Investigation of Base Transport Mechanism in Silicon-Germanium Heterojunction Bipolar Transistor Operating over Wide Temperature Range

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Abstract. A high breakdown voltage silicon-germanium heterojunction bipolar transistor operated over a wide temperature range from 300 K to 10 K has been investigated. The measured Gummel characteristics illustrate that the collector current and base current both shift to the higher voltage as the temperature decreases. The $f_t/f_{max}$ are extracted to be 23/40 GHz at 300K, 28/40 GHz at 90 K, and 25/37GHz at 10K, respectively. The effective amplification range becomes narrow as the temperature decreases. And the ideality factor of base current in the low current region is shown to be temperature-dependent and its value is much larger than 2 at cryogenic temperatures. This phenomenon indicates that the base current is not only contributed by drift, diffusion, and Shockley-Read-Hall recombination, but also by trap-assisted tunneling. The Hurkx local trap-assisted tunneling has been used to analyze the non-ideal base transport mechanism. And a calibrated TCAD device model is developed to further verify this non-ideal transport mechanism.

1. Introduction
Due to the excellent current gain, radio frequency (RF), and noise characteristics at cryogenic temperature, silicon-germanium heterojunction bipolar transistor (SiGe HBT) has attracted significant attention for quantum computing [1], [2]. For instance, SiGe HBT can be used as a pre-amplifier in quantum computing readout circuit, where the extremely low temperature drops down to 4.2 K, even down to tens of mK [3]. It is important to understand the cryogenic transport mechanisms of SiGe HBT for successful cryogenic applications. At cryogenic temperature, quantum transport mechanisms such as trap-assisted tunneling (TAT) and direct tunneling become non-negligible [4]. John D. Cressler et al have focused on studying the tunneling mechanism of collector current, and found that the direct tunneling was sensitive to the base width and Ge profile [5], [6]. Base transport mechanism has also been investigated, and an analytic TAT model of base current has been developed to describe the non-ideal characteristics [7]. The excess base current caused by non-ideal transport is one of the critical factors affecting the effective amplification range at low temperatures. The excess current leads to a large quiescent operating point, which causes high quiescent power dissipation. This power dissipation will be converted into heat, resulting in the variation of the low-temperature environment. Due to the quantum information is sensitive to the change of temperature, it is important to decrease the quiescent operating point to meet the low power dissipation requirement. However, the base non-ideal transport mechanism affecting the effective operating point at low temperatures has not been studied adequately. In this work, the direct current (DC) and RF performances of SiGe HBT are characterized from 300 K
down to 10 K. The TAT effect in base-emitter junction is introduced to analyze the non-ideal transport mechanism of base current in the low current region. And TCAD simulation calibrated by the device structure and doping profile of the investigated SiGe-HBT has been taken to verify the transport mechanism.

2. Device and Experimental Details

The investigated NPN SiGe HBT device was fabricated by the 0.5 µm SiGe technology and designed as a CEBEC layout structure with an emitter geometry of $2 \times (0.6 \times 20)$ µm$^2$ and a high BVCEO of 6 V at room temperature. The cross-section schematic of the investigated SiGe HBT is shown in Fig.1. After the formation of an n+ sub-collector on the p-type substrate, the lightly phosphorus-doped n− collector epitaxy was deposited. An ultra-thin SiGe base layer with heavy boron doping was epitaxy grown with 14% Ge content. And the device was fabricated with a lightly selectively implanted collector (SIC), a heavily doped poly-Si emitter, and a heavy boron-doped extrinsic polysilicon base. Local oxidation of silicon (LOCOS) was used for device isolation.

![Figure 1](image1.jpg)

**Figure 1** The cross-section schematic of the investigated SiGe HBT.

Device measurements were performed over the wide temperature range from 300 K down to 10 K, which was provided by the Lakeshore Cryogenic Probe Station. To characterize the SiGe HBT’s electrical behavior across temperature, the Gummel characteristics were measured by Agilent B1500A Semiconductor Parameter Analyzer and the S parameters were measured by Keysight PNA-X Network Analyzer from 300 K to 10 K. The forward-active mode Gummel characteristics at $V_{CB} = 0$ V from 300 K to 10 K are shown in Fig.2. These measurement results illustrate that the collector current ($I_C$) and base current ($I_B$) both shift to higher operating voltage as the temperature decreases. After being de-embedded with open and short test structures, the $f_T/f_{max}$ are extracted from S parameters at $V_{CE} = 2$ V, as shown in Fig.3. The $f_T/f_{max}$ have a value of 23/40 GHz at 300K, 28/40 GHz at 90 K, and 25/37GHz at 10K, respectively.

