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Experimental determination of quantum-well lifetime effect on large-signal resonant tunneling diode switching time

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An experimental determination is presented of the effect the quantum-well lifetime has on a large-signal resonant tunneling diode (RTD) switching time. Traditional vertical $In_{0.53}Ga_{0.47}As/AlAs$ RTDs were grown, fabricated, and characterized. The switching time was measured with a high-speed oscilloscope and found to be close to the sum of the calculated RC-limited 10%–90% switching time and the quantum-well quasibound-state lifetime. This method displays experimental evidence that the two intrinsic resonant-tunneling characteristic times act independently, and that the quasibound-state lifetime then serves as a quantum-limit on the large-signal speed of RTDs. *© 2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4933258]

Since the late 1980s, the double-barrier resonant-tunnel diode (RTD) has served as the paradigm quantum-transport device operating at room temperature.[1] It is relatively easy to grow epitaxially and to fabricate in vertical mesa structures having a pronounced "n-type" negative-differential-resistance (NDR) region, and a maximum oscillation frequency (f_{max}) up to 712 GHz,[2] or more recently up to ≈1.1 THz.[3] In spite of this impressive speed, RTDs have not become popular as THz oscillators because of severe output power limitations related to their very steep NDR region and the requirement to achieve dc-bias stability. A more promising application of this NDR behavior of RTDs is a picosecond switch. Switching is simpler than oscillation from a circuit standpoint, more useful in digital and timing circuits, and more tolerant of the inherent lack of input-output isolation that two-terminal devices present.

The fast room-temperature switching speed capability of RTDs was first realized in the late 1980s by Whitaker *et al.*[4] using mode-locked-laser driven electro-optic sampling to measure the switching waveform. For example, they reported a peak-to-valley switching time of 2.1 ps in a GaAs/AlAs RTD with thin (1.5 nm) AlAs barriers—the same type of RTD that was demonstrated in self-oscillators up to 100 s of GHz. However, the accuracy of the electro-optic sampling method was quickly called into question on the grounds that the dynamic signal (a photoconductive switch) used to ramp the bias on the RTD can accelerate the switching process, similar to what happens by "over-clocking" digital circuits. And as justification for this concern, measurements on similar RTDs yielded switching times in the 5–10 ps range in good agreement with the calculated RC-limited switching time.[5] However, faster switching-time performance was soon realized with RTDs made from superior materials, such as InAs with AlSb barriers, which produced switching times down to 1.7 ps (Ref. 6) using devices designed with similar characteristics to the fastest RTD oscillators at that time.[2]

Throughout this early development, and persisting to the present, has been a mystery regarding the effect on the switching speed of the quantum-well (QW) lifetime—an inherently quantum mechanical effect that researchers generally agreed should always reduce small-signal f_{max} because of its inductive retardation of the instantaneous RTD current relative to the instantaneous voltage. However, in the large-signal switching case, opinions varied widely, and some authors claimed the QW lifetime was insignificant in the highest-speed RTDs,[5] and others claimed that it posed the fundamental switching-speed limit.[7] The goal of this work was to study RTD switching on a device in which the large-signal RC time is comparable to the QW lifetime, and then determine how much each factors into the overall experimental switching time. In addition to the practical issue of fundamental RTD switching limits, this work also addresses the question of whether the QW lifetime is correlated to the classical RC time—a nontrivial issue considering that the QW charge in RTDs should affect the overall device capacitance in a dynamic sense.

The epitaxial growth of the two samples used in this study was done by molecular beam epitaxy on semi-insulating (SI) InP wafers. The growth stack shown in Fig. 1(a) is that of sample A and has thick n-type doped $In_{0.53}Ga_{0.47}As$ layers to help reduce the specific capacitance as well as for ease of processing. Sample B is the same active layer stack, but it has an $In_{0.65}Ga_{0.35}As$ cap layer. The higher indium concentration in the cap layer is implemented to help improve the quality of the top ohmic contact. The barrier and QW thicknesses can be scaled down to increase the current density, but this design was chosen to allow for easier switching speed measurements. The two samples were co-processed to avoid any differences due to equipment, environment, or process deviation. The active region comprised unintentionally doped (UID) AlAs barriers around an $In_{0.53}Ga_{0.47}As$ quantum-well. On either side of the active region, there are 2 nm UID $In_{0.53}Ga_{0.47}As$ spacers. The energy band diagram in Fig. 1(b) illustrates the large

