Photocurrent Noise in Quantum Dot Infrared Photodetectors

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Abstract.
Low-frequency current noise and current-voltage (I-V) characteristics have been studied in InAs/GaAs self-assembled Quantum Dot Infrared Photodetectors in dark conditions and under illumination, at $T = 77K$ and $T = 5K$. The noise behavior is consistent with a generation-recombination fluctuation process mainly related to thermally excited charge carriers at $T = 77K$. At $T = 5K$ the current noise is consistent with a mechanism of fluctuations driven by the electric field, related to tunneling rather than emission-capture of charge carriers from the Quantum Dots. A very effective noise suppression mechanism, related to the tunneling regime, determines a decrease of fluctuation intensity as a function of the voltage. At $T = 5K$, an interesting behavior is observed in the current-voltage and noise power spectra for some of nominally identical QDIP structures in the presence of irradiation. Some devices indeed exhibit (i) a very high photoresponse and (ii) a $1/f$-shaped noise spectrum at low frequencies. The noise suppression mechanism still acts in the presence of radiation, thus reducing the noise intensity proportionally to the photocurrent intensity.

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Quantum Dot Infrared Photodetectors (QDIPs) are zero dimensional structures evolved from the Quantum Well Infrared Photodetectors (QWIPs) technology, widely studied in the past decades. QDIPs have attracted more and more attention in the last years since they are expected to reach higher gains and exhibit lower dark current. Furthermore they are sensitive to normally incident infrared radiation not requiring particular optical coupling. QDIPs are similar to QWIPs but the charge confinement is 3-D. The QDIP detection mechanism is based on the intersubband photoexcitation of the charge carriers from confined states in the dots to the continuum [1, 2, 3].

Current noise and current-voltage (I-V) characteristics have been measured in InAs/GaAs self-assembled QDIPs in dark conditions and under illumination, at $T = 77K$ and $T = 5K$. The noise power spectral densities at $77K$ is consistent with a generation-recombination (g-r) fluctuation process related to charge carriers thermally excited from confined to continuum states in the QD layers. The shape of the power spectrum is Lorentzian. The noise gain $g_n = S_I/4eI$ varies as a linear power of I. At $T = 5K$, the noise gain $g_n = S_I/4eI$ varies as I^γ with $\gamma < 1$ in the region of tunneling. This behavior is consistent with current fluctuations driven by the electric field, related to a transport process ruled by tunneling rather than by emission-capture of charge carriers from the Quantum Dots. Since $\gamma < 1$, a noise suppression mechanism of coulombian origin, determines the overall behavior of the average current and its fluctuations.

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At $T = 5K$, a complicated behavior is exhibited by the I-V and the noise power spectra in the presence of irradiation for some of nominally identical QDIP structures. Some devices indeed exhibit (i) very high photoresponse and (ii) $1/f$ noise at low frequencies in the presence of infrared radiation. This behavior might be related to the inhomogeneous dopant distribution in the interdot region.

EXPERIMENTAL DETAILS

The devices are made of quantum dot separated by barrier layers, produced by the Stranski-Krastanov technique. The dots are self-assembled and the barriers are thick in order 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 disk-shaped with diameter of about $18nm$ and thickness of about $2.5nm$. This implies a stronger confinement in the growth direction compared to the in-plane one, leading to several energy levels in each dot leading to a broader infrared response compared to QWIPs [1, 2]. Their intersublevel energies are suitable for long wavelength excitations. All layers have been grown on a semi-insulating GaAs substrate: an undoped $300nm$ GaAs buffer layer, a $760nm$ n^+ GaAs bottom contact layer, a $5nm$ GaAs spacer layer, 50 repeats of self-assembled InAs QD layers separated by $30nm$ GaAs barriers and a $400nm$ n^+ GaAs top contact layer. The doping level for QD layers is $1.5 \times 10^{10} cm^{-2}$. The average QD electron density was estimated as 5 electrons per dot. Top and bottom contacts were Silicon doped to $1.2 \times 10^{18} cm^{-3}$, covered with Ni/Ge/Au and annealed. Wet chemical etching was used to define the geometry of the mesa devices with a section area of $240 \times 240 \mu m^2$.

Photoresponse and current noise measurements have been performed in an in-vacuum steady-bath cryostat to reduce all kind of mechanical disturbances, due to boiling and convective motions of cryogenic liquids. The cryostat uses a double vessel and a double thermal shield on the cold plate area. A black-body source (i.e. a white-hot filament) mounted inside the vacuum chamber was used rather than LASER or LED affected by additional noise. A parabolic reflector and baffles served to spot the light on the QDIPs. Thus devices could be exposed directly to the IR source in high vacuum conditions ($10^{-7} mbar$). Appropriate sample-holders properly shone the devices on their 45^o polished facet with polarized radiation.

The basic scheme of voltage noise measurements is based on a balanced circuit at the input of a Stanford Research 560 low noise amplifier. The bias was supplied by a low pass filtered dry cell pack. The noise power spectra were obtained as 50 averages of single power spectral densities by a dynamic spectrum analyzer, Hewlett-Packard 3562A via a GPIB interface. The QDIP differential resistance was calculated from the I-V curves measured by a source-measure unit Keithley 236 [4, 5].

