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Photo and dark current noise in self-assembled quantum dot infrared photodetectors

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ABSTRACT

Current noise is investigated in InAs/GaAs self-assembled quantum dot infrared photodetectors in the dark and under irradiation at $T = 4.2$ K. At low temperature, the noise is consistent with a mechanism of fluctuations driven by the electric field, related to field- and photon-assisted tunneling rather than trapping–detrapping of charge carriers from the quantum dots. In particular, a strong noise suppression effect determines the decrease of the fluctuation intensity as the voltage increases in the negative differential photoconductivity region of the *I–V* characteristics. The noise suppression mechanism acts in the dark and under irradiation. The noise intensity decreases consistently with the occurrence of the nonlinear differential photoconductivity effect.

1. Introduction

Quantum dot infrared photodetectors (QDIPs) are zero-dimensional structures, with three-dimensional charge confinement, evolved from the Quantum Well Infrared Photodetectors (QWIPs) technology. Quantum dot infrared photodetectors have attracted more and more attention in the last years since they are expected to reach higher gains and exhibit lower dark current than QWIPs. Furthermore they are sensitive to normally incident infrared radiation not requiring special optical coupling [1–10].

The detection mechanism is based on the intersubband photoexcitation of the charge carriers from confined states in the dots to the continuum. Under the assumption that the elementary thermal or photoexcited current events in the quantum dots are statistically independent, the low-frequency current noise power spectrum $S_I(0)$ can be estimated within the generation–recombination (g–r) model:

$$S_I(0) = 4eIg_n, \tag{1}$$

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

$$g_n = \frac{\tau_r}{\tau_d}, \tag{2}$$

where τ_r and τ_d are, respectively, the average recombination time and the drift time. The noise gain g_n is usually related to the capture probability p_c and to the number N of the quantum wells or dots. During the past decades many models have been proposed for the dark and photo current noise in photodetectors [10–18]. Eq. (1) holds in the range of electric fields and temperatures where statistical correlations between the elementary capture–release events from quantum dots are negligible. In the recent years, current noise measurements have been reported in self-assembled quantum dot infrared photodetectors in dark conditions at temperatures $T \geqslant 77$ K [16,17]. The noise power spectral densities are consistent with a generation–recombination process related to charge carriers thermally excited from confined to continuum states in the quantum dot layers. The shape of the power spectrum is Lorentzian and g_n increases as a power of the current $I, g_n = I^\gamma$, with $\gamma \geqslant 1$.

The study of current fluctuations in the dark and in the presence of irradiation at low temperature, in the presence of strongly correlated processes can add further insights in the several new physical phenomena observed in these devices. Here, we report on a study of current noise in self-assembled quantum dots at helium temperature ($T = 4.2$ K) in dark conditions and under irradiation. We find that the noise gain g_n varies as I^γ with $\gamma < 0$. The decreasing behavior of g_n with I is found both in the dark and under irradiation. The decrease of g_n with I cannot be accounted by a generation–recombination noise model where the noise gain depends on the applied electric field only through the drift time τ_d. The noise behavior is consistent with current fluctuations mostly driven by the electric

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field, related to tunneling rather than emission–capture of charge carriers from the quantum dots. The exponent $\gamma < 0$ indicates a noise suppression mechanism of Coulombian origin operating in the quantum dots in the voltage range where the negative differential photoconductivity is observed, determining the overall behavior of the average current and its fluctuations.

2. Experiments

The devices are InAs/GaAs self-assembled quantum dots, produced by the Stranski–Krastanov technique, separated by thick barriers to suppress the dark current between adjacent layers. The dot size and shape determine the electronic shell structure of the bound states. The InAs dots on GaAs substrate are lens-shaped with diameter of about 18 nm and height of about 2.5 nm. This implies a stronger confinement in the growth direction compared to the in-plane one, leading to several energy levels in each dot. The intersublevel energies are suitable for long wavelength excitations with a broader infrared spectra compared to QWIPs [7–9]. All layers have been grown on a semi-insulating GaAs substrate: an undoped 300 nm GaAs buffer layer, a 760 nm n^+ GaAs bottom contact layer, a 5 nm GaAs spacer layer, 50 repeats of self-assembled InAs QD layers separated by 30 nm GaAs barriers and a 400 nm n^+ GaAs top contact layer. The barriers are delta-doped with Silicon to 1.5×10^{10} cm^{-2}. The average QD electron density was estimated as ranging from 5 to 12 electrons per dot. Top and bottom contacts were Silicon doped to 1.2×10^{18} cm^{-3}, covered with Ni/Ge/Au and annealed. Wet chemical etching was used to define the geometry of the mesa devices. The section areas considered in this work are 240×240 μm^2 and 400×400 μm^2.

