Università di Pisa

Resonant tunneling diodes: transport mechanism and circuit applications

Giuseppe Iannaccone
Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni,
Università di Pisa

G. Iannaccone, "*Resonant tunneling diodes: transport mechanism and circuit applications*", Nano et Micro Technologies, **3**, pp.127-132 (2003).

University of Bologna , 2002, p. 395-398.

[ZHU 98] L. ZHUANG, L. GUO , S. Y. CHOU, "Silicon single-electron duantum-dot transistor switch operating at room temperature", *Appl. Phys. Lett.*, vol. 72, 1998, p. 1205-1207.

[AUG 00] R. AUGKE , ET AL., "Doped silicon single electron transistors with single island characteristics", *Appl. Phys. Lett.*, vol. 76, 2000, p. 2065-2067.

[SAK 98] T. SAKAMOTO, H. KAWAURA , T. BABA, "Single-electron transistors fabricated from a doped-Si film in a silicon-on-insulator substrate", *Appl. Phys. Lett.*, vol. 72, 1998, p. 795-796.

[UCH 01] K. UCHIDA, J. KOGA, R. OHBA, S. TAKAGI , A. TORIUMI, "Silicon single-electron tunneling device fabricated in an undulated ultrathin silicon-on-insulator film", *J. of Applied Phys.*, vol. 90, 2001, p. 3551-3557.

[SAN 00] M. SANQUER , ET AL., "Coulomb blockade in low-mobility nanometer size Si MOSFET", *Phys. Rev. B*, vol. 61, 2000, p. 7249-7252.

[SPE 02] M. SPECHT, M. SANQUER ,S . DELEONIBUS , G. GUÉGAN, "Signature of Kondo effect in silicon quantum dots", *Eur. Phys. J. B*, vol. 26, 2002, p. 503-508.

[HAF 95] I. M. HAFEZ, G. GHIBAUDO, F. BALESTRA , M. HAOND, "Impact of LDD structures on the operation of silicon MOSFETs at low temperature", *Solid-State Electronics*, vol. 38, 1995, p. 419-424.

[PIK 97] F. G. PIKUS , K. K. LIKHAREV, "Nanoscale field-effect transistors: An ultimate size analysis", *Appl. Phys. Lett.*, vol. 71, 1997, p. 3661-3664.

[FOW 86] FOWLER A. B., TIMP G. L., WAINER J. J. , WEBB R. A., "Observation of Resonant Tunneling in Silicon Inversion Layers", *Phys. Rev. Lett.*, vol. 57, 1986, p. 138-141.

[BOE 03B] BOEUF F., , ET AL., "Experimental study of transport in nanoscale Planar MOSFETs near the ballistic limit", *Silicon Nanoelectronics Workshop, Kyoto June 2003, accepted in IEEE trans. on Nanotechnology.*

[PIC] PICHARD J. L., SANQUER M.,SLEVIN K.,, DEBRAY P., "Broken symmetries and localization lengths in Anderson insulators: Theory and experiment", *Phys. Rev. Lett.*vol. 65, 1990, p. 1812-1815.

Resonant tunneling diodes: transport mechanism and circuit applications

Giuseppe Iannaccone

Dipartimento di Ingegneria dell'Informazione
Università degli Studi di Pisa
Via Diotisalvi 2, I-56122 Pisa, Italy
g.iannaccone@iet.unipi.it

ABSTRACT. In this paper we present a brief review of physical properties and proposed circuit applications of resonant tunnelling diodes, that, since their proposal in the seventies, have represented the prototypical nanoelectronic device .The paper follows the outline of the lecture given at the MIGAS summer school "Towards Nanoelectronics". We review the transport mechanism and stress the equivalence between the coherent and the sequential tunnelling models, if both models are properly extended. We then provide a brief review of digital and mixed signal applications, and the main references for the reader interested in an in-depth treatment of the discussed subjects.

KEYWORDS: resonant tunnelling diodes, tunnelling, nanoelectronic circuits.

RS - NMT – 3/2003. MIGAS'03, pages 127 to 132

1. Introduction

The Resonant Tunnelling Diode (RTD) has been proposed and demonstrated in the pioneering work of Tsu, Esaki, and Chang (Tsu *et al.*, 1973, Chang *et al.*,1974). Since then, it has been extensively investigated both for device applications, and for studying problems, relating energy levels in quantum wells and tunnelling, that are of general interest in condensed matter physics.

