Transient photocurrent overshoot in quantum-well infrared photodetectors

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We report a strongly nonexponential behavior of the transient photocurrent in quantum-well infrared photodetectors (QWIPs) in response to a step-like infrared illumination. The transient photocurrent displays an overshoot on the time scale 0.1–1 ms at low temperatures ($T<70$ K), exceeding the steady-state photocurrent by as much as ≈50%. The overshoot behavior is attributed to a nonlinearity of responsivity caused by the modulation of the electric field in QWIP under relatively high illumination power, when the photocurrent exceeds the dark current. This explanation is confirmed by the experimental data and numerical simulation. These effects can play an important role when QWIPs operate in nonlinear regimes, such as in a heterodyne mode or in low-temperature and low-background applications.
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Quantum-well infrared photodetectors (QWIPs) have been actively investigated over the last two decades, and the basic physics of their operation relevant to high-background thermal imaging applications is well understood.[1–4] However, QWIP physics is not yet fully understood for some operating regimes, such as thermal imaging at low-background or low-temperature, or heterodyne detection. In these regimes, QWIP performance is associated with several nonlinear phenomena, such as the degradation of responsivity,[5–8] very slow transients under varying illumination conditions,[9] unexpectedly high values of the noise equivalent power in a heterodyne mode,[8,10] temperature dependence of responsivity,[11] etc. It is necessary to have a clear understanding of the mechanisms of these nonlinear phenomena in order to suppress the effects leading to the deterioration of the QWIP performance. In this letter, we report a nonlinear effect in QWIPs—transient photocurrent overshoot, which can not be explained by the ''classical'' theory of QWIP transient photoconductivity.[3,12,13] Our experimental and simulation results show that the overshoot is caused by the redistribution of the electric field in the QWIP active region when illuminated and the resulting degradation of QWIP responsivity. This phenomenon involves two effects studied earlier—the nonlinearity of QWIP responsivity[5,6] and the transient photoconductivity.[12,13]

The QWIP samples studied here include molecular-beam epitaxy grown GaAs/AlGaAs quantum-well detectors with 4, 8, 16, and 32 periods. The $Al_{0.27}Ga_{0.73}As$ barriers 250 ± 5 Å wide were undoped and 60 ± 2 Å GaAs wells were center δ doped with Si to $9\times10^{11}\,cm^{-2}$. The top and bottom contacts were also Si doped to $1.5\times10^{18}\,cm^{-3}$. The area of the mesa was $240\times240\,\mu m^2$. The QWIPs spectral response had a peak at about 8.4μm and a full width at half maximum of $\sim1.6\,\mu$m for $T=80$ K. The detailed description of the QWIP structure and its steady-state characteristics have been published earlier.[14] To satisfy the selection rule, infrared (IR) light was coupled into the structure through a polished 45° facet.

The samples were mounted and cooled in a closed-cycle refrigerator and carefully shielded from 300 K background radiation by a copper foil (at sample temperature) with a 0.5 mm diameter pinhole, located at about 2 mm in front of the sample in the path of the focused IR radiation. The outer 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 a 100 Hz chopped 9 μm IR radiation from a CO_2 laser through a KRS-5 window. Attenuated by a neutral density filter, IR power was measured by a thermal sensor with an accuracy of ~5% at KRS-5 window. The peak-to-peak photovoltage across the load resistor, which is the voltage difference across the load resistor under IR and background illumination, was recorded.

The transient photocurrent characteristics of the QWIP with four quantum wells (QWs) for different operating conditions are plotted in Fig. 1. At low infrared power [curve 5 of Fig. 1(a)], the transient photocurrent is well described by a simple exponential model $I(t)=I_0\exp(-t/\tau)$ (for turn on) and $I(t)=I_0[1-\exp(-t/\tau)]$ (for turn off), where I_0 is the steady-state photocurrent, and τ is the time constant. In the present experiments, the time constant τ is limited by the parasitics, and it does not reveal the intrinsic QWIP speed.[12,15] The behavior of the photocurrent at relatively high IR power [curves 1–3 of Fig. 1(a)] is strikingly different from the low-power case. The first noticeable feature is a strong asymmetry between the turn-on and turn-off transients at high power. This feature is absent in the low-power transient characteristics, as expected theoretically.[12,13]

The turn-on transient is characterized by a relatively fast increase in the photocurrent, followed by a relatively slow decay to a steady-state value. The rise time is determined by the parasitic effects, such as the finite rise time of the IR signal ($\sim10\,\mu$s) and the RC delay time of the measurement