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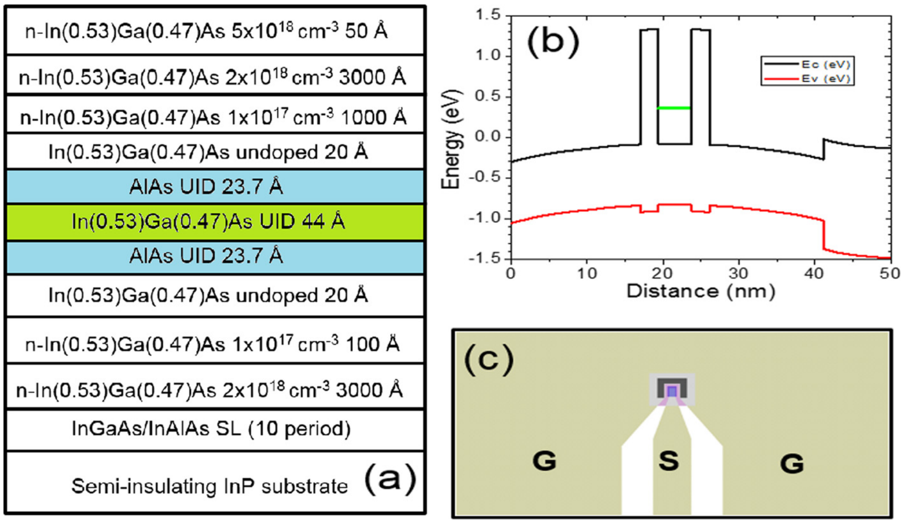

FIG. 1. (a) Growth stack for the RTD used in this study. (b) Band diagram for the RTD showing the first confined energy level. (c) Top-down view of the completed device and RF pad layout.

conduction band offset between $In_{0.53}Ga_{0.47}As$ and AlAs used to create the bound energy state displayed within the quantum-well. The $6 \times 9\,\mu m^2$ devices were fabricated using a 5-level mask set which consisted of the following steps: (i) top contact/mesa definition, (ii) bottom contact definition, (iii) device isolation, (iv) via creation, and (v) RF pad definition [top-down view seen in Fig. 1(c)]. The top and bottom ohmic contacts were a Ge/Au scheme, while the RF pads were Ti/Au. The isolation was done with a PECVD SiO_2 and the via holes were dry etched with a CF_4 plasma chemistry.

The devices on both samples were processed in such a way to allow for complete device isolation and ground-signal-ground (GSG) probing atop the SI substrate. The devices were tested using the equipment setup illustrated in Fig. 2(a). The samples were contacted using a 200 μm pitch GSG probe which fed into a bias tee. The bias tee was connected to both the ramp generator (8.6 kHz ramp) and the high-speed real-time Tektronix MS073304DX oscilloscope. The triangular ramp signal used had a PP of 1.98 V and an offset of roughly 1 V [Fig. 2(b)]. Using a variable power supply hooked directly into the bias tee allowed for basic DC current-voltage measurements to ensure proper operation of the RTDs prior to the switching measurements. The IV characteristics of both samples are shown in Fig. 2(c). The NDR onset voltage is pushed out significantly under positive bias due to the extra thick doping layers. Only the switching times under forward bias were tested during this study.

The high-speed oscilloscope was used to determine the peak-to-valley (P-V) and valley-to-peak (V-P) switching times for both samples A and B. As is illustrated in Figs. 3(a) and 3(b), the P-V switching times between the two samples are identical. Additionally, the V-P switching times are slower than the P-V times, as expected. This is caused by the fact that the valley region of RTDs is generally much broader in voltage than the peak region, so the available current (difference between the RTD resistive current and the load current at any given voltage) is smaller for V-P switching, which makes the process slower, especially during the initial stage. However, the values measured here are not the intrinsic RTD switching times, but rather a combination of the RTD switching time and the oscilloscope rise-time.

