# *Shot Noise Reduction in Double-Barrier Resonant-Tunneling Structures*

**P. Ciambrone**
Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni,
Università di Pisa

**Massimo Macucci**
Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni,
Università di Pisa

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

**Bruno Pellegrini**
Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni,
Università di Pisa

**M. Lazzarino**
Laboratorio TASC-INFM, Trieste

P. Ciambrone, M. Macucci, G. Iannaccone, B. Pellegrini, M. Lazzarino, L. Sorba, F. Beltram, *Shot Noise Reduction in Double-Barrier Resonant-Tunneling Structures* , Proceedings of the 7th Vilnius Conference on Fluctuation Phenomena in Physical Systems, Palanga, Lithuania, October 4th-7th, 1994, pp. 139-144.

**L. Sorba**
Laboratorio TASC-INFM, Trieste
**F. Beltram**
Laboratorio TASC-INFM, Trieste

P. Ciambrone, M. Macucci, G. Iannaccone, B. Pellegrini, M. Lazzarino, L. Sorba, F. Beltram, *Shot Noise Reduction in Double-Barrier Resonant-Tunneling Structures*, Proceedings of the 7th Vilnius Conference on Fluctuation Phenomena in Physical Systems, Palanga, Lithuania, October 4th-7th, 1994, pp. 139-144.

*Proceedings of the 7th Vilnius Conference on Fluctuation Phenomena in Physical Systems*

*1994, Palanga Lithuania*

# SHOT NOISE REDUCTION IN DOUBLE-BARRIER RESONANT-TUNNELING STRUCTURES

P. Ciambrone, M. Macucci, G. Iannaccone, B. Pellegrini

Dipartimento di Ingegneria dell'Informazione:
Elettronica, Informatica, Telecomunicazioni
Università degli Studi di Pisa
Via Diotisalvi, 2, I-56126 Pisa, Italy

M. Lazzarino, L. Sorba, F. Beltram

Laboratorio TASC-INFM
34012 Trieste, Italy

## ABSTRACT

We have investigated the shot noise suppression in two custom designed resonant tunneling diodes at several temperature values. Noise measurements have been performed with the application of a recently developed method allowing higher insensitivity to spurious contributions and stray capacitances. Results have been compared with the predictions of existing theories.

## INTRODUCTION

In the last few years the problem of shot noise suppression in Double Barrier Resonant Tunneling Structures (DBRTS) has received widespread attention particularly from the theoretical point of view. After the early experiments by Y. P. Li *et al.* [1], several attempts at explaining this phenomenon have appeared in the literature [2-6] on the basis of coherent or incoherent tunneling models. Very few experimental results are, on the other hand, currently available besides the ones in Ref. [1]: E. R. Brown [5] reports data for a device at 77 K, exhibiting a very strong reduction, below one half of the full shot noise value. We have been interested in collecting further data on the noise behavior of DBRTSs with the inclusion of the effects of temperature. Two devices have been designed for this purpose, fabricated and tested on a wide temperature range. Similar investigations have been performed at the same time by H. C. Liu *et al.* [7], whose results are in qualitative agreement with ours.

## SAMPLES

Two samples with different layer arrangements have been fabricated. Both samples were grown by Molecular Beam Epitaxy (MBE) on $n$-doped

GaAs(001) substrate ($1 \times 10^{18}$ cm$^{-3}$). The first sample has symmetric tunneling barriers and an area of $2 \times 10^{-9}$ m$^2$. The layer structure is the following: 600 nm of $n$-doped ($1.1 \times 10^{18}$ cm$^{-3}$) GaAs, 20 nm of intrinsic GaAs, 5 nm of intrinsic $Al_{0.36}Ga_{0.64}As$ (first barrier), 4 nm of intrinsic GaAs (well), 5 nm of intrinsic $Al_{0.36}Ga_{0.64}As$ (second barrier), 25 nm of intrinsic GaAs and, finally, 500 nm of $n$-doped ($1.1 \times 10^{18}$ cm$^{-3}$) GaAs. As a consequence of the reduced barrier thickness, we obtain a relatively large current density in correspondence with the peak ($13.5 \times 10^6$ A/m$^2$). The I-V characteristic for this device at the temperature of 14 K is shown in Fig. 1, where a clear hysteresis effect is visible. The curves in Fig. 1 have been obtained sweeping the bias voltage according to the direction of the arrows.

