Quantum Transport Devices Based on Resonant Tunneling

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Introduction

- Some general aspects of resonant tunneling diodes will be discussed
- RTDs can be considered as devices which are in active competition with conventional CMOS

Electron Tunneling

- Transfer Matrix Method
  - Electrons have a wave like character
  - In structures with dimensions in the range of electron wavelength, quantum mechanical transport becomes relevant
  - One of these transport mechanisms is the tunneling process
  - Electrons can penetrate through and traverse a potential barrier with a finite transmission probability independent of temperature
  - In classical view electrons can overcome a potential barrier only thermodynamically

Electron Tunneling

- Envelope function description of electron state : rapid changing electron potential is approximated with an envelope potential
- Envelope function is based on effective mass description of the band structure and leads to electron effective mass Schrödinger equation :

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

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

m^* : electron effective mass , $\Phi(z)$: potential energy at the conduction band minimum

Electron Tunneling

- Occupation probabilities can be predicted from absolute square of wave function $|\Psi(z)|^2$
- Consider a sequence of n different layers (fig 1) with different potential energies (φ_i) and electron effective masses (m^*_i)

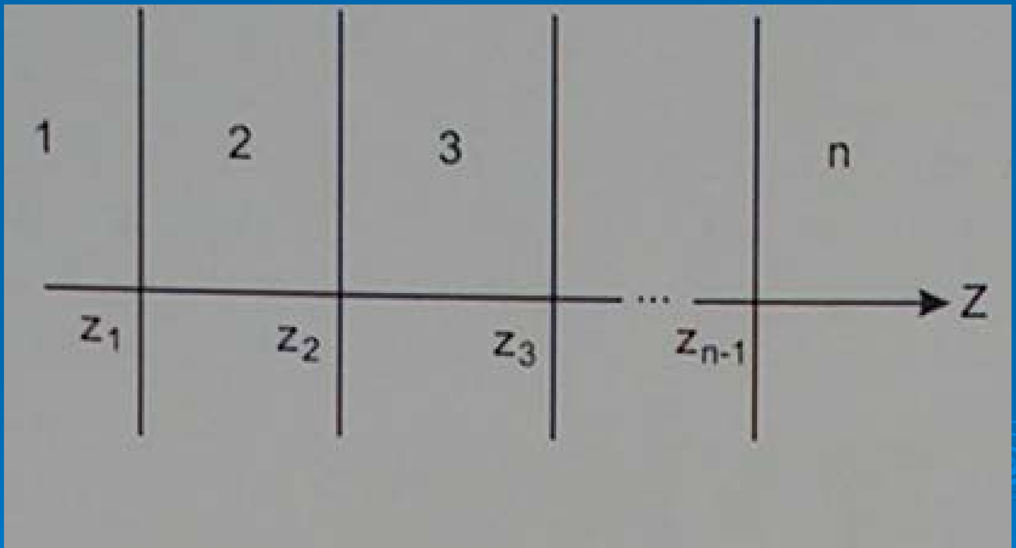


Figure 1: Sequence of n different layers; in each layer the effective mass m_i^* and the potential Φ_i was assumed to be constant.

Electron Tunneling

- $\Psi_i(z)$ can be written as a superposition of propagating waves in z and –z direction with amplitudes A_i and B_i

$$\Psi_i(z) = A_i e^{ik_i z} + B_i e^{-ik_i z} := A_i \Psi_{i+} + B_i \Psi_{i-}$$

boundary conditions :

$$\Psi_i(z_i) = \Psi_{i+1}(z_i)$$

$$\frac{1}{m_i^*} \frac{d}{dz} \Psi_i(z_i) = \frac{1}{m_{i+1}^*} \frac{d}{dz} \Psi_{i+1}(z_i)$$

In matrix form :

$$definition : TM_i := \begin{bmatrix} \Psi_{i+} & \Psi_{i-} \\ \frac{1}{m_i} \Psi'_{i+} & \frac{1}{m_i} \Psi'_{i-} \end{bmatrix}$$

$$\mathrm{TM}_{1(z=z1)} \begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = \mathrm{TM}_{2(z=z1)} \begin{bmatrix} A_2 \\ B_2 \end{bmatrix}, \ \mathrm{TM}_{2(z=z2)} \begin{bmatrix} A_2 \\ B_2 \end{bmatrix} = \mathrm{TM}_{3(z=z2)} \begin{bmatrix} A_3 \\ B_3 \end{bmatrix}, \ldots$$

$$\mathrm{TM}_{n-1(z=z_{n-1})} \begin{bmatrix} A_{n-1} \\ B_{n-1} \end{bmatrix} = \mathrm{TM}_{n(z=z_{n-1})} \begin{bmatrix} A_n \\ B_n \end{bmatrix},$$

Electron Tunneling

- Amplitudes of the propagating waves in z and –z direction in last layer can be written as:

$$\begin{bmatrix} A_n \\ B_n \end{bmatrix} = TM \begin{bmatrix} A_1 \\ B_1 \end{bmatrix}$$

$$TM = TM^{-1}_{n(z=z_{n-1})} \ldots TM_{2(z=z2)} TM^{-1}_{2(z=z2)} TM_{1(z=z1)}$$

