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Escape and response times of double-barrier heterostructures

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The escape and resonant tunneling response times of double-barrier heterostructures are investigated within the Breit-Wigner formalism. It is shown that the practice of using the inelastic scattering rate is inappropriate for estimates of the inelastic partial width. Furthermore, interface roughness can invalidate the Breit-Wigner formalism, introducing overlapping localized well states, making the elastically broadened linewidth an ambiguous measure of the escape time. A microwave impedance measurement is proposed which can be used to map the dynamical effects of scattering.

I. INTRODUCTION

Epitaxially prepared double-barrier resonant tunneling devices (RTD's) have proven to be both potentially useful for high-speed electronics[1–3] and as a vehicle for the study of quantum transport.[4] The useful features of this device are its extremely nonlinear current-voltage (I-V) characteristic and its very fast switching time. Interestingly, the enhanced speed of the RTD's, as compared to a p-n-junction (Esaki) tunnel diode, comes from its smaller capacitance per unit area and higher current density. The resonant tunneling process is actually much slower than that of single-barrier devices and this makes the study of resonant tunneling dynamics feasible in RTD's. In particular, the slower tunneling rate and control over that rate via RTD structural parameters may allow the investigation of the dynamics of resonant tunneling as well as the effects of scattering upon it.

The role of scattering, both elastic and inelastic, in conduction through RTD's has proven to be both interesting and contentious. This applies to both the static I-V curve as well as to tunneling dynamics. A simple specular theory sufficed to phenomenologically explain the first reported resonant tunneling.[5] Since then work has proceeded with experiments measuring the effects of elastic impurity-scattering,[6] multiple-band conduction,[7] and interface roughness[8] on the I-V curve as well as with theoretical studies of the effects of scattering due to impurities,[9] interface roughness,[10,11] alloy fluctuations,[12,13] bulk[14,15] and interface phonons,[16] and to other electrons.[17] Work has also been performed that includes the effects of scattering in the RTD as a generic process parasitic to specular resonant tunneling.[18–21] Interestingly, the peak current is relatively insensitive to all scattering processes, their effect being most noticeable in the off-resonant valley current.

RTD dynamics have proven to be harder to study because the resonant tunneling mechanism in high-quality devices is still quite fast. To date, measurements of RTD's as microwave circuit elements have not clearly shown any effects of a tunneling delay or response time.[22–26] Probes of the transient electron population in the well region of the RTD using pulsed excitation and time-dependent photoluminescence have been made[27] but these are an indirect measure of the dynamics of the RTD as a circuit element. In addition, some theoretical work has been performed on the dynamical effects of various individual scattering mechanisms such as alloy variations,[13] bulk phonons,[14,15] and a generic relaxation mechanism within a quantum transport formalism.[28] In this work, we perform a synthetic analysis of scattering effects on RTD dynamics and propose a practical experiment for their measurement.

II. ESCAPE AND RESPONSE TIMES

For the purposes of this paper we adopt the scattering matrix formalism and, *where possible*, use the Breit-Wigner constraints on the form of each scattering matrix element near resonance, in order to include the effects of inelastic scattering. Three key elements of the Breit-Wigner formalism are reiterated here:[20] (1) it applies only to systems with isolated resonances, (2) the total width of the resonance is $\Gamma = \hbar/\tau_e$, and (3) in the absence of inelastic scattering, τ_e refers to decay into only two channels, one in each electrode. Furthermore, we adopt the position that elastic tunneling is coherent and inelastic tunneling is sequential in nature. Within the Breit-Wigner formalism the resonant and near-resonant tunneling through a pair of planar barriers, as shown in Fig. 1, is given by

$$T(E_z) = T_0 \frac{\Gamma^2/4}{(E_z - E_r)^2 + \Gamma^2/4} , \qquad (1)$$

where T_0 is the peak (resonant) transmission, E_r is the resonant energy, Γ is the full width of the transmission line shape at its half maximum value, and E_z is the kinetic energy associated with motion toward the barriers. In systems with variable effective mass, T_0, E_r, and Γ are also functions of E_x and E_y.

