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Experimental observation of transient photocurrent overshoot in quantum well infrared photodetectors

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Abstract

The experimental results on nonlinear transient photocurrent behavior in quantum well infrared photodetectors (QWIPs) are presented. When the background photocurrent was less than the transient photocurrent, the QWIPs with small number of QWs revealed a strongly nonlinear behavior. A photocurrent overshoot, the amplitude of which could be over 50% of the steady state photocurrent, in response to a high power step-like infrared illumination, was observed. Numerical simulations reveal that this effect is related to the time dependent nonlinearity of QWIP responsivity due to the redistribution of the electric field in QWIP. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Quantum well infrared photodetector; Transient photocurrent; Nonlinearity; Photocurrent overshoot

1. Introduction

Quantum well infrared photodetectors (QWIPs) have advanced from a theoretical concept [1] to focal plane array cameras [2] in a comparatively short time span of 15 years. The detectors based on different material systems have covered a wide range of wavelengths [3]. The longest cut off wavelength observed in a $GaAs/Al_xGa_{1-x}As$ QWIP was around 28 μm [4], while InGaAs systems have produced 35 μm cut off QWIPs recently [5]. Although these technological advances have been achieved in a short time, there are several device physics issues which has yet to be studied. These include phenomena at low temperatures such as degradation of responsivity [6], slow transient photoresponse to changes in the illumination [7], and dependence of responsivity on temperature [8]. In this paper, the results of experimental study of transient photocurrent in QWIPs operating at low temperature and high IR illumination powers are reported.

2. Experimental details

The detector samples studied here include $GaAs/Al_xGa_{1-x}As$ quantum well structures with 4, 16 and 32 periods grown by molecular beam epitaxy. The $Al_{0.27}Ga_{0.73}As$ barriers were 250 ± 5 Å wide and 60 ± 2 Å GaAs wells were center δ-doped with Si to 9×10^{11} cm^{-2}. The top and bottom contacts were also Si-doped at 1.5×10^{18} cm^{-3} and with thicknesses of 0.4 and 0.8 μm, respectively (Fig. 1). The area of the QWIP mesa was

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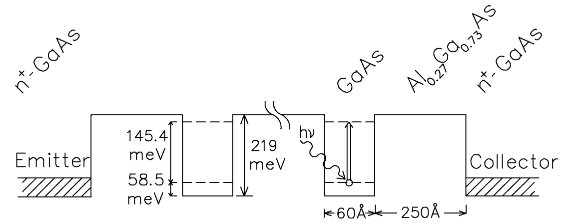

Fig. 1. QW detectors were composed of 250 ± 5 Å $Al_{0.27}Ga_{0.73}$ As barriers and 60 ± 2 Å GaAs wells δ-doped at the center with Si to 9×10^{11} cm^{-2}. The 0.4 and 0.8 μm contact regions were also Si-doped to 1.5×10^{18} cm^{-3}. The QWIPs had a peak response at 8.4 μm which corresponds to the transition $E0 \rightarrow E1 = 145.4$ meV.

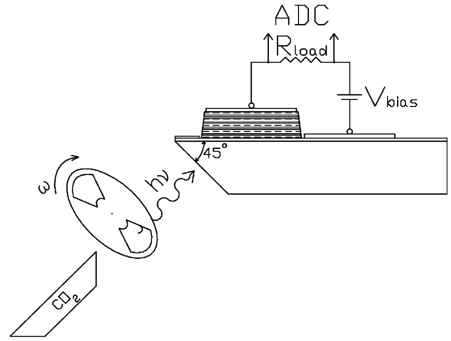

Fig. 2. Cooled in closed-cycle refrigerator and biased $Al_{0.27}$-$Ga_{0.73}$As/GaAs QWIPs were illuminated by a 100 Hz chopped 9 μm IR radiation produced by a CO_2 laser. The peak to peak voltage was recorded by an ADC.

240×240 μm^2. The contacts were separated from the QWs by the barriers identical to inter-well barriers. The Kronig–Penney model indicates that the MQW structure should have the ground state level of $E_0 = 58.5$ meV, the first excited level of $E_1 = 204$ meV, the quasi-bound level of $E_q = 228$ meV, for the barrier height of 219 meV. As one can see the transition $E_0 \rightarrow E_1$ corresponds to a wavelength $\lambda = 8.5$ μm. The QWIPs spectral responsivity has a peak at about 8.4 μm and a full width at half maximum of ~1.6 μm for 80 K [9]. To satisfy the selection rule IR light was coupled into the structure using a polished 45° facet.

