Strain-Induced Performance Modulation in IGBT Devices: A TCAD-Based Analysis

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Abstract. In this paper, the performance of an IGBT with a $Si_{0.75}Ge_{0.25}$ layer in the p-body is analyses using TCAD. SiGe has a small bandgap, enhancing carrier mobility and hole injection efficiency and improving conduction characteristics. The simulation results show that the SiGe-engineered IGBT has a total current density (0.822 A/cm^2 vs 0.791 A/cm^2) and a saturation current (24.6 nA vs 23.5 nA) that are 4% and 5% higher, respectively, than those of conventional PT-IGBT structures, yet with the same threshold voltage (0.9 V). These improvements, however, are accompanied by a 2 per cent decline in breakdown voltage (1232 V vs 1257 V) owing to altered impact ionisation rates. The effects of the SiGe p-body are also investigated by analysing the quasi-Fermi levels, which show that the carrier injection barrier in the SiGe device has been reduced, increasing carrier transport efficiency.

Keywords: SiGe, IGBT, TCAD Simulation, Bandgap Engineering, Power Semiconductor, Carrier Mobility.

1 Introduction

Insulated gate bipolar transistors (IGBTs) are used in high-power systems, primarily in applications such as motor drives, renewable energy systems, high power system and power converters [1]–[3]. Since the 1980s, numerous improvements in IGBT technology have achieved a fundamental balance among conduction loss, switching speed, and voltage blocking capability [2,4]. In the last 3 decades, the key improvements to IGBT structures included reducing conduction loss, slow switching speed, and poor voltage blocking [2]–[5]. Early IGBTs suffered from high saturation voltage and tail current [1], which were addressed by optimised doping profiles, trench-gate designs, and local lifetime control, allowing for lower switching losses and higher conduction efficiency [1], [6], [8]. Non-punch-through (NPT) designs meet higher-voltage requirements but incur higher on-state losses [9]. Punch-through (PT) IGBT structures incorporate an N+ buffer layer near the collector to reduce tail current and conduction losses [2], [3], [8]. However, the high electric field near the collector limits

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its reliability above 1.2 kV [5], [9]. [13] has studied the entire evolution of IGBT structures and limitations in detail. To overcome these limitations, the use of different materials other than silicon, such as high-K, SiC, and SiGe, has been prominent. Research on the deposition of SiGe (silicon-germanium) layers in IGBT designs has been impressive [3], [5], [10]. In SiGe IGBT research, the use of SiGe in the carrier storage N region, p-body region, N buffer region, and collector region has been reported, but its use in the P body region has not yet been reported. The combination of Si0.75 and Ge0.25 alters the band gap, a key characteristic of SiGe, thereby increasing carrier mobility and hole injection efficiency [1], [4], [5], [10]. It is a good alternative to conventional IGBTs because this modification increases switching speed, lowers threshold voltage, and reduces conduction loss, which is promising [4],[11],[12].

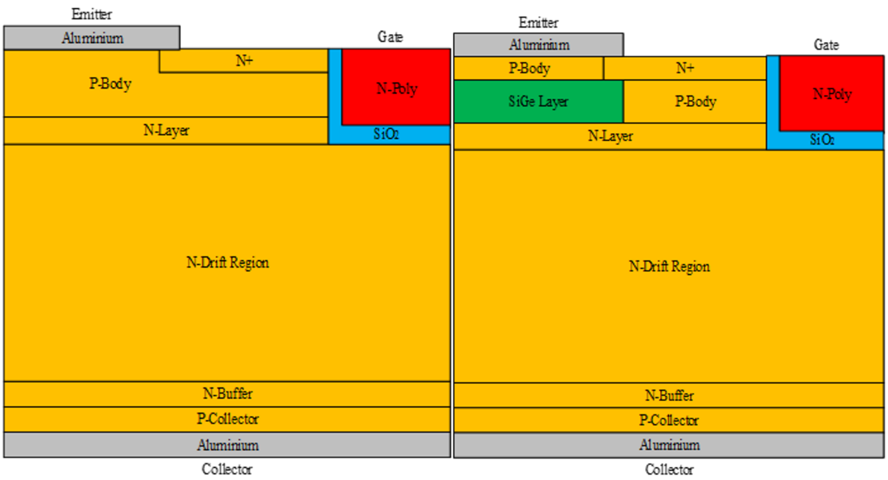


Fig. 1. Device structure of (a) Conventional IGBT (PT IGBT), (b) Device structure of proposed IGBT (SiGe IGBT)

