Optical and Quantum Electronics **25** *(1993) S965–S971*

Carrier escape dynamics in a single quantum well waveguide modulator

R. BAMBHA, D. C. HUTCHINGS*, M. J. SNELLING,
P. LIKAMWA, A. MILLER‡
Center for Research in Electro-Optics and Lasers, University of Central Florida, Orlando, FL 32826, USA

A. L. MORETTI, R. W. WICKMAN, K. A. STAIR, T. E. BIRD
Amoco Technology Company, P.O. Box 3011, Naperville, IL 60566, USA

J. A. CAVAILLÈS¶, D. A. B. MILLER
AT&T Bell Laboratories, Crawfords Corner, Holmdel, NJ 07733, USA

Received 9 June; accepted 22 July 1993

Picosecond excite–probe studies are performed on a single quantum well waveguide modulator giving a direct measure of the escape of photogenerated carriers from a quantum well. Both the effects of exciton saturation and external field screening are observed in the transient transmission change. The results are consistent with the escape of carriers by thermionic emission.

Quantum well devices are finding applications as photodetectors, optical modulators and all-optical switching elements [1]. However, the fundamental limits of such devices in terms of speed and optical power limitations have yet to be fully addressed. Quantum well devices usually operate in the resonant regime where electrons and holes will be photogenerated. These carriers can influence the optical properties principally by two mechanisms. First, while the carriers are within the quantum wells, the oscillator strength of the exciton will be reduced owing to screening of the exciton potential and phase space filling [2, 3]. Second, if the quantum well is in an electric field, as the carriers escape from the quantum well they will screen this field, leading to a blue shift of the excitons through the reversal of the quantum confined Stark effect (QCSE) [4]. The fundamental limitations of such devices will be determined by the dynamics of these photogenerated carriers. For example, in [5] the reset speed of a waveguide directional coupler switch was increased by sweeping the photogenerated carriers out of the quantum wells using a transverse electric

---

*Present address: Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow G12 8QQ, UK.

‡Present address: Department of Physics and Astronomy, University of St. Andrews, Fife KY19 9SS, UK.

¶Present address: Alcatel-Alsthom Recherche, Route de Nozay, 91460 Marcoussis, France.

0306–8919

field. In the case of quantum well modulators operating under intense illumination, it is desirable for the carriers to escape from the wells quickly (1) to prevent accumulation of a high carrier density in the wells leading to problems of device saturation, and (2) to rapidly cycle through the electric field screening process that occurs when the carriers have escaped but are still in the vicinity of the well.

One of the methods employed to investigate the carrier escape process is an all-optical excite–probe technique in a multiple quantum well structure (MQWS) [6–9]. An excite pulse causes the photogeneration of carriers in the well and their escape is monitored by the change in transmission of a time-delayed probe pulse. However, modelling such a response is extremely complex as carriers can exhibit resonant tunnelling when energy levels in adjacent wells align and can subsequently be recaptured into other wells [10]. Interwell scattering (sequential tunnelling) may also play a significant role. Furthermore, transverse electron diffusion within the n-type layer superimposes a second time constant on this experiment [11]. Hence, although these experiments may have a high temporal resolution, the measured response may not accurately reflect the carrier escape time.

To avoid the complexity of the carrier dynamics and the optical response in a multiple quantum well sample, a single quantum well was studied. A waveguide geometry was used because there is insufficient absorption for propagation perpendicular to the quantum well. In references [12, 13] a single asymmetric quantum well waveguide was studied in an attempt to individually distinguish the electron and hole escape rates. Here a symmetric GaAs/$Al_{0.3}Ga_{0.7}As$ quantum well is studied, which is closer to a typical device structure.

