Fast escape of photocreated carriers out of shallow quantum wells

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We report that at room temperature the field-induced escape of photogenerated carriers out of shallow GaAs/Al$_x$Ga$_{1-x}$As multiple quantum wells is as fast as for pure GaAs of the same thickness, if the value of x does not exceed 0.04. Our experimental findings can be explained by assuming that carriers are efficiently scattered into the unconfined barrier states by absorption of a LO phonon, as long as the effective barrier height is less than the LO-phonon energy. The application of shallow quantum wells with $x<0.04$ in self-electro-optic effect devices, providing not only strong excitonic electroabsorption but also fast sweep-out times at small biases, should lead to shorter switching times.

Recently, strong and well-resolved excitons have been observed in the room-temperature absorption spectra of shallow GaAs/Al$_x$Ga$_{1-x}$As quantum wells for values of x as low as 0.02.[1] In addition, these shallow quantum wells exhibit strong electroabsorption at low electric fields applied perpendicular to the layers. This pronounced electroabsorption effect at low biases is not only caused by the red shift of the exciton as observed for deeper quantum wells,[2] but is mainly due to the fact that the low Al$_x$Ga$_{1-x}$As barriers cannot prevent the field ionization of the exciton.[1]

Both a strong electroabsorption and a fast sweep out of carriers from the quantum wells in the intrinsic region of the *p-i-n* structure are desirable, since the sweep-out rate is the key parameter to improve the switching speed of self-electro-optic effect devices (SEED).[3] The symmetric SEED (S-SEED), for example, consists of two *p-i-n* quantum well modulators in series. To switch such a SEED between its bistable states the quantum well modulator has to be charged or discharged like a capacitor by the photocurrent.[4] Accordingly, the switching speed increases with the operating light intensity. At high intensities, however, the carrier sweep-out from the quantum wells limits the speed for two reasons: first, the rate of charging or discharging of the capacitor cannot exceed the rate of transport of the carriers out of the wells to the electrodes (the *n* and *p* regions); second, at high power levels too many carriers accumulate in the quantum wells due to the finite carrier escape time and as a consequence, the exciton absorption saturates degrading the electroabsorption.[5] In either case, faster carrier escape rates lead to an increased saturtion intensity allowing faster switching of SEEDs.

It has been found that for deep ($x>0.2$) quantum wells the carrier sweep-out rates increase with decreasing barrier height but decrease with decreasing electric field.[5,6] To improve the speed performance of SEEDs by using shallow quantum wells it is important to know how fast the carrier sweep out becomes for small x values at low electric fields. Here, we demonstrate that at room temperature the sweep-out times of photogenerated carriers out of the intrinsic shallow quantum well region of a *p-i-n* structure is as fast as for pure GaAs of the same thickness, if the Al concentration in the barriers does not exceed 0.04. Even at forward bias carriers are swept out with the saturated drift velocity of GaAs. To understand the physical carrier escape mechanism out of the shallow quantum wells we have also performed temperature-dependent measurements of the escape times. The results are in agreement with a phonon-assisted tunneling model.[7] According to this model, the reason for the fast escape of carriers out of the shallow quantum wells is given by the fact that carriers can be efficiently scattered to unconfined continuum states by absorption of a LO phonon, if the effective barrier height for the carriers is less than the LO-phonon energy.

Four shallow GaAs/Al$_x$Ga$_{1-x}$As multiple quantum well samples with $x = 0.02$, 0.04, 0.06, and 0.08 were prepared by molecular beam epitaxy each consisting of 50 periods of 10 nm GaAs quantum wells and 10 nm Al$_x$Ga$_{1-x}$As barriers. The multiple quantum well structure forms the intrinsic region of a *p-i-n* diode[8] so that the internal electric field can be controlled by applying a voltage to the diode. In addition, an $x = 0$ "shallow quantum well" sample was grown, i.e., the intrinsic region consists of pure GaAs having the same total thickness (1 μm) as the other samples. All samples were processed into 200 μm$\times$200 μm mesas and gold top contacts were deposited. The samples were mounted on sapphire and the n^+-GaAs substrate etched for the transmission experiments.

