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Growth and Transistor Applications of $Si_{1-x}Ge_x$ Structures by Rapid Thermal Chemical Vapor Deposition

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Introduction

In this paper the use of rapid thermal chemical vapor deposition for the growth of $Si_{1-x}Ge_x$ structures and the performance of heterojunction bipolar transistors (HBT's) fabricated in thin films will be described. Specific issues to be discussed include interface abruptness and collector current enhancement, base currents and lifetimes, and tunneling currents at heavily doped junctions

Growth and Rapid Temperature Switching

Our experiments are performed in a low-pressure CVD quartz-walled reactor pumped by a rotary vane pump. The wafer is suspended on quartz pins without a suscpetor and heated by a bank of tungsten-halogen lamps, as in rapid thermal processing. Initial epitaxial growth experiments with such a configuration were done by stabilizing the reactive gas flows while the reactor was cold (no growth), and then starting and stopping the growth reactor by rapidly (300 K/s) ramping the wafer temperature in an open loop fashion. This approach, known as Limited Reaction Processing (LRP) [1], minimizes absolutely the thermal exposure of the substrate. To avoid the resulting extended times at cold temperatures between subsequent layers, we instead start and stop the growth by gas switching techniques with the wafer already at the growth temperature, and directly switch from one growth temperature to another between subsequent layers. The gas switching can be done with minimal extra time at high temperature because typical growth times at low temperature are on the order of minutes, and gas switching takes only on the order of seconds.

Rapidly switching from one growth temperature to another requires an accurate non-invasive monitor of the wafer temperature. Because of the many problems associated with pyrometry in the low temperature range, the wafer temperature can alternatively be monitored in situ by measuring the infrared transmission of the substrate [2]. A schematic of the reactor used for such measurements is shown in fig. 1. Semiconductor lasers at 1.3 and 1.5 μm are modulated and projected onto the wafer, and the transmitted signals are recovered by lock-in amplifiers. This method allows the absolute temperature of the wafer to be measured to within a few degrees without any adjustable parameters such as emissivity, and the growth of thin SiGe layers does not affect the technique. The transmission signal is used as feedback for closed loop control of the lamp power. The degree of control available is shown in fig. 2, where the setpoint for the wafer temperature was alternated between 625 and 700 °C on 20 s intervals. $\sim$5 s is required to switch from one temperature to another. High quality epitaxial growth in our system is performed from 600 to 1100 °C, depending on the optimum conditions for the layer of interest.

HBT Collector Current and Interface Abruptness

$Si/Si_{1-x}Ge_x/Si$ (emitter/base/collector) npn HBT's work on the principle that the narrow bandgap base leads to an increased collector current compared to an all silicon

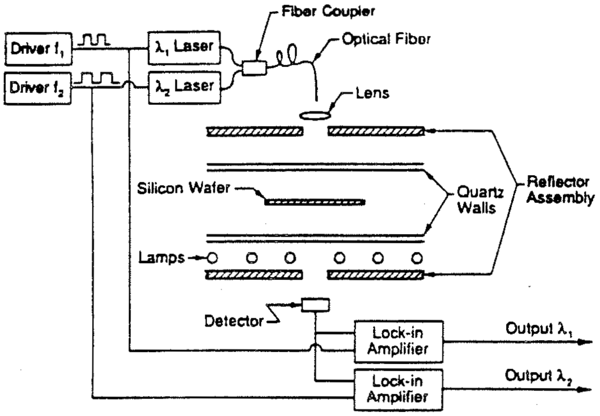

Fig. 1. Schematic view of the RT-CVD chamber equipped for in-situ measurement of infrared transmission.

