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$Si/Si_{1-x-y}Ge_xC_y/Si$ Heterojunction Bipolar Transistors

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Recently, great interest in silicon-based heterojunction devices has been caused by high-speed $Si_{1-x}Ge_x$ base HBTs with f_t exceeding 100 GHz. [1, 2] To extend silicon heterojunction technology beyond strained $Si_{1-x}Ge_x$, several groups have pursued $Si_{1-x-y}Ge_xC_y$ alloys, which are of interest because carbon is expected to allow the possibility of strain-free silicon heterostructures which will eliminate a major constraint on device design. Several groups [3,4] have succeeded in growing strain compensated $Si_{1-x-y}Ge_xC_y$ layers on silicon, but to date there have been no $Si_{1-x-y}Ge_xC_y$ electrical devices of any kind or experimental bandgap studies reported. In this paper we present the first electrical devices of any kind containing $Si_{1-x-y}Ge_xC_y$ alloys and present preliminary measurements of $Si_{1-x-y}Ge_xC_y$ bandgaps. Temperature studies of these devices indicate that the partially strain compensated $Si_{1-x-y}Ge_xC_y$ bandgap remains comparable to the bandgap of strained $Si_{1-x}Ge_x$, a most surprising and fortuitous result.

The epitaxial layers were grown by rapid thermal chemical vapor deposition (RTCVD). The base layers were grown at 550°C using a mixture of DCS, germane, diborane, and methylsilane (the carbon precursor). The emitter was then grown at 700°C using silane and phosphine. Four device structures were fabricated with different levels of C in the base while holding the Ge content fixed. Figure 1 shows x-ray diffraction (XRD) spectra from the four HBT structures. The base of the control device (1665) contained 25% Ge and no C. As C was added, note that the peak of the strained $Si_{1-x-y}Ge_xC_y$ layers moved towards the Si substrate peak, indicating a reduction of strain. From Fig. 1, C fractions of 0.001, 0.007, and 0.011 were estimated for samples 1673, 1675, and 1676, respectively.

Double-mesa transistors (Fig. 2) were fabricated by a very simple three mask process using a combination of selective wet and dry etching designed to examine the transport of electrons in the base and to determine the bandgap of the base, not for high performance. Figure 3 shows the I-V characteristics of the BE and BC diodes from the device with 0.7% C. Figure 4 shows the HBT characteristic from the same sample (0.7% C), showing well behaved transistor characteristics with $V_A > 100V$ and a $V_{B,CEO} = 5V$. The low gain (~2.5) was limited by excessive base current, presumably due to recombination at the unpassivated mesa edges. Note that the collector current, which depends on transport across the $Si_{1-x-y}Ge_xC_y$ base, was ideal (see Gummel plot, Fig. 5).

Figure 6 shows the ratio of the collector currents in devices with 0.7% and 1.1% C in the base to that of the control device as a function of inverse temperature. Using this standard technique for narrow base HBTs [5], the slope can be used to give the difference in bandgap of the base regions. The curves are nearly flat, indicating that the bandgap of the $Si_{1-x-y}Ge_xC_y$ alloys did not increase as C was added. This indicates that it should be possible to grow completely strain-free $Si_{1-x-y}Ge_xC_y$ structures which still have a substantial bandgap reduction compared to Si. The HBT results are consistent with photoluminescence of similar $Si_{1-x-y}Ge_xC_y$ layers grown in our lab (Fig. 7), which also show that the bandgap of strained $Si_{1-x-y}Ge_xC_y$ on Si does not increase as C is added. These results appear to be consistent with the theoretical calculations of Ref. 6 which predict a surprisingly low bandgap for dilute C alloys due to strong atomic relaxation around certain substitutional C sites.

In summary, we have demonstrated the first electrical devices of any kind in the $Si_{1-x-y}Ge_xC_y/Si$ heterojunction system. The HBTs demonstrated the potential promise of this new material system and also show that it may be possible to achieve a significant bandgap offset relative to silicon with a strain-free material.

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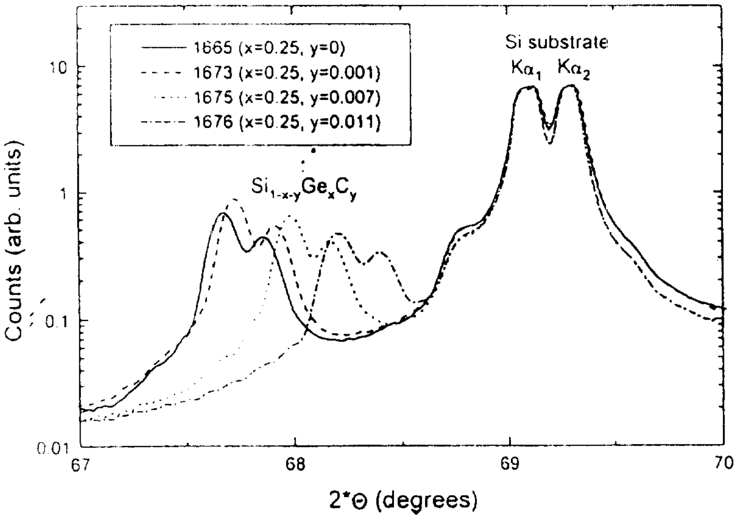

Fig. 1. X-ray diffraction spectra from four SiGeC HBT structures.

