Extremely low-power consumption nano-RTD photodetectors for future neuromorphic computing

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Abstract

This paper describes the fabrication of nanometre-sized resonant tunnelling diode (RTD) photodetector devices which may be used as excitable neuromorphic spike generators. Submicron diameter devices have been fabricated and exhibit peak currents under 250 µA, peak and valley voltages of around 0.6 V and 0.8 V and a peak to valley current ratio of around 2.4. If operated as a spike generator from the valley voltage point, the expected energy consumption will be under 10 fJ per spike. This nano-RTD technology could underpin the development of energy efficient neuromorphic computing.

Introduction

The recent rise of Artificial Intelligence (AI) systems powered by computers that can learn without the need for explicit instructions is transforming our digital economy and our society as a whole. They use computational deep neural network models1 inspired by information processing in the human brain. However, today's computing hardware, based on von Neumann architectures, is inefficient at implementing these neural networks largely because of the high power consumption per unit area required, typically >10 W/cm^2 compared to around 0.01 W/cm^2 for the brain [1]. As such, research for new low energy computing paradigms is underway.
The RTD is a nanoelectronic structure that can be easily integrated with conventional electronic and photonic devices on a chip working at room temperature. Its unique current-voltage characteristic exhibits a negative differential resistance (NDR) region, and so it can be used in the design of excitable spike (pulsed) generators to produce excitable short electrical and optical pulses mimicking the spiking behaviour of biological neurons thus making it one of the target candidates for such neuromorphic applications [2].
In this paper, we report on the fabrication on nano-sized RTDs which may be suitable for the realisation of low energy consumption excitable spike generators. The measured device characteristics and initial experiments with spike generation are reported.

Experimental

In the fabrication process, we start with epitaxial RTD wafers grown on a semi-insulating InP substrate by molecular beam epitaxy (MBE) by partner IQE Ltd. In the results described here, we employed a double barrier quantum well (DBQW) structure comprising a 5.7 nm $In_{0.53}Ga_{0.47}As$ quantum well, 1.7 nm AlAs barriers, with one wafer having 100nm and another 250 nm thick lightly doped InAlGaAs spacers. The collector and emitter layers are made of highly Si doped $In_{0.53}Ga_{0.47}As$ layers. The 100/250 nm thick spacer layers were originally incorporated for light absorption in the 1310-1550 nm wavelength range. Details of the epitaxial layer structure are shown in **Table 1.**

Table 1. Structure Specification of two wafers (1000A for wafer1, and 2500A for wafer2 in layer10)

Layer	Type	Doping level	Material	Thickness (Å)	Description
12	N++	2.0e19	InGaAs	1000	Contact
11	N+	2.0e18	InAlAs	1000	Collector
10	N-	2.0e16	InAlGaAs	1000 **(2500)**	Spacer
9	I		InGaAs	20	
8	I		AlAs	17	Barrier
7	I		InGaAs	57	Well
6	I		AlAs	17	Barrier
5	I		InGaAs	20	
4	N-	2.0e16	InGaAs	200	Spacer
3	N+	2.0e18	InAlAs	1000	Emitter
2	N++	2.0e19	InGaAs	5000	Contact
1	I		In(x)AlAs	1000	
Substrate			InP		

The fabrication process for 500, 700, and 800 nm diameter mesa size devices include metal evaporation of Ti/Pd/Au to form the top contact of the RTD. Dry etching with $Cl_2/CH_4/H_2$ (6/10/15 sccm) gases at 60°C was used to define the RTD mesa. The bottom contact metal (Ti/Pd/Au) was then evaporated. 1.6 µm thick of BCB was used for device passivation, followed by etch back process. Finally, top and bottom bond-pad metallisation was carried out using Ti/Au. Fig.1 shows the SEM images for different stages of nano-RTD fabricated devices.

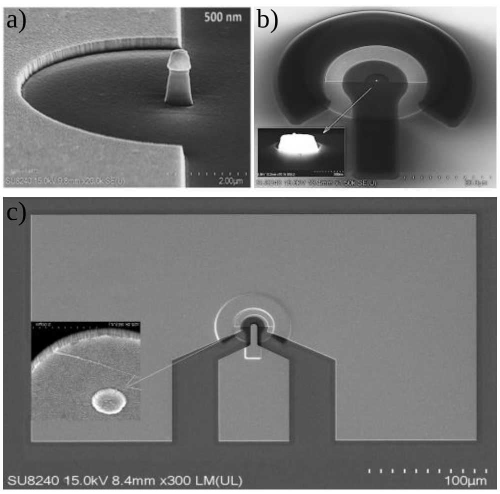

Fig. 1. SEM images of 500 nm fabricated nano-RTD **a)** top contact/mesa and bottom contact, **b)** after etch back the BCB, and c) the bond pads of completed device; the inset showing the bond pad over the 500 nm top contact.

Results and discussion

The measured DC current-voltage (IV) characteristics of the fabricated nano-RTDs with diameters of 500, 700, and 800 nm for wafer 1 are shown in **Fig. 2a**, and a comparison of 500nm devices for both wafers 1 and 2 are shown in **Fig. 2b** showing a decrease in current with increase in spacer thickness. The peak DC power consumption is 64.8 µW. If a 500nm diameter device from wafer 1 is operated at 10 GHz, the energy consumption per spike will be 6.48 fJ.