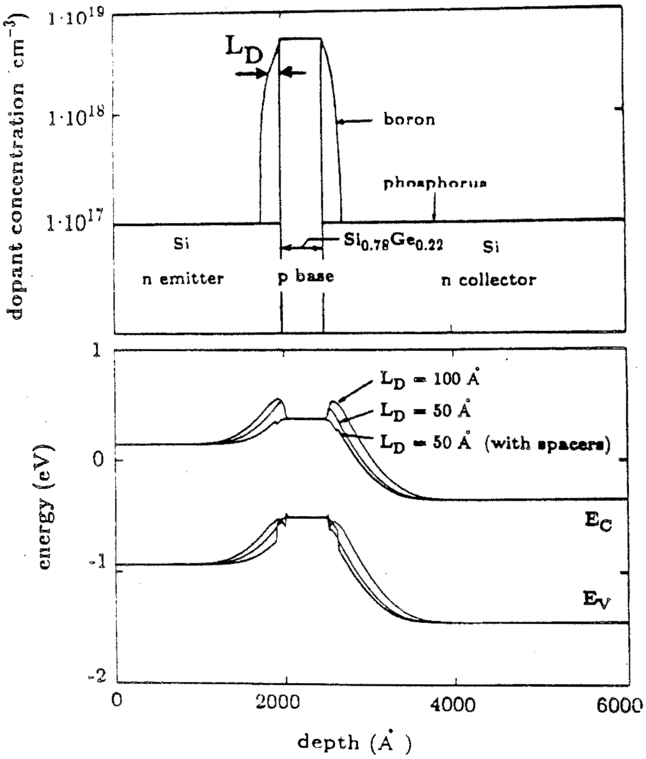

Fig. 3. Boron concentration of the HBT structure used in simulating the effect of boron outdiffusion on device performance, and resulting band diagrams for $V_{BE} = 0.5$ V and $V_{CE} = 1.0$ V. Boron outdiffusion lengths are $L_D = 5$ nm and 10 nm, and 5 nm with 10 nm spacers.

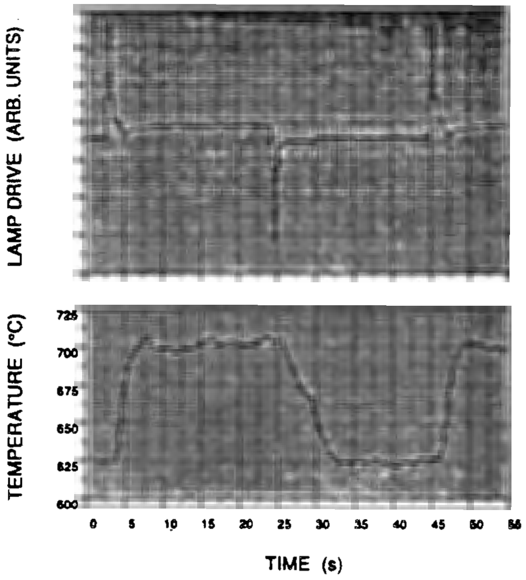

Fig. 2. Wafer temperature (using closed loop control by IR transmission) and lamp power control signal as a function of time as the wafer temperature setpoint is switched between 625 and 700 °C on 20 s intervals.

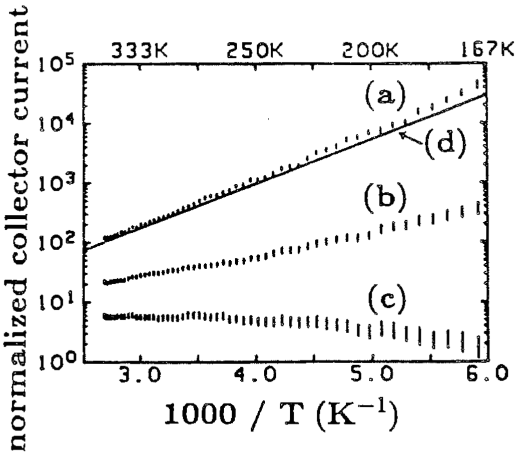

Fig. 4. Data of normalized HBT collector current for (a) $N_B = 10^{19}$ cm^{-3} without spacers, (b) $N_B = 10^{20}$ cm^{-3} with 8 nm spacers, (c) $N_B = 10^{20}$ cm^{-3} without spacers, and (d) prediction by $\exp(\Delta E_G/kT)$.

homojunction device. To first order, this collector current enhancement over that of an all silicon device can be modelled as $\exp(\Delta E_G/kT)$ [3], where ΔE_G is the valence band offset. However, HBT's often contain heavily doped bases and lightly doped emitters and collectors. In this case, outdiffusion of minute amounts of base dopant from the SiGe into the silicon collector or emitter can cause the formation of parasitic barriers in the conduction and valence band (fig. 3) [4]. The dopant tails can be caused by thermal diffusion or by autodoping, etc. during growth. These barriers will reduce the electron flow from the emitter to the collector, reducing the collector current enhancement and thus degrading the emitter efficiency of the device. By comparing actual HBT performance, one can thus extract information on the abruptness of the base-emitter and base-collector interfaces.

