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# ANALYTICAL MODELING OF CURRENT GAIN - EARLY VOLTAGE PRODUCTS IN Si/Si<sub>1-x</sub>Ge<sub>x</sub>/Si HETEROJUNCTION BIPOLAR TRANSISTORS

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## ABSTRACT

The tradeoff between common emitter current gain  $\beta$  and Early voltage  $V_A$  in heterojunction bipolar transistors (HBT's), where both bandgap and doping can vary in 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<sub>1-x</sub>Ge<sub>x</sub>/Si narrow gap base HBT's with a two layer stepped base,  $\beta V_A$  products of over 100,000 V have been achieved for devices with a base width of only 400 Å.

However, the presence of parasitic potential barriers for minority carriers at the base-collector junction of a HBT degrades  $V_A$  because changing the base-collector voltage not only affects the width but also the height of these barriers. They can be caused e.g. by base dopant outdiffusion into the collector due to high temperature processing. An analytical model of the effect of such barriers on the Early voltage is presented.

## INTRODUCTION

To date, heterojunction bipolar transistors have been used primarily to increase the performance of digital circuits. The increased emitter injection efficiency caused by the heterojunction at the emitter-base interface can be traded for increased base doping. This allows reducing the base width resulting in short base transit time and low base sheet resistance.

For analog circuit applications of bipolar transistors, the product of common emitter current gain  $\beta$  and Early voltage  $V_A$  is an important figure of merit. Analytical expressions are developed to show that thin narrow bandgap layers inserted in the base near the base-collector junction cause large Early voltages with negligible effect on current gain. This concept is then used to achieve  $\beta V_A$  products of over 100,000 V in Si/Si<sub>1-x</sub>Ge<sub>x</sub>/Si HBT's with base widths of about 400 Å.

Then the sensitivity of current gain and Early voltage to high temperature processing is studied. An analytical model shows that  $V_A$  is degraded by parasitic potential barriers for minority carriers in the base of HBT's which can be caused by small amounts of base dopant outdiffusion or nonabrupt heterojunctions. In the following we assume  $npn$  HBT's. The generalization for  $pnp$  devices is straightforward.

## ANALYTICAL MODEL FOR $\beta - V_A$ TRADEOFF

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  $W_B$ ,

$$\frac{\partial W_B}{\partial V_{CB}} = - \frac{C_{BC}(V_{CB})}{qN_A(W_B)} \quad (1)$$

where  $C_{BC}$  is the base-collector capacitance per unit area and  $N_A$  the base doping [1]. It leads to a finite output resistance, commonly characterized by the Early voltage  $V_A$ ,

$$V_A = \beta \frac{\partial V_{CE}}{\partial \beta} - V_{CE} \approx I_C \left. \frac{\partial V_{CB}}{\partial I_C} \right|_{I_B = \text{const.}} \quad (2)$$

where  $\beta$ ,  $V_{CE}$ ,  $I_B$ , and  $I_C$  are common-emitter current gain, collector-emitter voltage, and base and collector current, respectively.

In HBT's where both bandgap and doping profiles can vary in the base the collector current density  $J_C$  can be calculated assuming low level injection and an absence of hot electron effects [2, 3],

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

The integral is taken over the neutral base region, and  $p$ ,  $n_i$ , and  $D_n$  are hole concentration, intrinsic carrier concentration, and minority carrier diffusion coefficient, respectively. If the base current is caused only by hole injection from base into emitter ( $J_B = J_{B,0} \exp(qV_{BE}/k_B T)$ ) and all dopant atoms are ionized ( $p = N_A$ )  $\beta$  and  $V_A$  can be calculated from Eqns. (1)-(3) [4],

$$\beta = \frac{q}{J_{B,0}} \left( \int_0^{W_B} \frac{N_A(x)}{n_i^2(x)D_n(x)} dx \right)^{-1} \quad (4a)$$

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

The integral in brackets will be dominated by the region with the largest doping and the smallest  $n_i^2$ , i.e. the largest bandgap (highest potential barrier for electrons), which therefore determines the current gain of the device. The Early voltage, however, depends exponentially on the difference between the largest bandgap in the base and that at the collector edge of the base region. The integral cancels in the  $\beta V_A$  product which is therefore independent of the base doping and bandgap profiles.  $\beta V_A$  depends only on intrinsic carrier concentration and minority carrier diffusion coefficient at the edge of the base-collector depletion region in the base,

