Scaling of the Nonlinear Optical Cross Sections of GaAs–AlGaAs Multiple Quantum-Well Hetero n-i-p-i’s


Abstract—We study the dependence of the Stark shift optical nonlinearity of GaAs–AlGaAs multiple quantum-well hetero n-i-p-i’s on the number of quantum wells per intrinsic region in otherwise identical hetero n-i-p-i’s. We determine that $\sigma_{ch}$, the nonlinear absorption cross section, is proportional to the number of quantum wells per intrinsic region. A study of the fluence dependence of $\sigma_{ch}$ shows that the saturation carrier density is inversely proportional to the number of wells per intrinsic region. We find that the turn-on time of the nonlinear absorption change in our samples is independent of the number of quantum wells per intrinsic region. All of these results are consistent with the absence of retrapping of photogenerated carriers.

I. INTRODUCTION

MULTIPLE quantum wells placed in the intrinsic regions of a p-i-n diode (p-i(MQW)-n) have been used in practical nonlinear optical devices such as the self-electrooptic effect device (SEED) [1], [2] and the semi-insulating multiple-quantum-well photorefractive device (SI-MQW) [3], [4]. Devices containing p-i(MQW)-n’s are attractive for practical applications because they have a large optical nonlinearity due to the quantum-confined Stark effect [5]. The large optical nonlinearity is achieved because any carriers that are injected into one quantum well can, in principle, screen the electric field experienced by all of the quantum wells in the intrinsic region of the p-i(MQW)-n [6]. Self-electrooptic effect devices and SI-MQW’s must operate at large voltages (up to $\approx 20$ V) to obtain an electric field of $\approx 100$ kV/cm, across the 1-2 optical absorption depths necessary for practical devices. At present, there is considerable interest in integrated optical and electrical devices, such as smart pixels and optical interconnects. Because of their large optical nonlinearities, SEED’s and other p-i(MQW)-n structures are attractive candidates for use in such applications. For practical devices in which electronics and optics are integrated, it is highly desirable to have optical components that use voltages low enough (1-2 V) to be compatible with the electrical components [7]–[9].

A structure that can achieve the combination of large electric field, long optical path length, and low voltage operation is the interdigitated multiple quantum-well hetero n-i-p-i [10]–[14], which consists of a stack of p-i(MQW)-n’s, in which each intrinsic region is $\approx 100$ nm thick and contains a few quantum wells.

A convenient figure of merit for p-i(MQW)-n’s, which is a measure of their suitability in SEED’s or SI-MQW’s, is $\sigma_{ch}$, the nonlinear absorption cross section. This cross section is defined as the ratio of the optically induced absorption coefficient change to the number density of electron–hole pairs photogenerated in a quantum well. In an S-SEED, for example, $\sigma_{ch}$ is related to the energy required to change the state of the device [6], so, in general, structures with a small $\sigma_{ch}$ will require more optical energy to switch. In photorefractive applications, materials with large values of $\sigma_{ch}$ will perform better (i.e., give a larger diffraction efficiency) than materials with small $\sigma_{ch}$ because a larger change in the absorption coefficient will be achieved for the same number of absorbed photons [15]. The nonlinear absorption cross section of p-i(MQW)-n’s is expected to depend on the number of quantum wells per intrinsic region; structures containing more quantum wells per intrinsic region should have larger values of $\sigma_{ch}$.

A disadvantage of the interdigitated hetero n-i-p-i is that the number of quantum wells per intrinsic region is expected to be small, which should give a small $\sigma_{ch}$. In this paper, we quantify the dependence of the nonlinear absorption cross section on the number of quantum wells per intrinsic region by measuring the optically induced absorption coefficient change in a set of multiple quantum-well hetero n-i-p-i’s that contain different numbers of quantum wells per intrinsic region. We also investigate the saturation behavior of the optically induced absorption coefficient change.

