Wavelength dependence of saturation and thermal effects in multiple quantum well modulators

G. D. Boyd, J. A. Cavaillès,[a] L. M. F. Chirovsky, and D. A. B. Miller
AT&T Bell Laboratories, Holmdel, New Jersey 07733

(Received 29 March 1993; accepted for publication 16 July 1993)

Experiments are described in biased AlGaAs/GaAs quantum well reflection modulators demonstrating that the degradation in continuous wave modulator performance due to absorption saturation at wavelengths $\lambda > \lambda_0$, is significantly reduced compared to that at λ_0, the zero field exciton wavelength, which in this case is 850 nm. This is of importance in the selection of operating wavelengths for the self-electro-optic effect device (SEED) used in photonic switching or optical interconnect applications.

Multiple quantum well (MQW) reflection modulators using the quantum confined Stark effect are currently used in photonic switching.[1] Current systems use the simple two diode symmetric self-electro-optic effect device (S-SEED),[2,3] whose typical switching energies are 1 pJ or more and operate at the zero field heavy hole exciton wavelength λ_0. The absorption coefficient decreases with applied field at λ_0, giving rise to bistability in S-SEEDs.[1] The reflectivity of a modulator increases with applied field, at λ_0, and so is normally off. For other applications simple modulation has often been investigated at longer wavelengths where the absorption increases with electric field. Define the wavelength λ_1, where $\lambda_1 > \lambda_0$, as the location of the shifted heavy hole absorption peak in the presence of some field E_h from an applied voltage V. At these longer wavelengths where absorption increases with electric field, the reflectivity decreases and the modulator is normally on. The S-SEED does not normally show bistability at λ_1. Only if the device includes a Fabry–Pérot and is designed to be normally off can one have bistability at λ_1.[4] Nevertheless in many applications, FET-SEEDs[5–7] for instance, bistability is not needed, so the choice of operating wavelength can be based on other criteria.

In switching these two classes of devices, normally off or normally on, between on/off states, the switching speed is proportional to the average power available up to the point where the intensity (power/unit area) is so high as to cause absorption saturation which degrades the change in reflectivity of the diode modulators and thus the contrast ratio. A figure of merit for quantum well modulators is the ratio of absorption coefficients with the field on and off.[4,8] Reduction in the change of absorption due to saturation is detrimental causing an increase in switching energy and a slowing of switching speed.

Previously[9–12] Morgan and Chirovsky *et al.* have observed that normally on modulators (operation at λ_1) exhibit less absorption saturation than those operating normally off (operation at λ_0). References 9 and 10 study saturation at λ_1 and Refs. 11 and 12 at λ_0. Improved saturation was fundamental to our recent demonstration of dynamic symmetric SEED operation at $\lambda_1 = 855$ nm.[13]

In this letter we will demonstrate this effect versus wavelength by observing the absorption spectrum at low and at high input intensities. A new experiment is described at a constant absorbed pump power that demonstrates that saturation as observed with cw excitation sources is worse when operating at the wavelength λ_0, where the change in absorption between field on and off approaches zero at high pump intensities (80 kW/cm^2), whereas the change in absorption when operating at λ_1 is not drastically reduced at the same pump intensities.

Fox *et al.*[14,5] have extensively studied sweep out and saturation in MQWs as have Cavaillès *et al.*[16,17] The saturation intensity versus voltage for various quantum wells are shown in their Fig. 1 (Ref. 14) (Fig. 7 of Ref. 15). The measurements are at the shifted heavy hole wavelength λ_1 for each voltage. Improved sweep out times were due to thinner barriers as pointed out by Fox *et al.*[15]

These papers show part but not all of the advantage of operation at λ_1. Once the excitonic absorption is bleached, significant interband absorption remains, on the edge of which the excitonic absorption peak usually rides at λ_0, the interband absorption hardly changes with applied field. However, in the absorption tail at the λ_1 wavelength with no field applied (almost no absorption) large interband absorption is introduced when enough field is applied. Thus there is still a large absorption change at λ_1 but none at λ_0, with applied field, after exciton saturation bleaching.

Our quantum well structure is similar to Fox's[15] thin barrier samples. We have 71 quantum wells of $Al_xGa_{1-x}As$ with $x=0.3$ barriers ($L_b=35$ Å) and GaAs wells ($x=0$, $L_w=100$ Å) having a zero field heavy hole absorption peak at 850 nm.

In our experiment the saturation of the excitonic absorption was produced with a continuous laser diode pump at a wavelength of $\lambda_p=786$ nm. The probe was a computer controlled cw $Ti:Al_2O_3$ laser (Spectra Physics 3900) tunable from 830 to 890 nm.