RESULTS AND DISCUSSION

The I-V characteristics at $5K$ both in dark (dotted line) and under radiation (solid line) are shown in figure 1 (a) and (b) for two nominally identical devices. A different shape

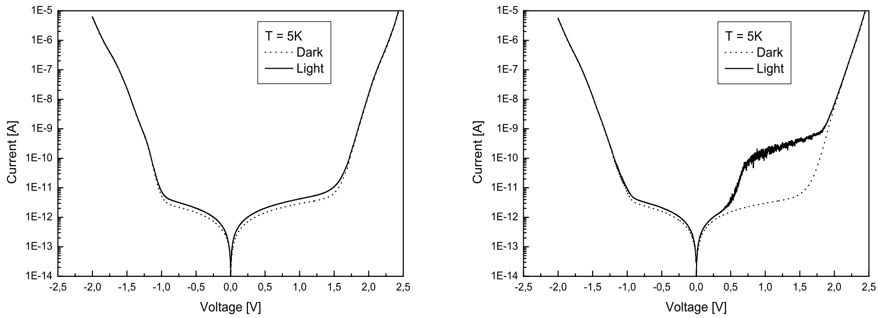

FIGURE 1. Typical behavior of dark (dotted) and photo- (solid) I-V characteristics of InAs/GaAs QDIPs at $5K$.

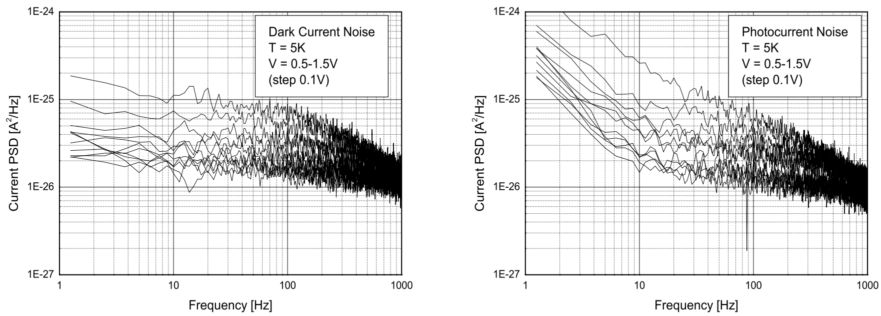

FIGURE 2. Dark (a) and photocurrent (b) noise spectra at $T = 5K$ for the same QDIP of figure 1b. The voltage varies from $0.5V$ to $1.5V$ from top to bottom with step $0.1V$. The roll-off above $100Hz$ is due to the capacitances at the amplifier input (about $25pF$) and along the coaxial cables.

of the photoresponse is observed by comparing the two plots, as already reported by Liu [2].

Current noise power spectral densities are plotted in figure 2 (a) and (b) for dark and irradiated conditions for the sample of figure 1b. The voltage varies from $0.5V$ to $1.5V$ from top to bottom with step $0.1V$. These voltage values corresponding to the tunneling region. The roll-off above $100Hz$ is due to the unavoidable capacitive coupling at the amplifier input (about $25pF$) and along the coaxial cables with the resistance values into play. The I-V characteristics and the current noise spectra measured at $77K$, not shown here, confirm a transport mechanisms where capture-emission processes dominate the average current and its fluctuation. The spectrum amplitudes are proportional to the square of the average current, in agreement with a capture-emission mechanism of the fluctuation process, originated by thermally excited charge carriers, as already observed in QDIPs grown by a different technology in [6, 7].

Current noise power spectral densities are plotted in figure 2 (a) and (b) for dark and irradiated conditions at $5K$ for the sample of figure 1(b). The voltage varies from $0.5V$ to $1.5V$ from top to bottom with step $0.1V$. Considering that the current increases of a factor 5 over the same voltage range, the noise gain g_n decreases with I, as opposed to the behavior observed at $77K$, when the fluctuations are mainly related to thermally excited capture-emission processes. Noise spectra are white in the investigated frequency range, i.e. Lorentzian.

As mentioned above, some samples show a high photogain as can be deduced from the I-V characteristics (figure 1(b)). These detectors exhibit a very high peak of responsivity, $\mathscr{R}_i = I_\phi/(h\nu\phi)$, in the tunneling region of the I-V characteristic [2]. While current noise spectra are white in dark conditions and for samples with very low responsivity, a $1/f$ noise component is observed on the devices with high optical gain. The g_n dependence on the inverse of the average current indicates that the noise suppression mechanism acts in the presence of radiation as well. The strong asymmetry of the I-V plots suggests that the effect should be the result of the combined interactions of the self-assembled quantum dot layer, the wetting layer and the center delta doping as a function of the applied bias and incident radiation.

CONCLUSIONS

Current noise measurements, both in thermal equilibrium and with photo-excitation, have been performed on InAs/GaAs self-assembled QDIPs. The results indicate that a noise suppression effect occurs when the tunneling regime dominates over the thermally emission-capture processes. The photocurrent noise spectral densities are Lorentzian for low optical gain devices. A $1/f$ component is observed for high optical gain detectors under irradiation in the tunneling regime. Remarkably, the noise suppression mechanism is even more effective when the photocurrent flows in the QDs confirming its Coulombian origin.

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