Nanoelectronics with Tunneling Devices

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Based on pages 187-208 of Nanoelectronics and Nanosystems (Karl Goser et al)
Introduction

- Tunneling Elements (TE) are most mature type of all quantum effect devices.
- Compared to Single Electron Transistors (SETs), they already function at room temperature.
- Technological advances like development of III-IV integration process are still a challenge to develop digital logic families.
Tunneling Elements (TEs)

- A TE consists of two conducting materials separated by a very thin insulator.
- By band gap engineering we can tune the I-V characteristics of TEs such that they have negative differential resistance (NDR).
- Circuit design with TEs takes advantage of NDR region.
Tunnel Effect and Tunneling Elements

- Figure (12.1) shows the schematic of two basic tunneling elements

Fig. 12.1. Schematic views of tunneling elements with vertical (b) oriented barriers
Tunnel Effect and Tunneling Elements

- Tunnel effect refers to particle transport through a potential barrier where total energy of a classical particle is less than the potential energy.

- This can be explained if the particle is treated as material wave.
  - Schrödinger equation:
    \[
    \left[-\frac{\hbar^2}{2m^*} \frac{d}{dz} \frac{1}{m^*} \frac{d}{dz} + \Phi(z)\right] \Psi(z) = W_z \Psi(z)
    \]

  \(\Psi(z)\): electron wave function, \(W_z\): electron energy is Z direction
  \(m^*\): electron effective mass, \(\Phi(z)\): potential energy at the conduction band minimum.
Tunnel Effect and Tunneling Elements

- The time dependent Schrödinger equation for one spatial dimension is of the form

\[
\frac{-\hbar^2}{2m} \frac{\partial^2 \psi(x, t)}{\partial x^2} + U(x)\psi(x, t) = i\hbar \frac{\partial \psi(x, t)}{\partial t}
\]

- For a free particle where \( U(x) = 0 \) the wave function solution can be put in the form of a plane wave

\[
\psi(x, t) = Ae^{ikx - i\omega t}
\]
Tunnel Effect and Tunneling Elements

- Solution of the wave function must satisfy certain boundary conditions at abrupt interfaces (continues and differential).

- Figure (12.2) shows a specific case.
Tunnel Effect and Tunneling Elements

- A certain portion of incident wave is transmitted and a certain portion reflected.
- Within the barrier, wave is attenuated.
- Figure (12.3) shows the tunneling probability of electrons with different energies.

*Fig. 12.3. Tunneling probability as a function of the normalized energy, according to the Schrödinger equation.*
Tunnel Effect and Tunneling Elements

- Not all electrons pass the barrier even if electron energy is higher than barrier height ($E > W_0$)

- The amplitude of wave function on both sides of the barrier is proportional to the probability of presence of particles

- The ratio of these amplitudes is given by:

$$D \approx C \left[ -\frac{d}{\hbar} \sqrt{2m(W_0 - E)} \right]$$
HomeWork

- Check this website:

- Using the tool in this site find wave function and tunneling probability for few different barrier configurations
Tunnel Effect and Tunneling Elements

- D is higher for lower and thinner potential barriers
- Tunnel current can be gathered from the tunneling probability
- An electric field can distort the barrier shape as shown in Figure (12.4)

Fig. 12.4. Example for the tunneling process: a) tunneling barrier in the ground state, b) tunneling element with applied voltage.
Tunnel Effect and Tunneling Elements

Tunneling elements are very attractive switching devices because:

- Electron transport takes place without any loss of energy
- Switching speed is very high since the potential barriers are very thin
- Whether switching in TEs is faster than speed of light is an open question (according to text)
- TEs are sources of errors in MOSFETs!
Tunneling Diode (TD)

- Tunneling diode is a negative differential resistance
- Figure (12.5) shows the potential barrier caused by the insulator
- There must be a free band on the other side of the insulator so that tunneling electrons can be positioned in it
- For higher electric fields the influence of barrier can be neglected and the common diode effect can be observed
Tunneling Diode (TD)

- I-V characteristic of TD is depicted in Figure (12.6)

![I-V characteristic of a tunneling diode](image)

**Fig. 12.6.** Typical I-V characteristics of a tunneling diode

**Fig. 12.5.** Tunneling effect in semiconductors: (a) Within material that shows a band structure tunneling is only possible if a free band is available on the other side of the barrier, (b) an electric field can displace the band structures so that tunneling becomes impossible.
Tunneling Diode (TD)

- The important parameters in this curve are the peak current $I_p$, Valley current $I_v$, peak voltage $V_p$ and Valley voltage $V_v$

- The ratio of $I_p$ to $I_v$ is important for circuit designers

- For low power applications $I_v$ must be reduced to approximately zero
Tunneling Diode (TD)

Figure (12.7) shows the behavior of TD

Fig. 12.7. Tunneling diode as a solid-state switch: I-V characteristics with NDR (a) and its band diagram (b)
Resonant Tunneling Diode (RTD)

- In RTDs, source and drain are separated from channel \((W)\) with tunneling elements (Figure 12.8)
Resonant Tunneling Diode (RTD)

- Band structure of channel has to be approximately the same as that of source.
- A serial combination with an Ohmic resistance shows three operating points (Figure 12.9).

