# Nonequilibrium Noise in the Current Flowing through Modulation-Doped Double-Barrier Resonant Tunneling Structures

S. SASAKI, D. G. AUSTING, T. HONDA and S. TARUCHA

NTT Basic Research Laboratories, 3-1, Morinosato Wakamiya, Atsugi-Shi, Kanagawa 243-01, Japan

Shot noise characteristics are studied for GaAs/AlGaAs double-barrier resonant tunneling structures with modulation-doped barriers in the vicinity of zero bias. Nonequilibrium current noise is measured using a highly sensitive SQUID probe at 4.3 K. We observe considerably less shot noise than that for conventional double-barrier structures with undoped barriers and that predicted theoretically probably because of a reduction of the hot electron effect, although the overall dependence on the symmetry of the device is qualitatively reproduced by the theory.

## 1. Introduction

Transport properties of semiconductor double-barrier resonant tunneling structures (DBRTS's) have been extensively studied over the past two decades. Measurements of the nonequilibrium noise present in the current are complementary to conventional conductance measurements, which help to clarify the nature of the tunneling process, *i.e.* whether it is coherent or sequential. Li *et al.*<sup>1)</sup> have reported shot noise measurements on GaAs/AlGaAs DBRTS's. They found that the noise power density tends to nearly half the full shot noise level, 2*el*, as the transmissivity of the two barriers are made more equal, and they attributed this to incoherent tunneling. However, subsequent theoretical investigations<sup>2,3)</sup> have shown that this interpretation is too simplistic. Moreover, the measurements by Li *et al.* were made by applying a large bias voltage to align the emitter Fermi level with the confined state in the well, so all the tunneling current is carried by hot electrons. Measurements in the absence of this hot electron effect are necessary for a more unambiguous discussion of the noise characteristics of DBRTS's. In this paper, we describe noise measurements on DBRTS's whose barriers are modulation-doped to ensure that the tunneling current flows near zero bias. We find that these modulation-doped DBRTS's give considerably smaller shot noise power – even less than half the full shot noise level – than that for undoped structures, which cannot be explained by the present theories.<sup>2-5)</sup>

#### 2. Experimental

DBRTS samples used in the present study are MBE-grown GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As structures whose barriers are modulation-doped with Si donors. Figure 1 schematically shows the structure of a typical DBRTS together with the *I-V* characteristic of a sample whose diameter is 4  $\mu$ m. It should be noted that the sample is conducting at zero bias because the confined state in the well,  $E_o$ , is already below the Fermi level, *i.e.* there is no threshold for resonance. A system incorporating a SQUID probe was recently developed which allows us to make high precision measurements of nonequilibrium current noise at temperatures below 5 K for frequencies below 30 kHz. The noise amplified by this SQUID system was measured by a FFT spectrum analyzer.

## 3. Results and Discussion

Figure 2 shows the noise power density spectrum observed at 4.3 K for the DBRTS shown in Fig. 1. The bias is applied so that the thinner barrier is the emitter barrier in forward bias. The current is increased from 1  $\mu$ A for the lower most curve to 15  $\mu$ A for the upper most curve in 1  $\mu$ A steps. The background spectrum at zero current including Jhonson-Nyquist noise is subtracted from each curve. Shot noise is observed which is almost proportional to the stationary current and is frequency independent (white noise) when the current is small. When the current is large, 1/*f* noise becomes dominant at lower frequency, so the shot noise component is estimated from the white noise part at higher frequency. The shot noise factor, defined as a ratio of the observed noise power density, *Si*, to the full shot noise level, 2*eI*, is plotted in Fig. 3 as a function of the bias voltage  $V_{SD}$  for both bias directions. The shot noise power is about 60 % that of the full shot noise level near zero bias, and it increases as the bias is raised close to that of the peak voltage. For forward bias, the noise first decreases once, reaching a minima at about  $V_{SD} = 0.2$  V and then increases again as the bias is increased further. Chen and Ting give the following expression for the shot noise factor in their theoretical model<sup>2</sup>

$$\gamma = \frac{31}{2eI} = 1 - \frac{2\gamma_1 \gamma_2}{(\gamma_1 + \gamma_2)^2}$$
(1)

