Operation of SiGe HBTs at Cryogenic Temperatures

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***Abstract*—The operation of SiGe HBTs at cryogenic temperatures is investigated experimentally and theoretically. It is demonstrated that the collector current at cryogenic temperatures is caused by electron tunneling through the base. The temperature dependence of the transistor characteristics reveals a transition from conventional thermally activated transport at room temperature to tunneling dominated transport at cryogenic temperatures. Experimental results are presented for HBTs with a peak current gain of 8 000 at 300 K and 45 000 at 10 K.**

I. INTRODUCTION

SiGe HBTs are attractive devices for cryogenic applications based on their excellent radio-frequency and noise performance at low temperatures [1], [2]. Transistor operation of SiGe HBTs down to temperatures as low as 70 mK has been recently demonstrated [3]. Moreover, a variety of highly-integrated circuits for operation at cryogenic temperatures has been successfully implemented in SiGe BiCMOS technologies for applications such as space communications and radio astronomy [4], [5].

A challenging application that has been addressed with cryogenic SiGe HBTs is the amplification of extremely weak signals in radio astronomy [6] or in the read-out electronics for quantum computing [7]. The noise characteristics of the transistor are fundamental for such applications. It has been shown in [6] that the noise parameters of the transistor can be estimated from DC characteristics which can be easily measured at cryogenic temperatures. The noise at frequencies significantly below the cut-off frequency of the transistor is dominated by shot noise generated by the DC base and collector currents. In this case, the minimum equivalent noise temperature T_{min} is determined by the current gain β, the transconductance g_m, and the collector current I_{C} according to

$$T_{\mathrm{min}} = qI_{\mathrm{C}}/(kg_m\sqrt{\beta})\,, \tag{1}$$

where q is the elementary charge and k is Boltzmann's constant [6]. Low noise temperatures require high current gain and high ratios of g_m/I_{C} which are both supported by low temperatures.

For an optimization of the transistor characteristics at cryogenic temperatures, it is essential to understand the basic mode of transistor operation in this regime. It has been clearly demonstrated in previous investigations [8], [9], [3] that conventional drift-diffusion theory cannot account for the observed characteristics at cryogenic temperatures. The observed currents at cryogenic temperatures are much higher than those predicted by the theory which is based on thermal activation of charged carrier. In [9], quasi-ballistic transport through the neutral base and enhanced effective electron temperatures have been mentioned as possible reasons for the deviation from conventional theory. However, a clear physical description of the relevant transport mechanism has not yet been worked out.

In this paper, we demonstrate that tunneling of electrons from the emitter to the collector through the base plays an essential role for the operation of SiGe HBTs at cryogenic temperatures. The role of tunneling, e.g., for the characteristics of Schottky barrier diodes at low temperatures has been recognized long time ago [10]. Here, the effect of tunneling on the collector current of SiGe HBTs is investigated. Moreover, we present measured characteristics at temperatures between 300 K and 10 K. The measured temperature dependence of the collector current can be reproduced quantitatively with a transport model that includes conventional drift-diffusion theory and tunneling through the base. Collector currents at cryogenic temperatures are almost exclusively due to tunneling.

II. EXPERIMENTAL SETUP

The investigated HBTs were fabricated in the SG13G2 technology of IHP [11]. In the present experiment, the boron and germanium profiles of the epitaxial base layer were adjusted in order to increase the current gain at room temperature. The peak Ge concentration was increased form 28% in the reference process to 30%. In addition, the peak boron concentration in the base was reduced by a factor of two and the width of the deposited boron profile was doubled. The resulting pinched base sheet resistance of 2.7 kΩ at room temperature is close to that of the reference process.

Transistors with an emitter area of $0.12 \times 0.96\,\mu\mathrm{m}^2$ were characterized at a temperature range from 300 K to 10 K. The diced devices were bonded to ceramic substrates and measured in a LakeShore closed-cycle cryostat. The sample temperature in the cooled helium flow was controlled with a calibrated GaAlAs diode.

