Lattice matched and pseudomorphic $In_{0.53}Ga_{0.47}As/In_xAl_{1-x}As$ resonant tunneling diodes with high current peak-to-valley ratio for millimeter-wave power generation

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Lattice matched and pseudomorphic $In_{0.53}Ga_{0.47}As/In_xAl_{1-x}As$ resonant tunneling diodes, with some of the best dc performance ever reported, have been fabricated and their high-frequency power generation capabilities have been theoretically studied. For the lattice matched system a peak-to-valley ratio of 7 (300 K) and 21 (77 K) with a peak current density of approximately 10 kA/cm^2 is measured. The pseudomorphic system with a $In_{0.53}Ga_{0.47}As$ well and AlAs barriers results in a peak-to-valley ratio of 24 (300 K) and 51 (77 K) with a peak current density of approximately 15 kA/cm^2. Based on a quasistatic large signal waveform analysis the power generating capability of the InGaAs device is compared with a GaAs based device with an equally high peak current density and it is found that for very high-frequency power applications the InGaAs based device is better.

I. INTRODUCTION

Ever since the first demonstrated application of resonant tunneling diodes by Sollner *et al.*[1] there has been a growing interest[2-12] in improving the negative differential resistance (NDR) characteristics of the double-barrier resonant tunneling structures (RTS). The two important performance criteria for device applications used at present are the current peak-to-valley (P/V) ratio and the peak current density. We report experimental results for lattice matched and pseudomorphic resonant tunneling diodes made from the $In_{0.53}Ga_{0.47}As/In_xAl_{1-x}As$ system with some of the highest (P/V) current ratios with reasonable peak current densities. An approximate analysis, based on a waveform analysis of the voltages and currents in the diode operating as an oscillator, indicates that these devices offer the potential of improved power generation at very high frequencies.

II. DISCUSSION

The choice of the InP based heterostructure material system is based on the advantages it presents for the high-frequency operation of the resonant tunneling devices. Inata *et al.*[7] have shown that lighter effective electron mass in the barrier improves the NDR of resonant tunneling devices. $In_{0.52}Al_{0.48}As$ has an effective mass of $0.075m_0$ compared to $0.092m_0$, for $Al_{0.30}Ga_{0.70}As$ and this reduction in the effective mass improves the peak current density.

The barrier potential height, on the other hand, has an effect on the current peak-to-valley ratio.[8] For the lattice matched GaAs/AlGaAs system the barrier height is approximately 0.23 eV. An increase in the Al composition of the barrier above a certain fraction and a certain barrier thickness,[13] results in the barrier material becoming an indirect band gap semiconductor which places some restrictions on the design of $GaAs/Al_xGa_{1-x}As$ RTSs. On the other hand, in the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ RTSs a relatively large potential barrier (≈ 0.53 eV) can be obtained with no such restrictions on the barrier or well widths because both materials are direct band-gap semiconductors. Thus performance for such a material system can be optimized. In the InGaAs system the barrier height can be further increased by using AlAs barriers. If conduction is assumed to be through the Γ valley, then the barrier height resulting from the $In_{0.53}Ga_{0.47}As/AlAs$ system would be ≈ 1.2 eV. AlAs layers on $In_{0.53}Ga_{0.47}As$ have a 3.7% lattice mismatch and the resulting strain limits the maximum thickness of the AlAs barriers. The critical thickness[14] at this strain, however, is larger than what is usually used for the barrier thickness.

$In_{0.53}Ga_{0.47}As$ has a higher mobility than GaAs which could become an important factor for high frequency RTSs using a transit-time drift region.[15] A practical advantage of the InGaAs material system is that it is relatively easier to make ohmic contacts to InGaAs than GaAs. In fact, by growing a heavily doped InGaAs cap layer, low contact resistance nonalloyed ohmic contacts can be obtained. Nonalloyed contacts are advantageous for resonant tunneling structures because they do not promote diffusion of impurities into the well region where they can enhance impurity scattering and thus reduce the peak-to-valley current ratio. Low contact resistance is important since one of the device parameters affecting the maximum oscillation frequency of practical oscillators is the minimum achievable contact resistance.

