Resonant Tunneling Diodes: Theory of Operation and Applications

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***Abstract*—Conventional transistor technology will not be able to support future ultrahigh-speed applications. Resonant tunneling diode is an important advancement to this problem. An introduction and optimization of these devices are investigated. Current limitations and applications to this technology are discussed.**

***Index Terms*—Resonant Tunneling Diodes, High electron mobility transistor, negative differential resistance, quantum well, peak-to-valley ratio**

I. INTRODUCTION

Tunneling diodes (TDs) have been widely studied for their importance in achieving very high speed in wide-band devices and circuits that are beyond conventional transistor technology. A particularly useful form of a tunneling diode is the Resonant Tunneling Diode (RTD). RTDs have been shown to achieve a maximum frequency of up to 2.2 THz as opposed to 215 GHz in conventional Complementary Metal Oxide Semiconductor (CMOS) transistors. [1] The very high switching speeds provided by RTDs have allowed for a variety of applications in wide-band secure communications systems and high-resolution radar and imaging systems for low visibility environments.

In this paper, the theory of operation of RTDs will be explained. Next, the tradeoffs in the optimization of this technology will be discussed followed by some current circuit applications of RTDs.

II. THEORY OF OPERATION

Tunneling diodes provide the same functionality as a CMOS transistor where under a specific external bias voltage range, the device will conduct a current thereby switching the device "on". However, instead of the current going through a channel between the drain and source as in CMOS transistors, the current goes through the depletion region by tunneling in normal tunneling diodes and through quasi-bound states within a double barrier structure in RTDs.

A TD consists of a p-n junction in which both the n- and p-regions are degenerately doped (>10^{19} cm^{-3}). There is a high concentration of electrons in the conduction band (E_C) of the n-type material and empty states in the valence band (E_V) of the p-type material. Initially, the Fermi level (E_F) is constant because the diode is in thermal equilibrium with no external bias voltage. When the forward bias voltage starts to increase, the E_F will start to decrease in the p-type material and increase in the n-type material. Since the depletion region is very narrow (<10nm), electrons can easily tunnel through, creating a forward current as shown in Figure 1. Depending on how many electrons in the n-region are energetically aligned to the empty states in the valence band of the p-region, the current will either increase or decrease. As the bias voltage continues to increase, the ideal diffusion current will cause the current to increase. When a reverse-bias voltage is applied, the electrons in the p-region are energetically aligned with empty states in the n-region causing a large reverse-bias tunneling current. The I-V characteristics of the tunneling diode are shown in Figure 2.

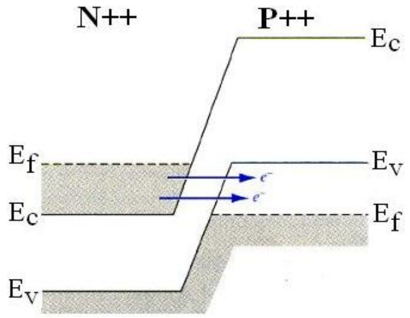

Figure 1. Band diagram of a TD. Diagram is showing maximum current across TD.

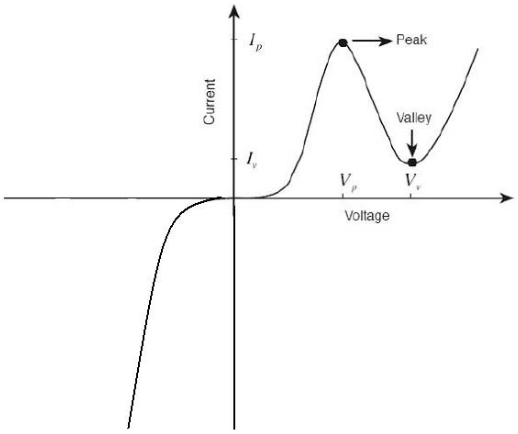

Figure 2. TD I-V characteristic. Where there is a reverse bias voltage, the current becomes extremely large.

The current-voltage (I-V) curve shows the negative differential resistance (NDR) characteristic of RTDs. For a specific voltage range, the current is a decreasing function of voltage. This property is very important in the circuit implementation because it can provide for the different voltage-controlled logic states corresponding to the peak and valley currents.

