Nanoelectronics with Tunneling Devices

Reza M. Rad , UMBC

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

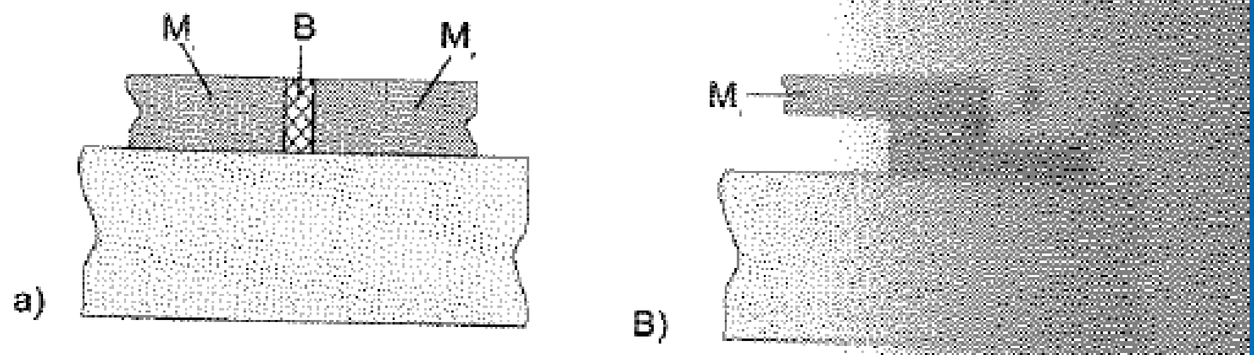


Fig. 12.1. Schematic views of tunneling elements with vert [illegible]
(b) oriented barriers

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 :

$$\left[-\frac{\bar{h}^2}{2}\frac{d}{dz}\frac{1}{m^*(z)}\frac{d}{d(z)}+\Phi(z)\right]\Psi(z)=W_z\Psi(z)$$

$\Psi(z)$: electron wave function, W_z : electron energy is Z direction

m^* : electron effective mass , $\Phi(\mathrm{z})$: 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

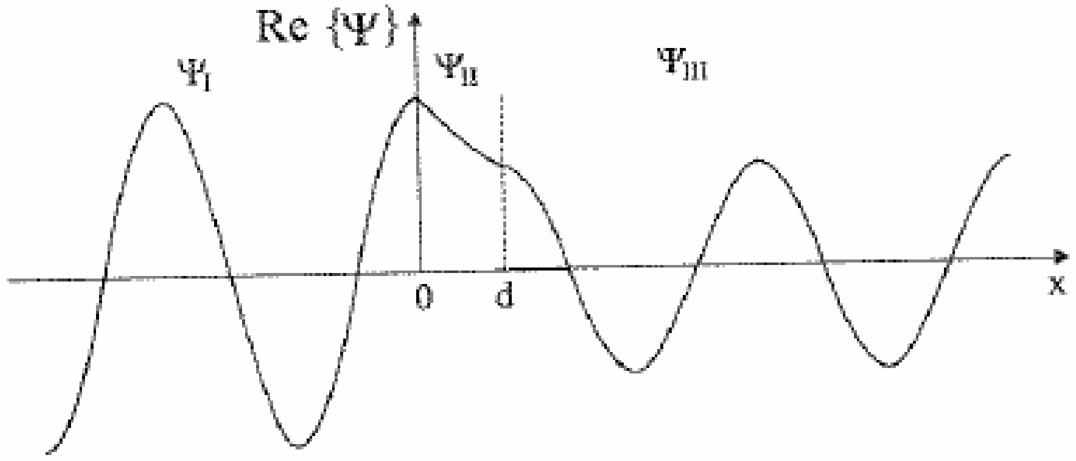


Fig. 12.2. Tunneling effect: The material wave is attenuated within the barrier

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

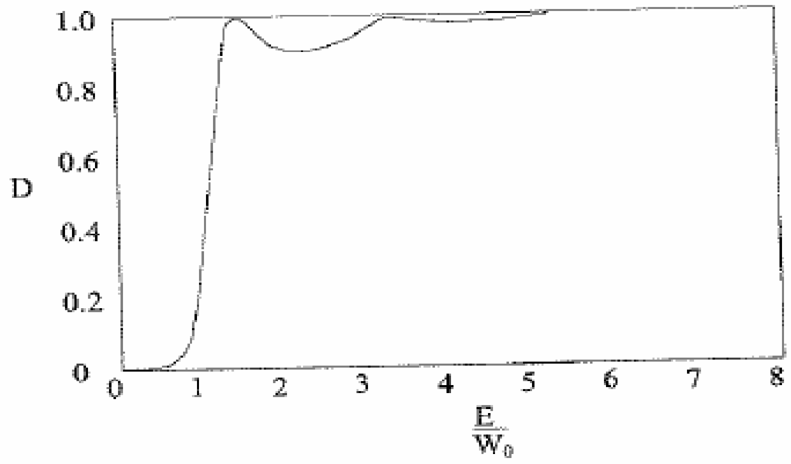


Fig. 12.3. Tunneling probability as a function of the normalized energy, according to the Schrödinger equation

Tunnel Effect and Tunneling Elements

- Not all electrons pass the barrier even if electron energy is higher than barrier height (E > W0)
- 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:

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

HomeWork

- Check this website:
  - http://phys.educ.ksu.edu/vqm/html/qtunneling.html
- 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)

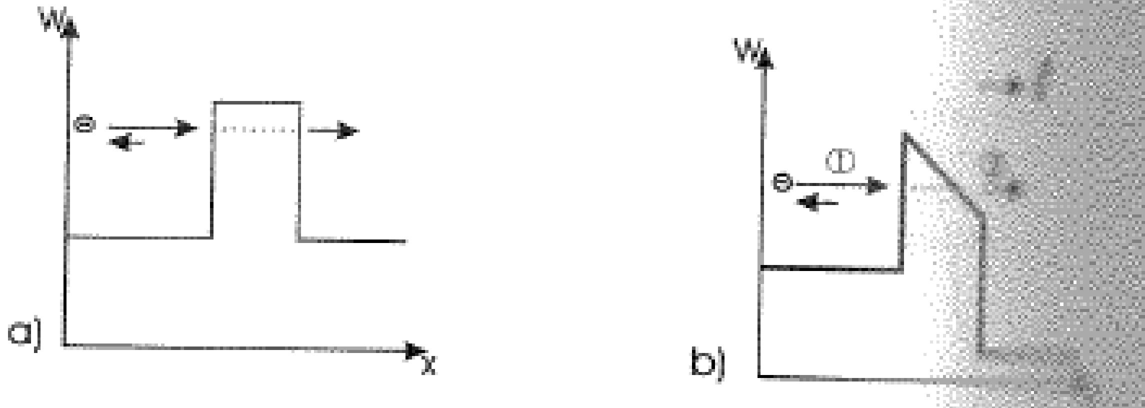


Fig. 12.4. Example for the tunneling process: a) tunneling barrier [illegible] state, b) tunneling element with applied voltage.