III. RESULTS

The lattice matched and pseudomorphic heterostructures were grown on n^+ InP substrates. The lattice matched $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ device structure is shown in Fig. 1(a). Mesa diodes were fabricated using conventional lithography techniques. Nonalloyed ohmic contacts of Ni/Ge/Au/Ti/Au were used. The peak-to-valley ratio at room temperature is found to be 7.1 while at 77 K the ratio in-

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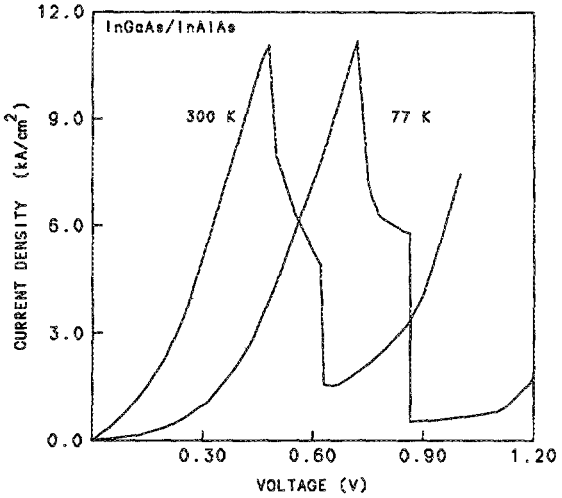
400 Å	Si : $\mathrm{In_{0.53}Ga_{0.47}As}$	5×10^{18}
0.3 μm	Si : $\mathrm{In_{0.53}Ga_{0.47}As}$	2×10^{18}
15 Å	i – $\mathrm{In_{0.53}Ga_{0.47}As}$	
41 Å	i – $\mathrm{In_{0.52}Al_{0.48}As}$	barrier
61.5 Å	i – $\mathrm{In_{0.53}Ga_{0.47}As}$	well
41 Å	i – $\mathrm{In_{0.52}Al_{0.48}As}$	barrier
15 Å	i – $\mathrm{In_{0.53}Ga_{0.47}As}$	
0.3 μm	Si : $\mathrm{In_{0.53}Ga_{0.47}As}$	2×10^{18}
S-doped InP Substrate		

(a)



(b)

FIG. 1. The lattice matched InGaAs/InAlAs RTS. (a) Schematic of the device structure, and (b) $I(V)$ characteristic at 300 and at 77 K.

creases to 21.6 [Fig. 1(b)]. The measured peak current density is approximately 10 kA/cm^2. To our knowledge, these are the best current peak-to-valley ratio results for this high current density.

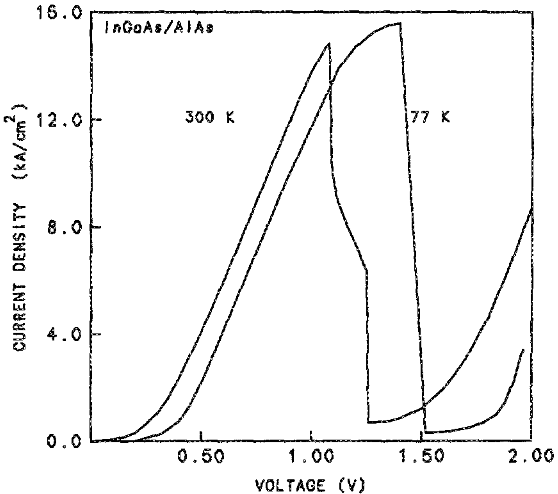
Special care was taken in measuring the dc $I(V)$ curves of these devices since it has been shown that if the measurement circuit oscillates then it can affect the shape of the $I(V)$ curve.[16] The measurements were made with the Hewlett-Packard 4145B semiconductor parameter analyzer. During the measurement it was made sure that the measuring circuit did not oscillate. However, this precaution does not exclude the possibility of the device oscillating at higher frequencies. This can affect the shape of the NDR region. For devices with NDR such as esaki diodes, it has been shown[17] that once the peak and valley points have been defined, the maximum power and the frequency are not much affected by local changes of the shape. Consequently, in an analysis such as this one, where only orders of magnitude are of interest, the dc $I(V)$ curves thus measured will be used to estimate power generation capabilities.

The device structure for the pseudomorphic RTS is shown in Fig. 2(a). Mesa diodes were fabricated using the procedure described above. The peak-to-valley ratio at room temperature is 23.9 while at 77 K a peak-to-valley ratio of 51.3 [Fig. 2(b)] is measured. These are believed to be the highest peak-to-valley current ratios ever reported for this material system. The peak current density was measured to be approximately 15 kA/cm^2.

