Shot-noise dependence on barrier symmetry in resonant tunneling diodes

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For spectrum density when $\omega << \lambda$ we obtain approximately:

$$S_{\phi-} \approx 2\,(<\delta\phi_{-}(0)\delta\phi_{-}(0)>)^{1/2}\,\Delta V/\lambda,$$

where $\Delta V \approx V_v - V_p$. Indexes p and v correspond to peak and to valley values of RTS current. In accordance with results of numerical calculations value q may changed from 0.25 up to -50. Therefore value λ is about 200 GHz at room temperature.

For power of noise in range $\Delta\omega = \lambda/2$ and for spectrum of noise power we have expressions:

$$P = (Gk_BT/e)\,(\Delta V/(SLn)^{1/2}),\ SP = (2G/e\lambda)(\Delta V/(SLn)^{1/2})$$

For structures investigated in experiment: $S \sim 10^{-5}$ cm^2, $\Delta I = I_p - I_v \sim 2\times10^{-1}$A. Calculations shown, that in researched area $n \sim 10^{16}$ cm^{-3}. Using these data, at room temperature (T=300 K) we obtain: $P = 1.6\times10^{-5}$ W and $SP = 3.1\times10^{4}$. As we see, theoretical value of P agree with experiment well. The experimental value of SP was calculated by division P on k_BT and $\Delta f \approx 25$ GHz. If we take into account, that according to estimations presented above $\lambda \sim 200$ GHz, for experimental SP value 3.6×10^4 will be obtained, that will be well agreed with theoretical result.

CONCLUSION

In this paper we shown, that relaxation of electrochemical potentials of different electrons lead to a noise of a new type, that may be observed in nanosize structures.

In resonant-tunneling devices under special conditions the instability of transport equations relatively of small fluctuations of electrochemical potentials may be appeared. It lead to a large power noise that demonstrate the nonthermal behaviour ($P \sim k_BT(S)^{1/2}$).

Good agreement between theoretical and experimental results demonstrated here by fluctuations analysis and in paper [3] by static characteristics modeling may serve as corroboration of efficiency of the proposed approach for description of the charge transport phenomena in structures with quantum properties.

REFERENCES

1. M. Reddy, R.Y. Yu, H. Kroemer et al. *IEEE Microwave and Guided Lett.*, **5**, 219 (1995).
2. O.T. Gavrilov, I.I. Kvjatkevitch, I.A. Obukhov, Yu.A. Matveev. *Tech. Phys. Lett.* **22**, 311 (1996).
3. I.A. Obukhov. In: *Proc. of Nanomeeting: Physics, Chemistry and Application of Nanostructures*. Ed E. Borisenko (Belarusian State University of Informatics and Radioelectronics: Minsk, 1995) p. 271.
4. O.T Gavrilov, I.A. Obukhov, S.A. Dianov. In: *Proc. of the Second International Conference on Nanometer Scale Science and Technology.* (Russian Academy of Technological Sciences: Moscow, 1994) p. 860.
5. R. Tsu and L. Esaki. *Appl. Phys. Lett.* **22**, 562 (1973).

SHOT-NOISE DEPENDENCE ON BARRIER SYMMETRY IN RESONANT-TUNNELING DIODES

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ABSTRACT

The shot-noise suppression factor in a quasi-symmetric resonant tunneling diode has been measured over three decades of current and compared with existing results for asymmetric devices. A shift towards lower current values of the suppression factor minimum is theoretically predicted for increasing barrier symmetry and appears in the experimental results.

INTRODUCTION

The phenomenon of shot-noise suppression in semiconductor nanostructures has raised very interesting theoretical and experimental issues in the last few years, since the time early results were obtained by Li *et al.* [1]. We have been investigating the reduction of shot noise in double-barrier resonant-tunneling heterostructures specifically designed and fabricated for noise measurements [2].

We have applied a technique purposedly developed for low-level current noise measurements, based on the careful evaluation of the transimpedance between the device under test and the output of the amplifier, and on the subtraction of the noise contributions due to the amplifier, the bias source and the the biasing network [3]. This procedure allows us to measure noise levels that are up to 3 dB below that of the available amplifiers with a maximum error around 10%.

For the successful application of our correction method, it is necessary to precisely measure the noise due to the amplifier: to this purpose the measurement is repeated after replacing the resonant-tunneling device with an equivalent impedance (equivalent within the frequency range of interest). Such impedance is kept at a known constant temperature and in equilibrium conditions (no externally imposed current flowing through it), thus it exhibits only thermal noise, which can be precisely evaluated and subtracted from the result of the measurement, thereby yielding the noise due to the amplifier and the passive components of the biasing network.