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

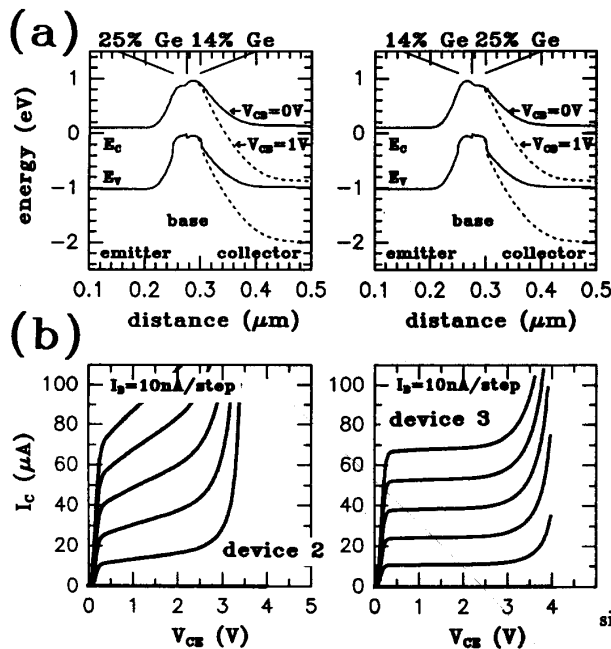


Fig. 1. (a) Calculated band diagrams and (b) measured collector current characteristics of devices 2 and 3 of Table 1 showing the effect of the location within the base of the largest bandgap on the Early voltage  $V_A$ .

$J_{B,0}$  and  $C_{BC}$  are properties of the emitter and collector, respectively (the collector in a HBT is usually less heavily doped than the base). Physically, the base width reduction has little effect on the output resistance of a HBT if the bandgap at  $x = W_B$  is much smaller than in the rest of the base, since changing  $V_{CB}$  has little effect on the barrier that controls  $J_C$ .

#### EXPERIMENTAL RESULTS FOR STEPPED-BASE HBT'S

To study the effect of the relative location of highest electron barrier and collector junction on the Early voltage, Si/SiGe/Si HBT structures were grown by rapid thermal chemical vapor deposition, and devices processed as described in Ref. 5, except that base and emitter implants were annealed at 700°C for 30 min. In strained SiGe layers, increasing the Ge concentration reduces the bandgap. Emitter and collector layers of all devices were identical, and the base consisted of two nominally 200 Å thick SiGe layers which had constant Ge profiles (i.e. constant bandgaps) and boron dopings of about  $10^{18}$  cm<sup>-3</sup> (devices 1-4 in Table 1). Devices 2 and 3 were designed to have different Ge concentrations in the two SiGe base regions resulting in a potential step in the conduction band at the heterojunction between the two layers. On both sides of the base, nominally 40 Å thick spacer layers were inserted to remove spike-and-notch and outdiffu-

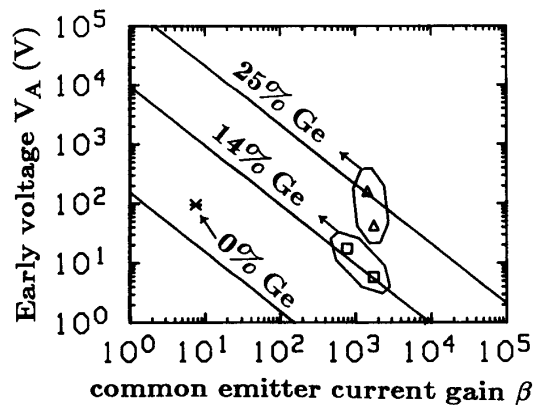


Fig. 2. Comparison of model and data for  $\beta - V_A$  tradeoff in Si/SiGe/Si HBT's. The  $\beta V_A$  product depends only on the bandgap and doping profiles at the base-collector junction. The bandgap and doping profiles in the rest of the base determine  $\beta$  vs.  $V_A$ .