Figure 3 shows the current peak-to-valley ratio versus the peak current density of various resonant tunneling structures reported in the literature. Some of the better results for the GaAs/AlGaAs and GaAs/AlAs system are also included for comparison purposes. Figure 3(a) shows the results at room temperature while Fig. 3(b) shows the results at 77 K. Recently, Broekaert, Lee, and Fonstad[9] have reported reso-

200 Å	Si : $\mathrm{In_{0.53}Ga_{0.47}As}$	5×10^{18}
0.3 μm	Si : $\mathrm{In_{0.53}Ga_{0.47}As}$	2×10^{18}
50 Å	i – $\mathrm{In_{0.53}Ga_{0.47}As}$	
23.7 Å	i – AlAs	barrier
44.0 Å	i – $\mathrm{In_{0.53}Ga_{0.47}As}$	well
23.7 Å	i – AlAs	barrier
50 Å	i – $\mathrm{In_{0.53}Ga_{0.47}As}$	
0.3 μm	Si : $\mathrm{In_{0.53}Ga_{0.47}As}$	2×10^{18}
10 period InGaAs/InAlAs superlattice		
S-doped n^+ InP Substrate		

(a)



(b)

FIG. 2. The pseudomorphic $\mathrm{In_{0.53}Ga_{0.47}As}$/AlAs RTS. (a) Schematic of the device structure, and (b) $I(V)$ characteristic at 300 and at 77 K.

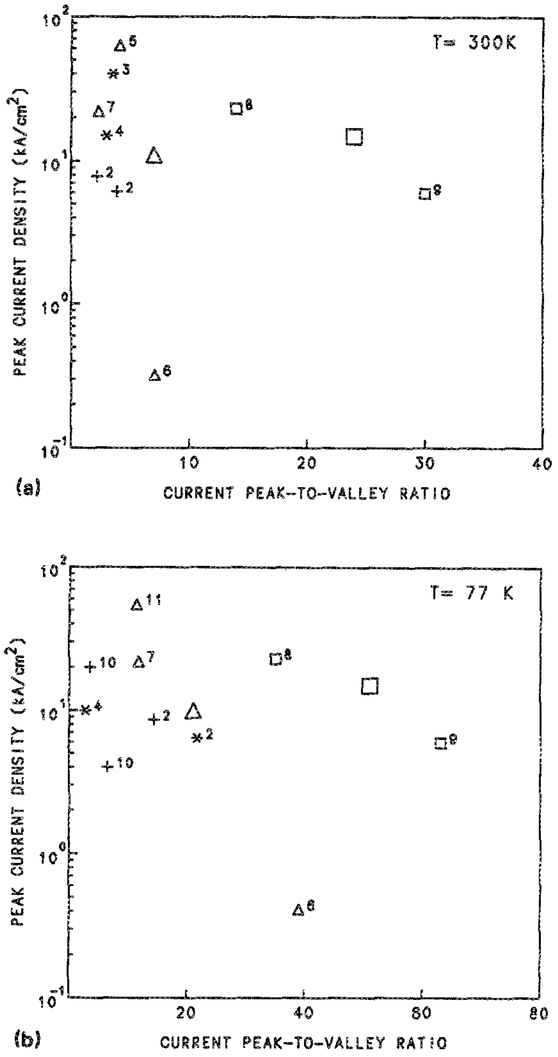


FIG. 3. Peak current density of RTSs as a function of the peak-to-valley ratio for various reported results. Results for GaAs/AlGaAs are also shown for comparison (a) at room temperature, and (b) at 77 K. The number corresponding to each data point refers to the reference number where the results were first reported. Data points with no numbers correspond to the results reported in this work. Legend for different material systems: + = GaAs/AlGaAs; * = GaAs/AlAs, Δ = InGaAs/InAlAs, and □ = InGaAs/AlAs.

about 7% lattice mismatch which might lead to serious device reliability problems. However, these results have been included in Fig. 3 for comparison purposes.

