Strain effect on the optical nonlinearity in an InGaAs/GaAs asymmetric Fabry–Perot modulator

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The effect of strain on the optical nonlinearities and operation of an all-optical asymmetric Fabry–Perot étalon is investigated. A high reflectivity modulation of 60% is reported with a contrast ratio of 12.2:1 and insertion loss of 1.87 dB. High contrast is achieved through absorption matching requiring a thick active layer. The effect of a thick structure on the strain reduced saturation carrier density is measured. The saturation density is calculated to be a factor of 2.5 less than in a similar GaAs modulator, showing thicker strained devices still display the advantages of thinner structures.

Many strained optical devices such as diode lasers and modulators, exploiting both electro-optic[1,2] and all-optical nonlinearities,[3] have been demonstrated with InGaAs as the active layer grown on GaAs. These devices have very good operating characteristics, despite the considerable lattice mismatch inherent in their growth. Strained lasers in particular have very low threshold currents.[4,5] It is widely believed that some of the advantageous characteristics of strained lasers are due to the strain modified valence band structure.[6] This modified band structure may also affect the operation of strained nonlinear devices dependent on optically generated carriers, as any change in the dispersion of the valence band will affect the density of states and, hence, the nonlinear properties of the strained layer. Indeed it has been shown recently that there is a significant decrease in the saturation carrier density in strained InGaAs quantum wells.[7] In this letter we will present the results of an investigation into the nonlinear saturation characteristics of the band edge absorption in a strained normally off nonlinear all-optical asymmetric Fabry–Perot modulator (AFPM). To achieve maximum contrast ratio in this type of device, it is necessary to have a high total absorption of the order of $\alpha d = 0.6$, with absorption α (cm^{-1}) and absorber thickness d (cm).[8,9] To achieve such high absorption active layers of the order of 30–50 periods of 10–15 nm quantum well/barrier pairs must be grown. Such thick wells and active layers have been shown to approach or exceed the critical layer thickness beyond which strain relief is significant.[10,11] As the reduction in saturation density (N_{sat}) in Ref. 7 is for a relatively thin sample with only 15 5-nm $\mathrm{In_{0.15}Ga_{0.85}As}$ wells, it is expected that a thicker structure in a working modulator would adversely affect the reduction in N_{sat} as the layer relaxes. To see if there is a significant disadvantage to using thicker structures we have investigated the nonlinear saturation density in an asymmetric Fabry–Perot modulator with good operating characteristics. The AFPM achieves a reflection modulation of about 60% with good contrast ratio and low insertion loss. We will show that even though the total thickness of InGaAs was over 5× greater than that in Ref. 7 the saturation density is still reduced by a factor of 2.5 as compared to a similar unstrained GaAs device.

Nonlinear asymmetric Fabry–Perot devices have shown great promise for all-optical modulation.[9,12] An AFPM with a GaAs/AlGaAs multiple quantum well (MQW) absorbing cavity has achieved a very high contrast ratio of 180:1 and reflectivity change of over 75%.[12] The reflectivity of an AFPM at resonance is critically dependent on the cavity absorption. An AFPM cavity is said to be impedance matched when the cavity absorption leads to an effective reflectivity for the back mirror equal to that of the front mirror. The impedance matching absorption condition is such that

$$R_f = R_b \exp(-2\alpha d), \tag{1}$$

where R_f is the front mirror reflectivity, R_b is the back mirror reflectivity, α is the cavity absorption, and d is the absorber thickness. With the cavity impedance matched, the on-resonance reflectivity is zero. If the cavity absorption can be controlled it is possible to modulate the reflectivity of the AFPM. In our experiments we exploit nonlinear absorption saturation at high optically generated carrier densities in the MQW layer of the device to control the reflectivity. Any dispersion present will also affect the reflectivity, as it will result in a change in the optical thickness of the cavity and a shift of the AFPM resonance away from the operating wavelength.

