# Shot noise of sequential tunneling in a triple-barrier resonant-tunneling diode

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The shot noise of a triple-barrier resonant-tunneling diode (TBRTD) has been characterized in the low-frequency regime. Suppression of shot noise has been observed in both bias polarities. The measured noise characteristics are the consequences of several electron transport mechanisms associated with the device. These include the Pauli exclusion principle, thermally activated tunneling, and electron energy relaxation. We describe the effect of these mechanisms in relation to the noise characteristics. The mechanisms lead to sequential electron tunneling, which is manifested in the noise characteristics of the TBRTD. [S0163-1829(97)06019-0]

Shot noise, which arises when a junction device is subject to nonequilibrium, is an interesting and important topic in the study of electron transport in mesoscopic devices. Some transport phenomena, while being difficult or impossible to be probed in conductance measurements, are readily observable in noise measurements. Shot noise is due to randomness in charge emission across a junction.[1] In the absence of any regulating mechanism, the charge flow across a junction is uncorrelated, resulting in full shot noise. The full shot noise can be suppressed by introducing correlations in the transport. Theories developed particularly for the double-barrier resonant-tunneling diode (DBRTD) (Refs. 2–5) show that correlations in electron transport exist if the effect of the Pauli exclusion principle is strong enough to provide a charge regulating mechanism. In the low-frequency limit, the noise current power density $S(0)$ is independent of frequency $f$, and is given by

$$S(0)=2eI[1-(2T_eT_c)/(T_e+T_c)^2], \qquad (1)$$

where $I$ is the dc current and $e$ is the electron charge, and $T_e$ and $T_c$ represent the transmission coefficients of the emitter barrier and the collector barrier, respectively. The term inside the brackets is the suppression factor $\gamma$. Suppression below the full level of shot noise occurs if $\gamma$ is less than unity. Equation (1) indicates that suppression is maximized when the device has a symmetric configuration in operation. For extremely asymmetric devices, in which only one barrier affects the current, shot noise approaches the full level, which is expected for single-barrier devices. Equation (1) can be used when tunneling is either coherent or sequential. The expression for the suppression factor is the same as the $1-T$ dependence, $T$ being the transmission coefficient, of the shot noise of quantum coherent transport derived using the Landauer formalism.[6] To date, shot noise suppression has been observed in several DBRTD's.[7,8]

In this paper, we report a characterization of the shot noise properties of a triple-barrier resonant-tunneling diode (TBRTD). Compared to the DBRTD, the TBRTD allows one to study the effect of sequential tunneling on shot noise in an unequivocal scheme. Sequential tunneling is the result of inelastic scattering of tunneling electrons, which occurs when electrons interact with phonons, photons, or other electrons as they traverse the quantum-well region. Inelastic scattering causes electron energy relaxation, making the scattered electrons bear a quantum-mechanical phase which is unrelated to that of the incident electrons. Therefore the tunneling process in a resonant-tunneling diode consists of a sequence of steps: electrons first tunnel from the emitter to the well region; they subsequently experience a series of phase-randomizing scattering events; finally the scattered electrons tunnel out of the well region to the collector. In general, sequential tunneling results in suppression of shot noise. If the scattering center is modeled as a voltage probe, then it is shown that current fluctuations vanish.[9,10] Also, the suppression depends on the degree of dissipation of the excess energy of the electron above equilibrium.[11] The transport behavior of the TBRTD has previously been studied in conductance measurements.[12] Our noise measurements show suppression of shot noise in both biasing polarities of the TBRTD. The suppression depends on specific scattering mechanisms in the quantum wells. We describe the scattering mechanisms in each polarity, and associate them with the measured noise characteristics. The suppression agrees with Eq. (1), and hence confirms the $1-T$ dependence.

The TBRTD sample was grown by molecular-beam epitaxy on a $n^+$ GaAs(001) substrate. The collector region, which was grown on top of the substrate, is made of a 0.5-$\mu$m $n^+$ GaAs (Si:$1.5\times10^{18}$ cm$^{-3}$) buffer, that is followed by 100 Å of GaAs with graded doping and a 150-Å undoped GaAs spacer. The active region consists of the following: 40 Å of undoped AlAs (barrier 3), 50 Å of undoped GaAs (well 2), 15 Å of undoped AlAs (barrier 2), 80 Å of undoped GaAs (well 1), and 40 Å of undoped AlAs (barrier 1). The emitter region has the same structural configuration as the collector region. The diodes are in the form of 64-$\mu$m square mesas defined by photolithagraphy and wet chemical etching. Forward bias is defined as the polarity in which electrons are emitted from the emitter into well 1. The noise measurements were made at 77 K using a spectrum analyzer, with the device immersed in liquid nitrogen.

