

Exciton saturation in electrically biased quantum wells

A. M. Fox, D. A. B. Miller, G. Livescu,^{a)} J. E. Cunningham,
J. E. Henry, and W. Y. Jan

AT&T Bell Laboratories, Crawford's Corner Road, Holmdel, New Jersey 07733

(Received 9 April 1990; accepted for publication 27 August 1990)

We have measured the heavy hole exciton saturation intensity in GaAs/AlGaAs quantum wells as a function of applied electric field and AlGaAs barrier design. We find that the saturation intensity increased with increasing applied field, and decreasing barrier thickness or height, because of increased carrier sweep-out rates. Time-resolved sweep-out time and temperature-dependent saturation intensity measurement point out the roles of both thermionic emission and tunneling in the field and barrier-dependent carrier escape time. By reducing the barrier Al composition from 30 to 20%, we achieved an increase in the saturation intensity by a factor of ~ 6 .

The physics of excitons in semiconductor quantum wells has attracted much recent research. One reason for this interest is the successful application of excitonic electroabsorption in optical modulators or switches, such as the self-electro-optic effect device (SEED).¹ These devices use the quantum-confined Stark effect in which the excitons red shift with applied electric field.² Although individual device switching energies are low, fast SEED systems operate at optical intensities well above the minimum. This is because enough power must be passed through one device to switch the next one after allowing for system losses. It is known, however, that the excitonic absorption saturates as the optical intensity is increased. This degrades the contrast ratio of the SEED at high powers. It is therefore important to study and understand the physics of quantum well exciton saturation in an applied electric field.

Exciton saturation has been extensively studied at zero applied electric field by cw and time-resolved laser spectroscopy.³⁻⁹ The microscopic mechanisms involved are well understood at zero field.¹⁰ In this letter, we empirically investigate quantum well exciton saturation as a function of electric field, barrier width, barrier concentration, and temperature. We consider the physical mechanisms which determine the saturation intensity, especially the field-assisted carrier sweep-out time from the wells. We conclude that the saturation intensity can be significantly increased by improving the barrier design.

Five *p-i-n* GaAs/Al_xGa_{1-x}As multiple quantum well samples were grown by molecular beam epitaxy, with the quantum wells as the intrinsic region of the diode. The well thickness L_w was 95 Å, and the barrier thickness L_b and barrier Al concentration x were varied according to the table in the inset of Fig. 1. The number of periods was varied where necessary to give a total intrinsic region thickness of 1.0 μm. We regard sample III as a reference, since it has the same barrier design as many SEED devices. The sample parameters were chosen to establish the effect of variable x at constant L_b , and vice versa.

Saturation measurements were made using tunable cw dye or titanium:sapphire lasers. The beam was chopped at

1 MHz with a 10% duty cycle by an acousto-optic modulator to reduce thermal effects. Spot radii on the sample ranged from 2 to 30 μm. The *I-V* photocurrent characteristics were measured as a function of incident laser power and wavelength with an HP4145B semiconductor parameter analyzer. Photocurrent peaks were observed at the voltage which red-shifted the excitons to the laser wavelength. At low powers the magnitude of the heavy hole photocurrent peak is linearly proportional to the laser power and occurs at a fixed voltage. At high powers, the peak increases sublinearly with the power and shifts to higher voltage. The sublinear behavior is caused by exciton saturation, while the shift is caused by series resistance and space-charge effects, as discussed below.

The *I-V* characteristics were analyzed to obtain the peak diode sensitivity S (photocurrent/laser power) as a function of power at fixed wavelength excitation. From S we deduced the absorption coefficient α at photon energy $\hbar\omega$ according to $S = (1 - R)|e|[1 - \exp(-\alpha L)]/\hbar\omega$, where R is the front surface reflectivity and L is the total

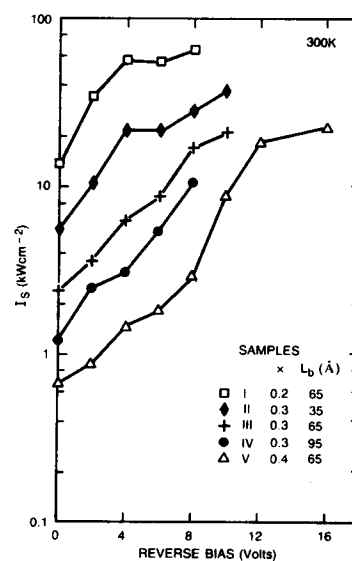


FIG. 1. Heavy hole exciton saturation intensity at 300 K vs reverse bias for the GaAs/Al_xGa_{1-x}As quantum well *p-i-n* samples. The well thickness was 95 Å throughout and the barrier composition and thickness L_b are as indicated.

