Current fluctuations in double-barrier quantum well resonant tunneling diodes

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The measurements of the spectral intensity of the current fluctuations in double-barrier quantum well resonant tunneling diodes as a function of temperature and bias current are reported. Two types of devices were studied: one with AlAs barriers and GaAs well and contact regions, and the other has $Al_{0.3}Ga_{0.7}As$ barriers. The frequency range covered is 1 Hz–100 kHz and the temperature range is 78–400 K. The noise spectra are decomposed in a $1/f$ part, resulting in the magnitude of the $1/f$ noise, and contributions due to carrier trapping, resulting in the activation energies of the traps. It is found that a reduction of the Al content in the barrier material reduces the number of traps and further that the magnitude of the $1/f$ noise is practically independent of the temperature and of the Al content of the barrier.

Double-barrier resonant tunneling structures (DBRTS) have attracted much attention recently because of their functionality in a wide variety of applications that include frequency multipliers, parity generators, multistate memory, analog-digital converters,[1] optoelectronic devices,[2] etc. While there would be variations of present or potential applications of resonant tunneling devices, DBRTS offer not only the key attributes for the applications mentioned above, but also tender opportunities for experimental studies on quantum effects in carrier transport.[3,4] In the last ten years the impressive advances in molecular beam epitaxy (MBE) have contributed greatly to the amelioration of the DBRTS making possible more refined studies of the characteristics of the devices such as the noise performance as it correlates with the presence of defects, impurities, and tunneling processes. We report here on an extensive study of just this low-frequency noise behavior of two types of DBRTS: one with Al barriers and GaAs electrodes and well, and another type with AlGaAs barriers and GaAs electrodes and well. The measured current noise spectra are interpreted in terms of $1/f$ noise and generation-recombination (g-r) noise. The noise spectroscopy has been applied before, to bulk semiconductors[5,6] as well as to DRTBS,[7] and has proven to be very successful in identifying carrier traps.

The noise behavior of two types of devices was investigated. The symmetric tunnel structures were grown by MBE on an n^+ substrate and are identical except for the barriers which are 3-nm-thick AlAs for one device type and 5-nm-thick $Al_{0.3}Ga_{0.7}As$ for the other type. The details of the layer structure are presented in Fig. 1. In all the doped layers Si was used as a dopant. Current-voltage characteristics of the two devices both at 77 and 300 K are shown in Figs. 2(a) and 2(b). The peak-to-valley ratio of the current of the AlAs barrier device is about 13 at 77 K and decreases to about 3 at room temperature. For the AlGaAs barrier device the current peak-to-valley ratio is about 5 at 77 K, dropping to 2.2 at room temperature, and further decreasing to 1.3 at 400 K.

In order to measure the noise as a function of temperature the devices were mounted in a flow cryostat. The noise signal was fed into a low-noise amplifier and detected by a fast Fourier transform dynamic signal analyzer. In calculating the spectra allowance was made for the amplifier noise as well as the nonflatness of the amplifier gain. The resultant noise spectra usually consisted of a $1/f$ component, Lorentzian-shaped bumps due to trapping and detrapping of carriers, and a white part due to the thermal noise.

The experimental investigation is divided into three parts: (i) spectral intensity of the current fluctuations as a function of temperature at a fixed current, (ii) current dependence of the noise for voltages smaller than the peak voltage, and (iii) current dependence of the noise for voltages larger than the valley voltage. To study the temperature dependence of the noise, the diodes were biased at a constant current of 0.7 mA, relatively close to the peak, and the temperature was varied between 78 and 400 K. The spectra consist of a $1/f$ part and Lorentzian-shaped bumps due to generation and recombination (g-r noise) of the carriers. Upon multiplication of the spectra by the frequency the $1/f$ contribution will appear independent of the frequency and the bumps associated with the g-r noise will appear as peaks. From these graphs one can readily extract the magnitude of the $1/f$ noise and the frequencies (f_p) for which the g-r peaks occur. A subsequent plot of the square of the temperature T divided by f_p as a function of the

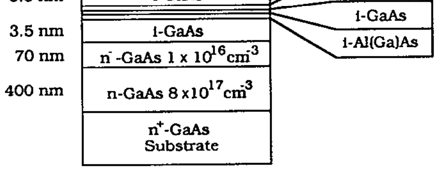

FIG. 1. Device layer configuration.

