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High Photo Conductive Gain with Lateral Transport Quantum Dot Infrared Photo Detector

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1. Introduction

The success in the growth of high quality quantum dot layers(1) allows to make QDIPs (Quantum Dot Infrared Photo detectors) utilizing their intersubband transitions. There have been increasing interests in the QDIPs(2)(3) because of their possible high detectivity and room temperature operation. It is understood that the key factors of the improved performance include 1) the low dark current by virtue of the peculiar density of states of QDs, and 2) their response to normally incident light. However, there was no report showing that the large photo-conductive gain of QDIP is important.

In this paper, we present the properties of lateral transport(LT) QDIP, which has extremely large photo conductive gain due to its unique device structure. This device, not optimized yet, could detect ~10 μm wavelength photons at room temperature with D* of $3x10^7$ $cmHz^{1/2}/W$. We expect that this is not only due to its low dark current but also the large photo conductive gain. The transit time of photocarrier in the device must be much less than the capture time of the carriers. The measured photo conductive gain is as high as ~180. Although LTQDIP presented here has just 5 layers of QDs it shows large responses owing to the large photo conductive gain.

2. LTQDIP structure and operations

Fig. 1 shows the device structure. The epitaxial layer was grown by RIBER 32 MBE system on semi insulating substrate. 5 stacked InAs/GaAs QD layers were grown on the GaAs buffer layer.

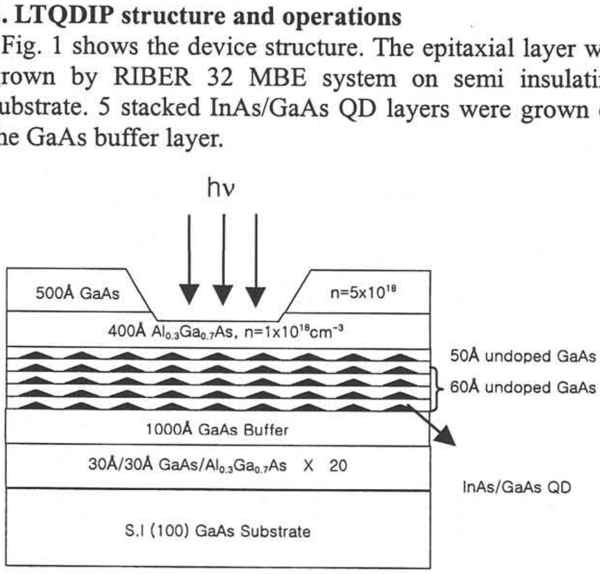

Fig 1. The schematic of device structure of LTQDIP

In the LTQDIP, the 2D electron channel and the QD light absorption layers are adjacent each other so that the photo carriers are readily collected to the 2-D channel by vertical electric field and go to the drain electrode. Since the 2-D channel is expected to have low noise properties and to shorten the carrier transit time between 2 electrodes, the device has low noise properties and the large photo conductive gain. The device is designed to achieve the condition that the 2-D channel formed at the hetero interface between $Al_{0.3}Ga_{0.7}As$ and GaAs must be depleted and the QDs are filled with electrons that are supplied from the doped $Al_{0.3}Ga_{0.7}As$ layer. At this condition, the low dark current and accordingly the high detectivity are expected. The depletion is controlled by the doping concentration in the $Al_{0.3}Ga_{0.7}As$ layer and recess process. Fig 2 shows the operations of the LTQDIP schematically.

Once electrons are trapped in QDs they are very difficult to thermalized. This is the reason for the low dark current at room temperature. Similarly, the electrons in channel are difficult to be captured. This is the very reason for high photo conductive gain. When ~10 μm light is illuminated on the device, the captured electrons in QDs are excited to the continuum state and contribute to the photo current. To meet the charge neutrality of the device, the electrons are supplied from source electrode. The electrons are not readily captured by the empty QD but swept to the drain because of very short transit time. That is the mechanism of photo conductive gain in LTQDIP.

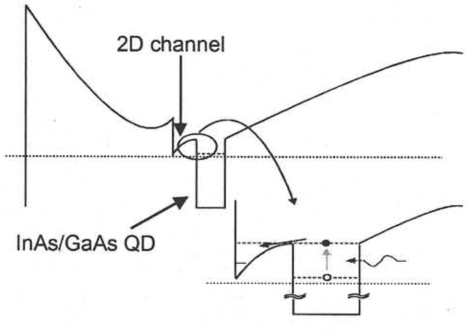

Fig 2. The schematic diagram which shows the mechanism of the LTQDIP Photo detector.

3. Measurement and Analysis.

Measurement setup consists of an EG&G 5209 lock-in amplifier and the glowbar IR source. The infrared from monochrometer was chopped at the frequency of 500 Hz.

And directly illuminated through ZnSe window.