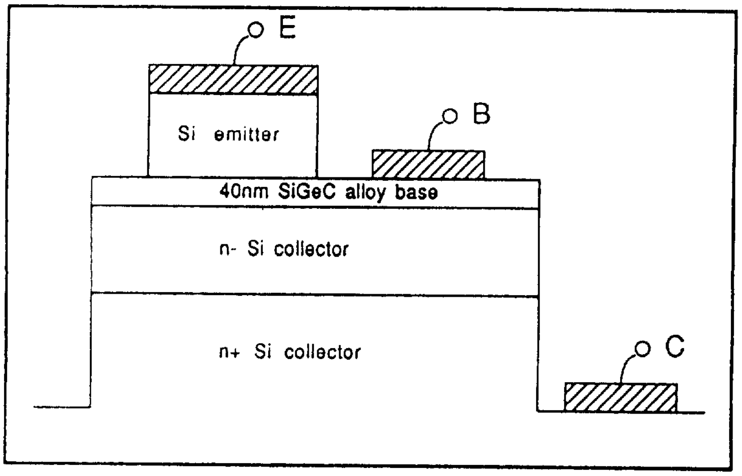

Fig. 2 Cross section of the SiGeC HBT structure.

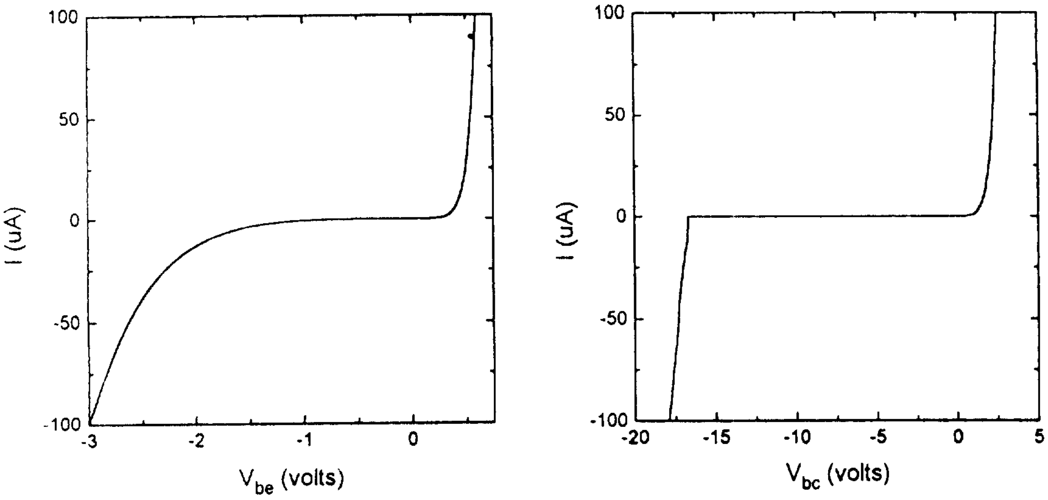

Fig. 3. Emitter-base and collector-base diodes of SiGeC HBT with 0.7% C in the base.

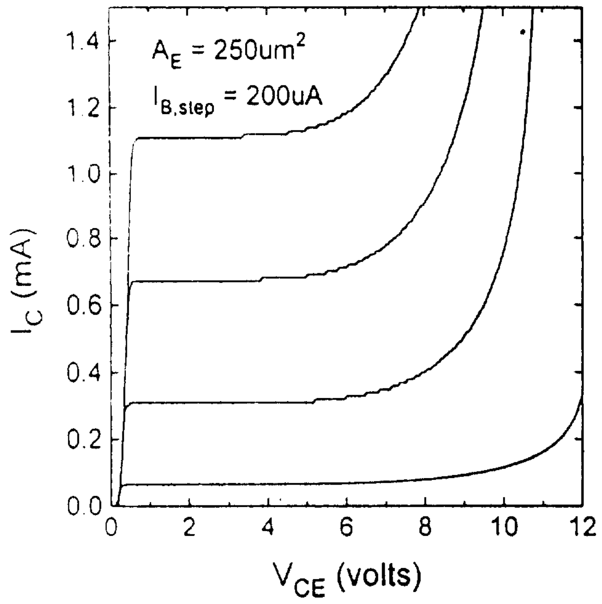

Fig. 4. Common-emitter characteristics of SiGeC HBT with 0.7% C in the base.