^{a)}Present address: AT&T Bell Laboratories, Murray Hill, NJ 07974.

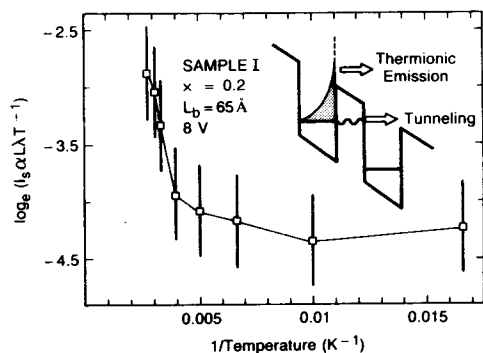


FIG. 2. Normalized temperature dependence of the heavy hole exciton saturation intensity for sample I at 8 V reverse bias.

thickness of quantum well material. We have assumed 100% internal quantum efficiency, as has been observed previously.^{1,2} We were able to verify this directly up to 200 K. The deduced low-intensity values of α are in good agreement with direct measurements in similar conditions.² By assuming a phenomenological dependence of α on the local intensity I of the form $\alpha(I) = \alpha_0[1 + (I/I_s)]^{-1}$, we deduced the saturation intensity I_s from the low-intensity slope of $\alpha(I)$. These values of I_s were then divided by the effective interaction length factor $\alpha_0 L[1 - \exp(-\alpha_0 L)]^{-1}$ to allow for absorption within the sample.⁴

In Fig. 1 we show the 300 K heavy hole exciton saturation intensities as a function of voltage for the five samples. Each point was taken at a specific wavelength, and the associated voltage is the position of the heavy hole peak in the I - V curves at low power. The average field is determined by this voltage and the intrinsic region width. From Fig. 1, we can draw three clear conclusions about I_s :

- (a) I_s increases with applied field;
- (b) I_s decreases with the barrier thickness L_b ;
- (c) I_s decreases with the barrier Al concentration, x .

It is clear that thin barriers with low x give the best saturation performance for SEEDs, and that the saturation performance can be greatly improved in this way.

We now discuss the physics behind the experimental behavior (a)–(c). A quantitative analysis of I_s is complicated at finite applied field because the steady-state electron and hole populations can differ due to differing sweep-out rates. Therefore we have to consider the different saturating efficiencies of the two particle types, and also the effect of space-charge buildup.

The particle lifetime τ_i can be expressed as

$$\tau_i^{-1} \approx \tau_R^{-1} + A_i \exp(-[\Delta E_i(F)/k_B T]) + B_i \exp(-[2L_b \sqrt{2m_i \Delta E_i(F)/\hbar}]). \quad (1)$$

The terms on the right of Eq. (1) refer to recombination, thermionic emission, and tunneling, respectively. The inset of Fig. 2 illustrates the latter two processes schematically. The subscript i refers to electrons or holes with effective masses m_i . T is the carrier temperature. The functional forms of Eq. (1) assume a simplified model of the thermal emission and tunneling, which however retains the basic

physical trends. In this model we average the potentials of the tilted barriers so that the effective barrier height $\Delta E_i(F)$ becomes $[\Delta E_i - E_{i1} - |e|F(L_w + L_b)/2]$, where E_{i1} is the first subband energy, F is the electric field, and ΔE_i is the band discontinuity. A and B are independent of the field. The electron and hole lifetimes can differ because of the different effective masses and band offsets in Eq. (1). On inspection of Eq. (1), we note that:

- (a') the lifetimes decrease with F through $\Delta E(F)$;
- (b') the lifetimes increase with L_b ;
- (c') the lifetimes increase with ΔE_i , i.e., with x .

The close parallel between (a)–(c) and (a')–(c') strongly suggests that the saturation intensity is inversely related to the carrier lifetimes, and that the variation in I_s between the samples is caused by differing tunneling and thermionic emission rates.

