

Design and fabrication of a very low peak voltage InGaAs/AlAs resonant tunneling diode incorporating a highly strained quantum well

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ABSTRACT

A highly strained quantum-well InGaAs/AlAs resonant tunneling diode (RTD), fabricated using molecular beam epitaxy (MBE) at a relatively low temperature of 430°C, demonstrated an exceptionally low peak voltage (V_P) of approximately 0.23 V in the forward bias and 0.41 V in the reverse bias at room temperature. The atomic-scale control offered by MBE enabled precise layer growth, leading to an extremely low peak voltage along with high peak current densities of approximately 450 kA/cm² and 790 kA/cm² in the forward and reverse directions, respectively, mainly due to the exceptional interface quality and low series resistance. The MBE-fabricated RTD demonstrated superior scalability and reverse-bias performance compared to metal oxide vapor phase epitaxy-grown counterparts. Here, the process development of a submicrometer InGaAs/AlAs RTD was successfully achieved using standard photolithography, making it well suited for implementation in RTD-based terahertz (THz) sources that require low DC input power.

Keywords: InGaAs/AlAs, Quantum well, Resonant tunneling diode, THz sources

1. INTRODUCTION

Resonant tunneling diodes (RTDs) are promising candidates for terahertz (THz) oscillators due to their negative differential resistance (NDR), scalability, and ability to generate fundamental frequencies from 100 GHz to 10 THz [1]. Their role in bridging the THz gap has been emphasized in the recent Terahertz Science and Technology Roadmap, which identifies compact, low-power THz sources as a key research priority [2]. The current record of 1.98 THz oscillation at room temperature was obtained through an InGaAs/AlAs RTD featuring an ultrathin quantum well of 2.5 nm with 1 nm barriers, monolithically integrated with an optimized thick slot antenna [3].

RTDs incorporating an indium-rich (80%) quantum well structure (In_{0.8}Ga_{0.2}As) were initially reported by Matsuzaki in 2002 [4]. The growth was aided by the metal oxide vapor phase epitaxy (MOVPE) system, which yielded 100 kA/cm² peak current density at 0.39 V peak voltage and a peak-to-valley current ratio (PVCR) of 3.7 obtained at room temperature. Subsequently, Sugiyama and group [5][6] demonstrated an improvement in the device performance, achieving a PVCR of 7.7 together with a peak current density of 146 kA/cm² at a peak voltage of 0.43 V. Likewise, an exceptionally high peak current density of 409 kA/cm² was

achieved, accompanied by a PVCR of 3.8, for devices incorporating barrier layers with a thickness of four (4) monolayers. These results were attained through controlled, meticulous growth parameters, particularly by ensuring high-quality AlAs barrier layers.

An exceptionally high peak current density of 1300 kA/cm², accompanied by a PVCR of 1.5, was studied by Teranishi and coworkers [7]. This performance was accomplished through the use of a thin barrier of 1.4 nm AlAs combined with a high electrode doping concentration of 6×10^{18} cm⁻³. Subsequently, a peak current density was observed as high as 2400 kA/cm² at approximately 0.8 V, along with a PVCR of 2.1, by employing a thin 1.2 nm barrier and a graded emitter design, enabling the realisation of a 1.04 THz oscillator [8].

The work was further advanced by Teranishi and the group, achieving a record peak current density of 2800 kA/cm² at around 0.9 V, with a PVCR of 2. This was accomplished using a 1.2 nm barrier, a graded emitter layer, and high-indium-composition transit layers, enabling oscillation at 1.08 THz [9]. From then until the present, the development of indium-rich quantum well structures grown by MOVPE at relatively higher temperatures in the range of 550°C – 580°C has been dominated and improved by the same group [10].