Because of its simplicity, and its peculiar properties based on quantum confinement and tunnelling, the resonant tunnelling diode has been the prototypical nanoelectronic devices, even if it is not particularly promising as far as aggressive downscaling is concerned.

In this paper, we describe the transport mechanisms and main applications in logic and memories of resonant tunnelling diodes. For reasons of brevity we will only be able to mention the main issues, following the structure of the lecture. The interested reader can find many details on physical models and digital application in two recent reviews (Sun *et al.*, 1998, Mazumder *et al.*, 1998).

The structure of the paper is the following: In section 2 we will discuss the main transport mechanisms proposed in the literature, and we will show that they can be seen as two different formalisms describing the same underlying physics. In section III we will review some digital and mixed-signal applications.

2. Transport model

A Resonant Tunnelling Diode (RTD) is a two-terminal device whose active region consists of two barriers, *i.e*, two layers of few nanometres with large energy gap (*e.g.* AlGaAs), separated by a quantum well, *i.e.* a layer of few nanometres with a smaller energy gap (*e.g.* GaAs). Two highly doped layers connect the barriers with the device terminals. The operating principle is illustrated in Figure 1, where conduction band profiles of an AlGaAs-GaAs diode with a 6.2 nm GaAs well and two $Al_{0.36}Ga_{0.64}As$ layers, with thickness 12.4 and 14.1 nm, are shown for three different applied voltages. The device considered has been considerably investigated from the theoretical and experimental point of view (Iannaccone *et al.*, 1998).

First, we must consider that tunnelling from the right contact (the emitter) two the well conserves energy, spin, and transversal momentum. At low bias (Figure 1, upper left) the energy of the ground state in the quantum well lies well above the Fermi level of the emitter so that current is quite low. When the bias is increased the ground state of the well is shifted down, and more electrons from the emitter may tunnel into the well, so that the current increases, as shown in the current-voltage characteristic shown in the bottom of Figure 1.

Maximum current is reached when the ground state in the well aligns with the lowest confined state in the emitter, as shown in Figure 1, upper centre. When the voltage is further increased (Figure 1, upper right) the ground state of the well goes below available states at the emitter, and the current suddenly drops. A further increase of the voltage then causes a current increase, due to the decrease of the barrier and of the second available state in the well.

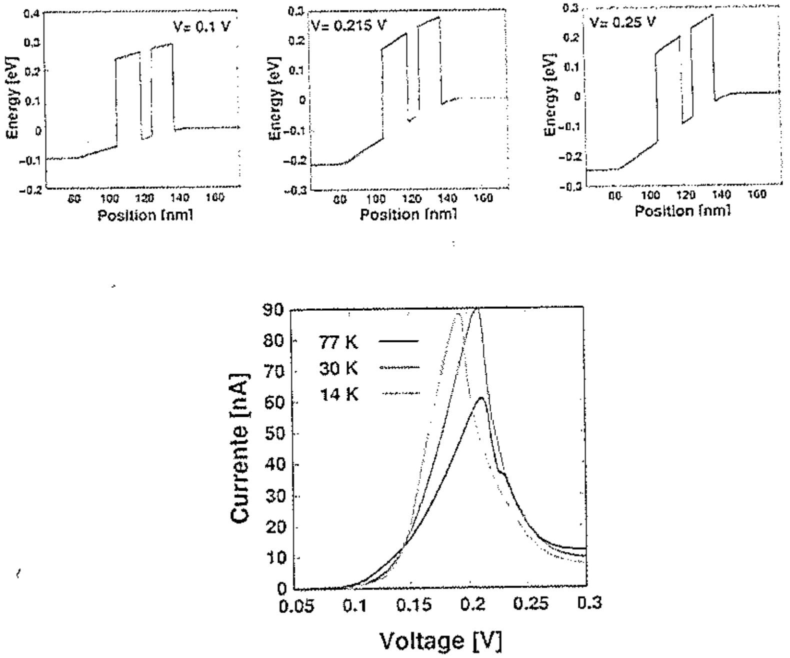

Figure 1. *Above: conduction band profiles of an AlGaAs-GaAs resonant tunnelling diode with two AlGaAs barriers with thickness 12.4 and 14.1 nm, and a 6.2 nm GaAs quantum well. Below: I-V characteristics of the same device at different temperatures*

The shape of the I-V characteristics resembles that of Esaki diodes, and is promising for applications such as oscillators, bistable circuits, and fast switching circuits, that exploit the negative differential resistance of the device.