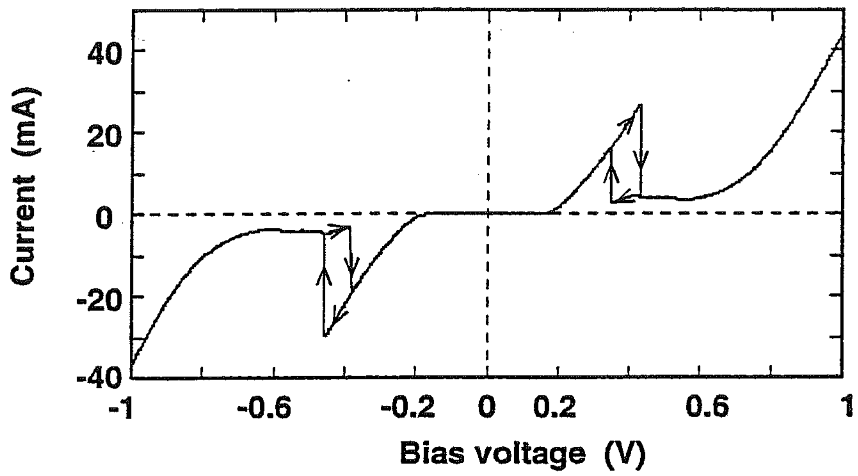


Fig. 1. I-V characteristic of the symmetric device.

The differential resistance along the slope preceding the peak is of the order of 10 Ω, therefore noise measurements in this bias region are extremely difficult. Problems due to the low differential resistance can be overcome using low-noise transformers between the sample and the amplifier, but the high current density leads to significant $1/f$ noise, thus making shot-noise measurements impossible. On the other hand, the high barrier transparency allows us to perform noise measurements for low values of the bias voltage, which are particularly interesting in a symmetric device. It is for vanishing bias voltage that the geometrically symmetrical structure approaches actual electrical symmetry (i.e. the condition with barriers characterized by the same transparency), for which some theoretical works predict maximum shot-noise suppression.

The second sample has asymmetric and much thicker barriers. Thicker barriers reduce the peak current density, thereby making shot-noise measurements in the peak region possible. The sample structure is the following: silicon doped ($n = 1.4 \times 10^{18}$cm$^{-3}$) 500 nm-thick GaAs buffer layer, undoped 20 nm-thick GaAs spacer layer to prevent silicon diffusion into the barrier, undoped 11.5 nm-thick $Al_{0.36}Ga_{0.64}As$ first barrier, undoped 5 nm-thick GaAs Quantum Well, undoped 10 nm-thick $Al_{36}Ga_{0.64}As$ second barrier, undoped 15 nm-thick GaAs spacer layer and silicon doped ($n = 1.4 \times 10^{18}$ cm$^{-3}$) 500 nm-thick GaAs cap layer to realize the emitter terminal.

We have used two barriers of different thicknesses in order to achieve maximum symmetry in resonant bias conditions, and the two spacer layers are asymmetrical because dopant diffusion is greater in the growth direction.

Ohmic contacts were defined by photolithography on the top layer and used as stop-etches to define the emitter circular mesas. The collector contact was formed by metalizing the whole substrate base.

The I-V characteristic is shown in Fig. 2 for the temperatures of 14 K, 77 K, 155 K and 223 K. The insets contain enlargements of the reverse (upper left) and forward bias (lower right) peak regions for 14 K, 77 K and 155 K. We assume the emitter electrode to be at the reference potential and the collector voltage to be positive (negative) for forward (reverse) bias.

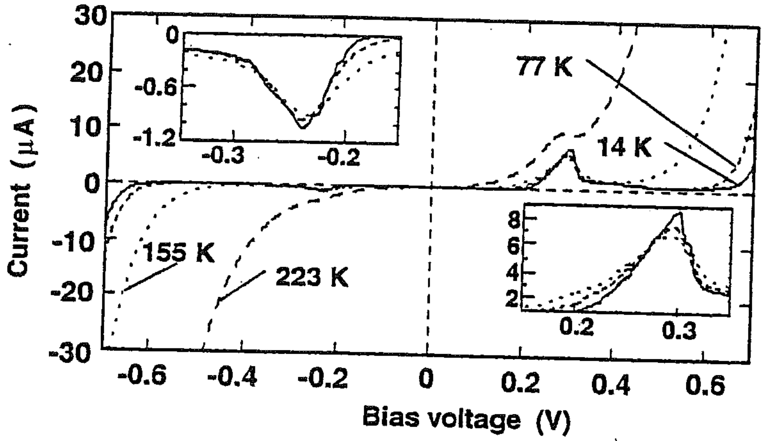


Fig. 2. I-V characteristics of the asymmetric device.

The device area is $0.7 \times 10^{-9}$ m$^2$ and the peak current density turns out to be $10.610 \times 10^3$ A/m$^2$ at 14 K.

