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D. C. Hutchings
University of Central Florida

C. B. Park
University of Central Florida

A. Miller
University of Central Florida

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Modeling of cross-well carrier transport in a multiple quantum well modulator

D. C. Hutchings, C. B. Park, and A. Miller^{a)}
 CREOL, University of Central Florida, Orlando, Florida 32826

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A self-consistent time and spatially resolved model is developed to explain the nature of cross-well transport in multiple quantum well devices. It is this cross-well transport that sets fundamental limits on the speed of such devices. This model is solved numerically to obtain a fit to experimental excite-probe data. A good fit to rise times is obtained with resonant tunneling features predicted and observed. It is also predicted that as the transient features in the transmission data relax, many carriers are still bound in the quantum wells.

Quantum well devices show great promise as optical modulators, photodetectors, and all-optical switching elements.¹ Many of these devices are fabricated with quantum wells in the intrinsic region of a reverse biased *p-i-n* structure and rely on the quantum confined Stark effect (QCSE) for their operation.² However, the fundamental speed limits of these devices have yet to be fully investigated. In particular, when light of a suitable frequency is absorbed generating free carriers, how long before these carriers influence the optical properties of the device? Several experimental techniques have been applied to this problem, namely electrical (see reviews in Ref. 3), time-resolved photoluminescence, e.g.,^{4,5} and all-optical excite-probe.⁶⁻⁹ In this letter, the emphasis will be on modeling the transient optical response obtained by these excite-probe measurements.

For low pump powers, it is proposed that the transient change in transmission is mainly due to the QCSE. As the pump pulse is absorbed, excitons are generated in the quantum wells which rapidly (on the time scale of hundreds of femtoseconds) thermalize to form a bound (by the quantum well) population of electrons and holes. These carriers will eventually escape from the wells and move toward the *n*-doped region in the case of the electrons and the *p*-doped region for the holes. This charge separation results in a change in the local electric field in the quantum well region. In fact, the applied electric field across the device is being reduced by the screening effect of these carriers. It is this local field change which detunes the exciton through the QCSE and leads to a change in transmission by the delayed probe pulse. Thus the rise time of the transient transmission change is a direct measure of the time for the carriers to escape from the wells and start moving towards the electrodes.

In a multiple quantum well system the transverse motion of the carriers can be very complex. The phenomenological model we use to calculate the transient response of the structure uses various time constants for the different processes that can affect the photogenerated electrons and holes. A schematic of these processes is shown in Fig. 1. A time constant is attributed to each of these processes.

(1) τ_{tun} : tunneling from a quantum well bound state

into the continuum. This field dependent time constant was calculated from the width of the tunneling resonance obtained by solving the Schrödinger equation for the simplified case of two wells in an electric field,¹⁰ $\tau_{\text{tun}} = \hbar/\Delta E$. The tunneling time shows a marked decrease when the electric field is of such a value that the *n*=1 electron energy level in one well is coincident with the *n*=2 electron energy level in the adjacent well¹¹ and is an obvious feature in experiments.

(2) Scattering between bound states in adjacent wells. For low excite powers (low carrier density) it is assumed that this process is insignificant compared to the tunneling escape process described above and is neglected in the present calculation. However, at higher carrier population levels or different structures this process may become relevant.

(3) τ_{thm} : thermionic emission from a quantum well bound state into the continuum. This field dependent time constant was determined for both electrons and holes using the same form as Ref. 12.

(4) τ_{dft} : drift of free carriers in an electric field. This field dependent time constant was obtained using the saturation drift velocity $\tau_{\text{dft}} = \mu F/(L_w + L_b)$. It is anticipated that the mobility values used here will be far smaller than those for regular GaAs as (i) the mobile carriers will be at energies well removed from the Γ point in the GaAs band structure and hence have a much larger effective mass and (ii) motion is not through a uniform material as both well and barrier are being traversed. For the following calculation the mobilities used were $\mu_e = 150 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for electrons and $\mu_h = 20 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for holes.

(5) τ_{cap} : capture of free carriers into bound states. Experimental measurements at room temperature estimate

FIG. 1. Diagrammatic representation for the various time constants involved in the cross-well transport of carriers.

^{a)}Also with the Departments of Physics and Electrical Engineering.

this to be of the order of <1 ps.⁴ Furthermore, in bulk GaAs the mean-free time between collisions for an electron is about 0.3 ps. In this calculation, the capture time is set to a constant value, $\tau_{\text{cap}} = 0.5$ ps for both electrons and holes.

The transient response is solved self-consistently by including the space-charge effects of the electron and hole populations, i.e., the change in the local electric field in the structure is calculated using Gauss' law for a plane parallel capacitor. Each well was approximated by a plane of charge corresponding to the difference in hole and electron populations at that instant. Previous calculations for these experiments have ignored space-charge effects. These effects will become more important at higher carrier densities as the change in the local electric field can become comparable to the applied electric field, thus leading to the inhibition of the motion of the carriers towards the doped regions.¹³

The set of coupled differential equations which describe the bound and free electron populations throughout the device is

$$\begin{aligned} \frac{\partial N_{we}(i)}{\partial t} &= -\frac{N_{we}(i)}{\tau_{\text{tun}}(F)} - \frac{N_{we}(i)}{\tau_{\text{thm}}(F)} + \frac{N_{fe}(i)}{\tau_{\text{cap}}}, \\ \frac{\partial N_{fe}(i)}{\partial t} &= \frac{N_{we}(i)}{\tau_{\text{tun}}(F)} + \frac{N_{we}(i)}{\tau_{\text{thm}}(F)} - \frac{N_{fe}(i)}{\tau_{\text{cap}}} \\ &\quad + \frac{N_{fe}(i-1) - N_{fe}(i)}{\tau_{\text{dft}}(F)}. \end{aligned} \quad (1)$$

We use the subscripts w and f to indicate that the carriers are bound in the quantum well or have sufficient energy to be free to move in the transverse direction, respectively. The same set of equations is used to describe the evolution of the hole populations with the omission of the tunneling term. Additionally the accumulation of photogenerated charge in the doped layers is described using a further two partial differential equations of the same form.

