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Recovery dynamics in proton-bombarded semiconductor saturable absorber mirrors

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Reduction of device response time, resulting from the proton bombardment of InGaAs/InP-based semiconductor saturable absorbers, was studied experimentally using an ultrafast degenerate, cross-polarized pump-probe technique. Proton bombardment is shown to reduce device response times to ~1 ps at low optical excitation densities. Under high excitation, the device dynamics are dominated by induced absorption. The extended recovery of highly excited carriers appears to be less sensitive to defects created by bombardment. Mode locking was demonstrated with the proton-bombarded samples in an erbium-doped fiber laser.
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Semiconductor saturable absorbers have important applications in optical switching and mode-locked lasers.[1] Ideally, materials with relatively short recovery times, which maintain high nonlinearities and low nonsaturable loss, are required for these applications. High quality materials exhibiting recombination times on the order of nanoseconds are not adequate for high-speed (GHz) operation. Thus, for fast devices, lifetime reduction techniques, such as low-temperature (LT) growth or ion bombardment, are necessary. Bombardment methods have the advantage of requiring relatively simple post-growth processing steps. In this letter, we report a study of the effect of proton bombardment on InGaAs/InP 1.5 μm saturable absorbers. The dynamics of the devices investigated are similar to those reported in comparable structures.[2] For low optical fluences (where bleaching rather than absorption dynamics dominate), lifetimes have been reduced to ~1 ps, without significantly increasing the nonsaturable loss. Lifetimes of 2.5 ps have been reported for LT InGaAs,[3] and 1.7 ps for O^+ or Ni^+ implanted InGaAs.[4] In the high fluence regime ($F \gg F_{sat}$, the saturation fluence), relaxation of induced absorption was not significantly affected by the bombardment, ultimately limiting the bombardment-produced lifetime reduction. It is important to characterize devices at high fluences, as these conditions occur during the startup of lasers and in *Q*-switching regimes. The samples investigated were also used to mode lock an erbium-doped fiber laser.

The saturable absorber mirrors studied consist of a 22-pair AlAs/GaAs mirror, with greater than 99.9% reflectivity at 1.55 μm. The absorber region consists of a half-wave layer of InP, containing six centered InGaAs quantum wells (QWs) with a band edge of ~1.58 μm. The mirror was deposited by metal-organic chemical vapor deposition, and the InGaAs/InP QW structure via gas source molecular beam epitaxy. The structures investigated have an antireflection coating (a single $\lambda/4$ layer of Al_2O_3) deposited by electron-beam evaporation, following epitaxial growth. A single layer was chosen to facilitate flexibility in post-growth processing.

The nonlinear absorption of the saturable absorber structures was studied in reflection with a Ti:Sapphire-pumped optical parametric oscillator (OPO). The OPO produced ~150 fs pulses tunable from 1.4 to 1.6 μm, with a repetition rate of 82 MHz. A degenerate collinear cross-polarized pump-probe setup was used, allowing high fluence measurements. In addition, since these structures were used in laser cavities at normal incidence, the collinear setup accurately reproduced the laser cavity conditions. A short focal length lens (ranging from 6.24 to 11 mm) was used to focus the beams onto the sample. The change in reflection was measured as a function of pump-probe delay for pump excitation fluences ranging from ~4 to 1290 $\mu J/cm^2$. All measurements were performed with a pump-to-probe fluence ratio of 10:1. At the highest fluences, the probe alone produced bleaching; to avoid this, a pump-to-probe ratio of ~500:1 is required.[2] However, the 10:1 pump-probe fluence ratio allows qualitative study of bleaching and absorption dynamics with their respective time constants, over a large fluence range. It has been shown that measurements with perturbational probe energies have yielded similar results.[5]

Initially, the dynamics of a nonbombarded structure were investigated. In Fig. 1, pump-probe traces are shown for a variety of fluences, ranging from the point of maximum modulation depth (~13 F_{sat} where F_{sat}~3.5 $\mu J/cm^2$) to even higher fluences (~369 F_{sat}). There are several different response regimes apparent. At low fluences, the response of the absorber consists of a fast bleaching component (spectral hole burning), followed by a slow component that is deter-

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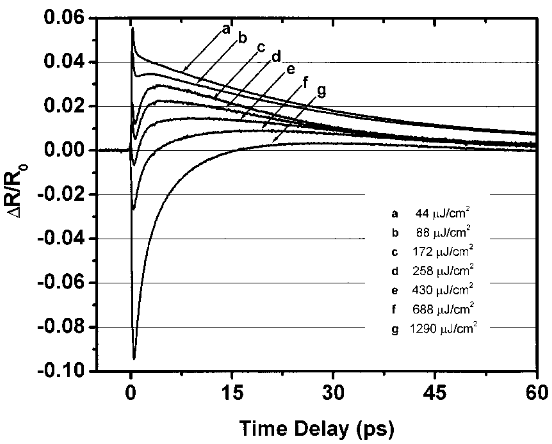

FIG. 1. Differential reflectivity measurements as a function of excitation fluence at 1.54 μm. The sample was nonbombarded. The change in reflection $\Delta R/R_0=(R-R_0)/R_0$ (R, R_0: reflection with and without the pump, respectively) is plotted as a function of delay between the pump and probe pulses.