RTDs utilize a quantum well with identically doped contacts to provide similar I-V characteristics. It consists of two heavily doped, narrow energy-gap materials encompassing an emitter region, a quantum well in between two barriers of large band gap material, and a collector region, as shown in Figure 3. A current method of growth for this device is Metal Organic Chemical Vapor Deposition using GaAs-AlGaAs. The quantum-well thickness is typically around 5nm and the barrier layers are around 1.5 to 5 nm thick. [4]

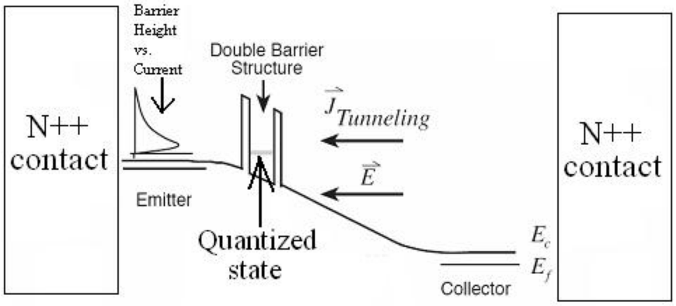

Figure 3. Structural diagram of RTD. [1] According to the graph on the emitter side, the current is at a maximum at the quasi-bound energy state indicated by the gray area in the quantum well.

When there is no forward voltage bias, most of the electrons and holes are stationary forming an accumulation layer in the emitter and collector region respectively. As a forward voltage bias in applied, an electric field is created that causes electrons to move from the emitter to the collector by tunneling through the scattering states within the quantum well. These quasi-bound energy states are the energy states that allow for electrons to tunnel through creating a current. As more and more electrons in the emitter have the same energy as the quasi-bound state, more electrons are able to tunnel through the well, resulting in an increase in the current as the applied voltage is increased. When the electric field increases to the point where the energy level of the electrons in the emitter coincides with the energy level of the quasi-bound state of the well, the current reaches a maximum, as shown in Figure 4.

Resonant tunneling occurs at specific resonant energy levels corresponding to the doping levels and width of the quantum well. As the applied voltage continues to increase, more and more electrons are gaining too much energy to tunnel through the well and the current is decreased. After a certain applied voltage, current begins to rise again because of substantial thermionic emission where the electrons can tunnel through the non-resonant energy levels of the well. This process produces a minimum "valley" current that can be classified as the leakage current, as shown in Figure 4.

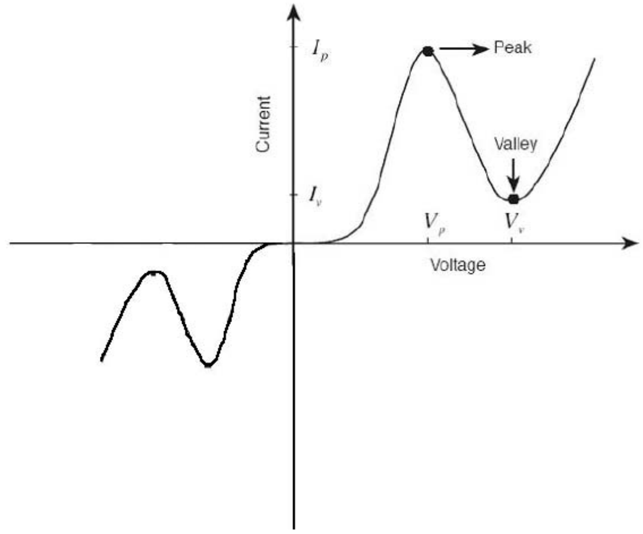

Figure 4. RTD I-V characteristic. When there is a reverse bias voltage, the current is not very large, unlike the TD.

RTDs have a major advantage over TDs. When a high reverse bias voltage is applied to TDs, there is a very high leakage current. However, RTDs have the same doping type and concentration on the collector and emitter side. This produces a symmetrical I-V response when a forward as well as a reverse bias voltage is applied. In this manner the very high leakage current present in normal TDs is eliminated. Thus, RTDs are very good rectifiers.

RTD bandwidths were reported for InAs/AlSb RTDs at about 1.24 THz due to their low ohmic contact resistance and short transit times. Higher bandwidths could be obtained using InAs Schottky-contact RTDs (SRTDs) because of the higher tunneling current densities and shorter transit times. However, InGaAs/AlAs/InP is usually used instead of InAs/AlSb because of its mature fabrication and growth technologies.

