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Effects of traps on the dark current transients in GaAs/AlGaAs quantum-well infrared photodetectors

A.G.U. Perera[a,*], S.G. Matsik[a], M. Ershov[a], Y.W. Yi[a], H.C. Liu[b], M. Buchanan[b], Z.R. Wasilewski[b]

[a] *Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303, USA*
[b] *Institute for Microstructural Sciences, National Research Council, Ottawa, Canada*

Abstract

In this work, experimental results showing very slow (up to 10^4 s) dark current transients in n-type GaAs/$Al_{0.27}Ga_{0.73}As$ quantum-well photodetectors (QWIPs) are reported. The transients with amplitudes of 0.1% to 65% of the steady-state current have been observed at 77 K. These effects are believed to be associated with initially ionized deep levels acting as traps reducing the positive charge in the structure. The time constant of the dark current (transient) decreases with increasing temperature with an experimentally determined activation energy ~75 meV. A fitting of the capture cross section to $\sigma(T) = \sigma_0 \exp(E_c/k_B T)$ gives an estimate for the capture activation energy of E_c~35 meV. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Dark current; quantum-well infrared detectors; Transients

1. Introduction

Variations in the dark current in quantum-well IR photodetectors (QWIPs) can have significant effects on their performance. Previously the effects of deep levels on current have been observed in the persistent photoconductivity [1,2]. This effect is believed to be due to the traps associated with deep levels in the AlGaAs barrier. In this work we present experimental results for transient dark currents in QWIPs with very long time scales on the order of minutes to hours. These transients have amplitudes of 0.1%–65% of the steady state current and time scales of 10^3–10^4 s for a GaAs/$Al_{0.27}Ga_{0.73}As$ QWIP at 77 K. At higher temperatures the time scales became much faster giving ~50 s time constants for 120 K. The amplitude of the transient initially increases as the temperature is increased and then decreases for temperatures above ~130 K.

2. Experimental data

The experiment consisted of measuring the dark current as a function of time in a QWIP at a fixed tem-

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[*] Corresponding author. Fax: 404-651-1427.
E-mail address: uperera@gsu.edu (A.G.U. Perera)

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Table 1
Parameters for the samples used in measuring the transients, the relative doping in the barrier and the growth temperature. Relative doping in the barrier is determined by integrating the dopant that migrated into the barrier [4] with samples #1127 and #1130 being taken as 1. All samples were grown at 605°C except #1327 which was grown at 550°C

Sample number	Well width (Å)	Barrier width (Å)	Number of periods	δ-doping offset	Relative doping in the barrier
#1127	59	250	4	0	1.00
#1300	59	350	25	0	1.00
#1301	59	350	25	6 Å	0.89
#1302	59	350	25	12 Å	0.79
#1327	55	250	25	0	0.00
#1328	55	250	25	11 Å	0.86
#1329	55	250	25	22 Å	0.68

perature after a fixed voltage had been applied to the sample. All current measurements were performed using a Keithley 2400 sourcemeter. The samples were cooled in a closed-cycle refrigerator, a continuous flow cryostat or by direct immersion in liquid nitrogen. Before each measurement, the samples were warmed up to room temperature to remove any accumulated space charge and have the same initial conditions. The first sample measured was designed as a 4-well QWIP (#1127) with a peak response at 8.5 μm [3]. This sample showed a strong transient whose time scale varied with temperature and field. A set of 25 well samples (see Table 1) with the same device parameters except for the δ-doping position were measured. The wells of samples #1300, #1301, and #1302 were δ-doped at the center, or off center by 6 and 12 Å (in the direction opposite to the growth direction) respectively. Samples #1327, #1328, and #1329 were doped in the center, 11 and 22 Å away from the center. These samples were previously used to study the dopant segregation effects in QWIPs [4] and were studied here to find any relationship between the transient and the dopant distribution in the structure.

Fig. 1 shows typical current–time curves for sample #1127 in the range 100–160 K when a constant voltage of 0.7 V corresponding to a field of 47 kV/cm is applied. All the curves have been normalized, with the actual currents ranging from 3 to 46 mA. The curves all show some similarities, with an initial increase in the current for the first ~100 s which could be due to heating of the sample. The absence of this increase for samples immersed in liquid nitrogen supports this explanation. After this heating transient, the current decreases until it eventually reaches a steady state value. The small variations on these general trends seen in the curves are due to the small temperature fluctuations on the order of ~0.01 K in the cooling system. It is possible to fit the current for $t > 500$ s to