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)

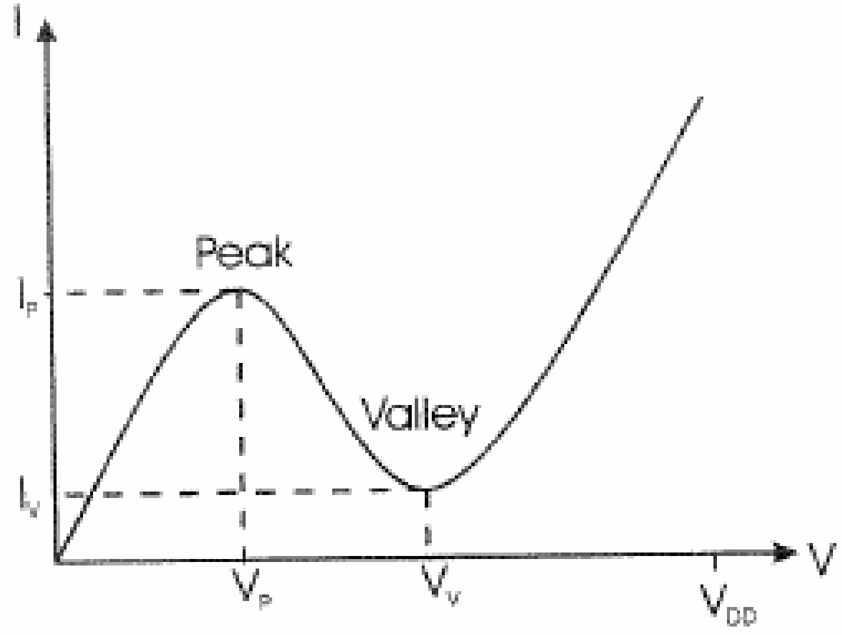


Fig. 12.6. Typical I-V charateristics of a tunneling diode

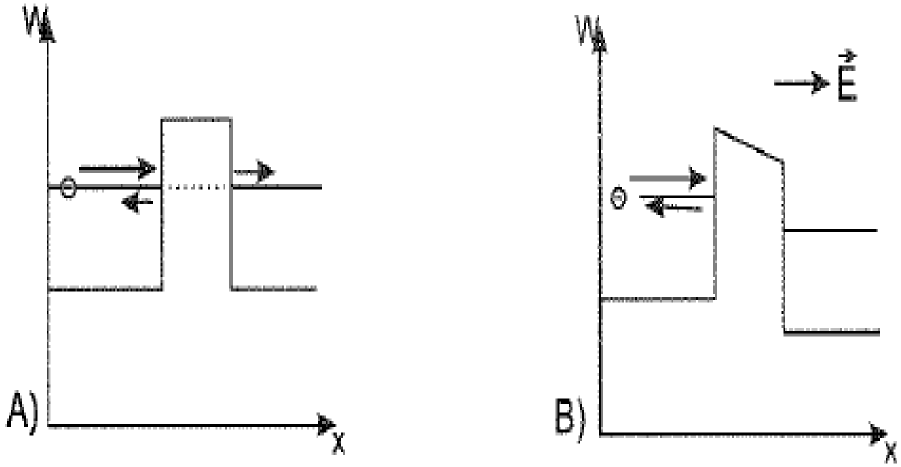


Fig. 12.5. Tunneling effect in semiconductors: (a) Within material that shows a band structure tunneling is only possible if a free band is available on the other side of the barrier, (b) an electric field can displace the band structures so that tunneling becomes impossible

Tunneling Diode (TD)

- The impotant parameters in this curve are the peak current Ip, Valley current Iv, peak voltage Vp and Valley voltage Vv
- The ratio of Ip to Iv is important for circuit designers
- For low power applications Iv must be reduced to approximately zero

Tunneling Diode (TD)