The switching energies of the SEED’s that have been described in the technical literature [8], as well as those that are commercially available [16], are significantly higher than one would estimate from the quantity of charge required to screen the electric field [6]. In other words, to switch an S-SEED, it is necessary to optically inject more charge than is required to screen the field in an equivalent capacitor. This effect, which is equivalent to a reduction in $\sigma_{ch}$, has been attributed to the trapping and recombination of photogenerated charge in quantum wells before that charge can drift to the doped regions [17]–[19]. As well as reducing the nonlinear absorption cross section, carrier retrapping should also increase the time required for the optical nonlinearity to form, as the
transport rate of carriers from the quantum wells in which they are generated to the doped regions will be reduced as they are trapped and escape again. We investigate this effect in multiple quantum-well hetero $n$-i-$p$-$i$'s by temporally resolving the formation of the nonlinearity.

II. NONLINEARITY SCALING AND SATURATION

The dependence of the nonlinear absorption cross section on the number of quantum wells in the intrinsic region of a hetero $n$-i-$p$-$i$ may be determined by considering the structure of the hetero $n$-i-$p$-$i$ and the mechanism of the nonlinearity. Multiple quantum-well hetero $n$-i-$p$-$i$'s are semiconductor structures that consist of alternating $n$- and $p$-doped layers, between which are intrinsic regions that contain quantum wells. One period of each of the hetero $n$-i-$p$-$i$'s that we study is sketched in Fig. 1. In our structures, the $n$- and $p$-doped layers are completely depleted. Each intrinsic region therefore contains an identical built-in electric field, $E_{bi}$. The built-in electric field shifts the quantum-well excitonic transitions to longer wavelengths via the quantum confined Stark effect [5]. We study the nonlinear change in the absorption coefficient caused by carriers which are photoionized into the quantum wells, from which they escape, drift to the doped regions, and screen the built-in electric field, causing the excitonic transitions to shift back to shorter wavelengths. To see how the per-carrier optical nonlinearity depends on the number of quantum wells in each intrinsic region, consider a single $p$-i(MQW)-n region of a multiple quantum-well hetero $n$-i-$p$-$i$, which contains $n$ quantum wells of width $w$. If the doped regions have a total thickness $d$, and the dopant density is $N_d$, the built-in electric field, $E_{bi}$, will be given by

$$E_{bi} = N_d d / 2 \varepsilon_0 \varepsilon_r$$

(1)

where $\varepsilon_0$ is the permittivity of free space, and $\varepsilon_r$ is the relative permittivity of the semiconductor. If a number density $N$ of carriers is optically injected into each quantum well, and if all these carriers escape from the wells and drift to the doped regions, the change in the electric field will be $\Delta E$, where

$$\Delta E = n N w / \varepsilon_0 \varepsilon_r$$

(2)

The energy of the excitonic line center depends approximately quadratically on applied electric field [6], but for small changes in the electric field the change in the energy of the excitonic line center, $\Delta \varepsilon$, may be approximated by $\Delta \varepsilon \propto -2 E_{bi} \Delta E$. For $\sigma_{ch}$ to be a useful figure of merit for comparing optical nonlinearities, it is necessary that $\Delta \alpha$ be a linear function of carrier density over the fluence range of interest. It is easy to show that $\Delta \alpha$, the absorption coefficient change caused by a shift of the excitonic line, is proportional to the change in the energy of the excitonic line center for shifts that are small compared to the excitonic line width. Therefore, $\Delta \alpha$ is proportional to the number of quantum wells in each intrinsic region, i.e., $\Delta \alpha \propto n N w / \varepsilon_0 \varepsilon_r$. Recall that the nonlinear absorption cross section, $\sigma_{ch}$, is given by

$$\sigma_{ch} = \Delta \alpha / N$$

(3)

so we expect that the nonlinear absorption cross section is proportional to the number of quantum wells per intrinsic region in multiple quantum-well hetero $n$-i-$p$-$i$'s.

The nonlinear absorption cross section is used as a figure of merit to quantify the excitonic bleaching optical nonlinearity of MQW's [6], [20]–[23], in which the photogenerated carriers remain in the quantum wells. Although carriers leave the quantum wells and drift to the doped regions in $p$-i(MQW)-n's, $\sigma_{ch}$ is still useful as a figure of merit if $N$ is redefined as the number of electron–hole pairs per unit volume injected into the quantum well. In this case, $\sigma_{ch}$ still relates the nonlinear change in the optical properties to the number of carriers used to cause that change.