The device was grown by molecular beam epitaxy (MBE) and consists of a GaAs substrate with a 15.5 period AlAs/GaAs dielectric Bragg stack high reflector, designed to give a reflectivity of 97% at 970 nm. Above this was a MQW region of 29.5 $\mathrm{In_{0.1}Ga_{0.9}As/GaAs}$ 150 Å/150 Å quantum well/barrier pairs. As the device was originally designed as an electro-optic device[2] it is capped with a 0.2-μm GaAs contact layer which also acts as the 30% air-semiconductor interface front mirror. The Bragg stack mirror and capping layer were doped n^+ and p^+, respectively. The MQW region was not intentionally doped but has a residual n-doping of around 3×10^{15} cm^{-3}. The dop-

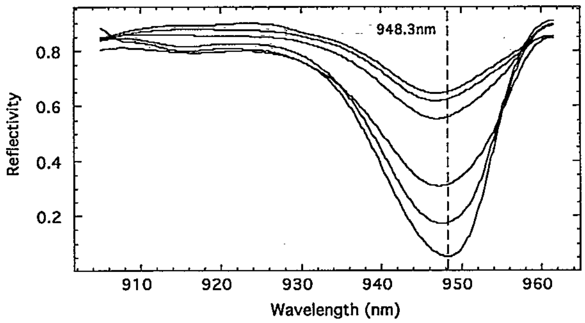

FIG. 1. Reflectivity spectra of the strained $In_{0.1}Ga_{0.9}As$ AFPM at various pump powers. The AFPM resonance is overlapped with the heavy-hole absorption at 948.3 nm to give a reflectivity of 5.3% at peak pump powers below 1 mW. The light-hole exciton can be seen in the low power spectra at 917 nm. The reflectivity at 948.3 nm increases to 64.7% for about 60-mW peak power onto the sample. A small shift of 1.4 nm in the position of the AFPM resonance can also be seen.

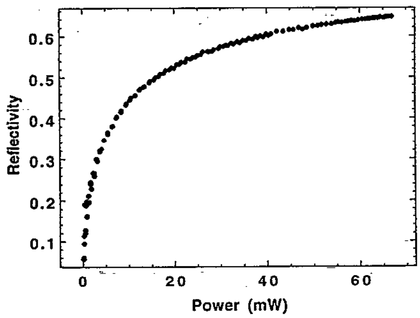

FIG. 2. Reflectivity dependence on incident power. The reflectivity at 948.3 nm increases with increasing incident peak power from 5.3% at 0.1 mW to 65% at 65 mW on a 5-μm spot. This corresponds to a contrast ratio of 12.2:1 and an insertion loss of 1.87 dB.

ing is not expected to play a significant role in the all-optical operation of this device. The MQW layer was designed so that the AFPM resonance and the heavy-hole (hh1) exciton absorption peak are spectrally overlapped. The number of wells should approach the correct cavity absorption to achieve impedance matching for an AFPM with $R_f=30\%$ and $R_b=97\%$ at low intensity. As the absorption is high for low incident powers the reflectivity is consequently low, the device is said to be "normally off". The sample is heavily crosshatched when viewed under a Nomarski interference microscope, indicating some strain relief and dislocation production has occurred. The effect of this dislocation production, and the associated change in thickness of the device, on the Fabry–Perot resonance should be minimal as the change in vertical dimension should be less than 0.2% of the total thickness. The effect of the strain relief on the expected reduction in saturation density is more interesting.

Reflectivity spectra at various powers of this device can be seen in Fig. 1. To avoid thermal effects at the higher input powers the titanium-sapphire laser output was modulated using an acousto-optic modulator to give 1-μs rectangular pulses at 0.1-ms intervals and focused onto the étalon at normal incidence (measured spot size 5 μm). In Fig. 1 the cavity and hh1 resonances are overlapped at 948.3 nm, yielding a low power on-resonance reflectivity of 5.3%. As the power increases onto the sample the reflectivity spectrum changes to give a reflectivity change of around 60% at 948.3 nm. This modulation corresponds to an insertion loss of 1.87 dB, and a contrast ratio of 12.2:1, with half that over 5 nm. A small shift in the position of the cavity resonance with increased power can also be seen. This is due to a small change of the order of −0.15% in the refractive index with absorption saturation.

