Reduction of $p^+\cdot n^+$ Junction Tunneling Current for Base Current Improvement in Si/SiGe/Si Heterojunction Bipolar Transistors

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Abstract—We report a three order of magnitude reduction in parasitic tunneling current at heavily doped $p^+\cdot n^+$ Si/Si and SiGe/Si junctions grown by rapid thermal epitaxial chemical vapor deposition compared to previously reported results in Si junctions fabricated by ion implantation [1]. The results are very important for the reduction of base current in scaled bipolar transistors, especially for SiGe heterojunction bipolar transistors (HBT's), and also show the high quality of the epitaxial interface.

I. INTRODUCTION

SEVERAL studies have shown that the forward current of heavily doped silicon junctions is dominated by a parasitic tunneling current [1]–[5]. This current is not band-to-band tunneling, but rather the tunneling of both electrons and holes to midgap states at the p-n interface. However, heavily doped layers are desired for good performance of bipolar junction transistors (BJT's) and heterojunction bipolar transistors (HBT's). Scaling of BJT's requires an increase in the base doping to avoid punchthrough, and heavily doped bases are also desired for low base resistance and high Early voltages. High emitter dopings are desired for high emitter efficiency and low series resistance. When the lightly side of the base–emitter junction exceeds a certain doping (> $10^{18}$ cm$^{-3}$ according to [1]), the space-charge region narrows, and tunneling barrier becomes very small. This causes nonnegligible tunneling to the midgap states. This tunneling current becomes a significant component of the base current, especially at low forward biases.

In this paper a significant reduction of tunneling current is reported in epitaxial $p^+\cdot n^+$ junctions grown by rapid thermal chemical vapor deposition (RTCVD) compared to the previous ion implantation results [1]. The implications of these results for HBT performance are also shown. Since Si/SiGe/Si HBT's generally contain high base dopings (e.g., $10^{19}$ cm$^{-3}$ [6] or more), the tunneling base current component becomes especially important. This is illustrated in Fig. 1 where it is shown how the tunneling current is predicted to limit the current gain in a Si/Si$_{0.85}$Ge$_{0.15}$/Si HBT with a base doping $N_B = 5 \times 10^{19}$ cm$^{-3}$ as the emitter doping is increased. Without the presence of tunneling the gain would follow the ideal curve shown in the figure. At high emitter doping levels, the ideal curve bends due to the bandgap narrowing in the heavily doped silicon emitter. With tunneling, the gain curves are predicted to drop rapidly after a certain doping is reached since tunneling causes a significant increase in the base current.

II. EXPERIMENTS AND RESULTS

Epitaxial $p^+\cdot n^+$ (i.e., like a base–emitter) Si/Si and Si$_{0.8}$Ge$_{0.2}$/Si diodes were fabricated by RTCVD. Thick silicon $n^+$ layers ($3-13 \times 10^{14}$ cm$^{-3}$) were grown on n-type substrates at high temperature (850–1000°C). The dopings ranged from $1 \times 10^{17}$ to $1 \times 10^{19}$ cm$^{-3}$. After the high-temperature step, the growth was stopped for 30 s and the temperature was lowered to 700°C to prevent outdiffusion and provide an abrupt junction. Thin epitaxial $p^+$ silicon layers (50 nm), doped $5 \times 10^{19}$ cm$^{-3}$, were then grown at low temperature (700°C). On some of the samples, a thin $p^+$ (30 nm) Si$_{0.5}$Ge$_{0.5}$ strained epitaxial layer was grown at 625°C (doped $5 \times 10^{19}$ cm$^{-3}$) between the $n^+$ and $p^+$ silicon layers. This provided a $n^+$-Si/p$^+$-SiGe junction. The dopings were confirmed by spreading resistance and CV measurements. The values calculated from zero-bias capacitances confirmed the dopings calculated from the slope of $1/C^2$ versus voltage. The junctions were isolated by a
no independent measurement of the multiplication, the depth of the channels, or the extraction of the depletion region's width. However, if a positive voltage is applied to the gate, the channel becomes conductive, and the current density decreases. The gate voltage controls the density of carriers in the channel, and thus the current. The channel width is determined by the distance between the source and drain terminals. The figure shows the relationship between current density and gate voltage for different channel widths.

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**Figure 1:**

- The current density is plotted as a function of gate voltage for different channel widths. The curves show the variation of current density with gate voltage for channel widths of 1, 2, and 3 micrometers.

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**Figure 2:**

- The current density is plotted as a function of gate voltage for different channel widths. The curves show the variation of current density with gate voltage for channel widths of 1, 2, and 3 micrometers.

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**Figure 3:**

- The current density is plotted as a function of gate voltage for different channel widths. The curves show the variation of current density with gate voltage for channel widths of 1, 2, and 3 micrometers.

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**Figure 4:**

- The current density is plotted as a function of gate voltage for different channel widths. The curves show the variation of current density with gate voltage for channel widths of 1, 2, and 3 micrometers.

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**Figure 5:**

- The current density is plotted as a function of gate voltage for different channel widths. The curves show the variation of current density with gate voltage for channel widths of 1, 2, and 3 micrometers.
the junction to confirm this hypothesis, however. Significant tunneling currents have also been observed in base-emitter junctions formed by the poly-Si emitter process [3], [4], but to the knowledge of the authors no data on tunneling current densities as a function of doping at the junction, like that of [1], have been reported.

The beneficial effect of the reduced tunneling current on heavily doped HBT properties can be seen in the simulations of Fig. 1, where the effects of the tunneling levels in our epitaxially grown junctions are contrasted to those previously reported. The reduction in parasitic tunneling current at the same doping level that we observed predicts a shift towards higher emitter doping and an increase in the peak gain. The low tunneling current enables high gain to be maintained to higher base doping levels, enabling reduced base resistances and increased Early voltages.

III. SUMMARY

Vastly reduced forward-bias tunneling current densities of RTCVD-fabricated Si/Si and Si/SiGe junctions compared to ion-implanted results [1] are reported. These results demonstrate the high quality of the epitaxial interface. Low tunneling currents allow higher limits to transistor base and emitter doping levels, which imply higher gains, reduced base resistances, and higher Early voltages of scaled bipolar devices as well as Si/SiGe/Si heterojunction bipolar transistors.

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REFERENCES