The structure studied in this work was grown by molecular beam epitaxy on an n-type conducting GaAs substrate. It consisted of a 0.25 μm GaAs buffer (doped $n \sim 1 \times 10^{18}\,\text{cm}^{-3}$) followed by a 1 μm lower cladding of undoped $Al_{0.4}Ga_{0.6}As$. The centre of the 0.5 μm waveguide core of undoped $Al_{0.3}Ga_{0.7}As$ contained a single GaAs quantum well 8 nm thick. The upper cladding was 1 μm undoped $Al_{0.4}Ga_{0.6}As$ and was capped with a 0.1 μm GaAs contact layer (doped $p \sim 8 \times 10^{18}\,\text{cm}^{-3}$). Lateral optical confinement was achieved by etching part of the way into the top $Al_{0.4}Ga_{0.6}As$ cladding layer to leave a rib of width 3 μm and height 0.75 μm. The device was finally cleaved to a length of 500 μm. By measuring the transmission spectrum of the waveguides, the absorption edge was found to be at 837 nm for TE polarized light and 827 nm for TM polarized light.

A cavity-dumped Styryl 9 dye laser (repetition frequency 7.6 MHz) was used to produce tunable pulses of about 1 ps, which were split into excite ($\sim$150 μW average power) and probe ($\sim$10 μW average power) pulses that could be temporally delayed with respect to each other. The polarization of the excite pulse was rotated and this beam was mechanically chopped. The two beams were recombined and focused onto the same input spot on the sample. The excite pulse was TE polarized whereas the probe pulse was TM polarized. Selection rules dictate that only transitions from the light-hole band are observed in TM polarization. At the output facet a polarizer was used to reject the excite pulse and the probe pulse was monitored using a photodetector and lock-in amplifier.

In Fig. 1 the change in transmission for the probe pulses is plotted against the time delay between the excite and probe pulses for wavelengths of 820 nm, 821 nm (on the short-wavelength side of the light-hole exciton peak) and 841 nm (on the long-wavelength side of the exciton peak). The data show that for the two shorter wavelengths there is an increase in transmission of the probe pulses and at the longer wavelength a decrease in transmission

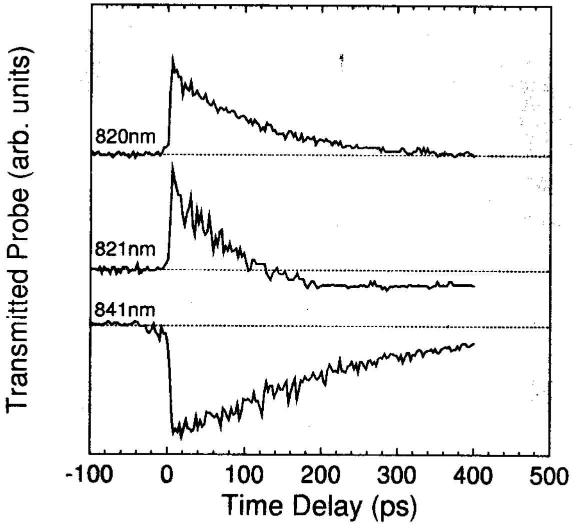

Figure 1 Change in transmission for the probe pulse as a function of time delay between excite and probe pulses for three different laser wavelengths indicated. The sample had no external bias applied in all three cases.

followed by a recovery on the order of 100 ps. This transmission change is consistent with exciton saturation due to the photogenerated carriers, which reduces the oscillator strength of the light-hole exciton but also causes a broadening that results in the increase in absorption at longer wavelengths. Although for these measurements there is no applied external electrical bias, there is an in-built voltage of around 1.5 V dropped across the intrinsic region of the device. The fast recovery time for the exciton saturation is determined by the carrier sweep-out rate in the built-in field. For the 821 nm measurement there is an indication of a small net residual decrease in transmission that persists longer than the maximum delay of 400 ps. As the carriers escape from the well they will screen the field, which causes a small blue shift of the exciton, giving a net absorption increase at shorter wavelengths that persists for a time related to the emission rate, the transit time of the carriers across the device and also the internal and external electrical parameters of the device. It is this contribution that gives different apparent recovery rates at different wavelengths.