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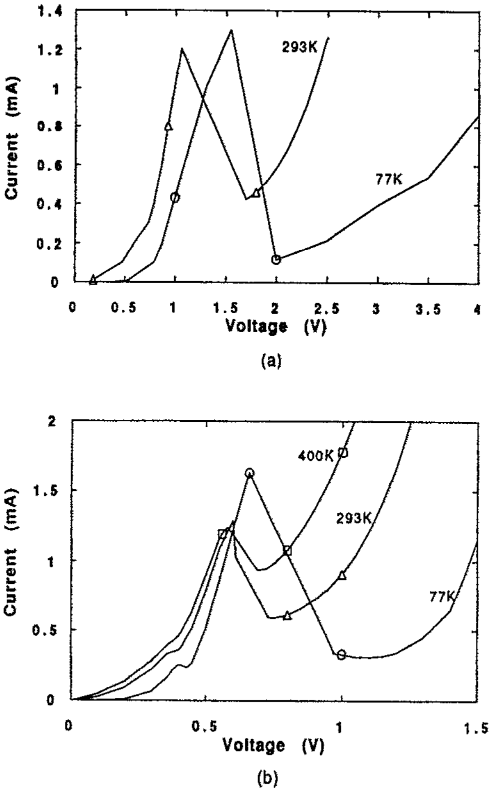

(a)

(b)

FIG. 2. Current-voltage characteristics of (a) the AlAs barrier and (b) the AlGaAs barrier device at different temperatures.

reciprocal temperature permits the calculation of the activation energies of the traps from the slopes of the curves.

In Fig. 3 we show these Arrhenius plots for the device with the AlAs barriers and for the device with the $Al_{0.3}Ga_{0.7}As$ barriers. For the mentioned range of temperatures five trapping levels could be detected in the AlAs barrier device with activation energies of 0.017, 0.15, 0.21, 0.38, and 0.55 eV. Under the same bias current and in the same temperature range the device with the $Al_{0.3}Ga_{0.7}As$ barriers showed only two traps with activation energies of 0.16 and 0.55 eV: these energies are close to two of the energies we found in the first device. Since the aluminum content of the barrier material is the main difference in the device structures, we attribute the presence of the three other traps to the larger Al mole fraction. Apparently, there is some trap assistance in the tunneling process and sweeping the temperature allows us to probe these traps by making noise measurements.

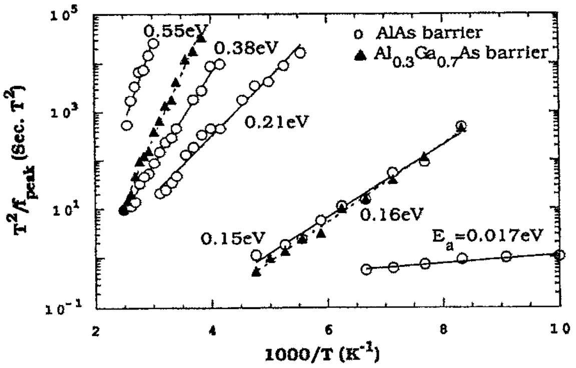

FIG. 3. Activation energies as deduced from the generation-recombination spectra for the AlAs barrier (circles) and the AlGaAs barrier (triangles) device. The quiescent current during the noise measurements was 0.7 mA.

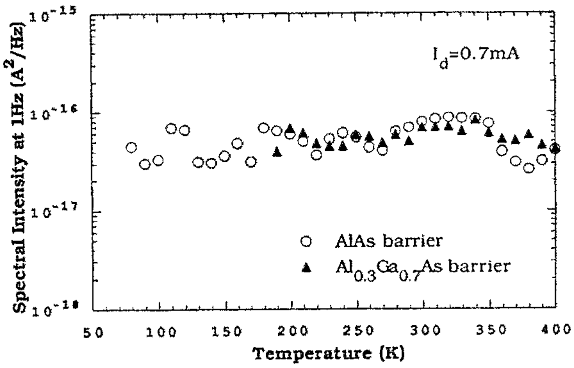

FIG. 4. Spectral intensity of the current fluctuations (1/*f* component) at *f* = 1 Hz and an operating current of 0.7 mA as a function of the temperature for the AlAs barrier (circles) and the AlGaAs barrier (triangles) device.

In Fig. 4 we present the magnitude of the 1/*f* component we observed in the noise spectra as a function of the temperature. The bias current (I_d) was held constant at 0.7 mA for both devices. We want to mention here that the frequency exponent of the spectra is equal to -1.00 ± 0.05. Due to the magnitude of the *g-r* noise in the AlGaAs barrier device (solid triangles) at temperatures below 190 K, it was not possible to reliably extract the magnitude of the 1/*f* noise.

Our measurements indicate that the magnitude of the 1/*f* noise component is relatively constant over the entire temperature range for both devices when the diodes are biased close to the peak (0.7 mA). This strongly suggests that the 1/*f* component is associated with the tunneling current since this current is independent of the temperature in first order. Because the device is biased relatively close to the peak we expect the main current component to be due to tunneling. We also observe that the magnitude of the 1/*f* noise is practically the same in the two different devices. This seems to imply that the physics (tunneling through the barrier at this operating point) that governs the transport, and therefore the noise, is the same for these devices, although the materials properties of the barriers differ.