The important measures of tunneling dynamics in static double barriers are the escape and traversal times, τ_e and τ_t, while the most important time that characterizes the transient response and small-signal impedance of

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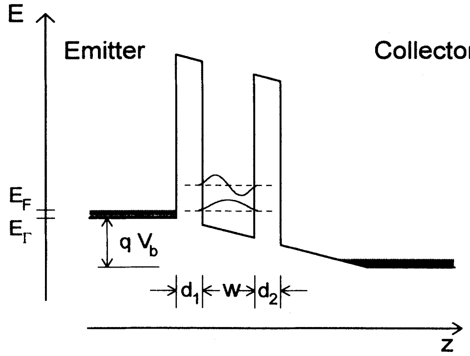

FIG. 1. A schematic diagram of the biased RTD conduction band energy vs position, $E_\Gamma(x)$. The emitter and collector electrodes are degenerately doped with $E_F > E_\Gamma$ and the first two quasibound states in the well region are indicated. Also indicated are the bias, V_b, and the widths of the barriers and well.

the RTD is the step response time, τ_r. Of these, τ_e and τ_r may be the only experimentally accessible (and important) parameters. Since we ultimately seek a parameter that describes the collective response to a change in RTD bias, the traversal time is only peripherally considered here. If important, the traversal time enters as a small correction; when τ_t is averaged over the full resonance and when the resonance is narrow with respect to variations in the electrode density of states, then $\tau_t = 2\tau_e/\pi$.[29]

The response to a step in voltage is complex,[28] however it is expected that τ_r will be a useful concept for characterizing the small-signal frequency response in the range $\tau_e^{-1} \lesssim \omega < E_{12}/\hbar$, where E_{12} is the intrasubband energy to the next nearest quasibound state. For $\omega \ll \tau_e^{-1}$ the change in potential is adiabatic; $\tau_e \approx \tau_r \approx \tau_t \ll \omega^{-1}$, and the tunneling is effectively instantaneous. For $\omega \geq E_{12}/\hbar$ multiple levels are involved and a single time is a poor measure of the response. In the intermediate regime we take $\tau_r \approx \tau_e$ (Refs. 4, 15, 28, and 30) and use examinations of τ_e in the presence of elastic and inelastic scattering to map the general trends of τ_r.

Consider resonant tunneling through a pair of ideal barriers in the absence of inelastic scattering. Under these conditions the tunneling is coherent and specular: $\tau_e = \tau_{e\ell}$ and $\Gamma = \Gamma_{e\ell}$. For double-barrier structures with individually opaque barriers ($T_L \ll 1$ and $T_R \ll 1$) and simple well potentials, $\tau_{e\ell}$ is accurately given by[19]

$$\tau_{e\ell} = 2t_w/(T_L + T_R) \quad , \tag{2}$$

where t_w is the classical transit time of the well region, and T_L and T_R are the transmission coefficients of the individual left and right barriers, respectively.

In the presence of inelastic scattering in the double barrier, the Lorentzian transmission peak is reduced and the resonance is broadened. Within the Breit-Wigner formalism this scattering opens many new channels, each with the same Lorentzian transmission line shape (with incident energy, E_z) but different peak value. These line shapes are all characterized by the total width $\Gamma = \Gamma_{e\ell} + \Gamma_i$, where Γ_i is the broadening due to all inelastic processes in the well.