Two main mechanisms have been proposed in the literature for transport in resonant tunnelling diodes: "Coherent" and "Sequential" Tunnelling. Coherent Tunnelling is a one-step process (Stone *et al.*, 1985, Jonson *et al.*, 1987): tunnelling of the whole double barrier region is resonantly enhanced when the incoming particle energy is equal to that of the confined state in the well. Sequential Tunnelling, instead, is a two-step process (Luryi 1985): electrons tunnel from the emitter to the quantum well, and then from the well to the other electrode (the collector).

We have shown that such "mechanisms" are just different descriptions of transport in the diode, and do not imply a real physical difference. Indeed, the main current components are sketched in Figure 2. Electrons injected from a contact have a probability T_{DB} of being coherently transmitted through the double barrier, and a probability R_{DB} of being coherently reflected. However, they have a finite probability $1 - T_{DB} - R_{DB}$ of losing phase coherence and being incoherently transmitted or reflected (blue arrows in Figure 2).

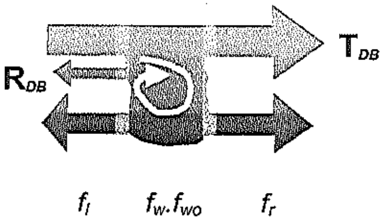

Figure 2. *Sketch of the current components in a resonant tunnelling diode*

The coherent tunnelling model typically focuses on the coherent current components (the red arrows in Figure 2), while the sequential tunnelling model focuses on the incoherent components (blue arrows). In (Iannaccone 1995, Iannaccone 1996), we have shown how the coherent tunnelling model can be slightly extended in order to include incoherent components, and, on the other hand, how coherent components can be included in the sequential tunnelling model. With these modifications, the two models have been demonstrated to be perfectly coincident. The interested reader can find all the details in the mentioned papers.

3. Device applications

All device applications of resonant tunnelling diodes exploit the negative differential resistance, which may be very useful in positive feedback circuits, such as oscillators or latches. In addition, the S-shape of the characteristics may be useful for circuits with large functionality to device count ratio.

3.1. *Static random access memories*

The main building block of a static random access memory is a latch, which can be very simply realized with two resonant tunnelling diodes in series (in contrast with the four transistors required in CMOS technology). Write and read operations are best performed if diodes are coupled with FETs, which provided current drive, as in the proposal illustrated in Figure 3 (Var der Wagt *et al.*, 1999). In such proposal a memory cell consists of an RTD latch, a write FET and a read FET. The design is rather compact, since the two RTDs are grown on the source region of the write FET. A reduction of power consumption of one order of magnitude is expected over conventional CMOS SRAMs (Seabaugh *et al.*, 1998).

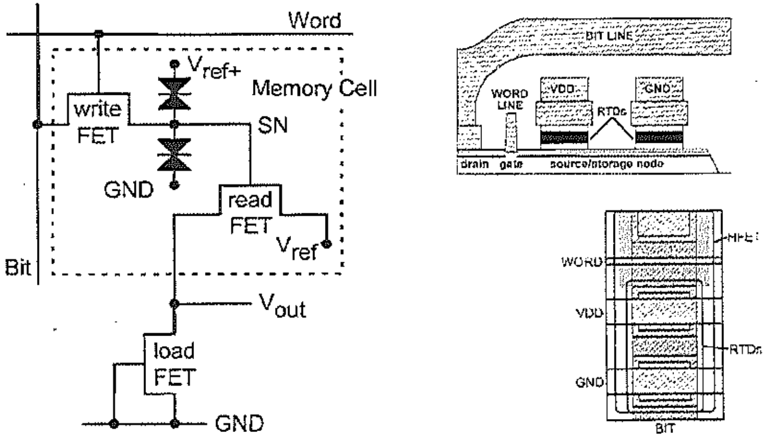

Figure 3. *SRAM cell with resonant tunnelling diodes and FETs (Van der Wagt et al., 1999). Left: circuit of a single cell and bit line readout; Right: cell layout. All figures are from Ref. (Van der Wagt et al., 1999)*

3.2. *Digital logic*

Digital logic with RTDs typically exploits the self-latching property that can be achieved with two diodes in series. Several prototypes have been demonstrated, such as for example a self-latching majority voting gate (Mazumder *et al.*, 1998), or a static shift register (Seabaugh *et al.*, 1998). In all cases, a significant reduction in transistor count is achieved with respect to conventional CMOS implementation. In the case of the shift register, for example, 8 transistors and 4 RTDs are needed in the RTD-FET circuit, with respect to 16 transistors required in the CMOS-only version.

