Si - Based Tunnel Diode Operation and Forecasted Performance

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Si / Si$_x$Ge$_{1-x}$ Interband Tunnel Diodes

- The main tunneling process is LA and TO phonon assisted tunneling from the $k_x$ and $k_y$ electron X-valleys to the hole $\Gamma$-valley.
- The direct tunneling of the $k_z$ electrons is negligible since their mass in the tunnel direction is 4 times that of the $k_{xy}$ electrons resulting in twice the decay constant.

![Diagram of Si/Si$_x$Ge$_{1-x}$ Interband Tunnel Diodes with labels for $k_x$, $k_y$, $k_z$, and perpendicular current flow through a Si wafer.](image-url)
Si / Si$_{0.5}$Ge$_{0.5}$ Tunnel Diode Design as of 4/98

- Two items that we will change.
- 8 nm Si$_{0.5}$Ge$_{0.5}$
- Doping throughout Si$_{0.5}$Ge$_{0.5}$
First Working Design

- First working design built 5/98 shown at right.
- Since then, improvement has been rapid.
- A peak-to-valley-current-ratio (PVCR) of 4.2 with a current density of 3 kA/cm$^2$ has been achieved with this exact design substituting P doping for Sb (R. Dushcl et al., Electronics Lett., 35, 1111 (1999)).
- Cutting the length of the Si$_{0.5}$Ge$_{0.5}$ region down from 4nm to 2nm, a current density of 22.1 kA/cm$^2$ with a PVCR of 2 was obtained shown below. (S. Rommel et al., 1998 IEDM Technical Digest (IEEE, New York, 1998) p. 1035.)

![Graph showing current density and PVCR](image-url)
Figures of Merit - Speed Index

- High speed switching applications, the Speed Index is the important figure of merit [1].
- \( \text{Speed Index} = \frac{I_p}{C} \) (volts / second) where \( C \) is the tunnel diode capacitance and \( I_p \) is the peak current.
- Optimization
  - \( C \) linearly increases as tunnel junction width is reduced.
  - \( I_p \) exponentially increases as tunnel junction width is reduced.
  - \( \Rightarrow \) Minimize tunnel junction width and maximize current \( I_p \).
  - \( C \) linearly increases with dielectric constant \( e_{Si} = 11.9; e_{Ge} = 16.0. \)
  - \( I_p \) exponentially increases as bandgap decreased, \( E_{GSi} = 1.12 \) eV; \( E_{GGe} = 0.66 \) eV.
  - \( \Rightarrow \) Maximize \( I_p \) using \( Si_x Ge_{1-x} \) tunnel region.
- For a 3.5 nm spacer with \( 10^5 \) A/cm\(^2\) peak current (see figure right), the speed index is calculated to be 30 V GHz, i.e., 1 V can be switched at 30 GHz.

Figures of Merit - Peak to Valley Current Ratio (PVCR)

- Both the peak currents and valley (excess) currents are tunnel currents. They are not thermally activated (see figure (a)).
- The physical mechanisms governing the valley current are still not understood.

(a) Temperature dependence of tunnel current.
Figures of Merit - Peak to Valley Current Ratio (PVCR)

- Tunneling from and through band-tails resulting from the heavy doping is one likely mechanism for the excess current [1].
- Optimization
  - Keep dopants out of the tunnel region.
- A PVCR of 4.2 has already been published and further optimization is highly probable.
- It is not yet possible to give a realistic maximum theoretical value.
- Our numerical calculations (see below) show the PVCR increasing from 1.9 to 3.4 to 7.7 as the bandtails are reduced by a factor of 2 and 2.5. Note that all of the current in figure (b) is tunnel current - not thermally activated p-n diode current. Also, compare with Fig. 4. of [1].

Calculated I-Vs with band-tails.
- 2nd neighbor sp\textsuperscript{3}s* band model.
- Direct, TA, and TO phonon-assisted tunneling.
- Non-equilibrium Green function approach.


C. Rivas et al., unpublished.
Figures of Merit - Peak to Valley Current Ratio (PVCR)

Gap States

- Low T grown heavily doped Si and Si$_x$Ge$_{1-x}$ need to be understood (or at least empirically characterized).

Key to Optimization of both Peak and Valley Currents - Precise Control of Dopant Profiles

Effect of Sb segregation

- The Sb segregates towards the surface resulting in
  - Wider tunnel barrier => Lower current density
  - Opportunity for higher peak current densities by confining the Sb.

NB: Peak current is exponentially dependent on the tunnel barrier width.


Using SIMS doping data
Key to Optimization - Precise Control of Dopant Profiles
Effect of B diffusion

- As dopants diffuse and compensate, the tunnel barrier widens; the speed index and PVCR are reduced.
- Maximize PVCR by keeping dopants out of the tunnel region.
- Maximize speed index by minimizing the length of the tunnel region.
- ==> Together this implies huge doping gradients.
- Consider diffusion barriers.
- Compare different dopant species.

Dopant profiles before and after rapid thermal anneal [1].

Tunnel junction before and after RTA and calculated peak current (inset) [1].

Open Questions: Dopant Species

How do they affect device performance?

- Sb segregates but does not diffuse.
- Historically, PVCR was highest with Sb doping, second highest with As doping, and lowest with P doping for both Si and Ge tunnel diodes [1].
- Currently, the highest PVCR comes from P doped devices [2].


M. Dashiell et al., preprint.

Open Questions: Delta Doping

Is it necessary? How does it affect device performance?

- The highest PVCR has been observed in d-doped devices [1].
- The highest current density has been observed in non-delta doped device [2].
- What is the effect of the quantum states in the d-doped wells?

Open Questions: The $x$ in the $\text{Si}_x\text{Ge}_{1-x}$

- Do we need $\text{Si}_x\text{Ge}_{1-x}$?
  - For high current density, minimize $x$ to minimize $E_G$.
  - BUT, the highest current density has been observed in an all-Si device [1].
- What is the optimum value of $x$?

How About Carbon? SiGeC?

- Diffusion barrier?
- Offsets?
- Band Gaps?
Forward Looking Issue - Scaling?

- How small in diameter can we make tunnel diodes?
  - Surface recombination will reduce PVCR.
- How small do we want to make them?
- For maximum speed -
  - Minimum area (minimum capacitance) maximum current density diodes.
Conclusions

• First working design built 5/98 followed by rapid progress.
• Published PVCR of 4.2.
• Published current densities of 22 kA/cm².
• Speed index - maximize current density ==> minimize intrinsic layer length.
  – Maximum estimated of 30 V GHz.
• PVCR - maintain clean intrinsic tunnel region.
  – Maximum of 4.2 published with better results already obtained.
• Nanometer control of dopant profiles is key to optimizing both speed index and PVCR.
  – Processing, dopant species, diffusion barriers.
• Open Questions: The x in SiₓGe₁₋ₓ? Dopant species? d-doping? SiGeC? Scaling?