![Figure 2](image2.jpg)

**Figure 2** Forward Gummel characteristics of measured SiGe HBT from 300 K to 10 K.
3. Trap-assisted Tunneling Analysis

As shown in Fig.2, the forward-active mode Gummel characteristics of SiGe HBT were measured at $V_{CB} = 0$ V, which could avoid the additional effects between base and collector caused by junction bias. The non-ideal current in the low current region, especially for base current, becomes more and more obvious when the temperature decreases. The current gain attenuation is caused by the excess base current in the low current region, consequently resulting in the narrowing of the effective amplification range. Fig.4 shows the current gain ($\beta = \frac{I_C}{I_B}$) varying with $I_C$ at different temperatures. The inset of Fig.4 presents the full width at half maxima (FWHM) of current gain as $\text{FWHM} = \log(I_{F,max}) - \log(I_{F,min})$, where $I_{F,min}$ and $I_{F,max}$ are the minimum and maximum collector current at half peak current gain respectively. The results show that the effective amplification range of SiGe HBT becomes more and more narrow as temperature goes down to 10 K. The extracted FWHM and $I_{F,min}$ are plotted in Fig.5. It is obvious that the FWHM decreases, but the $I_{F,min}$ increases with the temperature cooling.

The excess base current caused by the non-ideal transport mechanism at the base-emitter junction is one of the most important factors contributing to the decreasing of FWHM and the increasing of $I_{F,min}$.

Fig.6 shows the ideality factor of base current in the low current region ($N_{F,IBL}$) extracted from Gummel characteristics. The extraction method is shown in the inset of Fig.6, where $k$ is the Boltzmann constant, $q$ is the electron charge and $T$ is the ambient temperature. The $N_{F,IBL}$ is equal to 2 at 300 K and increases to 56 as the temperature is lowered to 10 K. The recombination theory of Shockley-Read-Hall (SRH) has illustrated that the ideality factor must be among 1 to 2. However, there are a large number of traps existing in the base-emitter space charge region (BE SCR). The base current can be aided by Hurkx trap-assisted tunneling (TAT) [4].
The energy band diagram and the paths of the TAT and SRH process are shown in Fig. 7. For the conventional SRH theory, the recombination center $E_t$ captures and emits carriers at the location $x_t$. However, due to the heavy doping of both emitter and base region which leads to a narrow BE SCR, an electron in conduction band at location $x < x_t$ may have a probability of tunneling to a trap $E_t$ at location $x_t$, and have a chance of being captured [8]. Because of the narrow BE SCR and a large number of traps inside the bandgap, the excess base current caused by TAT cannot be neglected, especially at low temperatures. It is well known that the probability of tunneling is weak temperature-
dependent. Hence, the base current in the low current region is dominated by TAT current and the slope is almost constant with temperature varying, as shown in Fig.2.

4. TCAD Simulation and discussion
A 2-D device model is created in Sentaurus TCAD to focus on studying the TAT mechanism in base current over the wide temperature range. The device structure and doping profile of the measured SiGe HBTs are used to calibrate the simulation device model. Simulations are performed by using the hydrodynamic transport model, Phillips unified mobility model, Slotboom bandgap narrowing model, and the Okuto-Crowell avalanche model to match the DC characteristics at 300 K. The local Hurkx model is used to simulate the TAT current of base current.

For the conventional SRH theory, the recombination rate can be expressed as following [8]:

\[
SRH = \frac{n_t^2 \left( \exp \left( \frac{qV_{BE}}{kT} \right) - 1 \right)}{\tau_p(n+n_l) + \tau_n(p+p_l)}
\]  

(1)

Where \( n_l = n_i \exp \left( \frac{E_i - E_t}{kT} \right) \) and \( p_l = n_i \exp \left( \frac{E_t - E_i}{kT} \right) \), \( n_i \) is the intrinsic carrier density, \( E_i \) and \( E_t \) denote intrinsic Fermi energy and trap level respectively, \( n \) (\( p \)) is electron (hole) density, \( \tau_n(p) \) is electron (hole) SRH lifetime. It has been clear that the ideality factor of SRH recombination current cannot be larger than 2. But when the Hurkx model is considered, the carrier lifetime is:

\[
\tau_{n(p)}^{TAT} = \tau_{n(p)} \frac{1 + \Gamma_{TAT}}{1 + \Gamma_{TAT}}
\]  

(2)

Where, \( \Gamma_{TAT} \) is the TAT factor which is related to trapping level and the probability of tunneling. By replacing the \( \tau_{n(p)} \) by \( \tau_{n(p)}^{TAT} \), we can obtain the TAT recombination \( SRH^{TAT} \). The TAT recombination current can be modeled by:

\[
I = qA \int_{x_{BE}}^{x_{EB}} SRH^{TAT} dx
\]  

(3)

Where \( A \) is the area of emitter.