The primary distinctions between this study and the previously reported study lie in the growth temperature as well as the growth system. In this study, the RTD with an indium-rich (80%) quantum well is grown using a low-temperature (430°C) molecular beam epitaxy (MBE) system, in contrast to a MOVPE system. Careful attention is given to both growth conditions and fabrication process, resulting in high-quality junction interfaces and low contact resistance. Consequently, the peak current (I_p) is achieved at a very low peak voltage (V_p), which is crucial for battery-powered, low DC-input THz sources.

2. THEORETICAL BACKGROUND

2.1. Resonant Tunneling Mechanism

The fundamental operation of an RTD relies on quantum mechanical tunneling through discrete energy levels within a quantum well. In a double-barrier resonant tunneling diode (DBRTD), a narrow-bandgap quantum well is positioned between two thin barrier layers with wider bandgaps. When a bias voltage is imposed, the emitter's Fermi level matches a quantized energy state in the quantum well (e.g., the first energy level, E_1), enabling electrons to tunnel through and produce a peak current. As the voltage continues to rise, this matching is disrupted, causing the current to decrease and producing the characteristic NDR region [11]. The transfer matrix method can be used to obtain the result for the electron transmission probability, $T(E)$, across a double barrier quantum well (DBQW) as follows [12]:

$$T(E) = 1 / [1 + (V_1^2 \cdot \sin^2(k_1 L_1) + V_2^2 \cdot \sin^2(k_2 L_2) + V_1 V_2 \cdot \sin^2(k_1 L_1) \cdot \sin^2(k_2 L_2)) / (4E(E - V_0))] \text{ Eq. (1)}$$

where V_1 and V_2 are the barrier heights, L_1 and L_2 represent the barrier thicknesses, k_1 and k_2 are the electron wave vectors within the barriers, and V_0 is the quantum well depth.

The thickness of the layers is directly related to the discrete energy level, with a higher density of energy levels in thinner wells and a higher tunnelling probability and current density in thinner barriers. Optimization of these parameters and the quantum well and barrier band gaps affects the energy gap between the quantum well ground state and the Fermi energy of the emitter, and therefore the electron transport properties of the device.

The high transmission at resonance leads to the current-voltage (I-V) characteristics hallmark of the RTD operation, the NDR region. This unique behavior allows RTDs to be used as a compact high-frequency oscillator, fast switch, and logic element, exceeding the capabilities of traditional semiconductor devices.

2.2. Effect of Layer Thickness on Quantum Wells

The quantized energy levels in the quantum well are mainly dependent on the thickness of the well and the effective mass of the carriers. In the case of an ideal square quantum well, the discrete energy states, E_n are given by [13]:

$$E_n = (n^2 \pi^2 \hbar^2) / (2m^* L_w^2) + E_c \text{ Eq. (2)}$$

where n refers to the quantum number, m^* denotes the electron effective mass, L_w resembles the quantum well width, while E_c presents the conduction band edge.

In practice, the resonance condition is set up by aligning the emitter Fermi level to one of these confined states. Thus, the energy separation of these quantized levels has a strong influence on the peak voltage in the RTD's I-V response. The narrower the wells, the higher the energy levels and the higher the resonant voltages, and the wider the wells, the lower the energy levels and the lower the bias required.

This well width and barrier thickness sensitivity is important in the design of RTDs. A thinner well will improve the peak current density but may also lead to more leakage because of greater wavefunction coupling across the barriers. On the other hand, thicker wells increase the confinement but decrease the tunnelling probability, which in turn decreases the current density. Optimization of the barrier height, thickness, and well width is thus crucial to obtain a stable NDR, high PVCR and device scalability for THz and ultra-low voltage applications.

In addition, the barrier and quantum well structure parameters that have a direct influence on the electrical and thermal properties of the device can be modelled through methods such as the Non-Equilibrium Green's Function (NEGF) formalism in conjunction with Hamiltonian descriptions. This approach allows for a detailed analysis of electron transmission coefficients and field emission energy distributions, which are significantly affected by variations in quantum well and individual layer thicknesses [14].