where  $\gamma_1$  and  $\gamma_2$  are tunneling rates of the emitter and the collector barriers, respectively. In this formalism, the minimum shot noise of half the full shot noise value is obtained when the transmission coefficients of two barriers are equal ( $\gamma_1 = \gamma_2$ ). When

the structure is very asymmetric ( $\gamma_1 \ll \gamma_2$  or  $\gamma_1 \gg \gamma_2$ ), the full shot noise is recovered. The experimental results shown in Fig. 3 qualitatively agree with equation (1). The transmission coefficients of the two barriers tend to equalize as the bias voltage increases from zero in forward bias, and are very different for large biases in either bias direction when the structure behaves like a single barrier. The increase of the shot noise at large bias voltages, however, may be due to the effect of hot electrons which was not taken into account in the theory of Chen and Ting.<sup>2)</sup> The reason for a small dip in *S*i for reverse bias is not clear, but can be due to an experimental error as other measurements (not shown) indicate.

Figure 4 shows the shot noise factors for several of our DBRTS's, as well as those measured by Li *et al.*<sup>1)</sup> and the predicted factor in the theory of Chen and Ting,<sup>2)</sup> as a function of the ratio of the transmission coefficients of the emitter and collector barriers, Te/Tc. In one undoped structure measured for comparison, the full shot noise is observed, which seems consistent with that in the previous report,<sup>1)</sup> and demonstrates the proper operation of the measurement system. Other modulation-doped DBRTS's, however, show very small *S*i – even less than the minimum value predicted by eq. (1) of half the full shot noise level. *S*i also changes appreciably in different bias directions although the change in the potential profile is negligible even if the bias direction is reversed as long as the bias voltage is small. This cannot be explained by eq. (1) which is symmetric on exchange of  $\gamma_1$  and  $\gamma_2$  and may be related to the charge accumulation in the well. All these findings are incompatible with the present theories,<sup>2-5)</sup> and suggest that a more sophisticated theory is necessary which incorporates the self-consistent modulation of the resonance energy and the transmission probabilities<sup>6,7)</sup> as well as the hot electron effect. Such theory may also have to take into account the effect of scattering in the contacts.<sup>8)</sup>

#### 4. Conclusions

We have measured the shot noise in GaAs/AlGaAs double-barrier resonant-tunneling structures with modulation-doped barriers using a highly sensitive SQUID probe at 4.3 K. Because the tunneling current flows with very small bias voltages in these modulation-doped structures, very different noise characteristics compared with those for undoped structures have been observed, which suggests that the suppression of the hot electron effect may be important in reducing the noise.

## References

1) Y. P. Li, A. Zaslavsky, D. C. Tsui, M. Santos and M. Shayegan: Phys. Rev. B41 (1990) 8388.

2) L. Y. Chen and C. S. Ting: Phys. Rev. B43 (1991) 4534.

3) A. L. Yeyati, F. Flores and E.V. Anda: Phys. Rev. B47 (1993) 10543.

- 4) J. H. Davis, P. Hyldgaard, S. Hershfield and J. W. Wilkins: Phys. Rev. B46 (1990) 9620.
- 5) L. Y. Chen and C. S. Ting: Phys. Rev. B46 (1992) 4714.
- 6) L. Y. Chen: Phys. Rev. B48 (1993) 4914.
- 7) M. M. Jahan and A. F. M. Anwar: Solid State Electronics 38 (1995) 429.
- 8) A. Sugimura: Solid State Commun. 87 (1993) 461.



Fig. 1. Schematic energy diagram of the modulation-doped resonant tunneling diode and a typical *I-V* characteristic. Note that the device is conducting at the origin.



Fig. 2. The noise power density spectrum in forward bias at 4.3 K. The frequency independent component increases almost proportionally with the current.



Fig. 3. The observed noise power normalized with the full shot noise level in both bias directions. The noise increases as the bias approaches the region of negative diffrential resistance.



Fig.4. The shot noise factor as a function of the transmittivity ratio for several double-barrier structures. F and R in the legend denote forward and reverse bias, respectively. The results from the literature are also shown for comparison.