The saturation behavior of $p$-i(MQW)-n's, i.e., the dependence of $\Delta \alpha$ on the number density of injected carriers, is also important when considering them for use in practical devices. In this paper, we study a set of multiple quantum-well hetero $n$-i-$p$-$i$ samples, each of which contains the same total number of quantum wells, although individual hetero $n$-i-$p$-$i$'s have different numbers of quantum wells per intrinsic region. Before optical excitation, each quantum well in each sample experiences the same built-in electric field. Therefore, $\Delta \alpha_{sat}$ should be similar for each sample, because each sample contains the same number of quantum wells, each of which can experience the same electric field change. This maximum absorption change will occur when sufficient carriers are generated to screen totally the identical built-in fields.

III. SAMPLES

A set of three [100]-oriented GaAs–AlGaAs hetero $n$-i-$p$-$i$'s was grown by molecular beam epitaxy (MBE). As shown in Fig. 1, each sample contained either one, two, or four quantum wells per intrinsic region. Each sample contained a total of 32 quantum wells. Specifically, one sample (hereafter referred to as W1) contained 16 $n$-i-$p$-$i$ periods with a single well per
intrinsic region; another (W2) contained 8 periods with two wells per intrinsic region; and the other (W4) contained four periods with four wells per intrinsic region. In all samples, the barriers and doped regions were Al0.15Ga0.85As, and the quantum wells were GaAs. The intrinsic regions were 130 nm wide, and the n- and p-doped regions were each 20 nm wide and were each doped to a density of $2 \times 10^{17} \text{cm}^{-3}$. Consequently, the built-in electric field, $E_{bi}$, in the intrinsic region of each of the hetero n-i-p-i samples should be the same, and was calculated to be $\sim 27 \text{ kV/cm}$. Each quantum well was 10 nm wide. During growth, great care was taken to minimize differences between the quantum wells in the three samples. The samples were grown in successive runs on the MBE machine to ensure that the calibrations for AlGaAs alloy concentration and dopant density (and consequently the built-in electric field) varied as little as possible. In each case, a 1-$\mu$m-thick Al0.3Ga0.7As etch-stop layer and a 0.1-$\mu$m-thick GaAs buffer layer were grown between the hetero n-i-p-i and the substrate. To make the quantum-well excitonic transitions accessible in transmission measurements, the GaAs substrate was then removed by a selective etching technique [24], and single stack antireflection coatings were applied to the etched side of each hetero n-i-p-i to reduce Fabry–Perot effects.

To confirm that the quantum wells in each sample were similar, we measured the room temperature optical transmission spectrum of each sample. All samples exhibited prominent $n = 1$ heavy hole (hh) and $n = 1$ light hole (lh) excitonic transitions near 855 nm and 849 nm, respectively. The spectra were very nearly identical: corresponding spectral features had similar wavelengths and strengths. For example, the position of the $n = 1$ hh exciton varied less than 1.5 nm from sample to sample. The small quantitative differences among spectra were consistent with slight variations in the alloy composition, well width, or doping level.

IV. EXPERIMENTAL PROCEDURES

The nonlinear absorption cross section, $\sigma_{ab}$, of each hetero n-i-p-i was measured with a two-color pump-probe differential transmission technique. The pump and probe pulses were produced by two independently tunable dye lasers, which were synchronously pumped by frequency-doubled, compressed pulses from an actively mode-locked Nd:YAG laser. One dye laser was operated with Styril 9, and the other with LDS 867. Both produced mode-locked satellite-free pulses of approximately 1 ps duration. Each dye laser was cavity dumped at 1 MHz. The two cavity dumpers were synchronized, and the jitter between the pulses from the two dye lasers was determined by a cross-correlation measurement to be approximately $\pm 2$ ps.

