SUBMILLIMETER-WAVE RESONANT-TUNNELING OSCILLATORS

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ABSTRACT

Recent advances in high-frequency resonant-tunneling diode (RTD) oscillators are described. Oscillations up to a frequency of 420 GHz have been achieved in the GaAs/AlAs system. These results are consistent with a lumped-element equivalent circuit model of the RTD. The model shows that the maximum oscillation frequency of the GaAs/AlAs RTDs is limited primarily by high series resistance, and that the power density is limited by low peak-to-valley current ratio. Recent oscillator results obtained with InGaAs/AlAs and InAs/AlSb RTDs show a greatly increased power density and indicate the potential for fundamental oscillations up to about 1 THz.

I. INTRODUCTION

Resonant tunneling in a double-barrier structure can be understood by the diagrams in Fig. 1, which pertain to a quantum well containing only one quasibound-state energy level E_1. If the total energy and momentum of the electrons in the plane of the heterojunctions are conserved during the process, then only those electrons having a longitudinal energy E_L on the cathode side approximately equal to E_1 can traverse the structure with any significant probability. As the bias voltage is increased from zero, the quasibound level drops relative to the electron energy on the cathode side and the current increases. This current increase can be explained in terms of an increase in the number of electrons in the cathode Fermi sphere that have $E_L = E_1$. The current eventually approaches a peak at a voltage close to that which aligns the quasibound level with the conduction band edge in the neutral region on the cathode side. At higher voltages there are no electrons with $E_L = E_1$, so that the current decreases precipitously and a negative differential conductance (NDC) region occurs. This NDC region is the basis for all of the high-speed oscillations observed to date in resonant-tunneling diodes.