To determine the sweep-out times we performed optical pump and probe experiments in transmission using laser pulses of about 0.7 ps duration at a repetition rate of 80 MHz. The laser photon energy is tuned to the lowest $n = 1$ heavy hole exciton and the light intensity is set to create carrier densities of about 5×10^9 cm^{-2} per pulse. For these low densities the nonlinear optical signal at positive time delays is caused by the field-induced separation of photocreated electrons and holes partly screening the field within the intrinsic region of the *p-i-n* diode and thus changing the optical properties of the quantum well structure due to the electroabsorptive effect.[6,9,10] Within the accuracy of the experimental data a single exponential function $[1-\exp(-t/\tau_{so})]$ can be fitted to the temporal rise of the nonlinear electroabsorptive signal. The experimentally de-

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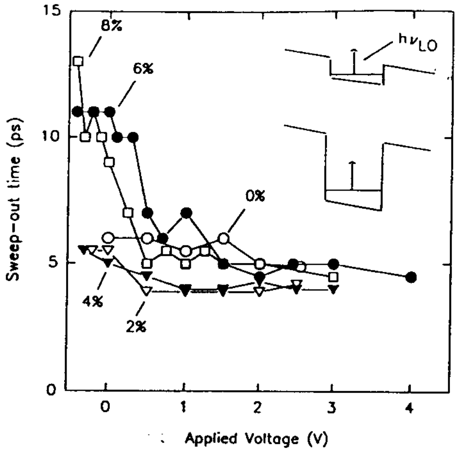

FIG. 1. Experimentally determined sweep-out times vs applied reverse bias voltage for all five shallow quantum well samples at room temperature. As an inset we schematically illustrate the situations when the effective barrier height is smaller or larger than the LO-phonon energy.

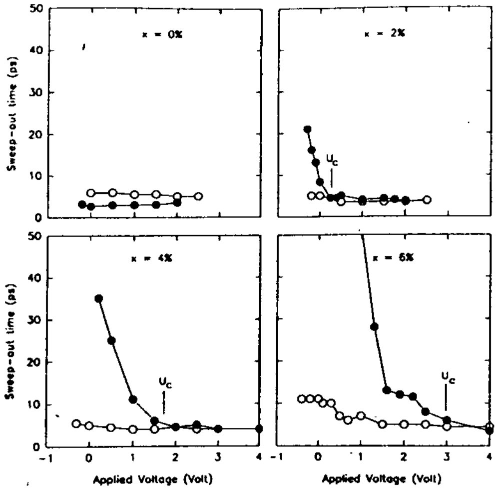

FIG. 2. Low-temperature (full circles) and room-temperature (hollow circles) sweep-out times vs applied voltage for the $x = 0$, 0.02, 0.04, and 0.06 shallow quantum well samples. U_c indicates the voltage at which the low-temperature and room-temperature time constants become equally fast.

termined values for the sweep-out times τ_{so} are shown in Fig. 1 versus the applied reverse bias voltage for all five samples at room temperature. The relative uncertainty of the time constants is estimated to be less than 15%. First of all, Fig. 1 shows that the sweep-out times for the sample with an intrinsic GaAs layer ($x = 0$) are virtually constant for the voltage range investigated and amount to about 5.5 ps. Assuming that on an average the carriers have to travel half of the total thickness of the intrinsic region in order to reach the contact layers we estimate the carrier drift velocity to be 10^7 cm/s. This corresponds to the saturated drift velocity of GaAs for electric fields larger than 10^4 V/cm.

For $x > 0$ shallow quantum wells we find the remarkable result that the carrier sweep-out rate for the $x = 2\%$ and $x = 4\%$ samples is still determined by the saturated drift velocity even at small forward bias voltages. This means that for these low $Al_xGa_{1-x}As$ barriers the carrier escape out of the shallow quantum wells is not a limiting factor for their sweep-out out of the intrinsic region. As can be seen in Fig. 1, this statement does not hold for the $x = 6\%$ and $x = 8\%$ shallow quantum well samples, since their sweep-out times increase for lower biases. We conclude that shallow $GaAs/Al_xGa_{1-x}As$ quantum wells with $x < 4\%$ not only show strong electroabsorption but also have the shortest possible sweep-out times at low voltages and thus are well suited to improve the speed of SEEDs.

