Direct measurements of large near-band edge nonlinear index change from 1.48 to 1.55 μm in InGaAs/InAlGaAs multiquantum wells

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Direct picosecond measurements of nonlinear refractive index change and nonlinear absorption in $In_{0.530}Al_{0.141}Ga_{0.329}As/In_{0.530}Ga_{0.470}As$ multiquantum wells in the range 1480–1550 nm are reported. Large low-threshold nonlinear index changes are found: Δn of up to 0.14 with figure of merit of 1.38 at a fluence of 116 $\mu J/cm^2$. The index-change-over-absorption figure of merit, F, is greater than unity over much of the spectrum, pointing to the prospective applicability of the materials studied to nonlinear switching devices. © *2003 American Institute of Physics.*
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Low-intensity-threshold, high-index-change nonlinear materials are desired for all-optical switching.[1] Transmission-based nonlinear devices rely on materials which effect a π phase shift due to a change in refractive index Δn, before the signal to be processed is attenuated to $1/e$ of its incident value as a result of absorption α_{eff}.[1] This requirement is expressed in terms of the figure of merit $F = \Delta n/\alpha_{\text{eff}}\lambda > 1$, where λ is the wavelength of light.

Bulk and multiquantum-well (MQW) semiconductors have been demonstrated to exhibit strong saturation of absorption near the electronic band edge when illuminated with intense light. Bandfilling effects have been identified as the dominant responsible physical effect. Experiments have shown strong saturation of absorption in various material systems such as bulk InSb,[2] bulk GaAs and GaAs/AlGaAs MQWs,[3,4] and InGaAs/InAlGaAs MQWs.[5]

Band edge saturation of absorption has been predicted and shown to cause large refractive index changes in the same spectral regions. Starting from the measured fluence-dependent absorption spectrum, the Kramers–Kronig transformation was used to predict large refractive nonlinearities. Absorption spectra were based on a single-beam continuous wave measurements in GaInAs/InP MQW,[6] and pump-broadband probe experiments on bulk GaAs and GaAs/AlGaAs MQWs[7–9] and InGaAs/GaAs MQWs.[8] Degenerate four wave mixing (DFWM) has been used to measure directly the nonlinear index change in bulk InGaAsP.[10] Comparison of DFWM results with predictions from the Kramers–Kroning transformation have shown discrepancies on the order of unity in the nonlinear refractive response.[10] Direct measurements of nonlinear index changes have also been made by analyzing the shift of the Fabry–Pérot fringe spectral positions in InGaAs/InP MQWs[11] and GaAs/AlGaAs MQWs.[9] This technique slso resulted in significant inaccuracies.[9]

These measurements of band edge refractive nonlinearity have predicted and demonstrated negative nonlinear index change up to $|\Delta n/n| \approx 3\%$ in the vicinity of the excitonic peak. The magnitude of the nonlinear index change per given fluence, as well as the maximum possible index change, were found to increase with decreasing quantum well width.

In this letter we present direct measurements of the band edge picosecond nonlinear response of MQWs across a wide spectral range pertinent to fiber-optic communications systems. Using the well-established z-scan technique we have measured both the strength and sign of the nonlinear index changes and saturation of absorption in $In_{0.530}Al_{0.141}Ga_{0.329}As/In_{0.530}Ga_{0.470}As$ MQWs in the range 1480–1550 nm at a variety of fluences. In contrast to the predictions based on the Kramers–Kronig transformation, our direct measurement provides information about a nonlinear response induced and experienced by an ultrafast signal. The strong nonlinear refractive and absorptive effects measured, and associated good figures of merit permit direct assessment of the applicability of the materials analyzed to all-optical switching.

The cross section of the sample is shown in Fig. 1. Using molecular beam epitaxy, 121 10 nm $In_{0.530}Al_{0.141}Ga_{0.329}As$ barriers and 120 5 nm $In_{0.530}Ga_{0.470}As$ wells were grown on an S-doped (001) InP 2 in. substrate, resulting in a total

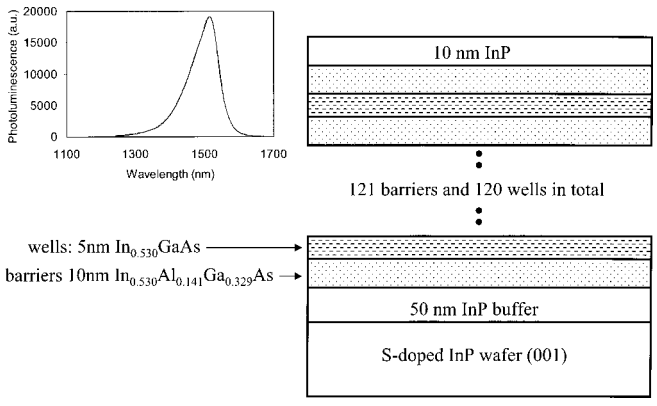

FIG. 1. Cross section of the sample. 121 10 nm $In_{0.530}Al_{0.141}Ga_{0.329}As$ barriers and 120 5 nm $In_{0.530}Ga_{0.470}As$ samples were grown on S-doped 001 InP 2 in. substrate. The inset shows the photoluminescence of the sample.