In Fig. 2 the change in transmission for the probe pulse is shown plotted against time delay between the excite and probe for applied reverse bias voltages of 0 V, 10 V and 20 V. All these data were taken on the long-wavelength side of the exciton at 850 nm. All three data sets indicate an initial decrease in transmission associated with the broadening of the saturated exciton. The result from the unbiased waveguide shows a similar characteristic to the result in Fig. 1 in that there is a recovery with a time constant of 150 ps, although there may be some signs of a very fast initial recovery. When the waveguide was electrically biased the results show (1) a faster recovery from the exciton saturation and (2) a net increase in transmission followed by a slower recovery of the order of 1 ns.

The explanation for the transient transmission under reverse bias is as follows. Although the absorbed excite pulse initially creates excitons, these will rapidly ionize on the order of a few hundred femtoseconds to give a population of electrons and holes bound in the quantum well that manifests itself as a saturation and broadening of the exciton resonances. As the carriers escape from the well, the exciton saturation will

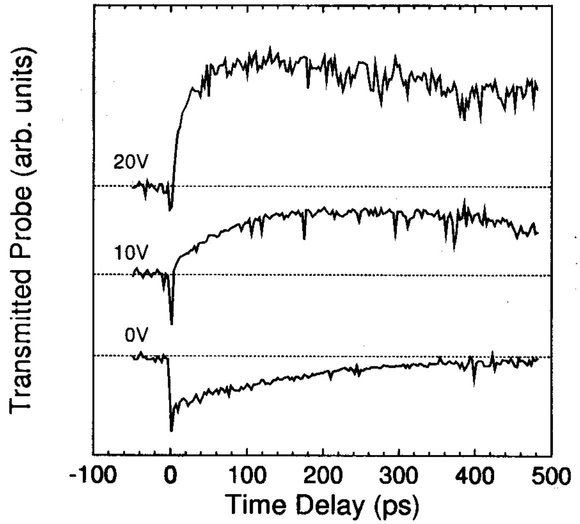

Figure 2 Change in transmission for the probe pulse as a function of time delay between excite and probe pulses for three different reverse bias voltages indicated. A laser wavelength of 850 nm was used in all three cases.

relax, but when both holes and electrons have escaped this leads to a screening of the applied electrical field in the region of the quantum well that manifests itself as a blue shift of the exciton absorption. Hence, at the long wavelengths, the transmission initially decreases owing to exciton broadening and then recovers to a net increase caused by field screening as seen. We believe that the observed longer (nanosecond) recovery of this increase in transmission may be a result of undesirable carrier accumulation at the heterojunction between the $Al_{0.3}Ga_{0.7}As$ and $Al_{0.4}Ga_{0.6}As$ layers that form the optical waveguide. Although the height of this heterojunction is smaller than that at the well, the density of states will be greater because the width of this region is larger than the well width. Therefore, the overall emission rates over this heterojunction will be smaller than one might expect from a simple comparison of barrier heights. Previous measurements [12, 13] also suggest that this long time constant is unlikely to be a carrier escape time for the quantum well. However, the time constant for the transmission decrease to become a transmission increase is a direct indication of the carrier escape time from the quantum well. This time constant can be determined by performing an exponential fit to the data in Fig. 2 and is shown plotted against the applied reverse bias voltage in Fig. 3. The time constant shows a steady decrease with increasing bias and varies from 150 ps at 0 V to around 20 ps at 20 V.

