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Noise characteristics of double-barrier resonant-tunneling structures below 10 kHz

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We report on the noise characteristics of double-barrier resonant-tunneling structures obtained from systematic noise measurements on three samples with different barrier structures. Our results provide direct evidence of incoherent tunneling and can be qualitatively understood if phase incoherence of the tunneling processes is taken into account.

Double-barrier resonant-tunneling structures (DBRTS) have been studied extensively since the original analysis by Esaki and Tsu,[1] and low-frequency noise measurements have recently been employed to identify electron traps in such structures.[2] The noise characteristics of the DBRTS depend on the degree of phase coherence[3-6] of the tunneling of electrons through the two barriers. In the limit of no inelastic scattering in the well, the tunneling conserves phase coherence and can be described by the coherent tunneling model.[7,8] In this model the charge transport is solely determined by the electron-tunneling probability through the two barriers as a whole. Therefore, full shot noise is expected for frequencies f less than the reciprocal electron transit time. That is, the noise current power density S_i is independent of f and $S_i = 2eI$, where I is the dc bias current and e is the electron charge.[9] In the limit where inelastic scattering in the well is sufficiently strong to destroy all phase coherence, the charge transport can be described by the sequential tunneling model.[10-14] In this model electrons from the three-dimensional states in the emitter first tunnel into the two-dimensional states in the well, where they lose phase coherence, and subsequently tunnel out through the collector barrier. Since the electrons tunnel through the two barriers incoherently and the amount of dynamic charge stored in the well[12] also fluctuates, the noise is expected to differ from the full shot noise. Between these two limits the tunneling is partially coherent. For a simplified treatment we can assume that the current through the device consists of a coherent component described by the coherent tunneling model and an incoherent component described by the sequential tunneling model, and that these components generate noise independently. In this case, the noise is expected to be the overall result of the contributions from both current components.

In this paper we report on the noise characteristics of the DBRTS obtained from systematic noise measurements on three samples with different barrier structures at 4.2 K. In particular, our results provide direct evidence of incoherent tunneling in the DBRTS. Accordingly, we discuss the effects of incoherent tunneling on the noise characteristics of the DBRTS, and we show that our results can be qualitatively understood if the phase incoherence of the tunneling processes is taken into account.

Each of our samples has 5000 Å of GaAs Si doped to $\sim 2\times 10^{17}$ cm^{-3}, 100 Å of undoped GaAs, a layer of undoped $Al_xGa_{1-x}As$ (first barrier, $x=0.5$), 56 Å of undoped GaAs (well), 85 Å of undoped $Al_xGa_{1-x}As$ (second barrier, $x=0.4$), 60Å of undoped GaAs, and 5000 Å of GaAs Si doped to $\sim 2\times 10^{17}$ cm^{-3}, grown on top of an n^+-type GaAs substrate successively. While the second barrier is identical in all three samples, the widths of the first barrier (105, 85, and 70 Å for samples 1, 2, and 3, respectively) were designed to be different so that we could study the noise as a function of the relative transmissivity T_e/T_c of the two barriers, where T_e and T_c are the transmissivity of the emitter barrier and the collector barrier (under bias), respectively. In this paper T_e/T_c was obtained through self-consistent calculations[12] based on the Wertzel-Kramers-Brillouin (WKB) approximation and the sequential tunneling model. The bias voltage V across the sample was stepped with a well-filtered digital-to-analog (D/A) converter and the noise was measured with a fast-Fourier-transform (FFT) spectrum analyzer. For each bias point, the response function of the measurement system was calibrated and the background noise was subtracted.

The results from sample 2, shown in Figs. 1 and 2, contain most of the features of the noise characteristics of the DBRTS. Under forward bias, $T_e/T_c \sim 2$. (In our convention, forward bias means the first barrier is the collector barrier and the second barrier is the emitter barrier.) There is a large bistable region[12,15] on the I-V curve (see inset of Fig. 2). Figure 1 illustrates S_i as a function of f and V for increasing V. It is evident that above 1 kHz S_i is independent of f and below 100 Hz there is a substantial amount of $1/f$ noise, and that S_i has a strong dependence on V, being larger where I is larger. In separate measurements, we extend f to 10 kHz and found S_i to be independent of f from 1 to 10 kHz. The general S_i versus f behavior described here was also observed in the other samples.

