Weak avalanche multiplication in SiGe heterojunction bipolar transistors on thin film silicon-on-insulator*

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In this paper, we propose an analytical avalanche multiplication model for the next generation of SiGe silicon-on-insulator (SOI) heterojunction bipolar transistors (HBTs) and consider their vertical and lateral impact ionizations for the first time. Supported by experimental data, the analytical model predicts that the avalanche multiplication governed by impact ionization shows kinks and the impact ionization effect is small compared with that of the bulk HBT, resulting in a larger base-collector breakdown voltage. The model presented in the paper is significant and has useful applications in the design and simulation of the next generation of SiGe SOI BiCMOS technology.

Keywords: avalanche multiplication, heterojunction bipolar transistor, thin film silicon-on-insulator, SiGe

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1. Introduction

With aggressive heterojunction bipolar transistor (HBT) device scaling, silicon-based SiGe technology has matured to a stage where a superb state-of-the-art HBT with a characteristic frequency exceeding 400 GHz has been achieved at room temperature by structural as well as intrinsic advancements made to the HBT device.[1] The flexibility of silicon-on-insulator (SOI) device architecture allows for optimal electrical properties for reduced parasitic capacitance, low leakage current and improved immunity to substrate noise and crosstalk.[2] Therefore, combining SiGe HBTs with SOI technology, especially thin film SOI, is attractive for low power and high speed applications. According to recent studies, a novel vertical SiGe HBT structure on thin SOI substrate proposed by IBM group,[3] investigated by many follow-up researchers, shows higher Early voltage and better trade-off between base-collector avalanche breakdown voltage and characteristic frequency,[4−6] and have been integrated in the next generation of SiGe SOI BiCMOS technology.[7]

Several models for SiGe SOI HBTs have been reported in Refs. [8]–[11], including Early voltage, depletion capacitance, base transit time and characteristic frequency except avalanche multiplication, although numerous device results regarding this mechanism have been reported.[5,7] Analytical models considering avalanche multiplication have been reported,[12,13] however, the avalanche multiplication model is based on a bulk HBT device. Our investigations concentrate on the understanding of the unique features of SOI HBTs compared with its bulk counterpart and the influence of the SOI substrate on avalanche multiplication. As the SOI HBT size is reduced, the internal electric field becomes higher for a given bias and its spatial variation becomes steeper, which can result in the onset of avalanche multiplication even at low voltages. Accurate knowledge of the ionization coefficient which governs this multiplication process and ultimate breakdown is therefore important in modern HBT device design. Due to impact ionization, the high electric field creates electron–hole pairs that undergo a multiplication effect leading to increased current. The reverse current flowing through the device causes high power dissipation, an associated temperature rise and potential device destruction.

To our knowledge, the effect of SOI substrate on

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avalanche multiplication has not been dealt with in theoretical studies of base-collector breakdown. In this paper, we include this effect by using a simple model of the junction and of avalanche multiplication. With this model, one can obtain the trend in the dependences of the breakdown property on doping concentration, collector length and junction bias.

2. Model of avalanche multiplication

A schematic cross section of an SOI SiGe HBT is shown in Fig. 1, where the symmetry of the structure has been used to restrict the analysis to half of the device, a similar analysis is applicable for the other half. The zero point of the x axis is located on the base side edge of the base-collector depletion region at zero bias, and the zero point of the y axis on the edge of the intrinsic base. $W_{\rm epi}$ and $L_{\rm epi}$ are the collector width and length, $W_{\rm B}$ and $W_{\rm E}$ are the base width and the emitter width, respectively.

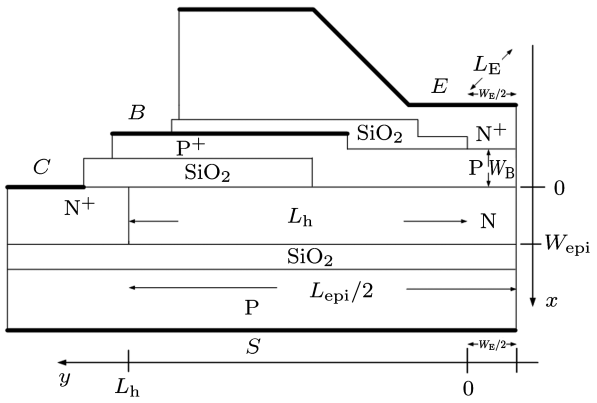


Fig. 1. Schematic diagram of an SiGe HBT fabricated on CMOS-compatible thin SOI.

