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Current Gain-Early Voltage Products in Heterojunction Bipolar Transistors with Nonuniform Base Bandgaps

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Abstract—**The trade-off between common-emitter current gain β and Early voltage V_A in heterojunction bipolar transistors (HBT's) where the bandgap varies across the base has been studied. The Early voltage depends exponentially on the difference between the bandgap at the collector side of the base and the largest bandgap in the base, allowing very high Early voltages with only very thin narrow bandgap regions. Using Si/Si$_{1-x}$Ge$_x$/Si HBT's with a two-layer stepped base, βV_A products of over 100 000 V have been achieved for devices with a cutoff frequency expected to be about 30 GHz.**

I. INTRODUCTION

TO DATE, Si/Si$_{1-x}$Ge$_x$/Si heterojunction bipolar transistors (HBT's) have been used primarily to increase the performance of digital circuits. In this paper we show that a significant performance increase can be expected for analog circuits as well. In these applications the product of common-emitter current gain and Early voltage, βV_A, is an important figure of merit. Analytical expressions are developed to show that thin narrow bandgap layers near the base-collector junction give rise to very large Early voltages with negligible effect on gain. This concept is then used to achieve βV_A products of over 100 000 V in Si/Si$_{1-x}$Ge$_x$/Si HBT's.

II. THEORY

The Early effect in bipolar transistors is the increase of collector current with collector-base voltage V_{CB} caused by the decrease of the neutral base width W_B [1]. It leads to a finite output resistance, commonly characterized by the Early voltage V_A:

$$V_A = J_C \frac{\partial V_{CE}}{\partial J_C} - V_{CE} \approx J_C \frac{\partial V_{CB}}{\partial J_C} \tag{1}$$

where V_{CE} and J_C are collector-emitter voltage and collector current density, respectively. For homojunction transistors, charge control theory gives the dependence of β and V_A on base charge Q_B [2]:

$$\beta \propto 1/Q_B \tag{2a}$$

$$V_A = \frac{Q_B}{C_{BC}} = \frac{q}{C_{BC}} \int_0^{W_B} p(x)\, dx \tag{2b}$$

where $p(x)$ is the majority-carrier concentration in the base and C_{BC} is the base-collector capacitance. Hence, for a given C_{BC}, which is usually determined by the lightly doped collector, there is a fundamental trade-off between V_A and β, and βV_A is fixed. These simple relationships can be generalized in the case of an HBT where the bandgap can vary across the base. For this case the collector current density can be calculated assuming low-level injection and an absence of hot-electron effects [3]:

$$J_C = q \left(\int_0^{W_B} \frac{p(x)}{n_i^2(x) D_n(x)}\, dx \right)^{-1} e^{\frac{qV_{BE}}{k_B T}}. \tag{3}$$

The integral is taken over the neutral base region, and n_i and D_n are intrinsic carrier concentration and minority-carrier diffusion coefficient, respectively. If the base current is caused only by hole injection from base into emitter, as in $J_B = J_{B,0} \exp(qV_{BE}/k_B T)$, and all dopant atoms are ionized ($p = N_A$), current gain and Early voltage can be calculated from (1) and (3):

$$\beta = \frac{q}{J_{B,0}} \left(\int_0^{W_B} \frac{N_A(x)}{n_i^2(x) D_n(x)}\, dx \right) \tag{4a}$$

$$V_A = \frac{q n_i^2(W_B) D_n(W_B)}{C_{BC}} \left(\int_0^{W_B} \frac{N_A}{n_i^2 D_n}\, dx \right) \tag{4b}$$

Note that n_i^2 depends exponentially on the bandgap of the semiconductor material. The integral in brackets will be dominated by the region with the smallest n_i^2, i.e., the largest bandgap. The gain, therefore, depends most significantly on the largest bandgap in the base, while V_A depends exponentially on the difference between the largest bandgap in the base and that at the collector edge of the base region. The βV_A product, however, is independent of the actual base profile and depends to first order only on n_i^2 (or the bandgap) at the collector edge of the base:

$$\beta V_A = \frac{q^2}{J_{B,0} C_{BC}} n_i^2(W_B) D_n(W_B). \tag{5}$$

$J_{B,0}$ is a property of only the emitter, and for light collector doping C_{BC} is also independent of the base profile.

