Chapter 4

Impacts of DC and RF Characteristics from the Association of Collector Doping Profiles and Deep Trench Structure

Preface

SiGe bipolar technology has become a popular fabrication process for wireless applications as its advantages of high quality, excellent stability and low cost. Including the applications in cellular phones, GPS and wireless LAN, SiGe bipolar technology associated with the DT isolation processes could provide high frequency and high isolation performances [1-2] while it increase the fabrication cost. While For low power applications, the cross-talk problems could be possibly suppressed or avoided by the optimizing the circuit orientation without adopting of the DT isolation process if the device characteristic deviations between the device with (denoted as DT devices) and without (denoted as non-DT devices) DT were well studied. However, limited information about this item has been published.

In this chapter, the electrical impacts due to the collector doping profile were continuously discussed with the involving of the deep trench (DT) isolation structure,
which has been widely adopted in analogy and radio frequency integrated circuits for suppressing the signal cross-talk between devices and modules. First, the associated fabrication process flow of the SiGe HBT devices with DT technology were presented along with the corresponding modulation on collector profile. Such physical modulation on collector profile could alternate the DC and RF characteristics of the HBT devices could impact the circuit performance in several ways. It was the first time that the electrical impacts of the DT technology on HBT devices was reported and those discovery and physical origins could benefit the device and circuit designers to fabricate their products with even higher stability and performance.

4.0 Associated Physics

In this section, the associated physics, the base pushing out effect (Kirk effect) of a SiGe HBT device under high current driving operation was introduced. Figures 4.0.1 (a) and (b) illustrated the base-collector (BC) junction under low and higher current injection condition, respectively. Under some specific high current injection, the high-density hole current was injected into the collector and thus compensated the n-type atoms on the low concentration BC junction on the collector side. At the same time, the p-type charges of in the base space charge region would also be sharked for the charge neutralization basis. Such phenomenon was denoted as base pushing out
effect (Kirk effect) and the specific current density level at which the Kirk effect took place was denoted as \( J_K \) in the following literature.

The deep trench isolation structure was fabricated subsequently to the selective collector implantation process. In this study, the HBT devices with (DT) and without DT structure (NDT) were designed in the fixed doping profile. However, several divergence between DT and NDT devices have been found in our study. In the following section, the electrical divergences would be discussed.

4.1 RF Characteristics of Deep Trench and Non-deep Trench Devices

In Figure 4.1.1, the basic parameters of the device RF performance, cutoff frequency \( f_T \) and maximum oscillation frequency \( f_{\text{max}} \) of devices with various collector doping levels, H-group (heavily doped), M-group (medium-doped) and L-group (light-doped) were illustrated. The traces with solid lines were \( f_T \) and dashed lines, \( f_{\text{max}} \). The traces with open symbols were the devices without deep trench structure while the ones with closed marks, the DT devices. The H, M and L-group devices were marked in rectangular, triangular and diamond symbols.

In Fig. 4.1.1, the \( f_T-J_C \) relationships between the DT and NDT devices in M-Group were divergent to each other. Such behavior seemed to be unusual for devices
designed in the fixed doping profiles. In addition, as the collector doping concentration decreased, such divergence was enlarged. On the other hand, as the collector doping level increased, such divergence shrank.

For further identifying the electrical divergence between DT and NDT devices, the DC characteristics of the devices were also pursued. In Figure 4.1.2, the measured values of breakdown voltage $BV_{CEO}$ and the base-collector voltage $C_{BC}$ of DT and NDT devices in H, M and L groups were illustrated. For wafer ID from 6 to 11, the devices were DT devices while from 12 to 17, NDT devices. The data in Fig. 4.1.2 were obtained from 48-points wafer mapping measurement and could be highly representative as the studying base in this research. From Fig. 4.1.2, the $C_{BC}$ values of DT devices was higher than that of NDT devices in M-group and such $C_{BC}$ divergence between DT and NDT devices were enlarged for L-group while for H-group, the divergence shrank. On the other hand, the values of the breakdown voltage $BV_{CEO}$ of DT and NDT devices in the three groups exhibited the similar behavior observed in Figs 4.1.1 and 4.1.2.

