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Graded collector heterojunction bipolar transistor

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A graded collector heterojunction bipolar transistor is proposed. The graded collector improves device speed performance at high current densities by reducing the influence of the Kirk effect.

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Heterojunction bipolar transistor (HBT) has attracted considerable attention recently primarily due to its predicted capability of ultrahigh speed performance and the rapid advancement in new crystal growth technologies such as molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOC VD).[1-3] The extra degree of freedom in device design provided by the use of heterojunctions has opened up new realms of device performance. Very impressive speed performance has been predicted for HBT's, and transistors with cut-off frequency f_T of 15 GHz have been demonstrated.[4] To improve device performance, Kroemer has suggested the use of a graded band-gap base transistor, utilizing the built-in electric field to reduce the base transit time.[5] Drift velocity in graded gap $\mathrm{Ga}_{1-x}\mathrm{Al}_x\mathrm{As}$ has been measured[6] and a graded gap bipolar transistor has been demonstrated recently.[7] However, for devices with very thin base, the base transit time is usually not the limiting factor. Fast switching and microwave transistors ordinarily operate at very high current densities ($\sim 10^4$ A/cm^2) in order to reduce the emitter depletion layer charging time.[8] In such transistors, it is also desirable to have lightly doped collectors for small collector capacitance (C_c), thus reducing the $R_b C_c$ time constant (where R_b is the base resistance). However, if the collector doping is low, base push-out (Kirk) effect[8,9] occurs when the collector current density J_c exceeds the value $eN_c v_{\mathrm{sat}}$ where N_c is the collector doping density and v_{sat} is the saturation velocity of the carrier. At the onset of the Kirk effect, the effective "base" becomes wider, giving rise to a larger emitter-base diffusion capacitance, resulting in longer switching delay and lower f_T. Therefore, when the base stretches, further increase in current density leads to longer switching time, and the base push-out effect becomes the limiting factor in transistor performance.[10,11] In this case, grading the base alone is insufficient. To combat the Kirk effect, one can either increase the collector doping level or employ a very thin collector,[11] but both of these lead to a larger C_c.

In this letter, we propose a graded collector HBT so that at high current densities, part of the extended base will be graded, thereby reducing the electron transit time. For a clearer comparison with the ordinary homojunction transistors to demonstrate the advantage of grading the collector, the base is left ungraded. In practice, the base can also be graded, but for devices with very thin base, the base transit time is not the limiting factor. Figure 1 shows the band diagram of the proposed structure at thermal equilibrium. The entire low doped collector is graded from higher band-gap GaAlAs to GaAs, thus providing an additional built-in electric field large enough to drive the electrons at their saturation velocity. Thus, even when the effective base becomes wider at high current densities, this built-in field maintains the electron velocity and thus the total delay due to base and collector depletion layer transit time remains almost constant as the base stretches. The total emitter to collector delay time therefore decreases as J_c increases, thereby eliminating the undesirable degradation in speed due to the Kirk effect. It should be pointed out the desired result could also be obtained in a nongraded device by increasing the doping level in the collector and applying a higher base-collector voltage. However, this would lead to higher power-delay product. This is thus an important advantage of the graded collector transistor in digital switching circuits. It should also be mentioned that the proposed structure is suitable for nonsaturation logic. For saturation logic, Kroemer[2] proposed the use of a wide gap collector for suppressing the hole

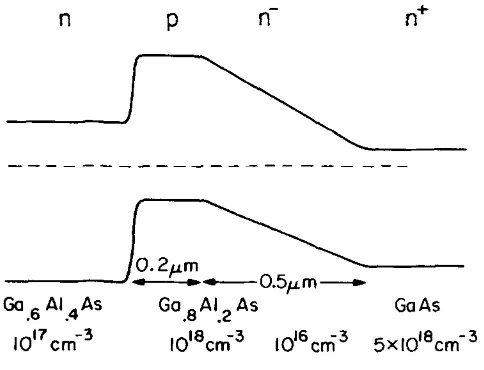

FIG. 1. Band diagram of the proposed graded collector heterojunction bipolar transistor at thermal equilibrium.