Figure 2 shows the reflectivity at the cavity resonance as a function of incident power. As the peak power of the pulses increases the density of carriers in the MQW region also increases. The increased carrier density leads to a decrease in absorption due to nonlinear effects such as phase space filling, Coulomb screening, and Fermion exchange.[13] The decrease in absorption results in an associated increase in reflectivity up to a maximum of 65% for around 65-mW incident power. As the reflectivity is initially 5.3% and immediately begins to increase with the incident power, we can conclude that the cavity was, in fact, undercompensated and more absorbing material would be necessary to achieve full impedance matching.

To estimate the saturation carrier density it is necessary to calculate and fit the absorption dependence on the optically generated carrier density. The cavity absorption (cm^{-1}) can be easily calculated as the reflectivity at resonance is directly dependent on the absorption. Off-resonance absorption calculation is slightly more complicated and indeed Fig. 1 shows there is a small shift in the resonance as the incident power increases. The shift of about 1.4 nm results in a reflectivity increase from the resonance reflectivity of only about 0.5%. This means the resonance shift can be ignored when calculating the absorption without significantly affecting the absorption results. The absorption depends critically on the carrier density and the absorption saturation can be shown to follow a simple model[14] of the form

$$\alpha=\alpha_0+\frac{\alpha_1}{1+(N/N_{sat})}, \tag{2}$$

where α_0 is the unsaturable absorption, α_1 is the saturable absorption coefficient, and N_{sat} is the saturation carrier density (cm^{-3}). In order to calculate the carrier density for a given intracavity intensity, I_{cav}, it is necessary to also know the absorption for that input power and the carrier lifetime. The carrier density N (cm^{-3}) can then be calculated from the steady state equation[14]

$$N=\frac{\alpha(I_{cav})I_{cav}\tau}{E}, \tag{3}$$

where $\alpha(I_{cav})$ is the intensity dependent absorption, τ is the carrier lifetime, and E is the energy of the pump beam. The carrier lifetime was measured using a simple pump-probe measurement[15] giving a lifetime of around 400 ps. The short lifetime in the AFPM might be thought to be due to strain or strain relief, through nonradiative recombination at dislocation centers. However, we have recently

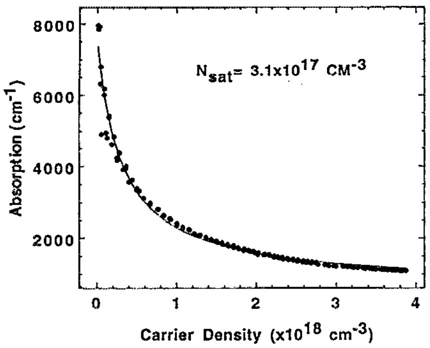

FIG. 3. Absorption dependence on carrier density. Absorption is calculated from the reflectivity measurements and carrier density is calculated from the absorption and intracavity intensity. The data fit well to a simple saturation model to give a saturation carrier density 2.5 times lower than for a similar GaAs AFPM.

shown that the lifetime in several InGaAs/AlGaAs samples, including this one, is independent of strain or strain relief.[16] The origin of the short lifetime remains undetermined. In Fig. 3 the absorption is plotted against the carrier density and the data clearly fits well to the simple absorption model in Eq. (2) to give a saturation carrier density of 3.1×10^{17} cm^{-3}. A similar calculation of the saturation density from the reflectivity modulation in a GaAs/AlGaAs AFPM[9] yields $N_{\text{sat}}=7.7\times10^{17}$ cm^{-3}. The saturation density in the strained device is a factor of 2.5 less than that of the similar GaAs device. This difference agrees well with a similar comparison of N_{sat} in strained and unstrained samples.[7] More importantly this result shows that even though there is over 5× more material in our device, as compared to that in Ref. 7, and some strain relief, as indicated by the crosshatching, the saturation density is not adversely affected, as the N_{sat} we measure is in fact smaller than in Ref. 7. This means that it is possible to grow thicker devices, with wider wells and a greater number of periods, and the probable associated strain relief does not affect the advantageous low saturation densities.