To avoid cw heating problems a low duty cycle (0.1 μs out of 2 μs) was used for the laser diode pump. The probe pulse was also a low duty cycle at the same repetition rate obtained with an acousto-optic modulator with a pulse width of 40 ns centered within the pump pulse duration. All pulses though were long compared to sweep out times.[14,15] Our setup also enabled us to investigate the

[a]Permanent address: 3 Rue de Mourabitine, Secteur Mixte, Agadir, Morocco.

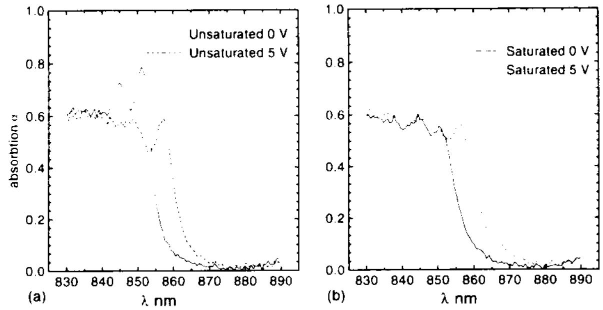

FIG. 1. The absorption coefficient (μm^{-1}) of the MQW reflection modulator as calculated from the ratio of reflected energy compared with that from Au metallization. The $Al_{(1-x)}Ga_xAs$ grown reflector quarter-wave stack of 15 pairs of $x=1.0$ and $x=0.11$ has a reflection coefficient $r_2=0.96$ and the assumed Au reflectivity is 0.92. In (a) the probe is prior to the laser diode pulse by ≈ 50 ns and in (b) they are coincident in time, the pump being ≈ 100 ns long. The diode is reverse biased with 0 or 5 V across the 1 μm MQW region.

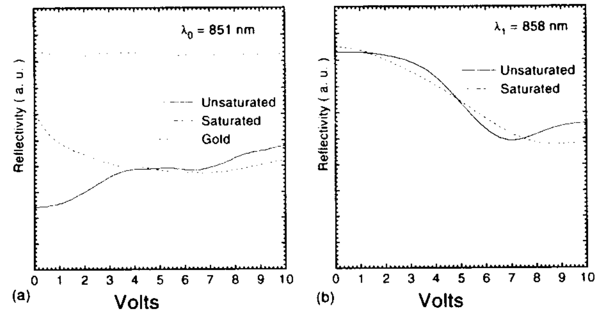

FIG. 2. The reflectivity vs voltage of the MQW device at two wavelengths corresponding to the heavy hole wavelength location at 0 and 5 V as observed in Fig. 1. The reflected signal is with saturation and without and the upper horizontal line represents reflection from Au.

modulator response as a function of delay of the probe pulse from the beginning of pump pulse so as to investigate thermal heating effects.

In Fig. 1(a) is shown the absorption coefficient calculated, according to Eq. (1), from the measured reflection coefficient R, where r_2 is the reflection coefficient of the underlying modulator mirror and d the modulator thickness. The top surface of the sample was antireflection coated:

$$\alpha=\ln(r_2/R)/2d. \qquad (1)$$

The measured absorption coefficient is somewhat less than previously observed[8] on similar structures perhaps due to a sharp focus of the probe (3.5-μm diameter) and the complex experimental geometry. The relative values of the absorption coefficient with and without field and saturation should be correct and are reproducible. Note in Fig. 1(a) that there is a large change in α for a change in applied voltage of 5 V at two wavelengths $\lambda_0=851$ nm, the normally off operation, and at $\lambda_1=858$ nm, the location of the shifted heavy hole at 5 V where operation is normally on.

Under exciton saturation conditions as seen in Fig. 1(b) observe that the change in absorption at the zero voltage exciton wavelength λ_0 at 851 nm almost disappears while at the shifted heavy hole wavelength λ_1 of 858 nm it is only slightly reduced. The average power in the pump beam (0.05 duty cycle) for this experiment is approximately 0.4 mW focused into a beam approximately 3.5 μm in diameter. The peak intensity is thus approximately 80 kW/cm^2. Fox reports[14,15] the saturation intensity at λ_0, the peak at 0 V, to be ≈ 6 kW/cm^2 (60 μW/μm^2) and at the shifted exciton peak λ_1 for 5 V as ≈ 20 kW/cm^2 (200 μW/μm^2). These saturation intensities are at the excitonic absorption peak only. Consequently, we are well into the full exciton absorption saturation region.

In Figs. 2(a) (for λ_0) and 2(b) (for λ_1) are shown the reflection signals (along with a normalization from Au versus voltage at each of the two wavelengths. The unsaturated (US) and saturated (S) reflectivity signals at 851 nm in Fig. 2(a) show a change between 0 and 5 V in the unsaturated reflectivity of a factor of 2/1.2, less than typical for a normally off device. The saturated absorption at 851 nm actually shows that the device has been converted to normally on even at λ_0 which can be explained as follows. Since the exciton absorption peak sits on the edge of the interband absorption, once that peak is saturated and the field applied, interband absorption can actually increase total absorption even at λ_0. In Fig. 2(b) for $\lambda_1=858$ nm,[4,8] observe that the change in reflectivity between 0 and 5 V is changed little by excitonic absorption saturation.

