Resonant tunneling diodes on InGaAs for monolithic integration with optoelectronic devices

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In this work we report the fabrication and characterization of micro-Resonant Tunneling Diodes (μ-RTDs) on an InP platform. The devices contain two symmetric AlAs barriers surrounded by InGaAs layers with both n contacts. Diodes show strong negative differential resistance behavior with peak at 1 V in both forward and reverse bias and voltage window of 0.5 V. All measured devices perform with extremally high Peak to Valley Current Ratio of up to 14 in forward bias and 9 in reverse bias. These characteristics enable electrical spike generation. The fact that the RTD is embedded in n-doped InGaAs layers, enables monolithic integration with light emitting and receiving devices for optical spike processing.

Introduction

In the recent years, deep learning neural networks are being deployed in software and hardware in new technological areas. The total power consumption of deep learning computation on conventional computing systems is increasing exponentially [1]; to reduce required energy, a different hardware approach is being investigated. Spiking neural networks (SNNs) use timing between spikes to process information and take power only while receiving or generating the spike [2]. To implement this approach on a photonic platform, a resonant tunnelling diode (RTD) has been proposed as the mechanism for excitability [3].

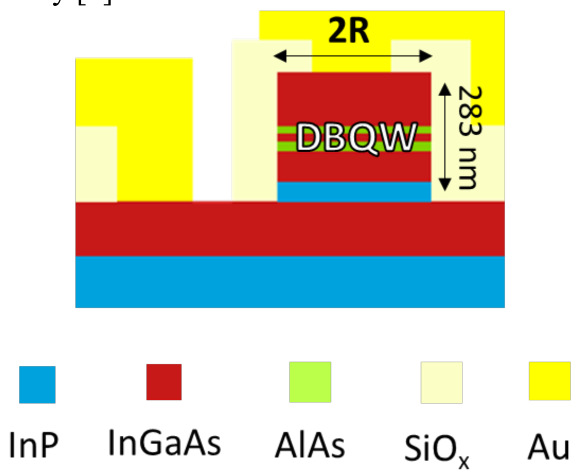

Figure 1 – Schematic cross-section view of InGaAs/AlAs circular mesa resonant tunnel diode.

The RTD active region contains an undoped InGaAs/AlAs double barrier quantum well (DBQW) nanostructure (see Figure 1). Bandgap mismatch between InGaAs and AlAs materials effectively form a quantum well system with discrete energy levels and enable resonant tunnelling through the barriers. This is evident in the IV characteristics (Figure 2). The conduction band profile of the RTD under different applied bias is also shown on the inset in Figure 2. Under a sub-threshold applied bias, the Fermi level in InGaAs (E_F) is below the first energy level in the quantum well (E_{QW}). As the bias increases, the Fermi level shifts up and reaches E_{QW} at threshold voltage (V_{th}). Resonant tunnelling current flow through quantum well results in diode-like current-voltage behaviour. Increasing the applied voltage further system will tune the device out of the resonant conditions, and the current will drop. The system will then exhibit a so-called negative differential resistance (NDR), as the current decreases with increasing voltage: E_F will be shifted from E_{QW}. Modulating this system in NDR region allows a high sensitivity to small variations and therefore electrical spike generation. Peak to Valley Current Ratio (PVCR) strongly influence current amplitude of generated spikes [4].