The processes described so far are sufficient only to describe the rise of the transient response. Experimental pump-probe measurements show that the transient signal decays on a time scale of a few hundred picoseconds. Of course this time scale is much faster than the external circuit can respond. It is also significantly faster than either carrier recombination or ambipolar carrier diffusion along the wells,¹⁴ both of which are of the order of tens of nanoseconds. However, the changes in electric field induced by the separation of the photogenerated carriers will have a transverse variation as the distribution of these carriers have a Gaussian form matching the laser spot. It is this transverse variation in the field which drives the transverse motion of the doping electrons in the n -type layer washing out the induced voltage. In fact, starting from the carrier diffusion equation one can derive the voltage diffusion equation as given in^{11,15}

$$\frac{\partial V}{\partial t} = D_V \nabla^2 V + \frac{\partial V_{\text{ph}}}{\partial t}, \quad (2)$$

where we use V_{ph} to denote the induced voltage from the photogenerated carriers only, and D_V is the diffusion constant, which can be obtained from the microscopic picture

$$D_V = \frac{e\mu_e N_e L_d}{CA}, \quad (3)$$

where μ_e is the electron mobility for the electron density N_e , L_d is the Debye screening length, and C_A is the surface capacitance. For our sample this gives a time constant of $t_c \sim 20$ ps.

Using a Gaussian form the transverse profile of V_{ph} results in the following integral for the total voltage at the beam center:

$$V(t) = V_{\text{ph}}(t) - \int_{-\infty}^t \frac{V_{\text{ph}}(t') t_c dt'}{(t' - t - t_c)^2}. \quad (4)$$

Thus we are able to incorporate the effect of voltage diffusion dynamically in the model. Note that the photogenerated carriers do not have to reach the contacts before relaxation occurs as the doping electrons respond to the transient voltage changes in the device.

An additional effect which is included in the present model is to include the effects of a nonuniform field throughout the sample due to impurities (background doping) in the quantum well layers. This is treated in a similar manner to Ref. 16, in that we calculate the change in electric field in the intrinsic region of the device due to an assumed homogeneous density of impurities, $N_b \sim 10^{15} \text{ cm}^{-3}$, by Gauss' law which gives a nonuniformity of $\Delta F \sim 20 \text{ kV cm}^{-1}$.

We thus have a coupled system of $4n_{\text{well}} + 3$ (243 for our system) partial differential equations which are solved by the Runge-Kutta method. The program allows access to the temporal and spatial evolution of the photogenerated populations as shown in Fig. 2 for 5 V reverse bias. The nonuniformity of the electric field results in the electrons nearer to the p region to be tuned to the tunneling resonance and to rapidly escape from the wells.

The change in the transmission is determined from the internal electric fields by comparison with experimental data for the device transmission as a function of reverse bias voltage under low-power continuous wave (cw) conditions. We can thus plot a direct comparison of the transmission change vs delay between experiment⁹ and the present numerical model (Fig. 3). From this transient transmission response we can use a rising and decaying exponential fit to extract the rise and decay times of the experimental and theoretical response as shown in Fig. 4. Rise times are in general agreement with experiment with the resonant tunneling at 5 V clearly shown.

Since the rise time of the response is generally longer than the relaxation time constant t_c , the shape of the decay of the transient signal is strongly dependent on the shape of the rising edge and we find a decaying exponential most appropriate. Indeed the relaxation is not to the situation where all of the electrons and holes reach the contacts but rather to an equilibrium situation where the transverse transport of the photogenerated carriers is at a slow enough rate that the transverse diffusion of the doping elec-

FIG. 2. Representation of the electron density in the quantum wells at the various delay times indicated. The device has a reverse bias of 5 V applied with the excite-pulse incident from the left onto the *p*-type region.

trons can effectively instantaneously compensate for voltage changes. This can be seen in Fig. 2 where even at 300 ps a large number of the photogenerated electrons are still bound in the quantum wells yet the transient response is decaying. This also answers the question of what happens to the holes? For our structure, the time constant for the escape of the holes is longer than the transverse diffusion

FIG. 3. A comparison of (a) experimentally determined transient transmission change as a function of probe delay for the various reverse bias voltages indicated (Ref. 9) with (b) the results of the computer model given here.

FIG. 4. Comparison of the rise time for the theoretical responses shown in Fig. 3(b) with the experimentally determined ones previously shown in Fig. 3(a) as a function of reverse bias voltage. The rise times are obtained by fitting the transient transmission change to a product of a rising and decaying exponential.

time constant of the doping electrons t_c , and thus this form of measurement is insensitive to the motion of the holes.

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