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Current Noise in Resonance Tunnel Diodes Based on InGaAlAs Heterostructures

N. V. Alkeev, V. E. Lyubchenko, C. N. Ironside,
J. M. L. Figueiredo, and C. R. Stanley

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Abstract—Noise in resonance tunnel diodes based on InGaAlAs structures is studied at two frequencies. A shot noise caused by the current flowing through two barriers of the heterostructure is identified. It was found that if the voltage across the structure is within the first ascending section of the current–voltage characteristics, the shot noise is suppressed with the suppression ratio $\Gamma \sim 1/15$. In the second ascending section of the current–voltage characteristic, the shot noise coincides with the shot noise of electrons passing through one barrier ($\Gamma = 1$) by the order of magnitude. The specific features of current flow affecting the behavior of noise in the resonance tunnel structures are discussed.

The resonance tunnel diodes (RTDs) based on two-barrier heterostructures are still intensively investigated, first, as one of model structures of rapidly progressing nanoelectronics, and second, because they offer unique promise for applications in microwave technology and superhigh-speed digital devices [1]. In particular, it is shown that RTDs can be used as elements with negative differential conduction (NDC) at frequencies as high as 1 THz [2] and they preserve their nonlinear properties at frequencies as high as 10 THz [3]. The most widespread method applied to analyzing the current flow in an RTD is the dc measurement of its current–voltage characteristics (CVCs). The CVC is compared to the results obtained using simulations or analytical theory. The same approach is applied when the impedance or equivalent circuit of an RTD is investigated. This, however, does not help to determine such RTD parameters as the barrier-tunnelling time of electrons, their lifetime in a quantum well, the well concentration of electrons, etc. These parameters are found using various methods. Thus, the tunnelling time of electrons is estimated from the intensities of photoluminescence and oscillations of the RTD's capacitance in the presence of a magnetic field [4, 5]. An efficient method for investigating current-flow mechanisms in various devices and determining their dynamic parameters is the measurement of their current noise. The current noise in RTDs is measured in various frequency bands [6–10].

In this paper, the current noise in the RTDs based on InGaAlAs structures is analyzed at 60 and 200 MHz. The 2-nm-thick AlAs barriers were separated by a 6-nm-thick InGaAs quantum well (for more details, see [11, 12]). The noise measurements were performed at room temperature by means of a KhK5-49 noise meter simultaneously measuring power transfer factor G and noise factor F of a two-port in a 50-Ω circuit in the frequency band 0.01–1.8 GHz. Simultaneously, the CVC of the RTD was recorded. The diode was installed into a gap of the microstrip line. One of its leads was grounded, and the other was connected to the ends of the microstrip line with wires. The noise measurements at 60 and 200 MHz yielded almost similar results. Hence, the contribution of the $1/f$ noise can be ignored. At the same time, according to previous results [12], there is no necessity to take into account the capacitance of the equivalent circuit of the RTD and the inductance of wires, connecting it with the microstrip line. This allows us to represent the diode in the frequency band under consideration by a simple equivalent circuit and to relate the spectral density of the current noise power to the measured quantities G and F. Note that, in [6], which was apparently the first publication on the RTD current noise in the microwave band, the authors ignored the capacitance of the RTD equivalent circuit and its dependence on the bias voltage. The current noise in the RTDs based on AlAs/GaAs structures was analyzed in the band 2–4 GHz [7]. Calculating the noise, the authors took into account the bias voltage dependence of the parallel capacitance and resistance in the RTD equivalent circuit. However, in our point of view, the accuracy of the determination of the noise level is still rather low because the capacitance and resistance of the equivalent circuit are measured with considerable errors in this frequency band.