The major differences between an HBT on bulk and an HBT on SOI are the collector thickness and the absence of a buried layer. The intrinsic collector space charge extension is lateral at $V_{\rm CB} = 0$ V for a fully depleted HBT and vertical at $V_{\rm CB} = 0$ V while lateral at higher reverse bias for a partially depleted HBT where $V_{\rm CB}$ is the reverse base-collector voltage. Electrons injected from the emitter flow vertically downwards into the collector and make a turn horizontally towards the N^+ collector contact region on the side.

For avalanche multiplication, a central issue is to determine the electron ionization coefficient, $\alpha(E)$, which is proportional to the probability with which an electron in an electric field E gains an energy exceeding a given threshold. The most important quantitative characteristic of the charge multiplication phenomenon is the impact ionization rate, defined as the number of carriers generated per unit distance by impact ionization by one injected carrier as it moves through the medium. The impact ionization rate strongly depends on the applied electric field. It has already become a tradition to describe experimental results for impact ionization rate as a function of applied electric field as expressed in the form of

$$\alpha = \alpha_0 \exp\left(-\frac{E_0}{E}\right), \tag{1}$$

where α_0 and E_0 are semiempirical constants representing the avalanche coefficient and the critical electric field, respectively.

Assuming a flat dope in the epilayer and an abrupt base-collector junction for the derivation. In the case of medium collector doping concentration, the base-collector space charge region (SCR) extension is vertical at a relatively low bias, $V_{\rm CB} < V_{\rm jPCv}$, where

$$V_{\rm jPCv} = \frac{qN_{\rm epi}}{2\varepsilon_{\rm Si}} W_{\rm epi}^2 - V_{\rm dc}$$

is the effective vertical punch-through voltage.[14] The further increase of the bias results in the lateral expansion of SCR. Neglecting substrate influence, the solution of Poisson's equation for the electric field is expressed in the form of [8,9,15]

$$E_x = \frac{qN_{\rm epi}}{\varepsilon_{\rm Si}}(x - x_1), \quad 0 < x < x_1, \tag{2}$$

$$x_1 = \sqrt{\frac{2\varepsilon_{\rm Si}(V_{\rm CB} + V_{\rm dc})}{qN_{\rm epi}}}, \quad 0 < V_{\rm CB} < V_{\rm jPCv}, \tag{3}$$

$$E_y = \frac{qN_{\rm epi}}{\varepsilon_{\rm Si}}(y - y_1), \quad 0 < y < y_1, \tag{4}$$

$$y_1 = \sqrt{\frac{2\varepsilon_{\rm Si}(V_{\rm CB} - V_{\rm jPCv})}{qN_{\rm epi}}}, \quad V_{\rm jPCv} < V_{\rm CB}, \tag{5}$$

where depletion and low injection approximations are made; the hole drift and diffusion currents, generation and recombination currents are ignored; the impurity atoms are assumed to be completely ionized; x_1 and y_1 are the vertical and the horizontal depletion widths; E_x and E_y are the vertical and the horizontal electric fields; $\varepsilon_{\rm Si}$ is the dielectric coefficient of Si; $V_{\rm CB}$ is the intrinsic reverse base-collector voltage; $N_{\rm epi}$ is the collector doping concentration; $V_{\rm dc} = V_T \ln(N_{\rm epi}^2/n_{\rm i}^2)$ is the built-in potential with $n_{\rm i}$ the intrinsic concentration of Si.

In the case of low collector doping concentration, the base-collector SCR reaches the Si/SiO_2 interface

and extends laterally even at zero bias $V_{\rm CB}=0$. With a similar derivation to that given above, we obtain

$$E'_x=\frac{qN_{\rm epi}}{\varepsilon_{\rm Si}}(x-W_{\rm epi}),\quad 0<x<W_{\rm epi}, \tag{6}$$

$$E'_y=\frac{qN_{\rm epi}}{\varepsilon_{\rm Si}}(y-y'_1),\quad 0<y<y'_1, \tag{7}$$

$$y'_1=\sqrt{\frac{2\varepsilon_{\rm Si}(V_{\rm CB}+V_{\rm dc})}{qN_{\rm epi}}}-W_{\rm epi},\quad 0<V_{\rm CB}, \tag{8}$$

where E'_x and E'_y are the vertical and the horizontal electric fields, and y'_1 is the horizontal depletion width for a fully depleted HBT.