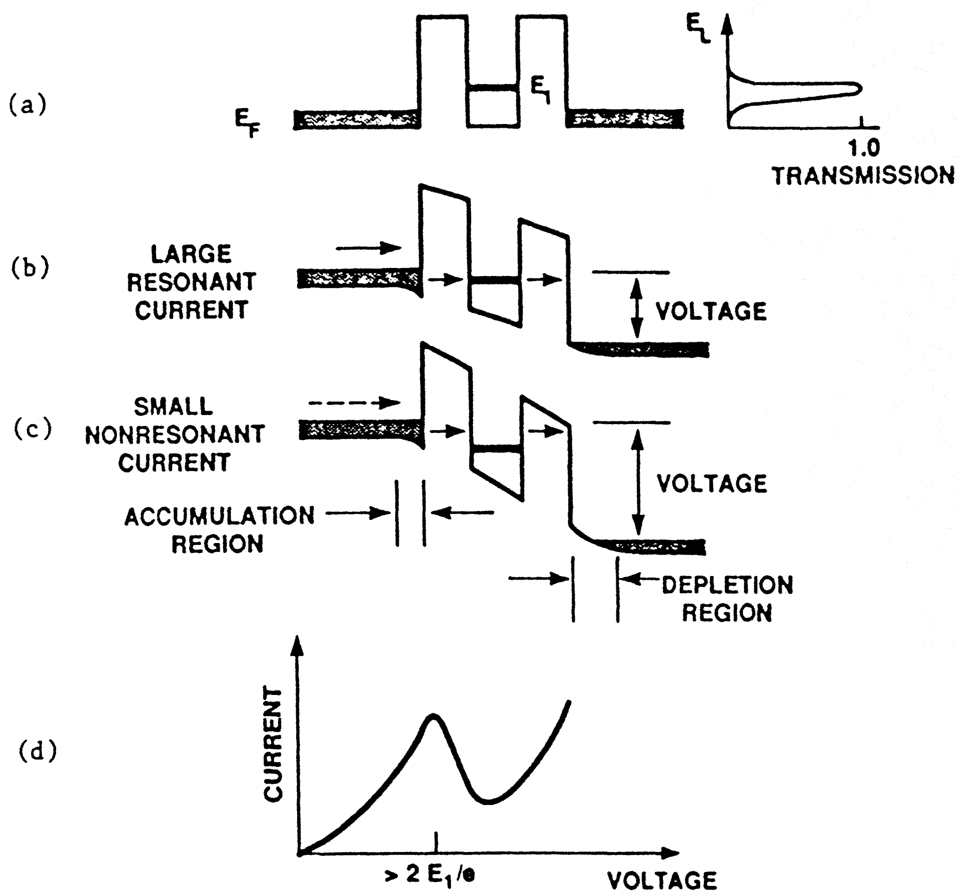

Fig. 1 (a) Band diagram of a generic double-barrier structure with quasibound-state energy E_1. (b) and (c) Schematic diagram of resonant-tunneling transport process. (d) Typical current-voltage curve for a double-barrier diode.

The fundamental requirement for resonant tunneling in a double-barrier structure is spatial quantization, which occurs when $E_1 > \hbar/\tau_s$, where τ_s is the inelastic scattering time. This requirement imposes limits on the size of the structure. For example, the thicknesses of the quantum well and barriers of a GaAs/AlAs structure must be less than roughly 10 and 3 nm, respectively, in order to observe resonant tunneling at room temperature. Fortunately such thin layers can be obtained by modern crystal growth techniques, such as molecular beam epitaxy. In fact these techniques can produce much thinner epilayers, as exemplified by the recent demonstration of double-barrier structures containing 0.8-nm-thick AlAs barriers (i.e., 3 monolayers of the AlAs zincblende lattice) [1]. Such control over layer thickness is a large part of the success of resonant-tunneling devices.

II. MATERIAL CHARACTERISTICS

The quality of a resonant-tunneling diode (RTD) is usually characterized by the peak-to-valley current ratio (PVCR) and the peak current density J_P. Fig. 2 shows the room-temperature current-density vs voltage (J-V) curves obtained for the fastest resonant-tunneling structures in three different material systems.