The steady-state carrier populations are given by $N_i = I\alpha\tau_i/\hbar\omega$, which implies a ratio τ_e/τ_h of the electron-to-hole populations. There can, therefore, exist a space charge which can screen the applied field and generate field nonuniformities. This reduces the exciton red shift produced by the external field, and leads to exciton broadening. Moreover, Eq. (1) shows that τ_e and τ_h can begin to depend on each other and on the laser intensity because of space-charge modifications to the field. Picosecond field screening effects have been studied in GaAs/AlGaAs quantum wells,^{11,12} and steady-state space-charge effects have been noted in InGaAs/InP.¹³ Wood *et al.* have recently given a self-consistent analysis of the intensity-dependent space-charge effects, also in InGaAs/InP.¹⁴ We expect the steady-state properties of the GaAs/AlGaAs system to be very different from InGaAs/InP because the band discontinuities are smaller, and thus the hole thermal emission times should be much shorter. In our experiments, we partly compensated for space-charge effects by measuring the photocurrent at the exciton peak as a function of fixed wavelength laser power. At constant voltage the spectral position of this peak shifts with increasing power; however, we always applied sufficient additional external voltage to move the exciton peak to the fixed operating wavelength. Hence, to lowest order, the average internal field is presumably always the same. However, we could not completely eliminate space-charge effects, because space-charge-induced field nonuniformities lead to exciton broadening and a reduction in the peak height, even though the average field is unchanged.

At 300 K the excitons saturate at zero applied field with a microscopic saturation density of N_s of $\sim 3 \times 10^{11} \text{ cm}^{-2}$ when the electron and hole densities are identical.^{3,4} At high temperatures where the carrier gases have Boltzmann distributions, the exciton saturation is essentially proportional to the number of carriers in the region of k space up to $\sim 1/a_x$, where a_x is the exciton radius.¹⁰ Hence the saturation density for a single thermalized carrier type is greater than N_s by a factor m_i/μ , where μ is the reduced mass. (The heavier carriers are distributed over a larger region of k space). Taking this into account, together with the different electron and hole populations and lifetimes, we obtain

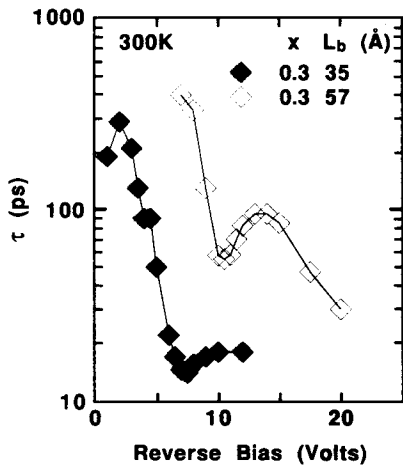


FIG. 3. Electron sweep-out time vs reverse bias for sample II and our previous quantum well sample at 300 K.

$$I_s = [\hbar\omega N_s / \alpha(L_w + L_b)] [(m_e + m_h) / (m_e\tau_h + m_h\tau_e)]. \quad (2)$$

Without detailed knowledge of both τ_e and τ_h , which is not readily available and difficult to measure, Eq. (2) cannot be analyzed quantitatively. However, our basic conclusion that I_s is dominated by the lifetimes is fully consistent with Eq. (2). This follows because the field and barrier dependence of α and N_s are comparatively small.¹⁵

We performed two additional measurements to test our understanding of the trends in the lifetimes based on Eq. (1). First, we measured the temperature dependence of I_s in sample I at 8 V between 60 and 360 K. In Fig. 2 we plot $(I_s\alpha L\lambda T^{-1})$ against T^{-1} . We chose the quantity $(I_s\alpha L\lambda T^{-1})$ to highlight the temperature variation of τ_e and τ_h after allowing for the linear T dependence of N_s .¹⁰ We interpret the results as follows: $(I_s\alpha L\lambda T^{-1})$ is essentially independent of T at low temperatures because the lifetimes are dominated by tunneling. As the temperature is raised, the thermal emission process becomes activated. The deduced activation energy is around 80 meV, which is consistent with thermal excitation of electrons over the AlGaAs barrier.

We then measured the electron sweep-out time versus field for two samples with differing L_b by the technique of time-resolved electroabsorption.^{12,16} The results are given in Fig. 3. The 57 Å data is reproduced from our previous work,¹⁶ while the 35 Å data is for sample II. The data shows how a reduction in the L_b at approximately constant x leads to a reduction in τ_e . In addition, both samples show a general trend to a reduction in τ_e as the field is increased. (The minima around 11 V and 7 V for the two samples are caused by resonant tunneling.) These measurements confirm our predictions from Eq. (1) that sweep-out times decrease with applied field, but increase with L_b , at least for electrons. Recently, the switching speeds of SEED de-

vices fabricated with 35 Å barriers have been shown to be significantly faster than those with 60 Å barriers,¹⁷ which gives further support to our interpretation. However, we cannot yet make quantitative comparisons between sweep-out times and saturation intensities because of uncertainties in hole sweep-out.