- Figure (12.7) shows the behavior of TD

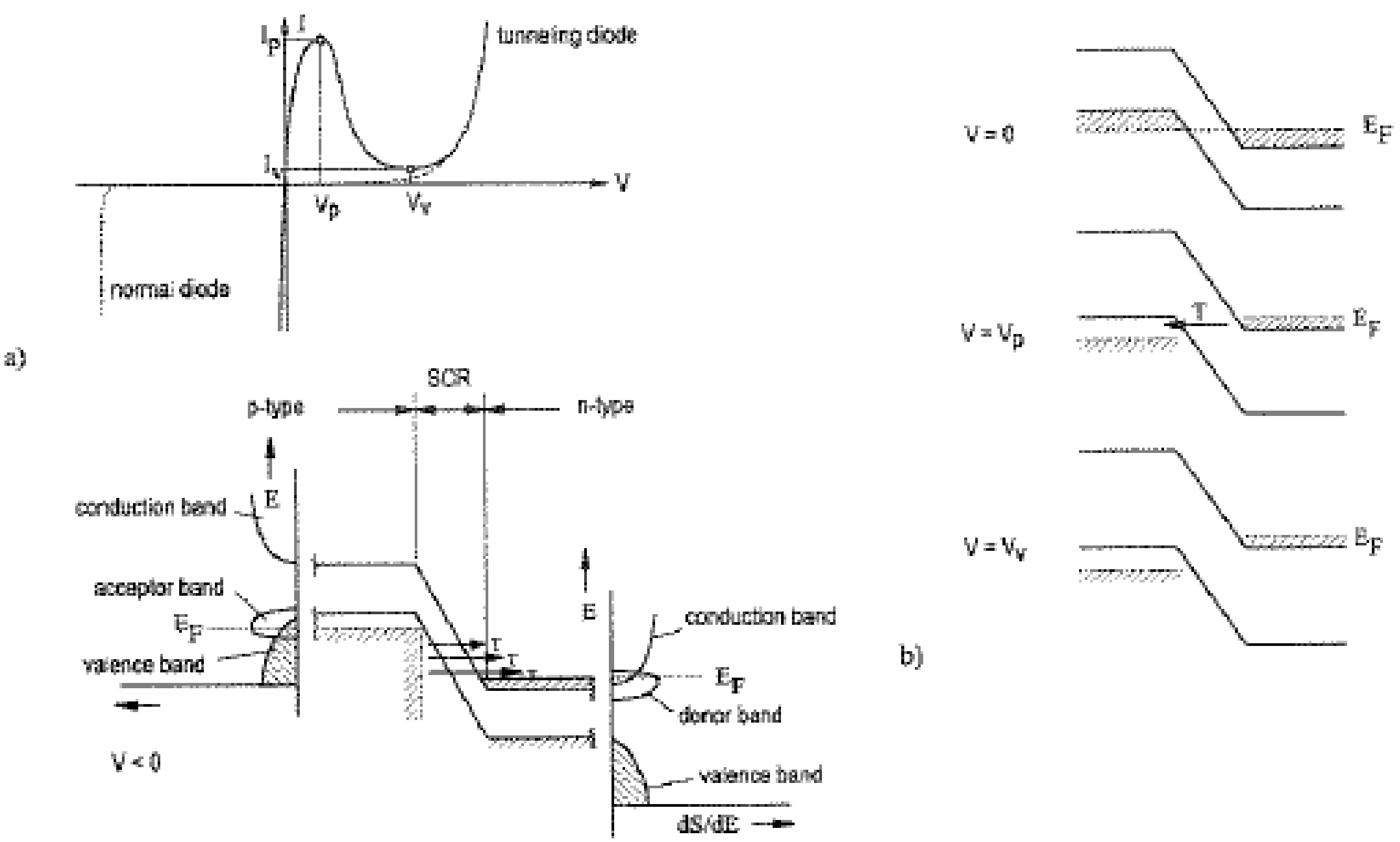


Fig. 12.7. Tunneling diode as a solid-state switch: I-V characteristics with NDR (a) and its band diagram (b)

Resonant Tunneling Diode (RTD)

- In RTDs, source and drain are separated from channel (W) with tunneling elements (Figure 12.8)

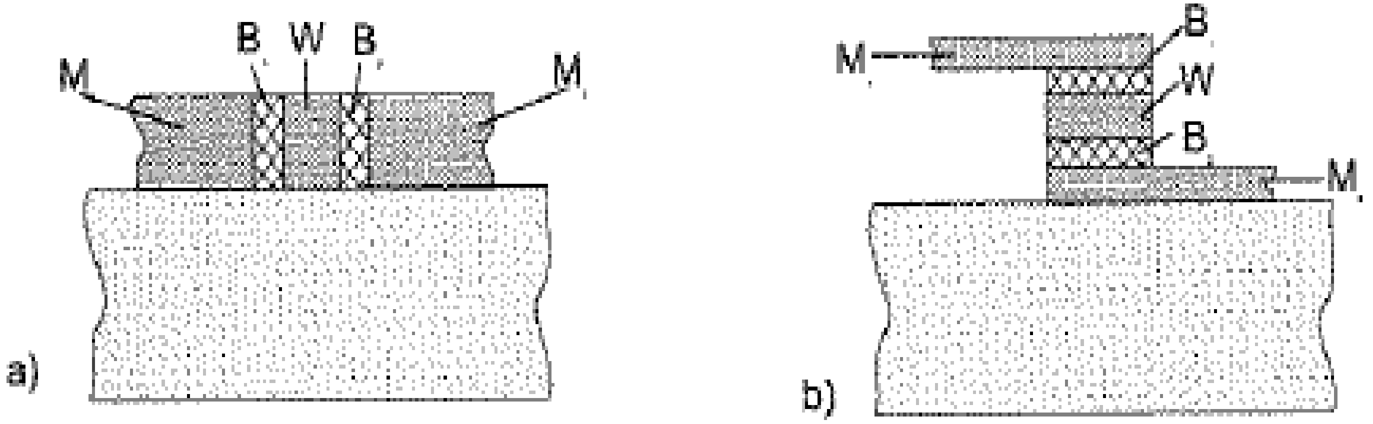


Fig. 12.8. Cross section of the RTD: (a) with vertical and (b) with horizontal barriers

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)

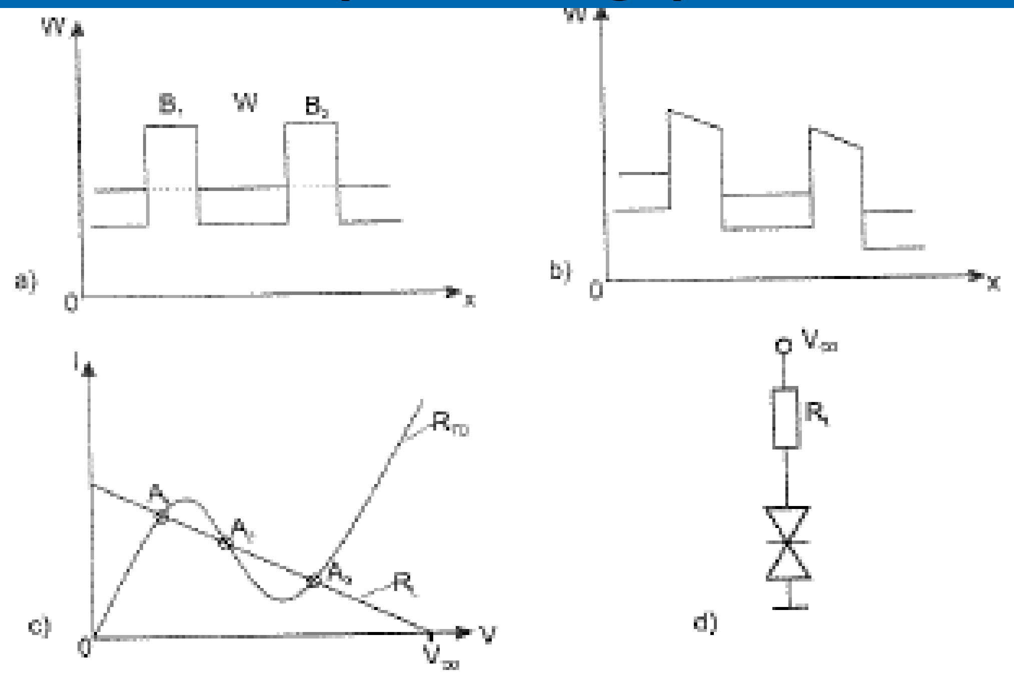


Fig. 12.9. Resonant tunneling diode: (a) band diagram for $V_{DD} = 0$, (b) band diagram for $V_{DD} > 0$, (c) I-V charactistics with three operating points, (d) RTD with load resistance R_L

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

Resonant Tunneling Diode (RTD)