sion 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<sup>2</sup>, except device 4 which had a  $J_{B,0}$  of 10 pA/cm<sup>2</sup>. Fig. 1 shows calculated band diagrams and measured collector current characteristics of devices 2 and 3. They had similar gain because of the similar bandgap and doping profiles in the region with the widest bandgap controlling  $\beta$ . The largest bandgap in the base of device 2 was located at the base-collector junction. Changing  $V_{CB}$  therefore strongly affected the width of the highest barrier for electrons resulting in a low Early voltage ( $V_A \approx 6$  V at  $V_{CB} = 0.5$  V). Moving the region with the largest bandgap in the base away from the base-collector junction as done in device 3 improved the output resistance dramatically ( $V_A \approx 120$  V) without changing  $\beta$ . Measuring  $V_A$  in reverse mode, i.e. emitter down, reversed the relative performance of devices 2 and 3 as expected. The corresponding values of  $V_A$  are listed in Table 1 together with measured values of  $\beta V_A$ ,  $J_{B,0}$ ,  $C_{BC}$ , the base sheet resistance  $R_B$ , and breakdown voltages  $BV_{CE0}$  and  $BV_{CBO}$  for the structures considered.  $BV_{CBO}$  was limited by avalanche multiplication in the collector, which also reduced  $V_A$  from its ideal value for  $V_{CB} > 1.5$  V.

Fig. 2 shows the tradeoff between  $\beta$  and  $V_A$  for different Ge concentrations (i.e. bandgaps) at the base-collector junction for devices with a base doping of  $10^{18}$  cm<sup>-3</sup>, according to Eqn. (5). In the calculations, the minority carrier diffusion coefficient was taken from Ref. 6 and the bandgap reduction in the strained SiGe layer from Ref. 7, and the reduction of the effective density of states caused by the strain was accounted for [8]. The model, which has no adjustable parameters, fits the experimental data points well. For device 3, the  $\beta V_A$  product was greater than 100,000 V. Its cutoff frequency is expected to be about 30 GHz based on published results of comparable device structures [9]. Com-

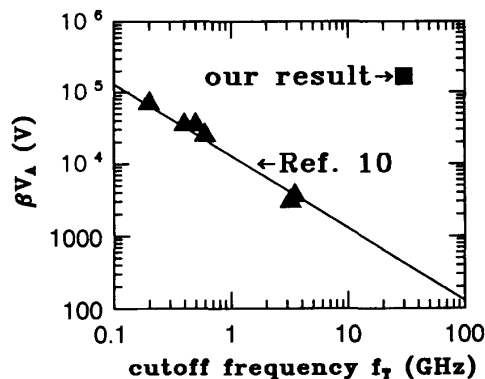


Fig. 3.  $\beta V_A$  product in state-of-the-art silicon homo-junction devices (Ref. 10) vs. cutoff frequency  $f_T$ , and our result of the 14%/25% Ge structure of Fig. 1 with an estimated  $f_T$  based on Ref. 9.

pared to state-of-the-art silicon devices, the  $\beta V_A$  product is increased by a factor of more than 100 as shown in Fig. 3 [10].

#### SENSITIVITY OF $V_A$ TO DEVICE PROCESSING

Very small diffusion ( $L_D \approx 50 \text{ \AA}$ ) of dopant from the base into the collector can cause a parasitic barrier for the minority carriers in the base at the base-collector junction and lower  $I_C$ , since in HBT's the base is often much more heavily doped than the collector [8]. Increasing  $V_{CB}$  will reduce this barrier and dramatically increase  $I_C$ , resulting in degraded output resistance and low Early voltage (Fig. 4). In this case, the above model and Eqns. (3)–(5) cannot be applied because the current-controlling barrier is in the base-collector depletion region which includes the Si side of the SiGe/Si heterojunction. The integral in Eqns. (3) and (4) cannot be extended to cover this region since  $p(x)$  is not simply related to the local electrostatic potential  $\Phi(x)$ , which is a key assumption in the formulation of Eqn. (3).