The sample was mounted and cooled in a closed-cycle refrigerator. Since for the observation of nonlinear photoresponse, 300 K background photocurrent should be less than the (IR) photocurrent, the samples were carefully shielded from 300 K background radiation by a copper foil with a ~0.5 mm diameter pinhole, placed at about 2 mm in front of the sample in the path of the focused IR radiation, and was kept at the same temperature as the sample. Another similar copper shield located about 1.5 cm from the sample was kept at 77 K. This allowed the background photocurrent to be reduced to about 25% of the full field of view 300 K background photocurrent.

The samples were illuminated by chopped at 100 Hz 9 μm IR radiation from a CO_2 laser through a KRS-5 window (Fig. 2), which transmits about 70% of the incident IR radiation in the range from 5 to 12 μm. The trapezoidally shaped transient IR signal had ~10 μs rise and fall times.

It is also important to note that a prolong exposure of the MQW structure to high power IR radiation brings into consideration the effect of heating.

Hence, to make sure that the steady state background and photocurrent do not change with time, the exposure area and total incident power were reduced with a pinhole. Attenuated by neutral density filters, IR power was measured by a thermal sensor at KRS-5 window outside of the refrigerator. The peak-to-peak photovoltage across the load resistor, which is the voltage difference produced by QWIP current under IR and background illumination, was recorded. The characteristic time constant τ_{RC} of the measurement setup was limited to ~10 μs with a parasitic capacitance of 20 pF for the cables and with a load resistor of 500 kΩ.

3. Experimental results

At temperatures below 65 K and illumination power higher than the equivalent IR power required to produce the background photocurrent, the device operates in a nonlinear regime. In this regime the photocurrent is higher than the background current. This means that a change in photocurrent due to a change in the incident IR radiation might lead to a change in the electric field distribution in the QWIP structure. In the linear regime where background current is greater than the photocurrent, the variations of the photocurrent do not cause appreciable changes in the electric field distribution in the structure.

Under these conditions an overshoot of the transient photocurrent (as shown in Fig. 3) was observed. The strong overshoot, ~50% of steady state photocurrent, was only observed for the 4 well sample. As shown in Fig. 4, the overshoot for 16 and 32 well structure is absent for similar transport conditions and appears for smaller electric field. This suggests that the overshoot phenomenon could be due to a noneven field distribution in the QWIP structure with small number of wells [10]. The time scale of the transient overshoot is about 1 ms.

The incident IR power dependence of the transient photocurrent is shown in Fig. 3. The overshoot phenomenon becomes less pronounced for lower incident powers. Overshoot disappears when the photocurrent is lower than the background current, i.e. in the linear regime. Fig. 5 shows the dependence of the decay time of the photovoltage signal, obtained by simple exponential fitting from power dependence of the photosignal. The decay time is decreased with increasing infrared power.

The dependence of the photosignal on applied bias across the structure is shown in Fig. 6. The relative amplitude of the overshoot decreases from 90% to 5% with applied average electric field increasing from 4.4 to 10 kV/cm. This is due to the increase in the background current from 1.5 to 10.6 nA.

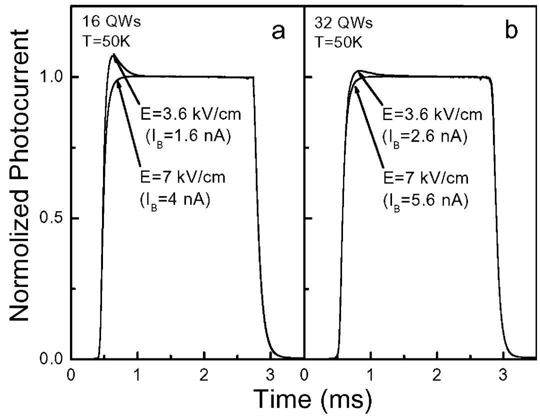

Fig. 4. The overshoot for the electric field 7 kV/cm disappears in 16 and 32 QWs while in 4-well QWIP the amplitude of the overshoot is over 40% of the steady state photocurrent (see Fig. 3). The amplitude of the overshoot decreases from almost 90% of the steady state photocurrent for four QWs to 7% and 3% for 16 and 32 QW structures.

