Switching speeds in double-barrier resonant-tunneling diode structures

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(Received 22 May 1991; accepted for publication 17 September 1991)

Switching speeds are calculated for GaAs-AlGaAs resonant-tunneling diode structures with different barrier widths from the time-dependent Schrödinger equation. The speed is determined by monitoring the device current as the bias voltage is instantaneously switched. Effective mass discontinuities at the barrier and quantum well edges are included. Comparisons with previously published results using the wave packet approach are given. It is found that the turn-off transient is dominated by the lifetime of the quasibound state; however, care must be used in calculating the lifetime.

Time-dependent calculations of resonant-tunneling diode switching times have been obtained using the Wigner function approach,[1,2] and from the time-dependent Schrödinger equation.[3,4] Guo *et al.*[5] have recently published a time-dependent analysis of tunneling times in resonant-tunneling diodes using the wave packet approach. In this method, a wave packet with energy distribution centered about the quasibound state energy of the quantum well is incident on the structure, and concentration in the quantum well is monitored; two characteristic times, a build-up time τ_b, and a decay time τ_d, are determined. It was found that τ_d is nearly equal to $\hbar/\delta E$, where δE is the full width at half-maximum of the transmission coefficient versus energy.

There are two factors that complicate the application of these times to determining device switching speeds. First, since the device current is not calculated using this approach, it is not clear how to relate these characteristic times to the transient response that would be observed. Second, the δE, τ_b, and τ_d quantities calculated in Ref. 5 are for the zero-bias case. Switching speed is of interest when the device bias voltage is changed between two values, neither of which is necessarily zero; in this case the width of the quasibound state in the quantum well, δE, is different from the zero-bias case.

In this communication, a method developed to solve the time-dependent Schrödinger equation for an ensemble of electrons[3,4] is used to determine the transient current response when the bias voltage is instantaneously switched between the peak and valley current points of the static *I-V* (current-voltage) curve. Discontinuities in effective mass are included in the calculation.[6] The current obtained is the spatial average of the electron current for the ensemble of states;[3] in fact, the actual terminal current density would include a displacement current term of the form $(\epsilon/W)dV/dt$, where W is the width of the simulated region. However, determination of this component requires a self-consistent calculation, which is not attempted here. The switching speed obtained may be regarded as the fundamental limit due to the tunneling process alone, not including RC charging time constants.

Table I shows the widths of the quasibound states, δE, and associated times from $\hbar/\delta E$ at different bias voltages calculated for GaAs-AlGaAs devices with 50 Å well width and two different barrier widths. (For all biases considered, any quasibound states above the ground state are well above the incident thermal distribution of electrons, so that they need not be considered.) These structures are identical to two cases treated by Guo *et al.*,[5] including the effective mass values. The calculations for $V=0$ correspond to the calculations in Ref. 5. Also shown are calculations for the devices biased at the peak (J_{max}) and valley (J_{min}) current points on the static *I-V* curve. The widths of the quasibound states, δE, were obtained using the same method as in Ref. 5, except for the J_{min} case. Here the transmission coefficient cannot be used, since the quasibound state is below the conduction band edge on the emitter side and, therefore, the transmission is zero. The method used was to monitor the integrated electron density in the quantum well for energy eigenstates of different incident energies E_{inc}. The quantity δE was taken as the width in E_{inc}, over which the integrated density drops to half the maximum value at resonance.

Figure 1 shows the calculated transients for the structure with 50 Å barriers when the bias voltage is switched from 0.154 to 0.103 V (a), and from 0.103 to 0.154 V (b). [The initial ringing in Fig. 1(a) is due to rapid oscillations in the quantum well after switching and may also be seen in Ref. 3. This ringing also explains why the current density undershoots below zero shortly after $t=0$.] To interpret these results, it is remarked that the turn-off transient is expected to be dominated by the decay time of the quasibound state (τ_d in Ref. 5). Fitting the tail of Fig. 1(b) to an exponential function yields a time constant of 0.970 ps, very close to the $\hbar/\delta E$ value in Table I of 0.9845 ps for $V=0.154$ V, or the expected lifetime of the quasibound state. This value is significantly lower than the 1.579 ps value (1.61 ps in Ref. 5) obtained for the zero-bias case, since the width of the quasibound state is larger with applied bias.

It is not clear whether the turn-on transient should be dominated by τ_b alone, or a combination of τ_b and τ_d. In this case, fitting an exponential to the latter portion of the turn-on transient in Fig. 1(a) yields a time constant of 0.836 ps, compared with the build-up time of 0.6 ps obtained in Ref. 5. (Although not calculated, it is expected

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TABLE I. Calculated values for GaAs-AlGaAs devices with 50 Å well and two different barrier widths.

