Current noise suppression in the tunneling regime of quantum dot infrared photodetectors

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Overview

The investigation of current noise is a crucial issue both for the improvement and for the understanding of the microscopic quantum processes underlying quantum IR devices.

Nevertheless, to date only investigations at temperature higher than $T = 77K$ (the realm of thermally activated processes) have been reported in QWIPs and QDIPs.

The question addressed in this work is:
What about current noise in the tunneling regime of quantum dot infrared photodetectors?

Generation-recombination (g-r) noise model in IR photodetectors [1] [2] [3]

The low-frequency current noise power spectral density $S_I(f)$ is usually estimated within the generation-recombination (g-r) model:

$$S_I(f) = 4eIg_n \ ,$$

where I is the average current, e the elementary charge and g_n the noise gain defined as:

$$g_n = \frac{\tau_r}{\tau_d} = \frac{v_d}{L}\tau_r \ ,$$

[1] A. Carbone and P. Mazzetti, Appl. Phys. Lett. **70**, 28 (1997).
[2] A. Carbone, P. Mazzetti and F.Rossi, Appl. Phys. Lett. **78**, 2518 (2001).
[3] A. Carbone, R. Introzzi and H.C. Liu, Appl. Phys. Lett. **82**, 4292 (2003).

Noise gain with thermally activated processes

$$g_n = \frac{\tau_r}{\tau_d} = \frac{v_d}{L}\tau_r$$

v_d is the drift velocity :

$$v_d = \mu F \left[1 + \left(\frac{\mu F}{v_s}\right)^2\right]^{-1/2}$$

where μ is the mobility, F the applied electric field, v_s the saturation velocity.
τ_r is independent of the applied field F.

The noise gain g_n increases with F as expected from v_d.

I-V characteristics at $T = 77K$

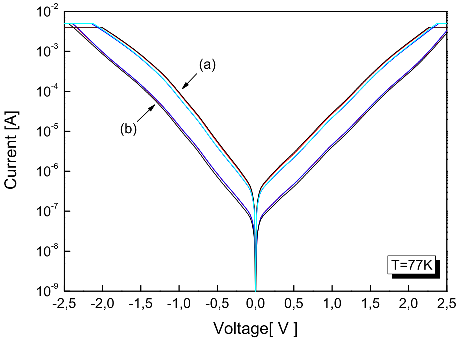


Figure: $I - V$ characteristics of InAs/GaAs quantum dot infrared photodetectors at $T = 77K$ in dark conditions.

Current noise power spectra at $T = 77K$

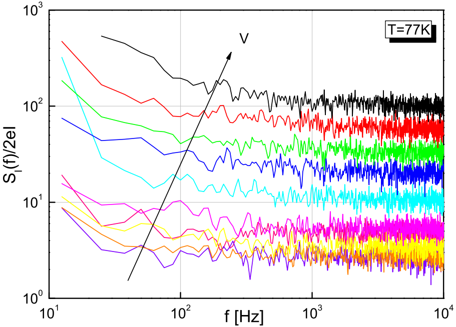


Figure: Current noise spectra of InAs/GaAs quantum dot infrared photodetectors at $T = 77K$ in dark conditions.

I-V characteristics and current noise spectra confirm a transport mechanism where thermally activated processes

I-V characteristics at $T = 4.1K$ - Low photoresponsivity

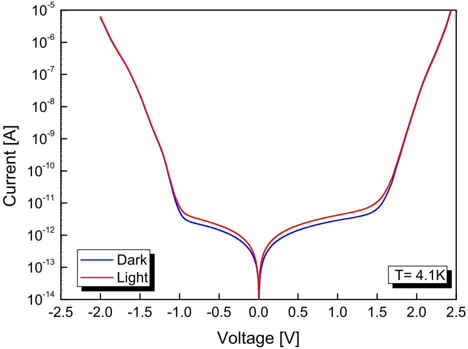


Figure: Dark (blue) and photo (red) $I - V$ characteristics of InAs/GaAs quantum dot infrared photodetectors at $4.1K$.

