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High-injection barrier effects in SiGe HBTs operating at cryogenic temperatures

J.D. Cressler, D.M. Richey, R.C. Jaeger, E.F. Crabbé*, J.H. Comfort* and J.M.C. Stork*

Alabama Microelectronics Science and Technology Center, Electrical Engineering Department, 200 Broun Hall, Auburn University, Auburn, Alabama 36849-5201, U.S.A.

** IBM Research Division, P.O. Box 218, Yorktown Heights, NY 10598, U.S.A.*

Abstract: We demonstrate that high-injection barrier effects associated with the collector-base silicon-germanium (SiGe) to silicon (Si) heterojunction are an important design constraint for SiGe heterojunction bipolar transistors (HBTs) operating at cryogenic temperatures. Due to its thermally activated nature, these barrier effects can have important *dc* and *ac* consequences at cryogenic temperatures even when undetectable under room temperature operation. We use measured results from advanced SiGe HBTs and Si BJTs over a wide temperature range, in combination with simulation, to shed light on the design issues associated with these high-injection barrier phenomena.

1. INTRODUCTION

Because the switching speed of non-saturating bipolar logic families such as ECL is very sensitive to parasitic collector-base (CB) capacitance, care must be taken in designing the collector profile of a high-performance bipolar technology. On the one hand, the collector doping level must be made high enough that base push-out (Kirk effect) occurs at current densities which are outside the circuit operating range. At the same time, however, raising the collector doping level increases CB capacitance, which in turn limits switching speed. An increased collector doping level also enhances impact-ionization in the CB space charge region because of the higher junction field, thereby degrading the breakdown voltage of the device (BV_{CEO}). Thus, there exists a well-known fundamental tradeoff between speed and breakdown voltage in bipolar devices. To minimize these difficulties, state-of-the-art bipolar technologies use advanced self-alignment schemes to minimize total CB junction area. In addition, self-aligned collector ion-implantation is used to locally increase the collector doping level only under the active region of the device where it is needed, hence minimizing the total capacitance of the transistor for a given minimum BV_{CEO} .

There has been considerable recent interest in the optimization of bipolar technologies for use in the cryogenic environment [1]. Due to its excellent performance at low temperatures, the SiGe HBT, in particular, is a very promising candidate for cryogenic applications which require the fastest possible switching speed together with the yield and cost benefits associated with conventional Si fabrication. Through the use of an optimized SiGe BiCMOS technology, for instance, the overall performance of many cryogenic systems could be substantially improved at realistic power consumption levels.

Operation at cryogenic temperatures partially relaxes the fundamental speed-breakdown tradeoff associated with SiGe HBT technology. Due to the increase in junction built-in potential with cooling, junction depletion capacitance decreases by 10-20% between room-temperature ($RT = 300$ K) and liquid-nitrogen temperature ($LNT = 77$ K). Because epitaxial-base profiles can be designed to minimize carrier freezeout in the neutral base, and the cutoff frequency of graded-base SiGe HBTs naturally improves with

cooling, the speed of SiGe HBT circuits can be designed to be faster at LNT than at RT [1]. While impact ionization at fixed collector-base voltage is enhanced with cooling due to higher carrier velocities at low temperatures, the BV_{CEO} of the transistor is only weakly temperature dependent, provided the current gain does not strongly increase at low temperatures [2]. In addition, due to the slight rise in carrier saturation velocity with cooling (roughly 15% between RT and LNT), and the presence of velocity overshoot in the CB space charge at low temperatures, the onset current density of Kirk effect also rises with cooling. The net result is that the collector doping level in an optimized LNT bipolar technology can be decreased compared to a RT design, yielding a substantial advantage in power-delay performance for a given device breakdown voltage [3].

This situation can become considerably more complicated in SiGe HBTs, however, when we take into account the presence of high-injection barrier effects at the SiGe/Si heterojunction in the CB space charge region of the device. As will be shown, these barrier effects can have important *dc* and *ac* consequences at cryogenic temperatures even when undetectable under room temperature operation. In this paper we use a combination of experimental measurements and numerical simulation to explore high-injection heterojunction barrier effects in SiGe HBTs operating in the cryogenic environment.