A weak avalanche is assumed for simplicity. Then the avalanche current becomes

$$I_{\rm avl}=I_{\rm epi}\int_0^{W_{\rm epi}}\alpha\,|E_x|{\rm d}x+I_{\rm epi}\int_0^{L_h}\alpha\,|E_y|{\rm d}y, \tag{9}$$

where $L_{\rm h}=(L_{\rm epi}-W_E)/2$ is the maxim horizontal depletion width.

For partially depleted devices, E_x and E_y can be rewritten as

$$|E_x|=E_{xm}\left(1-\frac{x}{x_1}\right)\approx\frac{E_{xm}}{1+x/x_1}, \tag{10}$$

$$|E_y|=E_{ym}\left(1-\frac{y}{y_1}\right)\approx\frac{E_{ym}}{1+y/y_1}, \tag{11}$$

where $E_{xm}=qN_{\rm epi}x_1/\varepsilon_{\rm Si}$, and $E_{ym}=qN_{\rm epi}y_1/\varepsilon_{\rm Si}$ are the maxim vertical and horizontal electric fields.

Substituting Eqs. (10) and (11) into Eq. (9), the total avalanche current is given in the form of

$$\begin{aligned}I_{\rm avl}/I_{\rm epi}=&\frac{\alpha_0}{E_0}x_1E_{xm}\left\{\exp\left(-\frac{E_0}{E_{xm}}\right)\right.\\&\left.-\exp\left[-\frac{E_0}{E_{xm}}\left(1+\frac{W_{\rm epi}}{x_1}\right)\right]\right\}\\&+\frac{\alpha_0}{E_0}y_1E_{ym}\left\{\exp\left(-\frac{E_0}{E_{ym}}\right)\right.\\&\left.-\exp\left[-\frac{E_0}{E_{ym}}\left(1+\frac{L_h}{y_1}\right)\right]\right\}.\end{aligned} \tag{12}$$

The avalanche current for a fully depleted device can be derived similarly as

$$\begin{aligned}I_{\rm avl}/I_{\rm epi}=&\frac{\alpha_0}{E_0}W_{\rm epi}E'_{xm}\left[\exp\left(-\frac{E_0}{E'_{xm}}\right)\right.\\&\left.-\exp\left(-\frac{2E_0}{E'_{xm}}\right)\right]\\&+\frac{\alpha_0}{E_0}y'_1E'_{ym}\left\{\exp\left(-\frac{E_0}{E'_{ym}}\right)\right.\\&\left.-\exp\left[-\frac{E_0}{E'_{ym}}\left(1+\frac{L_h}{y'_1}\right)\right]\right\},\end{aligned} \tag{13}$$

where $E'_{xm}=qN_{\rm epi}W_{\rm epi}/\varepsilon_{\rm Si}$, and $E'_{ym}=qN_{\rm epi}y'_1/\varepsilon_{\rm Si}$.

It is obvious from Eqs. (12) and (13) that the avalanche current is strongly dependent on the maximum electric field dominated by the base-collector depletion width and as the SCR is two-dimensional for the cases of different applied reverse base-collector biases, the avalanche current behaviour shows a kink from partially depleted operation mode to fully depleted mode, which will be validated later.

It should be noted that as the lateral base-collector SCR reaches the lateral collector contact region, it extends no longer. Therefore, the effect of the collector length on avalanche multiplication is also important. After both vertical and lateral full depletion of SCR, the increase of reverse base-collector bias causes a relatively rapid increase of electric field and then a rapid increase of the avalanche current. While the avalanche current model is quite different and so is the electric field in this case, the problem is modeled approximately by solving the one-dimensional Poisson's equation below.

