View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

東北大学機関リポジトリ
TOUR
Tohoku University Repository

Shot Noise Experiments in Multi-barrier Semiconductor Heterostructures

著者	Mendez E. E., Song W., Newaz A. K. M., Lin Y., Nitta J.
journal or publication title	AIP Coference Proceedings
volume	780
page range	431-434
year	2005
URL	http://hdl.handle.net/10097/51590

doi: 10.1063/1.2036785

HTML ABSTRACT + LINKS

Shot Noise Experiments in Multi-barrier Semiconductor Heterostructures

E. E. Mendez[1], W. Song[1,2], A. K. M. Newaz[1], Y. Lin[3,4], and J. Nitta[3,5]

[1] *State University of New York at Stony Brook,, Stony Brook, NY 11794-3800, USA*
[2] *Current address: Korea Research Institute of Standards and Science, Daejeon, Korea*
[3] *NTT Basic Research Laboratories, Atsugi, and CREST -JST, Saitama, Japa*
[4] *Current address: National Tsing Hua University, Hsinchu 300, Taiwan*
[5] *Current address: Tohoku University, Sendai, 980-8579, Japan*

Abstract. We have found strong deviations from Poissonian behavior in the low-temperature noise characteristics of triple-barrier and superlattice heterostructures. Although our results can be explained qualitatively by existing models, a quantitative comparison between experiment and theory suggests an incomplete understanding of shot noise in multi-barrier systems.

Keywords: shot noise, semiconductor heterostructures, resonant tunneling, superlattices
PACS: 73.50Pz, 73.50Td

INTRODUCTION

Until recently our knowledge of electronic tunneling in semiconductor heterostructures has been derived primarily from electrical conductance measurements, but lately the attention has shifted to the measurement of the electrical noise, which can provide additional information about the transport mechanism, especially correlation effects. Thus, when electrons tunnel through a biased single potential barrier between two metallic electrodes (such as in an undoped GaAlAs thin layer between two heavily doped GaAs thick regions), the motion of electrons is uncorrelated and the spectral density of the shot noise, $S_I(\omega)$, is $2eI$, where I, is the tunnel current. In contrast, in double-barrier heterostructures $S_I(\omega)$ can differ significantly from the Poissonian value, $2eI$, because of correlation effects in the transport process: when the correlation is negative noise is reduced while when the correlation is positive the noise is enhanced over $2eI$ [1-3].

In this work we have extended the study of noise to multi-barrier heterostructures, namely, triple-barrier and superlattice structures [4]. We have found experimentally strong deviations from Poissonian behavior, which can be explained qualitatively by existing models. However, a quantitative comparison between experiment and theory suggests an incomplete understanding of shot noise in multi-barrier systems.

CP780, *Noise and Fluctuations: 18th International Conference on Noise and Fluctuations-ICNF 2005,*
edited by T. González, J. Mateos, and D. Pardo
© 2005 American Institute of Physics 0-7354-0267-1/05/$22.50

Downloaded 22 Jul 2011 to 130.34.134.250. Redistribution subject to AIP license or copyright; see http://proceedings.aip.org/about/rights_permissions

EXPERIMENTAL RESULTS

For the triple-barrier experiments, we have used $In_{0.53}Ga_{0.47}As$- $In_{0.52}Al_{0.48}As$ heterostructures, in which the InAlAs regions formed the potential barriers through which electrons tunnel. We focus here on a typical heterostructure, which consisted of two end 100 Å-thick barriers and a 52 Å central barrier, with quantum wells in between having widths of 53 Å and 82 Å. Heavily doped n-type InGaAs electrodes completed the structure. (See Fig. 1) As a reference we used a double-barrier structure identical to that triple-barrier structure except that the central barrier and the 82 Å well had been eliminated.

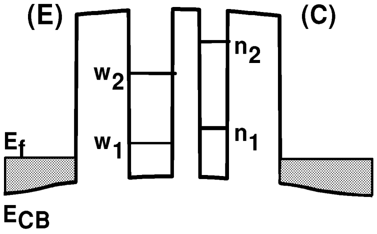

FIGURE 1. Conduction-band profile of an InGaAs-InAlAs triple-barrier structure, showing the quasi-bound quantum-well states. The doped emitter and collector are denoted by (E) and (C), respectively.