III. MEASUREMENT RESULTS

Measured Gummel characteristics for various temperatures are plotted in Fig. 1. The slope of the collector current characteristics strongly increases when the temperature is decreased from 300 K to 77 K. However, this increase of the slope of $I_{\mathrm{C}}(V_{\mathrm{BE}})$ saturates for further reduction of temperature and the measured characteristics at 17 K and at 10 K fall essentially on top of each other. Similarly, the slope of the base current $I_{\mathrm{B}}(V_{\mathrm{BE}})$ first increases with decreasing temperature while the reduction of T from 17 K to 10 K does not change the base current anymore.

The resulting current gain β is depicted in Fig. 2. The measured peak current gain increases from 8 000 at 300 K to 45 000 for temperatures below 36 K. The base current is found to decrease more rapidly with decreasing temperature than the collector current. In SiGe HBTs, the energy barrier that holes have to surmount for injection from the base into the emitter is larger than the corresponding barrier for electron emission from the emitter into the base due to the different

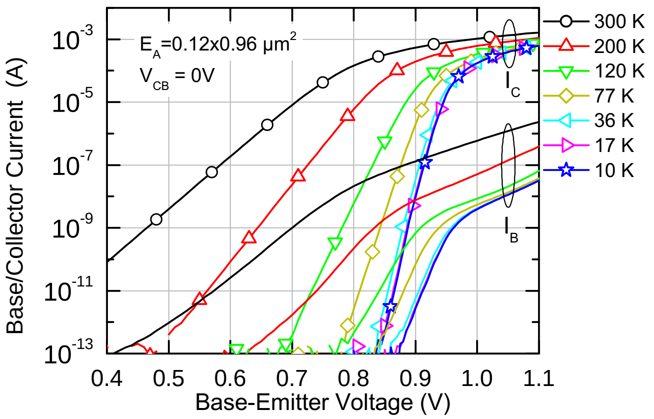

Fig. 1. Gummel characteristics measured at a series of temperatures between 300 K and 10 K for an HBT with an emitter area of $0.12 \times 0.96\,\mu\mathrm{m}^2$. Lines with symbols are collector currents and lines without symbols are base currents

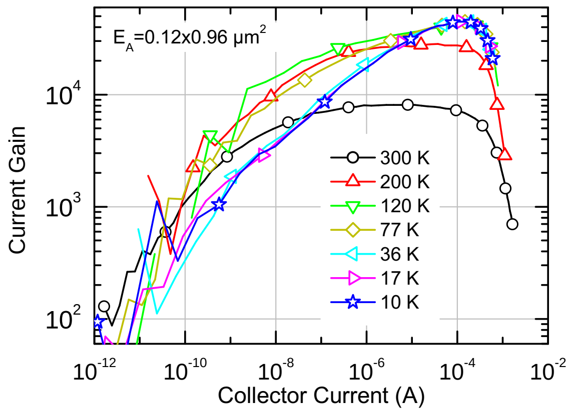

Fig. 2. Measured current gain vs. collector current of an HBT with an emitter area of $0.12 \times 0.96\mu\mathrm{m}^2$ at a series of temperatures between 300 K and 10 K.

band gaps in base and emitter. Consequently, thermionic emission of holes into the emitter decays more rapidly with decreasing temperatures than electron emission into the base. Base currents at cryogenic temperatures are dominated by non-thermally-activated processes such as recombination in the neutral base or tunneling of charge carriers into defect states in the base or emitter regions. The observed very low base currents at cryogenic temperatures are attributed to a low density of recombination centers. As a consequence, we found for the devices with an emitter area of $0.12 \times 0.96\,\mu\mathrm{m}^2$ a current gain greater than 100 down to collector currents of 10 pA for the whole temperature range down to 10 K (Fig. 2). This behavior is favorable for amplification of ultra-low-power signals at low noise.

Next, we take a closer look at the temperature dependence of the measured transconductance. It is plotted in Fig. 3 as a function of collector current and normalized to its ideal value $g_{m0} = qI_\mathrm{C}/kT_0$ at $T_0 = 300\,\mathrm{K}$. According to conventional drift-diffusion theory, g_m is equal to g_{m0} at 300 K for collector currents below the onset of high injection and current limitation by resistive effects. For reduced temperatures, g_m is expected to increase proportional to $1/T$. This relation is roughly fulfilled for temperatures above 77 K. For temperatures below 36 K, g_m/g_{m0} saturates at a value of about 5.