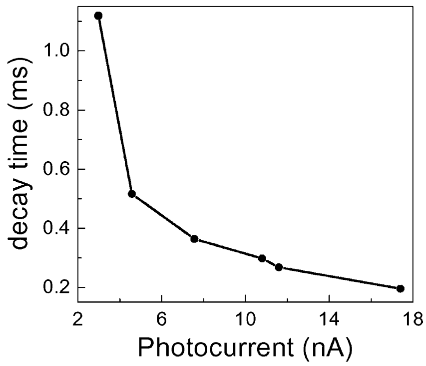

Fig. 5. The exponential decay fitting observed from power dependence of the overshoot Fig. 3 shows that the decay time decreases as the IR photocurrent grows.

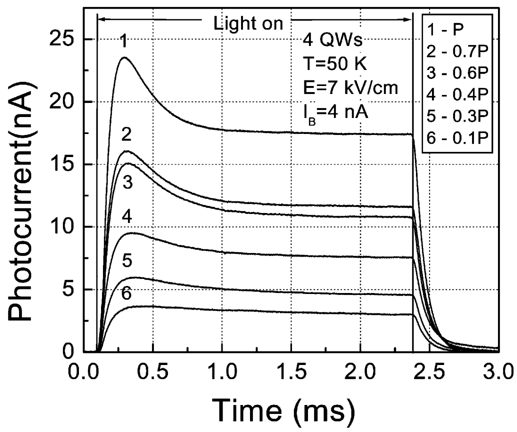

Fig. 3. The power dependence of the transient overshoot for 4 well sample at $T = 50$ K, electric field 7 kV/cm and background photocurrent 4 nA: (1) P (200 mW), (2) $0.7P$, (3) $0.6P$, (4) $0.4P$, (5) $0.3P$, (6) $0.1P$ shows as the intensity of the incident IR radiation grows (6) → (1) the amplitude of the transient overshoot grows as well. Note that overshoot disappears (1) when the IR photocurrent becomes smaller then the background photocurrent.

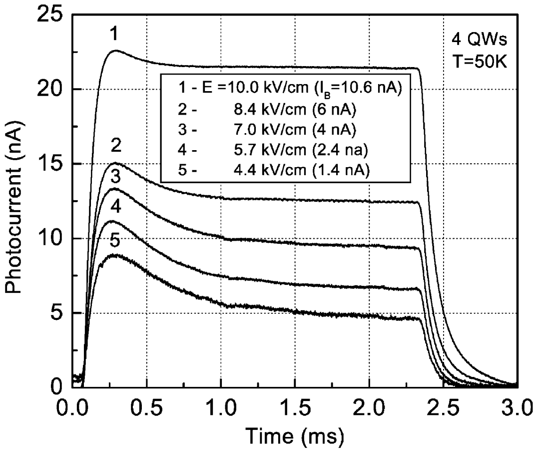

Fig. 6. Field dependence of the overshoot: (1) $E = 10$ kV/cm background photocurrent $I_B = 10.6$ nA, (2) $E = 8.4$ kV/cm, $I_B = 6$ nA, (3) $E = 7$ kV/cm, $I_B = 4$ nA, (4) $E = 5.7$ kV/cm, $I_B = 2.5$ nA, (5) $E = 4.4$ kV/cm, $I_B = 1.5$ nA. As one can see the amplitude of the transient overshot decreases with the increase of background photocurrent caused by the growth of the applied electric field (5) $\rightarrow$ (1).

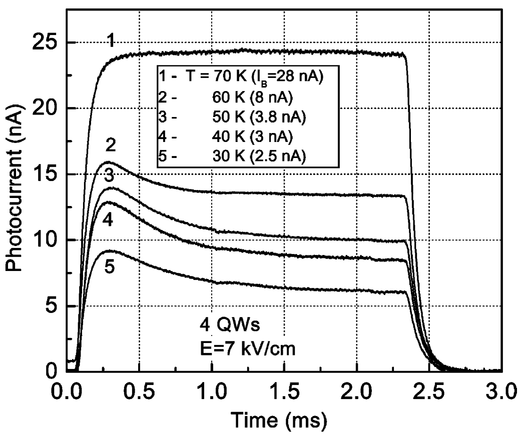

Fig. 7. As the background photocurrent I_B increases due to the temperature growth (5) $\rightarrow$ (1) the amplitude of the overshoot decreases and it disappears when the IR photocurrent becomes smaller than background one: (1) $T = 70$ K, $I_B = 28$ nA, (2) $T = 60$ K, $I_B = 8$ nA, (3) $T = 50$ K, $I_B = 4$ nA, (4) $T = 40$ K, $I_B = 3$ nA, (5) $T = 30$ K, $I_B = 2.5$ nA.