Subsequently, we averaged S_i between 2.5 to 5 kHz to reduce the uncertainty of the data and the average S_i is plotted against I in Fig. 2. We note that when V is swept down (not shown in Fig. 1), S_i repeats its values obtained with V swept up, except in the bistable region. In the resonant-tunneling region, we found that S_i is proportional to I with $S_i/2eI \approx 0.86$ (seemingly suppressed shot

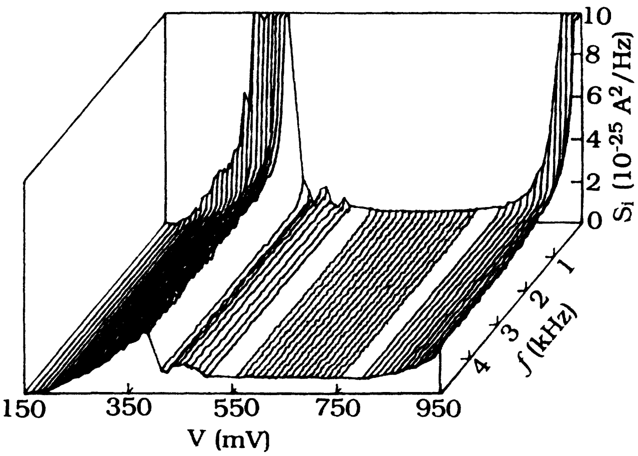

FIG. 1. Noise current power density S_i vs increasing bias voltage V and frequency f for sample 2 under forward bias.

noise). Shown also in Fig. 2 is S_i versus I in the phonon-assisted tunneling[12] and the onset of the second tunneling peak regions, to which we will return later. The noise suppression in the resonant-tunneling region (compared to the full shot noise) is not due to any series resistance in the sample. The fact that we were able to bias the sample up to $1.5V$ and get a current of $\gtrsim 100$ times larger than its peak current (1.1 μA) indicates that the series resistance must be less than 5% of the minimum differential resistance in the resonant region (≈ 200 kΩ). The suppression is not due to any parallel conduction in the samples either, since the current peak-to-valley ratio is high $(>\frac{7}{1})$.

Figure 3 shows $S_i/2e$ versus I in the resonant-tunneling region for all three samples. The data further confirm that the noise suppression results from intrinsic electron-tunneling processes in the DBRTS. Under reverse bias, $T_e/T_c \sim 0.01$ for sample 2 and $T_e/T_c \sim 3\times 10^{-4}$ for sample 1. Our results show that $S_i/2eI \approx 0.98$ for sample 2 and $S_i/2eI \approx 1.05$ for sample 1, both very close to the full shot noise. Sample 3 has $T_e/T_c \sim 0.2$ for both forward and reverse basis. The peak currents for both bias directions are quite close, and the bistable region on the I-V curve (not shown) is very small (~ 5 mV) for forward bias and absent for reverse bias. The current peak-to-valley ratio is larger than $\frac{9}{1}$ for both bias directions. We found that when $I/I_{\text{norm}} < 0.8$, under forward bias $S_i/2eI \approx 0.55$, and under reverse bias, $S_i/2eI \approx 0.50$ and S_i displays a weak nonlinear dependence on I. We did not measure sample 1 under forward bias for the whole resonant-tunneling region, since the current was much larger than our optimal measurement current.

We summarize the behavior of $S_i/2eI$ in the resonant-tunneling region as a function of T_e/T_c in the inset of Fig. 3. It appears that at least for our structures, $S_i/2eI \approx 1$ for extremely asymmetric ones with $T_e/T_c \lesssim 0.01$, $S_i/2eI < 1$ for less asymmetric ones with $0.01 \lesssim T_e/T_c \lesssim 10$, and $S_i/2eI$ has a minimum for T_e/T_c