As an example, consider Si/Si$_{1-x}$Ge$_x$/Si HBT's. In these

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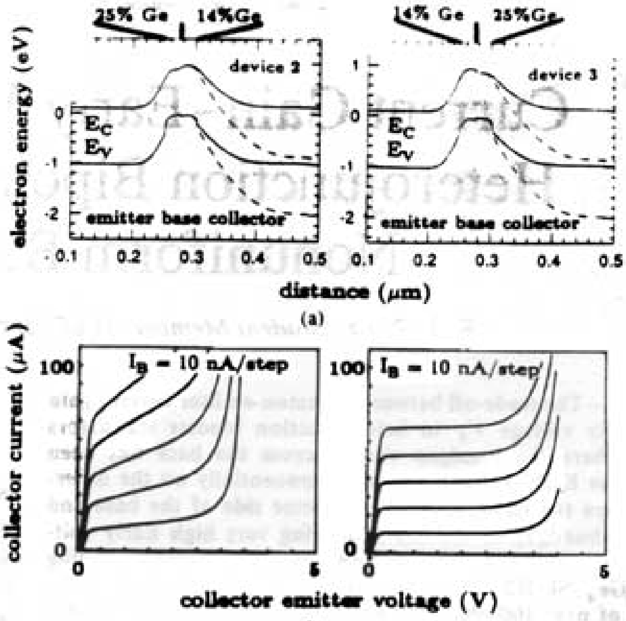
devices, the base bandgap decreases with increasing Ge concentration. For HBT's with a flat Ge profile in the base, V_A should be the same as in a Si homojunction device, but β is increased by a factor $n_i^2(\mathrm{SiGe})/n_i^2(\mathrm{Si})$ because of the lower barrier for electrons (note that $J_{B,0} \propto n_i^2(\mathrm{Si})$). The band diagrams in Fig. 1(a) show two extreme cases for the position of the highest barrier for electrons relative to the edge of the base-collector depletion region in the base: in device 2 the highest barrier is at the base-collector junction, and its width is affected by a change in V_{CB}. This should result in a low Early voltage similar to that of a HBT with a flat Ge profile in the base. Device 3 has the highest barrier removed from the base-collector junction. A change in V_{CB} has little effect on the width of the electron barrier, and should result in a high Early voltage.

III. Experimental Results and Discussion

Si/SiGe/Si HBT structures with various base germanium profiles were grown by rapid thermal chemical vapor deposition, and devices processed as described in [4], except that base and emitter implants were annealed at 700°C for 30 min. All devices had identical emitter and collector layers. The bases consisted of two nominally 200-Å-thick SiGe layers with constant Ge profile and boron doping of about 10^{18} cm^{-3}, as shown in Table I, to correspond to the structures of Fig. 1. On both sides of the base, nominally 40-Å-thick intrinsic SiGe spacer layers were inserted to remove spike-and-notch and outdiffusion effects [5]. The base currents of all devices had ideality factors between 1.0 and 1.2 with a $J_{B,0}$ of about 4 pA/cm^2, except device 4 which had a $J_{B,0}$ of 10 pA/cm^2 leading to a smaller gain than expected. Fig. 1 shows calculated band diagrams and measured collector current characteristics for devices 2 and 3. Current gains and Early voltages were determined at a reverse bias of $V_{CB} = 0.5$ V, where all devices had a C_{BC} of about 55 nF/cm^2 (see Table I). Device 1 had about half the gain of devices 2 and 3, because its barrier was twice as thick. The βV_A's of devices 1 and 2 were similar, because they had the same Ge concentration at the base-collector junction. Device 3 had a vastly increased Early voltage compared to device 2 and similar gain, leading to a βV_A of over 100 000 V. This is expected because the highest part of the electron barrier was moved away from the base-collector depletion region edge. Collector current characteristics were also measured in reverse mode, i.e., emitter down. In this case the relative performance of devices 2 and 3 should be reversed. Although the base currents were nonideal, device 2 indeed had the highest Early voltage in reverse mode compared to devices 1 and 3.