I-V characteristics at $T = 4.1K$ - High photoresponsivity

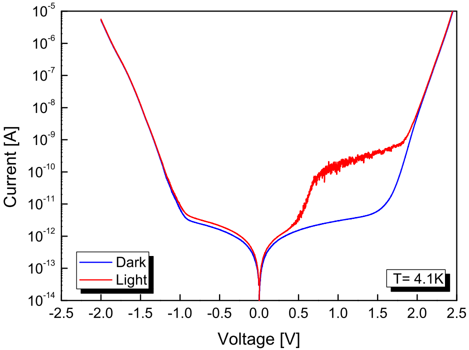
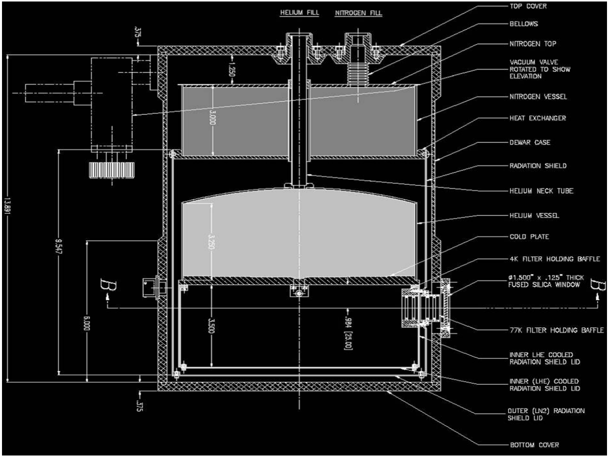
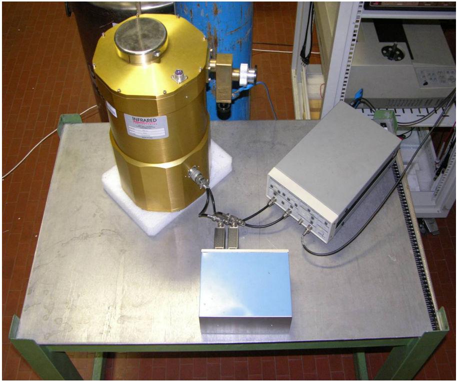


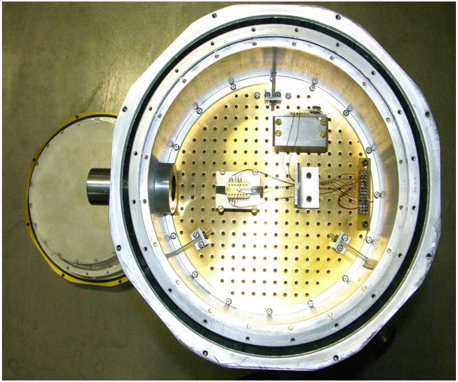
Figure: Dark (blue) and photo (red) $I - V$ characteristics of InAs/GaAs quantum dot infrared photodetectors at $4.1K$.

Scheme of the double vessel steady-bath cryostat.



Noise measurement set-up - NOISELAB - Politecnico di Torino





Dark-Current noise spectra at $T = 4.1K$

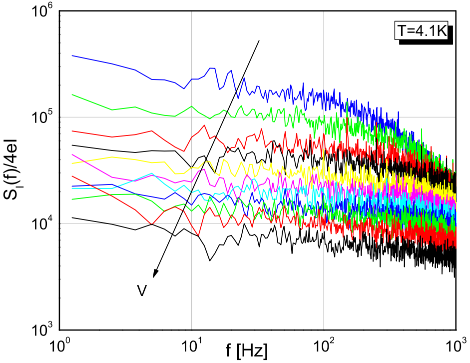


Figure: Current noise spectra for quantum dot infrared photodetectors at $T = 4.1K$ in dark conditions. The curves refer to different voltages ranging from $0.5V$ to $1.5V$ with step $0.1V$.

Photo-Current noise spectra at $T = 4.1K$

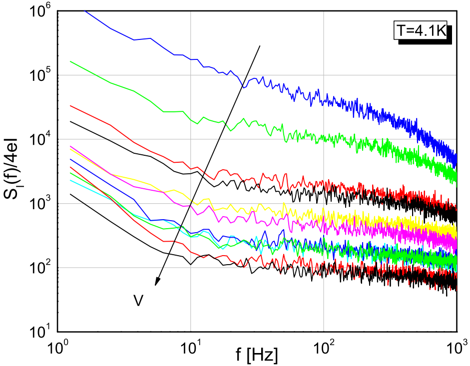


Figure: Current noise spectra for quantum dot infrared photodetectors at $T = 4.1K$ under irradiation. The curves refer to different voltages ranging from $0.5V$ to $1.5V$ with step $0.1V$.

Dark and Photo Noise Gain at $T = 4.1K$

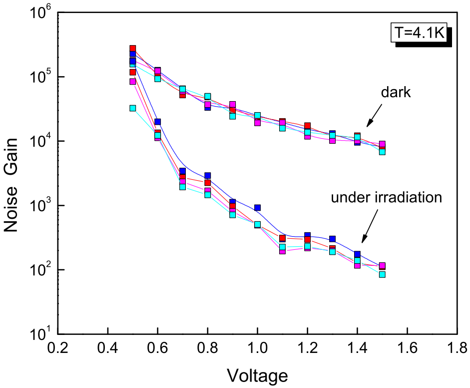


Figure: Noise gain vs. voltage at $T = 4.1K$ in dark conditions and under irradiation.

Recombination time τ_r [4] [5] [6].

