Performance characteristics of InGaAs/GaAs and GaAs/InGaAlAs coherently strained superlattice photodiodes

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The properties of $In_{0.24}Ga_{0.76}As/GaAs$ and $GaAs/In_{0.05}Ga_{0.58}Al_{0.37}As$ superlattice photodiodes grown by molecular beam epitaxy have been investigated. From the temporal response characteristics, deconvolved rise times ~60–100 ps are obtained. The measured responsivities of the photodiodes with dark currents of 5–10 nA at 10 V are ~0.4 A/W, which correspond to peak external quantum efficiencies of ~60%. These results indicate that very high performance photodiodes can be realized with strained layers.

Superlattice (SL) and multiquantum well (MQW) photodiodes are of interest for a variety of reasons. First, they allow a tailoring of the spectral response characteristics by a variation of the quantum well parameters. Second, the initial proposal[1,2] of enhancement of impact ionization coefficient ratios, α/β, in these artificial materials for low-noise applications has been borne out by measurements.[3–5] Third, a certain amount of tunability is provided by the shift in the position of the exciton resonances with applied electric field perpendicular to the layers. In this letter we demonstrate that very high-speed multiquantum well photodiodes can be realized with strained-layer superlattices (SLS's). In particular, we have characterized devices made with $In_{0.24}Ga_{0.76}As/GaAs$ and $GaAs/In_{0.05}Ga_{0.58}Al_{0.37}As$ SLS's. The devices also exhibit external quantum efficiencies of ~60%.

The MQW *p-i-n* photodiode structures were grown by molecular beam epitaxy on conducting Si-doped GaAs substrates. The schematics of the structures with the two strained MQW systems are shown in Figs. 1(a) and 1(b). The InGaAs/GaAs SLS was grown at 520 °C, while the GaAs/InGaAlAs structure was grown at 600 °C. The SLS absorption regions in the two structures are 1.2 and 1.0 μm thick, respectively. The mismatch values in the InGaAs/GaAs and GaAs/InGaAlAs SLS systems investigated by us are 1.4 and 0.35%, respectively. Low-temperature absorption measurements were made to ascertain the structural quality of the SLS regions. The measurements were made with a tungsten-halogen source, a 1-m Jarell–Ash scanning spectrometer, and a liquid N_2-cooled photomultiplier. The spectra were recorded after suitable amplification by lock-in techniques. The spectra are shown in Figs. 2(a) and 2(b). In the spectrum of the GaAs/AlGaInAs MQW, the two dominant transitions result from the HH1 ($n = 1$ electron to heavy hole) and LH1 ($n = 1$ electron to light hole) transitions. These are, as expected, separated by 6–7 meV. The spectrum for the InGaAs/GaAs MQW shows one dominant peak, which we believe is the HH1 transition and several very weak ones at higher energies. The one closest to the main peak, and separated from it by 17 meV, is believed to be due to a transition from $n = 1$ electron to $n = 2$ heavy-hole subband. This transition is, in general, forbidden, but becomes possible due to band mixing, and hence the intensity is very small.

The device fabrication procedure is as follows. A square mesa ($20\times25\ \mu m^2$) defining the active area is formed by etching with $1H_3PO_4:1H_2O_2:8H_2O$ up to the n^+ InGaAs or AlGaAs layer. 3000 Å SiO_2 is deposited on the whole structure and openings of dimension $5\times5\ \mu m^2$ are made by etching with buffered HF for the *p*-type contacts. 500/3500 Å Ti/Au and 300/400/3500 Å Ni/Ge/Au *p*- and *n*-type contacts are formed on the top and back, respectively. The calculated zero-bias junction capacitance of the diodes is less than 0.1 pF. Excellent rectifying characteristics were obtained. The dark current at 10 V is 5–10 nA for both material systems.

The spectral response characteristics of the devices were

(a)

p^+	GaAs	50 Å
p^+	$Al_{0.1}Ga_{0.9}As$	200 Å
Undoped	$In_{0.24}Ga_{0.76}As/GaAs$ SLS, L_Z=100 Å, L_B=150 Å	1.2 µm
n^+	$In_{0.1}Ga_{0.9}As$	0.4 µm
n^+	GaAs	0.3 µm
n^+	GaAs substrate	

(b)

p^+	GaAs	50 Å
p^+	$Al_{0.3}Ga_{0.7}As$	0.5 µm
Undoped	$In_{0.05}Ga_{0.58}Al_{0.37}As/GaAs$ SLS L_B = 220 Å, L_Z = 150 Å	1.0 µm
n^+	GaAs	500 Å
n^+	$Al_{0.3}Ga_{0.7}As$	0.5 µm
n^+	GaAs	0.3 µm
n^+	GaAs substrate	

FIG. 1. Schematics of (a) $In_{0.24}Ga_{0.76}As/GaAs$ SLS and (b) $GaAs/In_{0.05}Ga_{0.58}Al_{0.37}As$ SLS photodiodes grown by molecular beam epitaxy.

