Capture dynamics of hot electrons on quantum dots in RTDs studied by noise measurement

S S Hees\textsuperscript{1,3,5}, B E Kardynal\textsuperscript{1,4}, A J Shields\textsuperscript{1}, I Farrer\textsuperscript{2} and D A Ritchie\textsuperscript{2}

\textsuperscript{1} Toshiba Research Europe Ltd, 260 Cambridge Science Park, Milton Road, Cambridge CB4 0WE, UK
\textsuperscript{2} Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge CB3 0HE, UK
E-mail: simon.hees@cantab.net

New Journal of Physics 10 (2008) 013027 (7pp)
Received 19 November 2007
Published 23 January 2008
Online at http://www.njp.org/
doi:10.1088/1367-2630/10/1/013027

Abstract. We investigate the noise in quantum dot resonant tunnelling diodes (QDRTDs), where the quantum dots (QDs) placed in the collector experience electric fields that vary in a wide range. The trapping/detrapping of electrons on the QDs dominated the measured electrical noise. The model that we derived for the noise explains the experimental data well. The QD capture cross-section is one to two orders of magnitude smaller than the physical size of the QDs due to the reduced probability of capturing a hot electron on the QD. The model is a powerful tool to design the noise characteristics of QDRTD single photon-detectors.

\textsuperscript{3} Present address: Carl Zeiss SMT Ltd, 511 Coldhams Lane, Cambridge CB1 3JS, UK.
\textsuperscript{4} Present address: COM Department, Technical University of Denmark, DK-2800 Kgs Lyngby, Denmark.
\textsuperscript{5} Author to whom any correspondence should be addressed.
Quantum dots (QDs) have found application in many devices [1]–[5]. As a result, the processes of the charge exchange between the QDs and the bulk of the device have received a great deal of attention. Most of these studies rely on techniques such as deep level transient spectroscopy (DLTS), photoluminescence (PL) or photo-current spectroscopy which yield the characteristic capture and escape times, confinement energies, escape mechanisms etc [6]. These experiments often require careful design of the devices and the results are not always easily translated into behaviour of real devices. In quantum dot resonant tunnelling diode (QDRTD) devices, for example, the QDs interact with hot electrons injected into the collector from the resonant level of the quantum well (QW) [1, 7]. In this paper, we show that we can use the noise of the QDRTDs measured in finite frequency bandwidth to study trapping/detrapping events in the RTDs under realistic operating conditions [1, 7]. For the experiments presented here a set of three QDRTDs with different QW widths are considered. The variation of the QW width allows for consideration of the electron escape and repopulation in different ranges of electric field.

QDRTDs are fabricated using wafers grown by molecular beam epitaxy. All wafers are grown on a semi-insulating GaAs substrate starting with a 200 nm GaAs buffer, followed by a 10 nm AlAs etch stop layer, a 380 nm graded n⁺ GaAs emitter layer, a 20 nm GaAs spacer layer, the RTD structure (comprised of a GaAs QW sandwiched between two symmetric AlAs barriers), a 2 nm GaAs spacer, a layer of self-assembled InAs QDs, a 100 nm GaAs absorber layer and finally a 50 nm n⁺ GaAs collector layer. Three wafers with the following RTD structure configurations are considered in this paper: 7 nm QW with 6 ML barriers, 10 nm QW with 5 ML barriers and 13 nm QW with 4 ML barriers.

Conditions during the growth of the wafers were the same for all wafers discussed here. The InAs QD layer and 10 nm GaAs cap were grown at a temperature of 505–510 °C with the remainder of the structure grown at 625–630 °C as measured with a kSA BandiT™ band edge thermometer. The growth rate for the InAs QDs was about 0.028 ML s⁻¹ while the rest of the structure was grown at conventional growth rates (1 ML s⁻¹ for GaAs and 0.5 ML s⁻¹ for AlAs).

The QD layer, nominally the same in all wafers, was characterized by means of PL spectroscopy. PL spectra were taken under excitation with an Ar⁺ laser at 488 nm where the laser is focussed on to the sample mounted in a continuous-flow cryostat with a base temperature of about 6 K. The spectra were acquired by Fourier transform infrared spectroscopy. An example of PL emission from one of the wafers is presented in figure 1(a). For the excitation power used to acquire this spectrum, the ground state \( E_0 \) and two excited states \( E_1 \) and \( E_2 \) can be identified. The graph also highlights the position of the emission peaks from the wetting layer and GaAs. Similar PL was observed for all the wafers presented in this paper.