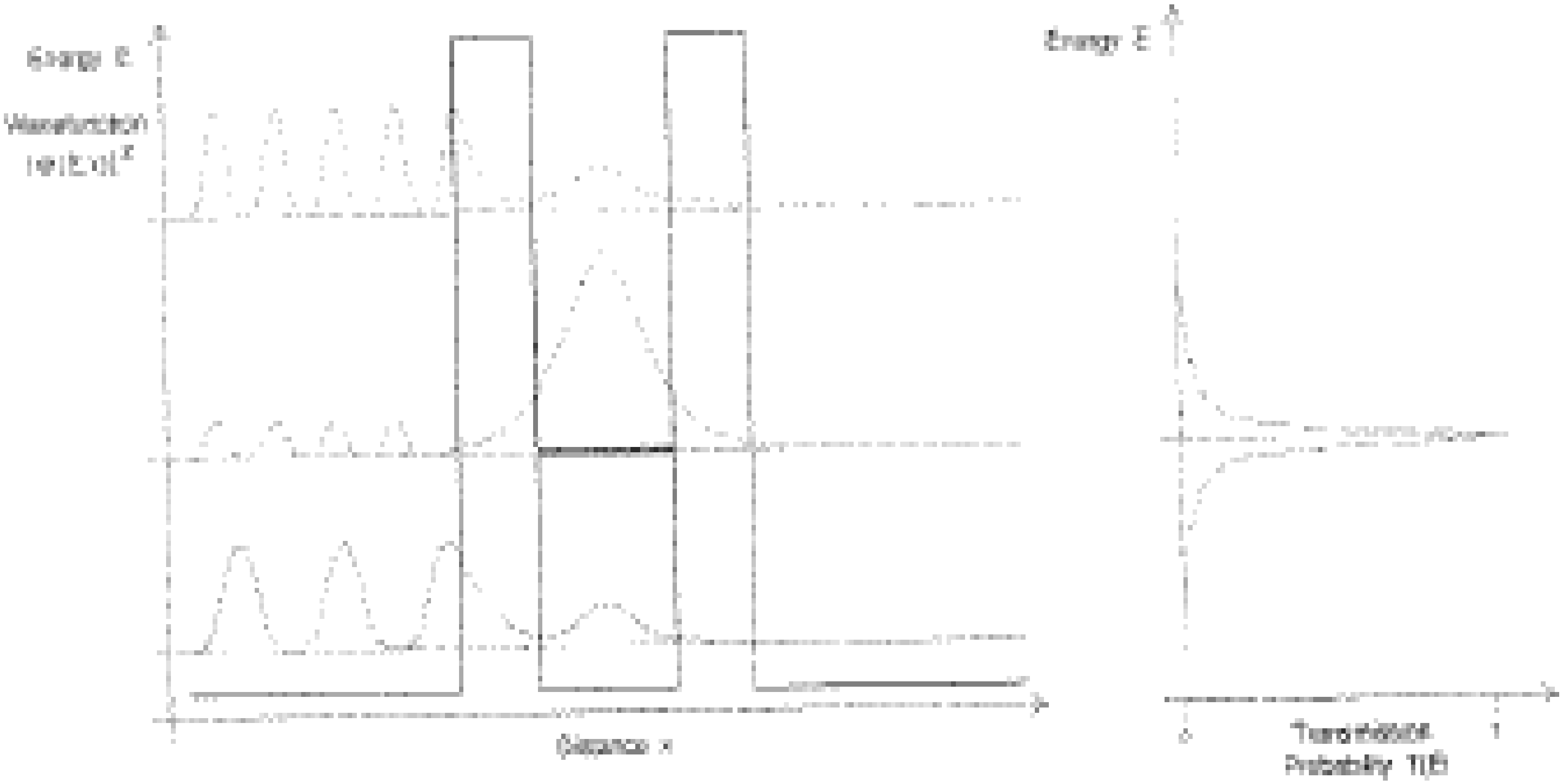


Fig. 12.10. Resonant effect: The material wave reaches its maximum if the energy of the tunneling electrons is equivalent to the level in the quantum well

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

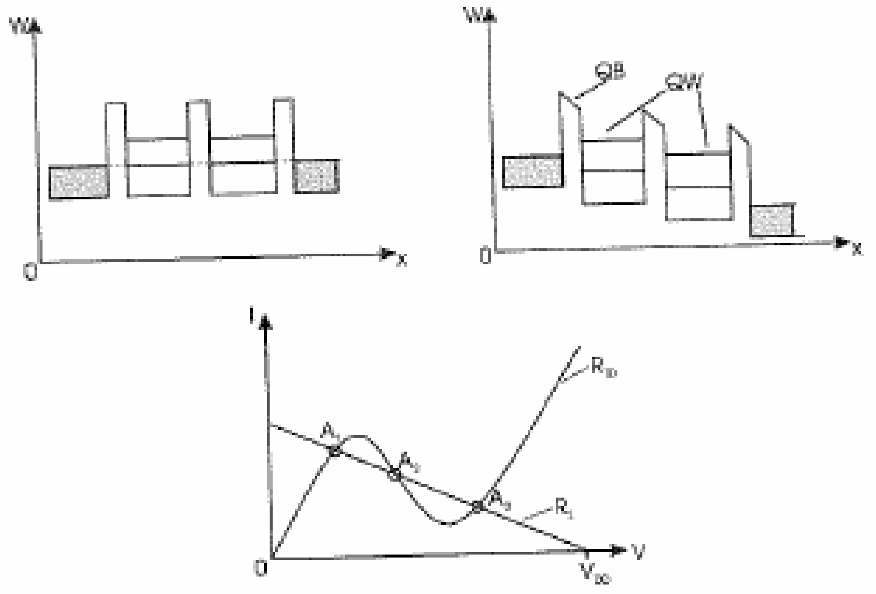


Fig. 12.11. RTD with two wells and three barriers

Resonant Tunneling Diode (RTD)

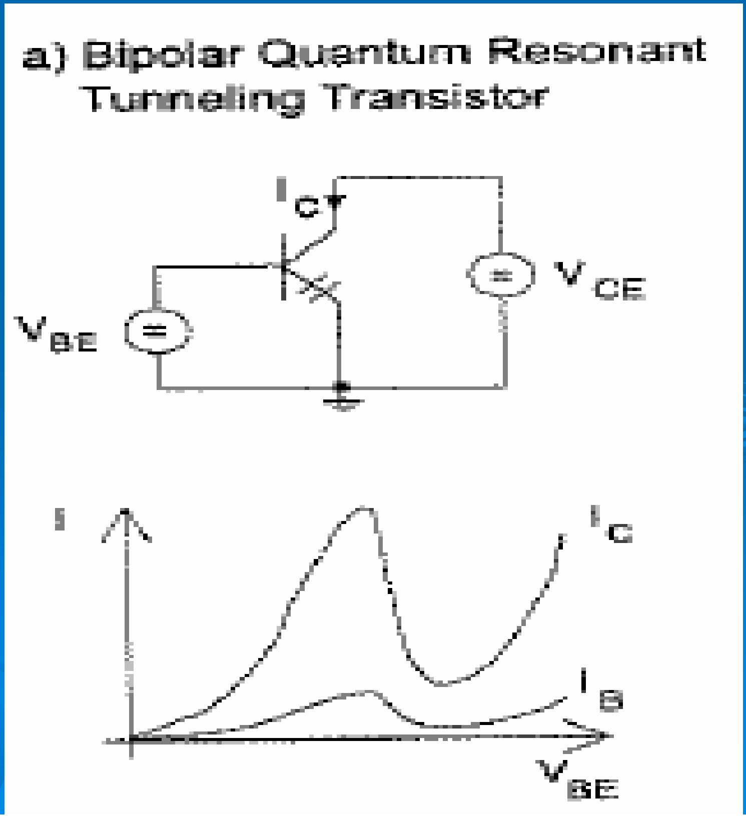
- RTD has very good switching properties but suffers from the drawback of being a two dimensional device
- Different three terminal tunneling devices are implemented
- These combine electronic amplification with NDR