Given that $1/\tau_e = \Gamma/\hbar$ is the total escape rate from the well, and that $1/\tau_{e\ell} = \Gamma_{e\ell}/\hbar$ is the escape rate in the absence of inelastic scattering, it has been very tempting to relate the mean time between inelastic collisions τ_i to Γ_i as $\tau_i = \hbar/\Gamma_i$ and to write the escape time in the presence of inelastic scattering as[19,31]

$$\tau_e^{-1} = \tau_{e\ell}^{-1} + \tau_i^{-1} \quad . \tag{3}$$

In addition, some authors bundle elastic scattering due to interface roughness, impurities, and alloy disorder with the inelastic scattering in the above rate equation, replacing τ_i with the inverse of the total transverse conduction scattering rate, τ_{scatt}.[1,21,32] This latter practice is not allowed in the Breit-Wigner formalism which can include only inelastic effects to a resonance involving a single intermediate state. In the approximation of weak elastic scattering due to point defects in the well region, others have derived the transmission coefficient as a broadened Lorentzian,[9,10] however the link to tunneling dynamics is unclear.

To estimate the effects of inelastic (and elastic) scattering predicted by Eq. (3), τ_i and τ_{scatt} can be inferred from mobility measurements of two-dimensional electron gases in narrow AlAs/GaAs/AlAs quantum wells. Typical values for both times are less than 1 psec for temperatures in the range of 100–300 K.[33] Below 100 K, interface roughness dominates τ_{scatt} and thus varies with epitaxial growth conditions. For the above-quoted quantum wells the rough GaAs on AlAs surface limited τ_{scatt} to below 1 psec.[33] For RTD's with AlAs barriers, typical calculated values of $\tau_{e\ell}$ range from one to hundreds of picoseconds, depending on barrier thickness.

For wide barriers, Eq. (3) has $\tau_e < \tau_i \ll \tau_{e\ell}$ which is clearly nonphysical: τ_e becomes independent of barrier width and height and no bound state is formed in the limit of infinite barriers. Measurements of time-resolved photoluminescent decay in AlAs/GaAs RTD's indicate escape times on the order of hundreds of picoseconds (at 77–90 K) in reasonably constructed RTD's.[27] For barriers less than 30 Å the measured escape times track $\tau_{e\ell}$ while the results of thicker barriers are obscured by a phonon-assisted escape process via the X valley.[34] Clearly, Eq. (3) lacks a deductive basis; another estimate for τ_e in the presence of inelastic scattering must be sought.

The fault with Eq. (3) probably does not lie in the use of additive rates (Matthiessen's rule) but rather that $\tau_{e\ell}$ and τ_i describe inequivalent processes; the quantity $1/\tau_{e\ell}$ is the rate of escape from the well while $1/\tau_i$ (and $1/\tau_{\text{scatt}}$) refers to the scattering rate out of one well state into another. The rate $\Gamma_i/\hbar \neq 1/\tau_i$ because $\Gamma_i/\hbar$ is a measure of the increased rate at which inelastically scattered electrons leave the well region.

The main flaw in using τ_i is that it is the mean time between inelastic events for the total motion in the well and so represents the total-energy relaxation time. Since the motion in the plane of the (smooth) RTD has no bearing on the escape process, what is more important is the relaxation time for E_z, τ_z. Unlike the free-particle motion allowed in the transverse directions, motion in the z direction is severely restricted; the density of states $\rho(E_z)$ has the same width as the transmission line shape.[20] While inelastic scattering can change E_x and E_y drastically with each scattering event, $\Delta E_z \approx \Gamma_e$. When Γ_e is small, the mean time between inelastic events is a poor estimate of τ_z. The phase of the electron wave in the well is fully randomized when $\Delta E_z \tau_z/\hbar \approx 2\pi$ which results in τ_z on the same order as $\tau_{e\ell}$. Of course these inelastic events broaden the resonance so ΔE_z is closer to $\Gamma_e + \Gamma_i$.

This clarifies the connection between inelastic scattering and the results of Buttiker.[20] In the regime of weak inelastic scattering, $t_w \ll \tau_i \lesssim \tau_{e\ell}$, Buttiker obtains Eq. (3) with $\tau_i = t_w/\epsilon$ where ϵ is the probability of inelastic scattering per traversal of the well. However, the model used in that work completely randomized the phase of the scattered electron with each scattering event so $\tau_i = \tau_z$. In addition, when τ_z replaces τ_i, the difficulties with Eq. (3) are removed. Because τ_z tracks $\tau_{e\ell}$, τ_e increases without bound in the limit of infinite barriers.