- Transmission probability Tc can be written as the ratio of outgoing to the incoming quantum mechanical probability current:

$$T_c = \frac{k_n}{k_1} \frac{m_1^*}{m_n^*} \frac{|A_n|^2}{|A_1|^2}, \quad A_n = \frac{\det TM}{TM_{22}} A_1$$

$$\det TM = \frac{k_1 m_n}{k_n m_1}$$

$$T_c = \frac{k_1}{k_n} \frac{m_n^*}{m_1^*} \frac{1}{|TM_{22}|^2}$$

Electron Tunneling

- Tunneling through a single barrier
  - A single potential barrier is shown in figure (fig2)
    - AlAs barrier embedded in GaAs

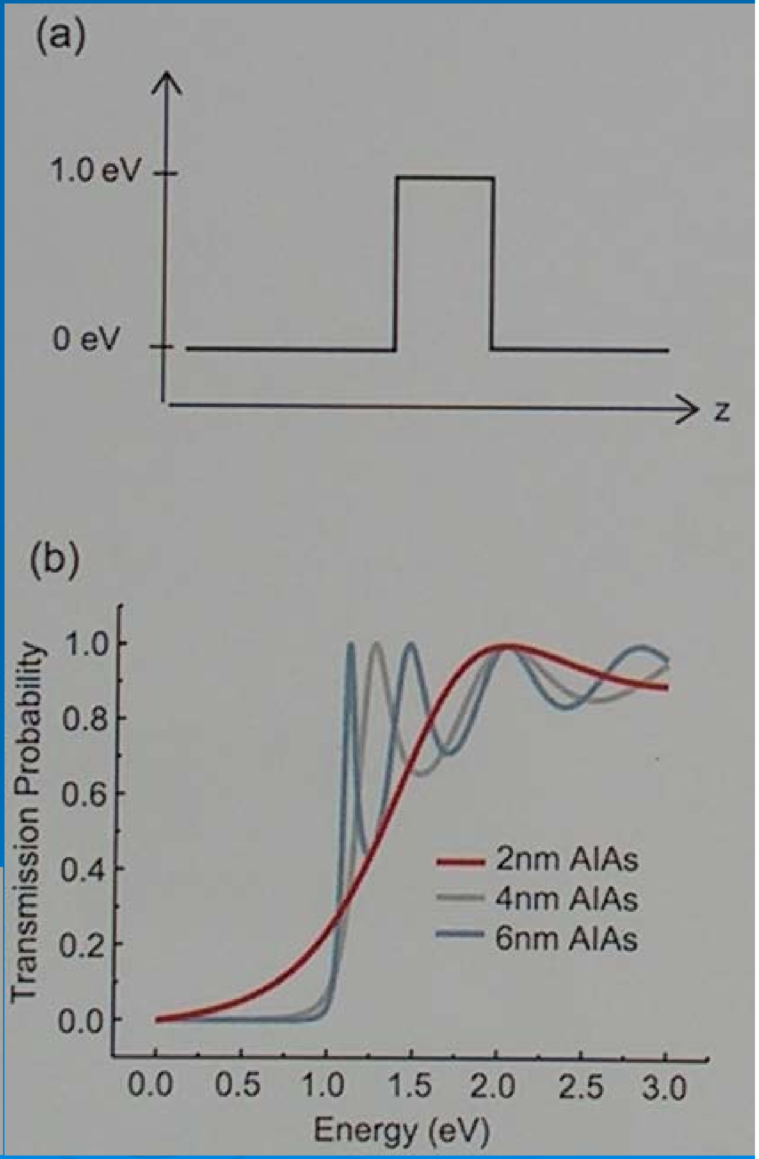


Figure 2: Schematic band diagram of a single AlAs barrier (a) and the corresponding tunneling transmission probability for different barrier thicknesses (b).

Electron Tunneling

- Transmission probability is calculated as a function of electron energy
- Finite transmission probability for electrons below potential height of 1 eV (tunneling)
- The smaller the barrier thickness the higher the tunneling probability

Electron Tunneling

- Tunneling through a double barrier structure
  - Figure (fig 3) shows the case of tunneling through a double barrier structure
    - 4 nm tick AlAs barriers separated by a 5 nm GaAs well