The 80% indium of $\text{In}_{0.8}\text{Ga}_{0.2}\text{As}$ exhibits a small band gap of approximately 0.50 eV, whereas $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ (53% indium lattice-matched to InP) has a larger band gap of 0.76 eV. Inserting an $\text{In}_{0.8}\text{Ga}_{0.2}\text{As}$ quantum well produces an outcome similar to that of an InAs sub-well [15]. The highly compressive strain in the $\text{In}_{0.8}\text{Ga}_{0.2}\text{As}$ layer relatively reduces the electron effective mass within the quantum well, which consequently lowers the first quantized energy level (E_1), as predicted by solutions to the Schrödinger equation for a finite potential well. Both approaches reduce the first resonance level in the quantum well, enabling electrons from the electrode to tunnel through it at a lower voltage.

Consequently, the peak current is achieved at substantially reduced voltage compared to a standard lattice-matched $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ quantum well of comparable thickness. Employing this particular quantum well material provides two advantages: it lowers the peak voltage while, at the same time, producing a high peak current density [16].

3. EXPERIMENTAL WORK

3.1. Epitaxial Layer Structure

The typical symmetric InGaAs/AlAs RTD in this study is fabricated by means of an in-house RIBER V100H solid-

source MBE system at a low temperature of 430°C on a (100) semi-insulating InP substrate. The designed epitaxial layer structure is shown in Table 1, where the cladding layers consist of In_{0.53}Ga_{0.47}As lattice-matched to the semi-insulating InP substrate, and tensile-strained AlAs is used for the barrier layers. The distinctive characteristic of such an RTD lies in its quantum well layer. A quantum well composed of highly compressive, strained In_{0.80}Ga_{0.20}As was fabricated for the RTD. The growth conditions and precise monolayer control of the MBE system are explained in our earlier study [17]. In sum, the growth method incorporated an ex-situ pre-calibration routine integrated with a very low growth rate for AlAs barriers.

Table 1. InGaAs/AlAs RTD (XMBE302) used in this work

Layer	Material	Doping (cm ⁻³)	Thickness (Å)
Collector 1	In _{0.53} Ga _{0.47} As (n++)	2 x 10 ¹⁹	450
Collector 2	In _{0.53} Ga _{0.47} As (n+)	3 x 10 ¹⁸	250
Spacer	In _{0.53} Ga _{0.47} As	undoped	50
Barrier	AlAs	undoped	11
Quantum well	In _{0.8} Ga _{0.2} As	undoped	45
Barrier	AlAs	undoped	11
Spacer	In _{0.53} Ga _{0.47} As	undoped	50
Emitter 2	In _{0.53} Ga _{0.47} As (n+)	3 x 10 ¹⁸	250
Emitter 1	In _{0.53} Ga _{0.47} As (n+)	1 x 10 ¹⁹	4000
Substrate	InP		

The contact layers on both sides are heavily doped, with concentrations of 2 × 10¹⁹ cm⁻³ for the collector (45 nm) and 1 × 10¹⁹ cm⁻³ for the emitter (400 nm). The heavily doped contact layers help minimize both the contact resistance and the series resistance. The electrodes (collector 2 and emitter 2, each 25 nm thick) are also heavily doped to promote electron accumulation in the contact regions. Undoped 5 nm spacer layers are placed on both sides to prevent dopant diffusion into the adjacent active layers during growth.

The DBQW active region comprises a single undoped, highly strained In_{0.8}GaAs quantum well (4.5 nm) positioned between ultra-thin AlAs barrier layers with 1.1 nm, which is characteristic of DBQW RTD structures. This structure is assigned as XMBE302.

3.2. Fabrication Process

The process was initiated with sequential cleaning of the sample using N-Methyl Pyrrolidone (NMP) solution, acetone, and propan-2-ol (IPA), with each step lasting 5 minutes. The NMP and acetone eliminate organic contaminants, whereas the IPA clears any remaining acetone. Except for the NMP step, both the IPA and acetone treatments are carried out using an ultrasonic bath for effective removal of contaminants.