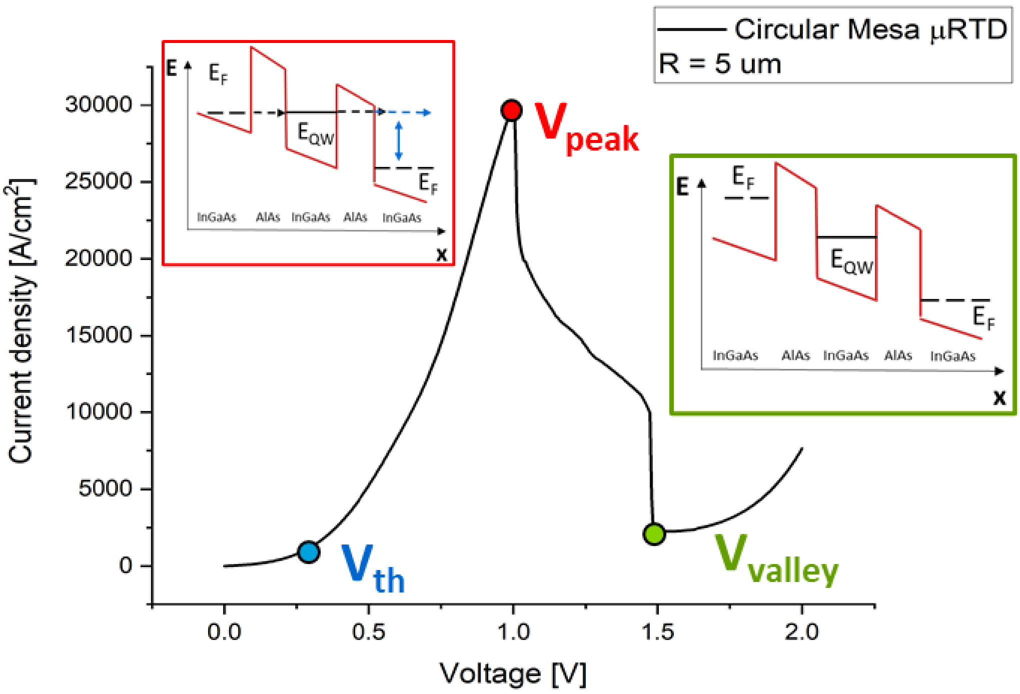

Figure 2 – IV characteristic of a single InGaAs/AlAs μRTD device. The inset pictures show conduction band profile for voltages between V_{th} and V_{peak} (red frame) and between V_{peak} and V_{valley} (green frame).

High amplitude electrical spikes can drive a light-emitting structure, generating optical spikes. For monolithic integration of RTD with LEDs or laser diodes without interfering with the optical mode, a DBQW should be embedded in the diode cladding or contact layers [5]. In this work, we demonstrate the fabrication of μRTDs embedded in highly doped n-InGaAs for later integration with light-emitting structures on an InP platform.

RTD fabrication and static characterization

Micro-RTD devices were fabricated on an epitaxially grown wafer (by IQE Ltd) on a semi-insulating InP substrate. The layerstack contained an undoped InGaAs/AlAs/InGaAs/AlAs/InGaAs (2 nm/1.7 nm/5.7 nm/1.7 nm/2 nm layers thickness) DBQW structure, surrounded by highly doped n-InGaAs contact layers. The definition of patterns was done with a MA6 mask aligner using UV exposure. Circular-shape mesa μRTDs were fabricated using this method, with radius size varying from 2.5 μm to 5.5

μm. Mesa etching was done with a single inductively coupled plasma (ICP) step with CH_4-H_2 chemistry, 110 RF at 60° C, using a 200 nm SiO_2 layer as a hardmask. After cleaning the surface, a new layer of 200 nm SiO_2 was deposited with plasma enhanced chemical vapour deposition (PECVD) to provide electrical isolation on the sides of micropillars and bottom n contact. Semiconductor surface opening for contacts fabrication was done using single Nitride reactive ion etching (RIE) step with pure CH_3 chemistry. Finally, Ti/Pt/Au contacts were defined by deposition with e-beam evaporation followed by lift-off and rapid thermal annealing steps. Static electrical characterisation of fabricated devices was done with Keithley 2602 source meter using DC probes. IV characteristics were obtained with voltage sweep from -2 to +2 Volts with 1600 measurement points.