## EXPERIMENTAL SETUP

Our samples have been cooled down in a two-stage helium expansion cryostat that has been custom modified in order to reduce vibrations of the sample holder. The sample holder is mechanically independent from the cooling stages while heat transmission is provided by a gaseous helium cushion. The sample holder is also connected to a heavy marble slab laying on a metallic table insulated from the floor with rubber pads. Vacuum in the sample chamber is obtained with a hydrocarbon-free dry pumping system.

Noise measurements have been performed with a recently developed technique [8], allowing an accurate estimate of spurious contributions from the input amplifier and from the biasing network. These contributions can thus be subtracted from the total noise spectrum. First, we perform a standard measurement of the amplifier output noise and evaluate the transimpedance between the DBRTS and the input of the signal analyser, including the effect of stray capacitors [8]. From them we compute the input current power spectral density. The DBRTS is then replaced with an equivalent impedance of known noise behavior, and the whole process is repeated. From this second measurement it is possible to obtain an accurate evaluation of the contribution due to spurious noise sources and subtract it from the previous result [8].

## RESULTS

For both of our samples and for most of the bias conditions we have investigated, the measured noise power spectral density is approximately constant at frequencies between 100 Hz and a few kHz. Below 100 Hz flicker noise becomes significant, while for frequencies higher than 10 kHz the equivalent input current noise of the amplifier becomes too large [8] in comparison to the shot-noise levels we are interested in. All the values reported in the following have been obtained by averaging over the above-mentioned frequency range.

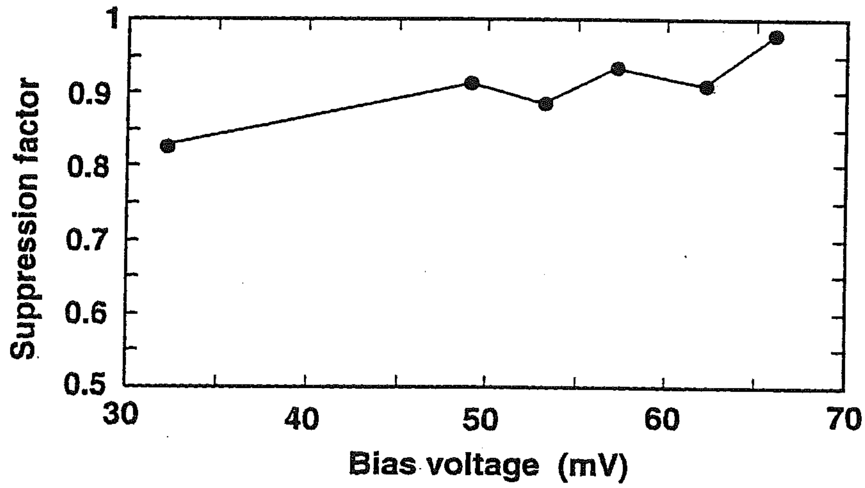


Fig. 3. Noise suppression factor for the symmetric device.

In Fig. 3 we show the noise suppression factor for the first (symmetric) sample versus bias voltage. We define as noise suppression factor the ratio of the measured noise level ($S_I$) to the theoretical full shot noise level $S_{Ifs} = 2qI$, where $q$ is the electron charge and $I$ is the bias current. Relative to full shot noise, we observe a reduction varying between 0.8 and 0.99. There seems to be a trend towards a decrease of the suppression factor for decreasing bias voltage and correspondingly increasing symmetry of the conduction band profile.

Results for the second (asymmetric) sample are presented in Fig. 4. The suppression factor is plotted versus bias voltage for 4 different values of the temperature: 14 K (solid circles), 77 K (solid squares), 155 K (empty squares) and 223 K (empty circles). For increasing temperature we observe an increase in the suppression factor that becomes rather large between 155 K and 223 K. There can be several phenomena contributing to this effect: thermal noise from the contact resistances, thermionic current over the barriers and increased scattering in the well, which may affect the noise suppression mechanism. From the estimates of the contact resistances that we have available, we would rule out a significant contribution from thermal noise. The increase in thermionic current would also appear to be insufficient to justify the measured variation in the suppression factor. Therefore, we think that a detailed theory of shot noise reduction in DBRTSs needs to be developed, capable of providing a quantitative estimate of the effect of inelastic scattering mechanisms. We notice that the suppression factor decreases moving towards bias values corresponding to the current peak in the I-V characteristic. In order to verify whether this result supports existing theories [2-4] predicting a suppression factor equal to $1 - T_{res}/2$ (where $T_{res}$ is the transmission factor at the resonant energy), we have computed $1 - T_{res}/2$ for the asymmetric structure both with a non-self-consistent and a self-consistent [9] model.