To measure the cross sections, the Styril 9 dye laser was tuned to a fixed wavelength of 820 nm, and a pump pulse from that laser was used to inject carriers into the conduction and valence bands of the quantum wells, well above the hh excitonic resonance. The absorption change produced by these carriers was then monitored by a weak, time-delayed probe pulse from the LDS 867 dye laser, which was tuned across the $n = 1$ lh and hh excitonic transitions. The quantity actually measured was the differential transmission, which is defined by

$$\Delta T/T = (T_{on} - T_{off})/T_{off}$$

(4)

where $T_{on}$ is the transmission of the sample in the presence of the pump, and $T_{off}$ is the transmission in the absence of the pump. The differential transmission signal was acquired by chopping the pump beam at 27 Hz, chopping the probe beam at 2.1 kHz, and detecting the transmitted probe using a photodiode and lock-in amplifiers. The change in absorption coefficient, $\Delta \alpha$, was then extracted from these measurements using the relationship

$$\Delta \alpha = -(1/d) \ln(1 + \Delta T/T)$$

(5)

where $d$ is the total thickness of the quantum wells in the sample—320 nm in each case. These measurements were performed as a function of time delay, probe wavelength, and pump fluence.

Before performing cross-section measurements, we measured differential transmission as a function of probe delay to ensure that we selected a probe delay for measurements of the absorption cross sections such that the nonlinearity was fully formed, but had not decayed significantly. The observed temporal evolution of the differential transmission in samples W1, W2, and W4 was consistent with the carrier dynamics that we have previously reported in similar samples [25]. Specifically, immediately following carrier generation, the absorption change had a spectral signature that was consistent with excitonic bleaching due to phase space filling, indicating that most of the carriers remained in the quantum wells. Subsequently, within a few ps, this spectral profile was replaced by one consistent with a blue shift of the exciton, indicating that the carriers had escaped from the wells and had moved to screen the built-in field on this time scale. Consequently, at carrier densities below that required to totally screen the built-in field, the nonlinear response was dominated by the blue shift of the exciton caused by the screening of the built-in electric field. The spectral profile of the absorption change remained consistent with a blue shift until the spatially separated carriers recombined, which occurred on much longer time scales. Consequently, to ensure that the screening was complete but that there had been no significant carrier decay, we fixed the time delay between the pump and probe at 100 ps for all the measurements reported here.

When making measurements of the hetero n-i-p-i nonlinear absorption cross sections at a repetition rate of 1 MHz, we had to correct for the incomplete recovery of the sample between pulses. This was necessary because the recombination of the spatially separated carriers in a hetero n-i-p-i is extremely nonexponential; the recombination rate slows as the carrier number density decreases [26], [27]. In fact, although the initial rate can be as high as $10^9 \text{s}^{-1}$, complete recovery can require as long as $10^{-3} \text{s}$. Consequently, carriers will accumulate from pulse to pulse. For example, for sample W1, at an injected electron–hole pair density of $5.3 \times 10^{15} \text{cm}^{-3}$ in the wells, the remaining absorption coefficient change 1 $\mu$s after the pump pulse (i.e., probe delay of $-100$ ps) was $\sim 25\%$ of the peak.
TABLE 1
MEASURED PEAK ABSORPTION COEFFICIENT CHANGE, REFRACTIVE INDEX CHANGE, CHANGE IN ABSORPTION COEFFICIENT PER ELECTRON-HOLE PAIR, AND CHANGE IN REFRACTIVE INDEX PER ELECTRON-HOLE PAIR FOR SAMPLES W1, W2, AND W4

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of wells per intrinsic region</th>
<th>$\Delta \alpha_{sp}$ ($10^3 \text{ cm}^{-1}$)</th>
<th>$\sigma_{eh}$ ($10^{14} \text{ cm}^2$)</th>
<th>$\Delta n_{sp}$ ($10^3$)</th>
<th>$n_{eh}$ ($10^{19} \text{ cm}^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W4</td>
<td>4</td>
<td>0.78</td>
<td>14.7</td>
<td>8.2</td>
<td>15.5</td>
</tr>
<tr>
<td>W2</td>
<td>2</td>
<td>0.43</td>
<td>8.1</td>
<td>4.6</td>
<td>8.7</td>
</tr>
<tr>
<td>W1</td>
<td>1</td>
<td>0.20</td>
<td>3.8</td>
<td>2.4</td>
<td>4.5</td>
</tr>
</tbody>
</table>

value. The inferred number density of carriers remaining from the previous pulse(s) was approximately independent of the initial carrier density. Therefore, for higher excitation levels, the accumulation was a smaller fraction of the initial carrier density. In order to compensate for this accumulation, the $\Delta \alpha$ used in our calculations of $\sigma_{eh}$ is the difference between the absorption coefficient change at +100 ps and that at -100 ps, i.e., $\Delta \alpha = \Delta \alpha(+100 \text{ ps}) - \Delta \alpha(-100 \text{ ps})$. This correction for the residual carrier number density should have no effect on the calculated nonlinear absorption cross section if we are in the linear regime where there is negligible saturation of the nonlinearity. All our measurements were at low enough fluences that the samples were in this regime.