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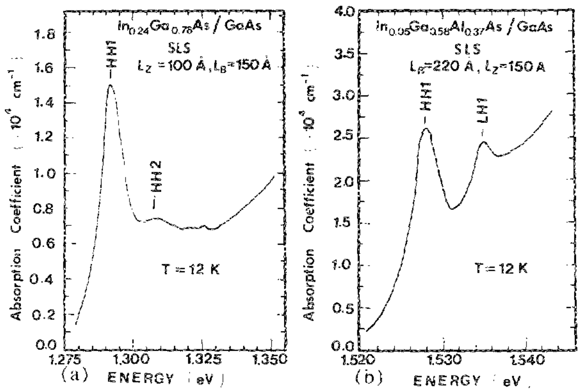

FIG. 2. Measured low-temperature absorption spectra of (a) InGaAs/GaAs SLS and (b) $GaAs/In_{0.05}Ga_{0.58}Al_{0.37}As$ SLS.

recorded with a monochromatic light source and lock-in amplification of the detected photocurrent. The measured photocurrents were calibrated with a Si photodiode. The spectral response of the diodes at a reverse bias of 15 V is shown in Figs. 3(a) and 3(b). The maximum responsivity of ~0.4 A/W is measured in both material systems, indicating that this value is almost intrinsic to the device design. The maximum external quantum efficiency for both types of SLS devices is ~ 60% at a bias of − 15 V and 0.75 μm wavelength light.

For the high-speed frequency response measurements, the photodiodes were mounted on a 50-Ω microstripline package. dc bias to the diode was provided through a HP 11612A bias-Tee with an operating range of 45 MHz to 26.5 GHz. Optical excitation was provided with 100 ps pulses from a Northcoast 810 AlGaAs (850 nm) laser diode with the output focused to a 50-μm spot on the device. The response of the photodiode to the optical pulses was observed on a sampling scope with an S-4 sampling head having a rise time of 25 ps. The high-frequency coaxial cables used in the circuitry have an approximate rise time of 10 ps. Figures 4(a) and 4(b) show the temporal response of the photodiodes as observed on the sampling scope. From these data the deconvolved rise times are calculated to be 100 and 60 ps in the InGaAs/GaAs and GaAs/InGaAlAs photodiodes, respectively. The corresponding full widths at half-maximum (FWHM) of the responses are 670 and 260 ps, respectively.