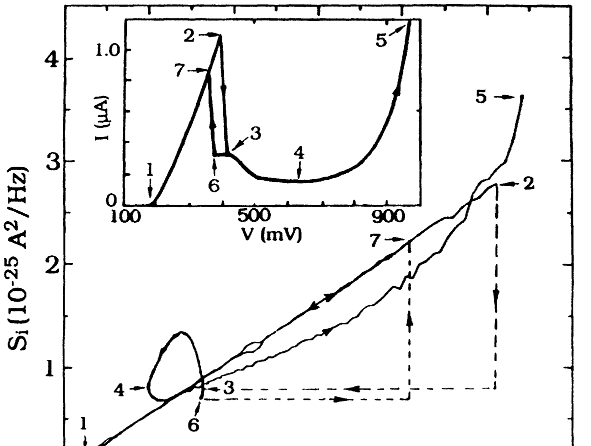

FIG. 2. Noise current power density S_i averaged between 2.5 and 5 kHz vs bias current I for sample 2 under forward bias. Inset: I-V curve. The data were taken by sweeping the bias voltage up from 1, 2, 3, 4 to 5, and then down from 4, 6, 7 to 1. Arrows on the curves indicate the direction of bias voltage sweep and the dashed lines are for a guide to the eye. 1-7-2: resonant-tunneling region. 6-3-4: phonon-assisted tunneling region. 4-5: onset of the second resonant peak. 2-3 and 6-7: load lines of the measurement circuit along which the device switches.

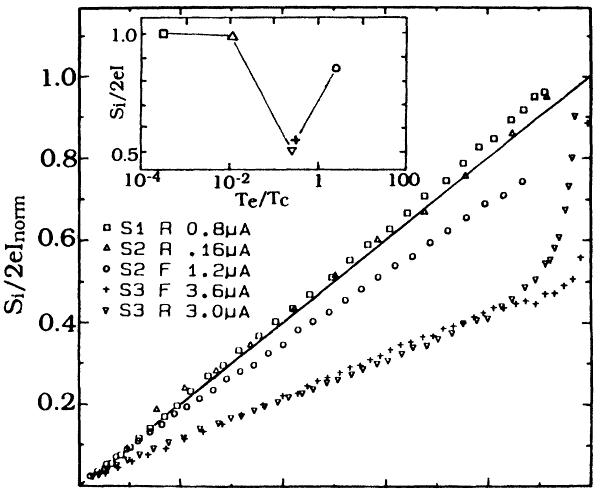

FIG. 3. $S_i/2eI_{\text{norm}}$ vs I/I_{norm} in the resonant-tunneling region for three different samples. I_{norm} is a normalization factor ($\approx$corresponding peak current). $S1\,R\,0.8$ μA in the legend stands for sample 1, reverse bias, $I_{\text{norm}} = 0.8$ μA. The solid line represents the theoretical full shot noise. The data were averaged between 2.5 and 5 kHz for sample 2 and between 5 and 10 kHz for samples 1 and 3. Inset: $S_i/2eI$ vs T_e/T_c, where T_e/T_c is calculated self-consistently as described in Ref. 12 and the data points are connected as a guide to the eye.

somewhere between 0.01 and 10. We speculate that $S_i/2eI \approx 1$ also for extremely asymmetric structures with $T_e/T_c \gtrsim 10$. It is reasonable that in extremely asymmetric structures the noise is close to the full shot noise, since even in the sequential tunneling picture, T_e or T_c alone dominates the transport processes and the noise is largely due to a single barrier. The noise suppression for the less asymmetric structures provides direct evidence that the tunneling of electrons in these structures is not completely coherent. However, the two barriers in the DBRTS do not suppress the noise in a simple way as putting two ordinary tunnel diodes in series. In the latter case, the noise currents from the two diodes are completely uncorrelated and add quadratically, and thus the overall S_i is suppressed by a factor of $(r_1^2+r_2^2)/(r_1+r_2)^2$, where r_1 and r_2 are the differential resistances of the two diodes respectively.[9] But for the DBRTS, when the observation time ($\sim 1/f$) is much longer than the lifetime of the dynamic electrons stored in the well ($\ll 10^{-4}$ sec), any increase in the emitter current will also be observed in the collector current. Consequently, unlike in the case of two tunnel diodes in series, the emitter current and the collector current are correlated through the stored dynamic electrons in the well.