V. MEASUREMENT OF NONLINEAR CROSS SECTIONS

The dependence of $\sigma_{eh}$ on the number of wells per intrinsic region was illustrated two ways. In the first of these, we injected the same number of carriers into each quantum well of each of the samples by irradiating each of the three samples with the same fluence. Typical measurements of the change in absorption coefficient as a function of $\Delta \lambda$, the offset from the hh excitonic line center, are shown in Fig. 2 for a fixed injected electron–hole pair density of $5.3 \times 10^{13} \text{ cm}^{-3}$. Notice that the peak absorption change for the sample with two wells per intrinsic region is approximately twice that of the sample with one, and the change for the sample with four wells per intrinsic region is approximately four times as large as the sample with one. Values for $\sigma_{eh}$ can be obtained directly from Fig. 2 by dividing $\Delta \alpha$ by the number density of carriers injected into each well. Since the number of photogenerated carriers per well (and indeed the total number of photogenerated carriers per sample) is the same for each sample, it is clear that $\sigma_{eh}$ is proportional to $n$, the number of quantum wells per intrinsic region. The largest absolute values of $\sigma_{eh}$ (measured at the minimum of the feature associated with the hh exciton) are given in Table I, together with peak values for the change in absorption coefficient. We chose to use the peak negative value for these comparisons because the hh exciton partially overlaps the positive peak of the hh exciton feature, making the values of the per-carrier nonlinearity obtained at the positive peak less reliable for comparison purposes. It is interesting to note that the peak value of $\sigma_{eh}$ for W1, as displayed in Table I, is roughly equal to those obtained for the bleaching of excitons in quantum wells fabricated from GaAs/AlGaAs [28], InGaAs/InP [23], and (InAs/GaAs)/GaAs [29].

Fig. 2. Change in absorption coefficient as a function of wavelength for an injected electron–hole pair density of $5.3 \times 10^{13} \text{ cm}^{-3}$ in each well of samples W1 (circles), W2 (squares), and W4 (triangles). The solid lines are fits to the data made by assuming that the absorption coefficient change for each sample is due to the blue shift of two excitons (hh and lh) with a Lorentzian absorption profiles.

The solid lines in Fig. 2 are numerical fits to the data assuming blue-shifted Lorentzian profiles for the hh and lh excitonic features. In these fits, the widths of the Lorentzians were taken from the room temperature absorption spectra. The effect of the electric field screening was modeled as a blue shift of the absorption line, and the change in absorption coefficient was calculated as the difference between the shifted and unshifted lines, where the size of the shift was taken from the experimental $\Delta \alpha$ data. The value of the ratio between the strengths of the shifted and unshifted lines was left as a free parameter. It was found that a better fit to the data was obtained by increasing the amplitude of the blue-shifted exciton slightly. The latter is consistent with the expected increase in strength and narrowing of the excitonic feature as the electric field is screened and as the overlap of the electron and hole wave functions is increased [30]. Clearly, a good fit to the data is obtained despite the simplicity of the model.