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

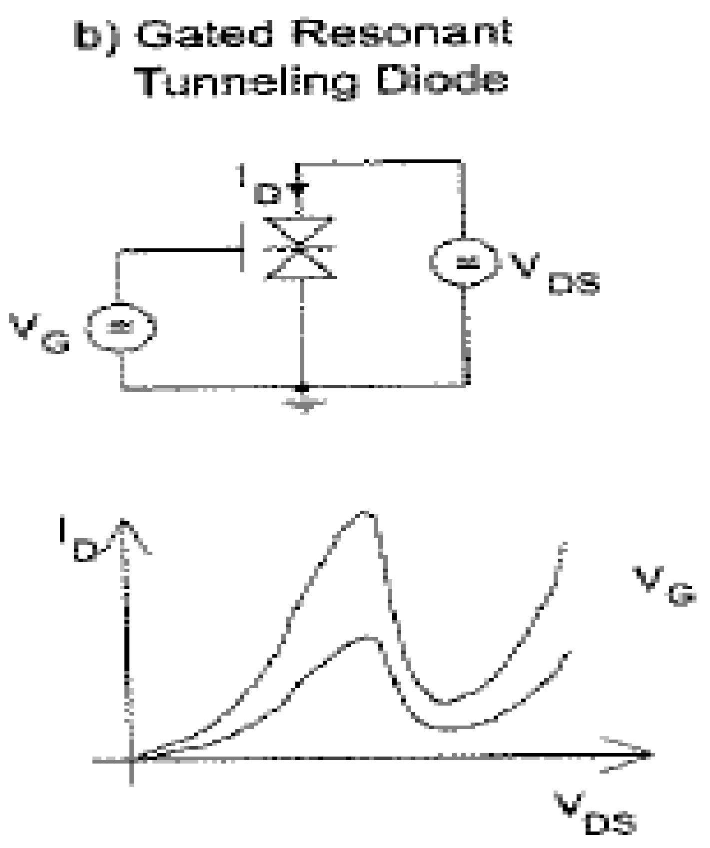
- In RTBTs the pn base-emitter junction is replaced with an RTD
- Figure (12.13a) shows the diagram and characteristics



a) Bipolar Quantum Resonant Tunneling Transistor

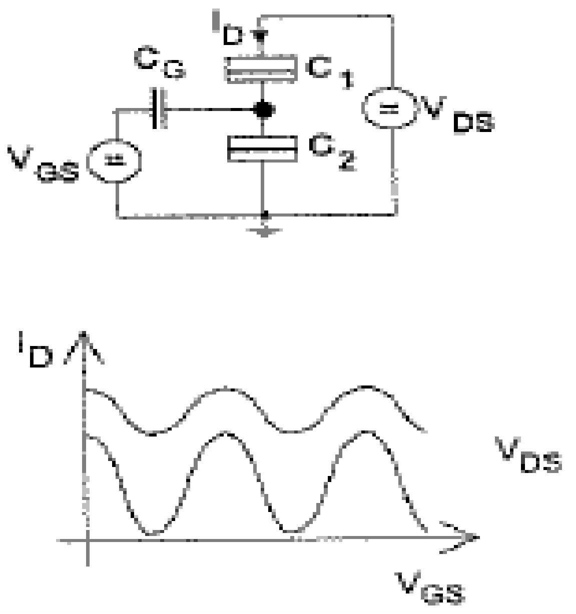
Three Terminal Resonant Tunneling Devices

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



Three Terminal Resonant Tunneling Devices

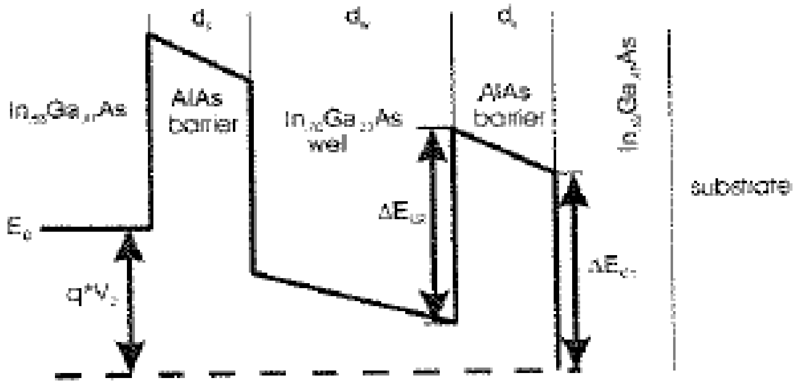
- Figure (12.13c) shows the diagram and characteristics of a single electron transistor (SET) which consists of a small capacitor and two tunneling elements



c) Single Electron Transistor

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



100 nm	InGaAs	N_D=1,5x10^{19}cm^{-3}
50 nm	InGaAs	N_D=7,5x10^{17}cm^{-3}
4 ML	InGaAs	spacer
d_1=8 ML	AlAs	barrier
4 ML	InGaAs	smooting
d_w=8 ML	InAs	well
4 ML	InGaAs	smooting
d_2=8 ML	AlAs	barrier
4 ML	InGaAs	spacer
50 nm	InGaAs	N_D=7,5x10^{17}cm^{-3}
100 nm	InGaAs	N_D=1,5x10^{19}cm^{-3}
10 nm	InAlAs	etch stop
300 nm	InGaAs	N_D=1,5x10^{19}cm^{-3}
s.i. -InP:Fe		substrate