When a switching circuit is subjected to two independent delays associated with 10%–90% rise-times of t_1 and t_2, the total rise time is given by $t_{tot} = [(t_1)^2 + (t_2)^2]^{1/2}$ as determined by Maichen.[8] In this case, t_{tot} is the switching time value of the device measured by the oscilloscope, t_1 is the intrinsic RTD switching time, and t_2 is the rise-time of the oscilloscope. A rise-time of 13 ps is reported for the Tektronix MS073304DX oscilloscope.[9] The 10%–90% value measured by the oscilloscope for the P-V switching time was determined to be roughly 24 ps for both samples A and B, as seen in Figs. 3(a) and 3(b). This value was determined using the on-tool functionality of the oscilloscope as well as an analysis of the point-by-point data. After many measurements, there

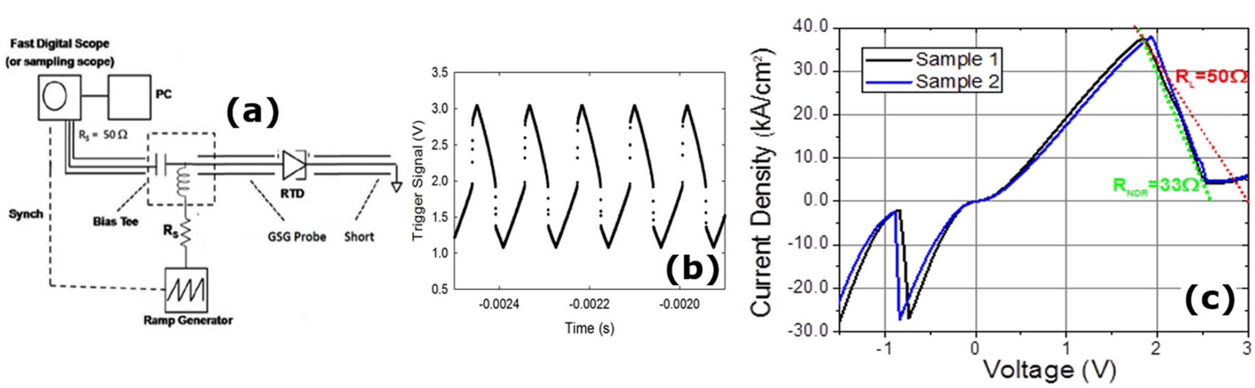

FIG. 2. (a) Experimental setup used to gather switching times. (b) Illustration of the triangular ramp signal used during measurement. (c) DC IV characteristics displaying the NDR resistance as compared to a 50 Ω load line for both samples.

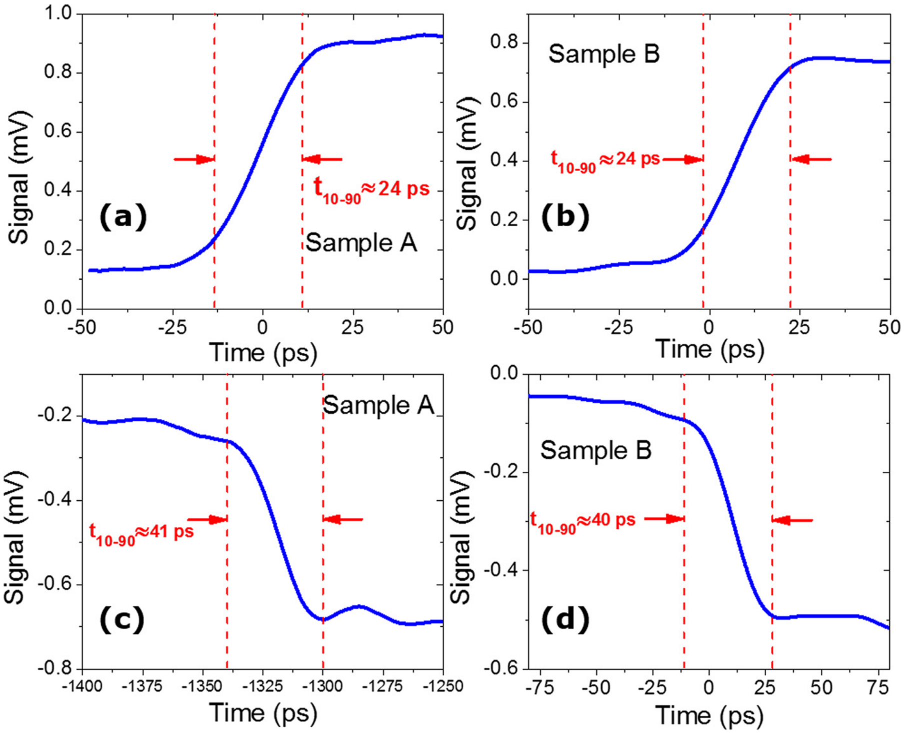

FIG. 3. (a) The high-speed switching time measurement shown for sample A was taken using a real-time Tektronix MS073304DX oscilloscope which has a 10–90 rise time of 13 ps.[9] (b) The switching time measurement for sample B was measured in the same manner as sample A. (c) The valley-to-peak switching time data of sample A. (d) The valley-to-peak switching time data of sample B.