The role of elastic scattering in typical high-quality RTD's is revealed in a separate set of measurements by Liu *et al.* in which the total width of the transmission coefficient is measured at 4.2 K on a pair of RTD's with 20- and 40-Å AlAs barriers.[35] These measurements use the linear, prepeak region of the *I-V* curve, and fit the slope to that of a zero-temperature expression for the current assuming a single Breit-Wigner resonance. Measured Γ is in the range of 1–3 meV, whereas calculated values of $\Gamma_{e\ell}$ are $\approx 10^{-2}$ and 10^{-4} meV for structures with 20- and 40-Å barriers, respectively.

The dominant scattering mechanism at 4.2 K is assumed to be due to interface roughness.[8,35] This is reasonable on three counts: the above-quoted results are from RTD's made using only binary alloys, the low density of impurities in the well region of the typical RTD, and interface roughness is poorly screened by electrons in narrow wells.[33,36] It is also well known that the growing surface of AlAs is much rougher than that of GaAs due to the much lower mobility of Al atoms on the crystal surface.[37] This typically results in two "smooth" AlAs on GaAs interfaces with wide (>1000 Å) monolayer islands and two "rough" GaAs on AlAs interfaces. The roughness of the these latter interfaces is often quoted as being that of 50–100-Å wide monolayer islands,[10,33] but this is by no means a set quantity as it can vary with epitaxial method, alloy composition, and growth conditions.[37,38] The actual roughness is quite hard to measure and simulations of the growing surface indicate a range of possibilities.[39]

Scattering due to interface roughness is coherent but not specular and it establishes a transmission probability between each incident emitter state and many outbound collector states. Enumerating these states by their wave vectors, the transmission probability can be written as $T(\mathbf{k}_e, \mathbf{k}_c)$ where $\mathbf{k}_e$ and $\mathbf{k}_c$ are the wave vectors in the emitter and collector electrodes, respectively. The total transmission probability for each incident state is simply $\sum_{\mathbf{k}_c} T(\mathbf{k}_e, \mathbf{k}_c)$, where the sum is over all $\mathbf{k}_c$ such that energy is conserved (Fig. 2). This type of scattering differs from inelastic scattering in that each resonance, $\mathbf{k}_e \to \mathbf{k}_c$, might not involve the same intermediate state and may involve several. In this sense the widths of each resonance are independent and cannot be expected to be the same.

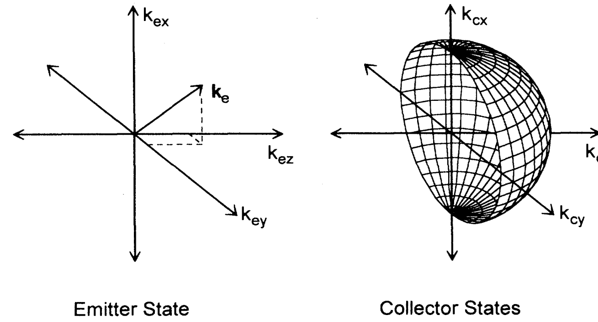

FIG. 2. The initial emitter state and the shell of allowed collector states for coherent, nonspecular resonant tunneling.

For the case of opaque barriers, insight into the role of interface roughness can be gained by considering the position of the interface. In structures with rough outer (barrier-electrode) interfaces and smooth inner interfaces, there is still only one resonant state (with $k_z = k_r$) in the well region: rough outer interfaces couple it to nominally off-resonant incident and outbound states. This scattering increases the off-resonant transmission and decreases the transmission of initially resonant electrons.[10] The detailed nature of the new transmission coefficient is heavily dependent upon the type of roughness (large monolayer islands, pseudosmooth, fractal, gratinglike, etc.) and no consistent type of "broadening" can be expected. The same intermediate state is, however, responsible for resonant transmission and the dynamics of the tunneling process are expected to be largely unchanged; the rough outer interface serves mainly to modify the incident electron population as it strikes the first barrier. As long as the interface variations are not gross, the time $\tau_{e\ell}$ for the average barrier should accurately predict the low-temperature escape rate: dynamic effects due to inelastic scattering in the well should be largely the same as that of the ideal barrier.