In order to identify the physical origins of the behaviors observed in Figs 4.1.1 and 4.1.2, the popular process simulation tool SUPREM-4 has been adopted. The doping species, Phosphorus (P, as the selective collector implant layer (SIC) in n-epitaxy region) and Arsenic (As, as the n-type barrier layer, NBL) presented in the
collector region were simulated for DT and NDT devices in L and H-groups and illustrated in Figure 4.1.3. In Fig. 4.1.3, both SIC and NBL profiles were wider than those in NDT devices. It could be highly possible that excess thermal has been introduced during the DT associated fabrication processes and then widen the profiles. Such profile widening resulting from the excess thermal during the DT technology approximately doubled the n-type carrier concentration at the BC junction edge on the collector side compared with the NDT devices in L-group illustrated in the inserted figure in Fig. 4.1.3. On the other hand, limited concentration increase at the BC junction edge on the collector side was observed for DT devices in H-group resulting from the higher SIC concentration level.

Based on the simulation results in Fig. 4.1.3, the behaviors in Figs. 4.1.1 and 4.1.2 could be demonstrated. First, the breakdown voltage values $BV_{CEO}$ of DT devices were relatively lower than those of the NDT devices in L-group resulting from the SIC profile widening effect. At the mean time, the $C_{BC}$ values of the DT devices exhibited relative lower values compared with those of the NDT devices in L-group resulting from the relatively higher electrical field in the space charge region. Second, the divergent electrical characteristics between DT and NDT devices in H-group in Figs 4.1.1 and 4.1.2 were limited resulting from the limited profile widening induced concentration modulation at the BC junction edge on the collector side. In other words,
increasing the doping level of the SIC layer could successfully suppress the sensitivity of the electrical parameters ($f_T$, $f_J$, $C_B$, and $B_{V,CEO}$) against the excess thermal induced NBL profile modulation during the DT fabrication.

In the subsequent sections, other critical performance factors, which could dominate the RF capability, were reported focused on the DT induced NBL profile modulation.

4.2 RF Noise Characteristics of Deep Trench and Non-deep Trench Devices

In this section, the key parameters, which could dominate the RF and noise characteristics including the minimum noise figure $N_{F,\text{min}}$, association gain $G_{\text{ass}}$, optimum source impedance $\Gamma_{\text{opt}}$ for obtaining $N_{F,\text{min}}$, input and output reflection coefficients ($S_{11}$ and $S_{22}$) and forward transmission coefficient $S_{21}$ would be discussed in accordance with the DT induced NBL profile modulation. It could provide the device and circuit designers to design their product further properly.

4.2.1 Impacts on Minimum Noise Figure and Association Gain

Figure 4.2.1 (a) and (b) illustrated the frequency dependency of minimum noise figure $N_{F,\text{min}}$ and association gain $G_{\text{ass}}$ of DT and NDT devices in L and H-groups.
under $V_{BE}$ 0.85 and 0.9 volts, respectively along with constant $V_{BC}$ 1volt. The $NF_{min}$-freq and $G_{ass}$-freq traces were illustrated in solid and dashed lines in which the NDT and DT devices were illustrated in open and closed symbols, respectively. In Figs. 4.2.1 (a) and (b), the frequency dependent $NF_{min}$ and $G_{ass}$ of DT and NDT devices exhibited inconsistently from 1.8 to 10 GHz. On the other hand, in the H-group, the behavior divergence in between DT and NDT devices was not significant. It was straightforward that the values of the association gain were directly related to the behavior of the small signal forward current gain $h_{FE}$ and thus the behavior of the cutoff frequency $f_{T}$. Similar behaviors of $NF_{min}$ were also observed in Fig. 4.2.1 (a) and (b). $NF_{min}$ could be illustrated in the following formula in terms of the device model parameters [3]:

$$NF_{min} = 1 + \frac{r}{r_{\pi}} [1 + \frac{1}{\beta} (\frac{f}{f_{T}})^2] + \frac{2r}{r_{\pi}} (1 + \frac{r}{2r_{\pi}}) + \frac{1}{\beta} \frac{2r}{r_{\pi}} (1 + \frac{r}{r_{\pi}}) (\frac{f}{f_{T}})^2$$  (4.2.1)