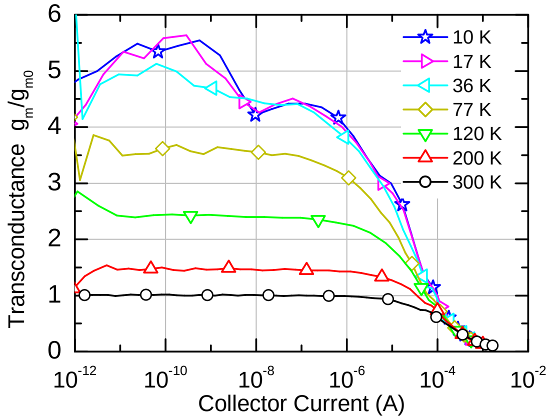

Fig. 3. Measured transconductance g_m vs. collector current of an HBT with an emitter area of $0.12 \times 0.96\mu\mathrm{m}^2$ at a series of temperatures between 300 K and 10 K. The transconductance is normalized to its ideal value at $T_0 = 300\,\mathrm{K}$ given by $g_{m0} = qI_\mathrm{C}/kT_0$.

The observed disappearance of the temperature dependence of the collector current and the transconductance is in qualitative agreement with previous investigations of SiGe HBTs at cryogenic temperatures [9], [2], [3]. However, it is incompatible with the model of thermally activated currents that is assumed in conventional drift-diffusion theory. In the reminder of this paper we investigate an alternative mode of transistor operation at cryogenic temperatures that is based on electron tunneling through the base.

IV. TUNNELING THROUGH THE BASE

We investigate here the tunneling of electrons from the emitter to the collector through the potential barrier defined by the conduction band edge in the base. First, we consider a simple one-dimensional (1D) example with a stepwise constant doping profile in the limit of strong degeneration ($T \to 0$ K). For this case, the tunneling current can be calculated analytically for an arbitrary potential barrier within the WKB (Wentzel-Kramers-Brillouin) approximation.

The probability that an electron with the energy component $E_x = m_x v_x^2/2$ in the tunneling direction can penetrate a potential barrier of height $V(x)$ is given by

$$T(E_x) = \exp\left\{\frac{-4\pi}{h}\int_{x_1}^{x_2}[2m_x(V(x)-E_x)]^{1/2}dx\right\}. \quad (2)$$

Here, h is Planck's constant and x_1 and x_2 are the boundaries of the potential barrier. The tunneling current density

$$j = \frac{4\pi n_\nu q m_\parallel}{h^3}\int_0^{E_m} T(E_x)\int_0^\infty f(E_x+E_r)dE_r dE_x \quad (3)$$

is derived from (2) by integration over the number of tunneling electrons approaching the barrier per unit of time. Here, n_ν is the number of equivalent electron valleys, E_m is the maximum electron energy, and f is the Fermi distribution function. Parabolic bands are assumed with an effective mass m_x in transport direction and an effective density of states mass $m_\parallel$ in the plane parallel to the Si/SiGe interface. For the case of npn

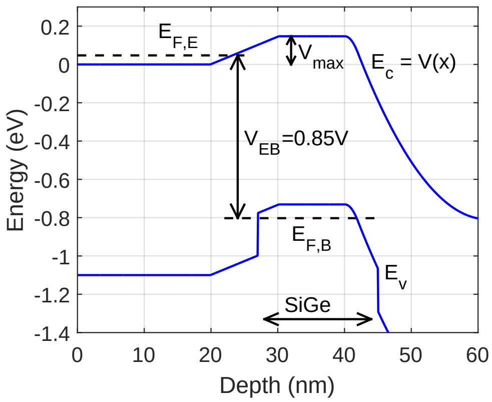

Fig. 4. Band diagram of an idealized HBT structure with stepwise constant emitter, base, and collector doping concentrations of 5×10^{19}, 3×10^{19}, and $3 \times 10^{18}\,\mathrm{cm}^{-3}$, respectively. A 10 nm wide undoped region is inserted between emitter and base doping. The width of the base doping is 12 nm centered in a box-shaped SiGe profile with 30% Ge and 18 nm width.