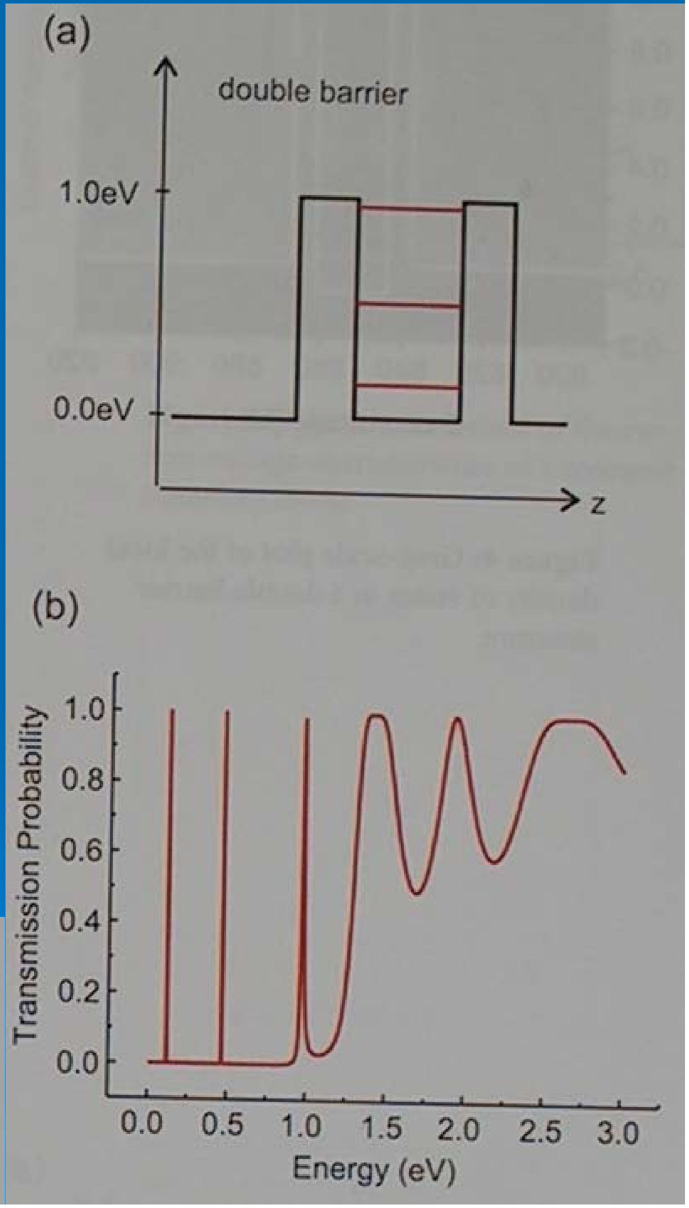


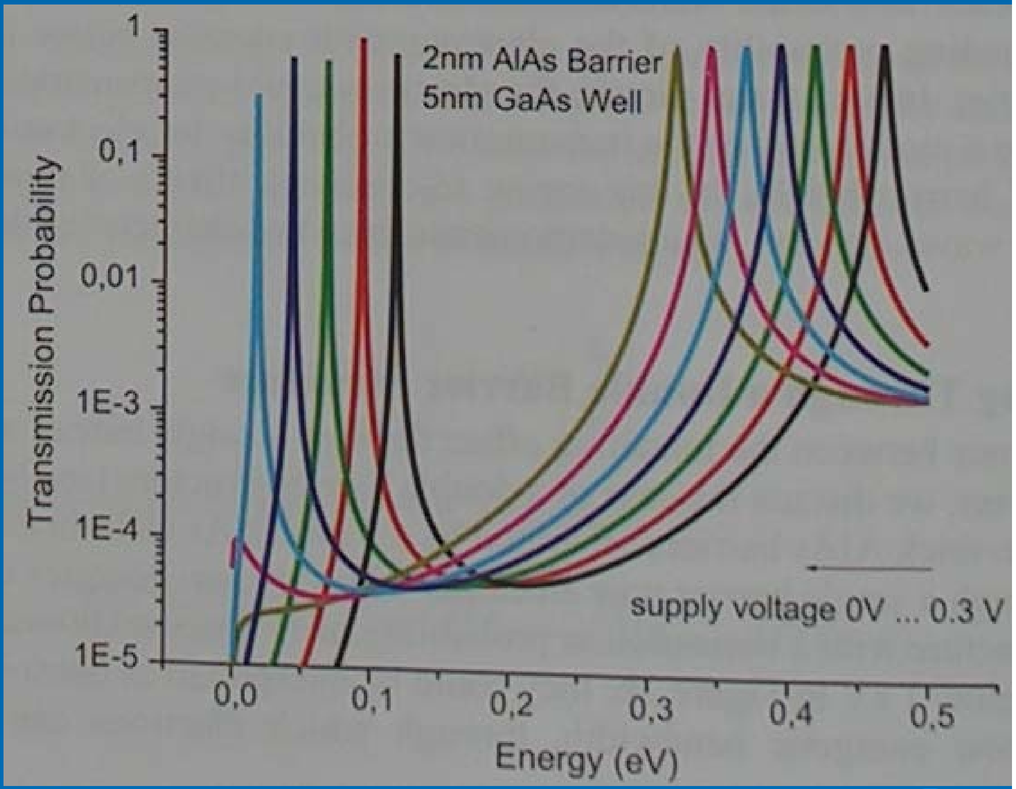
Figure 3: Schematic band diagram of a double barrier structure of AlAs embedded in GaAs (a) and the corresponding tunneling transmission probability (b).

Electron Tunneling

- In contrast to single barrier, there are three sharp maxima below 1 eV
  - Interpreted as quasi-bound states with narrow energetic bandwidth through which electrons can tunnel through open channels in the barrier
- This is not describable by a sequential picture of two wells
- Quantum mechanical devices cannot be put too close together without changing the characteristics of the single device

Resonant Tunneling Diodes

- Resonance properties
  - Resonant tunneling diode is the experimental realization of double barrier structure
  - Figure (fig 5) shows the behavior of resonances
  - A resonance can be considered as a channel which opens electron flux, current density first increases then decreases