 

The zero-bias conduction-band energy diagram of the TBRTD, and the modeling of the energy band diagram and the voltage-energy conversion ratios of the quantum wells are available in Ref. 12. At zero bias, the first quasibound state of well 1, $S_{1-1}$, is at an energy of 47 meV above the Fermi level, while the first quasibound state of well 2, $S_{2-1}$, is 101 meV above the Fermi level. The forward-bias and reverse-bias current-voltage $(I-V)$ characteristics of the TBRTD are shown in Figs. 1(a) and 1(c), respectively. In the forward-bias polarity, the threshold of the tunneling current occurs at 130 mV, and the resonant peak occurs at 240 mV. The left inset of Fig. 1(a) shows the schematic conduction-band profile at the threshold. This inset indicates that at and above the threshold the emitter electrons are at resonance with $S_{1-1}$. Throughout this region, $S_{2-1}$ is at a higher energy above $S_{1-1}$. The right inset shows the schematic conduction-band profile at the peak, where the wave function of $S_{1-1}$ overlaps that of $S_{2-1}$ so that the two wells are coupled to each other. Thus, near the peak, the emitter electrons tunnel resonantly into the coupled wells, and subsequently tunnel out to the collector. The small feature centered at 370 mV is due to GaAs LO-phonon emission between the emitter and $S_{1-1}$. In the reverse-bias polarity, as depicted in Fig. 1(c), the threshold occurs at 300 mV. The left inset of Fig. 1(c) shows that, at this bias, the collector electrons are at resonance with $S_{2-1}$, which is 112 meV above $S_{1-1}$. The right inset shows that near the peak (575 mV) the wave function of $S_{2-1}$ overlaps that of the second quasibound state of well 1, $S_{1-2}$, so that the two states are coupled to each other. Beyond the peak, the double-step structure is due to oscillations in the biasing circuit rather than an intrinsic effect associated with the device itself.[13]

We have made noise measurements at a series of biasing points starting near the threshold of each biasing polarity. The experiment setup did not allow measurements to be made in the negative differential resistance region. Figure 1(b) shows the values of the shot noise suppression factor $\gamma$ in the forward-bias polarity. Each point represents the average value of $\gamma$ at three frequencies, namely, 100, 200, and 300 kHz. The noise measurements show that $\gamma$ is close to unity above the threshold, and, near the peak, $\gamma$ shows a slight drop. At the threshold of resonant tunneling (130 mV), the electrons at the Fermi level of the emitter are at resonance with $S_{1-1}$. As the bias is increased beyond the threshold, the electrons below the Fermi level are brought into resonance. At 77 K, thermally activated resonant tunneling[14] from $S_{1-1}$ to $S_{2-1}$ is substantial since the difference in energy between them is only 32 meV at the threshold. Therefore, the $S_{1-1}$ electrons can reach the collector either via $S_{2-1}$ by thermally activated tunneling or by direct tunneling across barriers 2 and 3. We have made estimations of the tunneling rates across the three barriers using the WKB method. The rate $T_2$ of tunneling from $S_{1-1}$ to $S_{2-1}$ by means of thermally activated resonant tunneling is much larger than the rate $T_1$ of tunneling from the emitter to $S_{1-1}$ and the rate of $T_3$ of tunneling from $S_{2-1}$ to the collector. The rate $T_{2+3}$ of tunneling from $S_{1-1}$ directly to the collector is much smaller than $T_1$ and $T_3$, whose values are close to each other. The rates seem to suggest that in this range of bias we can treat the electron transport across the triple-barrier structure as a double-barrier problem with an effective central electrode. Then, we can apply Eq. (1) to estimate $\gamma$, which turns out to be 0.6 as for a symmetric device. However, the measured value of $\gamma$ is close to unity. The reason is that, to treat the two wells as a single effective electrode, $T_{2+3}$ should be vanishingly small, which is not true in our case. Therefore, the actual structure is asymmetric, implying that the dwelling time of the electrons in the well region is less than the maximum value.[2,3] In other words, the occurrence of full shot noise is due to the fact that $T_2$ and $T_3$ are greater than $T_1$, and the fact that $T_{2+3}$ is not zero. This means that electrons leave $S_{1-1}$ at a faster rate than the rate at which electrons arrive at $S_{1-1}$ from the emitter. Thus the effect of the Pauli exclusion principle is weak, and little correlation exists in the transport of electrons. As the bias is increased toward the peak, the wave functions of $S_{1-1}$ and $S_{2-1}$, overlap, although $S_{2-1}$is still higher in energy than $S_{1-1}$, as shown in Fig. 1(a). The overlapping couples the two wells between barriers 1 and 3. Within this narrow range, $T_2=0$, and $T_{2+3}=0$. Tunneling electrons bounce back and forth between barriers 1 and 3 before tunneling out to the collector. Now the structure is more symmetric with similar rates $T_1$ and $T_3$, which implies a longer dwelling time and hence more correlation. This explains the measured drop in $\gamma$.