Fig. 12.9. Resonant tunneling diode: (a) band diagram for $V_{DD} = 0$, (b) band diagram for $V_{DD} > 0$, (c) I-V characteristics with three operating points, (d) RTD with load resistance $R_L$. 


Resonant Tunneling Diode (RTD)

- A1 and A3 are stable whereas A2 is metastable.
- Stable points can be used for storing data.
- Resonant happens if energy of tunneling electrons is equivalent to the level in the quantum well (Figure 12.10).
- Under these conditions transmission probability (T) reaches its highest peak.
Fig. 12.10. Resonant effect: The material wave reaches its maximum if the energy of the tunneling electrons is equivalent to the level in the quantum well.
Resonant Tunneling Diode (RTD)

- A different implementation of RTDs uses three barriers (Figure 12.11)
- The typical IV characteristic depends on displacement of the two quantum wells

Fig. 12.11. RTD with two wells and three barriers
Resonant Tunneling Diode (RTD)

- RTD has very good switching properties but suffers from the drawback of being a two dimensional device.
- Different three terminal tunneling devices are implemented.
- These combine electronic amplification with NDR.
Three Terminal Resonant Tunneling Devices

- Switching of two terminal devices like RTDs can be controlled by a third terminal.
- Resonant tunneling Bipolar Transistor (RTBT) is made through integration of an RTD structure into the emitter branch of a bipolar transistor.
Three Terminal Resonant Tunneling Devices

- In RTBTs the pn base-emitter junction is replaced with an RTD
- Figure (12.13a) shows the diagram and characteristics
Three Terminal Resonant Tunneling Devices

- Series or parallel combination of FETs and RTDs can also solve the gain problem (Figure 12.13b)
Three Terminal Resonant Tunneling Devices

- Figure (12.13c) shows the diagram and characteristics of a single electron transistor (SET) which consists of a small capacitor and two tunneling elements.
Technology of RTDs

- Despite the simple structure of RTDs, a complex layer structure is needed to achieve a stable assembly of these thin layer devices.

- Figure (12.16) shows an example.
Technology of RTDs

- Figure (12.15) depicts micrograph and cross section of an RTD-FET implemented in Indium-phosphide technology.

Fig. 12.15. Micrograph and cross section of FET-RTD combination, W. Prost, F.-J. Tegude
Technology of RTDs

- RTD can be implemented in a mesoscopic device where other components such as wiring and contacts are still too large.
- The negative aspects are low packing density and large parasitic.
Digital Circuit Design based on RTDs

- Figure (12.18) illustrates a static memory cell which is composed of serially connected RTDs and FETs.
Digital Circuit Design based on RTDs

- In the style of classic CMOS circuitry RTD-based logic gates can be composed.
- Figure (12.19) shows implementation of inverter and OR gate
- RTD offers the advantage of high gain at switching point because of the NDR
- Therefore switching is very fast
Digital Circuit Design based on RTDs

Fig. 12.19. Inverter and logic OR gates based on RTDs.
Dynamic Logic Gates

- Monostable bistable logic transition element (MOBILE) is a good example that takes more advantage of NDR.
- High speed logic families based on MOBILEs have been proposed for tunneling devices.
- MOBILE is composed of two RTDs that operate in a monostable bistable state depending on the clocked power supply voltage.
Dynamic Logic Gates

- This is pseudo dynamic logic device.
- In contrast to dynamic logic where capacitor charge represent the logic states, MOBILE circuits are in a static self stabilizing state due to inherent stability of the RTDs.
- They are more robust against charge leakage and precharging in not necessary.
Dynamic Logic Gates

- Figures (12.21),(12.22),(12.23),(12.24) and (12.25) show implementation of Threshold gate, RTBT MOBILE, RTBT Threshold gate, and RTBT 2 to 1 mux respectively.
**Fig. 12.21.** Linear threshold gate $y = \text{sign}(x_1 + x_2 - x_3 - x_4 - \Theta)$ and MOBILE circuit

**Fig. 12.22.** Load-line diagram of the basic RTBT gate
Fig. 12.23. Schematic view and chip foto of the RTBT threshold gate, W. Prost, F.J. Tegude.

Fig. 12.24. Schematic view of the RTBT multiplexer