In Fig. 3 we show the measured absorption versus wavelength with the saturation pump pulse in place as in Fig. 1 for consistent average heating but with the probe pulse timed to arrive at different times with respect to the pump pulse. The delay time, -40 ns, means the probe is before the turn on of the pump pulse which in this case is extended to 600 ns with a repetition period of 2 μs. The absorption coefficient is plotted versus λ at different delay times at 0 V applied, Fig. 3(a), and 5 V applied, Fig. 3(b). In Fig. 3(b) observe at 862 nm the increase in absorption as the probe pulse is moved from near the beginning of the pump pulse at 100 ns to near the end at 540 ns.

In Fig. 4 we show plots of the reflectivity versus the delay of the probe pulse relative to the beginning of the pump pulse for two cases of $\lambda_0=851$ nm with 0 V applied and at 862 nm, with 5 V applied, a few nm above λ_1 (858 nm). Note the fall in reflectivity at 862 nm in the presence of an applied voltage. This we attribute to sensitivity to heating of the substrate by the current flow due to the applied voltage V at the location of the pump produced photocarriers. The local resistive heating is $I(V+V_{bi})$, where V_{bi} is the built in voltage of the diode, ≈ 1.5 V. Presumably the heating shifts the absorption causing an increase in absorption at the wavelength 862 nm. Note in Fig. 3(b) that there is little change in performance directly at 858 nm despite the heating. The photocurrent can be suppressed by proton implanting the samples, as recently demonstrated by Woodward *et al.*[18] Consequently such resistive heating in modulators can be reduced.

Sizer *et al.*[19] found a thermal relaxation time of approximately 40 ns. Previously[20] thermally induced optical bistability was studied. As a simple model consider a laser beam focused to a 3.5-μm-diam beam which is large com-

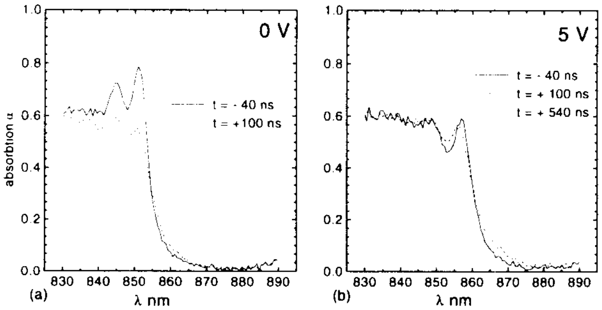

FIG. 3. Absorption coefficient in the presence of the saturation pulse only with (a) and (b) being at 0 and 5 V, respectively, and with the probe pulse being displaced in time relative to the pump pulse. A negative displacement means the sample is not saturated when the probe reflectivity is measured. In this experiment the pump pulse is 600 ns long.

pared to the multiple quantum well thickness $d=1$ μm. The thin layer of thickness d is uniformly heated by the incident laser beam in a short period (assuming a mode locked pulse source) after which the heat diffuses into the semi-infinite substrate. This problem is solved in Ref. 21 in terms of erf functions. At the top surface the temperature decays as

$$T(x=0,t)=T_0\sqrt{(t_0/t)}, \qquad (2)$$

where

$$t_0=d^2/\pi D, \qquad (3)$$

and from Ref. 22 the thermal diffusivity $D=0.24$ cm^2/s yields $t_0=13$ ns. Observe that the thermal diffusion into the substrate is functionally slow $(1/\sqrt{t})$ but at 13 ns is shorter than our 40-ns probe and shorter than the saturation pump which varies from about 50 to 600 ns in this letter. Consequently, the assumption of instantaneous heating by the pump is not valid and thus the MQW continues to heat up during the pump duration and the modulator performance degrades.

For both normally on and normally off devices whether at λ_0 or at λ_1, one state is at 0 V supplied and the other at several volts supplied. So for all of the above devices most of the heating occurs in one state, but not the other. Hence, the effect of IV heating on modulator performance will be different for different cycling rates and/or

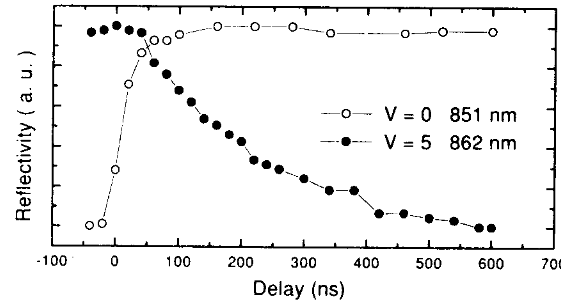

FIG. 4. An extraction of data from measurements as in Fig. 3 showing the change in reflection coefficient as the probe (40 ns) is displaced relative to the beginning of the pump pulse.

duty cycles. More sophisticated experiments are needed to ascertain properly how heating affects modulator performance. We have, nevertheless, identified IV heating as the main cause of thermal effects in a quantum well modulator consistent with Refs. 18 and 19.

