Model generation of the silicon–germanium (Si$_{1-x}$Ge$_x$) bipolar inversion channel field effect transistor utilizing a two-dimensional device simulator

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Abstract

The development of an accurate model for an inversion base transistor in the bipolar inversion channel field effect transistor (BICFET) configuration is investigated in this report. Simulations were accomplished through the use of the Medici software, acquired from Avant! Corporation of Sunnyvale, California. This software, which is capable of modeling semiconductor devices comprised of conventional and/or user-defined materials, impurities, structures and operating conditions, was used to develop a model based on experimental device results from Stanford University. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Microelectronics; Compound semiconductors; Device modeling

1. Introduction

In a previous work, the binary and ternary compounds of silicon–germanium (Si$_{1-x}$Ge$_x$ or SiGe) and silicon–germanium–carbon (Si$_{1-x}$Ge$_x$C$_y$ or SiGeC) were discussed in terms of the potential for incorporating these materials in high-speed, silicon-based semiconductor devices [1]. Conventional device structures incorporating heterojunctions were also reviewed in the above-mentioned work. The basic premises and fundamental operation of the heterojunction bipolar transistor (HBT) and heterojunction field effect transistor (HFET) were presented, along with several examples of the proven advantages of incorporating silicon–germanium in these devices in terms of characteristics such as device speed and power consumption. Although the inclusion of heterojunctions into conventional device configurations has proven effective, these structures remain as limited in terms of dimensional constraints as their homojunction counterparts. As a means of reducing or eliminating both material and dimensional concerns, a three terminal device named the bipolar inversion channel field effect transistor (BICFET) was briefly introduced. This work will expound on the operation of the BICFET structure, from the original device as proposed in 1985 and realized as a III–V structure, to the fabrication of a Si$_{1-x}$Ge$_x$ version investigated at Stanford University in the early 1990s [1–4,6]. An accurate device model based on the Stanford University experimental results has been developed using the Medici two-dimensional device simulator obtained from Avant! Corporation of Sunnyvale, California [5].

2. The bipolar inversion channel field-effect transistor

The original proposal for a BICFET device was presented by Taylor and Simmons in 1985 [1,3]. This proposal involved a heterojunction device that would operate through a field-effect mechanism to induce an inversion channel. The inversion channel created in this manner would act as the base of a conventional bipolar junction transistor (BJT). The perceived advantage of a structure of this type was the relaxation of scaling limitations imposed by punchthrough effects in the bipolar operational mode. Additionally, the absence of a dedicated base region for bipolar operation would reduce fabrication complexity from that of a traditional BJT, as well as effectively negating the concerns with regards to base doping levels, doping profiles, and the often diametrically opposed requirements for optimum device performance.

A modification to the original BICFET structure was
investigated and fabricated at Stanford University in the early 1990s [2,4]. The fundamental BICFET structure remains the same as the Taylor and Simmons model with a second base diffusion added. Inclusion of the second base diffusion provides the potential for the BICFET device to operate in both bipolar and HFET modes [1]. Additionally, the wide bandgap material in the original structure is replaced with an undoped Si$_{1-x}$Ge$_x$ channel, a compound that has a narrower bandgap than silicon for any mole fraction $x > 0$ [1].

The basic principle of operation for the BICFET in bipolar mode is that the p+ δ-spike creates a zero bias negative charge layer to prevent electron flow between the emitter and collector. Application of base biases with the appropriate polarities injects holes into the inversion channel. Holes injected in this fashion compensate the negative charge sheet of the p+ spike. Compensation of the ionized impurities lowers the barrier to thermionic transport and allows current to flow between the emitter and collector contacts. The band offsets at the heterojunction, which for SiGe may be considered exclusively contained to the valence band, present a barrier to hole current flow even under forward active bias [1]. Therefore, to first order approximations, current gains are an exponential function of the valence band offset, or

$$\beta \approx e^{\frac{\Delta E_v}{kT}}.$$  \hspace{1cm} (1)