Figure 1 demonstrates the diagram of the facility for measuring the RTD noise, and Fig. 2 illustrates the connection of the RTD in the 50-Ω circuit. At the frequencies considered, we represent the RTD in the form of an equivalent circuit that consists of differential conductivity g_d of the diode and current generators I_{therm} and I_{flow}. The I_{therm} creates the noise current due to the differential conductivity of the diode g_d with the spectral density (SDNC) $S_{Itherm} = 4kTg_d$. Here, k is the Boltzmann constant, T is the diode temperature, and subscript I means that the current generator is a noise source. The generator I_{flow} generates the RTD noise due to the current flow with the SDNC S_{flow}. It is known that electrons passing through a single barrier generate the shot noise with the SDNC $S_{I\text{shot}} = 2eI\Gamma$, where e is the electron charge, I is the current flowing through the barrier, and Γ is the suppression factor depending on the specific features of the current flow through the barrier. In the absence of these features, $\Gamma = 1$. The input of the RTD holder is connected to 50-Ω load R_{in} along with the corresponding noise voltage generator $\mathcal{E}_{\text{therm}}(S_{V\text{therm}} = 4kTR_{\text{in}})$. The output of the holder is also connected to the 50-Ω load R_{l}, which, in our case, can be considered noiseless. Now, let us find a relation between the measured quantities G and F, and the quantity S_{flow}.

Usually, the power transfer factor (power gain) G and noise factor F of a two-port are determined as follows [13]:

$$G = P_{\text{s out}}/P_{\text{s in}}$$

$$F = \frac{P_{\text{n out}}/P_{\text{s out}}}{P_{\text{n in}}/P_{\text{s in}}} = \frac{P_{\text{n out}}}{GP_{\text{n in}}},$$

where $P_{\text{s out}}$ and $P_{\text{s in}}$ are the output and input signal powers and $P_{\text{n out}}$ and $P_{\text{n in}}$ are the output and input noise powers of the two-port, respectively (the input noise power is the power of the thermal noise generated by the 50-Ω resistor). We can represent the noise power as $P_{\text{n out}} = GP_{\text{n in}} + P_{\text{n1}}$, where P_{n1} is the power of the intrinsic noise of the two-port dissipated in the load resistance. Then,

$$F = 1 + P_{\text{n1}}/GP_{\text{n in}}$$

$$F = 1 + \overline{U_2^2}/\overline{U_1^2}.$$

Here, $\overline{U_1^2}$ is the average squared amplitude of the load noise voltage U_1 generated by the source $\mathcal{E}_{\text{therm}}$, and $\overline{U_2^2}$ is the average squared amplitude of the load noise voltage U_2 generated by the generators I_{therm} and I_{flow} (see Fig. 1). The values of U_1 and U_2 can easily be found using the equivalent circuit (see Fig. 2):

$$U_1 = \frac{\mathcal{E}_{\text{therm}}}{2 + 50g_{\text{d}}} \quad \text{and} \quad U_2 = \frac{I_{\text{therm}} + I_{\text{flow}}}{1/25 + g_{\text{d}}}.$$

Hence, assuming that the RTD thermal and shot noises are uncorrelated, we find

$$F = 1 + 50g_{\text{d}} + \frac{(25)^2 S_{\text{flow}} g_{\text{d}}}{kT}. \tag{1}$$

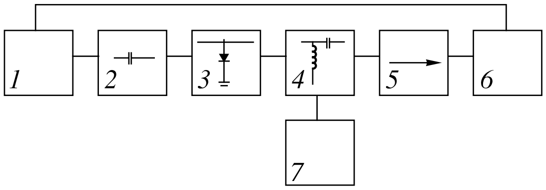

Fig. 1. Diagram of the facility used for RTD noise measurements: (*1*) noise generator; (*2*) blocking capacitor; (*3*) holder with RTD; (*4*) bias voltage input; (*5*) gate; (*6*) KhK5-49 noise factor meter; and (*7*) RTD bias voltage source.

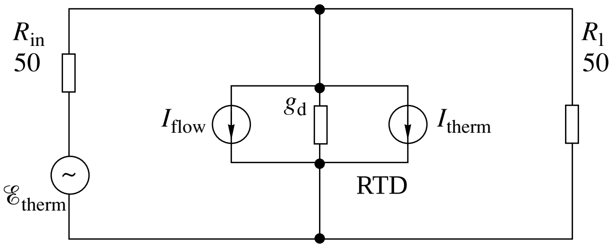

Fig. 2. Equivalent circuit of the RTD connected to the 50-Ω circuit.