Photoresponse and current noise measurements have been performed in vacuum, in a steady-bath cryostat (see Fig. 1). The cryostat uses a double vessel and a double thermal shield on the cold plate area. The steady-bath cryostat allows to reduce disturbances due to boiling and convective motions of cryogenic liquids and to electrical and mechanical vibrations. A black-body source mounted into the vacuum chamber, with parabolic reflector and baffles, couples the light on the quantum dot infrared photodetectors. Thus the devices could be exposed directly to the IR source ($\sim$10 mW mm^{-2}) in high vacuum conditions (10^{-7} mbar).

The voltage noise measurements are based on a balanced circuit at the input of a low noise amplifier (Stanford Research SR560). The bias is supplied by a low pass filtered dry cell pack. The noise power spectra were obtained as averages of single power spectral densities by a dual channel dynamic spectrum analyzer, (Hewlett-Packard 3562A) via a GPIB interface. The *I–V* curves are obtained by a source-measure unit (Keithley 236).

3. Results

In Fig. 2, the current–voltage characteristics are shown at $T = 4.2$ K for dark (blue)[1] and irradiated (red) conditions. One can notice that different charge transport regime takes place at the two different temperatures as can be deduced by comparing the two plots. The curves clearly exhibit the typical features of quantum dots at low temperature such as asymmetry and negative differential photoconductivity. The current–voltage characteristics refer to nominally identical devices, however a different photoresponse is observed, very likely related to the variability of the self-assembled quantum dot structures [8,9]. The QDIPs exhibit a peak of responsivity, $\mathscr{R}_i = I_\phi/(h\nu\phi)$, in the flat region of the characteristics.

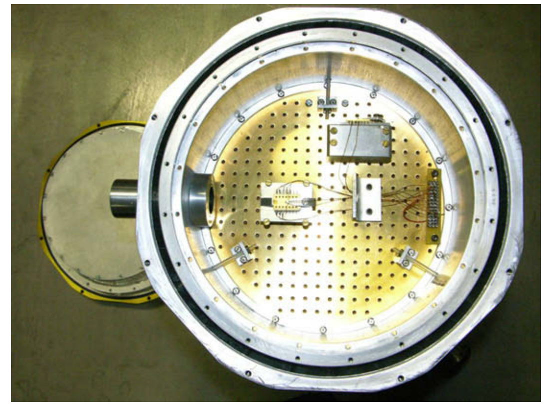

Fig. 1. Inside view of the double vessel cryostat for the photocurrent noise measurements. The QDIP sample is placed in the center of the cold plate. The optical window is located in front of the QDIP sample on the left side of the cold chamber.

In Fig. 3, the current noise power spectra are plotted at $T = 4.2$ K under irradiation. The voltage varies from 0.5 V to 1.5 V with step 0.1 V. The values of the relative power spectra $S_I(f)$ decrease with voltage. The g_n dependence on the inverse of the average current indicates that a noise suppression mechanism of Coulombian origin acts in the presence of infrared radiation. Therefore, the simple generation–recombination model, holding for thermally activated trapping–detrapping processes from the quantum dots, is ruled out at low temperature.

In Fig. 4, the noise gain g_n is plotted for dark and illuminated conditions. The noise gain decreases with *I*. We remark that this behavior is opposed to what is observed at high temperature, where the fluctuations are mainly related to thermally excited capture–emission processes from the quantum dots.

4. Discussion

Here, we will discuss the behavior of noise gain observed in the high responsivity region of the *I–V* characteristics at temperature $T = 4.2$ K. We recall Eq. (2):

$$g_n = \frac{\tau_r}{\tau_d} = \frac{v_d}{L}\tau_r \tag{3}$$

where v_d is the drift velocity defined as:

$$v_d = \mu F\left[1 + \left(\frac{\mu F}{v_s}\right)^2\right]^{-1/2} \tag{4}$$

where μ is the mobility, F the applied electric field, v_s the saturation velocity. The recombination time τ_r for a random distribution and spherical symmetric trapping rates has been calculated in the average matrix approximation in [19–22]:

$$\frac{1}{\tau_r} = N_t(4\pi D R_t)\left\{1 - \left[\frac{D}{V_t R_t^2}\tanh\left(\frac{V_t R_t^2}{D}\right)\right]^{1/2}\right\} \tag{5}$$

where N_t is the density of quantum dots (traps), with effective radius R_t and capture rate V_t, D is the band diffusivity.

Eq. (5) has two relevant limits:

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

$$\frac{1}{\tau_r} = N_t 4\pi V_t R_t^3. \tag{6}$$

The recombination rate is independent of the electric field. The charge carrier transport occurs by drift with velocity given by Eq. (4). This condition holds at high temperature.

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.