In conclusion we have reported on the operation of a strained normally off all-optical asymmetric Fabry–Perot modulator which achieves a modulation of 60% with a contrast ratio of 12.2:1 and an insertion loss of 1.87 dB. The carrier density necessary to saturate the heavy-hole absorption is a factor of 2.5 less than in a similar unstrained GaAs device. This reduction is due to the effect on the valence band dispersion that is a result of the InGaAs wells being compressively strained. This result is important as it shows that low saturation densities can be achieved in devices that require thick InGaAs strained layers to achieve good modulation. The origin of the short lifetime in this device is unclear and leaves open the possibility of achieving longer lifetimes in these strained materials. If the typical lifetime in InGaAs devices can be significantly improved, then long lifetimes coupled with the reduced saturation density hold the promise of very low power optical modulators and switches at the strategically important wavelength range of low-threshold strained lasers. Further work is underway to investigate the influence of various strain parameters on the saturation carrier density.

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[1] B. Pezeshki, D. Thomas, and J. S. Harris, IEEE Photon. Technol. Lett. **26**, 807 (1990).
[2] T. E. Sale, J. Woodhead, A. S. Pabla, R. Grey, P. A. Claxton, P. N. Robson, M. H. Moloney, and J. Hegarty, Appl. Phys. Lett. **59**, 1670 (1991).
[3] R. Jin, G. Khitrova, H. M. Gibbs, C. Lowry, and N. Peyghambarian, Appl. Phys. Lett. **59**, 3216 (1991).
[4] E. Yablonovitch and E. O. Kane, J. Lightwave Technol. **6**, 1292 (1988).
[5] R. L. Williams, M. Dion, F. Chatenoud, and K. Dzurko, Appl. Phys. Lett. **58**, 1816 (1991).
[6] I. Suemune, IEEE J. Quantum. Electron. **27**, 1149 (1991).
[7] R. Jin, K. Okada, G. Khitrova, H. M. Gibbs, M. Pereira, S. W. Koch, and N. Peyghambarian, Appl. Phys. Lett. **61**, 1745 (1992).
[8] M. Whitehead, A. Rivers, G. Parry, J. S. Roberts, and C. Button, Electron. Lett. **25**, 984 (1989).
[9] J. F. Heffernan, M. H. Moloney, J. Hegarty, J. S. Roberts, and M. Whitehead, Appl. Phys. Lett. **58**, 2877 (1991).
[10] I. J. Fritz, S. T. Picraux, L. R. Dawson, T. J. Drummond, W. D. Laidig, and N. G. Anderson, Appl. Phys. Lett. **46**, 967 (1985).
[11] R. Grey, J. P. R. David, P. A. Claxton, F. Gonzalez Sanz, and J. Woodhead, J. Appl. Phys. **66**, 975 (1989).
[12] J. F. Heffernan, M. H. Moloney, J. Hegarty, J. S. Roberts, and M. Whitehead, Optical Society of America Photonic Switching Topical Meeting, Salt Lake City, UT, 1991, Paper No. WE8-1.
[13] S. Schmitt-Rink, D. S. Chemla, and D. A. B. Miller, Adv. Phys. **38**, 89 (1989).
[14] M. H. Gibbs, *Optical Bistability: Controlling Light with Light* (Academic, New York, 1985).
[15] W. H. Knox, R. L. Fork, M. C. Downer, D. A. B. Miller, D. S. Chemla, C. V. Shank, A. C. Gossard, and W. Wiegmann, Phys. Rev. Lett. **54**, 1306 (1985).
[16] M. H. Moloney, J. Hegarty, L. Buydens, P. Demeester, R. Grey, and J. Woodhead, Appl. Phys. Lett. **62**, 3327 (1993).