We argue that at low electric fields the fast carrier escape out of shallow quantum wells with $x < 0.04$ is due to the fact that electrons in the conduction band as well as holes in the valence band are effectively scattered to unbound continuum states by absorption of a LO phonon. Since the effective barrier heights are definitely not larger than the LO phonon energy of 36 meV, continuum states with a pronounced probability of being in the well region become available as possible final states for the scattering of carriers out of the bound quantum well state. Once in these continuum states the carriers rapidly move away from the well region. This phonon-assisted tunneling model[7] can explain the fact that the sweep-out rates are limited by the saturated drift velocity even at low electric fields. In the case of deeper quantum wells the leakage of the continuum wave functions, which are available as final scattering states, into the quantum well is reduced leading to smaller matrix elements, i.e., longer scattering times. In accordance with our experimental findings shown in Fig. 1 the low-field sweep-out times for deeper wells ($x > 0.06$) are limited not only by the transit time through the intrinsic region but also by the LO-phonon scattering time. We thus find a simple qualitative explanation for the experimental fact that for low applied voltages the room-temperature sweep-out rate is extremely high as long as the Al concentration does not exceed $x \approx 0.04$. As schematically illustrated in the inset of Fig. 1, the sweep-out rate crucially depends on whether the effective barrier height is less or more than the LO phonon energy.

In order to verify our assumption of LO-phonon-assisted tunneling we investigated the temperature dependence of the carrier sweep-out rate. In Fig. 2 the experimentally determined sweep-out times for $T = 295$ K (hollow circles) and for $T = 10$ K (full circles) are shown versus the applied voltage for the $x = 0$, 0.02, 0.04, and 0.06 samples. In the case of the "$x = 0$" sample with the intrinsic GaAs region, the sweep-out times at low temperature are again independent of the applied voltage within the investigated voltage range. However, they turn out to be shorter than at room temperature, which can be explained by the higher carrier mobility at low temperatures. In contrast, for the $x > 0$ shallow quantum wells below some characteristic value, U_c, of the applied voltage, the low-temperature sweep-out times increase. This definitely rules out the possibility that the fast room-temperature sweep-out times for voltages lower than U_c are due to direct tunneling out of the quantum well, since the rate for direct tunneling should be independent of temperature.

It is, however, reasonable to assume that the long sweep-out times at low temperature and low biases reflect the direct tunneling out of the shallow quantum wells.[6] With increasing electric field the effective barrier height of the quantum wells decreases leading to an enhanced leakage of the quantum well wave function into the barrier material. Consequently, the tunneling rate increases with electric field[11] in agreement with our measurements at low temperature. As indicated in Fig. 2, for voltages larger than U_c the tunneling process out of the quantum wells is efficient enough that the carrier sweep-out is limited by the saturated drift velocity. In agreement with the finding that the exciton ionization occurs at higher voltages if the barrier Al concentration of the shallow quantum wells is raised,[1] the value of U_c increases with increasing x.

Our assumption that the temperature-activated process is due to LO-phonon-assisted tunneling can also be tested in a more quantitative way. We investigated the temperature dependence of the sweep-out times for the temperature range from $T = 10$ K up to $T = 295$ K. In Fig. 3, the experimentally determined time constants (circles) are shown versus the crystal temperature for the $x = 0.04$ shallow quantum well at $U = 0.5$ V. It is seen that already at a temperature of about 130 K the sweep-out rate saturates and is mainly determined by the saturated drift velocity for higher temperatures. The dotted line in Fig. 3 represents the result of a simple calculation. We assume that the sweep-out time τ_{so} is given by the sum of the time τ_{esc} it takes to escape out of the quantum wells and a constant transit time τ_{tr} to reach the contacts:

$$\tau_{so} = \tau_{esc} + \tau_{tr}. \tag{1}$$

In a first approach, we merely consider scattering of carriers to the continuum states by absorption of an LO phonon as a possible escape mechanism:

$$\tau_{esc}^{-1} = \tau_{sc}^{-1} = \tau_0^{-1}(e^{h\nu_{LO}/kT} - 1)^{-1}. \tag{2}$$