The two principal mechanisms whereby carriers can escape from a single quantum well are quantum-mechanical tunnelling and thermionic emission. The tunnelling rate is calculated using an Airy function transfer matrix technique [14] and the thermionic emission rate from [15]

$$\frac{1}{\tau_{\text{thm}}} = \left(\frac{k_B T}{2\pi m_i L_w^2}\right)^{1/2} \exp - \left(\frac{H_i}{k_B T}\right) \tag{1}$$

Here H_i is the field-dependent barrier height from the quantum well state, m_i is the effective mass of the particle, k_B is Boltzmann's constant, T is the temperature and L_w is the well width. It is assumed in Equation 1 that there is a negligible number of carriers in energy states higher than the $n = 1$ electron (heavy-hole) bound state. These escape

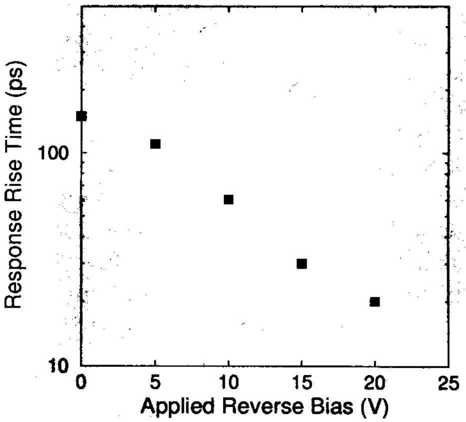

Figure 3 Rise time of the increase in transmission of the probe pulse obtained by fitting exponentials to the data in Fig. 2.

times are shown in Fig. 4 for both the electrons and heavy holes. It can be seen that at low fields it is the thermionic emission that dominates, with the holes escaping faster than the electrons owing to their smaller barrier height of 0.133 eV compared with the electron barrier height of 0.247 eV. It should be noted that the calculated escape times are very sensitive to the values used for the well thickness and barrier height; for example, slightly wider wells of 9.5 nm give roughly equal times for electron and hole escape [12, 13]. At sufficiently high fields quantum-mechanical tunnelling ought to dominate (with the electrons escaping faster). With an intrinsic region 2.5 μm wide, the highest applied voltage of 20 V corresponds to an electric field of only 86 kV cm^{-1}, with thermionic emission still dominating. Hence, the heavy holes will escape prior to the electrons. However, the observed fast

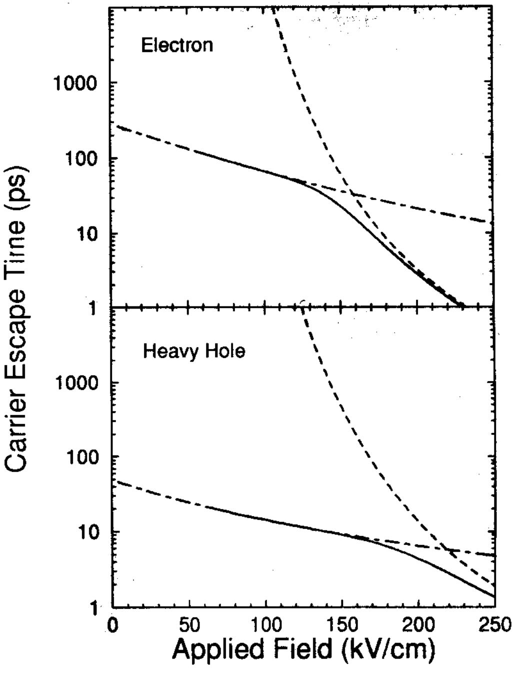

Figure 4 Calculated escape time from a single GaAs quantum well of thickness 8 nm surrounded by $Al_{0.3}Ga_{0.7}As$ barriers for electrons and heavy holes as a function of electric field due to thermionic emission (chained curve), tunnelling (dashed curve) and the net effect of both (solid curve).

partial recovery of the exciton saturation seems to occur faster than can be accounted for by simple thermionic emission of the heavy holes, as also noted in [12]. It may be that thermionic emission via higher hole bound states, such as the light hole (which would have a faster escape due to a lower effective mass), plays a significant role. The effect of screening of the applied electric field on the escape of just one type of carrier (holes) will be asymmetric with respect to the well and any influence on the other type of carrier (electrons) in terms of energy and escape time will be limited. The saturation will recover completely as the electrons escape and also, as there now will be oppositely charged carriers on either side of the well, the full effect of screening of the applied field will be realized. The calculated time for electron escape due to thermionic emission is in broad agreement with the observed time scales (Fig. 3), though the sensitivity of the calculated times to the sample parameters makes an exact fit impracticable.