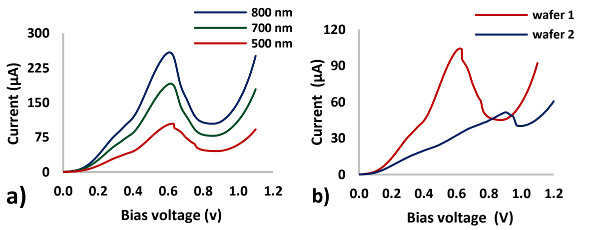

Fig. 2. I-V characteristics of **a)** 500,700,800 nm RTD device of wafer 1, and **b)** 500 nm RTD device of wafer 1& 2.

To assess the spiking behaviour of the devices, an RTD device from (wafer 1) was used. When biasing at the point close to the valley in the second PDR region (0.86 V), a slight manual change in the biasing voltage with about ±0.5 mV was done to investigate the effect of the NDR region to generate spikes from self-oscillation of the circuit. Thus, a number of spikes appeared when the bias voltage was in the NDR region, and no spike when bias voltage was in the 2nd PDR region as shown in **Fig.3 a**. A similar response was observed when biasing the RTD device around the peak region (~0.6 V), the only difference was spike profile was flipped to a positive spike followed by a negative one, as shown in **Fig.3** b& c. **Fig.4.** shows the measurement setup.

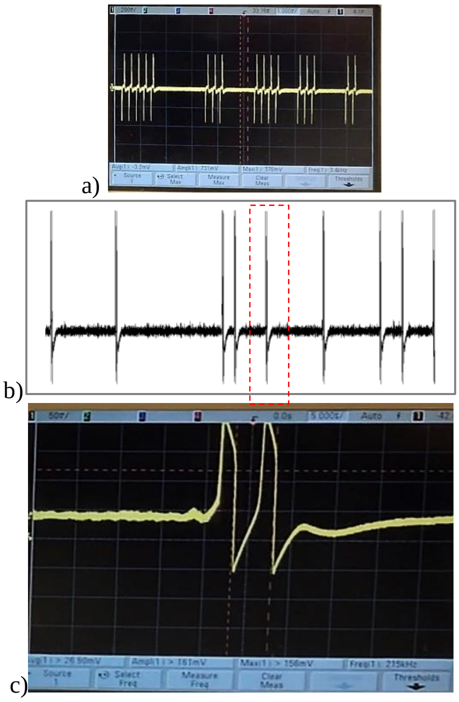

Fig. 3. Experimental traces of output spikes generated by 700 nm nano-RTD device, a) biasing in valley point, b) slightly changes (± 0.5 mV) around the valley point has been applied. c) a shape of spikes during slightly change at the peak point applied, and d) zoom in of one spike of (c).

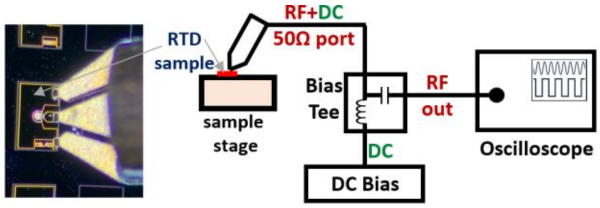

Fig.4, Schematic circuit for the measurement.

Fig.5 shows another set of experimental results of generated spikes using an RTD-oscillator [3] as DUT. The oscillator was driven by pseudo-random bit sequence (PRBS) with an amplitude of 1 V, biased at -0.56 V, and the frequency of the PRBS was set at 500 MHz. The resultant spiking behaviour is shown in **Fig.5**. The amplitude of the spikes is around 2.5mV, and the spike duration is 450 psec. The amplitude of spikes is rather low (~2mV), that attenuated due to the shunt circuit of the RTD-oscillator circuit.

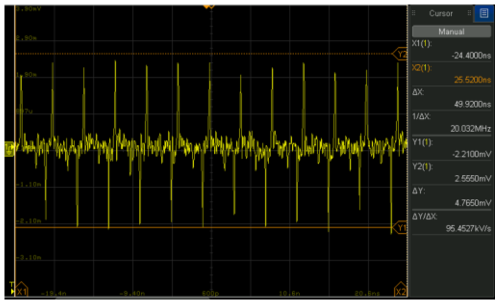

Fig. 5. Experimental traces of output spikes generated by an RTD driven by pulse generator. The input bias voltage the PRBS square wave amplitude was set to 1V, the RTD oscillator was biased at 0.56V, the frequency was set at 500 MHz.

Conclusions

The fabrication and characterization of submicron diameter nano-RTD devices which may be used in extremely low power consumption neuron-like spike generators was described in this paper. Initial results to assess spike generation are promising. Note though that details of how to design a spike generator with specified characteristics are still being developed. The RTD includes a light absorption layer and so may be optically controlled. Further work in this regard is ongoing.

Acknowledgments

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