Fig. 12.16. Layer structure of an RTD, courtesy of F.-J. Tegude

Technology of RTDs

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

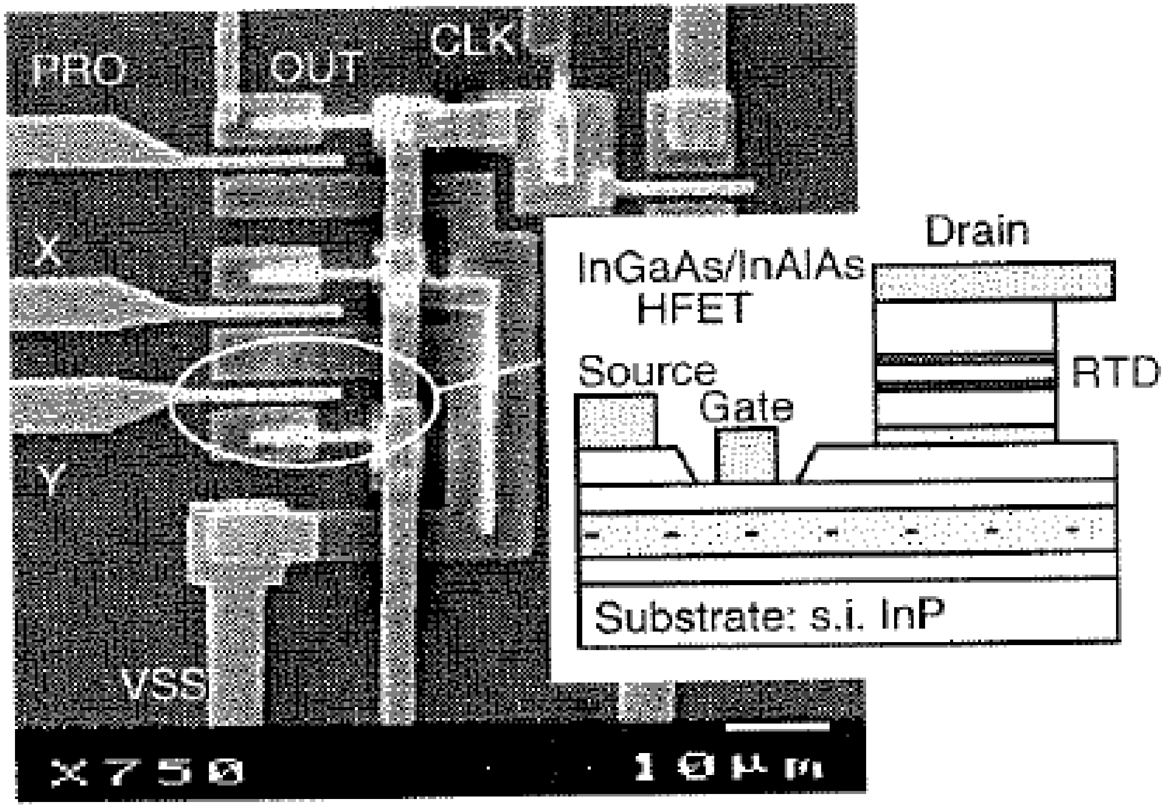


Fig. 12.15. Micrograph and cross section of FET-RTD combination, W. Prost, F.-J. Tegude

