Optoelectronic Integrated Chips employing Resonant Tunnelling Diodes

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Introduction

- Currently, in many optoelectronic systems the 
optoelectronic chip is made from an epilayered, 
heterostructured III-V semiconductor and the purely 
electronic part of the system is made from silicon.
- With optoelectronic integrated circuits (OEICs) the aim is to 
integrate some of the electronic functionality onto the III-V 
semiconductor chip
- In the emerging mass markets of fibre to the home and 
ubiquitous high bandwidth wireless access then all the 
benefits integration will be important, particularly low 
power and cost.
Outline

- Resonant Tunnelling Diode (RTD) operation principle – the physics behind the negative differential resistance (NDR).
- The Resonant-Tunelling Diode integrated with a laser diode
- The nonlinear dynamics of RTD-LD
- The applications wireless/optical interface and chaos generation
- The resonant tunnelling diode in an optical waveguide and the RTD-OW and the closely related RTD photodiode (RTD-PD).
- Conclusions
The Resonant Tunneling Diode: the epilayer structure

- Emitter
- InGaAs
- AlAs
- InGaAs
- Collector
- InGaAs
- AlAs
- InGaAs

10nm

InP substrate

One monolayer = 0.5nm

Lowest conduction band energy

Energy

z
Tunneling through resonant states
The current voltage curve and negative differential resistance
The measured I-V curve for a RTD

Oscillation in the NDR region
Oscillations up to 831 GHz

The Resonant Tunneling diode laser diode (RTD-LD) – semiconductor layers

- **n-type**
- **i-type**
- **p-type**

Injected current

Metal n-contact

RTD

Active light emission region

Metal p-contact
# The details of the RTD-LD Wafer Design

<table>
<thead>
<tr>
<th>Layer no.</th>
<th>Material</th>
<th>Comp. fraction</th>
<th>Thickness µm/ Å</th>
<th>Doping type</th>
<th>Doping conc.</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Wafer</td>
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<td></td>
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<tr>
<td>1</td>
<td>InGaAs</td>
<td>X=0.53</td>
<td>0.2µm</td>
<td>p</td>
<td>5*10¹⁸cm⁻³</td>
<td>Bottom contact layer</td>
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<tr>
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<td>p</td>
<td>5*10¹⁷cm⁻³</td>
<td>Cladding</td>
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<tr>
<td>3</td>
<td>InₓAlᵧGa₁₋ₓ₋ᵧAs</td>
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<td>i</td>
<td></td>
<td>Waveguiding core</td>
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<td>Active Layer</td>
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<td></td>
<td></td>
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<td>1 µm</td>
<td>n</td>
<td>5*10¹⁷cm⁻³</td>
<td>Cladding</td>
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<td>X=0.53</td>
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<td>1*10¹⁸cm⁻³</td>
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<td>InGaAs</td>
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<td>20 Å</td>
<td>i</td>
<td></td>
<td>Spacer</td>
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<tr>
<td>9</td>
<td>AlAs</td>
<td></td>
<td>25Å</td>
<td>i</td>
<td>Barrier (strained)</td>
<td></td>
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<tr>
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<td>X=0.53</td>
<td>50Å</td>
<td>i</td>
<td>Quantum well</td>
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<td>11</td>
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<td>i</td>
<td>Barrier (strained)</td>
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<td>i</td>
<td>Spacer</td>
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<td>13</td>
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<td>0.1µm</td>
<td>n</td>
<td>1*10¹⁸cm⁻³</td>
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<tr>
<td>14</td>
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<td>0.2µm</td>
<td>n</td>
<td>5*10¹⁸cm⁻³</td>
<td>Cap layer</td>
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<table>
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<tr>
<th>Quantum wells</th>
<th>Material</th>
<th>Comp. fraction</th>
<th>Thickness Å/ ML</th>
<th>Doping type</th>
<th>Doping conc.</th>
<th>Comments</th>
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<tr>
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<td>X=0.53 Y=0.20</td>
<td>90 Å</td>
<td>i</td>
<td></td>
<td>Barrier (*5)</td>
</tr>
</tbody>
</table>
Integrated RTD-LD Chip layout

- 3µm wide laser ridge
- 22µm wide ridge
- p-type contact
- n-type contact
- Silica Insulating Layer 3µm wide laser ridge
- Semi-insulating substrate
- Heavily p-doped InGaAs contact layer
- Laser emission
- Laser active region
- RTD
Scanning Electron Microscope Images of a RTD-LD device

- Scanning electron microscope images of the bare etched wafer and completed device.