Comparison of \( I_C \) and \( I_B \) between experiment and simulation results using Hurkx TAT model at 300 K, 260 K, and 140 K is shown in Fig.8. The excess base current in the low current region can be well described by the TAT model, which is presented in Eq. (3). Since the heterojunction barrier effects are not considered during the simulation, there is an existing deviation of the base current in the high current region between simulation and experiment [9]. When the temperature is lowered, the collector current and mid base current are higher than the experiment results. This phenomenon may be caused by the temperature dependence of bandgap narrowing introduced by the heavy doping [10].

![Fig.8 Comparison of collector current and base current between experiment and simulation results using Hurkx TAT model at 300 K, 260K and 140 K](image)

5. Conclusion
A high breakdown voltage SiGe HBT operated over the wide temperature range from 300 K to 10 K has been investigated. The measured DC and RF characteristics have illustrated that the collector current and base current both shift to the higher voltage as the temperature decreases. The excess base...
current caused by the non-ideal transport mechanism is one of the dominant factors leading to the narrowing of the effective amplification range. The ideality factor of base current in low current region is shown to be temperature-dependent and much larger than 2 at low temperatures, indicating that the current is not only contributed by drift, diffusion, and Shockley-Read-Hall recombination, but also by TAT. The Hurkx local trap-assisted tunneling model has been used to analyze this non-ideal base transport mechanism. And a calibrated TCAD device model is simulated to verify this non-ideal transport mechanism. The simulation results show that the TAT mechanism dominates the excess base current at low temperatures.

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6. References
[1] W.-T. Wong, M. Hosseini, H. Rucker, and J. C. Bardin, “A 1 mW Cryogenic LNA Exploiting Optimized SiGe HBTs to Achieve an Average Noise Temperature of 3.2 K from 4–8 GHz,” IEEE/MTT-S International Microwave Symposium (IMS), Los Angeles, CA, USA, Aug. 2020, pp. 181–184, doi: 10.1109/IMS30576.2020.9224049.
[2] P. S. Chakraborty, A. S. Cardoso, B. R. Wier, A. P. Omprakash, J. D. Cressler, et al., “A 0.8 THz fmax SiGe HBT Operating at 4.3 K,” IEEE Electron Device Lett., vol. 35, no. 2, pp. 151–153, Feb. 2014, doi: 10.1109/LED.2013.2295214.
[3] M. J. Curry, T. D. England, N. C. Bishop, G. Ten-Eyck, J. R. Wendt et al., “Cryogenic preamplification of a single-electron-transistor using a silicon-germanium heterojunction-bipolar-transistor,” Appl. Phys. Lett., vol. 106, no. 20, p. 203505, May 2015, doi: 10.1063/1.4921308.
[4] G. A. M. Hurkx, D. B. M. Klaassen, M. P. G. Knuvers, and F. G. O’Hara, “A new recombination model describing heavy-doping effects and low-temperature behaviour,” International Technical Digest on Electron Devices Meeting, Washington, DC, USA, 1989, pp. 307–310, doi: 10.1109/IEDM.1989.74285.
[5] H. Ying, J. Dark, A. P. Omprakash, B. R. Wier, L. Ge et al., “Collector Transport in SiGe HBTs Operating at Cryogenic Temperatures,” IEEE Transactions on Electron Devices, vol. 65, no. 9, pp. 3697–3703, Sep. 2018, doi: 10.1109/TED.2018.2854288.
[6] D. Davidović, H. Ying, J. Dark, B. R. Wier, L. Ge et al., “Tunneling, Current Gain, and Transconductance in Silicon-Germanium Heterojunction Bipolar Transistors Operating at Millikelvin Temperatures,” Phys. Rev. Applied, vol. 8, no. 2, p. 024015, Aug. 2017, doi: 10.1103/PhysRevApplied.8.024015.
[7] Z. Xu, G. Niu, L. Luo, and J. Cressler, “A Physics-Based Trap-Assisted Tunneling Current Model for Cryogenic Temperature Compact Modeling of SiGe HBTs,” ECS Trans., vol. 33, no. 6, pp. 301–310, Dec. 2019, doi: 10.1149/1.3487560.
[8] G. A. M. Hurkx, D. B. M. Klaassen, and M. P. G. Knuvers, “A new recombination model for device simulation including tunneling,” IEEE Trans. Electron Devices, vol. 39, no. 2, pp. 331–338, Feb. 1992, doi: 10.1109/16.121690.
[9] K. Lee, D. Cho, K. Park, and B. Kim, “Improved VBIC model for SiGe HBTs with an unified model of heterojunction barrier effects,” IEEE Trans. Electron Devices, vol. 53, no. 4, pp. 743–752, Apr. 2006, doi: 10.1109/TED.2006.871194.
[10] S. E. Swirhun, D. E. Kane, and R. M. Swanson, “Temperature dependence of minority electron mobility and bandgap narrowing in p+ Si,” Technical Digest., International Electron Devices Meeting, San Francisco, CA, USA, 1988, pp. 298–301, doi: 10.1109/IEDM.1988.32816.