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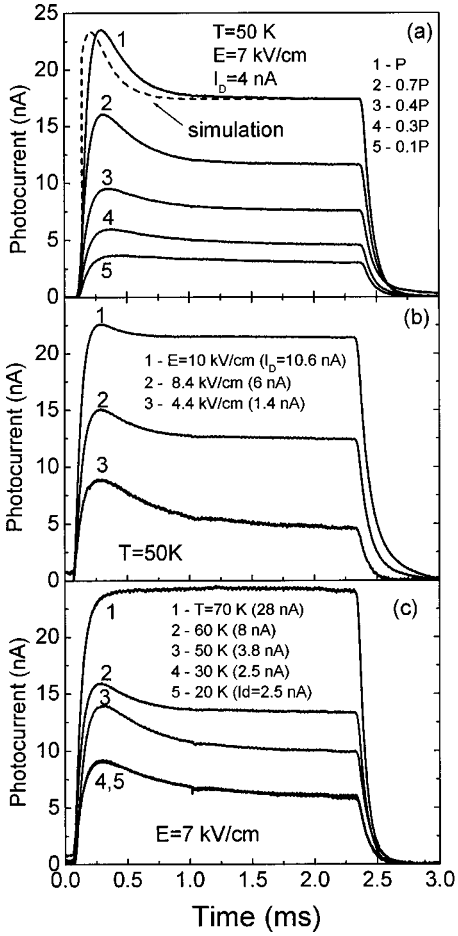

FIG. 1. Transient photocurrent in QWIP with four QWs at various (a) IR powers (temperature $T=50$ K, the average applied electric field $E=7$ kV/cm, the dark current $I_d=4$ nA, and the maximum IR power $P\approx 200$ W/cm^2), (b) applied voltages (electric fields), and (c) operating temperatures is shown. The overshoot disappears at high voltages and high temperatures, when the dark current is larger than the photocurrent. The dashed line shows simulation results for operating conditions of curve 1 of plot (a).

setup ($\tau_{RC}=RC\sim 10\,\mu$s, where $R=500$ kΩ is the load resistor and $C\approx 20$ pF is the cable capacitance). The decay time is much longer, on a time scale of 0.2–1.0 ms, and it decreased strongly with increasing IR power (or photocurrent). The photocurrent decay is attributed to the intrinsic QWIP behavior. The combination of the rise and decay of the photocurrent with different time constants results in a characteristic ''overshoot'' turn-on transient—the photocurrent displays a maximum which significantly (up to 50%) exceeds the steady-state photocurrent. The overshoot behavior is more pronounced at higher IR powers—the amplitude of the overshoot is increased while its time constant is decreased with increasing IR power. The turn-off transient does not show an overshoot or ''undershoot'' behavior even at the highest IR power, and can be approximated by an exponential decay.

The transient photocurrent overshoot is related to the nonlinearity of the photoconductivity in QWIPs at high IR power, studied earlier for the steady-state conditions.[5,6] Photoconductivity nonlinearity shows up as a saturation of the photocurrent, or, equivalently, the decrease of the responsivity (photocurrent normalized by the incident IR power) at high power. This is related to the redistribution of the electric field in a QWIP active region at high power, which is most strongly revealed by samples with a small number of wells. The nonlinear effects can be more easily observed under such operating conditions when the dark current (or background current) in QWIP is small, i. e. at lower biases, lower operating temperatures, and low-background IR fluxes.

To confirm this interpretation, a series of experiments were performed on QWIPs with a different number of QWs (from 4 to 32) operating under various conditions (temperatures and applied voltages). Figures 1(b) and 1(c) shows the transient photocurrent characteristics for four well QWIP at various applied biases [plot (b)] and operating temperatures [plot (c)]. It is seen from Fig. 1(b) that the overshoot effect is enhanced with the decrease of the applied bias. In agreement with our expectations, the photocurrent to dark current ratio also increases with decreased bias. At the highest bias $V=0.15$ V ($E=10$ kV/cm), the photocurrent is of the same order of magnitude as the dark current, and the overshoot is barely visible. Figure 1(c) shows that the overshoot is absent at high temperature (curve 1, $T=70$ K), when the dark current is as high as the photocurrent. Photocurrent overshoot becomes strongly pronounced at lower temperatures, when the dark current is lower than the photocurrent. At temperature $T\lesssim 40$ K, the transient photocurrent does not depend on temperature, as the dark current is determined by tunneling and not by the thermionic emission, and so the transport properties are independent of temperature in this range. Thus, the crossover from the simple exponential transient to the transient with overshoot takes place whenever the photocurrent exceeds the dark current in QWIPs with four QWs.

Transient photocurrent in QWIPs with 16 and 32 wells does not display overshoot at $E=7$ kV/cm. Thus, the nonlinear effects are not important for these QWIPs, which is consistent with earlier results on steady-state QWIP nonlinearity.[5,6] However, at a lower bias ($E=3.6$ kV/cm), the overshoot effect appears, but it is much weaker than that in a four well sample.