The structure of the Stanford BICFET, while possessing the potential for extremely high current gains ($\sim 10^5$ for $x = 0.5$) and maximum unity gain frequencies on the order of 100 GHz for large-scale geometries, nevertheless possesses major drawbacks. Fabrication variations with respect to the relative positions of the dopant spike and silicon–germanium channel indicate an extreme sensitivity to the relative positions of the dopant spike and allows current to flow between the emitter and collector contacts. The band offsets at the heterojunction, which for SiGe may be considered exclusively contained to the valence band, present a barrier to hole current flow even under forward active bias [1]. Therefore, to first order approximations, current gains are an exponential function of the valence band offset, or

$$\beta \approx e^{\frac{\Delta E_v}{kT}}.$$  \hspace{1cm} (1)

3. Medici

The Medici program is a two-dimensional device simulator capable of analyzing electrical and optical characteristics and properties of conventional or user defined structures and materials, or combinations thereof. Well-defined and understood materials such as oxides, silicon, germanium, silicon–germanium and silicon carbide, as well as a host of III–V compounds, are included in the software as standards. The constituent parameters that define the behaviors and characteristics of these media may be refined and manipulated to define a new material, or a generic semiconductor may be created and defined. Doping of semiconductor materials and devices is also extremely tailorable to the application under consideration. Regional dopant profiles may be specified in terms of impurity concentration and given either a uniform assignment or one of several geometric distributions that may account for diffusivity considerations and/or fabrication variations. Changes may be defined in terms of a monotonic increase/decrease in one or both of the two device dimensions, or the definition of a maximum or minimum mesh spacing within a section or structure may be effected. Refinements to the initial mesh definition may be performed in terms of the regrid algorithm, and may be executed for the entire structure or specific areas within the structure. Regrids may be accomplished, individually or in a sequential combination, in terms of factors such as dopant or potential variations, majority or minority carrier concentrations or electric field strength. There is also a provision for smoothing at the mesh, node, or element level to prevent anomalous results, such as lack of solution convergence or plots that may be distorted and difficult to resolve due to an inappropriately distorted mesh structure. Electrical analysis may be performed in terms of dc or ac small signal for both transient and steady state conditions. Device electrodes and contacts may possess user-defined boundary conditions in terms of voltage, current or charge, and/or may have designated ohmic or Schottky as well as possessing distributed or lumped resistive, inductive and/or capacitive element behaviors.
To conform to experimental reports, the initial BICFET model was defined as a 10 \( \mu \)m channel device using the regional specifications delineated in Table 1. The vertical structural description and regional impurity concentrations indicated in Table 1 are based on devices fabricated and investigated in the early 1990s at Stanford University and serve as a baseline for verification and validation of simulation results \([2,4]\).

For purposes of symmetry, and to allow facilitation in future structural scaling operations, the base diffusions were each defined as 5 \( \mu \)m. A Medici rendering of the initial, ideal structure is illustrated in Fig. 1 and consists of an undoped silicon–germanium alloy channel in intimate contact with a \( p^+ \) dopant spike to create a zero bias barrier to electron current flow. The BICFET model developed in this work allows analytic investigations into a wide variety of novel deviations from the ideal structure to emulate process and fabrication induced disparities. Anomalies explored included vertical shifting of the \( p^+ \) dopant spike from the SiGe channel in 10 \( \AA \) increments, as well as possible lateral asymmetries that have been designated for purposes of discussion as left asymmetry and right asymmetry. The left asymmetric case involves the occurrence of the undoped silicon–germanium channel extending under the barrier oxide and into the base diffusion, while the base diffusion region is still aligned with the oxide and the silicon region that defines the emitter. Conversely, the right asymmetric situation emulates the condition in which the base diffusion extends under the undoped silicon–germanium channel, while the channel region remains aligned with the oxide and silicon emitter regions. Also built into the initial mesh definition for the BICFET structure was the provision for removing the \( p^+ \) dopant spike and directly doping the alloy channel. Behaviors of the device created in this manner were investigated for the doped channel denoted as located in the original position when placed between the base diffusions and occupying the vertical distance between 0.14 and 0.15 \( \mu \)m. Structural variations involving doped channel offsets from the original position at 0.14 \( \mu \)m by 0, 50 and 100 \( \AA \) shifts were also built into the device model. The doped channel offsets are completely defined in Table 2, with the device geometry illustrated in Fig. 1. Initial BICFET structure with no asymmetries.