The top contact pattern was initially patterned using conventional i-line photolithography with a Karl Suss MA4 mask aligner, with an additional soft-reflow process to achieve submicron lateral dimensions, similar to our previous work [18]. The soft-reflow initial steps involved spin-coating a thick layer (300 nm) of LOR3A (lift-off resist based on polydimethylglutarimide), and then depositing a 200 nm layer of silicon nitride (Si₃N₄). Next, a photoresist with a thickness of 420 nm is spin-coated onto Si₃N₄ surface using Shipley S1805 photoresist for pattern transfer from the photomask. After undergoing the soft-reflow procedure, the pattern opening reduced from 1 μm to 350 nm.

The top contact metallization was thermally evaporated with Ti/Au (50 nm/220 nm) onto the surface of the heavily doped In_{0.53}Ga_{0.47}As collector and lifted off in NMP solution. The top metal contact (collector) and the bond pad are connected via an air-bridge structure on the same plane, measuring 1 μm in width and 5 μm in length. The submicron active mesa area is etched using a reactive ion etching (RIE) with CH₄:H₂, producing an anisotropic sidewall that extends 200 nm down to the emitter layer.

The sample then underwent an orthophosphoric-based (H₃PO₄/H₂O₂/H₂O in a 3:1:50 ratio) wet-etching process to isolate neighboring devices by vertically etching about 300 nm down until it reached the surface of the InP substrate at a rate of 90 nm per minute. The suspended air-bridge structure was developed simultaneously through lateral undercut due to isotropic etching.

Finally, the bottom ohmic contact and the bond pad were created by thermal evaporation of Ti/Au (50 nm/500 nm). This is followed by a lift-off process in NMP solution. The fully fabricated device is presented in Fig. 1.

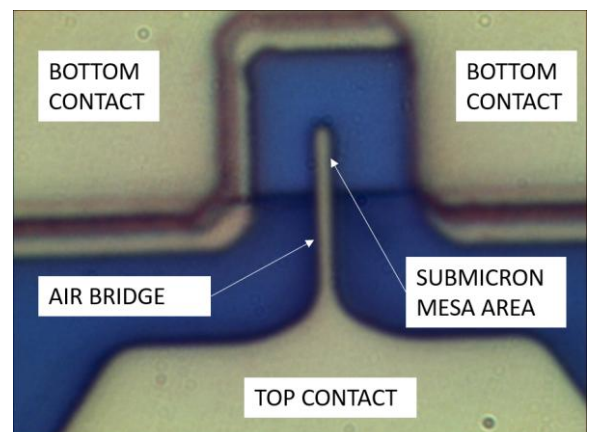


Figure 1. Microphotograph of a completed 0.8 μm² active mesa InGaAs/AlAs resonant tunneling diode in this work

4. RESULTS AND DISCUSSION

4.1. Contact Resistance

Upon completion of the fabrication process, the top and bottom quality ohmic contacts are measured by extracting the contact resistance values, R_c, via a transmission line model (TLM). This process control monitoring technique is facilitated by 4-point probe measurement on all TLM

structures located across the sample. The details on this technique have been discussed in our recent work [19].

The average value was approximately $0.04 \Omega \cdot \text{mm}$ of contact resistance, R_c , while the sheet resistance was $4.8 \Omega/\square$ obtained for the top metal. This low contact resistance shows the high quality of the ohmic contact alloying, which helps reduce parasitic voltage drops during device operation. The bottom contact metal exhibited a lower average contact resistance R_c of $0.01 \Omega \cdot \text{mm}$ and a sheet resistance of $10.3 \Omega/\square$. The designed doping profile in the collector region was responsible for the higher sheet resistance in the bottom layer in order to balance current transport efficiency.

