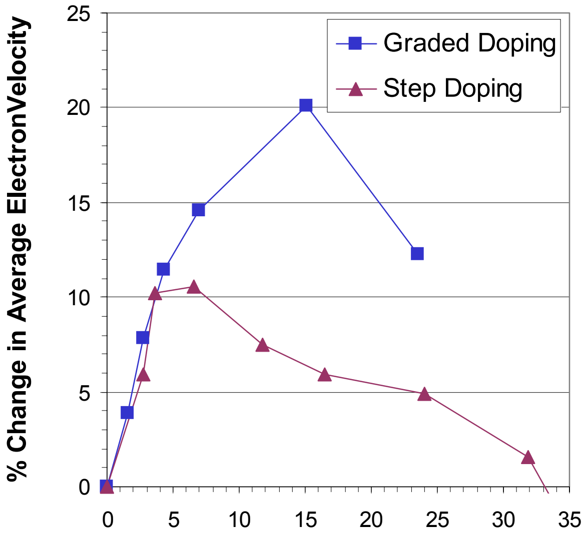


Fig. 4. Both step or graded doping profiles result in an increase in electron velocity. At a distance of 100 Å from the collector the structure with a stepwise change in doping has reached a maximum velocity. The average velocity of the doping grade continues to increase until 600 Å of a 950 Å base layer are graded.

advantage of structures where an accelerating field is concentrated near the collector.

The velocity increase with either doping structure is similar for $X_L \leq 200$ Å. Both yield a 10 % increase in average velocity for a 4 % increase in base sheet resistance.

RF measurements were carried out on small area devices processed at Skyworks Solutions. The samples with graded doping having $X_L$ = 100 Å and 200 Å were processed and compared to a sample with constant doping. The unity gain cut-off frequency, $f_T$, of these samples is plotted in Fig. 5. This plot shows an increase in $f_T$ as the 100 Å doping grade is introduced, and then increased still further when it is extended to 200 Å. An increase in $f_T$ of 3 % for the sample with 200 Å of dopant grading is consistent with the 12 % increase in average velocity across the base when combined with the other transit times in the structure. This is accomplished with a minimal 4 % increase in base sheet resistance.

## IV. Conclusion

This work has shown the impact of base doping changes adjacent to the collector, whether a step change or graded. Similar velocity increases result when the entire 950 Å base has a doping grade or when only the 200 Å adjacent to the collector are graded. However, the short doping grade is able to keep a low base sheet resistance necessary for many applications.

Both doping profiles yield similar results where the base transit time can be reduced 10 % while only increasing the base sheet resistance 4 %. This is a result of the drift field, while confined to a small region adjacent to the collector, acts to increase the diffusion velocity of carriers across the majority of the base layer thickness.

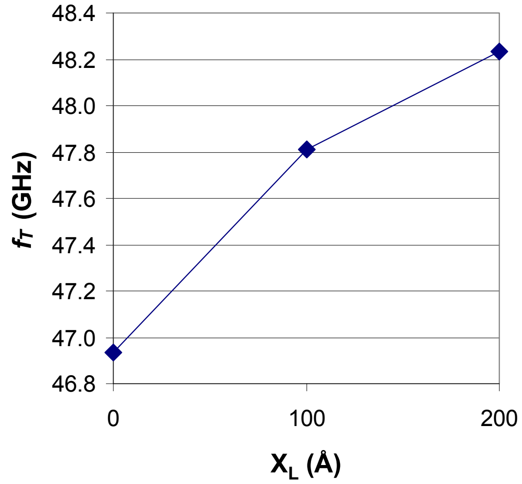


Fig. 5. The decrease in base transit time observed in beta is confirmed with increases in $f_T$ as the base doping is graded over 100 Å and 200 Å adjacent to the collector.


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