4. \( \text{Si}_1-\text{Ge}_x \), BICFET simulations

<table>
<thead>
<tr>
<th>Region</th>
<th>Thickness (( \text{Å} ))</th>
<th>Composition/doping level (( \text{cm}^{-3} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emitter</td>
<td>1000</td>
<td>( n^+ \text{Si} / N_D = 10^{19} )</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>( n \text{Si} / N_D = 10^{18} )</td>
</tr>
<tr>
<td>( p^+ ) dopant spike</td>
<td>50</td>
<td>( p^+ \text{Si} / N_A = 10^{19} )</td>
</tr>
<tr>
<td>Narrow bandgap</td>
<td>100</td>
<td>Undoped ( \text{Si}<em>{0.61}\text{Ge}</em>{0.39} )</td>
</tr>
<tr>
<td>Base diffusions</td>
<td>500</td>
<td>( p \text{Si} / N_A = 10^{19} )</td>
</tr>
<tr>
<td>Body/collector</td>
<td>2600</td>
<td>( n \text{Si} / N_D = 10^{18} )</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>( n^+ \text{Si} / N_D = 10^{19} )</td>
</tr>
</tbody>
</table>

![Table 1: Initial BICFET composition](image1.png)

<table>
<thead>
<tr>
<th>Defined condition</th>
<th>Top (( \mu )m)</th>
<th>Bottom (( \mu )m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original position</td>
<td>0.140</td>
<td>0.150</td>
</tr>
<tr>
<td>0 ( \AA ) offset</td>
<td>0.130</td>
<td>0.140</td>
</tr>
<tr>
<td>50 ( \AA ) offset</td>
<td>0.125</td>
<td>0.135</td>
</tr>
<tr>
<td>100 ( \AA ) offset</td>
<td>0.120</td>
<td>0.130</td>
</tr>
</tbody>
</table>

![Table 2: Doped silicon–germanium channel](image2.png)

Fig. 1. Initial BICFET structure with no asymmetries.
Fig. 1. A single grid capable of realizing individual or multiple simultaneous deviations from the ideal case was formulated in an effort to ensure that observed behaviors and characteristics were the result of structural and/or conditional variations rather than differences due to mesh generation.

4.1. Bipolar operational mode of the SiGe BICFET

Although it was not always possible to draw quantitative conclusions of the Medici results with respect to the works presented in Refs. [2,4] since experimental bias conditions were not clearly delineated, Medici simulations for the BICFET with the silicon–germanium alloy channel behaved consistently as expected qualitatively. A fundamental limitation of the BICFET structure observed in all previous works had to do with the occurrence of current crowding in the device due to the high resistivity of the undoped alloy channel. In this phenomenon, current flow through a device is not uniform, but rather is manifested as an increased current density near a junction periphery. The current crowding effect is extremely deleterious to device performance and lifetime, since hot spots are created due to the increased current density and localized power dissipation. These sites of increased temperature in turn cause an increase in current, ultimately resulting in a form of thermal runaway and the subsequent destruction of the junction. This was clearly illustrated in Medici simulations as depicted in the vector plots for electron and hole currents of Fig. 2. Although Fig. 2 is a representation of the ideal BICFET structure with no induced lateral asymmetries or deviations in the position of the p+ dopant spike, significant current crowding at the perimeter of the channel region was observed for all configurations involving an undoped alloy channel.

In marked contrast to this behavior, removal of the p+
spike and directly doping the silicon–germanium channel appears to alleviate this condition. Examinations into the effect of removing the dopant spike and directly doping the alloy channel were performed for the original and three separate offset positions as detailed in Table 2. In the original case, the doped silicon–germanium channel remains in the initial vertical position within the device structure, positioned between and aligned with the base diffusions. The doped channel was then displaced from this initial position, and the bottom of the 100 Å silicon–germanium region was offset by either 0, 50, or 100 Å, with respect to the base diffusions located at 0.14 μm from the top of the device and as defined in Table 2. The extreme circumstance of channel movement analyzed in this work is depicted in Fig. 3, wherein the directly doped alloy region is offset by 100 Å with respect to the nominal base position. It was consistently observed that, regardless of the vertical position of the doped channel, the current crowding effect demonstrated for the undoped channel was removed.