Both sets of values agree with the theoretical values for the known doping levels of the collector and emitter layers, thus confirming the excellent quality of the epitaxial growth and metallization. These precisely characterized contact properties are critical for ensuring the optimal performance of the fabricated devices, particularly in high-frequency and high-power applications where parasitic resistances can severely degrade device efficiency and reliability.

4.2. DC Characteristics

Room-temperature DC measurements were performed using an HP 4142B DC parameter analyser. The peak current density for submicrometer mesa active areas, ranging from $0.4 \mu\text{m}^2$ to $1.6 \mu\text{m}^2$, is displayed in Fig. 2. The peak current density is approximately 450 kA/cm^2 in the forward direction and 790 kA/cm^2 in the reverse direction. Various sizes of RTDs showed good uniformity, with variations below 10% and 12% in the forward and reverse direction, respectively.

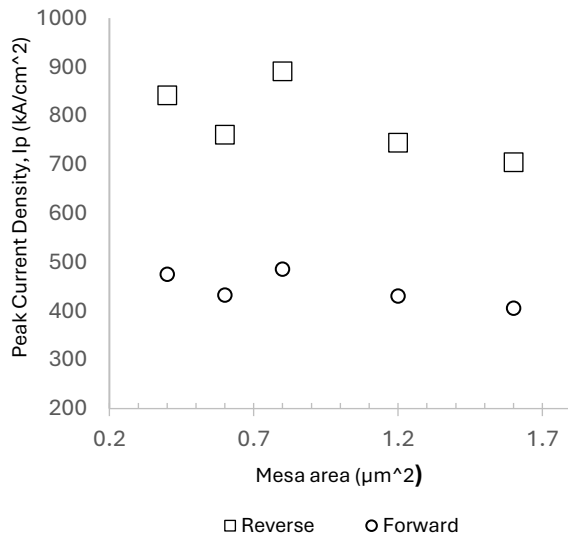


Figure 2. Measured peak current density at room temperature, showing excellent scalability in forward and reverse directions

In forward operation, electrons flow from the emitter to the collector, and opposite for the reverse operation. Prominently, small peak voltages of 230 mV in forward operation and 410 mV in reverse operation (at which current is maximum) were measured, as depicted in Fig. 3.

The low voltage performance is observed, attributed to low series (and contact) resistance as the attributes of high doping concentration and excellent control of the back-end metallization process. The obtained low voltage effect can also be related to exceptional material quality owing to atomic-layer precision control during the growth of both compressively strained quantum wells and tensile-strained barriers.

Evidently, the highly strained quantum well lowers the first resonant energy level, thereby lessening the energy necessary for electrons to tunnel within the double-barrier structure, resulting in a lower peak voltage. A low peak voltage is especially crucial for minimizing power dissipation in RTD-based circuits. Apart from its excellent DC characteristics, sample XMBE302 in this work has been demonstrated to achieve a maximum frequency, f_{max} beyond 860 GHz with large mesa area of $4 \times 4 \mu\text{m}^2$ [20].

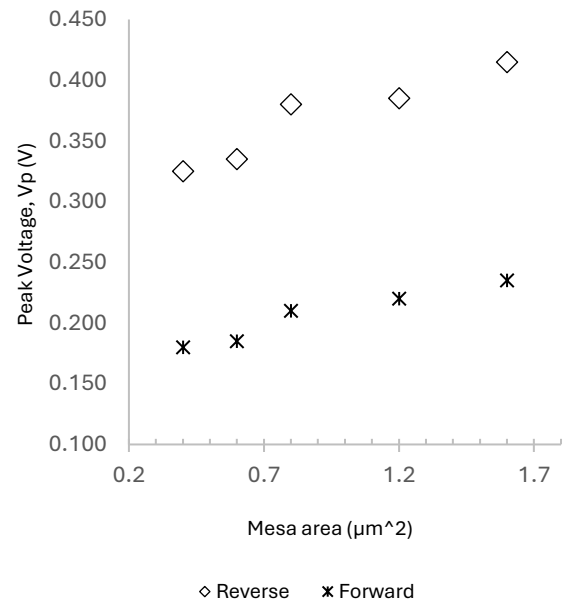


Figure 3. Measured peak voltages at room temperature in forward and reverse direction