Fig. 3. Shows the IR spectral response of the QDIP at the temperatures of 80K and 300K, where 5V was applied between drain and source. The wavelength at the peak is 10.6 μm and 10.4 μm at 80K and 300K, respectively. The photon flux was estimated by the commercial HgCdTe IR detector which covers 8~12μm. The measured photon flux was 15.5×10^{-10} W at λ=10.6 μm and the noise was measured by lock-in amplifier with bandwidth of 0.137 Hz and the QDIP window area is 7x200 μm^2

The measured detectivity of the QDIP was 6×10^{10} and 3×10^{7} $cmHz^{1/2}/W$ at temperatures of 300K from the equation (1)

$$D^* = \frac{S}{N}\frac{1}{P_s}\sqrt{A\Delta f} \qquad (1)$$

Where S is signal, N is noise, Ps = Photon flux, A is active area and Δf = noise bandwidth.

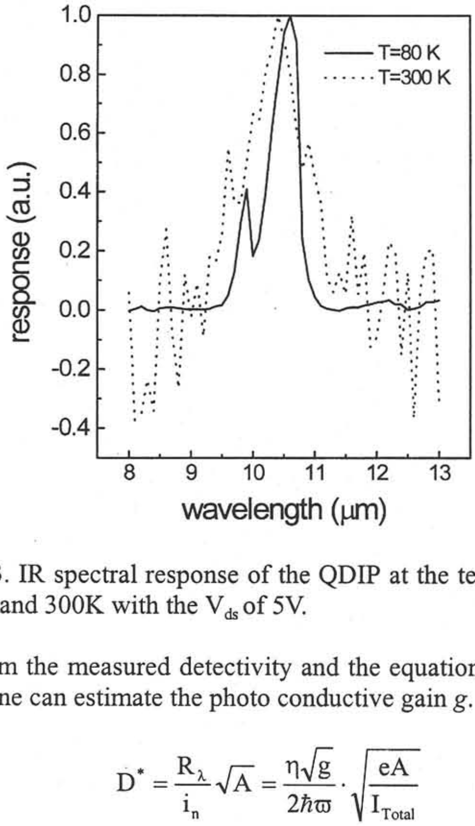

Fig 3. IR spectral response of the QDIP at the temperature 80K and 300K with the V_{ds} of 5V.

From the measured detectivity and the equations (2), and (3) one can estimate the photo conductive gain *g*.

$$D^* = \frac{R_\lambda}{i_n}\sqrt{A} = \frac{\eta\sqrt{g}}{2\hbar\varpi}\cdot\sqrt{\frac{eA}{I_{Total}}} \qquad (2)$$

$$I_s = \frac{e}{\hbar\varpi}\cdot\eta g P_s \qquad (3)$$

where D^* is $6\times10^{10}\,cmHz^{1/2}$, $\hbar\omega$ is 117 meV, e is 1.6×10^{-19} C and I_{Total} was 127 nA at the temperature of 80K. The photo-conductive gain of ~180 and the quantum efficiency of ~4 % were obtained. The high photo-conductive gain comes from long life time of the photo excited carriers compare to the transit time. Photo conductive gain can be written as

$$g = \frac{\tau_L}{\tau_t} \qquad (4)$$

where τ_L is recombination time and τ_t is the transit time.

The transit velocity of 2-D channel in the device is much faster than that of the conventional vertical diodes(4)(5). The transit time of the 7 μm gap between source and drain is several decade pico second but the relaxation time by the multi phonon scattering in the QD is several hundred pico second.

To increase the photo conductive gain the higher electric field has to be applied, but in this case the noise current increases more rapidly than signal. Fig. 4 shows the bias dependent total current and the response current of the device at the temperature of 80K with the illumination of 10.6 μm light. One can find that the response becomes saturated above 5V.

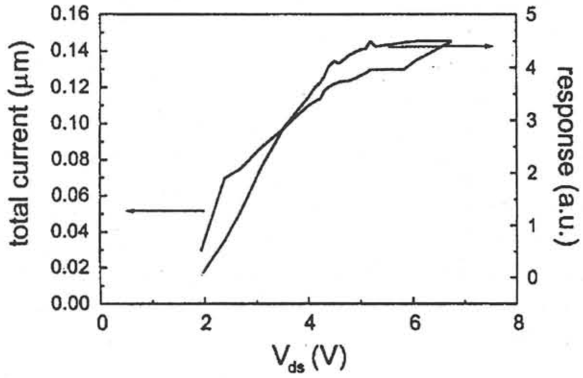

Fig 4. Total current and responses of the LTQDIP at the temperature of 80K with 10.6μm light illumination.

4. Conclusions.

We fabricated an infrared photo detector utilizing the lateral transport. The high detectivities, 6×10^{10} and 3×10^{7} $cmHz^{1/2}/W$ at the temperatures of 80K and 300K, respectively are shown. This good property is due to the small dark current and the high photo conductive gain of the device.

The device was estimated to have the photo conductive gain as high as ~180 and the quantum efficiency of ~4%. This high photo conductive gain is owing to the short transit time and the long life time of carriers in this particular structure.

Acknowledgment

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