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 FET

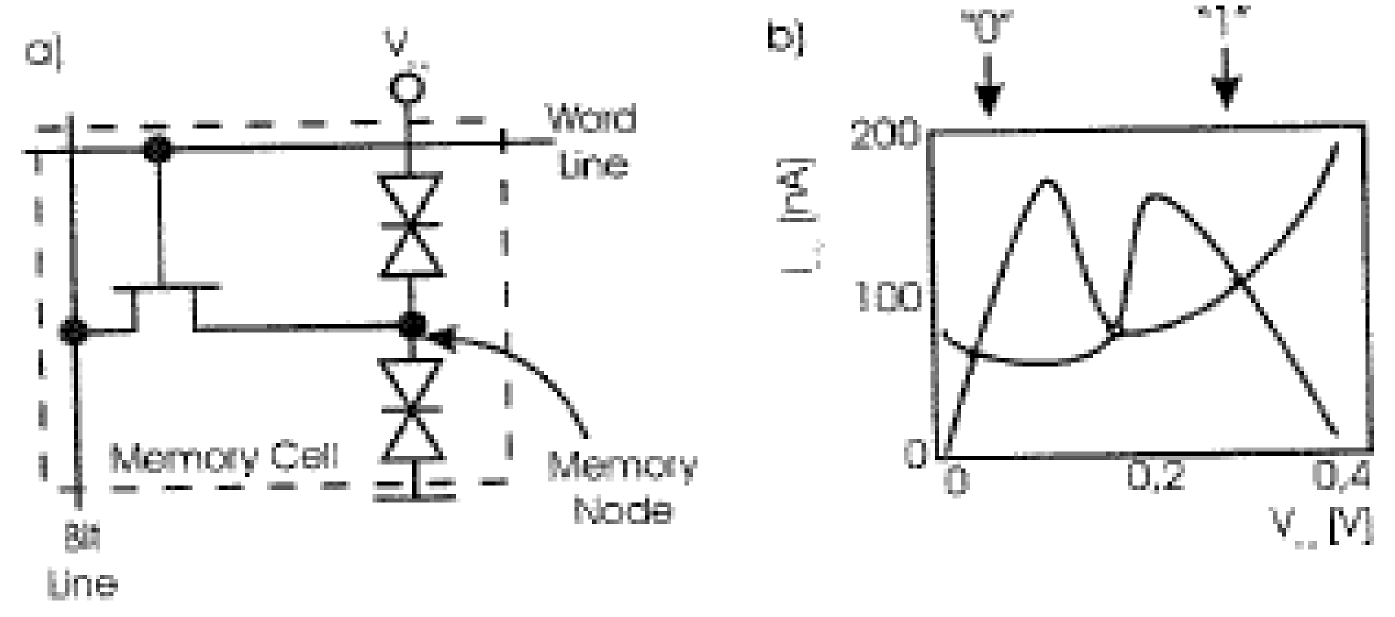


Fig. 12.18. Static memory cell based on RTDs

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

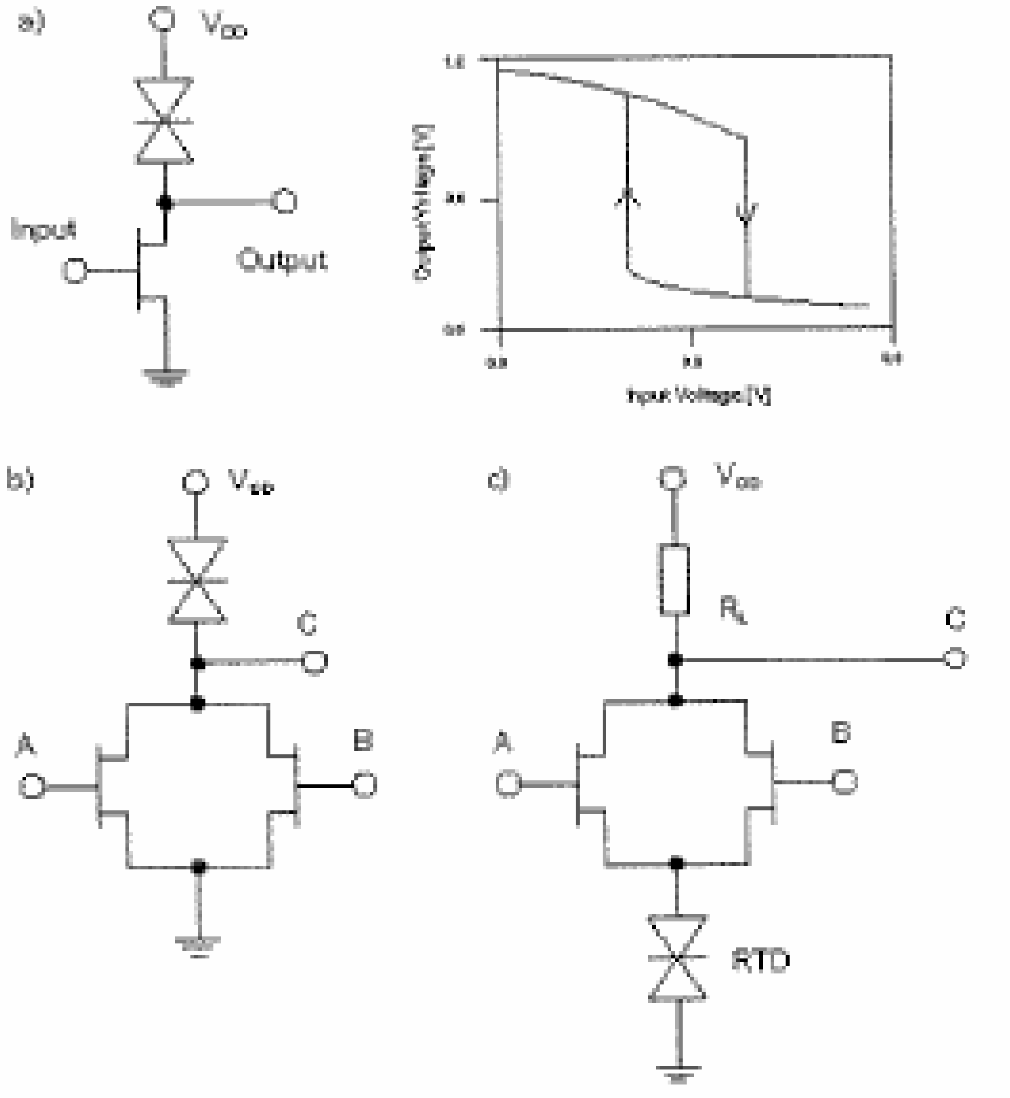


Fig. 12.19. Inverter and logic OR gates based on RTDs.

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

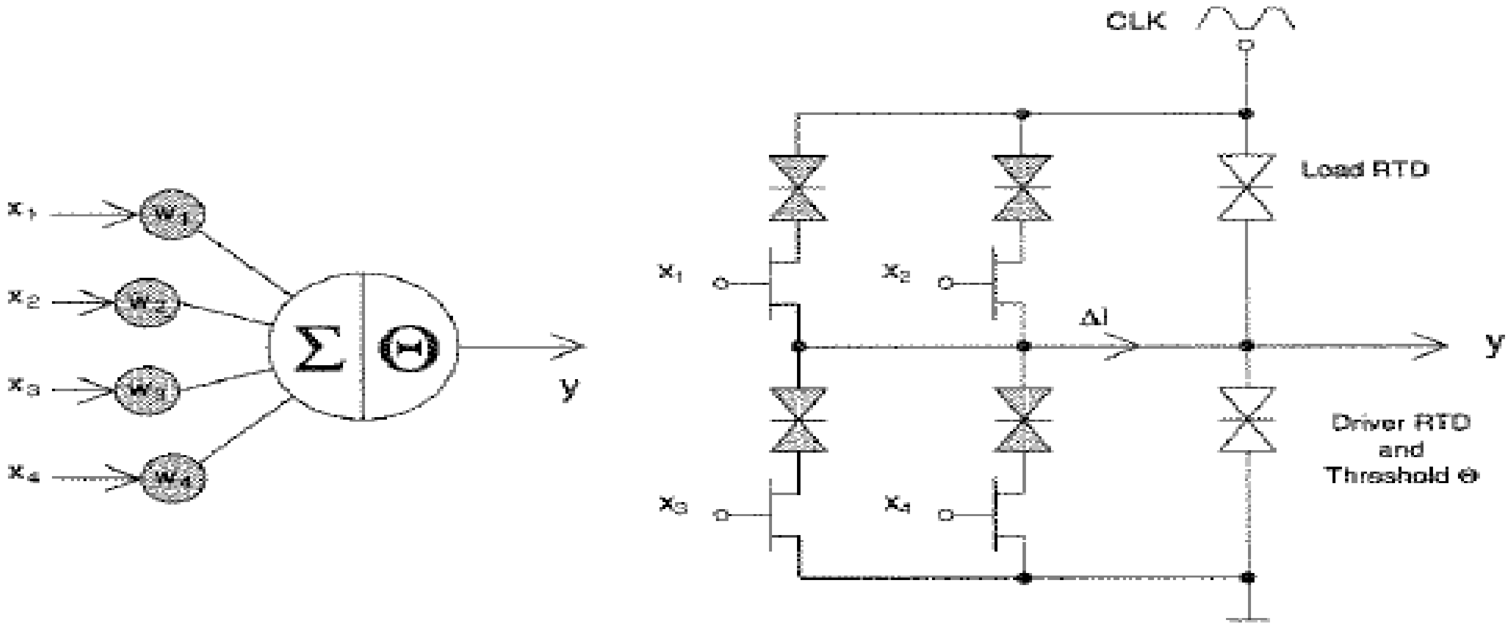


Fig. 12.21. Linear threshold gate $y = \mathrm{sign}(x_1 + x_2 - x_3 - x_4 - \Theta)$ and MOBILE circuit