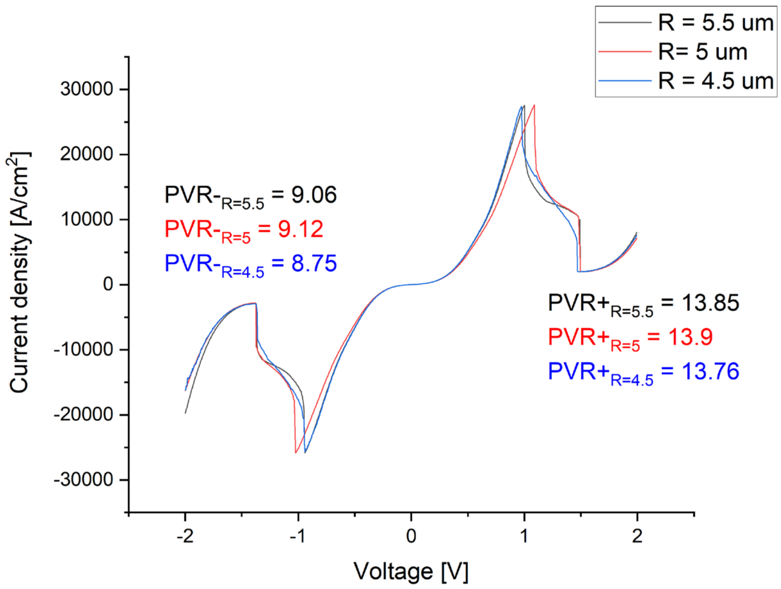

Figure 3 – IV characteristic of three circular mesa InGaAs/AlAs μRTDs with R = [4.5, 5, 5.5] μm.

The IV characteristics of the measured devices (see Figure 3) shows strong NDR behaviour, typical for RTD. NDR region is starting at 1 V both in forward and reverse bias. The voltage window (difference between peak and valley voltages) is 0.5 V. PVCR was calculated to be around 14 in forward bias and 9 in reverse bias. Symmetric RTDs typically show same behaviour in forward and reverse bias, in our case asymmetry may be introduced by etch stop InP layer (see Figure 1).

Figure 4 shows measurement results of 2 and 3 RTDs connected in parallel. In contrast to single RTDs, measurements were done for devices with mesa R=2.5 μm. This mesa size was at the resolution limit of the lithography method, so with structures connected in parallel, the chance for one of them experience successful top contact opening is higher.

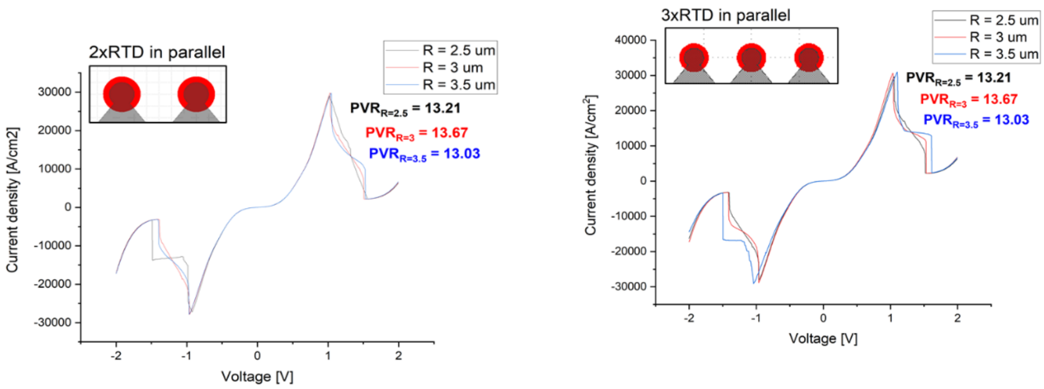

Figure 4 – IV characteristic of circular mesa InGaAs/AlAs µRTDs with R = [2.5, 3, 3.5] µm (left: two µRTDs connected in parallel; right: three µRTDs connected in parallel).

Compared to single devices, measured arrays show slightly higher peak current density, with similar PVCR. Uniform high PVCR for different mesa sizes (spread over the wafer) show high potential to use this RTD design for reproducible electrical spikes generation and potential for integration with optoelectronic devices.

Conclusions

We demonstrated the fabrication of InGaAs/AlAs µRTDs on InP platform, embedded in highly doped n-InGaAs layers. The fabricated diodes exhibit NDR with current peaks at 1 V in both forward and reverse bias, and a voltage window of 0.5 V. The measured devices show high PVCR up to 14 in forward bias, allowing for high amplitude electrical spikes generation and future integration with light-emitting structures for optical spiking devices.

Acknowledgment

This project has received funding support from the European Union's Horizon 2020 research and innovation program under Grant No. 828841.

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