SiGe HBTs, the strain splitting of the conduction band valley in the SiGe layer results in $n_\nu = 4$, $m_x = m_t = 0.19 m_e$, and $m_\parallel = \sqrt{m_t m_l} = 0.43 m_e$ with the free electron mass m_e. Following the approach of [12], the integral in (2) can be approximated by an average potential

$$\overline{V} = \frac{1}{(x_2 - x_1)} \int_{x_1}^{x_2} V(x)dx \tag{4}$$

resulting in

$$T(E_x) \simeq \exp\left\{-A(\overline{V} - E_x)^{1/2}dx\right\}, \tag{5}$$

where

$$A = \frac{4\pi}{h}\sqrt{2m_x}(x_2 - x_1)\alpha, \tag{6}$$

$$\alpha = 1 - \frac{1}{8\overline{V}^2(x_2 - x_1)} \int_{x_1}^{x_2} [V(x) - \overline{V}]^2 dx. \tag{7}$$

The tunneling current density (3) can be calculated analytically in the limit of strong degeneration ($T \to 0$ K) with the help of the approximation (5) resulting in

$$j = \frac{4\pi n_\nu q m_\parallel}{h^3}\left(g(\overline{V} - E_F) - g(\overline{V})\right), \tag{8}$$

with

$$\begin{aligned} g(x) = {} & \frac{2(\overline{V} - E_F)}{A^2}(1 + A\sqrt{x})e^{-A\sqrt{x}} \\ & + e^{-A\sqrt{x}}\left(\frac{(x^{3/2}}{A} + \frac{3x}{A^2} + \frac{6x^{1/2}}{A^3} + \frac{6}{A^4}\right). \end{aligned} \tag{9}$$

The potential barrier $V(x)$ is defined by the conduction band edge as indicated in Fig. 4. Here, we consider an idealized HBT structure with stepwise constant emitter, base, and collector doping concentrations of 5×10^{19}, 3×10^{19}, and $3 \times 10^{18}\,\mathrm{cm}^{-3}$, respectively. A 10 nm wide undoped region is inserted between emitter and base doping. The SiGe layer has a constant Ge concentration of 30% and extends 3 nm beyond the base doping profile at the emitter and collector sides. The potential barrier of the idealized transistor was calculated from the solution of Poisson's equation in depletion approximation. The corresponding maximum barrier height is given by

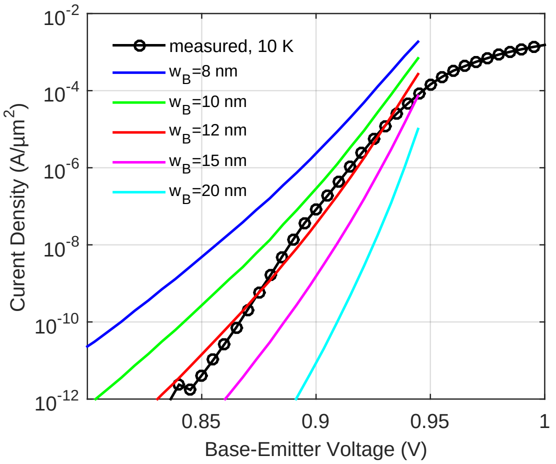

Fig. 5. Calculated tunneling current densities as a function of base-emitter voltage for various base width w_B. Measured collector current densities at 10 K are shown for comparison

$$\begin{aligned} V_\mathrm{max} &= E_{g,\mathrm{B}} + E_{F,\mathrm{E}} - E_{c,\mathrm{E}} + E_{v,\mathrm{B}} - E_{F,\mathrm{B}} - qV_\mathrm{EB} \\ &= 0.997\,\mathrm{eV} - qV_\mathrm{EB}, \end{aligned} \tag{10}$$

where $E_{g,\mathrm{B}}$ is the band gap in the base. The Fermi energy $E_{F,\mathrm{E}}$ in the emitter lies 47 meV above the conduction band edge $E_{c,\mathrm{E}}$.

Tunneling currents calculated from (8) are plotted in Fig. 5 as a function of the base-emitter voltage. The height of the potential barrier is defined by (10). The width of the tunneling barrier is determined by the base width w_B. Larger base widths result in a steeper slope of the tunneling characteristics. Fig. 5 indicates that the calculated tunneling currents are close to the measured collector currents at 10 K for a base width of 12 nm which is close to the experimental value.