existed an average value of 25.3 ps and a standard deviation of 2.6 ps. This results in a coefficient of variation of approximately 10%. Given the effects of jitter in the ramp generator and scope trigger, physical noise and numerical errors (e.g., roundoff) in the oscilloscope, this is a reasonable variation. Deconvolving the intrinsic RTD switching time yields a value of around 21.7 ps. This value would be much lower if the barriers were thinner, but for the purpose of this study, a well-known, robust RTD device design was chosen to increase the reliability, measurability, and yield of the RTDs.

Calculation of the theoretical peak-to-valley switching time is possible if a few assumptions are made. The diode is biased at the peak tunneling voltage, V_P, through a load resistance, R_L, consistent with DC bistability. In this particular case, as seen in Fig. 2(b), $R_L > \Delta V/\Delta I$, where $\Delta V/\Delta I$ is the NDR resistance, R_{NDR}. The values for ΔV and ΔI can be calculated by taking the difference of the peak voltage and valley voltage (V_P–V_V) and the peak current and the valley current (I_P–I_V), respectively. The diode capacitance is assumed to be constant and equal to the value at the V_P. A slight increase in the bias at this point causes a switch to the stable point (valley or beyond). To accurately model the NDR region, the following parabolic form is used:[10]

$$i_d = \frac{\Delta I}{\Delta V^2}(V - V_V)^2 + I_V, \tag{1}$$

where i_d is the diode current. Applying Kirchoff's current law for a load resistance equal to $\Delta V/\Delta I$, the 10%–90% RC switching time t_R can be determined by evaluating (1) using the equation

$$t_R = \int_{V_P+0.1\Delta V}^{V_V-0.1\Delta V} \frac{CdV}{-\frac{\Delta I}{\Delta V}(V - V_V) - \frac{\Delta I}{\Delta V^2}(V - V_V)^2}, \tag{2}$$

where C is the diode capacitance. Evaluation of this integral yields[10]

$$t_R \approx 4.4\frac{\Delta V}{S}, \tag{3}$$

where the speed index $S \equiv \Delta J/C'$, ΔJ is the available specific current, and C' is the specific capacitance. C' for the present RTDs was obtained from numerical computations of band-bending using the BandProf software tool.[11] This yielded a value of $\approx$1.8 fF/μm^2 at the peak voltage of $\sim$2.0 V in Fig. 4. Applying the experimental values to Eq. (3) resulted in a RC switching time, t_R, of 14.5 ps. Based on the above calculations, the RC switching time is expected to decrease with temperature since the valley current generally decreases at lower temperatures due to a suppression of phonon-related, inelastic tunneling.

In the previous analysis,[10] the quantum-well quasi-bound-state lifetimes τ_{QW} of various RTD designs with varying barrier thicknesses was calculated using a quasi-stationary-state, envelope-function method to compute the transmission probability, T(E), where E is the kinetic energy

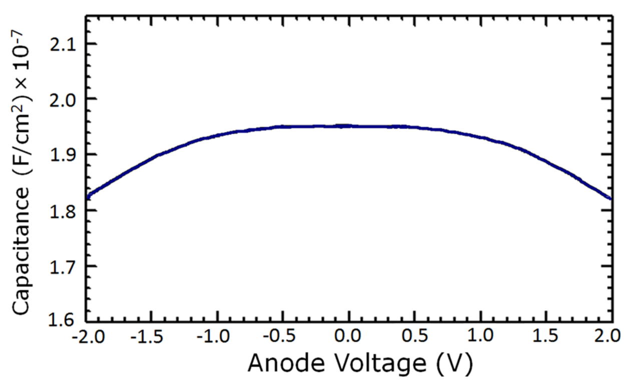

FIG. 4. Capacitance vs. voltage calculated using BandProf.[11]

of electrons incident on the double barrier structure from the emitter side. The lifetime was then calculated using the Breit-Wigner approximation, $\tau_{QW} \approx \hbar/\Gamma$, where Γ is the full-width at half-maximum of the first resonant peak in T(E). In this way, it was determined that the first quasibound state lifetime for the RTDs considered in this study was approximately 5.5 ps. We note that T(E) was computed at zero bias field rather than the peak (or valley) bias. This is considered sufficiently accurate for the present structures since they are thin enough (9.1 nm) to make Γ nearly constant with bias field, even though the maximum T(E) drops with field significantly below unity.[12]