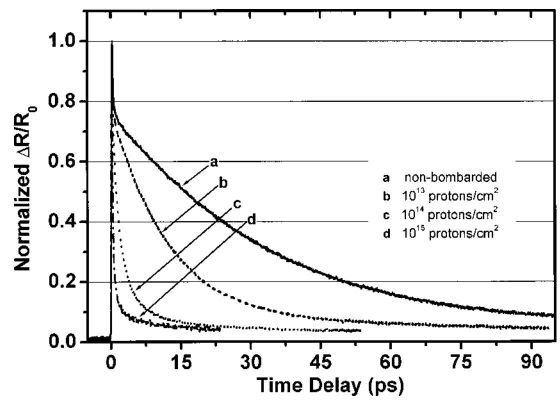

FIG. 2. Differential reflectivity measurements as a function of bombardment at 1.54 μm and a fluence of $\sim$44 μJ/cm^2. Normalized data is plotted to allow comparison.

mined by the carrier recombination time. Throughout the range of fluences, the recovery time for the nonbombarded sample remains constant, $\sim$40 ps, considerably shorter than the nanosecond recovery times observed in lattice-matched samples. Defect states at the InP/GaAs interface, due to the significant lattice mismatch, are the most probable cause of this lifetime shortening.[2] Exponential fits indicate a longer lasting residual component, recovering on the order of a few hundred picoseconds. The longer lasting components may be caused by residual temperature changes or absorption due to longer-lived trapped carriers.

At higher fluences, an additional nonequilibrium carrier dynamic with a time constant of $\sim$1 ps becomes apparent (Fig. 1, time delay $<$ 5 ps, F$\sim$88 and 172 μJ/cm^2). The $\sim$1 ps time constant is due to the cooling of hot carriers[6] via carrier–phonon scattering that subsequently causes an increase in bleaching by state filling at the bottom of the band. The details of the dynamics in this nonequilibrium regime under various experimental conditions have been the subject of previous work.[2,5,7,8]

The longer recovery, at increased fluence (Fig. 1, F $\sim$172 and 258 μJ/cm^2), requires a dual exponential fit: one negative exponential (representing the effects of induced absorption) and one positive exponential (representing the effect of carrier recombination). Also, in this high fluence regime, the effect of two-photon absorption (TPA) reduces the spectral hole-burning peak. At extremely high fluences ($F \gg F_{sat}$, F$\sim$1290 μJ/cm^2), an induced absorption component, with a time constant of $\sim$4 ps, is observed. The induced absorption is the result of TPA and TPA-induced free-carrier absorption (FCA). Several different mechanisms may be responsible for the extended relaxation of the induced absorption:[5] carrier capture outside the InGaAs QWs,[9] carriers trapped in satellite valleys,[10] or phonon bottleneck effects.[11]

Figure 2 shows pump-probe traces at low fluence from a nonbombarded structure and from structures bombarded with 40 keV protons, of differing doses. (Normalized data is plotted to allow comparison.) Bombardment energies were chosen to produce maximum damage within the QWs. Device response times are respectively: nonbombarded 40 ps; 10^{13} protons/cm^2 $\sim$12 ps; 10^{14} protons/cm^2 $\sim$3 ps; and 10^{15} protons/cm^2 $\sim$1 ps. The decrease in lifetime is also accompanied by a small increase in nonsaturable loss (a few percent) and a decrease in maximum modulation depth (from $\sim$5.8% to $\sim$4%), consistent with observations in LT GaAs.[12] To reduce the nonsaturable loss in the 10^{15} protons/cm^2 sample, annealing was investigated. A 20 s 325 °C anneal increased the modulation depth by one-third, while reducing the nonsaturable loss by 1%–2%. Also, the time constant lengthened slightly to 1.6 ps. The saturation fluence of the absorbers did not appear to change significantly with bombardment. Even in the 10^{15} protons/cm^2 sample, from the pump-probe data, we did not observe evidence of amorphous layers, which can result from bombardment with heavier ions.[13,14]

The fluence-dependent dynamics for a 10^{15} protons/cm^2 absorber are shown in Fig. 3 (note the time scale difference from Figs. 1 and 2). Proton bombardment does not appear to drastically affect the cooling time constant. This is expected, since proton bombardment primarily affects the interband dynamics, and cooling is an intraband process. The cooling time decreases from $\sim$1 ps for the nonbombarded to $\sim$0.6 ps for the 10^{15} protons/cm^2 sample. Due to the rapid absorber recovery time, in the case of the 10^{15} protons/cm^2 sample, cooling dynamics appear at higher fluences than those of the nonbombarded absorber (Figs. 2 and 3).