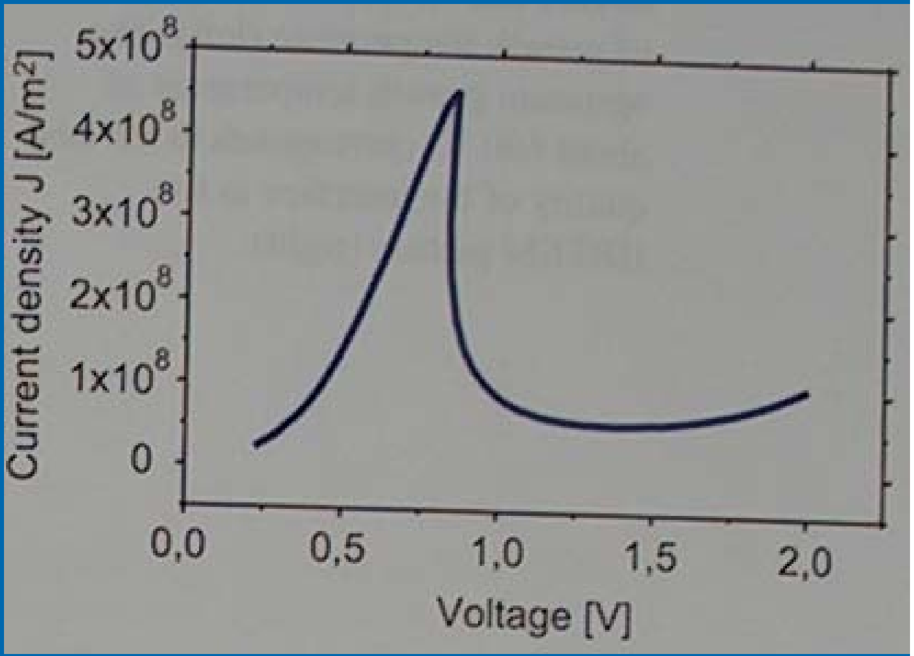


Resonant Tunneling Diodes

- Current voltage characteristics
  - Current density can be calculated based on transmission probability and the corresponding occupation densities
  - Text gives a relation for calculating current density based on the potential profile φ of the structure
  - The potential can be obtained by coupling effective mass Schrödinger equation with Poisson equation in a self-consistent manner

Resonant Tunneling Diodes

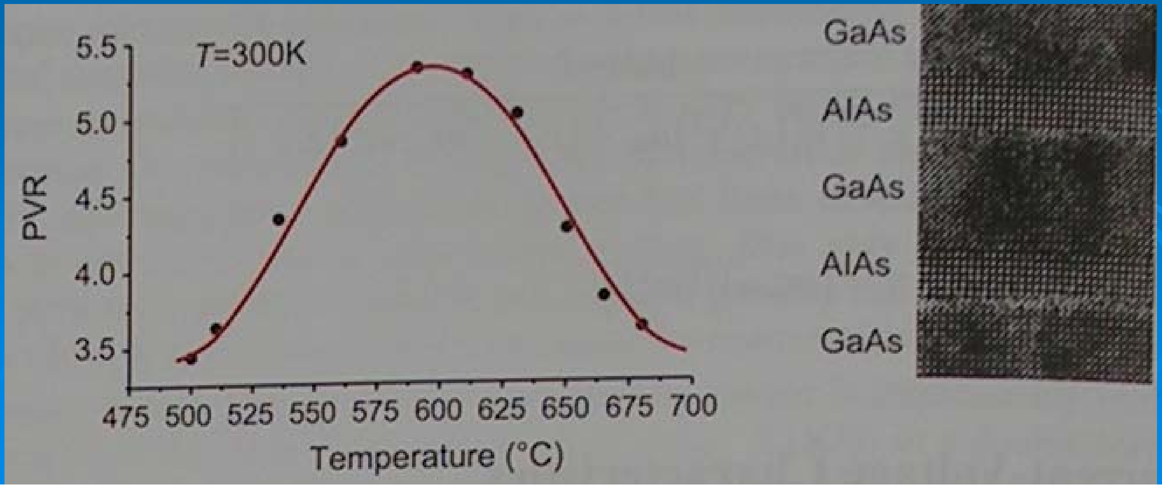
- Figure (fig 6) shows a typical current-voltage characteristic
- Negative differential resistance is a main feature



- The quantum device simulation package NEMO (NanoElectronic MOdeling) simulates a wide variety of quantum devices including RTDs

Resonant Tunneling Diodes

- Interface and growth temperature
  - PVR (Peak to Valley Ratio) is a merit of quality for RTDs
  - Highest PVR coincides with sharpest interface between barriers and the well
  - Temperature range between 580 and 600 results in highest PVR for AlAs/GaAs RTDs (fig 8)