3.3. *Analog and mixed-signal applications*

Oscillators typically exploit negative differential resistance devices, to compensate losses in LC tanks and as a means for obtaining instability in the circuit. Oscillations at frequencies of a few hundred gigahertz have been typically achieved.

Waveforms usable for digital clock signal have also been recently obtained (Seabaugh *et al.*, 1999) with very simple circuitry.

4. Discussion

The resonant tunnelling diode is an extremely interesting device from the point of view of understanding transport in highly confined structures, and for circuit applications. At present, research mostly focuses on transport and noise in the presence of strong magnetic fields, and on silicon-based resonant interband tunnelling diodes, that have the great advantage of being easily integrable with CMOS technology.

5. References

Chang L. L., Esaki L., Tsu R., "Resonant Tunneling in semiconductor double barriers", *Appl. Phys. Lett.*, Vol. 24, 1974, pp. 593-595.

Iannaccone G., Lombardi G., Macucci M., Pellegrini B., "Enhanced Shot Noise in Resonant tunneling: Theory and Experiment", *Phys. Rev. Lett.*, Vol. 80, 1998, pp. 1054-1057.

Iannaccone G., Pellegrini B, "Compact formula for the density of states in a quantum well", *Phys. Rev. B*, Vol. 53, 1996, pp. 2020-2025.

Iannaccone G., Pellegrini B, "Unified approach to electron transport in resonant tunneling diodes", *Phys. Rev. B*, Vol. 52, 1995, pp. 17406-17412.

Jonson M., Grincwaig A., *Appl. Phys. Lett.*, Vol. 51, 1987, pp. 1279-1281.

Luryi S., "Frequency limit of double barrier resonant tunneling oscillators", *Appl. Phys. Lett.*, Vol. 47, 1985, pp. 490-492.

Mazumder P., Kulkarni S., Bhattacharya M., Sun J. P., Haddad G. I., "Digital Circuit Applications of Resonant Tunneling Diodes", *Proc. IEEE*, Vol. 86, 1998, pp. 664-686.

Seabaugh A., Brar B., Broeakaer T., Morris F., var der Wagt P., Frazier G., "Resonant-Tunneling Mixed-Signal Circuit Technology", *Solid State Electronics*, Vol. 43., 1999, pp. 1355-1365.

Seabaugh A., Deng X., Blake T., Brar B., Broekaert T., Lake R., Morris F., Frazier G., "Transistors and tunnel diodes for analog/mixed-signal circuits and embedded memory", *IEDM Technical Digest*, pp. 429-432.

Stone A. D., Lee P. A, "Effect of inelastic processes on resonant tunneling in one dimension", *Phys. Rev. Lett.*, Vol. 54, 1985, pp. 1196-1199.

Sun J. P., Haddad G. I., Mazumder P., Schulman J. N, "Resonant Tunneling Diodes: Models and Properties", *Proc. IEEE*, Vol 86, 1998, pp. 641-661.

Tsu R, Esaki L., "Tunneling in a finite superlattice", *Appl. Phys. Lett*, Vol. 22, 1973, pp. 562-564.

Van Der Wagt, "Tunneling-based SRAM", *Proc. IEEE*, Vol. 87, 1999, pp. 571-595.

Detailed numerical simulation of nanoelectronic devices

Giuseppe Iannaccone

Dipartimento di Ingegneria dell'Informazione
Università degli Studi di Pisa
Via Diotisalvi 2, I-56122 Pisa, Italy
g.iannaccone@iet.unipi.it

ABSTRACT. Issues related to the numerical simulation of nanoelectronic devices are addressed, with particular reference to the approach adopted in the EU funded project NANOTCAD. Basics of numerical simulation are described, as well as the structure of the 2D and 3D codes for the simulation of semiconductor devices developed within the NANOTCAD project. Reference is provided to typical simulation results, to additional material and to possibility of using the NANOTCAD codes, with sample input files and complete user's manuals on the PHANTOMS simulation hub.

KEYWORDS: noise, nanoelectronics, shot noise, mesoscopic devices, ballistic MOSFETS.

RS - NMT – 3/2003. MIGAS'03, pages 133 to 142