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Base-Emitter-Injection Characterization in Low-Temperature Pseudo-Heterojunction Bipolar Transistors

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Carrier injection characteristics in the pseudo-heterojunction biolar transistor, the basic homojunction structure for low-temperature operation, is clarified both theoretically and experimentally. It is found that a novel, low-concentration external-base structure completely rejects carrier injections and selectively injects electrons into the intrinsic base at low temperatures. The analysis reveals that the low-temperature bipolar transistor has a very small emitter- and external-base charging time, which enables excellent vertical and horizontal scalability far superior to that of conventional room-temperature transistors.

I. INTRODUCTION

The limiting factors that are inherent in scaled Si bipolar transistors have begun to affect the actual performance. These factors, which include emitter efficiency reduction, increased base-resistance, and emitter-base tunnelling current, have motivated research on Si heterojunction bipolar transistors (HBTs) [1,2]. Moreover, wiring resistance, electromigration, and emitter peripheral current[3] also severely limit bipolar scaling.

In spite of these limitations, the Si bipolar transistor is still expected to be the dominant very-high-speed device due to its current drive capability and a small transit time that is independent of the lithographic capability. The recent prominence of BiCMOS-technology provides additional motivation for the improvement of homojunction-transistor performance.

In spite of several previous efforts [4,5], any meaningful advantage which would offset the increased cost of cooling has not been found in the low-temperature operation of conventional homojunction bipolar transistors. However, the authors have found that at low temperatures the homojunction is capable of bahaving exactly like a heterojunction, due to the strong bandgap narrowing effect. We have demonstrated that this "pseudo-heterojunction effect" can be used in a novel narrow-bandgap-base bipolar transistor, named pseudo-HBT [6,7], which has the potential for extending the conventional room-temperature limitations.

In this work, the carrier injection characteristics of pseudo-HBTs are both theoretically and experimentally quantified to clarify the potential superior scalability of low-temperature transistors. Emphasis was placed on the unique property of selective carrier injection into a heavily doped base region at low-temperatures and its impact on bipolar-transistor scaling.

II. THEORETICAL CHARACTERIZATION OF LOW-TEMPERATURE CARRIER INJECTION

The crucial phenomena which constrain scaled bipolar-transistor performance are:

1) Backward hole injection into the emitter
2) Peripheral electron injection into the external base

The prominent feature of low-temperature operation is its ability to build a barrier against the above mentioned undesirable injections, utilizing the "pseudo-heterojunction effect". The two injections are characterized by the respective parameters h_{FEO} and n_{Bint}/n_{Bext}, defined as

$$h_{FEO} = n_{Bint}/p_E = n_E/p_{Bint} \cdot \exp\{ (\Delta E_{Bint} - \Delta E_E)/kT \} \qquad (1)$$

$$n_{Bint}/n_{Bext} = p_{Bext}/p_{Bint} \cdot \exp\{ (\Delta E_{GBint} - \Delta E_{GBext})/kT \} \quad (2)$$

where subscript $_E$, $_{Bint}$, and $_{Bext}$ denote emitter, intrinsic base, and external base, respectively, n and p denote the electron and hole concentrations, and ΔE_G denotes the bandgap narrowing. The calculated results (Figs. 1 and 2), which consider the influence of the bandgap narrowing effect [8], carrier freezeout, impurity-level shift due to screening, and Mott transistion, clearly demonstrate that the above injections are significantly suppressed at 77 K by a novel impurity profile: a low-concentration emitter, a heavily-doped intrinsic base, and a low-concentration external base. For example, when the transistor has the intrinsic base of $5\times10^{19}/cm^3$ and the external base of $5\times10^{17}/cm^3$, the value of n_{int}/n_{ext} is as high as 1000, as shown in Fig.2. Therefore, the electrons are expected to be very selectively injected into only the intrinsic base in this structure. Note that this impurity profile is completely opposed to the conventional design principle. The low-concentration external base can be placed between the emitter and the high-concentration external base without increasing the base resistance. At room temperature, the value of h_{FEO} and n_{Bint}/n_{Bext} are small in any impurity profiles and will decrease further with increased base concentration, as shown in Figs. 1 and 2. This is the unfavorable aspect of scaling at room temperature.