4.3. MBE versus MOVPE Grown InGaAs/AlAs RTD of Similar Structure

A direct comparison can be made between RTDs grown by MBE and those grown by MOVPE, both featuring a 1.1 nm AlAs barrier and a 4.5 nm strained $\text{In}_{0.8}\text{Ga}_{0.2}\text{As}$ quantum well. To facilitate this comparison, the structural layers and their respective DC attributes are compiled in Table 2. Notably, the RTD structure reported by Sugiyama *et al.* [21] closely resembles the MBE-grown RTD identified as XMBE302 in the present study. The primary differences in Sugiyama's MOVPE-grown RTD lie only in the electrode regions, specifically in the doping concentrations and layer thicknesses of both the emitter and collector.

Overall, the forward-direction peak current densities were similar for both RTDs. In contrast, the XMBE302 RTD exhibited a significantly higher peak current density in the reverse direction, measuring 666 kA/cm^2 relative to 378

kA/cm² for the MOVPE-grown RTD. Considering that the barrier thicknesses of both devices are comparable, the enhanced reverse-direction current in XMBE302 is likely resulting from an inadvertent reduction in the top barrier thickness. For the MOVPE-grown RTD, the ratio of forward to reverse peak current density is 1.08, reflecting the symmetry of its barrier layers.

Table 2. Comparison between MBE- and MOVPE-grown InGaAs/AlAs RTD with indium rich quantum well (80%). All thickness (in nm) are nominal unless otherwise stated.

Layer	MOVPE-grown RTD [16]		MBE-grown RTD in this work	
Collector 1 (nm, cm ⁻³)	Not applicable		45 (doped 2x10 ¹⁹)	
Collector 2 (nm, cm ⁻³)	110 (doped ~10 ¹⁸)		25 (doped 3x10 ¹⁸)	
Spacer (nm)	5		5	
Barrier (nm)	1.1		1.1	
Quantum well (nm)	4.5		4.5	
Barrier (nm)	1.1		1.1	
Spacer (nm)	5		5	
Emitter 2 (nm, cm ⁻³)	285 (doped ~10 ¹⁸)		25 (doped 3x10 ¹⁸)	
Emitter 1 (nm, cm ⁻³)	200 (doped ~10 ¹⁹)		400 (doped 1x10 ¹⁹)	
Peak current density (kA/cm ²)	409 (forward)	378 (reverse)	385 (forward)	666 (reverse)
PVCR	3.8 (forward)	4.2 (reverse)	2.5 (forward)	2.5 (reverse)
Peak voltage (V)	0.68 (forward)	0.61 (reverse)	0.23 (forward)	0.41 (reverse)
Mesa area	2x3 μm ²		< 1 μm ²	

The XMBE302 RTD exhibits an exceptionally low forward peak voltage of 0.23 V, a characteristic that distinguishes it from the other RTDs reported in this study. This low voltage can arise from the quantum well of superior quality and the very low contact resistance at both the top as well as bottom terminals [22]. Moreover, variation in growth temperature significantly influences the roughness at the InGaAs and AlAs interface. While the MOVPE-grown RTD was fabricated at 550°C, the XMBE302 sample was grown at a lower temperature of 430°C.

An elevated growth temperature leads to smoother interfaces, thereby reducing interface roughness (IR)

scattering [23]. Consequently, the MOVPE-grown RTD exhibits an enhanced PVCR (~4) compared to the MBE-grown RTD (PVCR 2.5), despite both devices having similar structures in terms of active epilayer. In the MOVPE-grown RTD, at a growth temperature set to 550°C, the 5 nm spacer layers appear sufficiently thick to restrict dopant diffusion into the active layers, as reflected by the elevated PVCR.

