Measurement of Noise and Gain in Quantum Dot Infrared Photodetectors (QDIPs)

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Abstract

We report measurements on a series of quantum dot infrared photodetectors grown with different combinations of monolayer thicknesses (2.2. 2.55 and 2.9 ML) and quantum dot layer sheet doping densities (6×10^{10} cm^{-2} and 12×10^{10} cm^{-2}). The dark current and noise current were higher in devices grown with a sheet doping density of 12×10^{10} cm^{-2}. At a given bias voltage the lowest dark current and noise current was obtained in devices grown with 2.55 ML and a sheet doping density of 6×10^{10} cm^{-2}. This combination gives sheet doping density to dot density ratio of approximately unity. Gain extracted from noise current was highest in devices with 2.55 ML and a sheet doping density of 6×10^{10} cm^{-2}.

Keywords: QDIP, Noise gain, Infrared, monolayer

Introduction

Recent interest in Quantum Dot Infrared Photodetector (QDIP) as an alternative for infrared (IR) photodetectors has been driven by its potential for large area arrays, normal incident operation and high operating temperature. However its advantages over Quantum Well Infrared Photodetector (QWIP) and the current market leading technology, Mercury Cadmium Telluride (CMT), have not been fully demonstrated to date. Operating temperatures of current QDIPs are still lower than those of CMT, probably due to non-ideal carrier confinement. Although the CMT has high detectivity, there are still significant challenges in the growth and fabrication of CMT for large area Focal Plane Arrays (FPAs) [1]. On the other hand QDIPs grown and fabricated using the relatively mature III-V technologies can potentially offer low cost large area high performance FPA.

A figure of merit commonly used to characterize these IR detectors is detectivity, defined as, $D^* = \frac{R(A\Delta f)^{1/2}}{i_n}$ mHz$^{1/2}$W^{-1}, where R is the responsivity, A is the detector area, Δf is the bandwidth and i_n is the r.m.s value of the noise current. It is now well known that at a given IR wavelength the absorption coefficient of QDIP is much smaller than those of QWIP and CMT due to the limited dot density. Hence a reduction of noise in QDIP is required to increase the detectivity. Several groups have reported QDIP noise characteristics as functions of temperature [2], doping concentration [3] and position of dopants in the dot [4]. In this work we report the effect of monolayer thickness and quantum dot (QD) sheet doping density on noise and study the gain mechanism in QDIPs.

Experimental details

A total of six QDIP wafers were grown, fabricated and characterized in this work. Our QDIPs, with five identical repeats of dot-in-well structure, are depicted schematically in figure 1(a). The series of wafers consist of combinations of different monolayer thicknesses (2.2, 2.55 and 2.9 ML) and QD sheet doping densities (6×10^{10} and 12×10^{10} cm^{-2}). The wafers were fabricated into circular mesa diodes with diameters of 200 µm and 400 µm for current voltage and noise measurements.

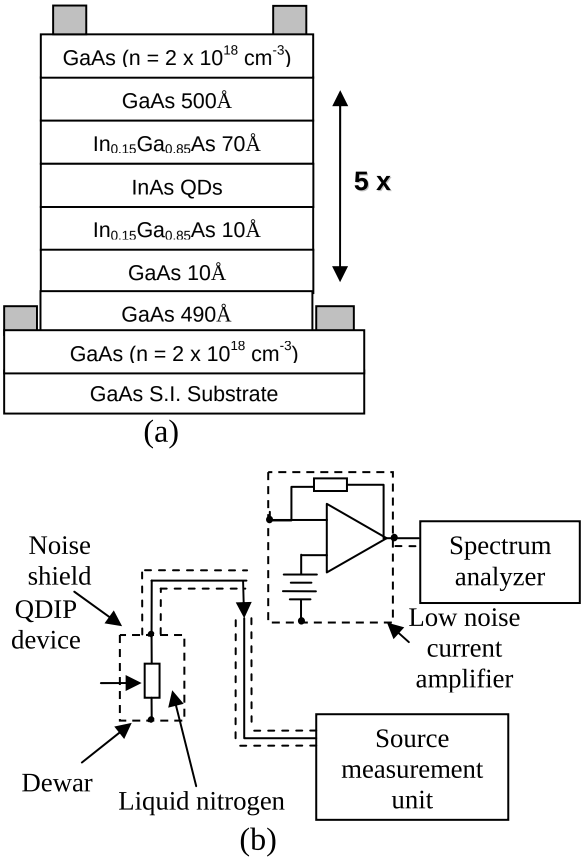

Figure 1: (a) QDIP structure used in this work. The quantum dots (QDs) were grown with different monolayer thicknesses and doping concentrations. (b) Schematic diagram of the noise measurement set-up.