The last part of our study of the noise behavior of resonant tunnel diodes involved the current dependence of the 1/*f* noise component both at different temperatures as well as for bias points with $0 < V < V_p$ and for bias points with $V > V_v$ for the two devices. The peak current occurs for $V = V_p$, the valley current occurs for $V = V_v$. In Fig. 5 we show the spectral intensity of the current fluctuations at 1 Hz versus the bias current measured at room temperature for the AlAs barrier device. The solid circles indicate bias points with $V < V_p$ and the solid triangles represents

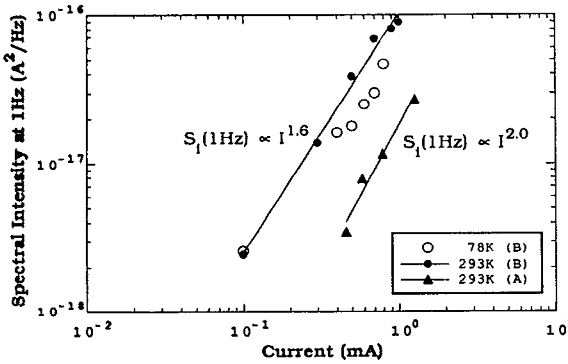

FIG. 5. Spectral intensity of the $1/f$ current fluctuations at $f = 1$ Hz vs the operating current for the AlAs barrier device. The solid circles represent the data taken at room temperature and for voltages smaller than the peak voltage. The solid triangles are room temperature data measured as the voltage was larger than the valley voltage. The open circles specify the data for $T = 78$ K and voltages smaller than the peak voltage. B labels before the peak, A labels after the valley.

the noise for the bias points for which $V > V_v$. In the domain where the current is due mostly to tunneling through the barriers the noise increases with the current and can be described by $I^{1.6}$. When the voltage is larger than V_v the current dependence of the noise is even stronger, close to I^2. The latter current dependence is expected for a resistor-like device. In this bias regime the current is due mostly to carriers that are excited over the barriers. It is important to observe that for the same current the device is noisier when biased at voltages smaller than the peak value.

When the temperature is lowered to 78 K the current dependence of the noise is less strong, the device noise tends to behave more like that of a regular diode, although the magnitude of the noise does not change very much (Fig. 5, open circles).

For the AlGaAs barrier device these measurements were repeated at temperatures of 400, 300, and 200 K (see Fig. 6). At the highest temperature we observe roughly the same behavior as we observed for the AlAs barrier device; the current dependence of the noise for the smaller voltages (circles) is less strong than it is for the voltages larger than V_v (triangles). However, the data for which $V < V_p$ show a knee close to the maximum current point. This is more dramatic for the 300 K data. The 200 K data do not show this behavior very strongly. A point to note is that as the temperature is lowered from 400 to 300 to 200 K, the noise in the after-valley-regime increases with respect to the noise when the device is biased in the before-peak regime. This is consistent with the remarks we made earlier that the $1/f$ noise in the before-peak regime is associated with the tunneling process whereas the $1/f$ noise in the after-valley regime is due to other processes and has a stronger temperature dependence.

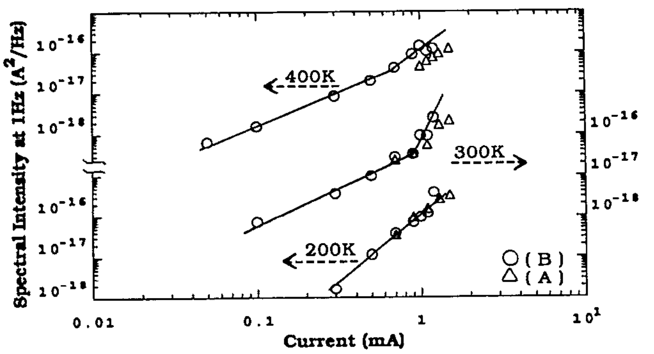

FIG. 6. Spectral intensity of the current fluctuations at $f = 1$ Hz of the AlGaAs barrier device vs the operating current at $T = 400$ K, $T = 300$ K, and $T = 200$ K. The circles represent data taken with voltages smaller than the peak voltage and the triangles show the data for applied voltages larger than the valley voltage.

In summary, measurements are presented here of the low-frequency noise of two types of resonant tunneling diodes, one with AlAs barriers and one type with $Al_{0.3}Ga_{0.7}As$ barriers. The temperature dependence of the $1/f$ noise is investigated when the devices are biased just below the peak in the current-voltage characteristic and found to be very small. Additionally, the magnitude of the $1/f$ noise is very similar in both device types. Both these observations are believed to be consistent with the main current component in this bias regime: the tunneling through the barriers.

Second, from generation-recombination noise measurements trap activation energies were extracted. We noticed five traps in the AlAs barrier device and two in the AlGaAs barrier device with activation energies equal to two of the traps we found in the AlAs barrier device. This seems to support the idea that the larger Al concentration in the barrier material introduces carrier traps in the device. Third, we compared the current dependence of the $1/f$ noise in the devices in the two biasing regimes: before the peak and after the valley. We observed a weaker current dependence of the magnitude of the $1/f$ noise when the device was biased in the tunneling regime than when it was biased in the field-assisted thermionic emission mode. The magnitude of the noise in the latter mode of operation is smaller consistent with expectations.

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