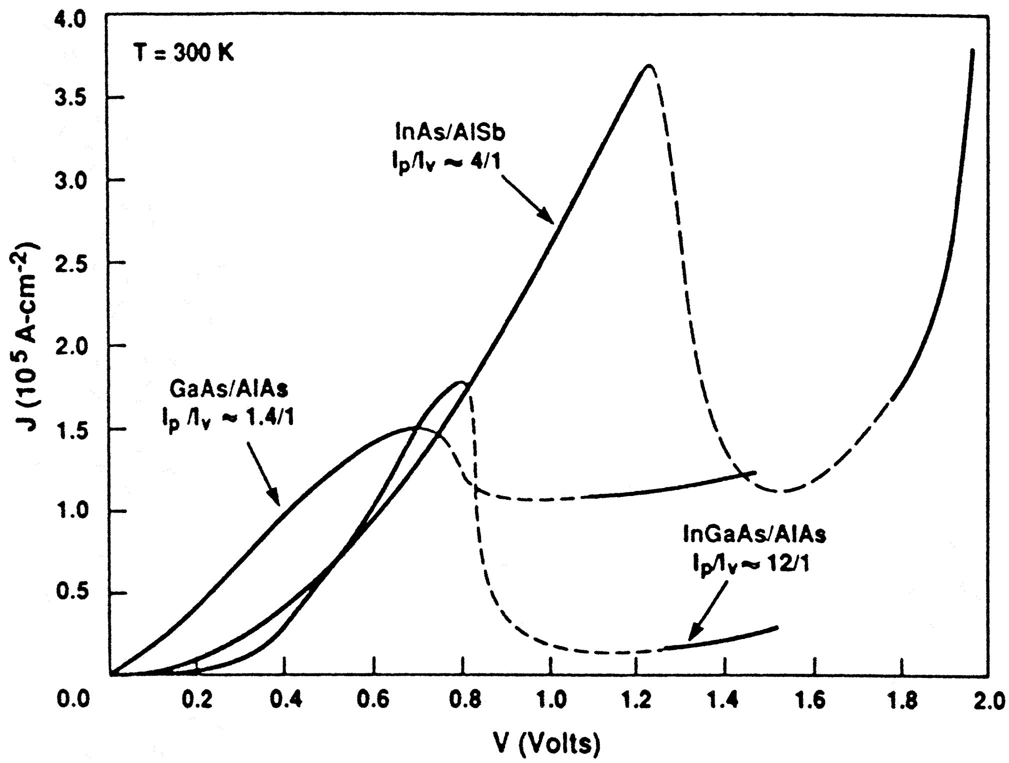

Fig. 2 Current density vs voltage for double-barrier diodes made from three different material systems. The dashed regions of the curves are the result of interpolation through the NDC region, which was highly distorted in the experiments by the occurrence of oscillations.

Each of these structures has a composition and doping profile similar to that shown in Fig. 3. The J-V curve for the GaAs/AlAs structure shows a PVCR $\cong 1.5$, which is a typical result in this material system for J_P greater than approximately 1×10^5 A cm^{-2}. In contrast, the $In_{0.53}Ga_{0.47}As/AlAs$ material system shows a PVCR $\cong 12$ at a J_P near 2×10^5 A cm^{-2}. These results display a useful empirical rule that has been observed over a large range of peak current densities. That is, $In_{0.53}Ga_{0.47}As/AlAs$ and GaAs/AlAs RTDs having the same J_P

differ in PVCR by about a factor of eight.

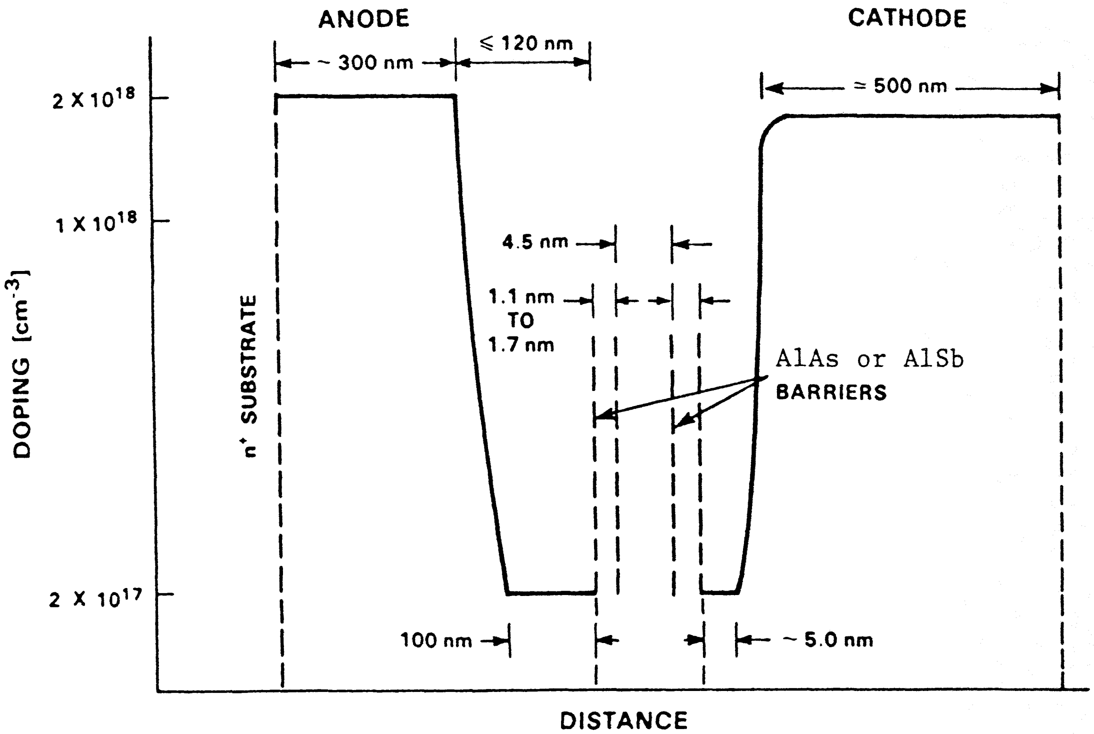

Fig. 3 Composition and doping profile for the fastest double-barrier diodes produced to date.