The experimental results and their interpretation just presented were confirmed by numerical modeling. A one-dimensional QWIP simulator[16] has been used to analyze the physical processes in QWIPs related to the transient photoresponse. The simulation program solves self-consistently the drift–diffusion current continuity equation for the continuum state electrons, the rate equations describing the QWs recharging, and the Poisson equation for the electric potential. All physical parameters of the model (drift mobility, QW capture velocity, QW escape probability, and thermal emission rate from the QWs), dependent on electric field, were fitted to experimental dark current and responsivity data.[5] The simulated transient photocurrent [dashed line in Fig. 1(a), corresponding to experimental curve 1] shows good agreement with experimental data. The microscopic physical mechanisms of the photocurrent overshoot can be understood by analyzing the spatiotemporal dynamics of the physical quantities in the QWIP active region (see Fig. 2). The electric field in the injecting barrier (barrier 1) increases with time to provide extra electron injection from the emitter. The electric field in the bulk of the QWIP is decreased, since the total applied voltage is constant. The redistribution of the electric field upon illumination is due to the recharging of the QWs [Fig. 2(b)]: the electron density in the first QW signifi-

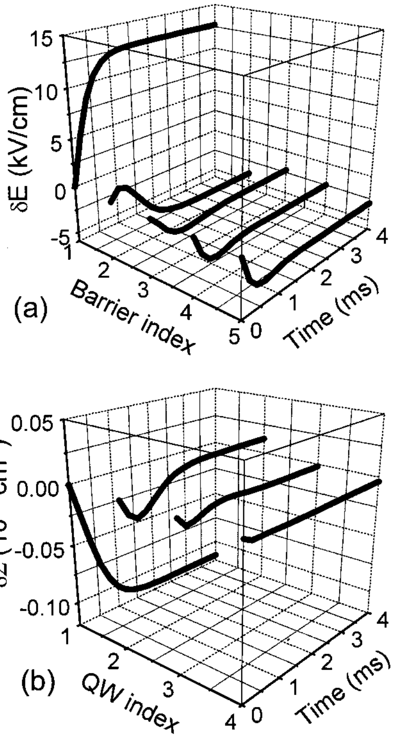

FIG. 2. Spatiotemporal dynamics of (a) electric field $\delta E = E(t) - E(0)$ and (b) carrier density in the QWs $\delta\Sigma = \Sigma(t) - \Sigma(0)$ in a four QW QWIP are shown. Simulations were performed for the operating conditions corresponding to curve 1 of Fig. 1. The characteristic time of the QW recharging determines the decay time of the transient velocity overshoot (see Fig. 1).

cantly decreases with time, while all other QWs are only slightly recharged. The characteristic time of the variation of the electric field (or the QW recharging time) determines the decay time of the photocurrent overshoot (Fig. 1). This time is decreased at higher IR powers.

Figure 3 shows the band diagrams and distributions of various physical quantities in the QWIP before and after the turn-on transient. The modulation of the electric field in the bulk of the QWIP leads to a deterioration of all transport parameters influencing the photoresponse. Due to the decrease of the electric field in the bulk, the drift electron velocity (calculated as $v_d = J/(en)$, where J is the current density, e is the electron charge, and n is the carrier concentration) is decreased. This leads to a strong enhancement of the QW capture probability $p_c = 1/(1 + v_d/v_c)$ (where v_c is the QW capture velocity). As a result, the photocurrent gain $g \propto 1/p_c$ is decreased from 2.5 to 0.6. In addition, the efficiency of the photoemission from the QW η is decreased due to a strong field dependence of the photoexcited carrier escape probability from the QWs.[5] Thus, the QWIP responsivity $R \propto g\eta$ is decreased and the photocurrent is saturated with increased incident IR power. The transient photocurrent overshoot reveals the time-dependent degradation of responsivity.

In conclusion, a strongly nonlinear effect—transient photocurrent overshoot—was reported for QWIPs. This phenomenon is due to the nonlinearity of photoconductivity in QWIPs at relatively high excitation power, caused by the redistribution of the electric field under illumination and deterioration of transport parameters. The effect is more pronounced in QWIPs with a small number of QWs operating at low temperatures and low applied voltages.

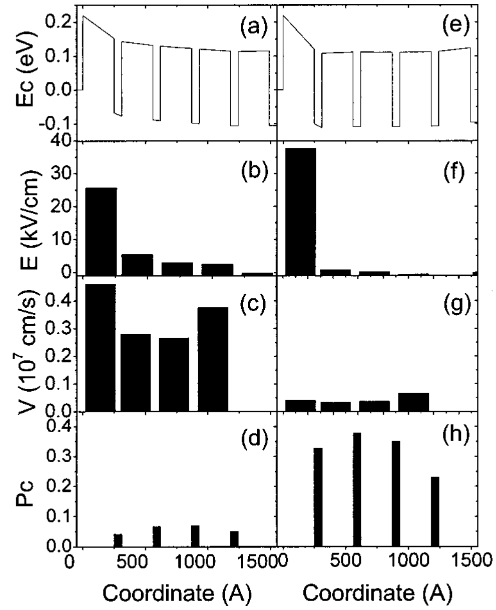

FIG. 3. Conduction band diagrams [(a) and (e)] and distributions of electric field [(b) and (f)], drift velocity [(c) and (g)], and QW capture probability [(d) and (h)] in a four well QWIP before [(a)–(d)] and after [(e)–(h)] the turn-on transient are shown.

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