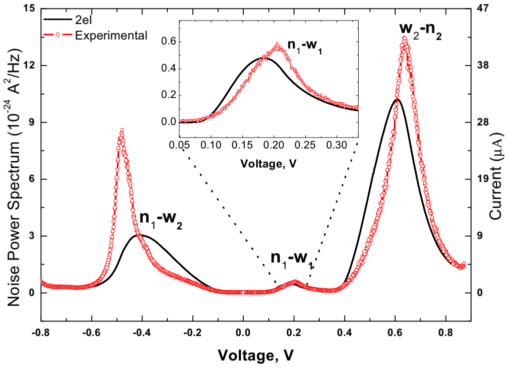

FIGURE 2. $2eI$ (Solid line) and noise (circles) characteristics at 4K of the InGaAs-InAlAs structure described in the text. The inset shows the current-noise of the first peak in forward bias. Note that the noise enhancement is much stronger for the reverse bias.

The current-voltage (*I*-*V*) characteristic of the triple-barrier structure at T = 4.2K (see Fig. 2) exhibits several regions of negative differential conductance that are the signatures of resonant tunneling involving quantum states. The two current peaks in forward bias correspond to the $w_1 - n_1$ and $w_2 - n_2$ resonances, while the peak in reverse bias is for the $n_1 - w_2$. For each peak, the current rise is gradual (see, e.g., the voltage region between 0.075 and 0.175 V or between -0.1 V and -0.4 V, in Fig. 2), which contrasts with the delta-function-like characteristic expected for electrons tunneling between two quantum wells (each a two-dimensional system), as discussed in detail elsewhere [5].

Figure 2 also shows the measured shot noise characteristic and compares it with the Poissonian value $2eI$. As it is apparent in the figure, the shot noise is reduced below $2eI$ whenever the current rises and is enhanced when the current drops. This behavior, which is qualitatively similar to that found previously in double-barrier structures [1-3] and in our own reference sample, is explained along the same lines as in a double-barrier configuration: while the current is rising the noise is reduced

Downloaded 22 Jul 2011 to 130.34.134.250. Redistribution subject to AIP license or copyright; see http://proceedings.aip.org/about/rights_permissions

as a consequence of the negative correlation caused by Pauli exclusion principle; when the current starts to drop and the density of states for tunneling becomes small, an electron tunneling into a quantum well creates a potential fluctuation that shifts the quantum state up in energy and in turn induces a positive correlation among the electrons, thus enhancing the shot noise.

There are, however, two aspects of the shot noise in Fig. 2 that should be highlighted. First, the noise reduction approaches 50% of the value $2eI$ for some voltages. Second, the noise enhancement for the $n_1 - w_2$ peak is three times larger than for any of the other two peaks, even though the corresponding minimum in the conductance is much less pronounced for $n_1 - w_2$ than for $w_2 - n_2$. To compare the noise reduction we have observed with theoretical predictions, we calculated the shot noise for a triple-barrier structure using a sequential-tunneling model [6]. The calculated noise reduction for the voltages at which the experimental reduction is the largest is at most 20% of the Poissonian value, that is, much smaller than what is observed experimentally. The discrepancy between the two results may lie on the fact that the calculation did not include Coulomb interaction effects.

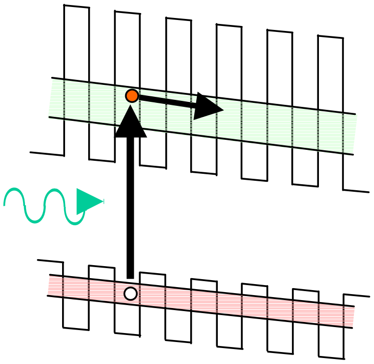

FIGURE 3. Conduction- and valence-band profiles of a superlattice in an electric field. A photon can excite an electron from the superlattice's valence miniband to its conduction miniband and generate a photocurrent. With increasing field, the minibands evolve into Stark ladders, which manifest themselves in the photocurrent.