The InAs/AlSb structure yields the highest J_P of all of our present structures, $J_P = 3.7\times10^5$ A–cm^{-2}, and also shows a PVCR ≅ 4, which is satisfactory for many applications. The very high J_P is due mostly to the Type II-staggered band alignment. This causes the electrons to tunnel through the AlSb barriers near the valence band edge where the tunneling wavevector is significantly smaller than at mid gap. Further information can be found in the growing literature on this material system [2].

The layer thicknesses and doping profile of the RTD that has produced the highest oscillation frequency to date is shown in Fig. 3. Very thin (1.1 to 1.7 nm) barriers are used to reduce the resonant-tunneling time and enhance J_P. The asymmetric doping profile is designed to provide an approximately 100-nm-wide depletion layer on the anode side of the double-barrier structure at the bias required for NDC, and also to provide a high bulk electron density (~ 1×10^{18} cm^{-3}) on the cathode side. This density, along with the width Γ_1 of the transmission-probability (T*T) resonance, determines the current density through the structure.

The depletion layer yields a low specific capacitance compared to most other tunnel devices, such as p-n tunnel (Esaki) diodes and Josephson junction diodes, while the high carrier concentration on the cathode side provides a comparable J_P. The ability to separately control the capacitance and current density is an advantage that the RTD has over Esaki and Josephson diodes, which require degenerate carrier concentrations on both sides of the thin tunneling region.

III. SPEED-LIMITATION MECHANISMS

The best measure of the speed of RTD oscillators is the maximum frequency of oscillation, f_{MAX}, which is defined as the frequency above which the real part of the terminal impedance is positive. To determine this frequency accurately, an impedance model of the RTD is required. At sufficiently low frequencies, the impedance is represented by an equivalent circuit consisting of a differential conductance G in parallel with a capacitance C, both in series with a resistance R_S. The capacitance is approximated by $C = \varepsilon A/(d+w)$, where A is the active area, ε is the permittivity of the double-barrier material, and d and w are the lengths of the depletion region and double-barrier structure, respectively. The series resistance arises from various contributions outside the active region of the device, as in a Schottky diode. When G is negative, this circuit implies that oscillations can occur up to a frequency of $f_{RC} = (2\pi C)^{-1}(-G/R_S-G^2)^{1/2} = (2\pi\tau_{RC})^{-1}$. For a given double-barrier structure, f_{RC} represents an upper limit on the maximum oscillation frequency f_{MAX}. The additional time-delay mechanisms described below can only decrease f_{MAX}.

At high frequencies, the quasibound-state lifetime τ_1 and the transit time across the depletion layer must be considered. A straightforward derivation of the effect of the lifetime is given in Ref. [3], and the result is the RCL equivalent circuit shown in the inset of Fig. 4. The new element, the quantum-well inductance, is given by $L_{QW} = \tau_1/G$, where τ_1 is the quasibound-state lifetime. Such an element is expected on physical grounds, since the resonant-tunneling process represents a delay of conduction current with respect to applied