This paper focuses on analysing the use of SiGe material in the P-body region of IGBTs. SiGe also presents integration challenges, particularly about breakdown voltage performance [1]. The modified band gap and doping profile affect the electric field distribution, resulting in changes in breakdown voltage compared to PT IGBTs [1], [10]. Simulation results show a reduction in breakdown voltage of approximately 2%, requiring careful optimisation of the doping profile and drift-field engineering [10-12]. Additionally, the lattice mismatch between SiGe and silicon raises concerns about thermal stability and reliability [5], [7], [11]. This paper builds on previous research [7], [10], [11] by providing a TCAD-based analysis of $Si_{0.75}Ge_{0.25}$ in IGBTs. We incorporate $Si_{0.75}Ge_{0.25}$ into the p-body of IGBTs and focus on a quantitative assessment of the trade-off between improved conduction and a breakdown-voltage drop, supported by in-depth physical analysis using quasi-Fermi-level measurements.

Furthermore, incorporating Si0.75Ge0.25 significantly improves hole mobility, thereby enhancing carrier transport and reducing conduction losses [7]. This will enable more optimised minority-carrier injection, resulting in improved turn-on behaviour and overall performance. The new band gap and doping profile affect the electric field distribution and, consequently, reduce the breakdown voltage compared to PT IGBTs [1],[10]. Nevertheless, despite the challenges, SiGe IGBTs have great potential to be next-generation power semiconductor components, offering improved conduction properties, efficiency, and switching rates. Furthermore, simulations indicate that the overall current density increases by 4%. Thus, improving SiGe-based IGBT structures and mitigating their drawbacks could pave the way for more efficient and reliable power conversion systems.

2 Device Structure

The siGe-IGBT device structure comprises several well-planned functional areas that provide its functionality. The device comprises a monocrystalline silicon substrate and a drift region (3.0 µm × 100 µm), which transports carriers and determines the voltage-blocking capacity through its carrier transport characteristics [2]. The P-body region consists of two sections: an emitter-adjacent part (0.9 µm × 0.5 µm) and a drift-region part (1.0 µm × 2.0 µm). This region is important in the channel formation and turn-on properties. It is covered with a layer of $Si_{0.75}Ge_{0.25}$ (1.0 µm x 2.0 µm) in P-body to increase carrier mobility and the efficiency of hole injection [1],[7]. The change minimizes conduction losses while preserving the threshold voltage.
An N-layer (2.0 µm x 0.5 µm) is added beneath the P-body to enable the movement of electrons through a conductive medium to allow the carriers to flow into the drift region easily [2]. Voltage blocking and charge transport are carried out by the N-drift region (3.0 µm x 96.0 µm) [6]. An N-buffer layer (3.0 µm × 0.5 µm) is positioned near the collector to minimise the electric-field gradient and enhance breakdown characteristics [7-9]. A P-collector (3.0 µm x 0.5 µm) will ensure proper carrier recombination and the collector contact region [9]. The N+ region (1.1 µm x 0.5 µm) is mounted next to the P-body to help in the effective injection of the electrons in the drift region. Other detailed device parameters employed in the simulation are outlined in Table 1.
The emitter (1.0 µm × 0.5 µm, aluminium) is mounted over the P-body and N^+ regions to facilitate charge-carrier injection into the channel. The gate (0.94 µm × 2.94 µm, polysilicon) is positioned above the channel and encased in a SiO_2 layer (vertical: 0.06 µm × 3.0 µm; horizontal: 0.94 µm × 0.06 µm) for switching control and isolation [2]. At the base, the collector contact (3.0 µm × 0.5 µm, aluminium) ensures effective conduction and power dissipation. These regions collectively optimise the trade-off between conductivity, switching speed, and voltage-handling capability in SiGe IGBTs.