The enhancement of $\sigma_{eh}$ with increasing number of wells per intrinsic region was demonstrated in a second way. In this case, we injected the same total number of carriers into each intrinsic region of each sample. This means that the density of electron–hole pairs injected into each well was four (two) times as large for the sample with one (two) well(s) per intrinsic region as in the sample with four wells per intrinsic region. Experimentally, this was accomplished by
irradiating samples W1 and W2 with fluences that were four and two times, respectively, the fluence used to excite W4. The results of measuring $\Delta \alpha$ as a function of detuning when the same total carrier density per unit area of $2.1 \times 10^{18} \text{cm}^{-2}$ was injected into each intrinsic region of each sample are shown in Fig. 3. Notice that the peak values for $\Delta \alpha$ are approximately equal for all three samples. Again, it is clear that the nonlinear absorption cross section is proportional to the number of wells per intrinsic region, since, for example, W4 had the same absorption coefficient change as W1 with only one-quarter as many carriers. This result also demonstrates that each well in each sample experiences the same degree of screening, despite the dramatically differing densities per well. That is, it demonstrates clearly that carriers from an individual well can move to screen and produce a blue-shift in all of the wells in an intrinsic region. The peak values of $\sigma_{eh}$ extracted from Fig. 3 for samples W1, W2, and W4 are $3.7 \times 10^{-14} \text{cm}^2$, $6.7 \times 10^{-14} \text{cm}^2$, and $1.4 \times 10^{-14} \text{cm}^2$, respectively. These are in good agreement with the values extracted from the data shown in Fig. 2 and presented in Table I, and they are approximately in the expected ratio of 1:2:4. Again, the solid lines in Fig. 3 are numerical fits to the data, using the same procedure as described for the fits shown in Fig. 2.

We compare our measured $\sigma_{eh}$ with a nonlinear absorption cross section for a p-i(MQW)-n structure with many quantum wells in the intrinsic region. In Fig. 4, we plot the measured values of $\sigma_{eh}$ tabulated in Table I against the number of quantum wells per intrinsic region. A straight line was fitted to our data and used to predict $\sigma_{eh}$ for a p-i(MQW)-n containing 60 quantum wells per intrinsic region. Measurements have been made of the nonlinear absorption of a p-i(MQW)-n structure containing 60 quantum wells similar to ours, albeit with higher barriers [18], [19]. The nonlinear absorption cross section was estimated from these measurements and is also plotted in Fig. 4. From the figure it can be seen that the linear relationship between $\sigma_{eh}$ and the number of quantum wells per intrinsic region suggested in Section II fails between four quantum wells per intrinsic region and 60 quantum wells per intrinsic region. This is consistent with the idea of carriers being trapped and recombining before reaching the doped regions [17]–[19].

The changes in refractive index, $\Delta n$, that correspond to the measured changes in absorption coefficient shown in Fig. 2 were calculated using a nonlinear Kramers–Kronig transformation [31]. The results of transforming both the data and fits to the data are shown in Fig. 5. The peak values of $\Delta n$, the change in the refractive index, obtained from the experimental $\Delta \alpha$ data are recorded in Table I. The ratios of the peak $\Delta n$ differ somewhat from the ratios of the peak $\Delta \alpha$ because of the presence of the hh lines and also because the slight differences in the widths of the hh excitonic lines from sample to sample. Because the Kramers–Kronig transformation involves an integral performed over all frequencies, the mutual discrepancies of the fitting parameters for the lh lines are reflected in the peak values of $\Delta n$. Also recorded in Table I are the peak values of the nonlinear refraction coefficient, $n_{eh}$, which is obtained from the refractive index change by $n_{eh} = \Delta n/N$.

**VI. SATURATION BEHAVIOR**

The saturation behavior of the hetero n-i-p-i's optical nonlinearity was investigated by measuring the peak absorption coefficient change at different carrier densities. This measurement was made at a probe delay of 100 ps, at the minimum of the feature associated with the hh exciton for each carrier density. The results are shown in Fig. 6 for injected carrier densities up to $6 \times 10^{16} \text{cm}^{-3}$. The solid lines in Fig. 6 are fits to the data of the form

$$\Delta \alpha = \Delta \alpha_{sat}/(1 + N_{sat}/N)$$

where $N$ is the density of carriers injected into each well, $N_{sat}$ is a saturation carrier density, and $\Delta \alpha_{sat}$ is the saturation absorption coefficient change. The values of $\Delta \alpha_{sat}$ and $N_{sat}$ used to fit each sample are listed in Table II.
intrinsic region to screen $E_{bh}$ by a certain amount is the same for each sample. The total number of carriers available to screen the field in an intrinsic region is proportional to the number of wells in that intrinsic region multiplied by the carrier density in each well. That is, the number of carriers necessary to screen the built-in field enough to change the absorption coefficient by $\Delta \alpha_{sat}/2$ is the same in each sample, and can be generated in the sample with four wells per intrinsic region at a fluence that is 1/4 of that needed in a sample with one well per intrinsic region.