To study the power generation capability of the InGaAs based devices reported, an approximate analysis is carried out. The static $I(V)$ curve is assumed to be instantaneous and the dc bias point is selected to be in the middle of the NDR region. This is a good approximation since it has been shown that the negative conductance of these devices is essentially constant in this frequency range.[18] An rf single frequency voltage of magnitude V_{rf} is imposed at this bias point and the corresponding current waveform is obtained. The current waveform is then Fourier analyzed to obtain the fundamental component. From the fundamental components of the current and voltage the power density and the negative conductance ($-G$) of the device as a function of the applied V_{rf} is calculated. Selecting the V_{rf} amplitude that results in the maximum power density and assuming that the corresponding $-G$ is constant with frequency, the area and rf power available from these devices as an oscillator terminated by a 1-Ω circuit resistance are calculated. The 1-Ω load resistance is selected from the limiting value at microwave frequencies. This is a standard practice used to estimate output power. It is not obvious that a 1-Ω load can be realized at very high frequencies. However, if a larger load resistance is present, then the efficiency will still be the same but the output power will scale inversely proportional to the load resistance. The susceptance of the device is estimated by a parallel plate capacitor model. The depletion region width is taken to be the double-barrier structure width plus the width of any intrinsic spacer layers. Figure 4(a) shows the expected power generation and the required device area for appropriate matching. For comparison purposes, the power generating capability of a GaAs/AlAs device reported elsewhere[12] with a similar peak current density is shown in Fig. 4(b). The capacitance of the GaAs device was calculated in the same manner as the InGaAs devices. The power generating efficiency, at the maximum output power density, is 11% for the InGaAs pseudomorphic device and 3% for the GaAs device. These results are for room-temperature operation. At 77 K the device peak current remains approxi-

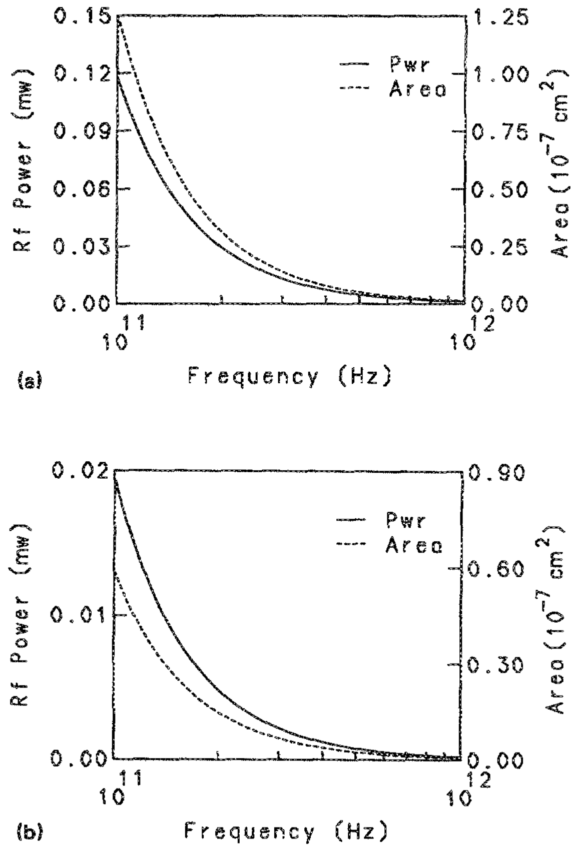


FIG. 4. RTSs as oscillators matched to 1-Ω circuit resistance. (a) Output power and the required matching area for the pseudomorphic InGaAs device reported in this paper, and (b) output power and the required matching area for the pseudomorphic GaAs device reported in Ref. 12.

mately the same but the peak-to-valley current ratio increases by almost a factor of two. This results in an increase of power output from 118 μW at 100 GHz to 150 μW at the same frequency. The general shape of the curve remains the same. The efficiency of the device increases to 17%.

IV. CONCLUSIONS

In conclusion, a peak-to-valley ratio of 7 (300 K) and 21 (77 K) with a peak current density of approximately 10 kA/cm^2 is reported for the lattice matched heterostructure system of InGaAs/InAlAs. The pseudomorphic $In_{0.53}Ga_{0.47}As/AlAs$ resonant tunneling structure resulted in a peak-to-valley ratio of 24 (300 K) and 51 (77 K) with a peak current density of ≈ 15 kA/cm^2. With the aid of a waveform analysis it is shown that the pseudomorphic InGaAs based devices can enhance power generation at very high frequencies where resonant tunneling diodes may be useful.

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