Resonant Tunneling Devices

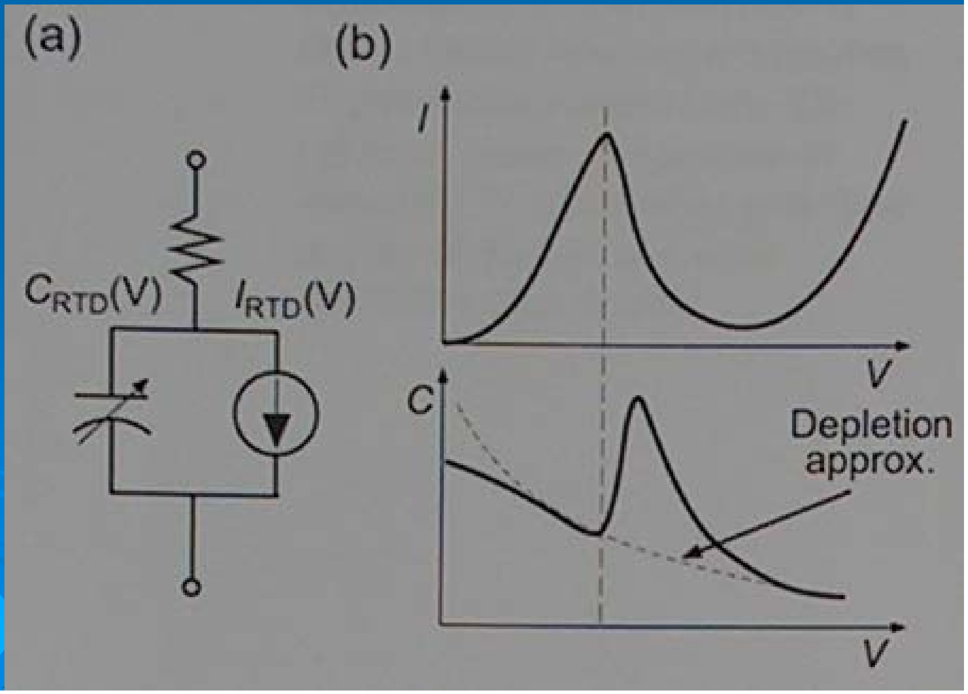
- Operation Speed of RTDs
  - One of the most attractive features of RTDs is their potential for extremely high speed operation
  - RTDs with 712 GHz oscillation and 1.5 ps switching times have been reported
  - It is important to differentiate “tunneling time” and “RC time”
  - Tunneling time is in order of the resonant-state lifetime or escape time which is the time it takes an electron in the quantum well to escape from it:

Resonant Tunneling Devices

- Shorter tunneling times can be obtained with thinner and lower barries
- Various non-idealities affect tunneling time in real RTDs
- Tunneling time determines the intrinsic delay of RTDs

Resonant Tunneling Devices

- In most applications, operation speed of RTDs is limited not by the intrinsic tunneling time but by the charging time of RTD capacitance
- Equivalent circuit of RTDs is shown in figure (fig 10)
- The capacitance-voltage curve is also shown in the figure



Resonant Tunneling Devices

- Applications of RTDs
  - Several applications exploit negative differantial resistance (NDR) of RTDs
  - Resonant tunneling transistors
    - To make a three terminal tunneling device RTDs are merged with conventional transistors and resonant tunneling bipolar transistors, resonant tunneling hot electron transistors and gated RTDs are fabricated

Resonant Tunneling Devices

  - Gated RTDs have Schottkey or junction gates around the emitter to control RTD area
- Concept of Monostable-Bistable transition logic elements (MOBILES)
  - The ultrahigh-speed logic gate : MOBILE exploits NDR of the RTDs
  - A circuit consisting of two NDR devices connected serially, to exploit monostable to bistable transition
  - Bias voltage is oscillated to generate the transition
  - NDR devices with third terminal are used to modulate their peak currents

Resonant Tunneling Devices

- Figure (fig 12) shows the load curves and the corresponding potential energy diagrams
- Figure (fig 13) shows the operation of a simple MOBILE inverter