First, the lateral punch-through voltage $V_{\rm jPCh}$ is defined similarly as $V_{\rm jPCv}$, with

$$V_{\rm jPCh}=\frac{qN_{\rm epi}}{2\varepsilon_{\rm Si}}L_h^2.$$

We use Poisson's equation in the collector region (N) and the collector contact region (N^+), respectively

$$\frac{{\rm d}E}{{\rm d}y}=\frac{qN_{\rm epi}}{\varepsilon_{\rm Si}},\quad 0<y\le L_h, \tag{14}$$

$$-\frac{{\rm d}^2V_2}{{\rm d}y^2}=\frac{{\rm d}E_2}{{\rm d}y}=\frac{qN_{\rm contact}}{\varepsilon_{\rm Si}},\quad L_{\rm h}\le y\le y_2, \tag{15}$$

with boundary conditions as

$$E_2(y_2)=0, \tag{16}$$

$$-\int_{L_{\rm h}}^{y_2}E(y){\rm d}y=V_{\rm CB}-V_{\rm jPCv}-V_{\rm jPCh}, \tag{17}$$

$$E(L_{\rm h})=E_2(L_{\rm h}), \tag{18}$$

where $N_{\rm contact}$ is the doping concentration of the collector contact region; y_2, E_2, and V_2 are the lateral depletion width when $V_{\rm CB}>V_{\rm jPCv}+V_{\rm jPCh}$, the electric field and electric potential from $L_{\rm h}$ to y_2, respectively; E is the lateral electric field of the collector region (N) from 0 to $L_{\rm h}$. The electric field is thus given as

$$E(y)=\frac{qN_{\rm contact}}{\varepsilon_{\rm Si}}(L_{\rm h}-y_2)+\frac{qN_{\rm epi}}{\varepsilon_{\rm Si}}(y-L_{\rm h}) \tag{19}$$

with

$$y_2=L_{\rm h}+\sqrt{\frac{2\varepsilon_{\rm Si}(V_{\rm CB}-V_{\rm jPCv}-V_{\rm jPCh})}{qN_{\rm contact}}}, \tag{20}$$

the electric field can be rewritten in a similar form to Eq. (11) as

$$|E| = E_m\left(1 - \frac{y}{\lambda}\right) \approx \frac{E_m}{1 + y/\lambda}, \tag{21}$$

where λ is the point at which the extrapolated electric field is zero, $E_{\rm m}$ is the maximum lateral electric field when $V_{\rm CB} > V_{\rm jPCv} + V_{\rm jPCh}$ and can be expressed as

$$\lambda = L_{\rm h} + \frac{N_{\rm contact}}{N_{\rm epi}}(y_2 - L_{\rm h}), \tag{22}$$

$$E_{\rm m} = \frac{qN_{\rm contact}}{\varepsilon_{\rm Si}}(y_2 - L_{\rm h}) + \frac{qN_{\rm epi}}{\varepsilon_{\rm Si}}L_{\rm h}, \tag{23}$$

neglecting impact ionization rate in the collector contact region (N^+) due to small electric field, the avalanche current when $V_{\rm CB} > V_{\rm jPCv} + V_{\rm jPCh}$ can be obtained by substituting Eq. (20) into Eq. (9) as

$$\begin{aligned} I_{\rm avl}/I_{\rm epi} = {} & \frac{\alpha_0}{E_0}W_{\rm epi}E'_{xm}\left[\exp\left(-\frac{E_0}{E'_{xm}}\right)\right. \\ & \left. - \exp\left(-\frac{2E_0}{E'_{xm}}\right)\right] \\ & + \frac{\alpha_0}{E_0}\lambda E_{\rm m}\left\{\exp\left(-\frac{E_0}{E_{\rm m}}\right)\right. \\ & \left. - \exp\left[-\frac{E_0}{E_{\rm m}}\left(1 + \frac{L_{\rm h}}{\lambda}\right)\right]\right\}. \end{aligned} \tag{24}$$

3. Verification and discussion

In order to evaluate the effectiveness of the analytical model for SiGe SOI HBTs, the analytical model results are compared with experimental data. The experimental results described in this paper refer to a 7-cell device with an effective emitter area of $7\times(0.15\times0.83)$ μm^2. The device under study has a linear Ge profile from 10% (emitter side) to 25% (collector side) on the base with an epilayer width of 150 nm, a collector length of 1040 nm, a base width of 25 nm and several $N_{\rm epi}$ parameters so as to explore the influence of collector characteristics on device avalanche multiplication, specifically at about 5.9×10^{16} cm^{-3}, 9.2×10^{16} cm^{-3}, and 1.9×10^{17} cm^{-3}, separately.[7] The impact ionization coefficients α_0 and E_0 for SiGe HBTs on SOI are calibrated based on each experimental result for avalanche multiplication. In the collector contact region, the doping concentration is assumed to be 1×10^{20} cm^{-3}.