Equation 4.2.1 were derived based on the high frequency noise model and chain-representation theorem. The frequency dependency of $NF_{min}$ illustrated in Figs. 4.2.1 (a) and (b) could attribute to the term $f/f_{T}$ in Eq. 4.2.1. Eq. 4.2.1 provided a direct relation between $NF_{min}$ and $f_{T}$. Besides, the $NF_{min}$ behaviors of DT and NDT devices in L and H groups observed in Figs. 4.2.1 (a) and (b) could directly attribute to the electrical modulation of $f_{T}$ since the other factors in Eq. 4.2.1 were defined by the processes subsequent to DT associated processes.
In addition to the DT thermal induced modulation on the frequency dependency of $\text{NF}_{\text{min}}$ and $G_{\text{ass}}$, the bias dependency of $\text{NF}_{\text{min}}$ and $G_{\text{ass}}$ could exhibit the similar behaviors. In Figures 4.2.1 (c) and (d), $\text{NF}_{\text{min}}$ and $G_{\text{ass}}$ values versus the collector currents of DT and DNT devices in L and H-groups at 2.4 and 5.8 GHz were illustrated, respectively. From Figs. 4.2.1 (c) and (d), the bias dependent characteristics of $\text{NF}_{\text{min}}$ and $G_{\text{ass}}$ for DT and NDT devices exhibited similarly while the divergence of $\text{NF}_{\text{min}}$ and $G_{\text{ass}}$ for DT and NDT devices in L-group grew with the collector current. Such phenomenon could be easily understood from the $f_{T}$-$J_{C}$ relationships of DT and NDT devices in L-group illustrated in Figs. 4.1.1.

4.2.2 Impacts on Optimum Source Matching Point $\Gamma_{\text{opt}}$

In 4.2.1, the impacts of the DT associated excess thermal on the basic RF noise factors of an active device, minimum noise figure $\text{NF}_{\text{min}}$ and association gain $G_{\text{ass}}$ have been discussed. In this paragraph, the DT induced performance modulation on another important factor defining the RF noise of the device, the optimum source matching point $\Gamma_{\text{opt}}$, would be reported.

In Figures 4.2.2 (a) and (b), the frequency dependency of the normalized magnitude and angle of $\Gamma_{\text{opt}}$ for DT and NDT devices in groups L and H were illustrated. Again, similar results could be observed in Figs. 4.2.3 (a) and (b). In order
to obtain the physical origins, the optimum matching admittance $Y_{opt} = G_{opt} + B_{opt}$

and illustrated as follow [3]:

$$G_{opt} = \sqrt{\frac{G_n}{R_n} - \left(\frac{C_i}{R_n}\right)^2}$$

$$B_{opt} = \left(\frac{C_i}{R_n}\right)^2$$

Where

$$R_n = \frac{T}{T_0} [r(1 + \frac{n_c}{\beta}) + r_x \frac{n_c}{2\beta^2} + r^2 G_n]$$

$$G_n = \frac{T}{T_0} \frac{g_x}{2} [n_b + \frac{n_c}{\beta} (1 + \frac{f^2}{f_T^2})]$$

$$C_i = -\frac{T}{T_0} \frac{n_c}{2\beta f_T}$$

(4.2.2)

In Eq. 4.2.2, $n_b$ and $n_c$ illustrated the ideal factors of the BE and BC junction respectively. The optimum source matching point $\Gamma_{opt}$ could be directly defined by $Y_{opt}$ and thus $G_{opt}$ and $B_{opt}$. $T$ denoted as the ambient temperature in absolute unit.

Similar to Eq. 4.2.1, the factors presented in Eq. 4.2.2 were defined by the processes subsequent to the DT associated process except for the cutoff frequency $f_T$. Once again, it was identified that the DT associated excess thermal could modulate the parameters $\Gamma_{opt}$ which defined the input matching network of an amplifier by which the minimum noise figure could be obtained.

Furthermore, the bias dependency of the normalized magnitude and angle of $\Gamma_{opt}$ were illustrated in Figure 4.2.2 (c) and (d) at 2.4 and 5.8 GHz, respectively. At higher collector current levels, the characteristic divergence between DT and NDT devices in
L-group grew while kept consistent for devices in H-group.

From the above discussion, it was demonstrated that increasing the doping concentration in the SIC layer, the divergence of the noise parameters could be suppressed as well. In the following paragraph, the DT induced impacts on the other RF parameters $S_{11}$, $S_{21}$ and $S_{22}$ of the HBT devices would be discussed.