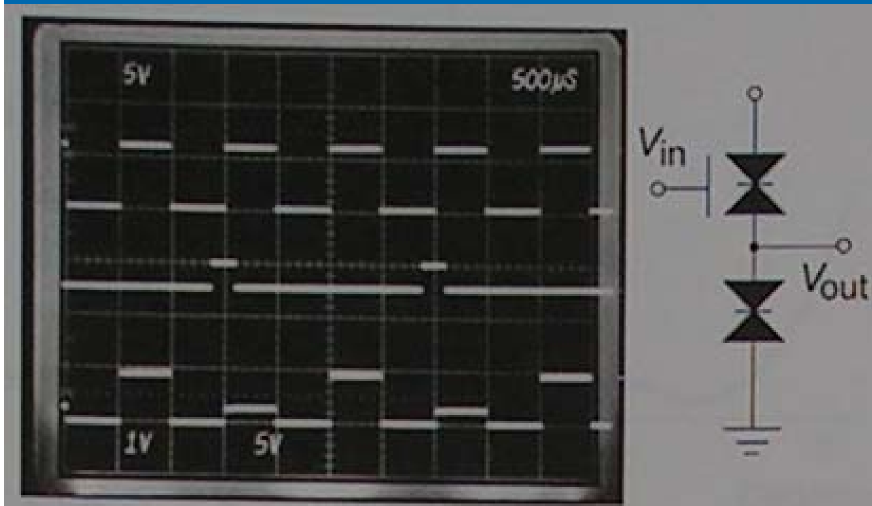
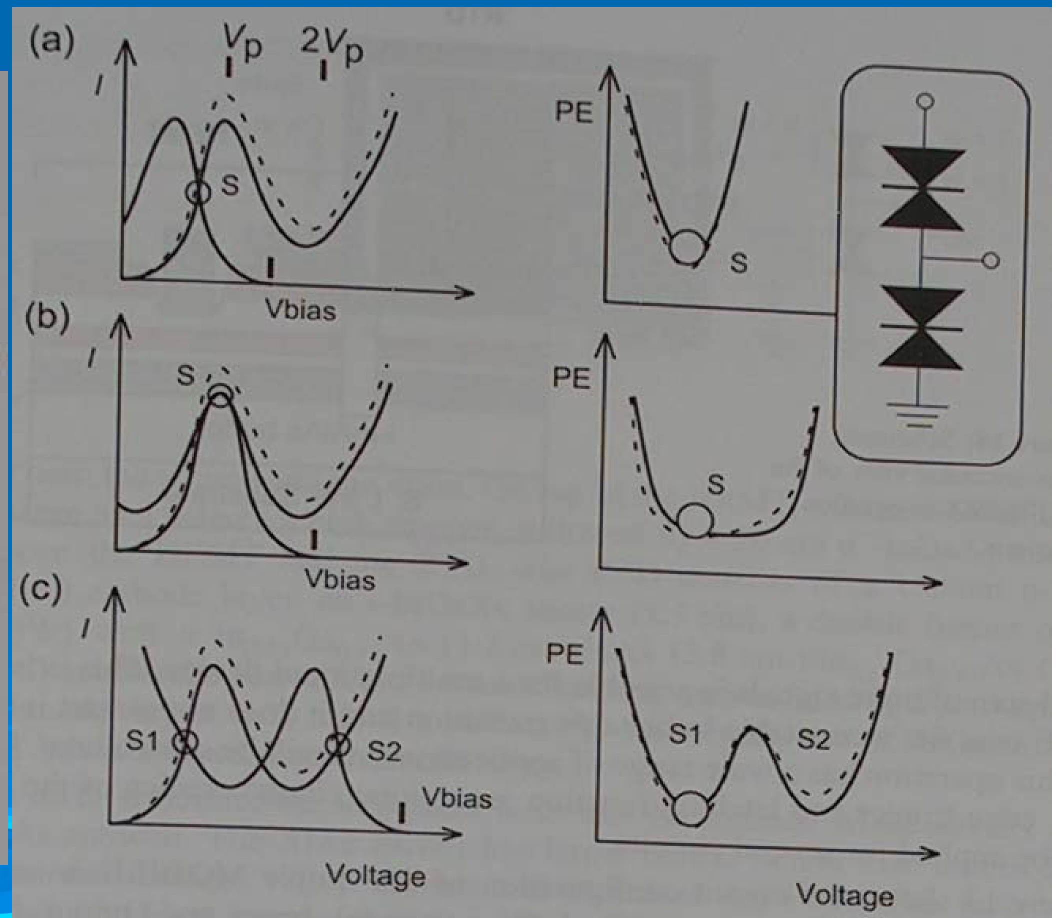


Figure 13: Circuit configuration and the operation wave form of the simple MOBILE inverter. Traces are the clock, input, and output voltages, from top to bottom, respectively.

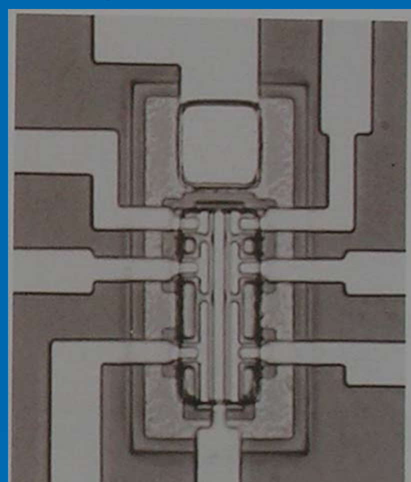


Resonant Tunneling Devices

- Integration Technology for MOBILEs
  - NDR devices with third terminal are required for MOBILEs
  - Gated RTDs were first used as three terminal NDR device, however they have disadvantages including high capacitance, difficult to optimize the layer structure, low PVR and difficult to fabricate
  - To overcome the problems, RTDs connected in parallel with HEMTs were fabricated

Resonant Tunneling Devices

- Examples of MOBILEs
  - Figure (fig 17 , 18) shows implementation of a weighted sum threshold logic function