In the reverse-bias polarity, the measured $\gamma$ has a different dependence on the bias. Figure 1(d) shows that in the entire resonant tunneling region $\gamma$ is suppressed, and, as in the forward-bias polarity, there is a drop in $\gamma$ near the resonance peak. This noise characteristic reflects electron energy relaxation due to inelastic scattering between the well states. At and above the threshold, the collector electrons are in resonance with $S_{2-1}$, which is above $S_{1-1}$. Electrons first tunnel from the collector to $S_{2-1}$ and then tunnel inelastically to $S_{1-1}$ and finally tunnel to the emitter. We have not identified the exact energy relaxation mechanism. It is not the emission of the GaAs LO or AlAs LO phonon.[15] We speculate that photon emission could be the relaxation process. Our noise measurements actually confirm the presence of sequential tunneling. The resonant electrons in $S_{2-1}$ can either tunnel directly to the emitter, or, alternatively, they can first tunnel inelastically to $S_{1-1}$ and then tunnel out to the emitter. If the first process is dominant, an estimation based on tunneling rates indicates $\gamma=1$. However, the measured $\gamma$ is much less than 1, indicating that inelastic scattering occurs so that electrons traverse the structure in a sequential manner. As the bias is increased toward the peak, the wave function of $S_{2-1}$ overlaps that of $S_{1-2}$, so that the two wells become coupled to each other. In this range of bias, the inelastic tunneling between $S_{2-1}$ and $S_{1-1}$ vanishes, and the tunneling electrons, as they enter the well region, bounce back and forth between the outer barriers before arriving at the emitter. The tunneling rates show that the tunneling structure is very symmetric. This explains the drop in $\gamma$ near the peak. Figure 1(d) shows that the value of $\gamma$ increases slightly when the bias is increased beyond 500 mV. This might be an indication that energy relaxation is becoming less effective. At 500 mV, the rate of thermally activated resonant tunneling is doubled compared to the rate at the threshold. This might also be the cause for the increase in $\gamma$ as thermally activated processes usually create shot noise. We have measured the noise at several higher biasing points beyond the resonant

