Concurrent effects of Pauli and Coulomb interactions in resonant tunneling diodes at low bias and low temperature

Giuseppe Iannaccone
Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni,
Università di Pisa
Massimo Macucci
Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni,
Università di Pisa
Giovanni Basso
Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni,
Università di Pisa
Bruno Pellegrini
Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni,
Università di Pisa

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Josef Sikula

Czech Noise Research Laboratory
Brno University of Technology

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CONCURRENT EFFECTS OF PAULI AND COULOMB INTERACTION IN RESONANT TUNNELING DIODES AT LOW BIAS AND LOW TEMPERATURE

G. IANNACCONE*, M. MACUCCI, G. BASSO, B. PELLEGRINI

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

In this talk we present a model for the physical simulation of noise in resonant tunneling diodes, based on the self-consistent solution of the Poisson-Schrödinger equation in one dimension. We focus on suppression of shot noise at low bias, as a concurrent effect of Pauli exclusion and Coulomb interaction, and show that such effect may be observable even at 77 K in a thin barrier AlGaAs-GaAs resonant tunneling diode, that we are presently investigating also from the experimental point of view.

1. Introduction

Deviations of the power spectral density of shot noise with respect to the value associated to a Poisson process have been investigated in several device structures and operating conditions. Such deviations are extremely interesting, since they are in most cases due to electron-electron interaction, of which they can represent a very sensitive probe.

Electrons typically interact through the electrostatic force and through Pauli exclusion, which tend to broaden the distribution of electrons in the phase space. Depending on the device structure and on the operating conditions, such interactions may alter the statistical properties of current fluctuations with respect to the case of non interacting electrons, in a way that is intimately related to the microscopic transport mechanisms.

When electrons are non-interacting, the transport process is Poissonian, and the power spectral density of the noise current is $S_{\rm full} = 2qI$, where q is the electron charge, and I is the DC current through the device. The Fano factor, defined as the ratio of the power spectral density of the noise current to $S_{\rm full}$, is the most used parameter for measuring the deviations with respect to a Poisson process. A broad review of many cases observed in the last ten years of noise literature can be found in Ref. [1].

In this talk, we want to describe the concurrent effects of Coulomb and Pauli interactions in a resonant tunneling diode at low bias and low temperature. The effect has been first predicted in Ref. [2], and has been studied from the analytical point of view in Ref. [3], but has not yet been observed in experiments, given the very low bias current and associated low differential conductance. Here, we consider a device with much thinner barriers with respect to those considered in Ref. [2], in order to verify whether the effect is still present is a device with higher differential conductance at low bias, and therefore easier to characterize at those regimes.

2. Model and Discussion

In order to investigate from a quantitative point of view such effects, we have developed a self-consistent 1D Poisson-Schrödinger solver which allows us to simulate DC and noise properties of resonant tunneling diodes. We shall refer to a particular structure, that we are presently investigating from the experimental point of view: it is an AlGaAs-GaAs double

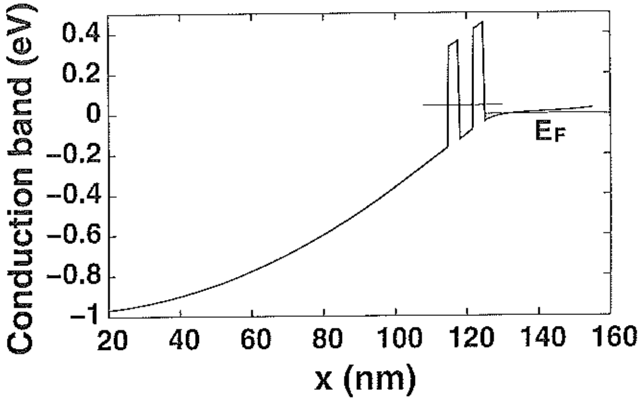

Fig. 1. Conduction band profile in the double barrier diode with applied voltage 1 V at 77 K, obtained from the self consistent solution of Poisson and Schrödinger equation .

barrier diode with a GaAs well of 4 nm, two $Al_xGa_{1-x}As$ barriers of 3 nm ($x = 0.6$), two undoped GaAs spacers of 15 nm on both sides, a 100 nm GaAs layer with donor doping of 10^{17} cm^{-3}, and heavily doped contact regions with donor doping of 10^{17} cm^{-3}.