**4.2.3 Impacts on Device S Parameters**

In Figures 4.2.3 (a) and (b), the optimum source matching point $\Gamma_{opt}$ and the output reflection coefficient $S_{22}$ of DT and NDT devices in groups L and H were illustrated in a Smith plane from 50 M to 40 GHz under $V_{BE}$ 0.85 and 0.9 volt, respectively. In the Smith plane, the DT induced modulation on $\Gamma_{opt}$ for various devices could be observed more precisely and directly for circuit designers. It directly reflected how the DT associated process could impact the circuit performance if the L-group devices were adopted. Besides, significant divergence of $S_{22}$ for NDT devices in L-group were discovered in Fig. 4.2.3 (a) and (b). Even for the DT and NDT devices in the H-group, more or less inconsistency could also be found. Based on the definition of the reflection coefficient, the collector profile could directly alternate the reflection coefficient $S_{22}$ of a device. For this reason, finite inconsistency of $S_{22}$ between DT and NDT devices could also be discovered in H-group. In Fig. 4.2.3 (b),
significant divergence of $\Gamma_{\text{opt}}$ between DT and NDT devices in L-group were found. It reflected again that the DT induced electrical modulation could be enlarged as the biasing current grew.

In Figure 4.2.3 (c) and (d), the input reflection parameter $S_{11}$ and forward transmission coefficient $S_{21}$ of DT and NDT devices in L and H groups under $V_{\text{BE}} = 0.85$ and 0.9 volts were illustrated. From Figs. 4.2.3 (c) and (d), the input reflection coefficients $S_{11}$ of the DT and NDT devices in L-group showed small inconsistency to each other while for the devices in H-group, the $S_{11}$ values of DT and NDT devices agreed with each other. It could result from the finite reverse transmission values of the active devices $S_{12}$ that blocked the incident wave from the output port. As a result, the values of $S_{11}$ could reflected limited information from the output port so as to be relatively insensitive to DT associated thermal compared with $S_{21}$ that could reflected the information along the signal path.

From the above discussion, it was demonstrated that the adoption of the DT technology in a designed circuit could failed to meet the simulation target if the device model did not included the DT associated excess thermal effect by which both RF and noise characteristics could be modulated. By heavily doping the collector region, the specific electrical properties could behave consistently while there still existed divergences in the devices parameters including $S_{21}$, $S_{22}$, $Y_{21}$ and $Y_{22}$ that
could induced potential performance instability in RFIC design.

### 4.3 Linearity Characteristics and Power Capability of Deep Trench and Non-deep Trench Devices

The SiGe HBT devices could have great potential to fabricated large signal or power amplifier in analog and RF ICs because of their high driving capability. For higher power application, the linearity and output power could be the critical device indexes for meeting the circuit specs. In this section, the DT associated thermal induced modulation on the linearity factor, third order intersection point TOI, the power gain $G_p$ and power added efficiency $PAE$ for DT and NDT devices in L and H-groups would be discussed.

#### 4.3.1 DT Associated Impact on TOI

In Figures 4.3.1 (a) and (b), the third order intersect point TOI of DT and NDT devices in L and H-groups under sweeping collector current density were illustrated at 2.4 and 5.8 GHz, respectively. From Figs. 4.3.1 (a) and (b), the TOI-$J_C$ values of DT and NDT devices in L-group exhibited significant inconsistency to each other while in H-group, the DT and NDT devices, limited divergence was found. Furthermore, the
characteristic divergence between DT and NDT devices in L-group grew as the
operation frequency was increased from 2.4 GHz to 5.8 GHz. In order to evaluate the
corresponding physical origins, the Voltaera approach [4] have been adopted in this
research associated with the fundamental network theorem by which the TOI values
could be linked to the cutoff frequency $f_T$.

$$OIP_3 \approx \sqrt{\frac{3}{4}} \left( \frac{W_T}{W_R S} \right)^{3/2} (G_{3IT}^2 + G_{3HI}^2 + \xi)^{1/4}$$

(4.3.1)

Where $G_{3IT}$ and $G_{3HF}$ were functions of device parameters including the low
frequency current gain $\beta$, emitter resistance $r_E$, transconductance $g_m$, the source
resistance $R_S$ and the cutoff frequency $w_T (2\pi f_T)$. In addition, the parameter $\xi$ was
simply a function of operation frequency along with $r_E$ and $R_S$. Therefore, the excess
thermal induced NBL profile modulation could also impact the behavior of device
TOI through the cutoff frequency. Furthermore, the peak TOI values could take place
near the current density at which the peak $f_T$ took place as well resulting from the TOI
cancellation created by the nonlinear transconductance and nonlinear storage charge
in the transistor. As a result, The DT associated process could globally impact the
electrical characteristics of the devices.

**4.3.2 DT Associated Impact on $G_p$ and PAE**

Similar to the behavior discussed above in this chapter, the key index $P_{OUT}$ and
PAE of a SiGe HBT for high power applications could be alternated by the DT associated impact. In Figures 4.3.2 (a) to (d), the power gain $G_p$ and power added efficiency PAE of DT and NDT devices in L and H-groups. In L groups, the behavior divergence of $P_{\text{OUT}}$ and PAE between DT and NDT devices could be even significant at higher operation frequency and higher bias current as well.