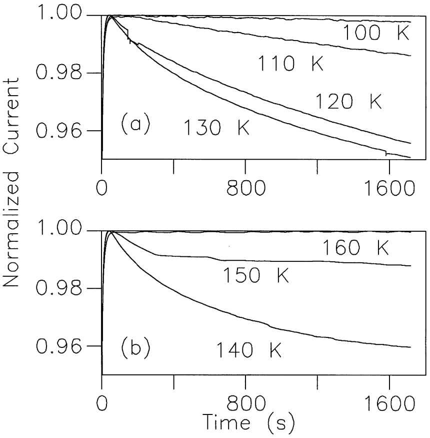

Fig. 1. Transient current in the 4-well sample for (a) $T = 100$–130 K and (b) $T = 140$–160 K at a field of 47 kV/cm. Note the increasing strength of the transient up to ~130 K followed by a decrease with the transient almost disappearing at 160 K. The time scale for the transient also decreases as the temperature rises.

$$I = I_0 + \Delta I \exp(-t/\tau), \tag{1}$$

where I_0 is the steady-state current, ΔI is the amplitude of the transient current and τ is a time constant related to the capture process, which was determined

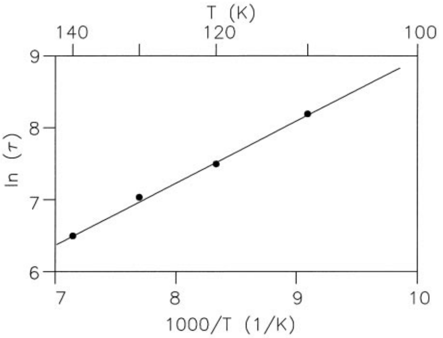

Fig. 2. Decay time for the transient versus $1/T$ for the temperature range 100–140 K indicating an activation energy of 75 meV. When the increase in current with temperature is included the capture energy was found to be ∼35 meV.

over a range of temperatures from 77 to 170 K. In the region of 100–140 K it was possible to determine an activation energy of 75 meV by plotting $\ln(\tau)$ versus $1/T$ (see Fig. 2). Below 100 K, τ became very long ($> 10^3$ s) making determination of τ imprecise. However, estimations based on measurements over 1–2 h agree in order of magnitude with the extrapolations of Fig. 2.

The time constant for charge capture should obey the equation

$$\tau = 1/nv\sigma, \tag{2}$$

where n is the carrier density, v is the carrier velocity and σ is the capture cross section. Since nv is proportional to the current, the temperature dependence of nv can be obtained from the steady state dark current measurements. This allows the extraction of the temperature dependence of σ. A fit to the expression

$$\sigma(T) = \sigma_0 \exp(E_c/k_B T), \tag{3}$$

gives the capture energy $E_c \sim 35 \pm 5$ meV which is close to the LO phonon energy. Sample #1302 gave a similar value of 37 ± 5 meV. This value is smaller than observed thermal and capture energies of ∼200 meV for DX centers in AlGaAs for Al fraction $x = 0.26$ [5]. However, the capture barrier can be much smaller than the thermal activation energy for other traps. Capture energies are not readily available in the literature for deep traps in AlGaAs. However, in GaAs $E_c = 40$ meV has been observed [6] for a deep level with 330 meV activation energy while other traps have capture energies up to several hundred meV. Although the addition of Al will change the various capture energies, AlGaAs can be expected to have traps with similar energies, which is confirmed by our results.

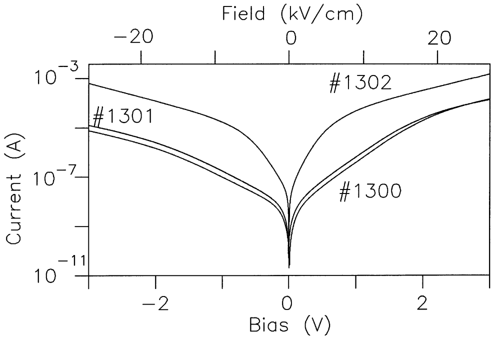

Fig. 3. Dark current for samples #1300, #1301 and #1302 showing the reduced dopant segregation in #1302.

To determine how the transient was related to dopant segregation, measurements were made on the samples (#1300, #1301, #1302, 1327, 1328 and 1329) with known dopant segregation. The sample in which the doping was at the center of the well (#1300) showed an asymmetric dark current indicating that there was migration of dopants in the growth direction. It showed a transient of ∼3% for a field of 9 kV/cm with electron flow in the growth direction but none for electron flow in the opposite direction. When the field on the sample was increased the time scale of the transient increased and the transient appears to become smaller. Above 28 kV/cm field the transient begins to increase again, and by 47 kV/cm reached 4%. Sample #1301 showed a more symmetric I–V and had similar behavior with a 2% transient at 9 kV/cm that initially decreased then began to increase as the fields was increased above 18 kV/cm. The sample with the largest doping shift (#1302) showed a larger and more symmetric dark current [see Fig. 3(a)] which is consistent with previous measurements of the same sample [4]. For sample #1302 the observed transient is strong (up to 7% at 77 K) for electron flow in the growth direction and nonexistent for electron flow in the opposite direction at fields of 14 kV/cm (see Fig. 4). The forward transient in this sample increased at fields of 9 kV/cm and continued increasing for fields up to 23 kV/cm.