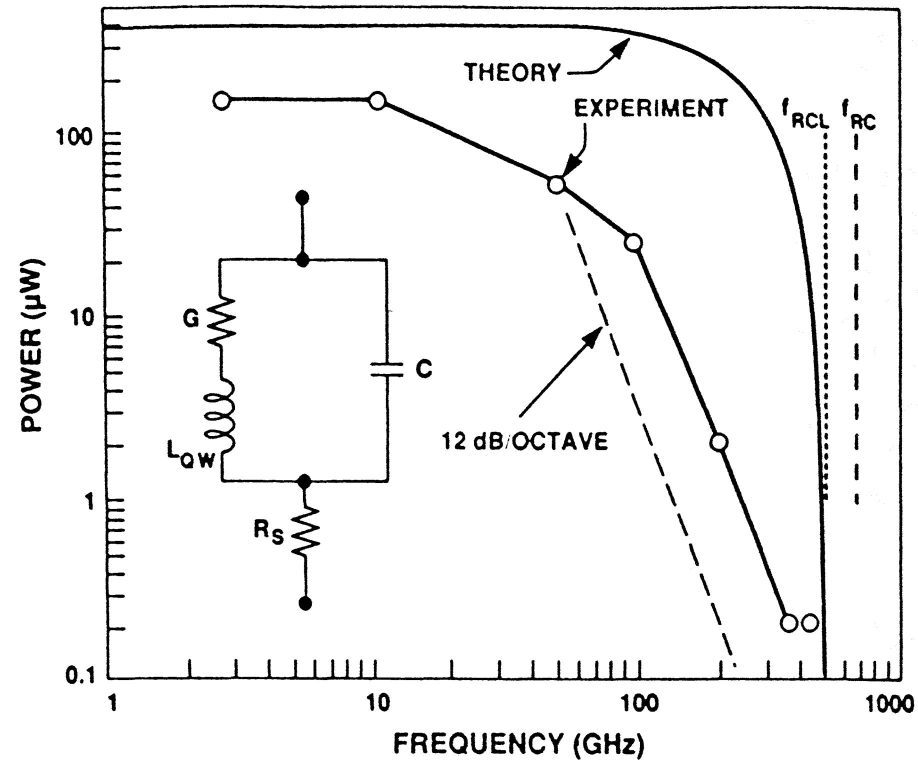

Fig. 4 Experimental and theoretical oscillator results for the fastest double-barrier diode in the GaAs/AlAs material system. The lumped-element equivalent circuit for the diode is shown in the inset.

voltage, similar to the delay that occurs in an ideal inductor. At a fixed bias point, the RCL circuit model yields an f_{MAX} given by

$$f_{RCL} = \frac{1}{2\pi}\left\{\left[\frac{1}{L_{QW}C}\left[1 - \frac{C}{2L_{QW}/G^2}\right]\right]\left[1 - \left[1 - \frac{(GR_S+1)/GR_S}{(C/2L_{QW}G^2-1)^2}\right]^{1/2}\right]\right\}^{1/2} . \qquad (1)$$

In the limit $\tau_1 \ll \tau_{RC}$, this expression reduces to f_{RC} as it should. Note that the imaginary part of the impedance of this circuit in the NDC region is always less than zero because L_{QW} is negative. This means that the diode cannot self-oscillate, i.e., oscillate on an internal resonance. The validity of the RCL circuit has been confirmed recently using several RTDs at Lincoln Laboratory, and in separate experiments at Fujitsu Labs in Japan [4] and the Electronic Technology Laboratory in the U.S. [5].

The second important time-delay mechanism at high frequencies is the transit-time delay across the depletion layer. For diodes having a material profile similar to that shown in Fig. 3, this delay is probably not very important. For example, f_{MAX} calculated using the parameters of the fastest GaAs/AlAs diode is only 10% less than f_{RCL} [6]. This calculation assumes that the average drift velocity across the depletion layer is 4×10^7 cm/s. This velocity is quite plausible in the present GaAs/AlAs double-barrier structure because the kinetic energy of the electrons injected into the depletion layer is high ($\cong$ 0.2 eV), and the mean-free path of the electrons is comparable to the depletion length. For the other two material systems of interest, $In_{0.53}Ga_{0.47}As$ and InAs, the effect of the transit time should be even less. Both the electron LO-phonon scattering time and the L-valley separation from the conduction band edge increase as the In fraction in $In_xGa_{1-x}As$ alloys increases. Consequently, the average drift velocity across the depletion layer should be even higher and the transit-time effects should be less. Based on these considerations, it is anticipated that depletion lengths of InAs RTDs can be significantly longer than those of GaAs RTDs, perhaps by a factor of two or more.