The critical position of the p⁺ dopant spike with respect to the undoped silicon–germanium channel seen in the Stanford formulations was also observed in Medici simulations. Medici results for a Si₀.₆₁Ge₀.₃₉ BICFET device with no lateral asymmetries and with an applied collector–emitter bias of 1.0 V are given in Fig. 4. When compared with estimated values from Refs. [2,4], there is consistently less than a 3% difference between the curves for collector current behaviors. There is, however, a deviation in the behaviors of the base current curves. The output of the Medici software indicates a shift in the effective turn on of the base current with a 30 Å shift in the p⁺ dopant spike that is not observed in Ref. [2,4]. It is believed that the increased sophistication of the Medici software, with respect to the device emulators available almost a decade ago, more accurately reflects the behaviors of the base current within the BICFET structure. The extreme sensitivity of the dopant spike position is not only reflected in the collector and base current turn on voltages as shown in Fig. 4, but in the associated dc gain curves. An ideal structure with no lateral asymmetries and no shift of the p⁺ spike furnishes a maximum dc gain of approximately 1.36 × 10⁴ A/A, while a shift of 30 Å degrades this characteristic to a value of 616 A/A for symmetrically applied base voltages of roughly 0.8 V.

The effect of introducing lateral asymmetries with a fixed, ideal position of the p⁺ dopant spike was also investigated in an attempt to clearly delineate the consequences of likely process induced variations within the device structure. Introduction of previously defined left and right asymmetries had negligible effect on both collector and base current turn on voltages with respect to the ideal structure behaviors. However, for the case of the asymmetry introduced by extending the base diffusion under the channel region (right asymmetric case), there is approximately a 130% modification in the I–V characteristics through a reduction in the collector current and an increase in the base current, which is believed to be due to the geometrical manipulation of the diffusion region and resultant reduction in available area for vertical current flow. Inspection of the dc current gain curves associated with the introduction of the lateral asymmetries indicates that the primary contribution to gain degradation is also the above-mentioned right asymmetric behavior. While lateral asymmetries do not introduce as drastic a reduction in the dc
gain characteristic as that due to the shift of the p⁺ dopant spike, there is a significant decrease observed, with almost a 54% loss in this parameter. The point of maximum gain with respect to applied double base biases remains relatively consistent in the vicinity of 0.75 V when compared to that of the ideal structure with no asymmetries and no shift of the p⁺ spike.

The final sequence of modifications to the original device structure involved the direct doping of the silicon–germanium channel and removal of the p⁺ dopant spike. Fig. 5 contains the Gummel plot representation of the various permutations to a directly doped alloy channel, which involve employing the individual and combined lateral asymmetries incorporated previously, as well as the physical offset of the channel region from its original location. It was observed that once again there was a notable deviation in the final values for both collector and base currents with the introduction of lateral asymmetries, particularly with the case of the extension of the base diffusion under the channel region. There was, however, an increased discrepancy due to the asymmetry comprised of channel extension into the base diffusion region when compared to the behaviors demonstrated in earlier simulations. The cumulative effect of the lateral asymmetries for the doped channel in Fig. 5 resulted in roughly a 31% decrease in the terminal value of $I_C$ and a 17% increase in the final value of $I_B$, compared to the outcomes of simulations involving no p⁺ dopant spike shift, which indicate −22% and +28%, respectively. All channel offsets were defined with respect to the position of the base diffusions at 0.14 μm from the top of the device. The channel width was a constant 100 Å throughout all variations and the vertical delineations for each defined offset condition are given in Table 2.