In conclusion, we have shown that the exciton saturation intensity increases with applied electric field, and decreases with barrier thickness or height. We explain the results qualitatively in terms of lifetime shortening by thermionic or tunneling field-assisted carrier sweep-out. A fuller understanding of the hole behavior will be necessary for a quantitative analysis, and for determining if the mechanism is pure exciton saturation or a more complex process involving space-charge effects. The most significant increase in I_s (~ 6 at 0 V) was achieved by decreasing x from 0.3 to 0.2. These results should lead to a considerable improvement in the power-dependent performance of quantum well electroabsorptive devices such as the SEED.

We would like to acknowledge many helpful discussions with G. D. Boyd and D. S. Chemla.

- ¹D. A. B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, W. Wiegmann, T. H. Wood, and C. A. Burrus, *Appl. Phys. Lett.* **45**, 13 (1984); for a recent review see D. A. B. Miller, *Optical Quantum Electron.* **22**, S61 (1990).
- ²D. A. B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, W. Wiegmann, T. H. Wood, and C. A. Burrus, *Phys. Rev. B* **32**, 1043 (1985).
- ³D. A. B. Miller, D. S. Chemla, D. J. Eilenberger, P. W. Smith, A. C. Gossard, and W. T. Tsang *Appl. Phys. Lett.* **41**, 679 (1982).
- ⁴D. S. Chemla, D. A. B. Miller, P. W. Smith, A. C. Gossard, and W. Wiegmann *IEEE J. Quantum Electron.* **QE-20**, 265 (1984).
- ⁵J. S. Weiner, D. B. Pearson, D. A. B. Miller, D. S. Chemla, D. Sivco, and A. Y. Cho, *Appl. Phys. Lett.* **49**, 531 (1986).
- ⁶A. M. Fox, A. C. Maciel, M. G. Shorthose, J. F. Ryan, M. D. Scott, J. I. Davies, and J. R. Riffat, *Appl. Phys. Lett.* **51**, 30 (1987).
- ⁷K. Tai, J. Hegarty, and W. T. Tsang, *Appl. Phys. Lett.* **51**, 86 (1987).
- ⁸S. H. Park, J. F. Morhange, A. D. Jeffrey, R. A. Morgan, A. Chavez-Pirson, H. M. Gibbs, S. W. Koch, N. Peyghambarian, M. Derstine, A. C. Gossard, J. H. English, and W. Wiegmann *Appl. Phys. Lett.* **52**, 1201 (1988).
- ⁹W. 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).
- ¹⁰S. Schmitt-Rink, D. S. Chemla, and D. A. B. Miller, *Phys. Rev. B* **32**, 6601 (1985).
- ¹¹R. J. Manning, P. J. Bradley, A. Miller, J. S. Roberts, P. Mistry, and M. Pate, *Electron. Lett.* **24**, 855 (1988).
- ¹²G. Livescu, D. A. B. Miller, T. Sizer, D. J. Burrows, J. E. Cunningham, A. C. Gossard, and J. H. English, *Appl. Phys. Lett.* **54**, 748 (1989).
- ¹³I. Bar Joseph, G. Sucha, D. A. B. Miller, D. S. Chemla, B. I. Miller, and U. Koren, *Appl. Phys. Lett.* **52**, 51 (1988).
- ¹⁴T. H. Wood, J. Z. Pastalan, C. A. Burrus, B. C. Johnson, B. I. Miller, J. L. de Miguel, U. Koren, and M. G. Young, *Appl. Phys. Lett.* **57**, 1081 (1990).
- ¹⁵From Ref. 10, we know that $N_s \propto 1/a_x^2$. Calculations indicate that a_x increases by no more than 25–40% in the field range of interest here. [See also S. Hong and J. Singh, *J. Appl. Phys.* **61**, 5346 (1987)]. The corresponding decrease in N_s is offset, to a large extent, by the accompanying decrease in α .
- ¹⁶G. Livescu, A. M. Fox, D. A. B. Miller, T. Sizer, W. H. Knox, A. C. Gossard, and J. H. English, *Phys. Rev. Lett.* **63**, 438 (1989).
- ¹⁷G. D. Boyd, A. M. Fox, D. A. B. Miller, L. M. F. Chirovsky, L. A. D'Asaro, J. M. Kuo, R. F. Kopf, and A. L. Lentine, *Appl. Phys. Lett.* **57**, 1843 (1990).