Rough inner interfaces severely complicate the analysis of resonant transmission as they introduce two new effects that each can invalidate the Breit-Wigner formalism. Specifically, there is now a distribution of possibly localized intermediate states[40] that overlap in both energy and position and a mechanism is introduced that allows transitions between them. In this case the decay process is not necessarily exponential;[41] any "characteristic" escape and response times are now due to the composite decay of all the intermediate states in the well region. This puts the low-temperature, *I-V*-based measurement of Γ in Ref. 35 in the proper light: when a single resonance is assumed, its "width" is determined by the distribution of resonant states and elastic scattering at the outer interfaces. Such a measurement reflects the width of the total transmission line shape and the ensuing large value for Γ is not related to $\tau_{e\ell}$. Long escape times are still possible, as the individual resonant states may be quite narrow. This interpretation is supported by I-V curve measurements of laterally confined RTD's (quantum dots).[42] In such structures conduction via single channels is discernible as steps in the I-V curve at the onset of resonant tunneling. The size of these steps yields a measure of $\Gamma_{e\ell}$ and these results are in rough agreement with calculations of $\hbar/\tau_{e\ell}$.

III. MEASURABILITY

The discussion above has been limited to what *not* to use when estimating the escape time in the presence of scattering—how one properly includes these processes is still an open question. To understand the dynamics of resonant tunneling, we propose a set of impedance (S parameter) measurements to be performed on specially fabricated structures. In view of the measured τ_e,[27] it seems quite possible to construct RTD's such that effects due to large τ_e can be observed at microwave frequencies on commercial equipment. To develop this idea, the quantum-inductance equivalent circuit for the RTD is adopted.[43] This circuit consists of a capacitor, C_d, in parallel with a series connected inductor, L_q, and resistor, R_d. We have

$$Z_{\rm RTD} = \frac{1}{C_d}\frac{\omega_{RL} + i\omega}{(\omega_n^2 - \omega^2) + i\omega\omega_{RL}} \ , \qquad (4)$$

where $\omega_{RL} = R_d/L_q$, $\omega_n = \sqrt{\omega_{RL}\omega_{RC}} = 1/\sqrt{L_q C_d}$. The capacitor accounts for the displacement current through the entire structure, R_d is the differential resistance at the bias point and L_q is due, essentially, to the delay in the current response associated with the decay or buildup of electrons in the well region before steady state is achieved. Here ω_{RL} represents the series-resistor-inductor cutoff frequency and ω_{RC} represents the parallel resistor-capacitor cutoff frequency. This is a linear, small-signal ac model that assumes an exponential response of the injected current, $\Delta i \exp(-t/\tau_r)$ where $L_q = \tau_r R_d$, to a step in applied voltage. It is assumed that the collector-side depletion region transit time is negligible. This equivalent circuit has been validated by calculations of RTD small-signal impedance[4,15] and step response.[28]

It should be noted that the quantum inductance equivalent circuit can be considered as the low frequency limit of a time-delay model. If the current response resembles a simple time delay then the low-frequency response is that of the quantum inductance circuit but the high-frequency response resembles that of a transit-time device.[44] Most notably the injected portion of the current acquires a phase that oscillates with increasing frequency. This behavior has also been demonstrated in simulations of RTD impedance[4] but is only important when $\tau_r \gg \tau_{RC}$, where $\tau_{RC} = R_d C_d$.