Consequently, samples with more quantum wells per intrinsic region will exhibit a larger nonlinear optical response per carrier, but will have a linear response over a more limited fluence range than samples with fewer wells per intrinsic region. This tradeoff between the nonlinear cross section and linear dynamic range is illustrated in Fig. 6 by the straight line segments which represent the gradients of the fit curves near $N = 0$. Each line segment terminates when the fractional difference between it and the corresponding fitted saturation curve exceeds 15%. The slope of these lines is proportional to the cross section $\sigma_{eh}$. Therefore, it is clear that one can fabricate a structure that has a large per-carrier nonlinearity and exhibits a linear response over a small fluence range, or one that has a small per-carrier nonlinearity and exhibits a linear response over a large fluence range.

Finally, we have a comment on the limits of applicability for the saturation equation and the discussion surrounding it. This equation is only valid when the dominant nonlinearity is the blue shift associated with the screening of the built-in field. At sufficiently high fluences, only a fraction of the photogenerated carriers is needed to completely screen the field and flatten the bands. At such fluences, only a small portion of the carriers escapes the wells and moves to screen the built-in field. Many carriers remain in the wells, bleaching the excitonic transition. Consequently, as flat-band conditions are approached, the simplistic model discussed above must be replaced with one that includes phase space filling in addition to screening.

### VII. Measurement of Nonlinearity Formation

To investigate the effect of carrier retrapping, we time-resolved the formation of the optical nonlinearity in the hetero-$n$-$i$-$p$-$i$ samples. The formation time is determined by the time required for the optically generated carriers to escape the wells and to move to screen the built-in field experienced by all the wells. This measurement was made with a single color differential transmission apparatus; i.e., the pump and probe pulses were generated by the same dye laser. Measurements were made at low fluences with the laser tuned to the negative peak of the feature associated with the hh exciton of each sample. The same number of electron–hole pairs was injected into each intrinsic region of the three samples, so the ratio of the pump fluences was 1:2:4 for samples W4, W2, and W1, respectively. The results are shown in Fig. 7; notice that the curves are almost identical. An equation of the form $\Delta \alpha(t) = b(1 - a \exp(-t/\tau))$, where $a$ and $b$ are constants and $\tau$ is the time constant for the nonlinearity formation, was
used to fit the data. (The fit curves are not shown.) The time constant, \( \tau \), for the nonlinearity formation was found to be the same within experimental error, approximately 11 ps, for each sample. Therefore, we see no evidence of carrier retrapping in these samples. It should be noted, however, that our samples contain at most four quantum wells in an intrinsic region that is 130 nm long, whereas SEED's contain 60–100 quantum wells in an intrinsic region that is approximately 1 \( \mu \)m long. Therefore, there is much more scope for carrier retrapping and recombination in the SEED than in the hetero n-i-p-i [18], [19].

VIII. SUMMARY AND CONCLUSION

We have used two-color spectrally resolved and picosecond temporally resolved differential transmission techniques to measure the dependence of the nonlinear optical properties of multiple quantum-well hetero n-i-p-i's on the number of quantum wells per hetero n-i-p-i period. In so doing, we measured the nonlinear absorption cross sections, saturation carrier density, and range of linear response of three samples that were identical except for the number of quantum wells per intrinsic region: one had one well, another had two wells, and the last had four wells. We found that the nonlinear absorption cross section, i.e., the change in absorption coefficient per photo-injected electron–hole pair, was proportional to the number of quantum wells per intrinsic region, while the saturation density per well was found to be inversely proportional to the number of wells. Since the maximum change in the absorption coefficient is the same in each sample, these results indicate that we can readily trade sensitivity (defined as nonlinear absorption change per carrier) for dynamic range (fluence range over which a linear response is obtained) in device applications by varying the number of wells per n-i-p-i period. In other words, one can fabricate a structure which has a large per-carrier nonlinearity over a small fluence range, or one which has a small nonlinearity over a large range. Finally, we found that the turn-on time for the nonlinearity was the same in each sample, and we concluded that no significant carrier retrapping occurred. This result is consistent with the scaling of the nonlinearity.

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