Cross-wire QDRTDs with areas of less than ten square microns were fabricated from all wafers [8]. The geometry of the device consists of two intersecting wires, the collector and the emitter wire. Fabrication of the device starts with etching of the mesa through the collector and RTD structure down to the emitter layer. This is followed by the etching of the emitter contact using an etch that selectively etches GaAs over AlAs. During this etch, the collector mesa, which is protected from top and sides by the photo-resist and from the bottom by AlAs layers, is undercut to form a free-standing bridge—the collector wire. A resonant tunnelling structure remains at the intersection of the emitter contact and the free-standing collector wire.

The devices have been characterized at 4.8 K using a custom-built ac transimpedance amplifier with a cryogenic pre-amplifier input stage. The amplifier bandwidth is centered about 1.7 MHz with 3 dB points at 275 kHz and 5.28 MHz and maximum gain of 88.38 mV nA⁻¹ at
Figure 1. (a) An example of PL emission from one of the wafers. (b) A schematic of the QDRTD conduction band biased on resonance, indicating the escape and retrapping of electrons on QDs from the tunnelling current.

Figure 2. (a) The current measured with the low-pass amplifier. (b) The RMS noise–voltage measured on the output of the ac amplifier is an indication of the trapping/detrappping of charge in the QDRTD. The voltage bias is corrected for any series resistances of biasing resistors in series with the RTD.

1.6 MHz. The amplifier also provides a low-pass path with a 3 dB point at 1 kHz to allow for monitoring of the current in the QDRTD [9].

We have chosen the RMS noise on the output of the ac amplifier as a measure of detector noise. It was measured using a digital oscilloscope with the signal coupling to the instrument set to 1 MΩ and ac type with 1 GHz bandwidth. The RMS of the signal was averaged over a time window of 2 ms with a resolution of $50 \times 10^6$ samples s$^{-1}$. The resulting noise–voltage characteristics are shown in figure 2 together with the $I$–$V$s acquired on the low-pass amplifier. The bias, as marked in the graph, is applied to the emitter of the device while the collector is grounded. Varying the QW width allows for observation of the resonance in different ranges of electric field. Variations in $dI/dV$ and noise value between the devices are caused by different $dj/dV$ and different areas of the devices, but this is not relevant for further analysis.

The noise shown in figure 2(b) evolves differently with voltage in the three devices. The 13 nm QW QDRTD displays a gradual increase of noise as the tunnelling current increases,
Figure 3. (a) The capture times measured on the 13 nm QW RTD with small QDs (black squares) can be approximated by the model in equation (1). (b) Example of the switching time $\tau_s$, $\tau_{in}$ and $\tau_{out}$ for a set electron energy level in the dot. In the example shown here both $\tau_{in}$ and $\tau_{out}$ fall in the same range of times, it is possible that lower (higher) confinement yields $\tau_{out}$ vastly smaller (higher) than $\tau_{in}$.

while for both the 7 and 10 nm QW QDRTD the noise increases abruptly at the onset of tunnelling, then saturates and decreases at higher currents.

The noise in figure 2(b) increases significantly at resonance compared with zero-bias conditions. It has been shown that this increase of noise is caused by presence of dots in the collector of the RTD [7]. Here, we show that the observed increase of noise when the devices are biased with QDs located in the collector can be attributed to the electron trapping/detrapping events on the QDs. These switching events can be characterized by the switching rate $\tau_s^{-1}$. This switching rate $\tau_s^{-1}$ is a sum of the electron capture rate $\tau_{in}^{-1}$ and the electron escape rate $\tau_{out}^{-1}$, defined in figure 1(b).

The capture rate $\tau_{in}^{-1}$ of an electron into a QD can be expressed as

$$\tau_{in}^{-1} = \frac{j_{CE} \sigma}{e},$$

where $j_{CE}$ is the current density, $e$ the electron charge and $\sigma$ the capture cross-section. The capture cross-section $\sigma$ is the area of the QDs modified with the capture probability.

Experimentally the capture time in QDRTDs can be directly measured in samples with small dots and therefore low noise [7]. Figure 3(a) shows the average capture time measured with a QDRTD with a 13 nm QW and small QDs together with a fit using equation (1).
The model follows the experimental data well apart from the low electric field range where a dip in the capture time is found. This deviation is attributed to inelastic tunnelling in the QDRTD at these electric fields which is characterized by a different capture cross-section compared with the elastic tunnelling discussed here. This signature of inelastic tunnelling is a shoulder in the $I–V$ characteristics but since it occurs at very low currents it is not visible in the data shown here.