Table I also shows measured values of βV_A, $J_{B,0}$, C_{BC}, the intrinsic base-sheet resistance R_B, and breakdown voltages BV_{CEO} and BV_{CBO} for the structures considered. The calculations of βV_A according to (5) were performed using our measured values of C_{BC} and $J_{B,0}$ of the individual devices, the minority-carrier diffusion coefficient from [6], and the bandgap reduction in the strained SiGe layer from [7], and taking into account the reduction of the effective densities of states caused by the strain [5]. The model, which has no adjustable parameters, fits the experimental data well. For device 3, the cutoff frequency is expected to be about 30 GHz based on published results of comparable device structures with similar f_T [8]. Compared to state-of-the-art silicon devices, the βV_A product is increased by a factor of more than 100, as shown in Fig. 2 [9].



(a)

(b)

Fig. 1. (a) Band diagrams for $V_{CB} = 0$ V (solid lines) and $V_{CB} = 1$ V (dashed lines) and (b) measured collector current characteristics for devices 2 and 3.

TABLE I
EXPERIMENTAL DATA SHOWING β-V_A TRADE-OFF IN SiGe HBT'S

device	1	2	3	4
%Ge at emitter	14	25	14	25
%Ge at collector	14	14	25	25
R_B (kΩ/□)	13.2	9.7	7.1	6.0
BV_{CEO} (V)	4.7	4.1	4.5	3.8
BV_{CBO} (V)	14.9	16.3	16.0	15.3
$J_{B,0}$ (pA/cm^2)	3.7	3.9	4.9	10
C_{BC} (nF/cm^2)	55	54	54	55
forward β	750	1800	1400	1750
forward V_A (V)	18	6	120	44
forward βV_A (V)	13 500	10 800	168 000	77 000
calculated βV_A (V)	10 700	8980	190 000	84 000
reverse V_A (V)	13	100	3.5	42

IV. Conclusions

These results are technologically very important since strain in the Si$_{1-x}$Ge$_x$ layers limits the thickness to which they can be grown before misfit dislocations occur at the Si/SiGe interfaces. Devices with high β require an entire base of low-bandgap (high Ge concentration) material, but for a high βV_A product only a very thin layer of the narrow-bandgap material at the collector side of the base is required. There-

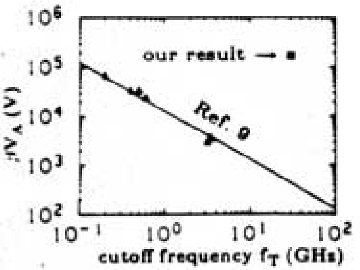


Fig. 2. βV_A product versus cutoff frequency f_T for conventional silicon bipolar devices from [9], and our result with an estimated f_T based on [8].

fore, it is possible to achieve much larger improvements in βV_A in Si/Si$_{1-x}$Ge$_x$/Si HBT's than improvements in β alone.

In summary, a theory for the Early voltage and hence the βV_A product in HBT's with nonuniform base bandgap has been presented. The Early voltage is dramatically increased when the bandgap at the collector edge of the base is lower than the maximum bandgap in the base. Using this concept, Si/Si$_{1-x}$Ge$_x$/Si HBT's with βV_A products of over 100 000 V have been demonstrated for devices expected to have an f_T of about 30 GHz.

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