The recombination time τ_r for a random distribution and spherical symmetric trapping rates:

$$\frac{1}{\tau_r} = N_t(4\pi D R_t)\left\{1 - \left[\frac{D}{V_t R_t^2}\tanh\left(\frac{V_t R_t^2}{D}\right)\right]^{1/2}\right\} \tag{1}$$

where N_t is the density of quantum dots (traps), with effective radius R_t , capture rate V_t, diffusivity $D = \mu kT/e$

[4] H. Lim, B. Movaghar, S. Tsao, M. Taguchi, W. Zhang, A.A. Quivy and M. Razeghi, Phys. Rev. B **74**, 205321 (2006).

[5] B. Movaghar, S. Tsao, S. Abdollahi Pour, T. Yamanaka, and M. Razeghi, Phys. Rev. B **78**, 115320 (2008).

[6] K.-K. Ghosh, L.H.Zhao and D.L. Huber, Phys. Rev. B **25**, 3851 (1982)

Mobility μ

The mobility μ:

$$\mu = \mu_o \frac{\left(\frac{e^{-E_t/kT} - e^{\varsigma E_t^{3/2}/eFa} e^{\varsigma E_t^{1/2}} e^{eFa/kT}}{1 - e^{\varsigma E_t^{1/2}} e^{eFa/kT}} \right)}{\left(x + \frac{e^{-E_t/kT} - e^{\varsigma E_t^{3/2}/eFa} e^{\varsigma E_t^{1/2}} e^{eFa/kT}}{1 - e^{\varsigma E_t^{1/2}} e^{eFa/kT}} \right)} \tag{2}$$

E_t is the trap energy, a the lattice constant and $\varsigma = a(2m_e^*/\hbar^2)^{1/2}$. The numerator is the escape rate out of the dot.

The escape rate changes from tunnel-like to thermally activated as the temperature increases at the point $\varsigma(E_t)^{1/2} = eFa/kT$.

Recombination time limited regime

Recombination time limited regime ($D/(V_t R_t^2) \gg 1$):

$$\frac{1}{\tau_r} = N_t 4\pi V_t R_t^3 \, .$$

The recombination rate is independent of the electric field. The charge carrier transport occurs by drift. This condition holds at high temperature.

Diffusion limited regime

Diffusion limited regime $(D/(V_t R_t^2) \ll 1)$:

$$\frac{1}{\tau_r} = N_t 4\pi D R_t \, .$$

In the diffusive limit, the charges can be considered to *diffuse* between collisions with constant velocity in the direction of the applied field rather than drifting. This condition holds at low temperature.

The previous two limits correspond to two limits of the noise gain:

1. High temperature: τ_r is independent of the applied field, thus the gain increases as a power of the electric field through v_d:

$$g_n = \frac{\tau_r}{\tau_d} = \tau_r \frac{v_d}{L} \sim I^\gamma$$

   with $\gamma \geq 1$.

2. Low temperature: the transport is diffusive, thus the gain is a function of the electric field only through the recombination time τ_r:

$$g_n \sim \tau_r \sim I^\gamma$$

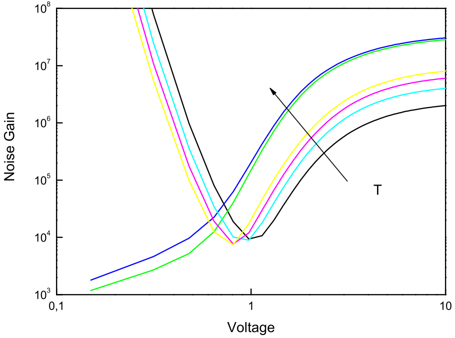
   with the possibility of $\gamma \leq 1$.

Devices parameters [7]

	2505	2504	2506	2174	2203
QD density ($10^{10} cm^{-2}$)	0.3	0.3	0.3	0.5	0.5
QD height (nm)	2.5	2.5	2.5	2.5	2.5
QD diameter (nm)	18	18	18	18	18
Doping ($10^{10} cm^{-2}$)	1.5	2	3.5	1	3.5
Electrons per QD	5	7	12	2	7
$\Delta E = E_{WL} - E_{QD}$ (meV)	140	60	40	210	60
E_a(meV)	105	$25 \div 55$	$5 \div 15$	130	60

[7] J.Y.Duboz, H.C. Liu , Z.R. Wasilewski, M.Byloss, R. Dudek J. Appl. Phys., **93**, 1320 (2003)

Theoretical noise gain calculated at different temperatures



In particular at low bias and temperature, the noise gain is a nonmonotonic function of voltage and a decreasing behavior of the gain is found in agreement with the experimental findings.

Conclusions

We have reported first data on current noise measured in the tunneling regime of QDIPs in the dark and under irradiation.

We have found an interesting noise suppression mechanisms acting both in dark and under irradiated condition.

The noise gain changes from tunnel-like (decreasing with I) to thermally activated (incresing with I) as the temperature increases.

These findings may provide useful insights for the development and optimal operation of quantum IR devices.