### 4.4 Conclusion

In this chapter, the deep trench associated impacts on device’s DC and RF performance have been reported and analyzed. Based on the theoretical and experimental results, the electrical behavior divergence could be efficiently suppressed by heavily implanting the collector region. For low power analog and RF application in which the signal cross talk issue could be less significant by carefully layout arrangement. As a result, high SIC concentration non-DT technology could be adopted for saving the fabrication cost and increasing the throughput without degrading the performance and stability of the products. However, the DT associated electrical modulation effects should be included in device model to reduce the IC design risk. The SPICE comparable model for predicting the DT corresponding effect could be valuable research topics.
Reference


Figures and Tables in Chapter 4

Electric current in the collector region under low current density condition

Figure 4.0.1 (a)
Electric current in the collector region under high current density condition

Figure 4.0.1 (b)
$f_T$-$J_C$ and $f_{\text{max}}$-$J_C$ measurement results of DT and NDT devices in H and L groups

Figure 4.1.1
$\text{BV}_{\text{CEO}}$ and $C_{\text{BC}}$ measurement results of DT and NDT devices in H and L groups

Figure 4.1.2
Doping concentration profile of phosphorus, arsenic and total carriers of DT and NDT devices in H and L groups

Figure 4.1.3
Minimum noise figure and association gain of DT and NDT devices in H and L groups versus operation frequency under $V_{BE} 0.85$ volt

Figure 4.2.1 (a)
Minimum noise figure and association gain of DT and NDT devices in H and L groups versus operation frequency under $V_{BE} 0.9$ volt

Figure 4.2.1 (b)
Minimum noise figure and association gain of DT and NDT devices in H and L groups versus operation current at 2.4 GHz

Figure 4.2.1 (c)
Minimum noise figure and association gain of DT and NDT devices in H and L groups versus operation current at 5.8 GHz

Figure 4.2.1 (d)
Magnitude and angle of $\Gamma_{\text{opt}}$ of DT and NDT devices in H and L groups versus operation frequency at $V_{\text{BE}}$ 0.85 volt

Figure 4.2.2 (a)
Magnitude and angle of $\Gamma_{opt}$ of DT and NDT devices in H and L groups versus operation frequency at $V_{BE}$ 0.9 volt

Figure 4.2.2 (b)
Magnitude and angle of $\Gamma_{\text{opt}}$ of DT and NDT devices in H and L groups versus operation current at 2.4 GHz

Figure 4.2.2 (c)
Magnitude and angle of $\Gamma_{\text{opt}}$ of DT and NDT devices in H and L groups versus operation current at 5.8 GHz

Figure 4.2.2 (d)
$\Gamma_{\text{opt}}$ and $S_{22}$ of DT and NDT devices in H and L groups versus operation frequency at $V_{\text{BE}}$ 0.85 volt

Figure 4.2.3 (a)
$\Gamma_{\text{opt}}$ and $S_{22}$ of DT and NDT devices in H and L groups versus operation frequency at $V_{\text{BE}}$ 0.9 volt

Figure 4.2.3 (b)
S11 and S21 of DT and NDT devices in H and L groups versus operation frequency at
V_{BE} 0.85 volt

Figure 4.2.3 (c)
$S_{11}$ and $S_{21}$ of DT and NDT devices in H and L groups versus operation frequency at $V_{BE}$ 0.9 volt

Figure 4.2.3 (d)
Third order intersect of HBT devices in H and L groups versus operation current at 2.4 GHz

Figure 4.3.1 (a)
Third order intersect of HBT devices in H and L groups versus operation current at 5.8 GHz

Figure 4.3.1 (b)
Third order intersect of HBT devices in H and L groups versus input power at VBE 0.85 volt and operation frequency 2.4 GHz

Figure 4.3.2 (a)
Third order intersect of HBT devices in H and L groups versus input power at VBE 0.85 volt and operation frequency 5.8 GHz

Figure 4.3.2 (b)
Third order intersect of HBT devices in H and L groups versus input power at VBE 0.9 volt and operation frequency 2.4 GHz

Figure 4.3.2 (c)
Third order intersect of HBT devices in H and L groups versus input power at VBE 0.9 volt and operation frequency 5.8 GHz

Figure 4.3.2 (d)