B (Å)	V (V)	Current (10^8 A/m^2)	δE (meV)	$\hbar/q\delta E$ (ps)
	0.0	0.0	8.863	0.074 23
25	0.105	$J_{max} = 26.42$	9.557	0.068 84
	0.199	$J_{min} = 5.020$	11.46	0.057 41
	0.0	0.0	0.4166	1.579
50	0.103	$J_{max} = 1.146$	0.5339	1.232
	0.154	$J_{min} = 0.077\ 57$	0.6682	0.9845

that the build-up time under applied bias will be shorter than the zero-bias value of 0.6 ps.)[7]

Figure 2 shows the calculated transients for the structure with 25 Å barriers. Fitting the latter portion of the turn-off transient in Fig. 2(b) to an exponential yields a time constant of 0.062 ps, close to the $\hbar/\delta E$ value of

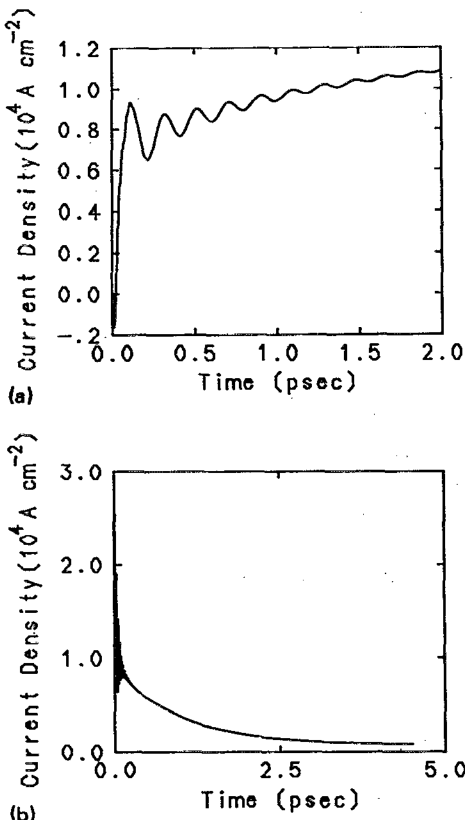

FIG. 1. (a) Turn-on and (b) turn-off transients for the $B = 50$ Å structure with bias voltage switched between 0.103 and 0.154 V.

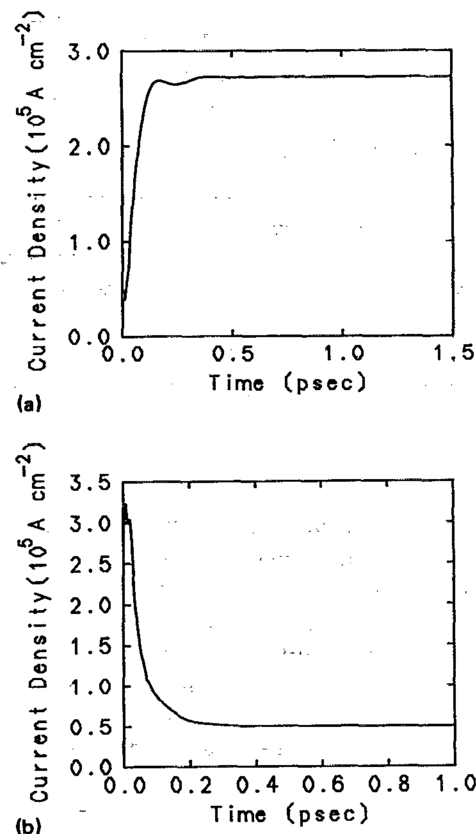

FIG. 2. (a) Turn-on and (b) turn-off transients for the $B = 25$ Å structure with bias voltage switched between 0.105 and 0.199 V.

0.05741 ps in Table I for $V = 0.199$ V. Fitting the latter part of the turn-on transient in Fig. 2(a) yields a time constant of 0.083 ps, compared with the zero-bias build-up time of 0.43 ps calculated in Ref. 5.

In conclusion, the quasibound state lifetimes obtained from $\hbar/\delta E$ are the dominating time constants in the turn-off transient; however, care must be taken to calculate δE at appropriate bias voltages. The dependence of the turn-on transient on the quantities τ_b and τ_d is not yet known.

This work was supported by the U.S. Army Research Office under the URI program, Contract No. DAAL03-87-K-0007.

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