IV. OSCILLATOR RESULTS

The oscillation power vs frequency for a 4–μm–diameter diode made of the fastest GaAs/AlAs resonant-tunneling structure is shown in Fig. 4. The results are consistent with theory in that the maximum observed oscillation frequency 420 GHz is below f_{RCL}, which is calculated to be 506 GHz. This calculation assumes that G is equal to the maximum negative value in the NDC region of Fig. 2, and $\tau_1 = \hbar/\Gamma_1 = 0.11$ ps, where Γ_1 is the full width at half maximum of T*T. A more detailed analysis shows that an increase in the magnitude of G would not significantly speed up the device, but that a three-fold reduction in R_S with the same G would increase f_{RCL} to approximately 900 GHz [4]. This reduction in R_S combined with a two-fold increase in the magnitude of G would further increase f_{RCL} to over 1 THz. Unfortunately, these improvements have not been made because of practical limitations on the ohmic-contact resistance to GaAs and on the PVCR attainable in GaAs/AlAs double-barrier structures. The other two material systems that have been developed, InGaAs/AlAs and InAs/AlSb, alleviate these deficiencies.

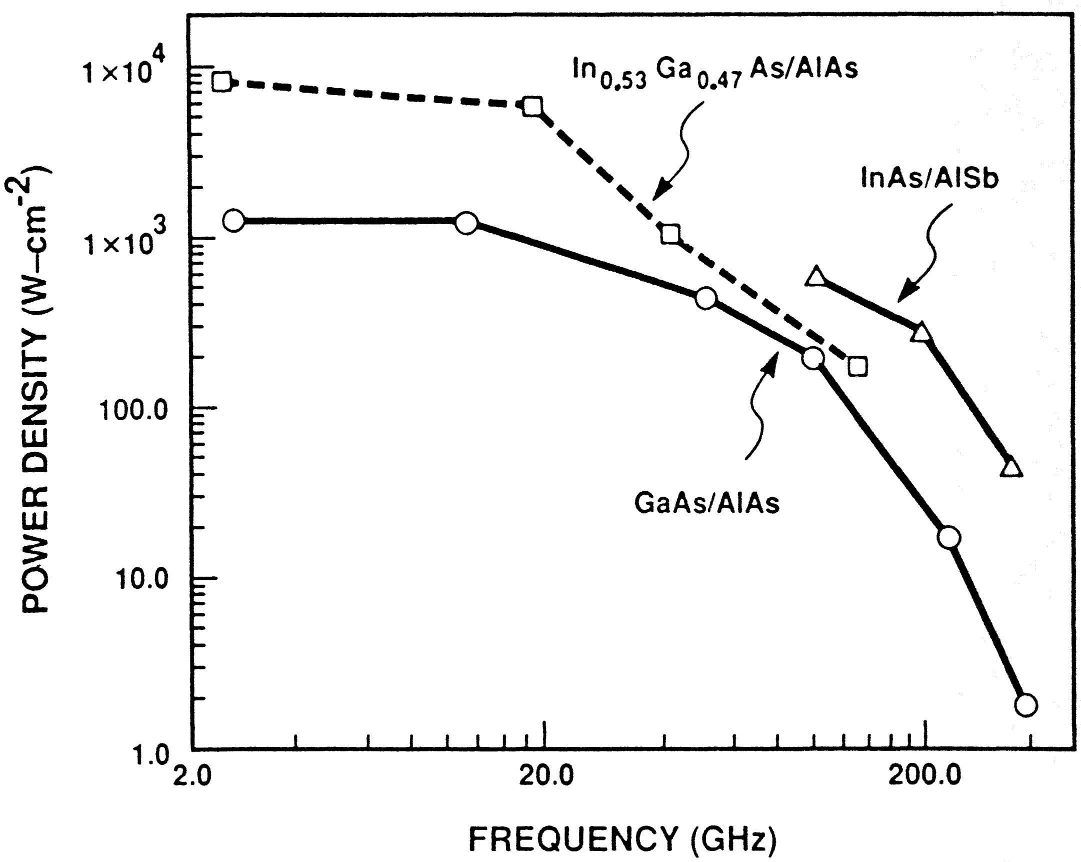

Fig. 5 Experimental oscillation results for double-barrier diodes made from three different material systems.

The oscillation results for the fastest diodes made to date in all three material systems are compared in Fig 5. The relatively poor PVCR of the GaAs/AlAs diode limits the power density to a maximum value just over 1×10^3 W cm^{-2}. The superior PVCR of the $In_{0.53}Ga_{0.47}As/AlAs$ diodes provides a low-frequency power density of 1×10^4 W cm^{-2}, which is comparable to that generated by IMPATT diodes. Because of the high PVCR at high current density, the $In_{0.53}Ga_{0.47}As/AlAs$ diode will likely be the RTD of choice for high-speed logic applications. At present the InAs/AlSb materials system is the most promising one for submillimeter-wave oscillator applications. The power density of the InAs/AlSb RTD at 360 GHz is a ten-fold improvement