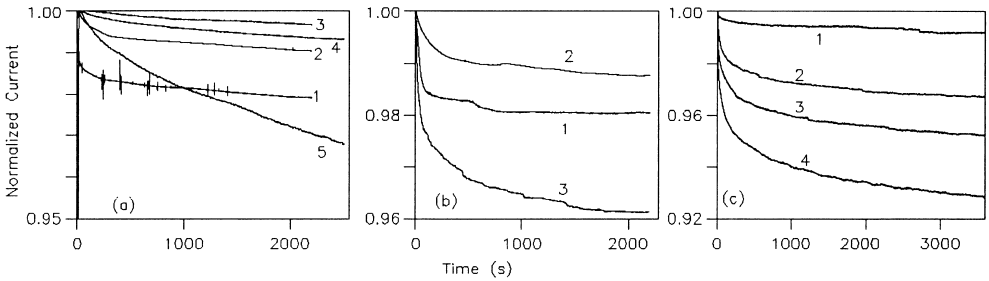

Fig. 4. Comparison of three samples with identical device parameters except for doping location. (a) #1300 center-doped sample, (b) #1301 shifted 6 Å opposite to growth direction and (c) #1302 shifted 12 Å. The fields in (a) and (b) are (1) 9, (2) 18, (3) 28, (4) 37 and (5) 47 kV/cm. The fields in (c) are (1) 9, (2) 14, (3) 18 and (4) 23 kV/cm.

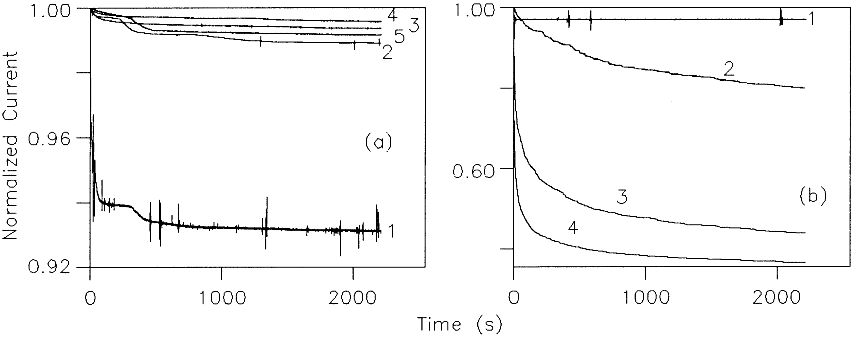

Fig. 5. Comparison of two samples with identical device parameters except for doping location. (a) #1328 shifted 11 Å opposite to growth direction and (b) #1329 shifted 22 Å. The fields are (1) 9, (2) 18, (3) 28, (4) 37 and (5) 47 kV/cm.

If the transient was only due to the enhanced number of traps in the barrier caused by dopant segregation sample #1300, which had the more asymmetric *I–V*, was expected to show the largest transient, with the transient decreasing in #1301 and #1302. However, sample #1302 showed the largest transient as well as having a transient at lower fields than the other two samples.

Similar behavior is seen in samples #1328 and #1329 (see Fig. 5) sample #1328 with a more asymmetric current showed a small transient that decreased as the bias was increased and then started to increase at 47 kV/cm. Sample #1329 showed only a small (~0.5%) transient at 9 kV/cm. For fields above 9 kV/cm the transient amplitude increased rapidly, reaching 65% for fields of 38 kV/cm.

Sample #1327 which was grown at lower temperature and had no significant dopant migration into the barrier showed no transient at any temperature even for fields above 47 kV/cm. This indicates that dopant migration may play some role in generating the traps related to the transient.

3. Conclusion

The presence of transient currents in QWIPs when electric fields above 9 kV/cm are applied has been experimentally demonstrated. Based on the temperature dependence of the transient the capture activation energy is estimated to be ~35 meV. Measurements on samples with and without dopant segregation in the wells indicate that the traps responsible for the transient may be associated with migration of the dopant into the AlGaAs barriers. However, measured activation energies do not seem to correspond with any known defects so further measurements are required to confirm the trap location and nature. Due to the small number of capture activation energies for traps in AlGaAs it is not possible to directly identify the "defect" associated with the trap. The lowering of the critical field at which transients become significant indicates that while shifting the location of the doping can reduce the current asymmetry caused by dopant segregation this also leads to large transients occurring at operating fields in the devices. These large transients could degrade the performance of the detectors in cases where high temporal uniformity is important.

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