III. EXPERIMENTAL CHARACTERIZATION OF CARRIER INJECTION

To verifiy the selective property of injection into the heavily doped region at low temperatures, the experimental upward Si pseudo-HBT shown in Fig. 3 was fabricated. It has a moderately doped n-type emitter region (P: $1.5\times10^{18}/cm^3$), which faces both a moderately doped p-type base region (B: $6\times10^{18}/cm^3$) and a heavily doped p-type base region (B: $1\times10^{20}/cm^3$).

The selective injection was verified by observing two characteristics:

1) Activation-evergy change of the injection current gain
2) Exponential temperature dependence of the ratio of peripheral current to bottom current

The injection current gain h_{FEinj} is defined as the ratio of electron current to hole current when the recombination current is excluded [7]. The measured temperature dependence of h_{FEinj} (Fig. 3) fits very well with the sum of two straight lines having different activation energies. The two activation energies coincide within a 10-meV accuracy to the two base regions' bandgap narrowing data, which was obtained using Slotboom's formula at room temperature. This clearly proves that the electron-injection region shifts from the low-concentration base region to the heavily doped base region at about 150 K (T_R).

This shift of the injection region is also observed directly by the area dependence of the collector current. The ratio of injected current density into the p^+ base to that into the p base region is estimated by the area dependence and increases exponentially with decreasing temperature (Fig. 4). The activation energy, which corresponds to the bandgap difference between the p^+ base and the p base, also coincides to the reported data. Therefore, at low temperatures below 150 K almost all electrons are proved to be selectively injected into the heavily doped region.

IV. IMPACT OF LOW-TEMPERATURE OPERATION ON BIPOLAR SCALING

Backward hole injection and external electron injection cause additional minority carrier storage time: emitter transit time τ_E and external-base transit time τ_{Bext}. Thus the transit time due to the diffusion capacitance is expressed as

$$\tau_{dif} = \tau_B + \tau_E + \tau_{Bext} \quad (3)$$

Each term can be expressed as

$$\begin{aligned} \tau_B &= W_B^2/(2D_n), \\ \tau_E &= W_E^2/(2D_P \cdot h_{FE}), \quad (4) \\ \tau_{Bext} &= W_{Bext} \cdot W_B \cdot W_E \cdot n_{Bext}/(2D_n \cdot X_E \cdot n_{Bint}) \end{aligned}$$

where, W_E, W_B, and W_{Bext} are the thicknesses of the respective emitter, intrinsic base, and external base, D_n and D_P are the electron and hole diffusion constants, h_{FE} is the current gain, and X_E is the emitter width. Assuming that the horizontal and vertical scaling must be such that the current gain and the base sheet resistance are at least constant with reducing dimensions, equation (3) can be simplified to

$$\tau_{dif} \fallingdotseq \tau_B \cdot [1 + C \cdot W_B^{-0.6}] \quad (300\ \mathrm{K})$$
$$\fallingdotseq \tau_B \quad (77\ \mathrm{K}) \qquad (5)$$

As shown in Fig. 5, with decreasing vertical and horizontal dimensions, both τ_E and τ_{Bext} will not decrease as rapidly as the τ_B at room temperature, showing considerable contribution to the total τ_{dif} in the sub-100-nm regime. This is because the emitter thickness cannot be reduced as quickly as the base thickness to meet the above conditions. By contrast, at low temperatures, both τ_E and τ_{Bext} are negligibly small compared with τ_B. Therefore, τ_{dif} is almost proportional to the square of W_B, enabling a transit time four times shorter than that at room temperature in the 10-nm-base transistor. Therefore, the low-temperature bipolar transistor offers scalability far superior to that of room-temperature transistors.

V. CONCLUSIONS

Carrier injection characteristics in the pseudo-heterojunction bipolar transistor were theoretically and experimentally clarified. It was shown that a novel external-base structure with a low-concentration external base selectively injects electrons into the intrinsic base at low temperatures. The low-temperature bipolar transistor offers negligibly small emitter- and external-base-charging times, showing excellent vertical and horizontal scalability far superior to that of room-temperature transistors.