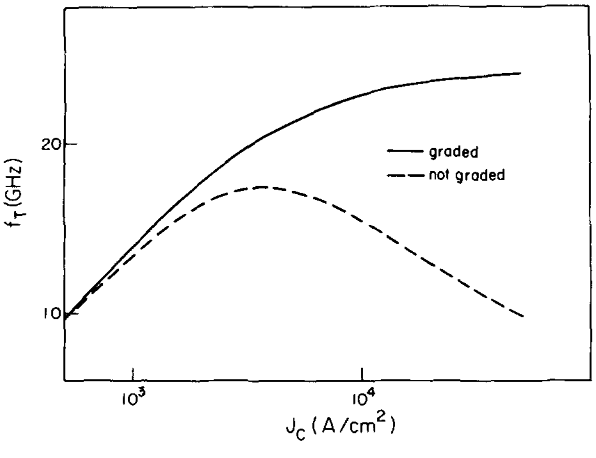

FIG. 2. Comparison of the cutoff frequency f_T for transistors with and without a graded collector.

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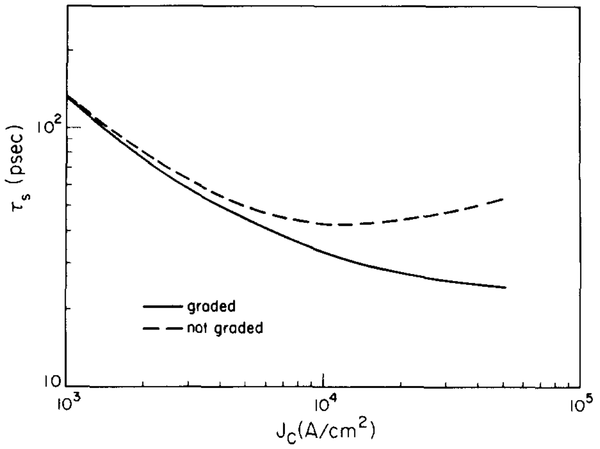

FIG. 3. Estimated switching delay time for transistors with and without a graded collector.

injection into the collector. In nonsaturation logic, wide gap collectors are, however, not suitable for high current density high-speed operation due to the base push-out effect.

A rigorous solution to the problem requires a numerical solution to the field and carrier transport equations.[9] However, to demonstrate the effect of the graded collector, the method adopted by Kirk[8] is used to provide an estimate and trend of the delay time. The dimensions and doping levels of the epitaxial layers are indicated in Fig. 1. The emitter is chosen to be the wide gap material of $Ga_{0.6}Al_{0.4}As$, and the base $Ga_{0.8}Al_{0.2}As$, taking full advantage of the flexibilities offered by a wide gap emitter.[2] The entire 0.5 μm of the n^- part of the collector is graded linearly from $Ga_{0.8}Al_{0.2}As$ to GaAs. This provides a built-in field of ~4 kV/cm, sufficient to achieve high electron drift velocities, which is taken to be constant. A conservative value of $v_{sat} = 10^7$ cm/s is used. The base-collector applied voltage is taken to be 0.4 V, and the entire n^- region is depleted at this voltage.

Figure 2 shows a comparison of the estimated f_T for the homo-base-collector and the graded collector transistors. The advantage offered by the graded collector can be seen to be quite significant. A comparison of a two-stage switching delay time estimated using the formula derived by Solomon[12] is shown in Fig. 3. Here again, the influence of the Kirk effect and the advantage offered by the graded collector is apparent. The velocity overshoot and possible near ballistic electron transport in GaAs has not been taken into account. To take full advantage of the high transient electron velocities possible in GaAs, abrupt heterojunctions can be used for launching hot electrons, but the dimension and structure of the device must be carefully designed. Use of the velocity overshoot effect in structures with abrupt heterojunctions will not be discussed in the present work.

In summary, a novel way to avoid the decrease in f_T and increase in switching delay time in high-speed HBT operating under high current densities due to the Kirk effect is proposed. The present scheme involves grading the collector of the transistor; preliminary estimates show that the graded collector offers substantial improvement in device performance.

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