RESULTS

We have optimized the double-barrier resonant-tunneling structures from the point of view of the differential resistance, by designing the barrier thicknesses and the cross-section in such a way as to obtain the best possible noise matching with the measurement amplifiers. Available ultra-low-noise amplifiers offer a good performance, with a very small noise figure, for a range of resistance values between a few kiloohms and several megaohms. For this reason the barriers in our samples are thicker than in most similar resonant-tunneling diodes, in order to reduce the current and, consequently, to increase the differential resistance. The diameter of the mesas defining the single devices has been shrunk down to 30 μm, which represents a practical limit, because bonding would become too difficult for smaller diodes. All the devices that we have designed have been fabricated at the TASC-INFM laboratory in Trieste.

Measurements reported in this paper have been performed with the devices kept at temperatures of 4.2 K and 17 K in cryogenic systems specifically designed to obtain an extremely low vibration level. This is particularly important for the measurements at bias currents below 10 nA, for which the spurious contributions from microphonic effects in the sample and in the connection cables become significant.

The results we are presenting focus on the dependence of the bias value for which maximum noise suppression is obtained on the symmetry characteristics of the device. Theoretical models [4-6] predict maximum suppression for the bias condition at which the transmission coefficients of the two barriers are equal. Most of the experimental data available in the literature [1-2] show a shot-noise minimum rather close to the resonance peak, because the structures considered approach symmetry only under relatively strong bias. We have thus aimed at the design, fabrication and characterization of a device as symmetric as possible, which could exhibit a maximum noise reduction for a bias condition far from the current peak.

The structure which we have mainly investigated was designed to be perfectly symmetrical, but, as a consequence of fabrication tolerances, has the following actual layer structure, as measured from a TEM cross-section: a first AlGaAs barrier of 11.7 nm, a GaAs well of 5.7 nm and a second barrier of 12.2 nm. For this almost geometrically symmetric device we have been able to measure a maximum of the suppression, corresponding to about one half of the full shot noise, at a current between one half and one third of the peak current, as reported in Fig. 1, where the shot noise suppression factor γ measured at 17 K is plotted versus the ratio of the bias current to the peak current (solid line). In Fig. 1 we report also (with the dashed line) the results previously obtained [2] for an asymmetric device with a 10 nm first barrier and an 11.5 nm second barrier, from which it is apparent that maximum shot noise suppression is achieved near the current peak.

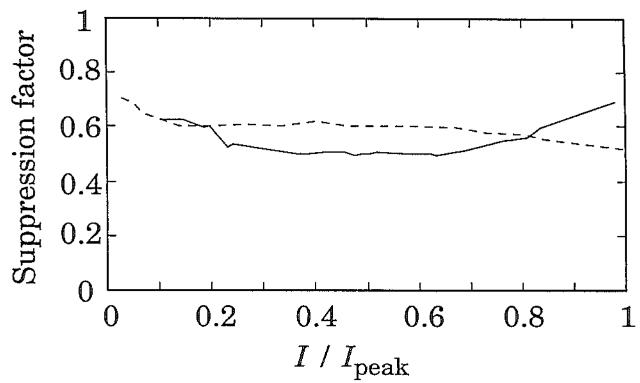

Fig. 1 Noise suppression factor as a function of the ratio of the bias current to the peak current for the quasi-symmetric device (solid line) and an asymmetric device (dashed line).

The factor γ is defined as the ratio of the measured noise current power spectral density to the expected full-shot noise spectral density $S_s = 2qI$, with q being the charge of the electron and I the bias current. The observed behavior of the suppression factor is in good agreement with the results of preliminary simulations performed assuming an effective mass $m^* = 0.096\, m_0$ in the AlGaAS barriers [2,7].

In the quieter environment of the liquid helium cryostat it has been possible to investigate the region of very low bias currents for the quasi-symmetric device, and to see how, reducing the current, the measured shot noise tends to the full-shot value. Results at the temperature of 4.2 K are shown in Fig. 2, in a semilogarithmic scale. It should be noticed that, as a consequence of the failure of the quasi-symmetric diode at the end of the measurements at 17 K, the results in Fig. 2 are for a different device, which is, however, nominally identical and located on the same chip.

The I-V characteristics at 4.2 K and at 17 K of the quasi-symmetric device are reported in Fig. 3. We have performed noise measurements also in the region beyond the current valley, observing a much less significant and almost constant shot-noise suppression, as theoretically predicted.