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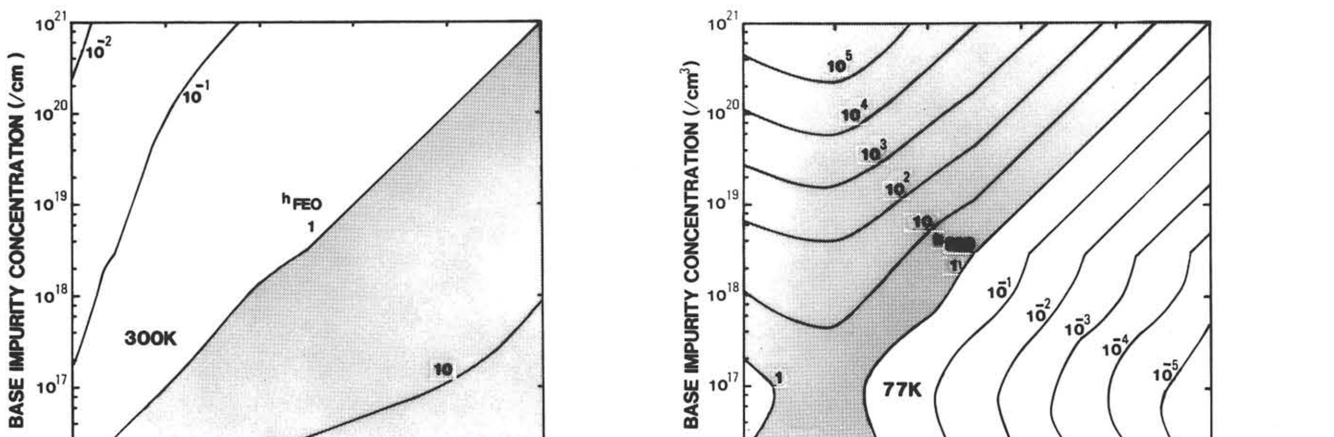

Fig. 1 The calculated dependence of current gain h_{FEO} (see eq.1) on the emitter and base impurity concentrations. The condition of $h_{FEO}>1$ is indicated by the shaded regions.

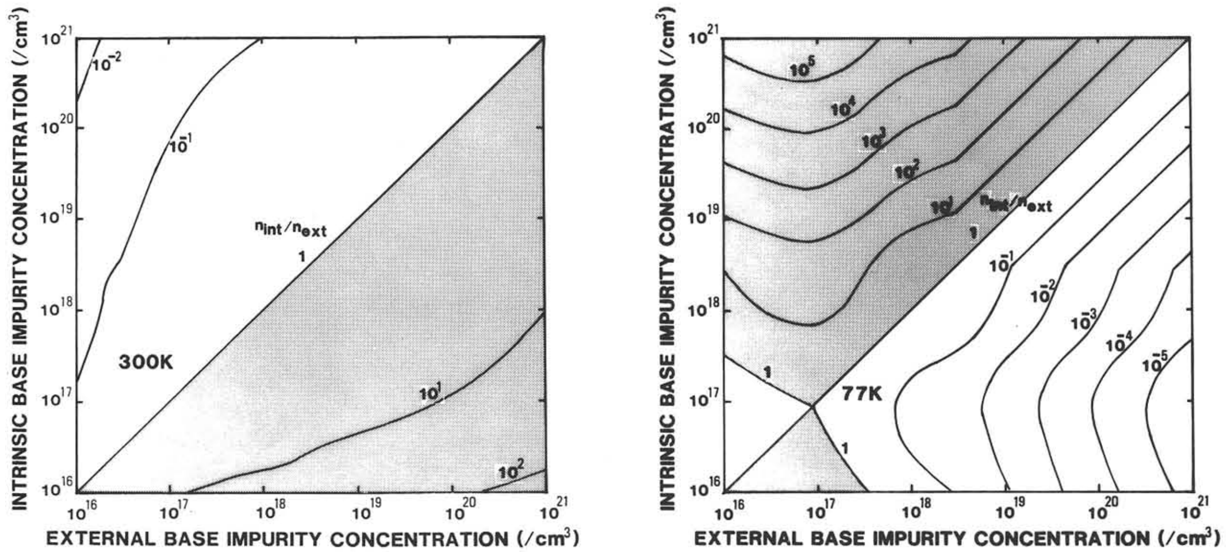

Fig. 2 The calculated ratio of electrons injected into the intrinsic base to electrons into the external base and the dependence of this ratio on the intrinsic-base and the external base impurity concentrations. The condition of $n_{Bint}/n_{Bext}>1$ is indicated by the shaded regions.

