Bandgap dependence of band-to-band tunneling and defect-mediated excess currents in SiGe/Si heterojunction tunnel diodes grown by RTCVD

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There is great interest in SiGe/Si heterojunction tunnel diodes for novel devices such as sharp subthreshold slope MOSFET's. High tunneling current densities are a clear goal (for MOSFET drive current, e.g.). This work presents two clear results: (i) a direct measurement of the dependences on bandgap (Ge fraction) of the direct tunneling current vs. the "excess" defect-assisted tunneling current, and (ii) the highest direct tunneling currents (NDR current peaks) observed in Si-based heterojunction diodes grown by chemical vapor deposition.

The device structure (Fig. 1(a)) uses in-situ boron-doped $Si_{1-x}Ge_x$ layers grown by rapid thermal chemical vapor deposition (RTCVD) at 625°C on phosphorus-implanted Si (100) wafers (n-type doping of 3×10^{20} cm^{-3} by SIMS analysis) (Fig. 2). Critical technology issues were the reduction of series resistance and the annealing (1000 °C) of implant damage to reduce tunneling via defect states. Very repeatable negative differential resistance (NDR) was observed with a peak current density 0.21 kA/cm^2 and peak-to-valley ratio 2.25 (for x = 0.30) (Fig. 1(b)). The previous highest peak current by CVD was 0.18 kA/cm^2 [1], although higher numbers were seen by MBE with more Ge and delta doping layers [2].

For analysis, we focused on tunneling in forward bias, because the NDR peak allows one to separate the band-to-band tunneling from the ever present "excess" current, which is mediated by defects and thus depends on fabrication technology (Fig. 3). The excess current does not have a NDR peak and is still present for a few tenths of a volt bias, while the band-to-band tunneling peak is by then forbidden. The data (Fig. 4) shows a clear NDR peak for x = 0.3, which is weaker for x = 0.22 and is swamped by excess current for x = 0.16. Both the band-to-band tunneling and excess currents increase strongly as bandgap decreases, although the direct tunneling increases faster (Fig. 5). This allows one to extrapolate to higher amounts of Ge and lower bandgaps, and to calibrate direct tunneling models in Si-based devices for numerical simulators. Conventional <u>homojunction</u> tunneling models also predict a steeper dependence on bandgap for tunneling current [3] (J_{peak}) than excess [4] current.

$$J_{peak} \propto \frac{qm^*}{2\pi^2\hbar^2}\exp\left(-\frac{\pi\sqrt{m^* E_g^3}}{2\sqrt{2}\hbar q\,|\vec{E}\,|}\right)\cdot\left(\frac{\overline{K}}{2}\right)\cdot D \qquad\qquad J_{excess} \propto \exp\left(-\frac{4\sqrt{2m^* E_x^3}}{3\hbar q\,|\vec{E}\,|}\right)$$

However, because factors such as K and D depend indirectly on bandgap in complicated ways, and these models do not take heterojunction effects, strain and band splitting, and impurity bands etc. into account, it is difficult to precisely relate them to experiment. We think the lower dependence on bandgap of the excess current is due to the lower tunnel barrier faced in a single step in that process.

In summary, we have shown SiGe/Si tunnel diodes with high peak current density and a clear trend of more dominant band-to-band tunneling over excess current as bandgap is reduced. This work was supported by the DARPA STEEP program.

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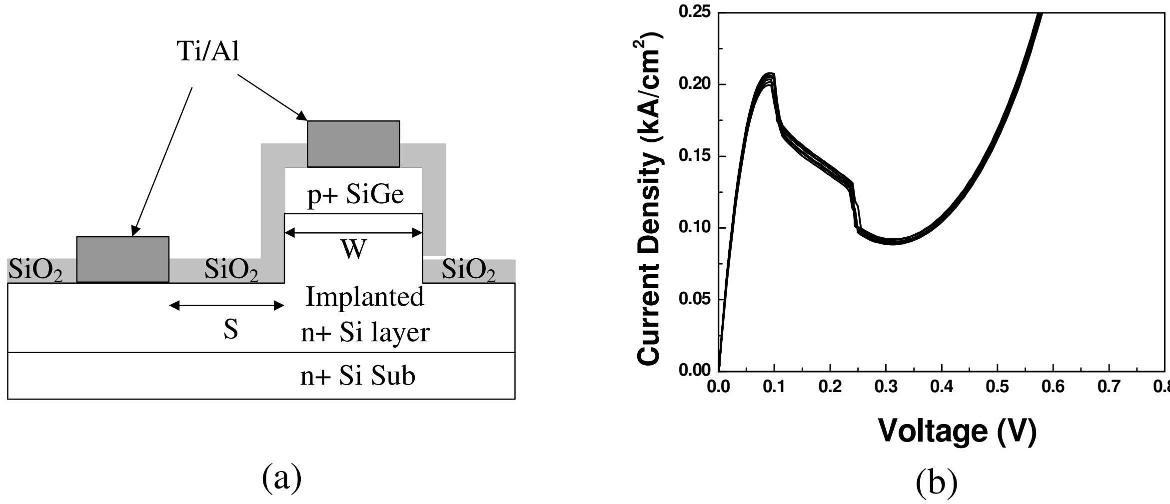


Fig. 1 (a) Cross section of test $Si_{1-x}Ge_x$/Si tunneling diodes; (b) I-V curves of 8 $Si_{0.7}Ge_{0.3}$/Si tunneling diodes with NDR effect. Side contacts were used to reduce series resistance effect.