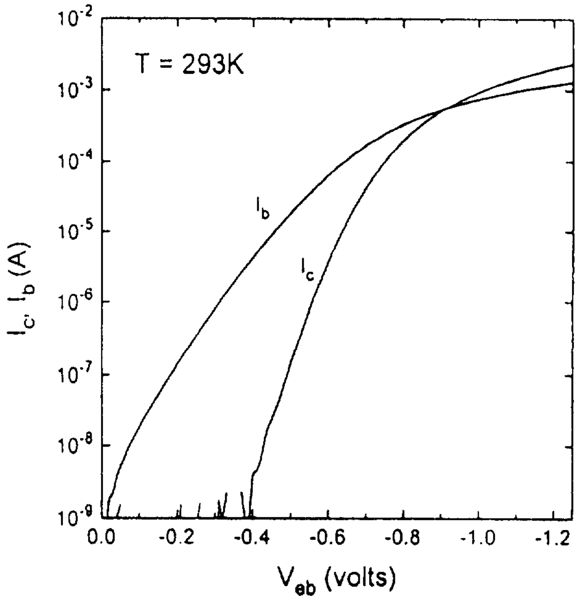

Fig. 5. Gummel plot of SiGeC HBT with 0.7% C in the base.

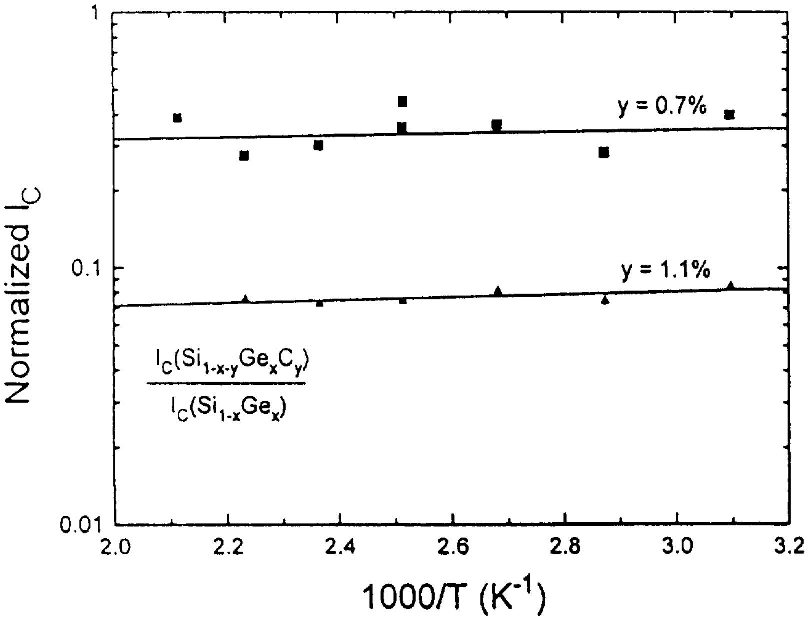

Fig. 6. Normalized collector current vs. inverse temperature from two SiGeC HBTs.

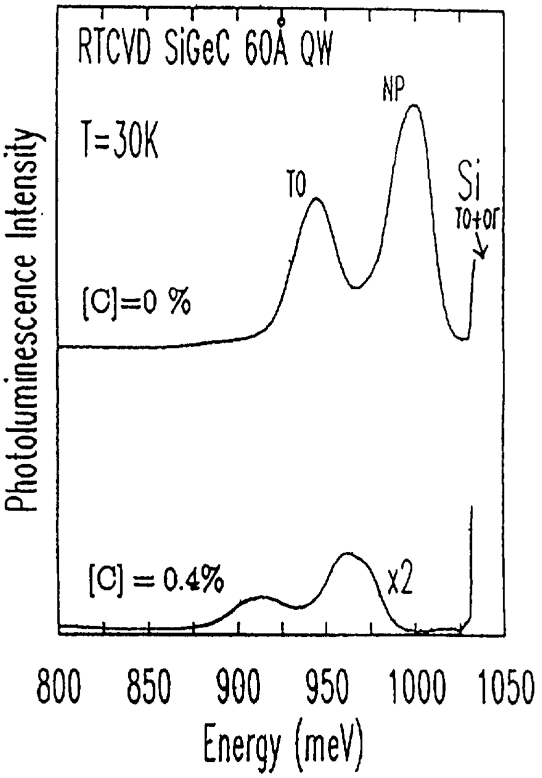

Fig. 7. Photoluminescence spectra from two quantum wells.