over that of the GaAs/AlAs RTD at the same frequency. We expect that this InAs/AlSb RTD will be capable of oscillating well over 600 GHz. The primary reasons for the superior performance are the low series resistance and the high available current density ($J_P - J_V \cong 2.8 \times 10^5$ A cm^{-2}) in the InAs/AlSb diodes. The low resistance reflects the nearly ideal ohmic contact that can be formed to InAs. In the present diode the contact resistance is so low that its measurement is difficult, but we estimate from the oscillator results that its specific resistance is less than 2×10^{-7} Ω cm^2.

V. SUMMARY

Resonant-tunneling oscillators in the GaAs/AlAs material system have been demonstrated up to frequencies of 420 GHz. The oscillation characteristics of the fastest diodes, as well as diodes designed for operation at much lower frequencies are consistent with an equivalent circuit model that represents the effect of the time delay in the resonant-tunneling process by a quantum-well inductance. The maximum frequency of oscillation of GaAs/AlAs diodes could be increased significantly by reducing the series resistance and increasing the peak-to-valley current ratio. Alternative material systems such as InGaAs/AlAs and InAs/AlSb should facilitate these improvements, and should produce oscillators operating up to about 1 THz in the near future.

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REFERENCES

[1] T.P.E. Broekaert and C.G. Fonstad, IEDM Technical Digest, Washington D.C., Dec. 1989, p. 559.

[2] J.R. Söderström, D.H. Chow, and T.C. McGill, *IEEE Electron Device Lett.* **11**, 27 (1990).

[3] E.R. Brown, C.D. Parker, and T.C.L.G. Sollner, *Appl. Phys. Lett.* **54**, 934 (1989).

[4] A. Tackeuchi, T. Inata, S. Muto and E. Miyauchi, *Jpn. J. Appl. Phys.* **25**, L750 (1989).

[5] D.W. Whitson, M.J. Paulus, C.E. Stutz, E. Koenig, R. Neidhard and E. Davis, Proc. of 12th Biennial Cornell Conference, Paper V-6, 1989.

[6] E.R. Brown, T.C.L.G. Sollner, C.D. Parker, W.D. Goodhue and C.L. Chen, *Appl. Phys. Lett.* **55**, 1777 (1989).