Dark current at 77K was measured using a Keithley 236 source measurement unit by immersing the devices in liquid nitrogen, as illustrated in figure 1(b). In the noise measurements, the source measurement unit is replaced by a Stanford Research SR 570 low noise current preamplifier and a Stanford Research SR 760 Fast Fourier Transform spectrum analyser. The dark current of the device under test, amplified the preamplifier, was transformed into noise spectral density by the spectrum analyzer. The device was biased using the internal input bias provided by the preamplifier. Care was taken to minimise effects of electrical interference and ground loops on the measurements. The measurement set-up noise was measured and subtracted from the noise measured by the spectrum analyser to give the device noise.

Results and Discussion

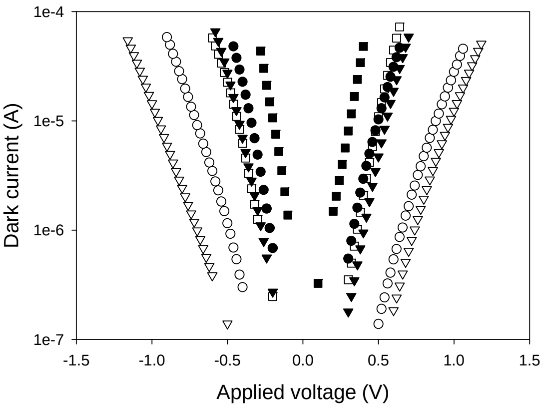

Figure 2: Dark currents measured at 77K for devices with sheet doping densities of 6×10^{10}cm^{-2} (open symbols) and 12×10^{10}cm^{-2} (close symbols). These devices have monolayer thicknesses of 2.2(□,■), 2.55(▽,▼) and 2.9(○,●) ML.

Current-voltage data showed that, at a given bias voltage, the dark current is lower in devices grown with a QD sheet doping density of 6×10^{10} cm^{-2} than those with 12×10^{10} cm^{-2}, as shown in figure 2. It appears that the higher sheet doping density of 12×10^{10} cm^{-2} may increase electron population in the excited states, resulting in higher dark current as electrons from the excited states can escape more easily than those in the ground state.

Figure 2 also shows that at a given bias the lowest dark current is obtained in devices with 2.55 ML, followed by the devices with 2.9 ML and 2.2 ML. Based on dot density characterization using atomic force microscope, the dot density was found to increase with monolayer thickness from 2.2 ML to 2.55 ML and subsequently decreases slightly for higher number of monolayers. Therefore it appears that the electron density is highest in the samples with 2.2ML, followed by those with 2.9ML and 2.55ML, consistent with the trend observed in the current-voltage measurements. Similar trend was observed in current-voltage data of devices with sheet doping density of 12×10^{10} cm^{-2}.

Our results indicate that higher electron density gives higher population in the excited states and hence higher dark current. Therefore in order to minimize the dark current it is important to optimize the doping level to avoid populating the excited states. To achieve this it is necessary to adjust the sheet doping density so that just enough dopants (2 electrons per ground state) are incorporated to populate the ground states only. However our results and those reported in [3] suggest that lowest dark current was achieved when the ratio of sheet doping density to dot density is approximately unity (1 electron per dot). This discrepancy may be due to partial population of the ground state by unintentional doping.

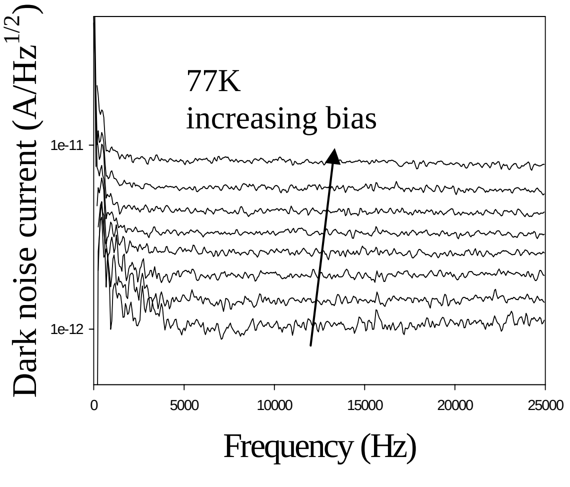

Figure 3: Typical noise spectrum measured.