HBT structures were grown starting with hydrogen cleaning (1000 °C), followed by n-type (n^+/n) Si epitaxial collector growth (phosphorus, $10^{19}/10^{17}$ cm^{-3}) at 1000 °C, p-type (boron) 50 nm thick $Si_{0.80}Ge_{0.20}$ base layers at 625 °C (~8 nm/min), and finally followed by an n-type (phosphorus, 10^{17} cm^{-3}) Si emitter at 850 °C. The emitter and collector layers were grown at relatively high temperatures because of the relative difficulty in controlling in situ n-type doping during low temperature silicon epitaxy. The 625 °C temperature was chosen for the SiGe to minimize misfit dislocations and islanding.

Temperature dependent measurements of collector current (normalized to that in a silicon device) are shown in fig. 4. Curve (a) is from a device with a "box" profile with coinciding doping and Ge interfaces, with a base boron level of $\sim 10^{19}$ cm^{-3}. The collector current enhancement is very close to that in an ideal box device predicted by $\exp(\Delta E_G/kT)$, as seen in the figure as curve (d). By comparison to simulations, one finds that in this device, any outdiffusion or autodoping of boron in the emitter or collector must be characterized by a diffusion length of at most 3 nm. For more heavily doped bases (10^{20} cm^{-3}), more severe effects would be expected because of the higher levels of dopant in the tails, and because of the near-linear dependence of the boron diffusion constant on boron concentration in this doping range. As seen in fig. 4, the device shows severe degradation compared to the lower doped device. Simulations shows this degradation to be consistent with an outdiffusion length of ~15 nm, roughly what is predicted by process simulations of the emitter growth (3 min, 850 °C) and implant annealing (10 min, 800 °C) cycles. Therefore we conclude that the degradation in interface abruptness can be attributed to thermal diffusion after growth of the interfaces, and is not due to an inherent non-abruptness of the grown interfaces, down to the nm scale.

To improve performance in the case of outdiffusion, undoped silicon-germanium spacers at the SiGe/Si interface can contain the boron within the SiGe layer and prevent the formation of parasitic barriers (fig. 3). As expected, heavily doped devices with 8 nm spacers show much improved collector current compared to devices without spacers (fig. 4).

Base Current and Lifetimes

Although there are many parasitic components of base current, in modern npn bipolar transistors the dominant source of base current should be the injection of holes from the base to the emitter. In narrow bandgap base HBT's, the barrier faced by holes from base to collector is unchanged as the base bandgap is changed. Therefore the base current should not depend on the composition of the base. Such results have been achieved by devices grown by UHV-CVD [5], but previous results by LRP had base currents which depended on the base composition [3]. These devices had high levels of oxygen in the SiGe base ($\sim 10^{20} cm^{-3}$) which may have reduced the lifetime and caused

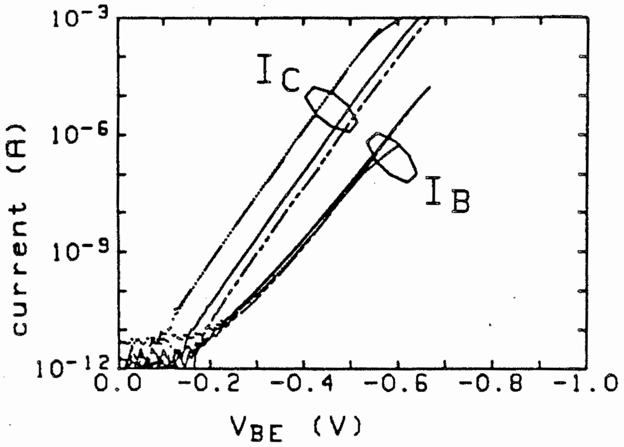

Fig. 5. Gummel plots of HBT's with varying base composition grading. 0 - 20% Ge, dot-dash; 7-20% Ge, solid; 13-20% Ge, dashed; and 20% Ge not graded, dotted.