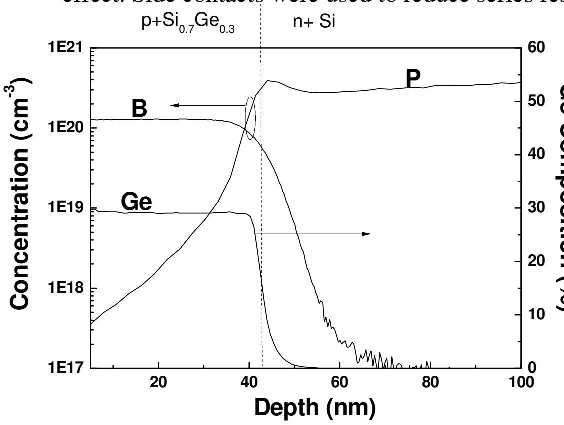


Fig. 2 Doping profiles and Ge composition vs. depth by SIMS analysis

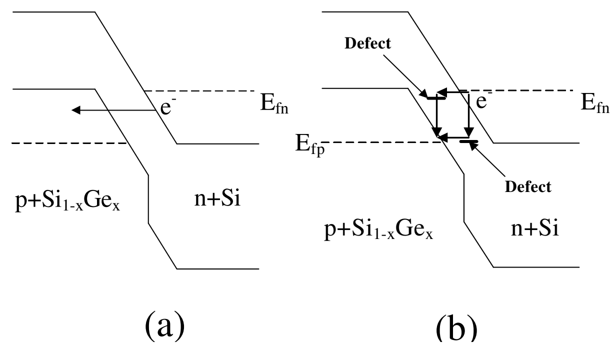
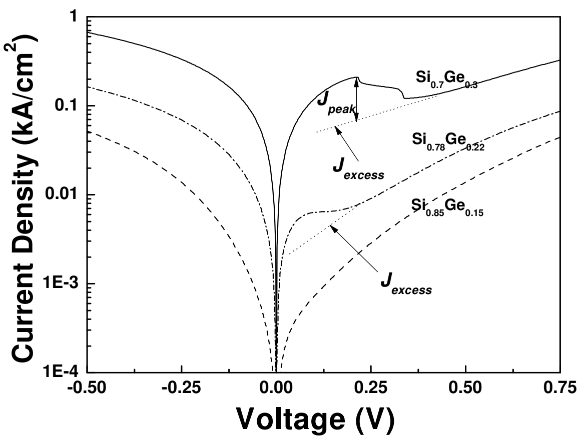


Fig. 3 Tunneling mechanisms of (a) band-to-band tunneling current and (b) defect-mediated excess current



$Si_{0.7}Ge_{0.3}$:	***$Si_{0.78}Ge_{0.22}$***:	***$Si_{0.84}Ge_{0.16}$***:
N_A= 1.5 x $10^{20}cm^{-3}$	N_A= 5.5 x $10^{19}cm^{-3}$	N_A= 2 x $10^{20}cm^{-3}$
N_D= 3 x$10^{20}cm^{-3}$	N_D= 3 x$10^{20}cm^{-3}$	N_D= 3 x$10^{20}cm^{-3}$

Fig. 4 I-V curves of SiGe/Si tunnel diodes with vs. Ge composition. Ge composition and doping concentration were obtained by SIMS.

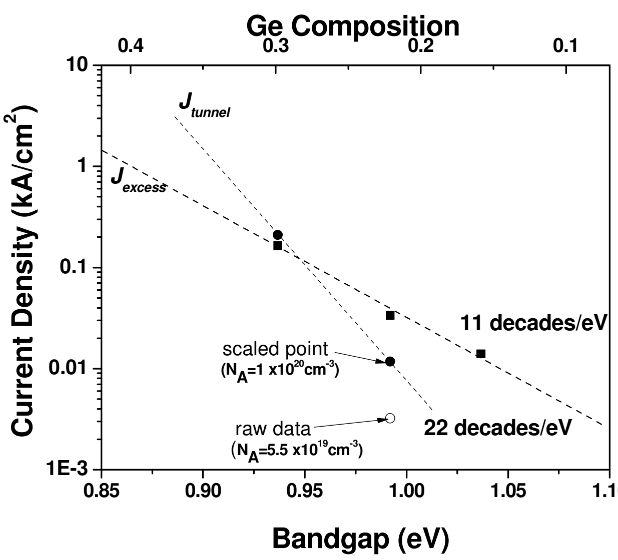


Fig. 5 Band-to-band tunneling current and excess current (at 0.5V) vs. bandgap energy (Ge composition). For 22% Ge, the experimental point has been scaled to the expected point for boron doping ($1x10^{20}cm^{-3}$) using [3]