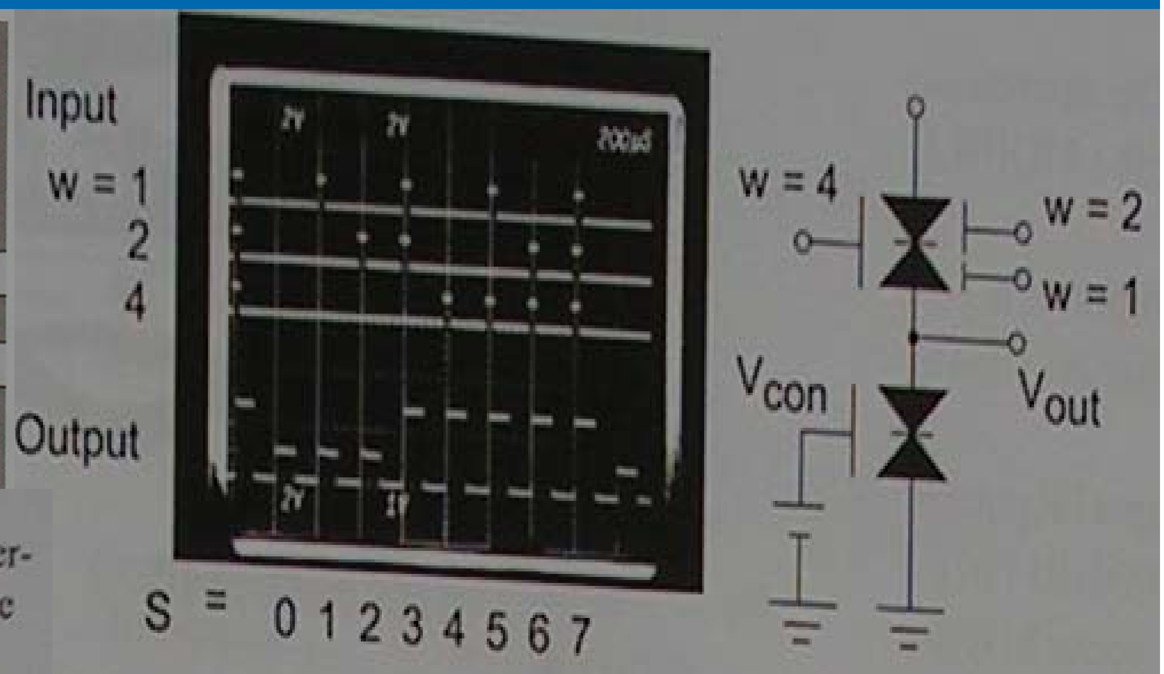
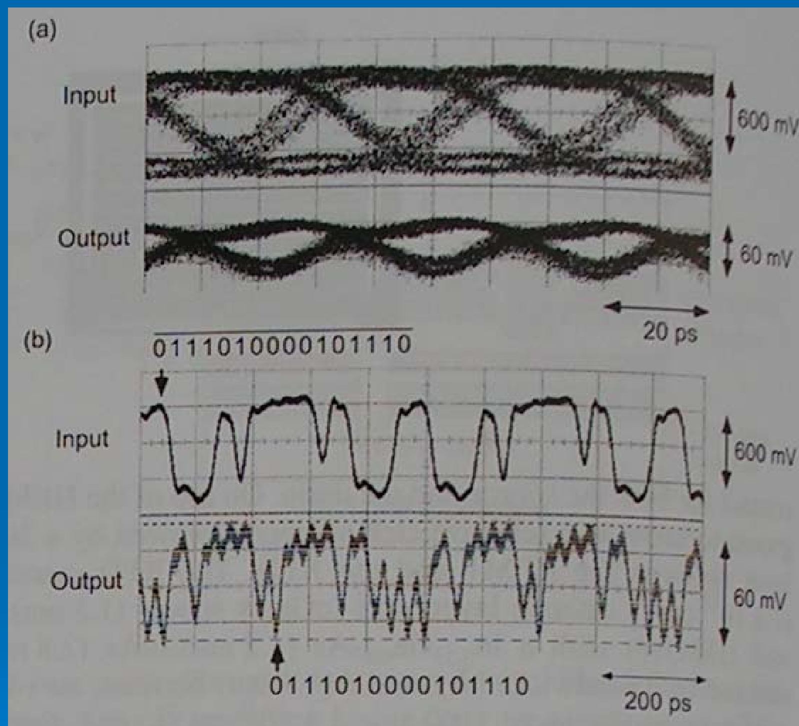


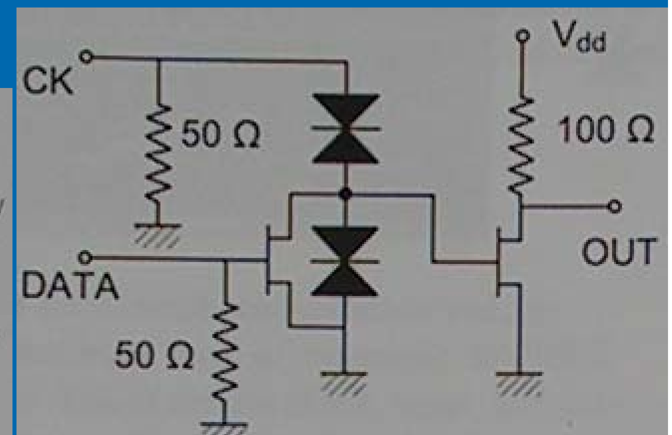
Figure 17: The circuit configuration and the operation of three-input MOBILE. The traces are the input 1 ($w = 1$), the input 2 ($w = 2$), the input 3 ($w = 4$), and the output, from top to bottom, respectively. The weighted sum (S) is shown at the bottom of the figure as a reference. The threshold value is selected by the control voltage, V_{con}, and it is chosen to be 2.5 in this figure.

Resonant Tunneling Devices

- Figure (19, 20 ,21) demonstrate a test circuit for evaluating operation speed of the MOBILE and the estimated power consumption

Figure 20: The operation waveform of the MOBILE D-FF
(a) with the input of a pseudo-random bit stream at 35 Gb/s,
(b) with an input bit pattern of (0111010000101110).
(The upper trace in b) is the complement of the input data stream.)