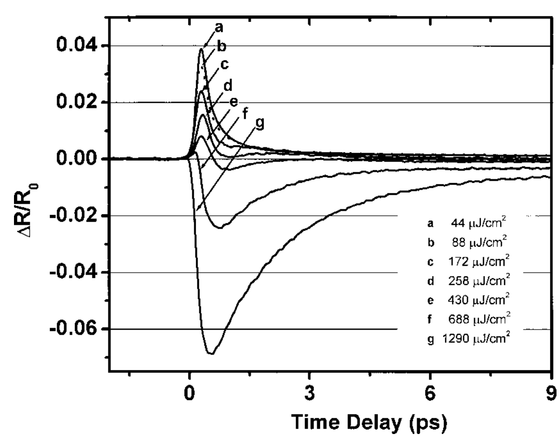

FIG. 3. Differential reflectivity measurements as a function of excitation fluence at 1.54 μm. The sample was bombarded with 40 keV protons, at a dosage of 10^{15} protons/cm^2.

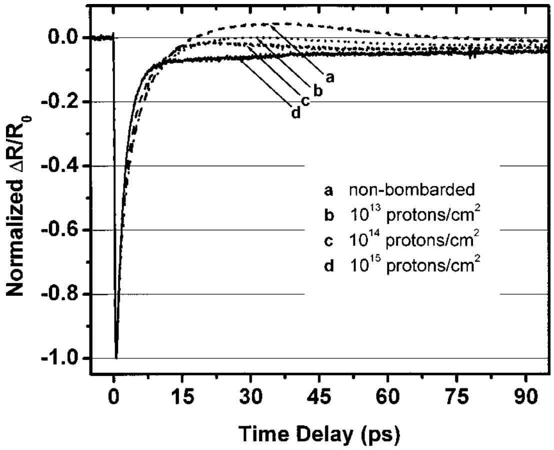

FIG. 4. Differential reflectivity measurements as a function of bombardment at 1.54 μm and a fluence of 1290 μJ/cm^2. Normalized data is plotted to allow comparison.

As fluence is increased to levels where significant induced absorption occurs (Fig. 3, F$\sim$688 and 1290 μJ/cm^2), it is clear that the device response time is limited by the nonequilibrium absorption dynamics. The 10^{15}protons/cm^2 absorber no longer recovers in $\sim$1 ps at these fluences; rather, the induced absorption recovers on the order of 2 ps. In this high fluence regime, the device is no longer functioning as a saturable absorber; instead, it functions as an intensity limiter. Pump-probe traces for nonbombarded and bombarded samples at F$\sim$1290 μJ/cm^2 are shown in Fig. 4. From the data, it is apparent that the relaxation of the excited state absorption is not affected significantly by the proton bombardment. In a nonbombarded sample, the induced absorption relaxation occurs in $\sim$4 ps; in the 10^{15} protons/cm^2 absorber, $\sim$2 ps. Because proton bombardment mainly affects interband (recombination) processes, the insensitivity of the intraband induced absorption relaxation to bombardment is not surprising. Saturation of defect states can also reduce the effectiveness of the bombardment. The results presented here indicate that the slower intraband relaxation times can ultimately limit the lifetime reduction produced by proton bombardment.

The induced absorption signal has contributions from both the InGaAs and the InP, as there are significant TPA and TPA-induced FCA components. Proton bombardment has similar lifetime reduction effects in InP (Ref. 15) as in InGaAs. The persistent negative step (Fig. 4, time delay $>$ 75 ps) reflects photoinduced absorption (PIA), the absorption of carriers trapped in defect states and has been observed in both LT grown and bombarded materials.[13,16]

Finally, bombarded samples were successfully used to mode lock a linear erbium-doped fiber soliton laser, producing subpicosecond pulses. Self-starting mode locking was observed for samples dosed with 10^{13} protons/cm^2 and 10^{14} protons/cm^2. With the 10^{15} protons/cm^2 sample, self-starting was not observed, but mode locking was initiated by translating the absorber. No significant differences in lasing threshold were observed between the three samples, validating the small nonsaturable loss increase with bombardment.

In conclusion, proton bombardment has been shown to reduce saturable absorber recovery times to $\sim$1 ps for low optical fluences. At higher fluences, recovery times were limited by slower intraband relaxation that is essentially unaffected by bombardment. Such high fluence conditions may be important for the startup of lasers and *Q*-switched mode locked regimes. Samples were shown to modelock a fiber laser, and show potential for high-repetition rate system applications.

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