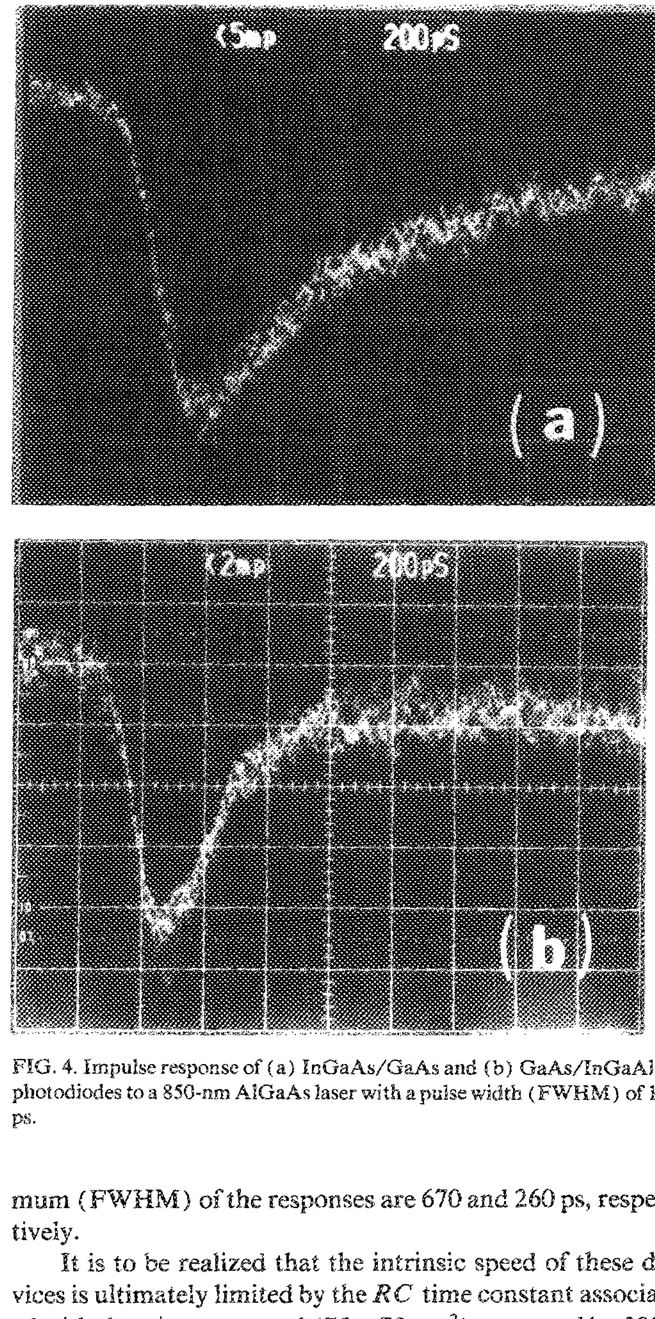

FIG. 4. Impulse response of (a) InGaAs/GaAs and (b) GaAs/InGaAlAs photodiodes to a 850-nm AlGaAs laser with a pulse width (FWHM) of 100 ps.

It is to be realized that the intrinsic speed of these devices is ultimately limited by the RC time constant associated with the p^+ contact pad ($75 \times 75\,\mu m^2$) separated by 3000 Å of dielectric from the n^+ layer below them. The calculated capacitance is ~700 fF, which is an order higher than the diode junction capacitance. In fact, InGaAs *p-i-n* diodes grown on semi-insulating InP substrates having a 0.75-μm absorption layer and having an identical geometry exhibit temporal responses with a rise time of 22 ps and FWHM of 27 ps. The RC time constant in the SLS devices, taking into account the pad capacitance, is approximately 36 ps. It is clear that a monolithic structure fabricated on semi-insulating substrates is more desirable for high-speed devices.

The rise times of 60 ps in the impulse response of the GaAs/InGaAlAs SLS devices reflect the carrier transport mechanism through the superlattice region under the applied bias, since the incident pulsed photoexcitation has an energy a little higher than the GaAs well band gap. As pointed out by Larsson *et al.*,[6] these values of the response time indicate carrier transit by field-enhanced emission and some

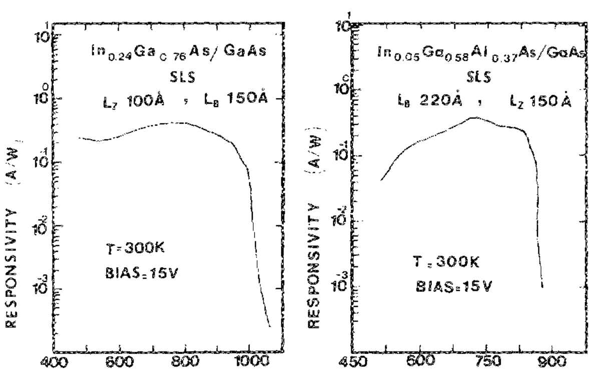

FIG. 3. Measured spectral response at room temperature of (a) InGaAs/GaAs and (b) GaAs/InAlGaAs SL photodiode under a reverse bias of 15 V. At this bias the *i* region is fully depleted in both cases.

tunneling through barriers. In the case of the InGaAs/GaAs SLS, the pulsed photoexcitation is observed above the barrier energy and the photoexcited carriers are transported almost as in bulk materials. Long tails in the temporal response, as observed in our diodes, have been previously reported by other authors.[6,7] We believe these long fall times result from a certain amount of carrier trapping in the wells, as shown by Parker *et al.*[8] and also from carrier trapping in bulk and interface traps and defects in the SLS. The fact that the response of the GaAs/InGaAlAs SLS with a 0.35% mismatch is much faster than the InGaAs/GaAs SLS with a 1.4% mismatch indicates that the higher strain and possibly higher interface defects in the latter might be responsible.

It is clear from the data presented above that fast photodiodes can be fabricated with strained-layer superlattices and their performance is comparable to bulk and lattice-matched SL photodiodes. We have demonstrated good performance in two types of SLS photodiodes in which the wells of the SL region are under tensile or compressive strain. More optimum device design can certainly lead to the use of these devices for data transmission at the rate of several gigabits per second. In addition, we have recently shown[9] that a higher responsivity can be obtained in the case of the GaAs/InGaAlAs SLS near the exciton resonances due to a merger of the light- and heavy-hole bands for certain alloy compositions. In the sample studied here, with $\sim 5\%$ In, two resonances are still separate, as seen in Fig. 2, and therefore, the quantum efficiencies in the two strained samples are comparable. With an increase in the absorption coefficient, it should be possible to use thinner absorption regions, thereby reducing the transit time of photoexcited carriers across it.

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