Figure 2 shows the original avalanche multiplications versus reverse base-collector bias for the cases of some different collector doping concentrations. As shown in the figure, at small and medium values of $V_{\rm CB}$, the region where the kink occurs indicates the transition between the partially depleted and the fully depleted modes of operation. $V_{\rm jPCv}$ corresponds to $V_{\rm CB}$ at which the kink occurs. For a fixed structure, $V_{\rm jPCv}$ increases as $N_{\rm epi}$ increases, which implies that the larger the value of $N_{\rm ep}$, the harder it is for device to fully deplete.

For relatively large $N_{\rm epi}$ and very small $V_{\rm CB}$, the device is partially depleted, which means that the base-collector SCR is vertical. As a result, the behaviour of $M-1$ is similar to that of a bulk HBT. For smaller $N_{\rm epi}$, the space charge extends further down to the Si/SiO_2 interface, and reaches the interface at relatively small $V_{\rm CB}$. If the collector doping dose is small enough, for instance 5.9×10^{16} cm^{-3} in this paper, the SCR is fully depleted at nearly zero bias. As $V_{\rm CB}$ increases before full depletion, the $M-1$ and hence the avalanche current increases rapidly due to the impact ionization in the high electric field region. For $V_{\rm CB} > V_{\rm jPCv}$, this rapid increase in avalanche current disappears, the behaviour of $M-1$ is quite different. The increase of $M-1$ with the increase of $V_{\rm CB}$ is due to larger maximum electric field, whereas a further increase of $V_{\rm CB}$ after full depletion results in a lateral extension of the SCR, with only limited effect on maximum electric field and hence on $M-1$.

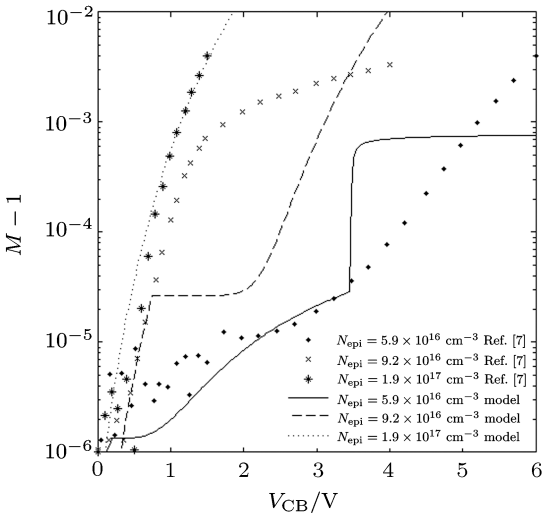


Fig. 2. Original avalanche multiplications versus reverse base-collector bias for different collector doping concentrations. The symbols denote experimental measurements and the lines refer to numerical calculations.

As shown in Fig. 2, large discrepancies occur for $N_{\rm epi} = 9.2 \times 10^{16}$ cm^{-3} with $V_{\rm CB}$ exceeding about 0.8 V and for $N_{\rm epi} = 1.9 \times 10^{17}$ cm^{-3} with $V_{\rm CB}$ exceeding about 3.5 V. The former is because of the two-dimensional extension of the base-collector SCR

even before full depletion, whereas we approximate the SCR extension as a first-vertical-later-horizontal behaviour for simplicity on the assumption that no horizontal depletion occurs before full vertical depletion, which results in a larger vertical punch-through voltage than that of the model. The latter is because of an abrupt doping concentration transition assumption from the collector region (N) to the collector contact region (N^+). This assumption is true for a not-too -tiny operation region, but the depletion in the contact region is so tiny due to much larger doping concentration, that the doping concentration transition is gradual. As a result, the model should be calibrated. The vertical punch-through voltage of the former is adjusted to a practical value based on experimental data and the doping concentration transition from the collector region to the collector contact region is assumed to be four-stage average doping values as 1×10^{17} cm^{-3}, 5×10^{17} cm^{-3}, 1×10^{19} cm^{-3}, 1×10^{20} cm^{-3} to observe the influence of gradual doping transition on avalanche multiplication after both vertical and horizontal full depletion.