Table 1. Devices evaluated in this work.

device	1	2	3	4	5
%Ge at emitter	14	25	14	25	14
%Ge at collector	14	14	25	25	14
$R_B$ (k $\Omega$ / $\square$ )	13.2	9.7	7.1	6.0	3.4
$BV_{CBO}$ (V)	4.7	4.1	4.5	3.8	4.9
$BV_{CBO}$ (V)	14.9	16.3	16.0	15.3	14.2
$J_{B,0}$ (pA/cm $^2$ )	3.7	3.9	4.9	10.4	4.0
the following values are taken at $V_{CB} = 0.5 \text{ V}$					
$C_{BC}$ (nF/cm $^2$ )	55	54	54	55	62
forward $\beta$	750	1800	1400	1750	151
forward $V_A$ (V)	18	6	120	44	8
forward $\beta V_A$ (V)	13500	10800	168,000	77000	1208
calc. $\beta V_A$ (V)	10700	9000	190,000	84000	5800
reverse $V_A$ (V)	13	100	3.5	42	16

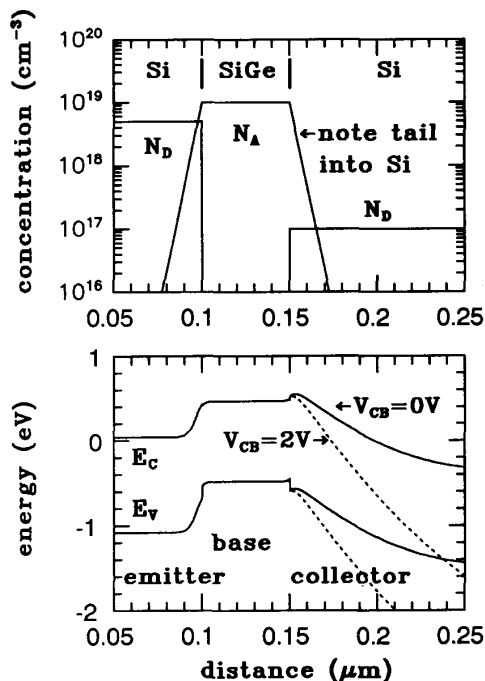


Fig. 4. Dopant concentrations assumed for our analytical model, vs. vertical distance into the device. An exponential boron outdiffusion tail (diffusion length  $L_D = 33 \text{ \AA}$ ) extends into the lightly doped collector ( $N_D = 10^{17} \text{ cm}^{-3}$ ) of a Si/Si $_{0.80}$ Ge $_{0.20}$ /Si HBT. Note the resulting parasitic electron barrier in the conduction band, shown in the band diagram calculated with a one-dimensional device simulator. Its width and height change with applied collector-base reverse bias  $V_{CB}$ .

However,  $I_C$  can still be calculated analytically, starting with Eqn. 7 of Ref. 2, but an explicit formula for the potential  $\Phi(x)$  in the barrier region is needed. It can be found for the case of a base doping profile decreasing exponentially towards a constant collector doping by using the depletion approximation and solving Poisson's equation for  $\Phi(x)$  with the boundary condition  $\Phi(W_C) - \Phi(L) = \Phi_{BI} + |\Phi_{ACC}|$ , where  $L$  is the location of the SiGe/Si heterojunction and  $W_C$  the depletion region width into the collector.  $\Phi_{BI}$  is the built-in voltage between the neutral SiGe base and the Si collector, and the only adjustable parameter in the model is the potential drop  $\Phi_{ACC}$  across the accumulation region at the SiGe side of the heterojunction in the base. Since the critical region is the peak of the barrier, we approximate it as a parabola to facilitate further analytical expressions. The effect of the barrier on  $I_C$  can now be described by an effective barrier width  $\sigma_0$ , a barrier height  $\Phi_0$ , and a location  $L_0$ . Since both the width and the height of the parasitic barrier depend on collector-base voltage, the collector current is a strong function of  $V_{CB}$  and the output resistance is

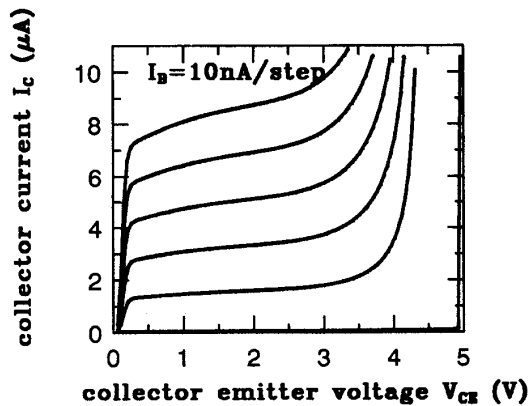


Fig. 5. Experimental result of HBT where dopant out-diffusion degraded the output resistance (device 5 of Table 1). Note that the Early voltage increases strongly with  $V_{CE}$  before avalanche base current causes breakdown at about 4 V.