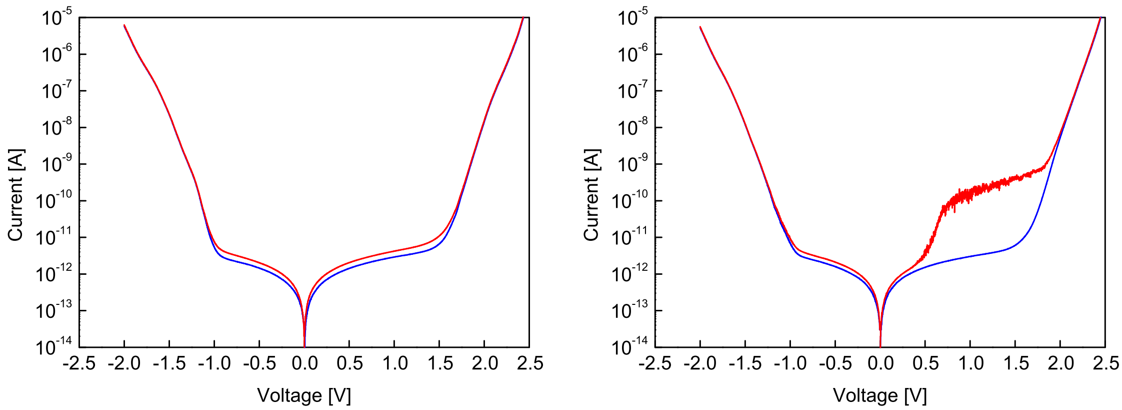

Fig. 2. Dark (blue) and photo (red) I–V characteristics of InAs/GaAs quantum dot infrared photodetectors at $T = 4.2$ K for nominally identical InAs/GaAs quantum dots. (For interpretation of the references to color in this figure legend the reader is referred to the web version of the article.s)

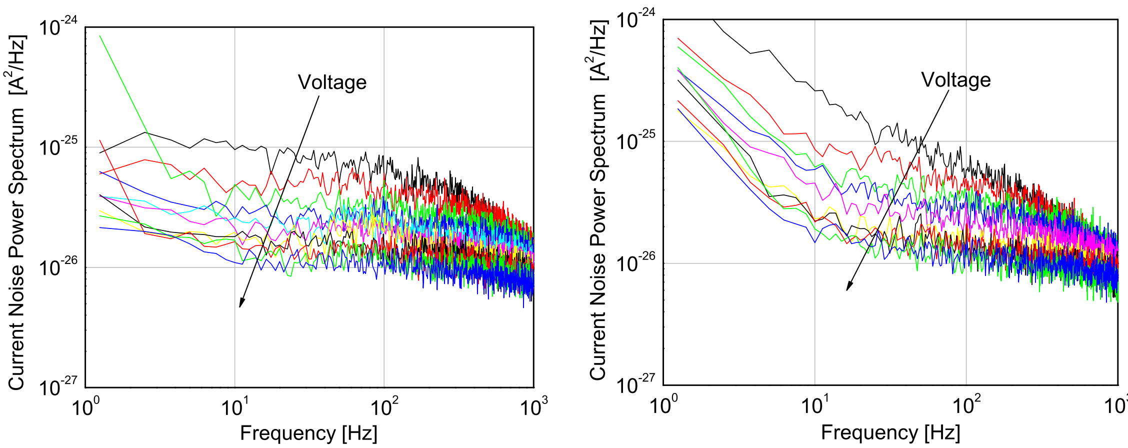

Fig. 3. Current noise spectra for quantum dot infrared photodetectors at $T = 4.2$ K under irradiation. The curves refer to different voltages ranging from 0.5 V to 1.5 V with step 0.1 V.

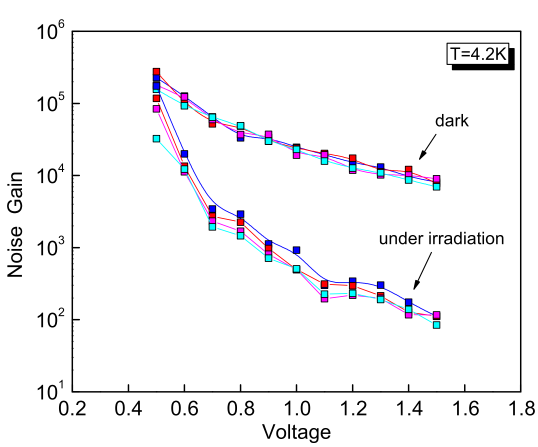

Fig. 4. Noise gain vs. voltage at $T = 4.2$ K in dark conditions and under irradiation.

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

$$\frac{1}{\tau_r} = N_t 4\pi D R_t. \qquad (7)$$

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 items (*a*) and (*b*) correspond, respectively, to two following limits of the noise gain:

(*c*) High temperature: τ_r is independent of the applied field, thus the gain increases as a power of the electric field through v_d:

$$g_n = \frac{\tau_r}{\tau_d} = \tau_r \frac{v_d}{L} \sim I^\gamma \qquad (8)$$

with $\gamma \geqslant 1$.

(*d*) Low temperature: the transport is diffusive, thus the gain is a function of the electric field only through the recombination time τ_r:

$$g_n \sim \tau_r \sim I^\gamma \qquad (9)$$

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

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