Finally, we have obtained preliminary results for another asymmetric device, which exhibits an almost constant suppression ($\gamma \simeq 0.6$) on a wide range of bias currents. Therefore it seems that the current value for which a minimum of the shot noise reduction factor is obtained depends not only on the geometrical barrier symmetry, but also on other factors. We believe that an important role is played by self-consistency effects, due mainly to charge accumulation in the well region, which may determine significant modifications in the potential landscape throughout the device and, in particular, in the transmission coefficients of the barriers. Further theoretical and experimental work aiming at a better understanding of these issues is currently in progress.

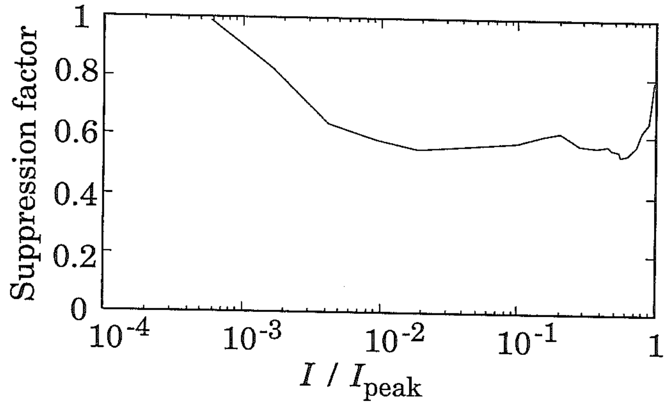

Fig. 2 Noise suppression factor as a function of the ratio of the bias current to the peak current for the quasi-symmetric device at liquid helium temperature.

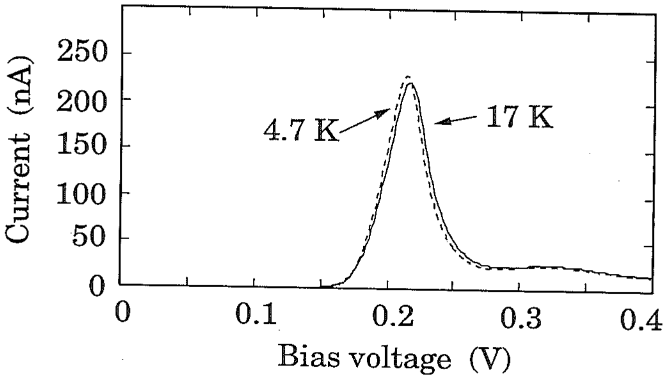

Fig. 3 I-V characteristic of the quasi-symmetric device.

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REFERENCES

1. Y. P. Li *et al.*, *Phys. Rev. B* **41**, 8388 (1990).
2. P. Ciambrone et *al.*, *Electron. Lett.* **31**, 503 (1995).
3. M. Macucci and B. Pellegrini, *IEEE Trans. Instrum. Meas.* **40**, 7 (1991).
4. M. Büttiker, *Phys. Rev. B* **46**, 12485 (1992).
5. J. H. Davies *et al.*, *Phys. Rev. B* **46**, 9620 (1992).
6. G. Iannaccone *et al.*, *Phys. Rev B* **55**, 4539 (1997).
7. G. Lombardi, Graduation Thesis, University of Pisa, 1996.

1/F FLUCTUATIONS IN IMPATT OSCILLATORS ON PUNCHED-THROUGH DIODES

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ABSTRACT

The AM and FM 1/f fluctuations in IMPATT oscillators on punched-through and non-punched-through diodes have been analysed on the base of a theoretic model, including two independent 1/f noise sources: recharge of traps and electron scattering on neutral metastable centres. It is found that in the case of punched-through diodes AM and FM noise levels are lower and that FM noise intensity varies with Q-factor (in the case of non-punched-through diodes FM noise intensity almost does not depend on this parameter).

INTRODUCTION

At ICNF'95 results of 1/F noise study in IMPATT oscillators on non-punched-through n-GaAs diodes have been communicated [1]. The theory, presented in [1], was based on a model, including two independent 1/F noise sources: recharging of traps and drift velocity fluctuations, arising from electron scattering on neutral metastable centres. It was found that the principal mechanism of 1/F frequency fluctuations is a diode capacitance modulation due to recharging of traps, which is accompanied by depleted layer length fluctuations. It must be noted that the participation of traps in IMPATT diode 1/F noise formation was established by direct experiments (illumination of diodes) [2].

In the case of punched-through diodes the length of depleted layer is fixed and this mechanism does not work; the magnitude and behaviour of frequency fluctuations are governed by other 1/F noise source: drift velocity fluctuations. The study of this case is of interest for two reasons:

(i) It offers an additional opportunity to verify 1/F noise source model, suggested in [1].

(ii) It seems to be of importance to know what can be the frequency noise reduction in oscillators on punched-through diodes as against non-punched-through diodes.