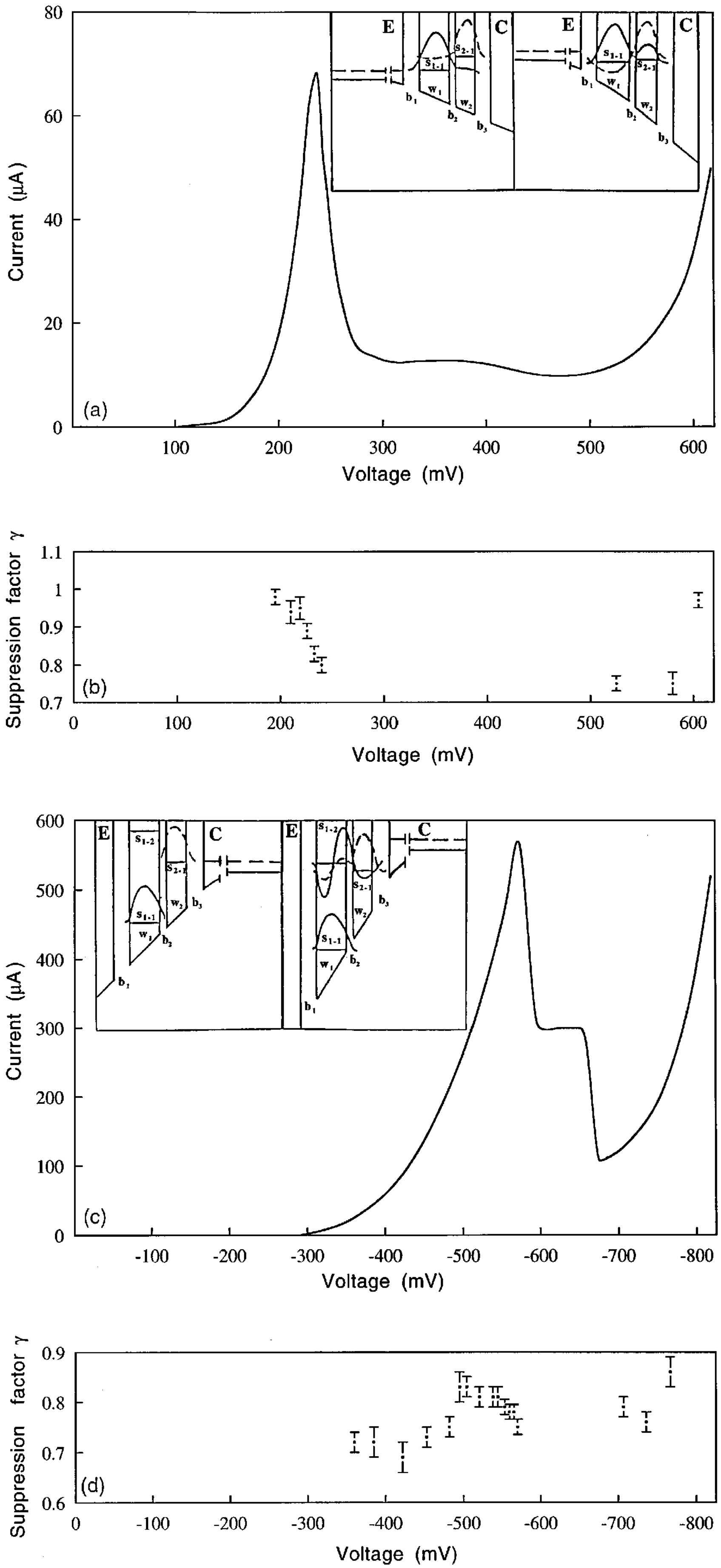


FIG. 1. (a) and (c) show the current-voltage characteristics of the forward and reverse biasing polarities, respectively. The right and left insets in (a) and (c) show the schematic conduction-band energy diagram at the threshold and near the peak of resonant tunneling, respectively. $E$ and $C$ denote the emitter and the collector, respectively. $b$, $w$, and $s$ denote the barrier, quantum well, and the well state, respectively. Dashed lines represent the Fermi energy. The wave functions of the states are shown. (b) and (d) show the shot noise suppression factor $\gamma$ in the forward and reverse biasing polarities, respectively.

peak in both polarities. The values of $\gamma$ approach unity as the bias is increased. We do not yet understand the exact reason for this phenomenon. However, in this range of bias, the tunneling electrons are not in resonance with any of the quantum-well levels. Thus, the tunneling structure is in effect a single barrier, and $\gamma$ is essentially equal to unity.

As described above, three processes that exist in electron transport across the TBRTD affect the noise characteristics. When the TBRTD is biased so that a tunneling current begins to flow, i.e., the electron distribution of the device is in thermal nonequilibrium, shot noise becomes the dominant source of noise. Since each tunneling electron stays in a quantum-well level for a finite time (the dwelling time), a temporal correlation is established in the electron flow due to the Pauli exclusion principle, which forbids other electrons with the same quantum numbers from tunneling to occupy the level simultaneously within the dwelling time. The correlation is strongest when the dwelling time is at a maximum, which occurs for symmetric devices. In our experiment, this correlation is responsible for the increase of suppression near the resonant peak in both polarities. The thermally activated tunneling between quantum-well energy levels causes fluctuations in the electron flow and hence generates shot noise. The situation is very similar to that of a vacuum diode operated in the temperature-limited region. Electron-energy relaxation is another process that makes tunneling in the TBRTD sequential. The fundamental reason for noise suppression by energy relaxation is that when tunneling electrons lose energy, the nonequilibrium electron distribution is reduced toward equilibrium. If the relaxation process results in exact equilibrium, the Fermi-Dirac statistics will suppress shot noise completely at zero temperature. In intermediate cases, shot noise will be partly suppressed. Specific mechanisms of suppression of shot noise by electron energy relaxation in a conductor have been treated in two publications. Beenakker and Buttiker[10] modeled the scattering center as an ideal voltage probe. The voltage fluctuations in the probe counterbalance the intrinsic current fluctuations, so that the net current fluctuations disappear. Therefore there is no accumulation of charge at the probe and hence charge neutrality holds. Recently, Shimizu and Ueda[11] showed that suppression of shot noise is closely related to electron energy relaxation. In general, the amount of suppression is proportional, in addition to electron transmission (the $1-T$ dependence), to the amount of energy transfer from the electron system to other systems such as the phonon and the photon, i.e.,

$$\gamma=(1-\kappa)(1-T), \tag{2}$$

where $\kappa$ is the percentage of energy relaxation. For our TBRTD, the quantum wells with their energy levels behave like voltage probes that absorb incoming electrons with energies above a level, and emit the relaxed electrons from that level. This process increases $\kappa$ in Eq. (2), resulting in suppression.

In conclusion, we have characterized the shot noise properties of a TBRTD. Suppression below the full level of shot noise has been observed. We show that this suppression is due to several electron transport mechanisms, which result in sequential tunneling. Our results are in agreement with Eq. (1), and hence confirm the $1-T$ dependence of shot noise suppression. Finally, we point out that the TBRTD is an ideal device to be used in studying sequential tunneling, and noise measurements of this device might be a new technique in obtaining information about other energy-dissipation processes.

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