Table 1. Key device parameters for simulation.

Parameter	Conventional IGBT	SiGe P_Body IGBT
Geometry (W x L)	3µm x 100µm	3µm x 100µm
Gate length (µm)	2.94	2.94
Gate oxide thickness (nm)	60	60
Collector doping conc.	1 X 10^{19} cm^{-3}	1 X 10^{19} cm^{-3}
Emitter doping conc.	1 X 10^{19} cm^{-3}	1 X 10^{19} cm^{-3}

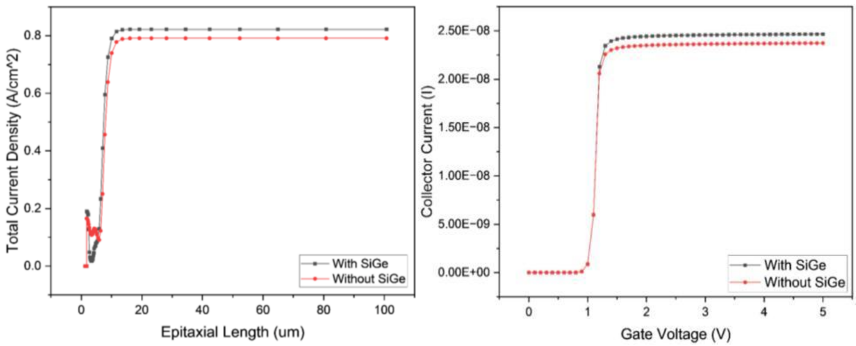
P-body doping conc.	1 X 10^{17} cm^{-3}	1 X 10^{17} cm^{-3}
N-drift doping conc.	1 X 10^{14} cm^{-3}	1 X 10^{14} cm^{-3}
N-buffer doping conc.	1 X 10^{17} cm^{-3}	1 X 10^{17} cm^{-3}
SiGe P-Body thickness	n/a	2
SiGe P-Body mole fraction	n/a	0.25 (25%)
Drift region thickness (µm)	96	96
N-buffer thickness (µm)	0.5	0.5
P-body thickness (total) (µm)	2.5	2.5

2.1 Simulation Framework and Physical Models

All simulations were performed using the Silvaco Atlas TCAD tool, with calibrated physical models, to accurately predict device behaviour. The following models were employed: concentration-dependent mobility (CONMOB), field-dependent mobility (FLDMOB), Shockley–Read–Hall (SRH) recombination, Auger (AUGER) recombination, and the Selberherr impact ionization model (IMPACT SELB) [2,5,12]. We set Bandgap parameters to 1.12 eV for silicon and ~1.0 eV for $Si_{0.75}Ge_{0.25}$ (composition-dependent). Simulations were conducted at 300 K under isothermal conditions. We use a non-uniform mesh with a resolution of <0.1 µm in critical channel and junction regions, and a coarser mesh in the drift region. Mesh convergence was verified by refining the mesh until the current variation remained below 1%.

3 Results and Discussion

The simulation results from Silvaco Atlas show that using a SiGe layer in the IGBT improves its current density, power handling, and efficiency [3],[7],[10],[11]. Simulation models such as concentration-dependent mobility (conmob), field-dependent mobility (fldmob), ShockleyReadHall (srh), Auger recombination (auger), and impact ionization (impact selb)- in the simulation can properly predict device behaviour [2],[5],[12].



(a) (b)

Fig. 2. Comparison Between PT IGBT and SiGe-based IGBTs (a) Total Current Density (TCD), (b) Threshold Voltage and Saturation current.