The power transfer factor G is also found from the results presented in Fig. 2 assuming that I_{therm} and I_{flow} are equal to zero

$$G = 1/(1 + 25g_{\text{d}})^2. \tag{2}$$

Expressing g_{d} through G and substituting it into Eq. (1), we obtain

$$S_{\text{flow}} = kT\frac{\sqrt{G}}{25(1-\sqrt{G})}\left(F - 1 - \frac{2(1-\sqrt{G})}{\sqrt{G}}\right). \tag{3}$$

Figure 3 demonstrates the RTD CVC, the transfer factor G, and the noise factor F as functions of the direct bias voltage U. The values $g_{\text{d}}(U)$ substituted into (2) are obtained by differentiation of the CVC shown in Fig. 3a. It can be seen from Fig. 3b that calculation by Eq. (2) is in good agreement with the experiment. Dashed lines in Fig. 3c show the noise factor calculated by formula (1) under the assumption that $S_{\text{flow}} = 0$, where $g_{\text{d}}(U)$, as before, is found by differentiating $I(U)$. Thus, the dashed lines show the noise factor of the holder with the RTD in the presence of only the thermal noise due to the RTD differential conductivity g_{d}. It can be seen that, at $U = 0$, the measured noise factor, as expected, practically coincides with the noise factor due to only the thermal noise of the differential conductivity g_{d}. With the increasing voltage across the RTD, its noise factor grows much more rapidly than the thermal noise factor due to the current noise.

Figure 4a demonstrates the SDNC current dependence on the first ascending branch of the CVC calculated by formula (3). The SDNC curve corresponding to the single-barrier passage $S_{I\text{ shot}} = 2eI\Gamma$ for $\Gamma = 1/15$ (dashed line) is also shown. The experimental results

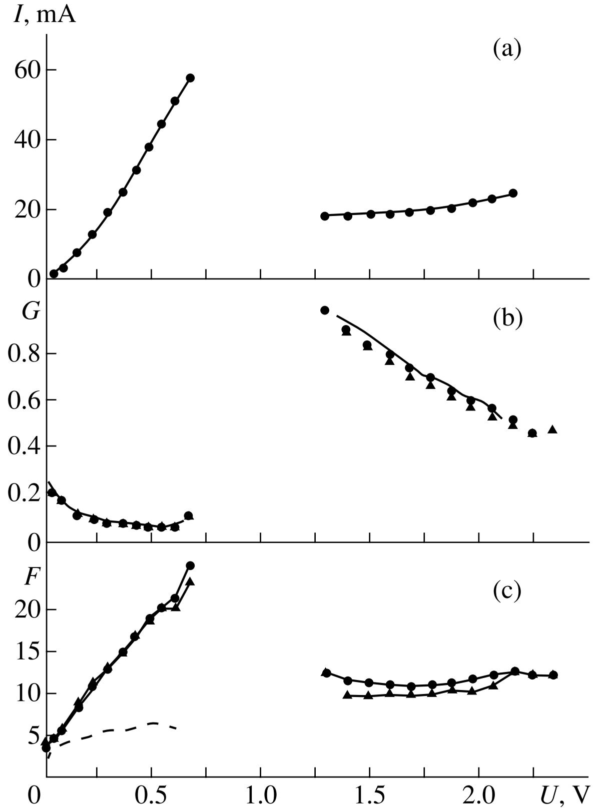

Fig. 3. RTD parameters vs. bias voltage: (a) RTD CVC, (b) power transfer factor G of the holder with the RTD, and (c) noise factor F of the holder with the RTD; (circles) measurements at 60 MHz, (triangles) measurements at 200 MHz; (dashed line) calculations: (b) by formula (2) and (c) by formula (1) taking into account the RTD thermal noise only ($S_{\text{flow}} = 0$).