The condition of 0 Å offset is similar to that of the originally positioned doped channel, except that a single, instead of a double, heterointerface is realized. This results in current-voltage ($I–V$) characteristics that are extremely similar numerically to those of the doped channel with asymmetries. Movement of the silicon–germanium channel to a vertical location within the device separate from the base diffusion regions results in an enhanced performance with respect to the condition tested for a doped channel with no asymmetries, as well as completely negating any concerns with respect to lateral asymmetric effects. Comparison of a 50 Å offset with the ideal doped channel results in a 3.7% increase in collector current and a 1.6% rise in the base current level. In addition, differences in $I–V$ characteristics between the 50 and 100 Å offsets are virtually negligible for $I_C$ and exhibit a 4% increase for $I_B$. These behaviors are reflected in the dc gain characteristic curves of Fig. 6. The 35% reduction in maximum gain from the deal doped channel to that which involves both possible asymmetries is reduced by an additional 7% for the case of a 0 Å offset. This trend is reversed for the instances of 50 and 100 Å offsets, where there are increases of 31 and 32%, respectively. Additionally, there is much less sensitivity of gain characteristics to movement of the doped channel than any other deviation from the ideal structure, with the curves becoming virtually indistinguishable over the bias ranges of interest. It is therefore anticipated that optimal results with respect to device gain and gain stability may be realized through a doped, offset alloy channel. Although the gain is reduced from that of the unrealizable, ideal structure by a
factor of ten, there is a much wider range of applied base voltages, where the gain remains essentially constant and a much more forgiving quality with regard to process and fabrication variations.

Characteristic curves for the Si_{0.61}Ge_{0.39} BICFET device in forward active bipolar operational mode are tend to substantiate the trends discussed above. Total base currents for the double base contact structure of 0–5 \mu A/\mu m were applied in 1 \mu A/\mu m steps, with current through each base defined as half of the total. Early voltages were estimated through the conventional methodology involving an extrapolation of the linear portion of the $I_C-V_{CE}$ curve through the horizontal axis. This early voltage is not the result of modulation of the effective base width due to depletion region width variation with collector base junction reverse bias as in conventional BJTs, but is instead due to the physical operation of the BICFET device and the inversion charge screening of applied collector bias. As discussed and derived in Ref. [2], this behavior of the BICFET is tantamount to the pinning of the hole quasi-Fermi level in the inversion channel under active bias, or when the inversion charge density exceeds $10^{12}$ cm$^{-2}$. This process recalls the basic operating principle of the BICFET device in which the barrier to vertical electron current flow between the emitter and collector is ultimately governed by adjusting the density of holes in the inversion channel, the ionized acceptor charge compensation with increased hole density, and the consequent lowering of the barrier between emitter and collector.

The structure comprised of an undoped channel with an unshifted p+ dopant spike, both with and without introduced lateral asymmetries, results in a nonlinearity initially observed for an applied collector emitter voltage of approximately 8 V, with an estimated early voltage of 9.1 V. The set of structural manipulations involving no lateral asymmetries in the undoped channel BICFET, but with individual shifts in the p+ dopant spike of 10 and 20 Å results in a significantly lower collector current for the active region, down from approximately 30 mA/\mu m for the ideal case to a maximum of 10 mA/\mu m for a 10 Å shift. Although the collector current values are consistently lower than formerly, the onset of nonlinear behaviors is delayed until a collector emitter voltage of approximately 11 V and the early voltage is increased to approximately 12.3 V. Investigations into the behavior of the BICFET device with a doped channel and removal of a dedicated region designated as a dopant spike are performed for the cases of the doped alloy channel in the original position in the device, with and without lateral asymmetries, and for the case of the doped, offset channel region. The range of applied collector emitter voltages was maintained to match preceding studies, and the double contact base currents also remained consistent. Under these conditions, there was no observed onset of nonlinear behaviors for any of the doped channel configurations, although a strikingly lower collector current for given base currents was noted when compared to the previous cases. Estimated early voltages are significantly higher for instances involving a directly doped channel, corresponding to roughly 24 V for the channel in the original position and 59 V for the offset channel. Desirable lower output conductance parameters $g_{oo}$ or equivalently, large output resistances $r_o$, follow the trend of the early voltage characteristic. Analyzed in this manner, it may be concluded that the doped, offset channel should

![Fig. 6. DC gain characteristics of BICFET device with doped alloy channel.](image-url)
yield the largest output resistance and may once again provide beneficial aspects that outweigh deficiencies with regard to collector current level when compared to other possible BICFET configurations.