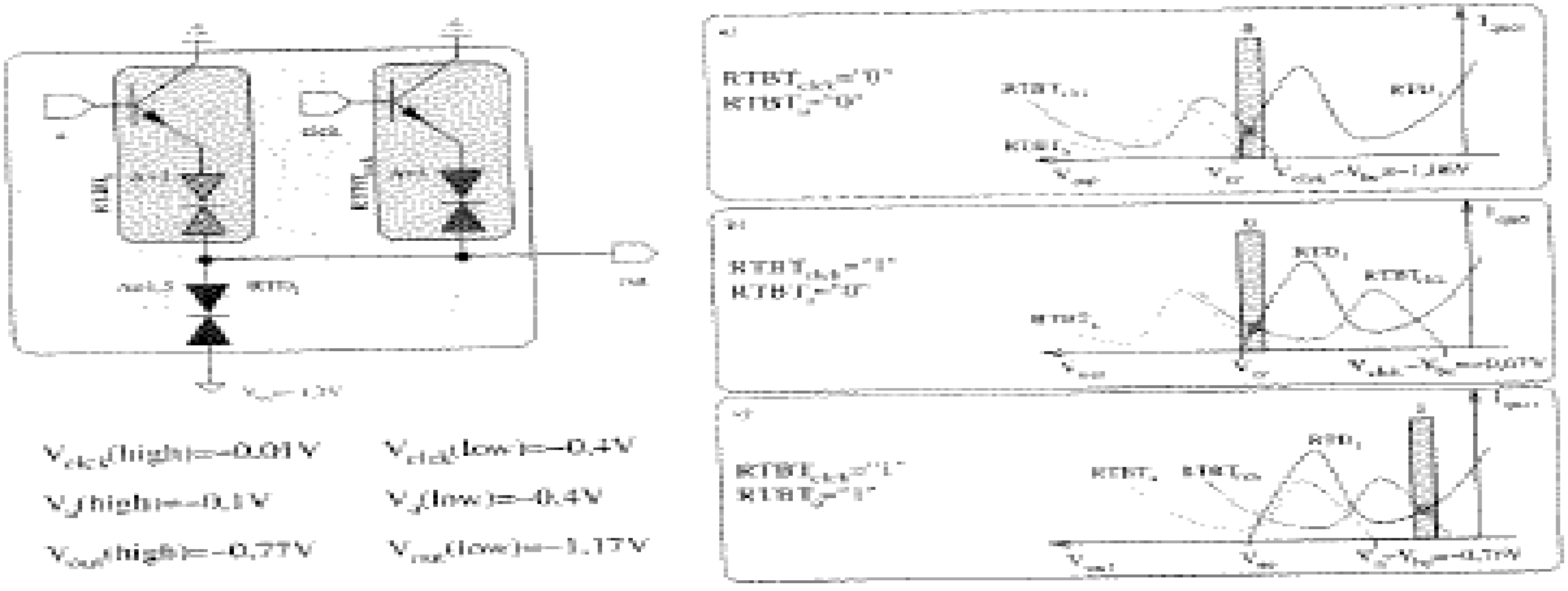


Fig. 12.22. Load-line diagram of the basic RTBT gate

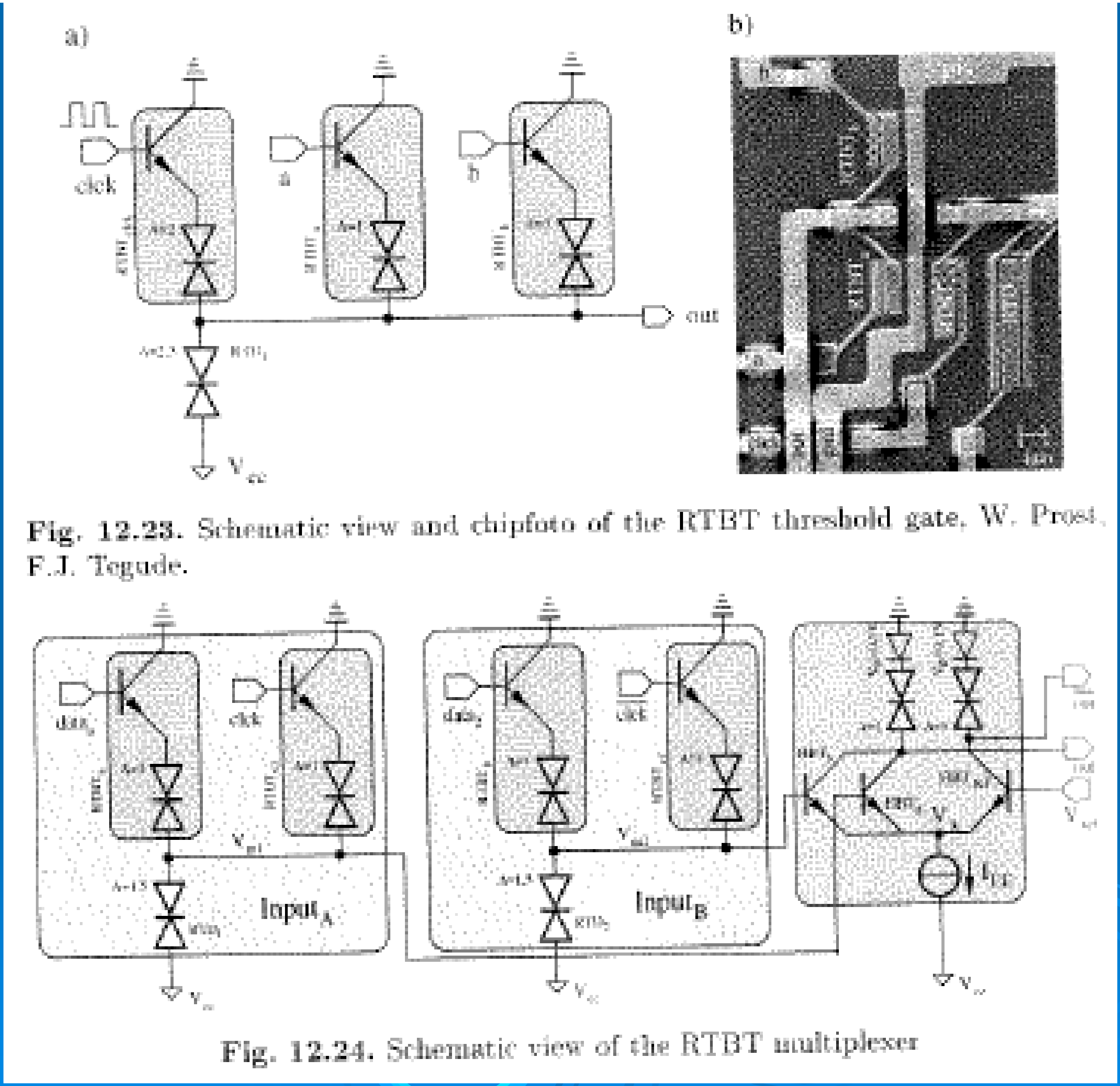


Fig. 12.23. Schematic view and chipfoto of the RTBT threshold gate. W. Prost, F.J. Tegude.

Fig. 12.24. Schematic view of the RTBT multiplexer