Using the quantum inductance circuit, we consider the effects of L_q to be measurable only if $Z_{\rm RTD}$ is that of an underdamped (circuit) resonance: $\omega_{RL} < 4\omega_{RC}$. Further, these effects must occur at an attainable frequency. For this latter condition we use $\omega_n < \sqrt{2}\omega_{\rm max}$, where $\omega_{\rm max}$ is the maximum test frequency. Assuming that the appropriate microwave test and calibration structures can be constructed, the measurement of τ_r can be made if

$$\tau_r > \frac{\tau_{RC}}{4}, \quad \tau_r > \frac{1}{2\omega_{\rm max}^2 \tau_{RC}} \ . \qquad (5)$$

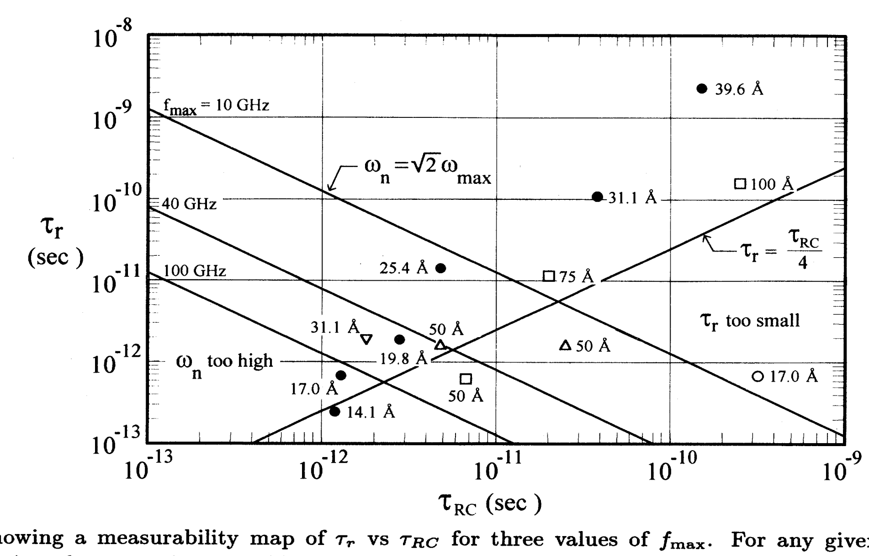

FIG. 3. A plot showing a measurability map of τ_r vs τ_{RC} for three values of $f_{\rm max}$. For any given $f_{\rm max}$ the intersection of the lines representing the two criteria yields the minimum measurable tunneling response time. Points plotted on the map correspond to $\tau_{e\ell}$ (calculated) for devices on which impedance measurements have been made (unfilled marks) and of the best thick barrier AlAs/GaAs RTD's (filled circles) published to date. The devices referenced here all have symmetric double barriers with their barrier widths indicated next to each point. The symbols are ●, best AlAs barrier devices [14.1 Å (Ref. 45), 17.0 Å (Ref. 2), 19.8–39.8 Å (Ref. 46)]; ○, AlAs barriers, $f_{\rm max}$ = 10 GHz (Ref. 26); □, $Al_{0.25}Ga_{0.75}As$ barriers, $f_{\rm max}$ = 12 GHz (Ref. 22); △, $Al_{0.30}Ga_{0.70}As$ barriers, $f_{\rm max}$ = 1.0 GHz (Ref. 23), $f_{\rm max}$ = 12 GHz (Ref. 24); ▽, $Al_{0.60}Ga_{0.40}As$ barriers, $f_{\rm max}$ = 26.5 GHz (Ref. 25). All values of τ_{RC} based on room-temperature measurements except the 39.8-Å device of Ref. 46 (80 K) and that of Ref. 23 (77 K).

Some practical insight is gained when τ_{RC} is expressed in terms of the parameters used to characterize most RTD's: the current density at the I-V curve peak, J_p, the capacitance per unit area, c_d, and the voltage at the peak current, V_p. In addition, the differential resistance is represented as a portion of the peak dc resistance, $R_d = V_p/(rI_p)$, where typically $5 > r > 1$ in the region of interest. With these parameters, $\tau_{RC} = V_p c_d/(rJ_p)$, and the measurement criteria become

$$\tau_r > \frac{V_p c_d}{4rJ_p}, \quad \tau_r > \frac{rJ_p}{2\omega_{\max}^2 V_p c_d} \ . \tag{6}$$

These criteria are seen to be independent of the device area: τ_r can be measured on any qualifying device by scaling its area for a good low frequency impedance match with the test set.