In conclusion, excite–probe studies have been performed in a single symmetric quantum well modulator to determine directly the rate at which photogenerated carriers escape from the well. These results indicate the importance of carrier retrapping in multiple quantum well devices. For instance, at zero external bias the response time is ~500 ps in a multiple quantum well device [3] and ~100 ps for the single quantum well device studied here. At an electric field of ~100 kV cm^{-1} the response time in the single quantum well device is ~20 ps but in a comparable multiple quantum well device the time scale is ~130 ps [5]. However, by making use of resonant tunnelling [10] or shallow barriers [16] to assist in the escape of the carriers, the response time of a multiple quantum well device can be decreased significantly.

The present study indicates that for 8 nm GaAs wells, 30% Al concentration in the barriers and moderate transverse electric fields, it is thermionic emission that dominates the carrier escape, with the holes escaping faster than the electrons, although there are indications that the hole escape rate is faster than can be accounted for by simple thermionic emission. However, it is the effect of the (slower) electrons that seems to dominate the optical response of the present device.

Acknowledgement

This research is supported in part by the Defense Advanced Research Projects Agency and the Army Research Office.

References

1. D. A. B. MILLER, *Int. J. High Speed Electron.* **1** (1990) 19.
2. S. SCHMITT-RINK, D. S. CHEMLA and D. A. B. MILLER, *Phys. Rev. B* **32** (1985) 6601.
3. A. MILLER, R. J. MANNING, P. K. MILSOM, D. C. HUTCHINGS, D. W. CRUST and K. WOODBRIDGE, *J. Opt. Soc. Am. B* **6** (1989) 567.
4. D. 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** (1985) 1043.
5. P. LIKAMWA, A. MILLER, J. S. ROBERTS and P. N. ROBSON, *Appl. Phys. Lett.* **58** (1991) 2055.
6. R. J. MANNING, D. W. CRUST, D. W. CRAIG, A. MILLER and K. WOODBRIDGE, *J. Mod. Opt.* **35** (1988) 541.
7. R. J. MANNING, P. BRADLEY, A. MILLER, J. S. ROBERTS, P. MISTRY and M. PATE, *Electron. Lett.* **25** (1989) 269.
8. G. LIVESCU, A. M. FOX, D. A. B. MILLER, T. SIZER, W. H. KNOX, A. C. GOSSARD and J. H. ENGLISH, *Phys. Rev. Lett.* **63** (1989) 438.
9. A. MILLER, C. B. PARK and P. LIKAMWA, *Appl. Phys. Lett.* **60** (1992) 97.
10. D. C. HUTCHINGS, C. B. PARK and A. MILLER, *Appl. Phys. Lett.* **59** (1991) 3009.

11. G. LIVESCU, A. M. FOX, D. A. B. MILLER, T. SIZER, W. H. KNOX, J. E. CUNNINGHAM, A. C. GOSSARD and J. H. ENGLISH, *Semicond. Sci. Technol.* **5** (1990) 549.
12. J. A. CAVAILLÈS, D. A. B. MILLER, J. E. CUNNINGHAM, P. LIKAMWA and A. MILLER, *Appl. Phys. Lett.* **61** (1992) 426.
13. J. A. CAVAILLÈS, D. A. B. MILLER, J. E. CUNNINGHAM, P. LIKAMWA and A. MILLER, *IEEE J. Quantum Electron.* **QE-28** (1992) 2486.
14. D. C. HUTCHINGS, *Appl. Phys. Lett.* **55** (1989) 1082.
15. H. SCHNEIDER and K. VON KLITZING, *Phys. Rev. B* **38** (1988) 6160.
16. J. FELDMANN, K. W. GOOSSEN, D. A. B. MILLER, A. M. FOX, J. E. CUNNINGHAM and W. Y. JAN, *Appl. Phys. Lett.* **59** (1991) 66.