2. HIGH-INJECTION HETEROJUNCTION BARRIER EFFECTS

In an optimized SiGe HBT, the near-abrupt transition in the CB junction from small base bandgap (SiGe) to large base bandgap (Si) is intentionally located within the CB space charge region so that the bandgap discontinuity is overshadowed by the built-in band bending of the junction. At very high injection levels, however, the excess electron density in the CB space charge region compensates the ionized donor doping, yielding a collapse of the local CB electric field and the consequent widening of the quasi-neutral base (Kirk effect). This "push-out" of the quasi-neutral base under high injection exposes the valence band offset of the SiGe/Si heterojunction, thus preventing holes from moving into the collector. Local charge pileup of holes leads to a new field distribution which induces a conduction band barrier to minority electron transport [4]. The current density at which the conduction band barrier appears, its magnitude, and the net impact on the device properties, depends on many factors, including: a) doping level and depth of the collector epi, b) CB bias, c) saturation velocity, d) the size of the valence band offset (% Ge), e) the built-in potential of the CB junction, and importantly, f) temperature. The barrier first appears at a critical current density ($J_{barrier}$), and produces an abrupt saturation in collector current due to charge pileup in the base. In addition, the charge pileup adversely affects the base transit time, yielding a strong decrease in cutoff frequency (f_T) at current densities beyond $J_{barrier}$. Second-order effects associated with barrier-induced 3-D charge "spreading" can become important as well [4]. In short, these SiGe heterojunction barrier phenomena can in principle negate the positive effects of cooling on the fundamental speed-breakdown tradeoff.

While SiGe/Si heterojunction barrier effects have been investigated by several groups at RT [5-7], in the present study we are most concerned with effects of temperature on the phenomena, and thus its importance in SiGe HBT profile optimization for cryogenic applications. In particular, because changes in the conduction band couple to electron injection in a thermally activated manner, the reduction of the thermal energy with cooling is expected to greatly enhance the consequences of these barrier phenomena on the device terminal characteristics. As will be seen, this is indeed the case.

3. SiGe HBT TECHNOLOGY

The self-aligned epitaxial-base transistor used in the present investigation has a planar structure with a conventional arsenic-doped polysilicon emitter contact (Figure 1) [8]. The base region was formed using the ultrahigh vacuum / chemical vapor deposition (UHV/CVD) low-temperature epitaxy technique [9]. Polysilicon-filled closed-bottom, deep trenches were used to isolate adjacent transistors, and a planar, beakless field oxide was fabricated using a chemical-mechanical polishing technique. The Ge profile was deposited as a trapezoid originating at about 300 nm below the final CB metallurgical junction, and terminating at approximately the metallurgical emitter-base (EB) junction. Because this SiGe HBT was optimized for digital applications at room-temperature (RT), the profile had very little Ge at the EB edge

of the quasi-neutral base. Instead, the Ge profile was strongly graded across the base to induce a large drift-field (about 20 kV/cm) for enhancement of electron transport across the base, thereby improving frequency response. In the as-deposited profile, thin undoped spacer layers ("i-layers" for "intrinsic") were incorporated on both the collector and emitter sides of the neutral base to locally tailor the CB and EB doping profiles. Because this SiGe HBT consisted of n^+ emitter / i-layer / p-SiGe base / i-layer / n^+ collector, the profile will be referred to as an "i-p-i" SiGe HBT design. Ion-implantation of phosphorus was used to form the collector doping profile, and the n^+ collector epi was about 0.5 μm deep. Representative secondary ion mass spectroscopy (SIMS) data from a device wafer is shown in Figure 2. The phosphorus doping concentration at the collector edge of the CB space charge region was about $2 \times 10^{17} \text{ cm}^{-3}$. We would like to emphasize that this SiGe HBT is an optimized design (for RT), and thus does not suffer from low-injection barriers associated with the misplacement of the Ge with respect to the neutral base [10]. Indeed, at RT it is very difficult in these devices to even detect a measurable high-injection barrier, which we know must be present due to the existence of the SiGe/Si heterojunction.

Fig. 1. Schematic device cross section of the SiGe HBT used in this investigation.

Fig. 2. Measured SIMS doping profile of the SiGe HBT.

Because we are examining an effect uniquely dependent on the existence of a SiGe/Si heterojunction, it is highly advantageous to have a Si homojunction device for comparison purposes. The Si BJT used in the present study was fabricated in the same fabrication lot as the SiGe HBT, using the identical transistor structure and processing conditions (complete with CB and EB i-layers). Importantly, the same collector ion-implantation dose and energy were used to ensure that the doping profile in the vicinity of the CB junction was comparable to that of the SiGe HBT. Additional details on the SiGe HBT and Si BJT profiles, and the resultant device and circuit properties can be found in [2,3].

4. RESULTS AND DISCUSSION

To quantitatively address barrier effects in SiGe HBTs operating at cryogenic temperatures, we have measured the dc and ac properties of advanced SiGe HBTs and Si BJTs over the temperature range of 310 K to 84 K. Figure 3 shows the Gummel characteristics of the SiGe HBT at 310 K and 84 K. Observe that at 84 K, at a critical current density of about $3.5 \text{ mA}/\mu\text{m}^2$, the collector current in the SiGe HBT abruptly saturates, yielding a drastic decrease in current gain. The effect is unique to low temperature operation, and cannot easily be observed in this device at temperatures above about 180 K (Figure 4). Figures 5 and 6 compare the collector current and current gain as a function of EB bias for the SiGe HBT and Si BJT at 310 K and 84 K. As can be seen by comparing the results of the SiGe HBT to those of the Si BJT (with a comparable collector profile), the effect is clearly associated with the SiGe-Si heterojunction, and not apparent in the SiGe HBT at RT.