III. OPTIMIZATION TRADEOFFS

An important parameter of RTDs is the current peak to valley ratio (PVR=I_p/I_v). To achieve the maximum dynamic range, the I-V curve in the negative resistance voltage range should be very sharp resulting in a high PVR. For high frequency operation, very high peak current densities are required in order to obtain the maximum power available from the RTD. This can be done by decreasing the thickness of the quantum well barrier and also increasing the emitter doping level. However both of these methods will decrease PVR and increase the valley current producing more power consumption due to increased leakage current. The valley current limits the minimum barrier thickness and maximum emitter doping levels.

In order to reduce power dissipation of the diode when it is "on", the peak voltage can be reduced by designing a lower quasi-bound energy level. However, this will come at the expense of a lower PVR. In most situations, decreasing the barrier width as much as possible is desired because the peak current increases more rapidly than the PVR degrades providing the largest dynamic range.

IV. APPLICATIONS

RTDs have attracted a lot of attention and have been researched for almost two decades because of their compatibility with many conventional technologies such as high electron mobility transistors (HEMTs) and metal oxide field effect transistors (MOSFETs). The high-speed, low power benefits can now be applied to digital circuit applications.

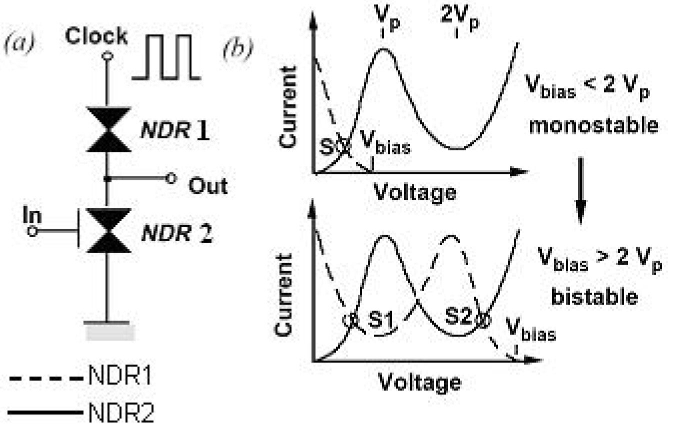

Figure 5. a) Circuit configuration of MOBILE b) The “latching” and “sampling” states of a MOBILE

The operation of the delayed flip flop is based on two RTDs in a circuit called the monostable-bistable transition logic element (MOBILE), as shown in Figure 5a. NDR1 is controlled by the clock (bias voltage) and NDR2 is controlled by an analog input. The monostable state occurs when the clock is on the falling edge causing the NDR1 current to intersect the NDR2 current only once. When the clock is on its rising edge, the circuit goes into the bistable state because NDR1 will intersect NDR2 at two points. The peak bias voltage of the clock is greater than the peak voltage of NDR1 but less than the peak voltage of NDR1 and NDR2 combined. The output voltage will switch back and forth between the two logic states “high (S2)” to “low (S1)” when the bias voltage (clock) exceeds twice the peak voltage (V_p) of the NDR device. Therefore, on the rising edge of the clock, the circuit “samples” the input. If the input is low, the peak voltage of the clock is less than $2V_p$ and the output voltage remains the same. If the input is high, the peak clock voltage is greater than 2Vp, causing the output voltage to switch from S1 to S2 or vice versa. When the clock is low or on the falling edge, the circuit “latches” onto the current output because there is only one stable state.

A MOBILE RTD is important in applications where a high sampling rate is required such as high-resolution imaging and communications systems. A conventional CMOS flip flop cannot match the ultra-high speeds of RTD devices.

It has also been reported that a 650 GHz oscillator has been achieved using Schottky collector RTDs (SRTDs). [2] Many other applications such as analog-to-digital converters and frequency dividers have also been achieved using RTDs. [7]

V. CONCLUSIONS

RTDs have allowed us to realize certain applications that will be beyond the capability of CMOS technology. These low-power, high speed, and small devices are especially important as we continue to scale down to the size of atoms where heat and parasitic effects are a major problem.

However, in order for RTDs to reach its full potential, more mature fabrication techniques are needed. Precise barrier thickness control is needed to insure uniformity across the whole wafer. Also, the output power of RTDs is limited. More research is needed to help realize RTD circuits without an amplifier or other drivers. This will minimize the power and area of the integrated circuit (IC).

Current applications of RTDs with advanced conventional transistors have shown that RTDs is very promising for future ultrahigh-speed digital devices.

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