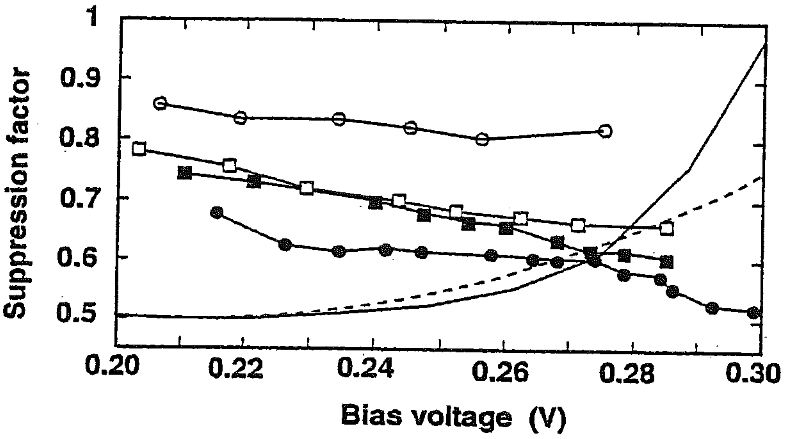


Fig. 4. Noise suppression factor for the asymmetric device (see text for symbol explanation).

For most bias values the difference between the non-self-consistent (dashed line in Fig. 4) and the self-consistent result (solid line) is not very large, probably because of the relatively small charge build-up that occurs in our devices. From Fig. 4 we conclude that our data do not support the theories in Ref. [2-4].

In Fig. 5 we show the results for the noise power spectral density versus bias current for the region before the forward bias peak (solid squares) and for the region following the valley in the I-V characteristic. The thick line represents the full shot noise level. The reduction in the region beyond the valley appears to be very small.

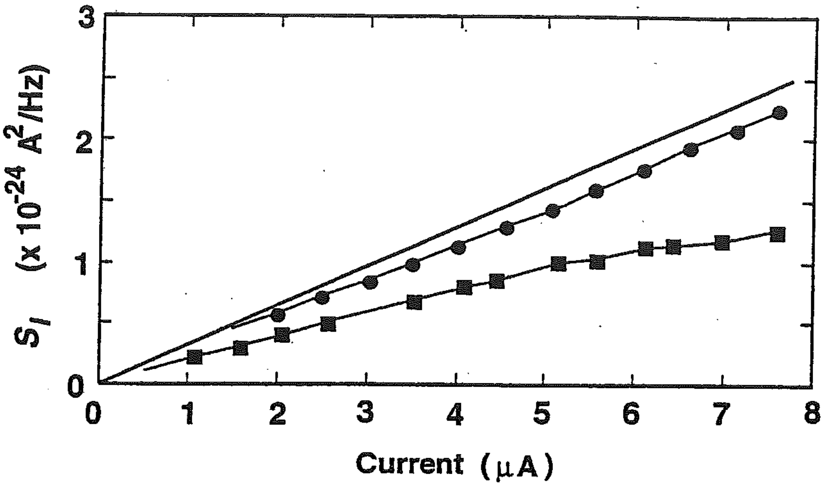


Fig. 5. Noise power spectral density for the asymmetric device in the region before the peak (squares) and beyond the valley (circles).


## ACKNOWLEDGMENTS

We wish to thank Paul Sotirelis and Patrick Roblin for providing the self-consistent transmission coefficients. We are also indebted to the authors of Ref. [7] for making their preprint available to us. One of the authors (G.I.) acknowledges useful discussions with G.C. Aers, C.R. Leavens and H.C. Liu. This work has been supported by the Italian Ministry of University and Scientific and Technological Research and by the Italian National Research Council (CNR).


## REFERENCES


[1] Y. P. Li, A. Zaslavsky, D. C. Tsui, M. Santos, M. Shayegan, Phys. Rev. B **41**, 1990.

[2] L. Y. Chen and C. S. Ting, Phys. Rev. B **46**, 4714 (1992).

[3] M. Büttiker, Phys. Rev. B **45**, 3807 (1992).

[4] J. H. Davies, P. Hyldegaard, S. Hershfield, J. W. Wilkins, Phys. Rev. B **46**, 1920 (1992).

[5] E. R. Brown, IEEE Trans. Elect. Dev. **39**, 2686 (1992).

[6] A. L. Yeyati, F. Flores, E. V. Anda, Phys. Rev. B **47**, 10543, (1993).

[7] H. C. Liu, J. Li, G. C. Aers, C. R. Leavens, M. Buchanan, Z. R. Wasilewsky, "Shot Noise Suppression in Resonant Tunneling," to be published.

[8] M. Macucci and B. Pellegrini, IEEE Trans. Instrum. Meas. **40**, 7 (1991).

[9] P. Roblin and Wan-Rone Liou, Phys. Rev. B **47**, 2146 (1993).