V. DEVICE SIMULATION

Simulations of a realistic transistor profile have been performed using Sentaurus TCAD [13]. The vertical doping profile was derived from SIMS measurements. The absolute value of the Ge mole fraction in the base has been used to fit the simulated collector current to the measurements at 300 K. The total boron dose has been fitted to the measured base sheet resistance of 2.7 kΩ. The simulations were carried out using drift-diffusion transport with Fermi statistics and standard parameter models (Masetti mobility model, Slotboom bandgap narrowing model). Only the internal 1D transistor has been considered in the simulation. A rectangular simulation domain with two artificial base contacts at both sides has been used to emulate the 1D transistor. Electron recombination has been disabled at the base contacts. Incomplete ionization has not been considered in the simulation because it only has a minor impact at high doping concentrations.

Sentaurus TCAD supports non-local tunneling according to (3). Simulated Gummel characteristics are shown in Fig. 6. The solid lines represent simulation results which include non-local tunneling of electrons in the conduction band. Simulations

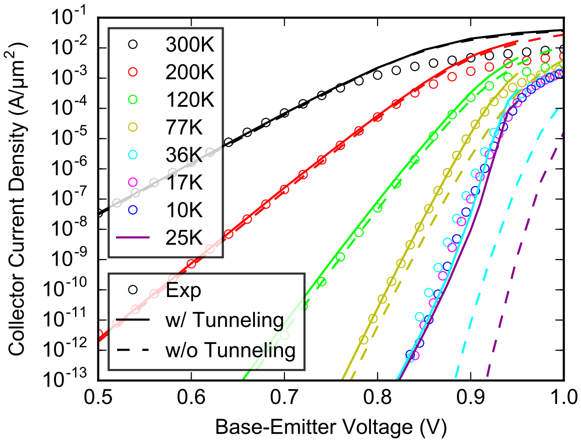

Fig. 6. Measured (symbols) and simulated (lines) collector currents at different temperatures. Simulations with (without) tunneling are plotted as solid (dashed) lines. The neglect of the emitter resistance in the 1D simulation results in an overestimation of the collector current densities at high injection in the theoretical curves.

without tunneling corresponding to conventional drift-diffusion theory are plotted as dashed lines. The lowest simulated temperature is 25 K. Simulations at lower temperatures were not possible due to convergence problems which are related to extremely small minority carrier densities at cryogenic temperatures [14]. The collector current characteristics at 300 K are hardly affected by the inclusion of tunneling. However, the simulations indicate already at 77 K a very strong contribution of the tunneling current to the total collector current exceeding the conventional thermally activated current by about a factor of four. Further reduction of temperature to 36 K and 25 K results in negligibly small currents in the drift-diffusion model due to the small kinetic energy of the carriers. The calculated total collector currents at $T \leq 36\,\mathrm{K}$ are dominated by tunneling of electrons from emitter to collector through the base. This tunneling current is independent of temperature.

VI. CONCLUSION

We have demonstrated here that tunneling of electrons through the base dominates the collector current of SiGe HBTs at cryogenic temperatures. The experimentally observed temperature-independence of collector currents in the cryogenic regime is explained by a transition from conventional thermally activated transport at room temperature to tunneling dominated transport at cryogenic temperatures. In this regime, the transconductance is determined by the width of the potential barrier and no longer by inverse temperature. The shape of the potential barrier is defined by the doping and germanium profiles in the base. The developed physical description of the carrier transport in cryogenic HBTs can guide the optimization of HBT characteristics for operation at cryogenic temperatures. The different modes of operation at room temperature and at cryogenic temperatures impose different boundary conditions for device optimization in the two temperature domains. We presented here experimental results for SiGe HBTs with doping profiles adjusted for a high current gain of 45 000 at 10 K. This high current gain is favorable for low-noise applications. Moreover, the measured current gain above 100 at 10 K down to collector currents of 10 pA for HBTs with emitter areas of $0.12 \times 0.96\,\mu\mathrm{m}^2$ could facilitate amplification at extremely low power.

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NOTE ADDED IN PROOF

An independent report on the tunneling nature of the collector current in SiGe HBTs at cryogenic temperatures [15] was published after submission of this work. The explanations of the collector current in [15] and in the present work agree with each other.

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