By taking the sum of the theoretical values for the RC switching time and the first quasibound state lifetime, a resulting intrinsic switching time for the RTD is 20 ps. When compared to the experimental value of 21.7 ps for these devices, the 1.7-ps difference can reasonably be attributed to errors caused by analytic assumptions, triggering jitter, and oscilloscope physical noise. Hence, our results suggest that the quantum-well lifetime can have a significant effect on the large signal switching time of RTDs, and that its effect is additive to the RC time constant.

Finally, we considered a third potentially important effect on RTD switching time—transit-time delay across the depletion layer. A useful estimation of this is $t_T \approx L_D/v_{sat}$ where L_D is the depletion length and v_{sat} is the electron saturation velocity. At the RTD peak bias of 2.0 V, BandProf predicted $L_D \approx 63$ nm, and $v_{sat} \approx 2.0 \times 10^7$ cm/s across this value of L_D in $In_{0.53}Ga_{0.47}As$ at modest electric fields.[13] The resulting value of $t_T = 0.34$ ps is well below the RC and quantum-well time constants, therefore considered negligible for the present analysis.

In conclusion, a method to experimentally determine the effect the quantum-well lifetime has on large-signal switching time of an RTD has been presented. By using a high-speed oscilloscope to determine the total switching time, one can isolate the intrinsic RTD switching time by applying a simple equation to extract the instrumental rise-time. By applying Kirchoff's current law and applying a large-signal model of the I-V curve, the RC switching time of a given RTD can be determined. The first quasibound state lifetime of a given device design can be calculated by using a quasi-stationary-state method. Taking the sum of the calculated RC-limited 10%–90% switching time and the quantum-well quasibound-state lifetime results in close to the same value found experimentally using a high-speed oscilloscope.

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[1]R. Tsu and L. Esaki, Appl. Phys. Lett. **22**, 562 (1973).
[2]E. R. Brown, J. R. Söderström, C. D. Parker, L. J. Mahoney, K. M. Molvar, and T. C. McGill, Appl. Phys. Lett. **58**, 2291 (1991).
[3]M. Feiginov, C. Sydlo, O. Cojocari, and P. Meissner, Appl. Phys. Lett. **99**, 233506 (2011).
[4]J. F. Whitaker, G. A. Mourou, T. C. L. G. Sollner, and W. D. Goodhue, Appl. Phys. Lett. **53**, 385 (1988).
[5]S. K. Diamond, E. Ozbay, M. J. W. Rodwell, D. M. Bloom, Y. C. Pao, E. Wolak, and J. S. Harris, IEEE Electron Device Lett. **10**, 104 (1989).
[6]E. Ozbay, D. M. Bloom, D. H. Chow, and J. N. Schulman, IEEE Electron Device Lett. **14**, 400 (1993).
[7]R. K. Mains and G. Haddad, J. Appl. Phys. **70**, 7638 (1991).
[8]W. Maichen, *Digital Timing Measurements* (Springer, USA, 2006), Sec. 1.5.3.
[9]Tektronix, *Digital and Mixed Signal Oscilloscopes*, MSO/DPO70000 Series Datasheet (Tektronix, USA, 2015), p. 17.
[10]E. R. Brown, "High-speed resonant-tunneling diodes," in *Heterostructure and Quantum Devices*, edited by N. G. Einspruch and W. R. Frensley (Academic, Orlando, 1994), pp. 306–347.
[11]W. Frensley, BandProf Software, University of Texas at Dallas, 2015.
[12]E. R. Brown, "Resonant tunneling in high-speed double-barrier diodes," in *Semiconductor Nanostructures: Physics and Applications*, Chapter V.3 in Hot Carriers, edited by J. Shah (Academic Press, San Diego, 1992), Sec. 3.1.
[13]P. R. De La Houssaye, D. R. Allee, Y. C. Pao, D. G. Schlom, J. S. Harris, Jr., and R. F. W. Pease, IEEE Electron Device Lett. **9**(3), 148 (1988).