4.2. Effects of temperature on the SiGe BICFET

Performance of the BICFET device under thermal considerations was explored, both in the context of collector and base current behaviors as a function of temperature with a fixed base emitter voltage and collector current as a function of temperature with an applied collector–emitter bias of zero volts. For the first instance, a constant base–emitter bias of 0.3 V was designated and temperature was varied from 100 to 400 K. These parameters were selected to generate a curve that could be compared to experimental results obtained at Stanford University [4]. Qualitatively, curves for the undoped channel device configuration that were generated by Medici agreed quite well with illustrations found in Ref. [4], with the curves exhibiting a change in current density as a function of temperature on the order of $10^{-5}$ A (cm$^2$ K)$^{-1}$. The strong dependence of collector and base currents on both temperature and channel configuration was also reflected for the cases involving the directly doped alloy channel. All structural manipulations studied for a doped channel exhibited a consistent dependence of current with temperature. However, when compared to the case of the undoped channel there was a marked deviation, with a variation of almost three orders of magnitude between the respective curves.

The second test of device properties with respect to temperature, that of collector current as a function of base emitter voltage with $V_{CE} = 0$ V, demonstrated the temperature dependencies of all permutations of the ideal BICFET structure. There was insignificant deviation observed between all curves generated for $I_C$–$V_{BE}$ plots, indicating that thermal stability with respect to process variations should not be a concern, particularly if limitations due to the current crowding effect are negated as discussed earlier. A transconductance parameter in the active bias region of 2932 mA/V per micron of device width is estimated and an average thermal variation of $-0.67$ mV/C was calculated over the temperature range tested. These characteristics compare quite favorably with conventional npn BJTs, which show a temperature dependence on the order of $-2$ mV/C with consistently lower values for $g_m$.

![Fig. 7. (a) Double base contacted BICFET device in bipolar mode. (b) Small signal midband model for common emitter connection.](image-url)
4.3. Predicted frequency response of SiGe BICFET

Analytic representation of predicted frequency response for the BICFET device is based on a double base contact bias scheme as illustrated in Fig. 7(a) with the corresponding small signal model, under midband operating conditions, shown in Fig. 7(b). In both representations, B1 and B2 indicate the individual base electrodes, E represents the emitter contact and C signifies the connection to the collector region. Additionally, in the small signal model, $R_3$ denotes the resistance of an external source. This source resistance is purely extrinsic in nature, being determined exclusively by the contact resistance of the source and the associated junction resistance. An interesting and beneficial feature inherent in the BICFET device structure is the absence of a dedicated base region as in a conventional bipolar junction transistor. This leads to a simplification in terms of the base emitter capacitance terms, $C_{B1E}$ and $C_{B2E}$, which are comprised exclusively of the junction capacitance instead of being dominated by the larger diffusion capacitance term found in traditional BJTs [4,7]. Since resistivity is inversely proportional to impurity concentration, and doping of the BICFET structure is such that aggregate resistance within each region remains quite small, resistances $R_{B1B1}$, $R_{B2B2}$, $R_{CE}$, and $R_{EE}$ may be neglected in the formulation of an expression for cutoff frequency [8]. Further, under the assumption of fabrication and bias symmetry, the following facilitation may be made:

$$
R_{B1E} = R_{B2E} = R_{BE} \quad C_{B1E} = C_{B2E} = C_{BE}
$$

$$
R_{B1C} = R_{B2C} = R_{BC} \quad C_{B1C} = C_{B2C} = C_{BC}
$$

If both bases are biased the same, the short circuit small signal model for the common emitter configuration is given in Fig. 8. The representation of Fig. 8 is customarily used for development of the unity current gain cutoff frequency, $f_T$, in terms of the short circuit current gain $A_i$. Using the presumptions and simplifications outlined above, and incorporating component values defined in Fig. 8, the current gain magnitude for high frequencies (such that $(\omega R_i(C_1 + C_2))^2 \gg 1$) may be expressed as