The escape of electrons from the QDs at low temperatures occurs predominantly via tunnelling across the triangular barrier (figure 1(b)) and is characterized by the tunnelling-out time $\tau_{\text{out}}$. This can be modelled

$$\tau_{\text{out}}^{-1} = \frac{eF}{4\sqrt{2m^*E_c}} \exp \left( -\frac{4\sqrt{2m^*E_c^{3/2}}}{3\epsilon h F} \right)$$

using equation (2) which describes the escape rate $\tau_{\text{out}}^{-1}$ from a Dirac potential well which depends on the electric field $F$, the effective mass $m^*$ and the electron confinement $E_c$ [6, 10, 11]. The tunnelling-out time $\tau_{\text{out}}$ is thus very sensitive to changes in $F$ and $E_c$ such that for a given $E_c \tau_{\text{out}}$ only falls within the amplifier bandwidth in a limited range of electric field. A very different dependence of $\tau_{\text{in}}$ and $\tau_{\text{out}}$ on the electric field means that in the low field range $\tau_{\text{in}}$ will be dominated by $\tau_{\text{out}}$ and the QDs are charged with electrons. As $\tau_{\text{out}}$ decreases sharply with field $\tau_{\text{in}}$ is equal to $\tau_{\text{in}}$ and the QDs are empty of electrons most of the time. This is illustrated in figure 3(b).

A trapping/detrapping event with a characteristic time constant $\tau_s$ is represented by a Lorentzian power spectrum $S_1 = A\tau_s(1+(\tau_s\omega)^2)^{-1}$, where $\omega = 2\pi f$, $f$ is the frequency and $A$ the amplitude at $f = 0$ [12]. The spectral voltage density of the noise at the amplifier output can be expressed as the spectral current density of the RTD multiplied by the gain frequency spectrum $G(\omega)$. The integral over the bandwidth BW of the amplifier of such a power spectrum yields the noise power of a single trapping/detrapping event. The square root of the sum of the individual switching events $E_c$ yields the RMS noise voltage at the output. This is expressed in equation (3).

$$V_{\text{RMS}} \propto \sqrt{\sum_{E_c} \int_{\text{BW}} G(\omega)^2 \frac{\tau_s}{(1+(\tau_s\omega)^2)} \text{d}\omega}$$

The experimental noise data shown in figure 2 can be fitted with the model described above with the main fitting parameter $\sigma$. $\tau_{\text{in}}$ was calculated from the $I–V$ data for each of the devices and $\tau_{\text{out}}$ is determined over a range of $E_c$. For all fitting $E_c$ was varied from 20 to 200 meV in steps of 20 meV. It was verified that using smaller steps in $E_c$ did not affect the result. In the limit of higher $E_c$ the range is determined by the electric field in the device. For the electric fields in the devices discussed here, strongly confined states, with $E_c$ higher than 220 meV, do not play a role as the field is not strong enough to cause tunnelling through the triangular barrier. For low $E_c$ it can be seen from PL spectroscopy shown in figure 1(a) that electron states are visible nearly up to the wetting layer. To include all states that electrons can potentially tunnel from, a low limit of 20 meV was selected. The same range of $E_c$ was used for all fitting described here. Figure 4 shows the resulting curves.

Data for all three RTDs are shown together with noise calculated for a range of $\sigma$ (as specified in the legend). The figure shows clearly the evolution of the noise with increasing capture probability, i.e. increasing $\sigma$. In order to allow for comparison of the shape to the
Figure 4. The trapping/detrapping noise is modelled for a range of $\sigma$ and the resulting data is compared to the experimentally measured noise. The subfigures (a), (b) and (c) present the data for the 13, 10 and 7 nm QW QDRTDs, respectively.

Experimental data the modelled data had to be scaled through multiplication by a constant. This scaling arises from the fact that the noise model does not describe the amplitude of the current fluctuations in $I_{RTD}$ caused by the trapping/detrappping events but their frequency. Another factor that affects the scaling is the uncertainty in device area. The scaling factors were chosen for each device individually but kept constant for all chosen $\sigma$. Fitting was performed to match the shape of the noise curve only (e.g. position of the maximum in noise) and for each noise curve only a small range of $\sigma$ exists where the shape can be reproduced. The scaling of the data does not change the shape of the noise curve nor does it affect the position of the noise maximum in terms of electric field, hence the value of $\sigma$ yielding the best fit is unique.

Figure 4(a) plots the data for the 13 nm QW QDRTD and the best fits are obtained in the range of $\sigma = 1.5$ to $3 \times 10^{-19}$ m$^2$. It can be seen that with increasing $\sigma$ the noise starts to flatten off at higher electric field as the noise becomes limited by the capture time. Figure 4(b) shows corresponding data for the 10 nm QW QDRTD where the best fits are achieved for $\sigma = 1.0$ to $1.4 \times 10^{-18}$ m$^2$. The noise decreases after an initial rise which can be attributed to the increase of the switching rate shifting the noise out of the bandwidth. The increase at high electric field in the experimental data is attributed to the bistabilities observed in the negative differential resistance region and not part of the model. The data for the 7 nm QW QDRTD is shown in figure 4(c) where the fit is best for $\sigma$ about $3 \times 10^{-19}$ m$^2$. The deviation of the model from the experimentally measured noise is caused by the presence of non-resonant currents, which would lead to wrong values of $\tau_{in}$ at these current levels.