As can be seen in Fig. 7, the behavior of the photocurrent overshoot with temperature shows that the overshoot disappears at temperatures above ~60 K, when the background current exceeds the photocurrent.

4. Numerical simulation

To understand the physics of the transient photocurrent in the QWIPs, numerical simulations of the transient photoresponse were performed. A one-dimensional self-consistent QWIP simulator [11] was used. The numerical model includes the current continuity equation, the Poisson equation, and the rate equation describing the recharging via a self-consistent potential.

The results of numerical simulation for the QWIP with four QWs are shown in Fig. 8. The simulated conditions correspond to the experimental conditions of the curve 1 in Fig. 3. The transient photocurrent in response to a step-like increase of infrared power displays an overshoot (Fig. 8(a)), with the amplitude and the characteristic time constant very similar to the experimental values. The physical mechanism responsible for

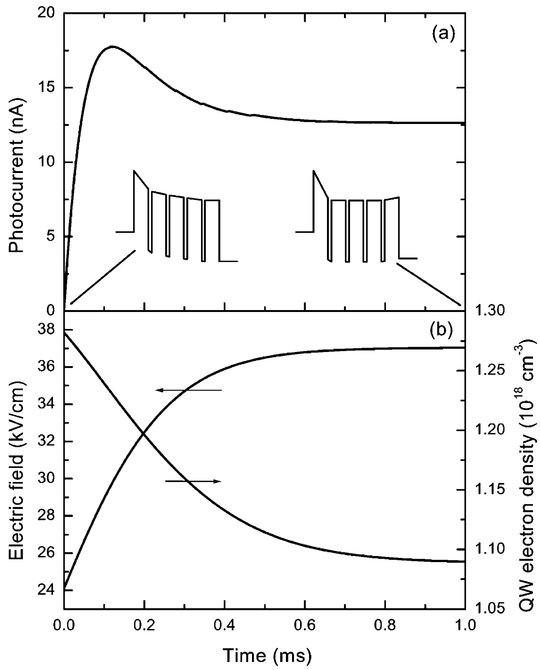

Fig. 8. Results of numerical simulation of four QWs: (a) transient photocurrent and (b) time dependence of the electric field in the injection barrier and QW electron concentration in the first QW. The simulated conditions correspond to the curve 1 in Fig. 1 ($E = 7$ kV/cm, $I_B = 4$ nA). The inserts show the band diagram before and after illumination.

the overshoot phenomenon can be revealed by analyzing the dynamics of the physical quantities in QWIP during the transient. The initial rise of the photocurrent is due to the transport of the carriers photoexcited from the QWs. It corresponds to the primary photocurrent [12].The intrinsic time constant of the primary photocurrent ($\sim$10 ps) can not be resolved in these experiments, and the rise time of the photocurrent is limited by the parasitic capacitance on the measurement setup. This parasitic (RC) time constant was taken into account in numerical simulation.

The slow transient after the initial rise is related to the recharging of the QWs and redistribution of the electric field in the QWIP, as can be seen from Fig. 8(b). The electric field in the injection barrier increases with time to provide the extra injection from the emitter. This is accompanied by the recharging of the first QW. The electric field in the bulk of QWIP decreases, since the total applied voltage is constant. The QWIP band diagrams before and after illumination are shown in the insert of Fig. 8(a). This leads to the reduction in the drift velocity, i.e. to the decrease of the photocurrent. As a result, the photocurrent decreases with time after the initial rise, displaying an overshoot behavior. The decrease of the responsivity can be interpreted in terms of the photocurrent gain. The steady state values of the photocurrent gain before and after the excitation were $\sim$4.0 and $\sim$0.5, respectively.

These effects are essentially nonlinear, since they arise only at relatively high excitation power, where the photocurrent exceeds the dark current. The steady-state nonlinearity of QWIP responsivity has been studied earlier [10]. Thus, the present experiments and simulation reveal the time resolved nonlinearity of the QWIP photoresponse.

5. Conclusion

This study has revealed that QWIP with four wells operated at low temperature (<65 K) and high power IR radiation shows transient photocurrent overshoot in response to a step-like illumination, which gradually degrades as the well number increases. This phenomenon is caused by nonuniform field distribution, having almost all the applied bias voltage drop in the first few barriers and by the slowness of the recharging of the wells. Future study, using structures with triangle type of the contact barrier [10] and/or bound to continuum transition, affecting the field distribution, could confirm the assumptions.

Acknowledgements

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