$$
|A_i| = \frac{\sqrt{G_c^2 + (\omega C_2)^2}}{\omega(C_1 + C_2)}
$$

By defining the cutoff frequency $f_T$ as occurring for the condition of the magnitude of the current gain in Eq. (3) being equal to one, the unity current gain bandwidth for the double base contact BICFET structure may be calculated in terms of physical device parameters as

$$
f_T = \frac{g_m}{2\pi C_{bc} \sqrt{1 + \frac{2C_{bc}}{C_{bc}}}}
$$

Eq. (4), in conjunction with the relevant circuit component values generated through the ac analysis capabilities of Medici, was used to generate curves representative of the ideal BICFET structure and all permutations of the doped and undoped channel configurations. The ideal conception of the 10 $\mu$m channel BICFET structure achieved a unity current gain cutoff frequency on the order of 80 GHz, which agrees remarkably well with the results of Ref. [2]. Since $f_T$ is inversely proportional to the capacitive parameters defined by physical dimensions, it is anticipated that the performance of the BICFET may significantly surpass conventional device configurations in the sub-micron regime.

A notable degradation in device characteristics is once again observable with the introduction of lateral asymmetries, particularly for the cases involving a base diffusion extending beneath the undoped channel region (or the right asymmetric notation as previously defined). The extreme dependence of device characteristics on the position of the p+ dopant spike is also reconfirmed. A deviation from the ideal location of this dopant spike of only 10 Å within the device structure results in a tenfold decrease in the unity gain cutoff frequency, from 80 to $\approx$ 7 GHz.

For the sequence of simulations involving the removal of the dopant spike, the directly doped channel was investigated in the original position with and without lateral asymmetries, as well as offset from its nominal position by 0, 50, and 100 Å as discussed earlier. The sensitivity to the induced right lateral asymmetry is also exhibited for doped channel considerations, but with a seemingly lower dependency than for the undoped channel design. An
An intriguing occurrence evidenced in the curves generated for this series is the increase of the unity gain cutoff parameter with offsets of 50 and 100 Å from the original channel position, and that $f_T$ is essentially constant for these two cases. Although the $f_T$ parameter is consistently lower for the doped channel investigations, it is worthy of note that none of the structural perturbations resulted in the drastic differences of the undoped channel cases.

5. Conclusions

Exhaustive investigations have demonstrated the efficacy of the Medici software to predict the behaviors of novel device configurations. Because the BICFET investigated in this work is silicon-based, it presents an attractive structure for exploitation in the area of high-speed devices. The potential for both bipolar and HFET operational modes using the same structure and elementary biasing modifications, as well as the cutoff frequency predicted for current device dimensions, may provide a further impetus for subsequent investigations of this configuration.

Models have been successfully developed and implemented using Medici for the device of interest. All structural and material definitions have been designed in such a manner so as to facilitate revisions in device dimensions, regional designations and profiles. The BICFET structure has been purposely defined in such a manner as to facilitate any modifications to conform to experimental data. The Medici program possesses inherent strengths in that region(s) and/or location(s) within a structure may individually define a myriad of material coefficients and parameters. Additionally, variations in compositional and doping gradients and profiles may be specified without alteration to the structure definition created.

Variations of the location of the alloy channel within the device structure were performed in the context of the sensitivity of device characteristics toward fabrication inconsistencies. A major drawback of previous III–V and SiGe BICFET implementations was the inordinate sensitivity of device response to structural deviations. While the Medici simulations also exhibited the negative properties associated with the original double base contact structure investigated at Stanford, the combination of directly doping the alloy region and physically removing the channel from between the base diffusions consistently eliminated or greatly improved previous deficits and anomalous behaviors. These results were encouraging, not only with respect to BICFET responses and characteristics, but with regard to removing excessively stringent fabrication and processing constraints. Behavioral improvement with channel movement, and the relative insensitivity with respect to the magnitude of the offset over the range tested also bodes well for the ease of device production.

References