Figure 3 shows the calibrated avalanche multiplications versus reverse base-collector bias for the cases of some different collector doping concentrations. The experiment accords well with the model. The discrepancy is probably due to the weak avalanche assumption over relatively high electric field which results in a smaller avalanche multiplication.

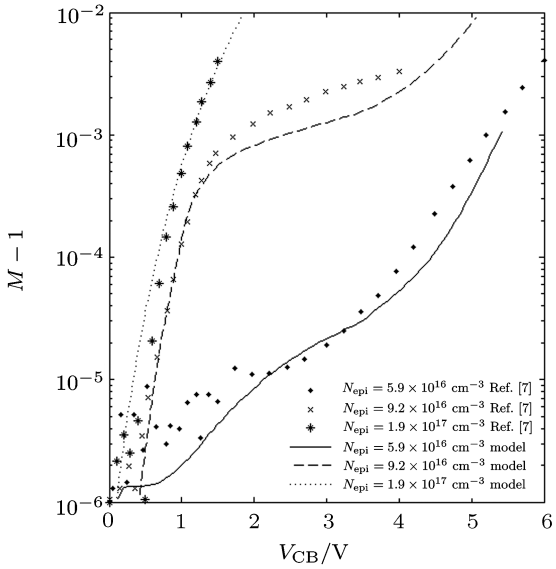


Fig. 3. Calibrated avalanche multiplications versus reverse base-collector bias for the cases of different collector doping concentrations. The symbols denote experimental measurements and the lines refer to numerical calculations.

Figure 4 indicates a theoretical comparison of $M-1$ versus V_{CB} between the SOI and bulk SiGe HBT with the same collector doping concentration 7×10^{16} cm^{-3}, where the semiempirical impact ionization coefficients α_0 and E_0 are taken to be the values of bulk SiGe HBT.[13] As predicted, the avalanche multiplication fits well for each case before full depletion of the collector of the SOI HBT and a large discrepancy is observed when $V_{CB} > V_{jPCv}$. The reason is that the base-collector SCRs in both devices are vertical before full depletion, but with $V_{CB} > V_{jPCv}$, the bulk SiGe HBT continues the vertical depletion and the trend towards increase for thick collector width, while the increase of $M-1$ in the SOI device is delayed due to lateral expansion of SCR with less effect on increase of the maximum electric field and thus on $M-1$. The smaller avalanche multiplication in the SOI SiGe HBT explains the inherent high breakdown voltage compared with that of its bulk counterpart.

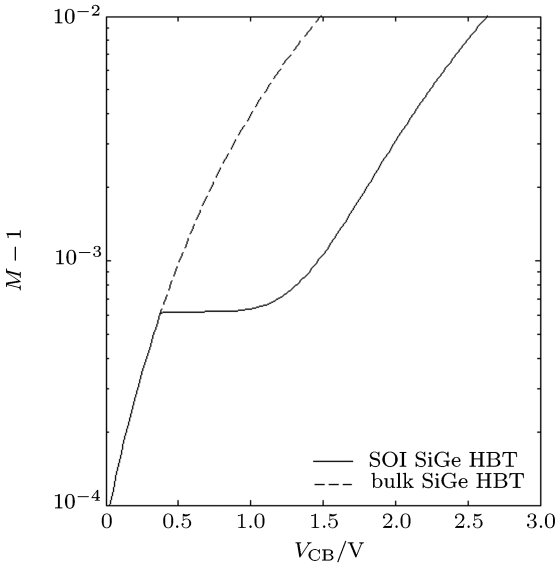


Fig. 4. Comparisons of the results from the avalanche multiplication model for the SOI and bulk SiGe HBT.

4. Conclusions

In this paper, an analytical avalanche multiplication model for the next generation of SiGe SOI HBTs with a consideration of vertical and lateral impact ionization is described for the first time. Supported by experimental data, the analytical model predicts that the avalanche multiplication governed by impact ionization shows a kink and the impact ionization effect is smaller than that of bulk HBT, resulting in a larger base-collector breakdown voltage. The presented model is significant and has useful applications

in the design and the simulation of the next generation of SiGe SOI BiCMOS technology.

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