It was recently reported[12] for a shallow quantum well structure with 3% depth that at zero electric field the excitons are ionized with a time-constant of about 0.3 ps leading to three-dimensional carriers in the continuum states above the barrier. For our calculation the value for τ_0 is chosen to obtain a LO phonon scattering time τ_{sc} of 0.3 ps at $T = 295$ K ($h\nu_{LO} = 36$ meV). Assuming a transit time τ_{tr} of 4 ps, which is in accordance with the saturated drift velocity, we end up with the dotted curve of Fig. 3. For $T > 100$ K the experimental data are well described by Eqs. (1) and (2) supporting our assumption that the fast room-temperature carrier escape mechanism out of shallow quantum wells is due to LO-phonon-assisted tunneling. Below 100 K the LO phonon scattering becomes very weak and a different escape mechanism dominates. Probably, direct tunneling of carriers out of the wells determines the sweep-out rate at low temperature. We can extend Eq. (2) by introducing a temperature independent escape time τ_{tun} as a fitting parameter:

$$\tau_{esc}^{-1} = \tau_{sc}^{-1} + \tau_{tun}^{-1} = \tau_0^{-1}(e^{h\nu_{LO}/kT} - 1)^{-1} + \tau_{tun}^{-1}. \tag{3}$$

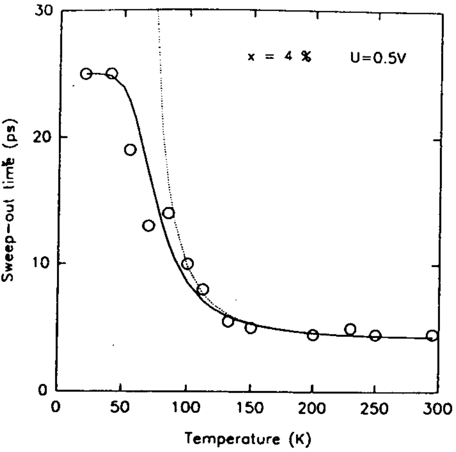

FIG. 3. Temperature dependence of the sweep-out times for the $x = 4\%$ sample at an applied voltage of 0.5 V. The dotted and solid curves represent calculated sweep-out times τ_{so} according to our simple model (for details see text).

For $\tau_{tun} = 21$ ps the solid curve in Fig. 3 is obtained for the sweep-out times τ_{so}, which is in very good agreement with the experimentally determined temperature dependence.

In summary, we have shown that the room-temperature low-field carrier escape out of the intrinsic GaAs/Al$_x$Ga$_{1-x}$As shallow quantum well region is as fast as for pure GaAs of the same thickness provided x does not exceed 0.04. This result has important implications for the improvement of the switching speeds of self-electro-optic effect devices. In addition, we have demonstrated that a LO-phonon-assisted tunneling model consistently explains our experimental findings. In conclusion, shallow quantum wells show strong electroabsorption and fastest possible sweep-out times at low reverse bias if the barrier heights for the carriers are less than the LO-phonon energy.

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[1] K. W. Goossen, J. E. Cunningham, and W. Y. Jan, Appl. Phys. Lett. 57, 2582 (1990).

[2] 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, 1043 (1985).

[3] For a recent review see D. A. B. Miller, Optical Quantum Electron. 22, 61 (1990).

[4] G. 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).

[5] A. M. Fox, D. A. B. Miller, G. Livescu, J. E. Cunningham, J. E. Henry, and W. Y. Jan, Appl. Phys. Lett. 57, 2315 (1990).

[6] A. M. Fox, D. A. B. Miller, G. Livescu, J. E. Cunningham, and W. Y. Jan (unpublished).

[7] M. G. Shorthose, J. F. Ryan, and A. Moseley, Solid State Electron 32, 1449 (1989).

[8] The detailed sample design can be found in Ref. 1.

[9] R. J. Manning, P. J. Bradley, A. Miller, J. S. Roberts, P. Mistry, and M. Pate, Electron. Lett. 24, 854 (1988).

[10] G. 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).

[11] A. Larsson, P. A. Andrekson, S. T. Eng, and A. Yariv, IEEE J. Quantum Electron. QE-24, 787 (1988).

[12] W. H. Knox, K. W. Goossen, G. E. Doran, D. A. B. Miller, J. Cunningham, and W. Y. Jan (unpublished).