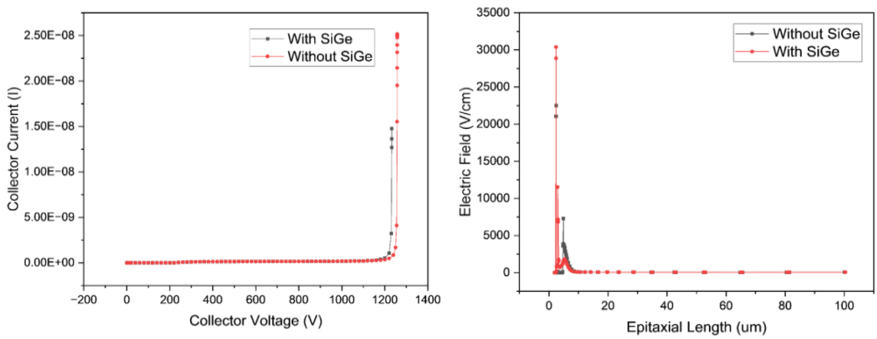
3.1 Current Conduction Characteristics

The current density and saturation characteristics are compared in Figure 2. The overall current density of the SiGe IGBT is 0.822 A/cm^2, which is about 4% higher than the 0.791 A/cm^2 in the conventional IGBT, primarily attributed to improved carrier transportation and lower recombination losses, as explained by the bipolar transport models (Fig. 2(a)).

The breakeven point of the SiGe IGBT and its conventional IGBT is the same at 0.9V, indicating no difference in turn-on with SiGe incorporation (Fig. 2(b)). This makes it compatible with the available drive circuitry while offering increased carrier mobility and conduction efficiency. On the same note, the SiGe IGBT saturation current is 24.6 nA, which is approximately 5% higher than that of the conventional IGBT (23.5 nA), indicating higher conductivity and greater energy waste (Fig. 2(b)).

3.2 Breakdown Voltage Analysis

Fig. 3(a) shows that the breakdown voltage of SiGe-based IGBTs is, however, 1232V, or about 2% less than the 1257V of the conventional IGBT. The SiGe IGBT has a breakdown voltage of 1232 V, which is only about 2% lower than the standard IGBT breakdown voltage of 1257 V (Fig. 3a). The voltage at the collector-emitter at which current grows exponentially should be defined as the breakdown voltage. This volatility in this analysis becomes 1 × 10^-7 A/mm (1 mm device width). It is reduced due to higher impact-ionisation rates in the SiGe layer, which are captured by the Selberherr impact-ionisation model (IMPACT SELB) [4-6,8]. The reduced bandgap of SiGe (approximately 1.0 eV vs 1.12 eV in Si) reduces the critical electric field required to initiate impact ionisation, leading to avalanches occurring earlier. The quantitative behaviour of the 2 per cent decrease in the breakdown voltage is consistent (quantitatively) with the decrease in the critical electric field, which should be approximately 10 per cent between the cases of Si0.75Ge0.25 and silicon, which confirms that the impact ionisation physics determines the physics of breakdown.



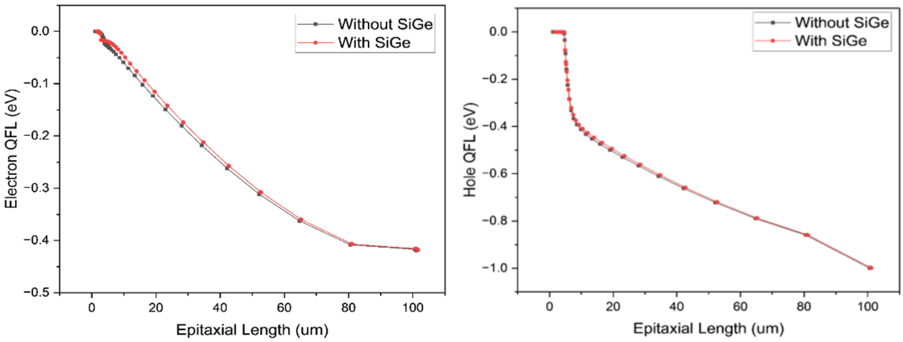
(a) (b)

Fig. 3. Comparison Between PT IGBT and SiGe-based IGBTs (a) Breakdown voltage, (b) Electric Field.

Examination of the electric field distribution (Fig. 3b) indicates that the p-body/n-drift junction of the SiGe structure exhibits a greater peak of the electric field as compared to that of the conventional structure. This field improvement is directly due to the changes in band alignment and doping profiles in the SiGe region. Although the field distribution is more homogeneous in the drift region, it may reduce the formation of hot spots; the dominant feature of the breakdown is the higher junction field.