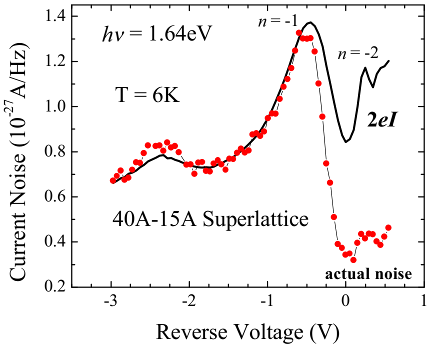

FIGURE 4. Experimental $2eI$ (solid line) and noise (circles) of the photocurrent in a 40Å/15Å GaAs-GaAlAs superlattice. For voltages larger than −0.5V, the experimental shot noise is much smaller than the Poissonian value ($2eI$), whereas for smaller voltages the two values are practically the same. This result is independent of the wavelength of the excitation, but the details depend on the superlattice configuration.

The large noise enhancement for the $n_1 - w_2$ peak is significant because previous experiments in double-barrier structures have shown a correlation between the strength of the negative differential conductance and the noise

Downloaded 22 Jul 2011 to 130.34.134.250. Redistribution subject to AIP license or copyright; see http://proceedings.aip.org/about/rights_permissions

enhancement [3], which does not appear in Fig. 2. The reason for this difference between the two cases is not clear, but it may have to do with the charge accumulated in both quantum wells, which depends on the specific quantum states involved in the various current peaks.

The behavior of current noise in superlattices also departs significantly from what a simple multi-quantum-well model predicts [6], as shown by our study of the shot noise in the photocurrent flowing through GaAs-GaAlAs superlattices embedded in the intrinsic regions of *p-i-n* diodes (Fig. 3). We have found experimentally that the noise can be drastically reduced in comparison with the Poissonian value, as shown in Fig. 4, where the measured photocurrent, multiplied by $2e$, of a 40 Å-15 Å superlattice is compared with the experimental shot noise. For small electric fields (of the order of 20 kV/cm), the shot noise is about 1/3 of $2eI$, but at a moderate field of about 60 kV/cm (transition field) the current noise abruptly becomes Poissonian or equal to $2eI$.

This result is independent of the exciting photon's energy, for a given superlattice configuration. The minimum shot noise value, however, depends on the superlattice period (or, consequently, on the interwell coupling). The general trend is for the minimum shot noise to be larger, the larger the period; the transition field depends weakly on the period. For a period of around 100 Å the shot noise is essentially Poissonian, from the low- to the high-field region.

Although the existing multi-barrier model developed for metals explains our results qualitatively [6], it cannot account for either the dependence of noise reduction on superlattice coupling at small fields or the abruptness of the field-induced transition from sub-Poissonian to Poissonian noise that we have observed.

ACKNOWLEDGMENTS

One of us (EEM) has benefited from a stay at NTT Basic Research Labs, where portions of this work were initiated. The work has been sponsored by the National Science Foundation of the US (Grant No. DMR-0305384).

REFERENCES

1. Li, Y. P., Zaslavsky, A., Tsui, D. C., Santos, M., and Shayegan, M., *Phys. Rev. B* **41**, 8388-8391(1990).
2. Iannaccone, G., Lombardi, G., Macucci, M., and Pellegrini, B., *Phys. Rev. Lett.* **80**, 1054-1057 (1998).
3. Kuznetsov, V. V., Mendez, E. E., Bruno, J. D., and Pham, J. T., *Phys. Rev. B* **58**, R10159-10162 (1998).
4. Most of work summarized here is reported in detail in Newaz, A. K. M., Song, W., Mendez, E. E., Lin, Y; and Nitta, J., *Phys. Rev. B* **71**, 195303 (2005).
5. Lin, Y., Nitta, J., Newaz, A. K. M., Song, W., Mendez, E. E., unpublished.
6. De Jong, M. J. M. and Beenaker, C. W. J., *Phys. Rev. B* **51**, 16867-16871 (1995).

Downloaded 22 Jul 2011 to 130.34.134.250. Redistribution subject to AIP license or copyright; see http://proceedings.aip.org/about/rights_permissions