demonstrated in Fig. 4a allow us to suppose that, on this branch of the CVC, the RTD current noise is caused by the shot noise of electrons passing through two barriers of the resonance tunnel structure. The shot noise can be suppressed due to the accumulation of electrons near the barriers during resonance tunneling and to the smoothing of the shot noise by this charge, similarly to the process in an unsaturated vacuum diode when the space charge accumulates [14]. This very important circumstance indicates the possibility of using RTDs in low-noise devices. Figure 4b demonstrates the SDNC calculated by formula (3) as a function of the RTD current on the second ascending branch of the CVC. The SDNC curve corresponding to the single-barrier passage $S_{I\,\text{shot}} = 2eI\Gamma$ at $\Gamma = 1$ (dashed line) is also shown. Figure 4b shows that the value of SDNC on this section of the CVC approximately corresponds to the SDNC of electrons passing through the single barrier. This result can be attributed to the fact that, on the second ascending CVC branch, the bottom of the conduction band of the RTD emitter region is higher than the main resonance level of the quantum well and the electron passage through the barriers is mainly due to thermoemission. It can be seen from Figs. 4a and 4b, the SDNC of the diode abruptly increases when approaching, both from the left and from the right, the NDC region of CVC, which seems to be a natural result of amplified fluctuations in the presence of NDC.

Similar results were obtained for the AlGaAs/GaAs RTDs with thick barriers [8]. In particular, on the first ascending branch of the CVC, $\Gamma \sim 0.5$ and, in the NDC region, $\Gamma \sim 6.6$. To explain the experimental results, the authors exploit the mesoscopic theory. On the first ascending branch of the CVC, the electron flow is assumed to be negatively correlated (sub-Poisson), which decreases the suppression ratio. According to the mesoscopic theory, the suppression ratio cannot be lower than 0.5. In the NDC region, the electron flow is positively correlated (super-Poisson), which increases Γ up to 6.6.

In our point of view, the mesoscopic theory does not apply to the analysis of RTDs with a rather large area

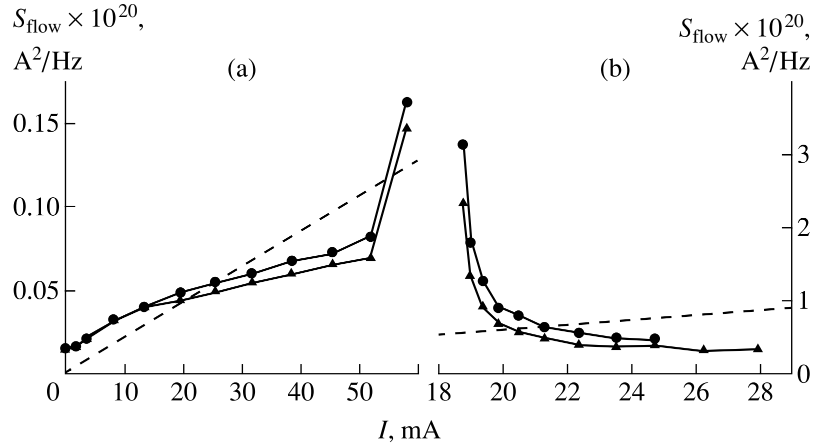

Fig. 4. SDNC S_{flow} of the RTD vs. RTD current calculated by (3); (circles) measurements at 60 MHz; (triangles) measurements at 200 MHz; (a) the first ascending branch of the CVC, (dashed line) $S_{I\,\text{shot}} = 2eI/15$ ($\Gamma = 1/15$); (b) the second ascending branch of the CVC, (dashed line) $S_{I\,\text{shot}} = 2eI$ ($\Gamma = 1$).

(the area of our diodes is 800 μm^2) and peak current of about tens of millimeters (I_p = 70 mA in our case). Indeed, when the current is I = 100 mA and the structure is 10 nm thick, the barrier is simultaneously crossed by as many as 10^4 electrons moving at the speed $v \sim 10^7$ m/s. In this case, the current through the RTD can be represented as a sum of a great number of parallel currents flowing through the individual regions of the RTD area. It can be proved [15] that the total flow is a Poisson one (the theorem for flows similar to the central limit theorem for a probability distribution). Thus, the mesoscopic theory cannot be used to explain the mechanisms of current flowing through RTDs under study. This is also confirmed by the value $\Gamma \sim 0.06$ obtained on the first ascending branch of the CVC.

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