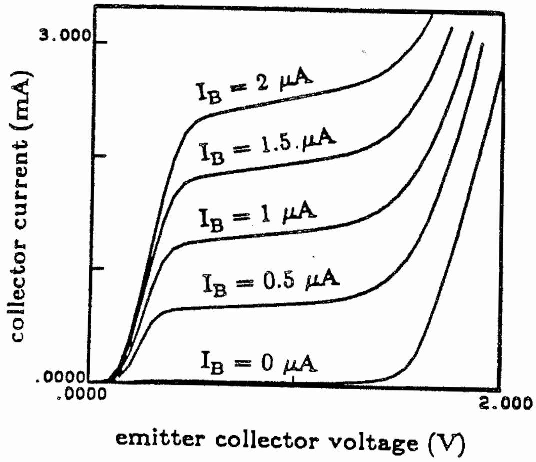

Fig. 6. Curve-tracer characteristics of a 13-20% Ge graded device at room temperature with a collector doping of 5 x 10^{17} cm^{-3}. The current gain is 2000.

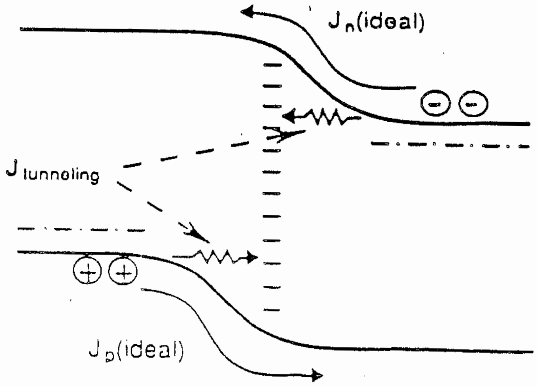

Fig. 7. Schematic view of tunneling by deep levels at p^+-n^+ junctions.

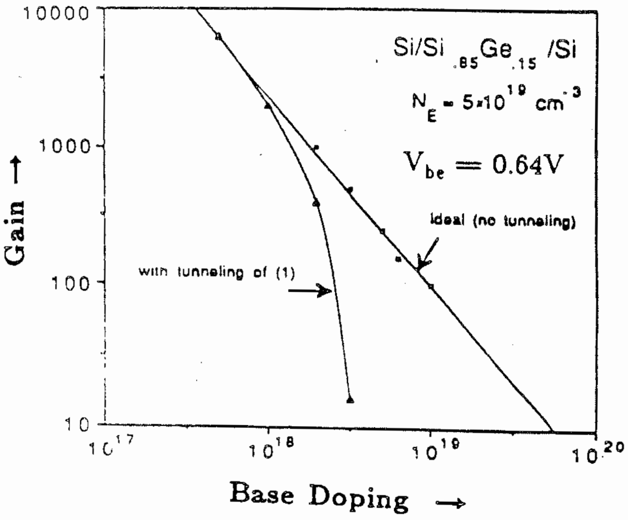

Fig. 8. Calculated gain of a $Si/Si_{0.85}Ge_{0.15}/Si$ npn HBT as a function of base doping using the tunneling data of [6].

the base current to be dominated by neutral base recombination. Through the use of a load-lock, oxygen concentrations in our 625 °C SiGe films have been reduced to below ~2 x 10^{18}cm^{-3}, and generation lifetimes in the μs range have been measured. Gummel plots of 4 HBT's with different base compositions, 0 (emitter side) to 20% (collector side) graded Ge content, 7 - 20% graded Ge, 13 - 20% graded Ge, and 20% - 20% Ge (not graded), are shown in fig. 5. As expected, the collector currents increase as the base germanium content is raised, but the base currents, which have a near ideal slope, are virtually identical in all devices. This shows that the base currents are indeed dominated by hole injection into the emitter, and not affected by base recombination. With such ideal base currents, one finds high gain in the devices (fig. 6) which is conserved at low temperatures for devices with sufficient amounts of germanium.

Tunneling Currents of Heavily Doped Junctions

HBT applications will probably require heavily doped bases for low base resistance. If such bases are used with a heavily doped emitter, the base emitter junction will be a n^+-p^+ junction. This can cause a parasitic source of base current coming from tunneling at the n^+-p^+ junction mediated by deep levels at the p^+-n^+ interface (fig. 7). As opposed to normal space-charge region recombination current, this current increases as the doping levels increase and space-charge regions decrease in thickness.