A typical noise spectrum measured in our QDIPs is shown in figure 3. The flat spectrum showed that the noise spectra of these devices is white and is independent of the 1/*f* noise for frequencies > 2 kHz. Figure 4 compares the noise current measured in our devices. For noise current below 1×10^{-12} A/Hz$^{1/2}$, the measurement is limited by the set-up noise and the bandwidth of the preamplifier. As expected devices with higher dark currents produce higher noise currents. At a given bias the lowest noise current is obtained from devices with 2.55 ML while devices with 2.2 ML produce the highest noise current.

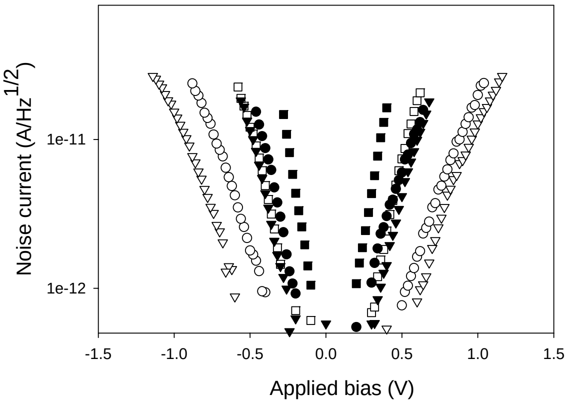

Figure 4: Noise currents measured at 77K for devices with sheet doping densities of 6×10^{10}cm^{-2} (open symbols) and 12×10^{10}cm^{-2} (close symbols) and monolayer thicknesses of 2.2(□,■), 2.55(▽,▼) and 2.9(○,●) ML.

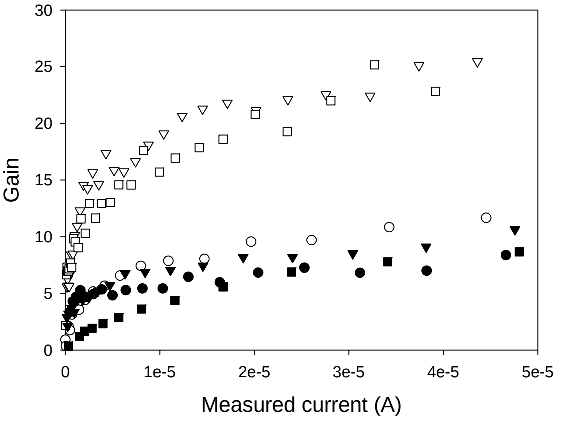

Figure 5: Noise gain extracted from noise current for devices with sheet doping densities of 6×10^{10}cm^{-2} (open symbols) and 12×10^{10}cm^{-2} (close symbols) and monolayer thicknesses of 2.2(○,●), 2.55(▽,▼) and 2.9(□,■) ML.

Our measured noise current is significantly greater than the thermal noise current, indicating that the dominant noise mechanism is generation-recombination. Assuming that the generation-recombination is the dominant noise mechanism the r.m.s noise current is given by $i_n = \sqrt{4qgI_d}$, where q is the electronic charge, g is the gain and I_d is the dark current. We can therefore extract the gain using $g = \frac{i_n^2}{4eI_d}$. Gain values up to 25 were extracted from our measurements. Figure 5 plots the gain against measured current. The gain is highest in devices grown with a sheet doping density of 6×10^{10} cm^{-2} and a monolayer thickness of 2.55 ML at a given measured current. Assuming that the gain factor is the same for both the photocurrent and noise (this is valid for small value of capture probability) we have $D^* \propto \sqrt{g}$ since $R \propto g$ and $i_n \propto \sqrt{g}$. This suggests that devices with higher gain will have higher D^* as well. The gain in our devices can be tuned by adjusting the monolayer thickness and sheet doping density of the dot layer.

Conclusion

We have performed current-voltage and noise measurements on a series of QDIPs grown with different combinations of monolayer thicknesses and QD layer sheet doping densities. Current-voltage measurements showed that to obtain low dark current it is important to optimize the doping level so that the excited states are not populated. This can be achieved by carefully matching the sheet doping density to the dot density, which can be adjusted by controlling the monolayer thickness.

In this work the combination of 2.55 ML with doping level of 6×10^{10} cm^{-2} gives the lowest dark current and the lowest noise current at a fixed bias. Assuming that generation-recombination is the dominant dark current generation mechanism, gain was extracted by comparing the measured noise current with ideal noise current. Devices with high gain will yield high detectivity if the photocurrent gain and noise gain are equal.

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