Accordingly, we have to consider the effects of phase incoherence on the noise characteristics of the DBRTS to a further extent. First, we take the limiting case of sequential tunneling. If we ignore the accumulation charge in the emitter and the depletion charge in the collector, we can regard the DBRTS as having three sources of fluctuations that generate the electronic noise. The number of electrons tunneling through the emitter barrier per unit time (emitter current), the number of electrons tunneling through the collector barrier per unit time (collector current), and the number of dynamic electrons stored in the well, all fluctuate around their mean values. The emitter current and the collector current both give rise to shot noise for which S_i has a white spectrum and a linear dependence on I. The fluctuations in the number of dynamic electrons stored in the well produce a noise spectrum given by $S(f) = S(f=0)/(1+4\pi^2 f^2 \tau^2)$, similar to generation-recombination noise.[16] The time constant τ involved here is the electron lifetime in the well. Thus at the frequencies of our measurements $S(f) \approx S(f=0)$, independent of f. Since these three sources of fluctuations are correlated with each other through the dynamic electrons stored in the well, the measured overall noise is not a simple quadratic summation of the three contributions. Instead, it is the combined effect of all three sources of fluctuations adapted through internal feedback to satisfy the external bias conditions. Generally, there is no obvious reason for S_i to be proportional to I for the DBRTS. However, if the number of dynamic electrons stored in the well is approximately proportional to I, as suggested by self-consisted calculations on sample 2 under forward bias, so is the mean-square fluctuation of the number of stored dynamic electrons. Consequently, the contribution to the overall S_i from the fluctuations of the stored dynamic charge is also proportional to I. The combined effect of this contribution and the shot noise from the emitter current and the shot noise from the collector current can yield a white spectrum for S_i and a linear relation of S_i versus I. Although we do not yet have a theory for the actual values of $S_i/2eI$, we believe that the departure of S_i from $2eI$ can be attributed to the phase incoherence of the tunneling processes.

In the more general case of partially coherent tunneling, the coherent component of I generates shot noise with $S_i = 2eI$, and the incoherent component generates noise as described above in the sequential tunneling limit. Since the noise contributed by both current components has a white spectrum (for 1 kHz $< f <$ 10 kHz), so should be the overall noise. Also, if the contribution to S_i from the incoherent component of I is proportional to I, so should be the overall S_i. This explains the qualitative behavior of our data in the resonant-tunneling region. Furthermore, since the deviation of S_i from $2eI$ is a consequence of the incoherent component of I, a detailed study of the S_i versus $2eI$ relationship should lead to a quantitative description of the degree of phase coherence of the tunneling processes in the DBRTS.

Finally, in the phonon-assisted tunneling region, S_i is generally nonlinear with I and $S_i/2eI$ may range from 0.7 to 1.6, as observed from sample 2 under forward bias (see Fig. 2) and sample 3 (not shown). We carefully checked our measurement setup and ensured that this behavior did not result from any instability associated with the negative differential resistance of the sample. The noise in this region may have an extra contribution, possibly from the electron-phonon interaction process itself. In the bistable region, when the device is biased very close to the points where the current switches, S_i can be much larger than in the middle of the resonant-tunneling region, indicating that the device is much noiser when working around these points. This was clearly observed in sample 3 in both bias directions as shown in Fig. 3 in the $I/I_{\text{norm}} > 0.9$ region. The same behavior was also observed in sample 2 (not shown). When V is further increased from the phonon-assisted tunneling region, I starts to increase again, primarily due to the onset of the second resonant peak. The results from sample 2 (see Figs. 1 and 2) indicate that in this region, for $I < 0.8$ μA, $S_i/2eI$ can be smaller than its value in the resonant-tunneling region corresponding to the same I, whereas when $I > 0.8$ μA both the $1/f$ noise below 1 kHz and the noise at higher frequencies increase rapidly.

In conclusion, we have reported on the noise characteristics of the DBRTS obtained from systematic noise measurements on three samples with different barrier structures at 4.2 K. Our results reveal that generally, for f below 100 Hz, $1/f$ noise dominates, and between 1 and 10 kHz, S_i has a white spectrum. In the resonant-tunneling region in structures with extremely asymmetric barriers with $T_e/T_c \ll 1$ under bias, the noise between 1 and 10 kHz is close to the full shot noise. In structures with less asymmetric barriers, the noise is suppressed compared to the full shot noise. The noise suppression in the resonant-tunneling region provides direct evidence of incoherent tunneling of electrons through the two barriers. We have given an account of the results by considering qualitatively the effect of fluctuations in the emitter current, the collector current, and the number of electrons dynamically stored in the well. We have pointed out that these sources of fluctuations are correlated and that a quantitative study of the S_i versus $2eI$ relationship should give a quantitative description of the phase coherence of the tunneling process in the DBRTS. Such a quantitative theory, which involves complicated self-consistent dynamic equations[12] and statistics, should be a subject of further research.

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