New Journal of Physics 10 (2008) 013027 (http://www.njp.org/)
For the fits it was assumed that $\sigma$ is constant across the range of electric fields for a given QW width thus ignoring potential dependence of sigma on the charge state of the QDs. The values of $\sigma$ found for the 7 and 13 nm QW are very similar while $\sigma$ of the 10 nm QW is a factor of about 3 to 8 larger. The values of $\sigma$ determined here are several orders of magnitude smaller than the values of $10^{-14} - 10^{-15}$ m$^2$ determined for QDs in DLTS measurements [13].

The electrons are injected into the collector of the QDRTD at the energy of the resonant state of the QW. In order to be captured into a QD an electron has to lose a considerable amount of energy (at least 35 meV) over the 2 nm distance from the collector barrier to the QD layer. This process most likely involves the emission of longitudinal-optical (LO)-phonons since this is the most efficient relaxation process at low temperature in GaAs [14]. The energy dissipation rate will limit the capture cross-section of the dot. Another factor that will modify the capture cross-section is the charge state of the QD with negative charge reducing $\sigma$ due to electrostatic repulsion.

In conclusion, we have shown how the noise in a QDRTD due to trapping/detrapping events on the QDs can be measured and modelled. The model can be used to fit the experimental noise data with $\sigma$ as a fitting parameter. The values of $\sigma$ that gave the best fit are several orders of magnitude smaller than determined in DLTS experiments. We attribute this difference to insufficient phonon emission rate by hot electrons in the QDRTDs. Variation of the electric field and the current density in the structure can be used as a means to control the trapping/detrapping rates and thus the occupation of the QDs and the noise in the QDRTD single photon detectors.

Acknowledgments

We thank Ken Cooper for help with device fabrication. SSH thanks the EPSRC, Toshiba Research Europe Ltd, the Cambridge European Trust and the Semiconductor Physics Research Group for funding.

References

[1] Blakesley J C, See P, Shields A J, Kardynal B E, Atkinson P, Farrer I and Ritchie D A 2005 Phys. Rev. Lett. 94 067401
[2] Stevenson R M, Young R J, Atkinson P, Cooper K, Ritchie D A and Shields A J 2006 Nature 439 179–82
[3] Ward M B, Karimov O Z, Uniti D C, Yuan Z L, See P, Gevaux D G, Shields A J, Atkinson P and Ritchie D A 2005 Appl. Phys. Lett. 86 201111
[4] Park G, Shchekin O B, Huffaker D L and Deppe D G 2000 IEEE Photon. Technol. Lett. 13 230
[5] Liu H C, Gao M, McCaffrey J, Wasilewski Z R and Fafard S 2001 Appl. Phys. Lett. 78 79
[6] Schulz S, Schramm A, Heyn C and Hansen W 2006 Phys. Rev. B 74 033311
[7] Hees S S, Kardynal B E, See P, Shields A J, Farrer I and Ritchie D A 2006 Appl. Phys. Lett. 89 153510
[8] Wang J, Beton P H, Mori N, Buhmann H, Mansouri L, Eaves L, Main P C, Foster T J and Henini M 1994 Appl. Phys. Lett. 65 1124
[9] Kardynal B E, Shields A J, Beattie N S, Farrer I, Cooper K and Ritchie D A 2004 Appl. Phys. Lett. 84 419–21
[10] Vincent G, Chantre A and Bois D 1979 J. Appl. Phys. 50 5484–7
[11] Kapteyn C M A, Heinrichsdorff F, Stier O, Heitz R, Grundmann M, Zakharov N D, Bimberg D and Werner P 1999 Phys. Rev. B 60 14265–8
[12] Tsormpatzoglou A, Hasrat N A, Tassis D H, Dimitriadis C A, Kamarinos G, Frigeri P, Franchi S, Gombia E and Mosca R 2005 Appl. Phys. Lett. 87 163109
[13] Engstrom O, Kaniewska M, Fu Y, Piscator J and Malmkvist M 2004 Appl. Phys. Lett. 85 2908–10
[14] Heilblum M, Galbi D and Weckwerth M 1989 Phys. Rev. Lett. 62 1057–60

New Journal of Physics 10 (2008) 013027 (http://www.njp.org/)