4.4. Comparative Analysis of RTD Structures and Material Systems

A recurring trade-off between peak voltage (V_P) and peak-to-valley current ratio (PVCR) is evident across reported RTD structures as depicted in Table 3. Low V_P devices can be used to reduce power consumption but usually exhibit moderate PVCR as a result of increased scattering at strained heterointerfaces. On the other hand, high PVCR structures will need to have high V_P , which will lead to high bias power and integration difficulties.

There are a number of differences when compared to other material systems. The most well-developed and studied RTD system is the GaAs/AlAs RTD, which usually has moderate to low peak voltages (0.28 V) and PVCR values between 1.5 and 3.0. They are the easiest to grow and are the best crystal quality and therefore were the first benchmark for RTD studies, but the thicker well and barrier layers make the device's capacitance too large for high frequency operation. The PVCR of MOVPE-grown InGaAs/AlAs RTDs is slightly better (~1.8), but these devices need higher bias (> 0.7 V), which decreases the power efficiency. The PVCR of InAs/AlSb RTD is superior (~3.2) but requires higher peak voltage (~1.1 V) and is challenging to scale because of lattice mismatch. Although GaN/AlN RTDs can emit THz signals at room temperature, they need a very high bias voltage (8–10), which leads to higher dissipation and less integration potential.

The InGaAs/AlAs RTD used in this work, on the other hand, is a combination of the benefits of low-temperature growth control of MBE with the highly strained quantum well design. This optimization allows achieving a very low peak voltage of 0.23 V for a reasonable PVCR of 2.5, one of the most competitive candidates for low-voltage and high frequency circuit integration. Such characteristics are particularly beneficial for oscillator applications, where reducing the required bias voltage directly translates into lower power consumption and improved system scalability.

Table 3. Comparison of reported RTD performance across different material systems and growth methods

Material Systems / Growth Method	Well / Barrier Thickness	Growth Temperature	V_P (V)	PVCR	Max Frequency / Application	Ref.
InGaAs/AlAs (MOVPE)	4.5 nm / 1.2 nm	>550 °C	0.75	1.8	Oscillator, detector	[24]
InAs/AlSb RTDs (MBE)	6.4 nm / 1.5 nm	500 °C	1.1	3.2	High PVCR RTDs	[25]
GaN/AlN RTDs (MBE)	1.75 nm / 2 nm	>700 °C	8.0 - 10.0	1.1	Room-temp THz demo	[26]
GaAs/AlAs RTD (MBE)	6.5 nm / 1.7 nm	>550 °C	0.28	3.3	THz oscillator candidate	[27]
InGaAs/AlAs (MBE)	4.5 nm / 1.1 nm	430 °C	0.23	2.5	THz oscillator candidate	This work

5. CONCLUSION

A highly strained InGaAs/AlAs RTD with a quantum well (80% indium) was successfully fabricated by standard i-line optical lithography in combination with a soft-reflow process, which allowed the device to be fabricated with dimensions less than 1 μm without the need for e-beam lithography. The device was grown at low temperature (430 $^{\circ}\text{C}$) using MBE and exhibited a high peak current density (105 A/cm^2) and PVCR (~ 2.5) at room temperature. Importantly, the nominally symmetric structure yielded an ultra-low peak voltage ($< 0.25\text{ V}$), which is due to the precise epitaxial control and well-formed alloyed ohmic contacts. This is an inexpensive and scalable fabrication process that shows that high-performance RTDs can be achieved using conventional processes and provides uniformity and reproducibility. These devices are potential candidates for compact, battery-operated THz oscillators, if they can be made sufficiently nonlinear at low bias. In addition to oscillators, the RRTDs are also becoming enabling components for THz communications and energy-harvesting applications in the future 6G IoT systems, following the general trend of THz technology development.

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