3.3 Quasi-Fermi Level Analysis

Figure 4 shows that the Quasi-Fermi Level (QFL) analysis further highlights performance differences. The simulation results show that both the Electron QFL (E-QFL) and the Hole QFL (H-QFL) are less negative in the SiGe IGBT than in the conventional IGBT [3], [9], suggesting that the carrier injection barrier is reduced, leading to lower energy losses during charge transport and improved carrier recombination efficiency.



(a) (b)

Fig. 4. Comparison Between PT IGBT and SiGe IGBT (a) Electron-QFL, (b) Hole-QFL.

There are also differences in performance, emphasised by the Quasi-Fermi Level (QFL) analysis [5], [11]. According to the outcomes of the simulation, both Electron QFL (E-QFL) (Fig. 4(a)) and Hole QFL (H-QFL) (Fig. 4(b)) are less negative in the SiGe IGBT than in the conventional IGBT. It implies that the carrier injection barrier decreases, leading to fewer energy losses during charge transport and an enhanced carrier recombination efficiency. As shown in Fig. 4(a), the QFL values are also smaller in the negative, indicating that charge flow dynamics generally improve conductivity and efficiency.

The Silvaco TCAD simulation of the SiGe IGBT shows better current conduction and power efficiency; thus, it is a good choice for high-power electric vehicles and industrial power electronics. The use of SiGe reduces IGBT breakdown voltage, optimises the doping profile, and enables drift-region engineering to balance high conduction efficiency with high-voltage reliability.

3.4 Performance Trade-Off Analysis and Reliability Considerations

The simulation results show a concrete quantitative trade-off: an increment in conduction performance (4% current density and 5% saturation current) and a 2% decrease in breakdown voltage. Such a trade-off would be considered for medium-voltage applications (below 1.2 kV), with low conduction losses in mind rather than the highest voltage margin, which would be greatly served by SiGe engineering. It is also applicable to high-voltage applications where maximum blocking is needed, which may necessitate further optimization to regain the BV loss.
The lattice mismatch introduced by the addition of a Si0.75 Ge0.25 layer on a silicon substrate could induce defect formation at the heterointerface, leading to strain that may shorten the carrier lifetime. Though the scope of this simulation study is not detailed enough to mention the reliability analysis, these points provide significant directions for future research. It would require higher-level 3D electro-thermal simulation and process modelling to measure defect generation and its effect on device lifetime.

4 Conclusion

$Si_{0.75}Ge_{0.25}$ integration in the p-body of an IGBT improves carrier mobility and injection efficiency, resulting in 4% and 5% increases in overall current density and saturation current, respectively, thereby reducing conduction losses by a significant margin. Nonetheless, this is accompanied by a 2% reduction in breakdown voltage due to increased ionisation rates. The threshold voltage remains the same, indicating compatibility with the existing drive circuitry. The key findings are summarized in Table 2. Quasi-Fermi level (QFL) analysis shows that the electron quasi-Fermi level (E-QFL) and hole quasi-Fermi level (H-QFL) are negative in the SiGe-based IGBT compared to conventional IGBTs, indicating a reduction in the carrier injection barrier and dissipation energy during charge transport. The electric field distribution in SiGe-based IGBTs is more uniform, thereby reducing hot spots and leakage current. The lower leakage current improves the reliability and thermal stability of IGBTs. These results demonstrate improved performance for SiGe-based IGBTs. These improvements will be crucial for the development of SiGe-based IGBTs for power electronics in future generations, especially for high-performance energy conversion, transmission systems, and industrial applications.

Table 2. Performance comparison summary.

Parameter	Conventional IGBT	SiGe P-Body IGBT	Change
Total Current Density	0.791 A/cm²	0.822 A/cm²	4%
Saturation Current	23.5 nA	24.6 nA	5%
Threshold Voltage	0.9 V	0.9 V	0%
Breakdown Voltage	1257 V	1232 V	-2%

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