As shown in Figures 7 and 8 the device transconductance (g_m) is a sensitive measure of the change in collector current at high injection levels at cryogenic temperatures. Despite the fact that g_m in both devices increases with cooling as expected, a drastic drop at current densities above J_{barrier} can be seen in the SiGe HBT at LNT. In addition, observe that the peak g_m of the SiGe HBT at RT is in fact slightly lower than that of the Si BJT, which should be the case given that the heterojunction barrier clearly must be present at RT as well as LNT. As expected, the induced conduction band barrier impacts not only dc behavior, but through minority carrier pile-up in the base, also adversely affects the frequency response. Figures 9 and 10 compare the current density dependence of the cutoff frequency of the SiGe HBT and the Si BJT. Despite the increase of the peak f_T of the SiGe HBT from 53 GHz to 59 GHz with cooling, the current density at which the peak f_T is reached decreases by a factor of about 2.5x at 84 K compared to the Si BJT.

Fig. 3. Current-voltage characteristics of the SiGe HBT at 310 K and 84 K.

Fig. 4. Collector current as a function of emitter-base voltage for a variety of temperatures for the SiGe HBT.

Fig. 5. Current gain and emitter-base voltage as a function of collector current at 310 K and 84 K for the SiGe HBT.

Fig. 6. Current gain and emitter-base voltage as a function of collector current at 310 K and 84 K for the Si BJT.

We have also performed numerical simulations using SCORPIO [11] which have been based on the measured SIMS doping profiles for the SiGe HBT (Figure 2). Figure 11 shows a sample SCORPIO simulation of the CB electric field distribution under a collector current density of 2.6 $\mu\text{A}/\mu\text{m}^2$ and 5.0 $\text{mA}/\mu\text{m}^2$. The positive electric field associated with the conduction band barrier can be clearly seen in the SiGe HBT under high-injection. Figure 12 shows the extracted barrier height as a function of collector

Fig. 7. Extrinsic transconductance as a function of collector current for the SiGe HBT at 310 K and 84 K.

Fig. 8. Extrinsic transconductance as a function of collector current for the Si BJT at 310 K and 84 K.

Fig. 9. Normalized cutoff frequency as a function of collector current density for the SiGe HBT and Si BJT at 310 K.

Fig. 10. Normalized cutoff frequency as a function of collector current density for the SiGe HBT and the Si BJT at 84 K.

current density for this device. Observe that the simulated value of J_{barrier} is in reasonable agreement with that inferred from the experimental data in Figure 7. The saturation in induced barrier height occurs at very high current densities when the Kirk effect becomes dominant and the base is completely pushed to the sub-collector.

There are several ways in which the SiGe HBT profile can be designed to minimize these heterojunction barrier effects. First, the collector doping level can simply be increased to raise J_{barrier} to a level which is outside the circuit operating range. We have confirmed this approach by making additional measurements on SiGe HBTs from a wafer which was processed in an identical manner to the one described above except for a decrease in the collector ion-implantation dose. The measured doping concentration at the edge of the neutral collector for this SiGe HBT was about $1 \times 10^{17} \text{ cm}^{-3}$, a factor of two lower than for the original SiGe HBT wafer. Using g_m measurements on an identical device geometry we observed a decrease in J_{barrier} from $3.5 \text{ mA}/\mu\text{m}^2$ to $2.3 \text{ mA}/\mu\text{m}^2$ at LNT. While raising the collector doping level is effective in increasing J_{barrier} , it is clearly not optimum in terms of the speed-breakdown tradeoff. Other techniques for minimizing barrier effects include a) using a more weakly graded Ge profile in the CB space charge region, which minimizes the abruptness of the valence band discontinuity, or b) placing the SiGe/Si heterojunction deeper in the collector, which increases J_{barrier} . These techniques are not always

Fig. 11. Simulated electric field distribution in the SiGe HBT and Si BJT under low and high injection levels.

Fig. 12. Simulated barrier height as a function of collector current density for the SiGe HBT.

practical, however, since both require the use of a thicker SiGe film, and maintaining film stability is a crucial design constraint for a viable SiGe HBT technology [12].

5. CONCLUSION

We have demonstrated that high-injection barrier effects associated with the CB SiGe/Si heterojunction are an important design constraint for SiGe HBTs operating at cryogenic temperatures. Due to its thermally activated nature, these barrier effects can have important *dc* and *ac* consequences at cryogenic temperatures even when undetectable under room temperature operation. At cryogenic temperatures, dramatic reductions in current-drive, g_m , and frequency response are observed experimentally, and are confirmed using simulation. While these heterojunction barrier effects can be minimized by careful profile design, they are expected to have a negative impact on the advantages in speed-breakdown performance that cooling provides.

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