When a voltage is applied to the diode, the conduction band has the profile shown in Fig. 1. There is strong quantum confinement both in the well and in the accumulation region near the cathode. The density of states in those regions is obtained by solving the 1D Schrödinger equation, and the potential profile from the self-consistent solution of the Poisson equation. Electron density of states in other regions in assumed to be semiclassical. Fig. 1 refers to the device described above and to an applied voltage of 1 V.

The 1D Poisson-Schrödinger equation is solved in the assumption quasi-equilibrium, i.e., considering that electrons in the three regions in which the device is divided (emitter, well, collector) obey to an equilibrium distribution with a given chemical potential. The chemical potentials of the emitter and collector regions are those of the respective contacts, while the chemical potential in the well is computed by enforcing charge conservation in the well. This complicates somewhat the solution of the Schrödinger equation, since an iterative bisection procedure has to be implemented in order to find the proper chemical potential in the well.

Once the conduction band profile is obtained, the transition rates from both contacts to the well and viceversa can be computed, assuming conservation of transversal momentum during tunneling and taking into account inelastic scattering with a Breit-Wigner model, i.e., assuming a lorentian shape for the longitudinal density of states in the quantum well. The shot noise suppression factor can be readily obtained by slightly varying the chemical potential in the well with respect to the stationary state. Indeed, the shot noise suppression factor can be written as

$$\gamma = \frac{S}{2qI} = \frac{(\frac{dg}{d\mu})^2 + (\frac{dr}{d\mu})^2}{(-\frac{dg}{d\mu} + \frac{dr}{d\mu})^2}, \qquad (1)$$

where g (r) is the generation (recombination) rate, i.e. the probability of transitions per unit time per unit area from the contacts to the well region (from the well region to the contacts), and μ is the chemical potential of the well.

The model and the derivation of (1) is described in detail in Refs. [4] and [5] and will not be repeated here. The theoretical J-V characteristics are shown in Fig. 2 at 77 and 300 K.

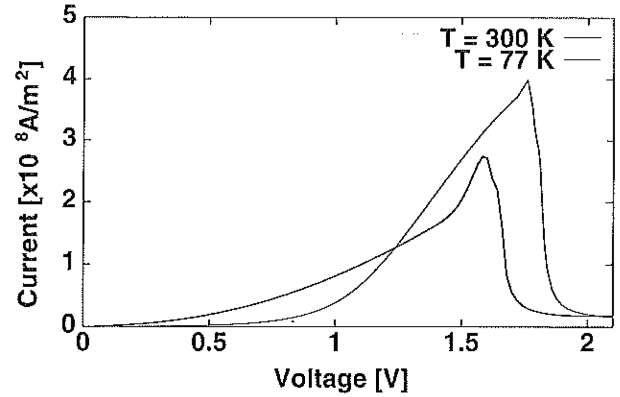

Fig. 2. Theoretical J-V characteristic of the resonant tunneling, obtained with the 1D PS solver, at the temperature of 300 K and 77 K.

It is worth noticing that already at 77 K, the noise suppression factor, i.e. the ratio of the power spectral density of the noise current to $S_{\rm full}$, plotted as a function of the applied voltage in Fig. 3, exhibits a shallow peak of a few percent.