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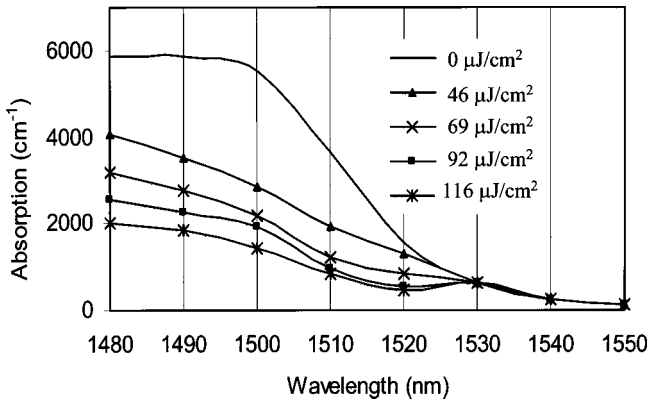

FIG. 2. Saturation of absorption in $In_{0.530}Al_{0.141}Ga_{0.329}As/In_{0.530}Ga_{0.470}As$ MQWs at a room temperature in the spectral range 1480–1550 nm at fluences of 46, 69, 92, and 116 μJ/cm^2.

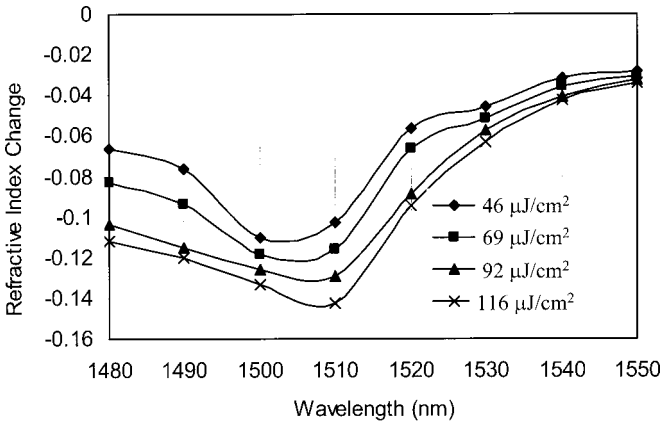

FIG. 3. Nonlinear index change in MQWs at the same experimental conditions as in Fig. 2.

thickness of the nonlinear sample of 1.81 μm. Following growth, the backside of the wafer was polished to allow transmittance measurements without scattering. In the inset of Fig. 1 we show the photoluminescence spectrum of our sample with a peak at 1516 nm. High sample quality and periodicity of the nanolayers were confirmed by the double crystal x-ray diffraction measurements. Nonlinear measurements were made using our tuneable picosecond laser amplification system, which produced pulses with the full width at half maximum width of a temporal intensity profile of $\tau_p = 1.2$ ps. at a repetition rate of 1 kHz.

The real and imaginary changes in the refractive index were measured using the z-scan method.[12] The laser beam was focused with a 12 cm focal length lens and the transmittance through the sample was recorded as the position of the sample was varied relative to the focal length of the lens. A reference beam detector was used to monitor fluctuations in the input laser beam. Two detectors were used to monitor the transmitted beam. Measurement with no aperture allowed determination of the sign and magnitude of nonlinear absorption; while measurement with an aperture in place allowed determination of the sign and magnitude of the nonlinear index change.[12]

Figure 2 shows the saturation of absorption in our sample in the spectral range of 1480–1550 nm at room temperature. Linear absorption and nonlinear absorption extracted from scans carried out at fluences of 46, 69, 92, and 116 μJ/cm^2 are shown. The fluence, P, was calculated according to $P=E/\pi w_0^2$, where E is the energy per pulse and w_0 is the radius of beam waist at the focus, measured at the $1/e^2$ of the transverse beam intensity profile. Open aperture z-scan traces were normalized to the value measured far from the focus. The change in the effective absorption of the sample, $\Delta\alpha$, was obtained from fitting the open aperture transmission traces into the formula $T_{\text{open}}(z)=\ln[1+q_0(z)]/q_0(z)$,[13] where z is the distance from the focus, and $q_0=\Delta\alpha L_{\text{eff}}/(1+z^2/z_0^2)$, with z_0 being the Rayleigh range of the beam. The effective length of the sample L_{eff} is defined as $L_{\text{eff}}=(1-e^{-\alpha_0 L})/\alpha_0$, where α_0 is the linear absorption and L is the thickness of the sample. After calculating the change in absorption, the effective absorption was obtained from $\alpha_{\text{eff}}=\alpha_0+\Delta\alpha$. $\Delta\alpha$ *was* negative in all our measurements.