We have measured the effects of cw saturation versus wavelength using a new technique with a short wavelength saturating pump pulse and a scanned wavelength probe beam. These measurements clearly show that the degradation in the change in reflectivity due to exciton absorption saturation is much less for wavelengths 5–10 nm beyond the exciton peak. Time resolved measurements indicated that absorption in the presence of an electric field induces such resistive heating as to seriously shift the exciton peak and interband absorption edge causing changes in the modulator performance.

The authors appreciate discussions with and help on this subject from our colleagues referenced and W. B. Joyce in Ref. 21. In addition, very helpful conversations with L. Carraresi, A. L. Lentine, and R. A. Morgan were of benefit at crucial points.

[1] D. A. B. Miller, Opt. Quantum Electron. **22**, S61 (1990).
[2] M. E. Price, N. C. Craft, M. M. Downs, R. E. LaMarche, L. A. D'Asaro, L. M. F. Chirovsky, and M. J. Murdocca, Appl. Opt. **30**, 2287 (1991).
[3] F. B. McCormick *et al.*, in *OSA Proceedings on Photonic Switching*, edited by H. S. Hinton and J. W. Goodman (Optical Society of America, Washington, DC, 1991), Vol. 8, pp. 48–55.
[4] G. D. Boyd, G. Livescu, L. M. F. Chirovsky, and A. M. Fox, in Ref. 3, pp. 222–226.
[5] D. A. B. Miller, M. D. Feuer, T. Y. Chang, S. C. Shunk, J. E. Henry, D. J. Burrows, and D. S. Chemla, IEEE Photon. Tech. Lett. **1**, 62 (1989).
[6] L. A. D'Asaro, L. M. F. Chirovsky, R. F. Kopf, and S. J. Pearton, in *Advanced Processing and Characterization Technologies*, edited by P. H. Holloway, American Vacuum Society Series 10, Conference Proceedings 227 (American Institute of Physics, Woodbury, NY, 1991), p. 192.
[7] T. K. Woodward *et al.*, IEEE Photon. Tech. Lett. **4**, 614 (1992).
[8] G. D. Boyd and G. Livescu, Opt. Quantum Electron. **24**, S147 (1992).
[9] R. A. Morgan, L. M. F. Chirovsky, M. W. Focht, and R. E. Leigenguth, Appl. Phys. Lett. **59**, 3524 (1991).
[10] R. A. Morgan, L. M. F. Chirovsky, R. E. Leigenguth, J. Opt. Soc. Am. B **9**, 858 (1992).
[11] R. A. Morgan, G. Livescu, L. M. F. Chirovsky, M. W. Focht, and R. E. Leigenguth, Opt. Lett. **17**, 423 (1992).
[12] R. A. Morgan, SPIE **1562**, 213 (1991).
[13] G. D. Boyd, L. M. F. Chirovsky, and R. A. Morgan, Appl. Phy. Lett. **59**, 2631 (1991).
[14] A. M. Fox, D. A. B. Miller, G. Livescu, J. E. Cunningham, and W. Y. Jan, Appl. Phys. Lett. **57**, 2315 (1990).
[15] A. M. Fox, D. A. B. Miller, G. Livescu, J. E. Cunningham, and W. Y. Jan, IEEE J. Quantum Electron. **27**, 2281 (1991).
[16] J. A. Cavaillès, D. A. B. Miller, J. E. Cunningham, P. LiKam Wa, and A. Miller, Appl. Phys. Lett. **61**, 426 (1992).
[17] J. A. Cavaillès, D. A. B. Miller, J. E. Cunningham, P. LiKam Wa, and A. Miller, IEEE J. Quantum Electron. **28**, 2486 (1992).
[18] T. K. Woodward, B. Tell, W. H. Knox, and J. B. Stark, Appl. Phys. Lett. **60**, 742 (1992).
[19] T. Sizer II, R. E. LaMarche, and T. K. Woodward, Appl. Phys. Lett. **61**, 420 (1992).
[20] I. Janossy, J. Gordon, H. Mathew, E. Abraham, M. R. Taghizadeh, and S. D. Smith, IEEE J. Quantum Electron. **22**, 2224 (1986).
[21] H. S. Carslaw and J. C. Jaeger, *Conduction of Heat in Solids*, 2nd ed. (Clarendon, Oxford, 1959). A heated layer is described by Eq. (3), p. 54 and a heated circle by Eq. (4), p. 264.
[22] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley, New York, 1981), p. 851.