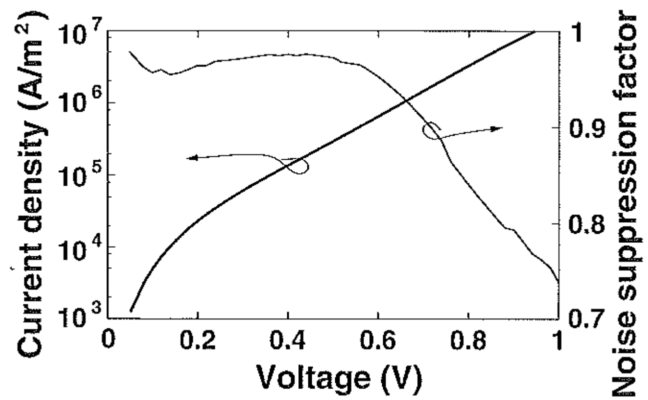

Fig. 3. Theoretical current density and noise suppression factor as a function of the applied voltage at 77 K.

Such peak has been associated [2] to the transition between a regime in which Pauli exclusion dominates electron-electron interaction (on the left of the peak), to a regime in which Coulomb repulsion dominates electron-electron interaction (on the right of the peak). This effect has never been observed experimentally, and was predicted at much lower temperatures, close to 4.2 K. It is worth noticing (see Fig. 3) that the peak occurs for a current density of 10^3-10^4 A/m^2, which corresponds, for a typical device with area 1 μm^2, to a current of 1-10 nA, and a resistance of 100 MΩ-1 GΩ, which can be characterized with very low noise measurement setup [6]. Work is presently in progress to observe this effect experimentally.

Acknowledgments

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DEVICE CHARACTERISTICS EXTRACTION BY LOW FREQUENCY NOIS MEASUREMENTS; SOME RESULTS ON THE STATE-OF-THE-ART MOSFE'

J. A. CHROBOCZEK, C. LEROUX, T. ERNST
LETI/CEA-Grenoble, 17, rue des Martyrs, 38054 Grenoble, France
E-mail: jan.chroboczek@cea.fr

A. SZEWCZYK
Gdansk University of Technology, ul. G. Narutowicza 11/12, 80952 Gdansk, Poland
E-mail: szewczyk@eti.pg.gda.pl

K. ROMANJEK, AND G. GHIBAUDO
IMEP/ENSERG, 23, rue de Martyrs, 38016 Grenoble, France
E-mail: ghibaudo@enserg.fr

We discuss low frequency noise measurements on (1) thin SiO_2 gate insulator (2) HfO_2 gate insulator and (3) SiO_2 insulator, SiGe buried channel, MOSFETs. The data are used for evaluating the density of slow traps located near the dielectric-Si interface in the devices. Comparisons with charge pumping technique are made for (1) and (2) – type devices. The SiGe and all-Si devices show comparable noise properties and so do the SiO_2 and HfO_2 dielectric devices.

1. Introduction

Low frequency noise, LFN, measurements in MOSFETs have been extensively used f extracting some of the devices characteristics, in particular the density, N_t, of electrical active defects located in the vicinity of the channel/gate dielectric interface. The carri number component of the 1/f noise is usually used for that purpose [1-3]. The accura and reliability of that procedure has significantly improved, first, thanks to the progre in the measuring techniques (cf. e.g. [4,5] and references therein), and, secondl because the device miniaturisation entails an increase in the LFN level.

We discuss, emphasizing the problems remaining to be solved, some LFN resul obtained on three groups of advanced MOSFET devices, (1) thin gate oxide insulat MOSFETS; (2) High-κ (HfO_2) MOSFETS; and (3) buried SiGe channel, oxic MOSFETs. We use the same technique for their LFN characterisation, that of the pow spectral density, PSD, measurements in an extensive current range and the analysis [based on the McWhorter's approach [1]. All the data were taken with a nov programmable point probe noise measuring system, 3PNMS [5].

2. Thin Gate Oxide Dielectric MOSFETs

For the gate oxide thinner than 20Å the gate tunneling currents reduce the precision charge pumping, CP, technique and the LFN methods have become increasingl attractive for the determination of N_t. In standard MOSFETs the LFN method has bee shown to give much lower N_t values [6] than does the CP technique. We have examine this issue using a lot of thin-gate transistors fabricated at the LETI/CEA-DTS i Grenoble [7]. Figure 1 shows typical data obtained on a device with 25Å-thick ga oxide (multiple runs). The solid line presents the results of the calulation based on