Due to the bandfilling effect, MQWs exhibit a very large absorption saturation in the vicinity of the excitonic peak and around the band edge. Similarily to what has been observed in other material systems as reported in Refs. 2–11, with increasing fluence the excitonic step around 1490 nm is washed out and the absorption decreases more than threefold throughout most of the spectral range studied.

Figure 3 shows the nonlinear index change at the same fluences and wavelengths as in Fig. 2. To determine the strength and sign of the nonlinear refraction, normalized (with respect to the value far from focus) closed aperture traces were divided by the normalized open aperture traces. The nonlinear index change was obtained by using the formula $\Delta n=0.406\lambda\Delta T_{p-v}/2\pi L_{\text{eff}}$,[12] where T_{p-v} is the difference between points of highest and lowest transmittance in the divided z-scan curve, and λ is the wavelength of light. The negative sign of the nonlinearity was deduced from the characteristic peak-valley shape of the curve.[12]

Nonlinear index changes with magnitude larger than $|\Delta n|>0.03$ were directly measured over the entire range studied. The largest value recorded was $\Delta n=-0.14$ obtained at 1510 nm at a fluence of 116 μJ/cm^2. As the signal wavelength was increased beyond the band edge, the refractive index and absorption changes decreased.

Figure 4 shows figures of merit calculated from the results shown in Figs. 2 and 3. Bandfilling shifts the onset of (positive-valued) absorption to higher energies. This shifts

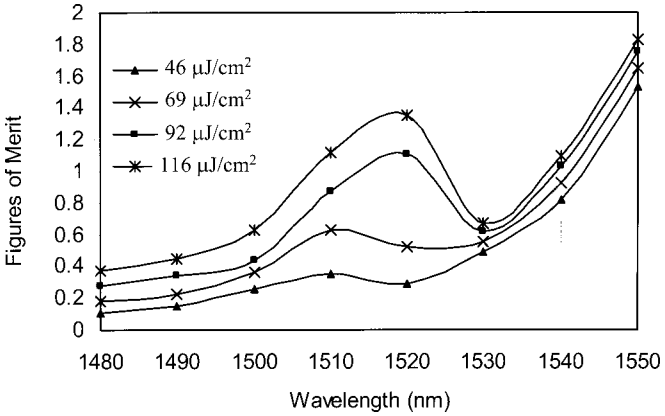

FIG. 4. Nonlinear figures of merit at the same experimental conditions as in Figs. 2 and 3.

the real-valued dielectric constant dispersion curve to higher energies. In the region 1480–1500 nm, moderate saturation of absorption and Δn results in comparatively poor F. Both the linear refractive index and the absorption peak locally near the excitonic feature (wavelengths 1500–1530 nm). A strong saturation of absorption in this spectral region results in a large nonlinear index change, giving large F. In the 1510–1520 nm region we report index changes well in excess of 0.1, with F in excess of 1. In the spectral region 1530–1550 nm, absorption is effectively washed out at increasing fluences. This combined with moderate Δn to produce large F. At 1550 nm we report an index change of 0.04 with a very good F: in our material, the signal would experience a π nonlinear phase change during propagation over about 6 μm, during which it would lose only about 1 dB of power. It would experience this phase change at fluences of 46 μJ/cm^2—corresponding to about 5 mW average power in a 1 μm^2 waveguided mode.

The strong saturation of absorption and large nonlinear index change reported in this letter are comparable in magnitude to effects previously reported[9–11] and predicted[2–8] in other bulk and MQW semiconductor materials. The nonlinear index changes predicted in continuous wave experiment of Ref. 6 are calculated to be at most $\Delta n = -0.05$. The figures of merit as implied by the results in Ref. 6 are higher than in the sample analyzed here since full saturation of absorption is reported in Ref. 6. Measurements reported in Ref. 2 were done at low intensity, when absorption is still high and nonlinear index change low. The nonlinear figures of merit presented in this letter cannot be directly compared with those estimated from the measurements in Refs. 7–10. The nonlinear pump-probe measurements and corresponding analysis based on the Kramers–Kronig transformation predict how a strong beam at one wavelength influences weak signal at a different wavelentgth, but do not provide direct information how the strong signal would influence its own propagation.

In conclusion, we have directly measured with picosecond pulses the saturation of absorption and negative nonlinear index changes in the $In_{0.530}Al_{0.141}Ga_{0.329}As/In_{0.530}Ga_{0.470}As$ MQWs. We have calculated associated loss-related nonlinear figures of merit. At wavelengths in the vicinity of 1.5 μm we have observed nonlinear index changes greater than $|\Delta n| > 0.1$ with acceptable figures of merit. The fluences required to effect the nonlinear index changes measured are similar to those inside a semiconductor laser.

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