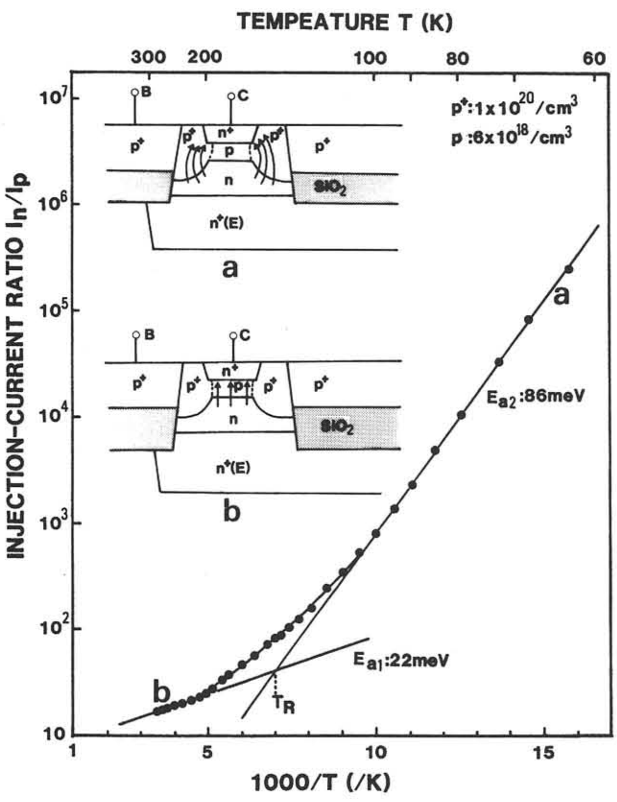

Fig. 3 The Arrhenius plot of the measured injection current gain. The inserts show schematic cross section of the measured pseudo-HBT. At temperatures over transition temperature T_R, the electrons are injected into the p-base region, whereas at temperatures below T_R the electrons are injected into p^+-base region.

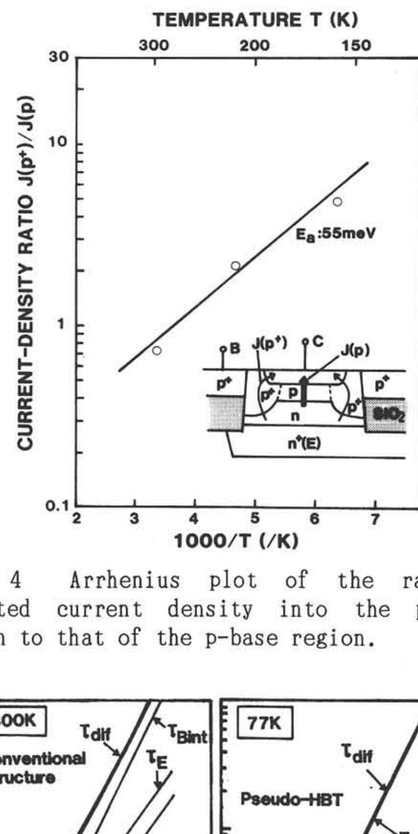

Fig. 4 Arrhenius plot of the ratio of injected current density into the p^+-base region to that of the p-base region.

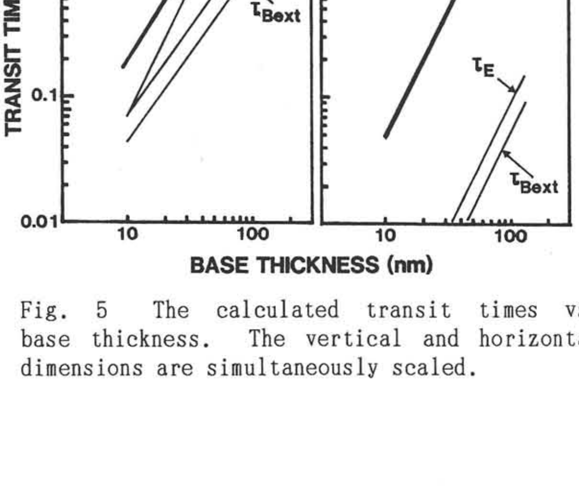

Fig. 5 The calculated transit times vs. base thickness. The vertical and horizontal dimensions are simultaneously scaled.