The measurement criteria are plotted in Fig. 3 for three values of $f_{\max}$: 10, 40, and 100 GHz. These frequencies are chosen for their technical merit: 10 GHz is a relatively easy test frequency, 40 GHz is about the maximum practical test frequency using microwave wafer probes, and 100 GHz is the upper limit for any foreseeable S-parameter measurement. The minimum τ_r that can be measured at 40 GHz is 1.4 psec. To the left of the line $\omega_n = \sqrt{2}\omega_{\max}$, measurable tunneling delay effects occur at frequencies above $\omega_{\max}$. To the right of the line $\tau_r = \tau_{RC}/4$, the circuit is overdamped and the measured impedance is indistinguishable from that predicted by $\tau_r = 0$.

Included on this plot is $\tau_{e\ell}$ for RTD's upon which impedance measurements have been made (unfilled symbols).[22–26] These points use published RTD parameters for τ_{RC} and calculated values of $\tau_{e\ell}$ using biased potential profiles and a 60/40 band-edge offset ratio for the $Al_xGa_{1-x}As$ material system. Of these measurements, only two devices from Ref. 22 meet the measurement criteria for their $\omega_{\max}$. Unfortunately, a parasitic series inductance obscured the effects of L_q for the thinner of these two devices, while an unfortunate choice of bias point (in a very nonlinear region of the I-V curve) and a limited set of test frequencies made the possible effects of L_q hard to observe in the other. Also plotted in the figure are $\tau_{e\ell}$ and τ_{RC} for some of the best AlAs/GaAs RTD's published to date (filled circles).[2,45,46] All but the thinnest of these devices have a measurable $\tau_{e\ell}$ and, assuming that $\tau_r \approx \tau_{e\ell}$, it would seem that devices with symmetric barriers 22.6–39.6-Å thick can be measured with $f_{\max} = 40$ GHz. For thicker barriers it is expected that X-valley conduction will obscure the tunneling current rendering them useless for this measurement.

IV. SUMMARY

In summary, the role of scattering in transmission line-shape broadening has been reexamined. In the presence of interface roughness it is found that the escape time should not be computed from the width of the total line shape. Such a width is most indicative of the spread in resonant energies for the nonspecular resonant tunneling processes as well as the scattering due to rough outer interfaces, rather than the width of any specific process. It is also found that it is inappropriate to use the inelastic intrasubband scattering rates alone to estimate Γ_i. These rates apply to transitions within the well and lead to extreme overestimates of the inelastic broadening, and thus to underestimates of τ_e and related tunneling times. Instead, a measure of the energy relaxation time for E_z should be used. Unfortunately this time is much more difficult to measure directly than the inelastic scattering rates applicable to the mobility of two-dimensional electron gases.

We emphasize that elastic and inelastic scattering play very different roles in resonant tunneling despite computational formalisms that cast elastic tunneling in a sequential context.[13,15,19,21] Experimental[27] and theoretical[13,14,28] evidence suggests that τ_e, and thus τ_r, is fairly insensitive to both elastic and inelastic scattering. Interestingly, τ_i remains as an important time scale by which the type of conduction can be categorized (coherent or sequential), although as far as τ_e is concerned the distinction may become moot.

Finally, a type of impedance measurement is proposed as a platform from which the effects of inelastic scattering on the response time of specially constructed RTD's can be measured. This analysis demonstrates why previous measurements have failed to measure L_q (and τ_r), and it is further shown that this is indeed possible using RTD's made with AlAs barriers. Accurate measurements of τ_r can be used to shed light on the roles of both elastic and inelastic scattering on resonant tunneling as a function of RTD structure, growth parameters, and device temperature.

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