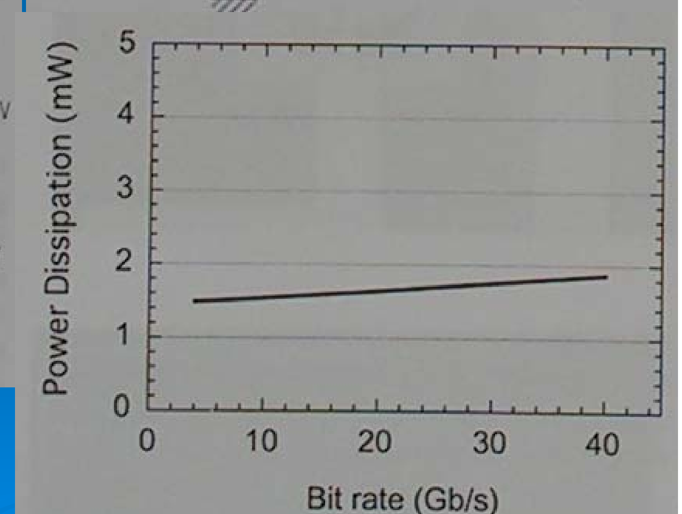
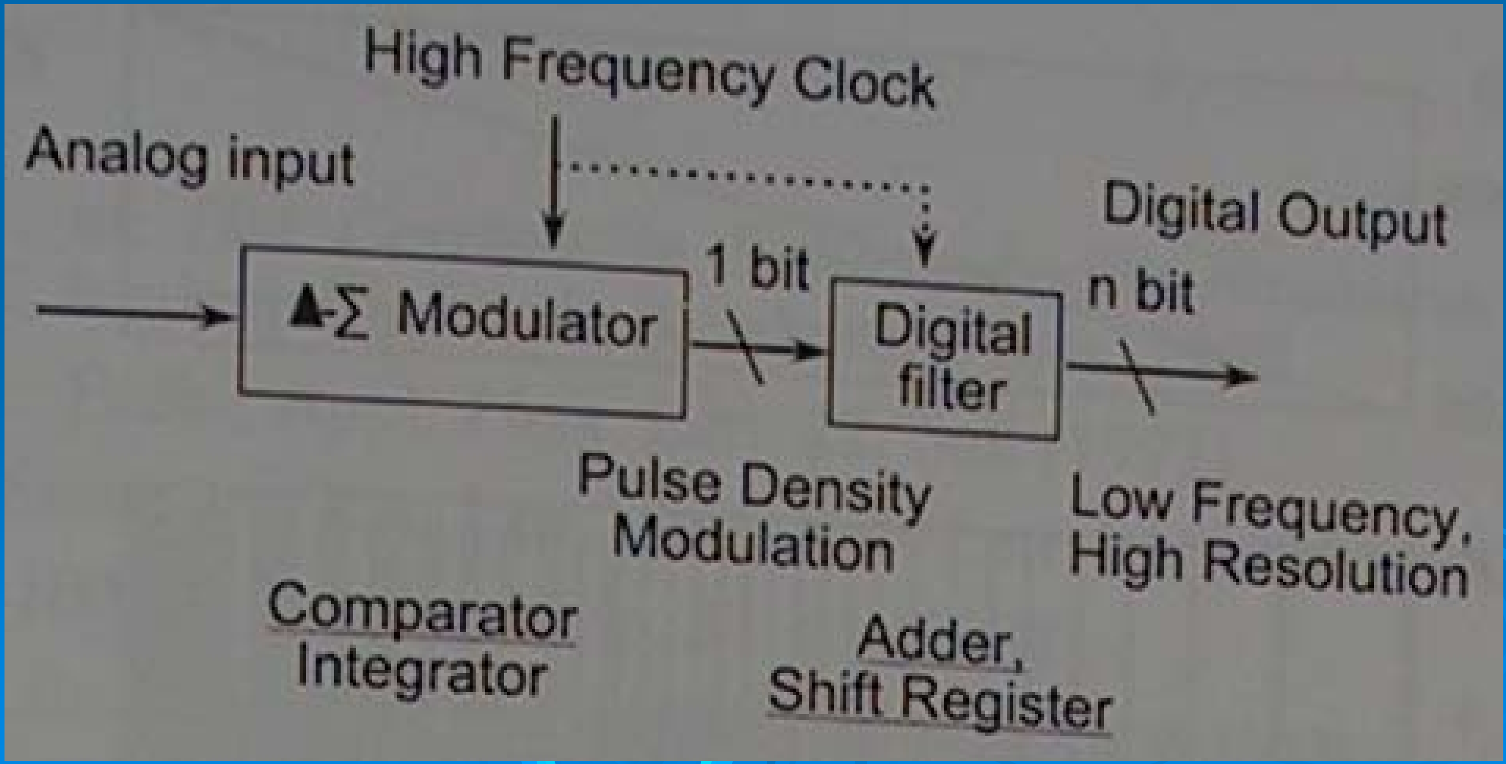


Figure 21: The calculated power dissipation of the core circuit shown in Figure 19.

Resonant Tunneling Devices

- One of the promising applications of MOBILEs is analog-to-digital-converter (ADC)
- Figure (fig 22) shows a block diagram of a ΔΣ ADC



Resonant Tunneling Devices

- ΔΣ modulator converts analog input into a pulse density at a frequency much higher than the Nyquist rate
- The filter cuts the high frequency component and down converts pulse density into the high-resolution digital output at Nyquist rate
- Higher resolution can be obtained by increasing sampling rate
- This method does not require a high accuracy analog component

Resonant Tunneling Devices

- MOBILEs can be used to fabricate high performance ΔΣ modulator
- Adder and shifter circuits used in digital filter can also be fabricated by MOBILEs
- Figure (fig 23) shows a ΔΣ modulator based on MOBILE