Based on measurements of this current in p^+-n^+ implanted junctions [6], one can calculate that the gain of a Si/SiGe HBT with an emitter doping of 5 x 10^{19}cm^{-3} would be sharply reduced if the base doping rises above 3 x 10^{18}cm^{-3} (fig. 8). This effect was experimentally investigated by growing abrupt n-Si/p^+-Si (or p^+-$Si_{0.80}Ge_{0.20}$) junctions with varying n doping and 10^{20}cm^{-3} p-doping. Typical results showing tunneling at low bias levels for a silicon device (n doping = 9 x 10^{18}cm^{-3}) are shown in fig. 9. Similar results were seen in Si and SiGe layers, with the tunneling current increasing as the n-doping level was increased. Results for all devices are summarized in fig. 10 for a bias level of 0.48V, along with the ion implanted junction data of [6]. From this data, one sees that the tunneling current in our junctions is ~ 3 orders of magnitude less than that in the ion implanted results, implying a similar reduction in the deep level interface states that mediate the current. This has the significance that the degradation of gain at high base doping in fig. 8 can be pushed out to base dopings of over 10^{19}cm^{-3}, an order of magnitude increase.

Conclusion

Rapid thermal processing using gas switching and infrared transmission for temperature control has been used to grow Si/SiGe/Si structures for heterojunction bipolar transistors. Based on temperature dependent transport measurements, the resulting devices have an intrinsic interface abruptness of at worst 3 nm, which can be degraded by subsequent thermal diffusion effects, especially in very heavily doped devices. The devices have near ideal base currents which are limited by hole injection into the emitter. Finally, the low tunneling currents at p^+-n^+ junctions show that heavily doped base-emitter junctions can be used in HBT's without the degradation of device properties.

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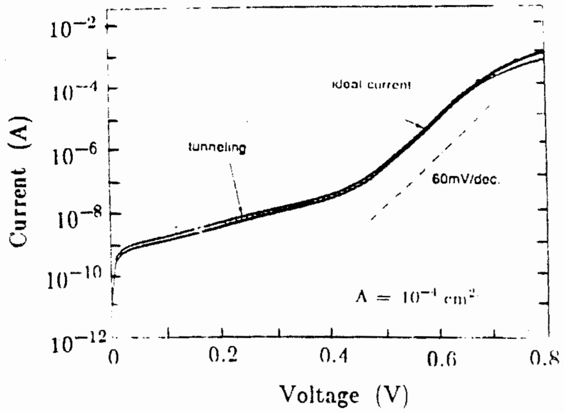

Fig. 9. Typical I-V characteristics ($N_D = 9 \times 10^{18}$ cm^{-3} showing tunneling at low currents.

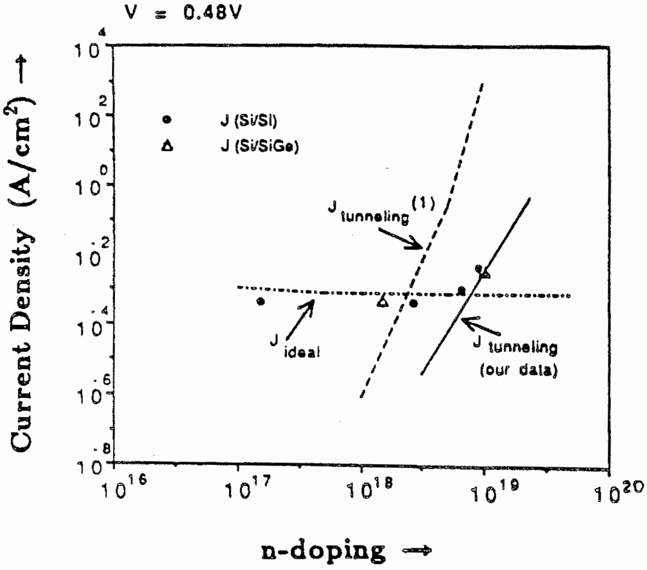

Fig. 10. Comparison of our currents at 0.48 V with the ion implanted data of [6] as a function of n-doping.