degraded. In the presence of potential barriers Eqn. (3) can be generalized by

$$J_C = q \left( \int_0^L \frac{N_A}{n_i^2 D_n} dx + \frac{\sigma_0}{n_i D_n} \Big|_{L_0} \right)^{-1} e^{qV_{BB}/k_B T} \quad (6)$$

As  $V_{CB}$  is increased, however, and the barrier is pulled down to become insignificant,  $V_A$  will again increase. This is seen in Fig. 5, where a HBT similar to that of Fig. 1(b) is shown, except that its base doping was higher leading to increased diffusion during emitter growth (device 5 of Table 1). The initially poor  $V_A$  of 5.6 V at  $V_{CE} = 0.5$  V improved with increasing  $V_{CE}$  to 14.6 V at  $V_{CE} = 2.0$  V until the avalanche effect set in. This increase in  $V_A$  was much stronger than the observed 30% decrease of the base-collector capacitance  $C_{BC}$  from  $V_{CE} = 0.5$  V to  $V_{CE} = 2.0$  V indicating the presence of parasitic barriers in the conduction band.

Fig. 6 shows the conduction band at the base-collector junction for the doping profile of Fig. 4 and a  $\text{Si}_{0.80}\text{Ge}_{0.20}$  base. The calculation of our analytical model agrees well with results obtained with a one-dimensional drift-diffusion simulator (modified SEDAN). The Early voltage is strongly dependent on the outdiffusion length  $L_D$  as shown in Fig. 7 for  $V_{CB} = 0$  V.

### CONCLUSION

In summary,  $\beta V_A$  products more than 100 times higher than in comparable all silicon devices have been obtained in Si/SiGe/Si HBT's. Analytical models to explain these results and to model the sensitivity of the devices to processing conditions have been developed for the first time.

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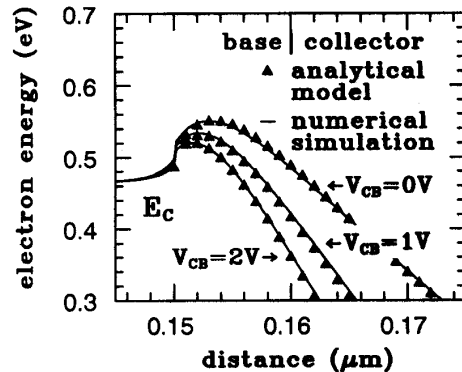


Fig. 6. Blow-up of the conduction band of Fig. 4 at the base-collector junction. Parasitic barriers were calculated for various values of  $V_{CB}$  for a Si/SiGe/Si HBT with 20% Ge in the base and an  $L_D$  of 33 Å. Note the good agreement between the points from our analytical model and the lines resulting from SEDAN simulations. Increasing  $V_{CB}$  decreases width and height of the parasitic barrier, leading to a big relative change in the collector current and a poor output resistance.

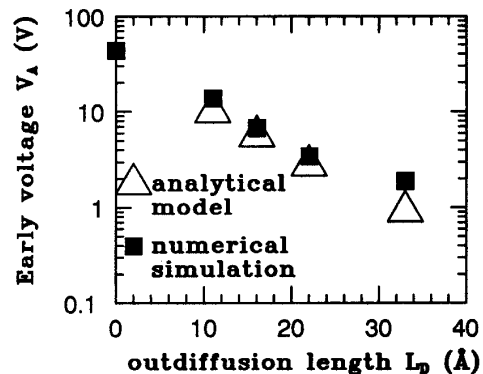


Fig. 7. Comparison of analytical model (triangles) and simulated results (squares) for Early voltage  $V_A$  vs. diffusion length  $L_D$  at  $V_{CB} = 0$  V. Both Early voltage and current gain degrade as a result of dopant outdiffusion.

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