Etched wafer - laser ridge and contact ridge

Complete device - inset shows 3µm ridge detail.
Monolithically Integrated Device- results

- CW results from a 500µm cavity length ridge waveguide laser cooled to 130K. Fig 1 shows current vs voltage, fig 2 shows Log optical power vs voltage.
- There is clear hysteresis in both the current and optical power.
- The hysteresis loop is wide (~1.5V) and the optical power on-off ratio is approximately 20dB.
The monolithic RTD-LD -> Hybrid RTD-LD

- The monolithic RTD-LD showed hysteresis – good for NRZ operation - but no oscillation and only pulsed room temperature operation.
- To gain a further insight into the operation of RTD-LD we moved to a hybrid version – with a RTD chip and a LD chip connected by a bond wire.
- The work we now present is based on the hybrid version.
- From this work it was clear the monolithic version had a large series resistance probably a contact resistance – thus heating and hysteresis.
The hybrid RTD–LD

Current-voltage (I-V) characteristics

Voltage controlled oscillator

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Hybrid RTD-LD electrical characteristics
Hybrid RTD-LD Optoelectronic oscillations

Electrical output

Optical output
Linear versus Nonlinear analysis of oscillators

- RTD have a highly nonlinear current voltage characteristic.
- All oscillators are nonlinear and involve amplifier plus feedback.
- One nonlinear effect always present is that the amplifier is driven into saturation and there may be other nonlinear effects.

<table>
<thead>
<tr>
<th>Linear analysis</th>
<th>Nonlinear analysis</th>
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<tbody>
<tr>
<td>Simple to implement</td>
<td>More complicated to implement</td>
</tr>
<tr>
<td>Predicts: approximately the oscillation frequency</td>
<td>Predicts: oscillation frequency, output power, output waveform; synchronisation, chaos</td>
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</table>
The nonlinear analysis of the RTD-OEICs

• Van der Pol Oscillator had been implemented before for negative differential resistance devices.

• Liénard’s Oscillator is a generalisation of the The Van der Pol oscillator and allowed us to predict the Voltage frequency curve (VCO), the synchronisation and chaos behaviour.

• Synchronisation is particularly important for the Wireless/Optical interface application and the operation of the RTD-LD as a Injection Locked Oscillator (ILO).
Nonlinear dynamics of the RTD-LD

The circuit can be described by the following equations:

\[ \frac{dV(t)}{dt} = \frac{i(t) - F(V)}{C} \]

\[ \frac{di(t)}{dt} = \frac{V_b - Ri(t) - V(t)}{L} \]

Which are equivalent to the Liénard’s second-order differential equation:

\[ \ddot{V}(t) + H(V)\dot{V}(t) + G(V) = 0 \]

Laser model introduced through single mode rate equations
RTD-LD The Optoelectronic Voltage Controlled Oscillator (VCO)
Synchronisation and the Injection Locked Oscillator

- Synchronisation is well known phenomena in nonlinear dynamics
- Using the RTD-LD we could apply this wireless to optical conversion
- Wireless signals are often phase modulated – phase shift keyed (PSK) – a small injected signal (-40dB compared to the output) controls the phase of the RTD-LD and thus the phase of the optical sub-carrier
- Digital information can be transferred from the wireless to the optical domain
**RTD-LD injection locked oscillator**

- Nonlinear dynamical system based on the Liénard’s driven oscillator and laser diode single mode rate equations.

**Electrical model:**

\[
\begin{align*}
\dot{V} &= \frac{1}{C}[I - F(V)] \\
\dot{I} &= \frac{1}{L}[-RI - V + V_{DC} - V_{TH} + V_{AC}\sin(2\pi f_{in}t)]
\end{align*}
\]

Liénard’s driven oscillator

\[\ddot{V}(t) + H(V)\dot{V}(t) + G(V) = V_{AC}\sin(2\pi f_{in}t)\]
Injection locking

- Experimental synchronization in the laser output
Liénard’s RTD-LD 2D Synchronization Map

- RTD-LD frequency locking structure showing the Arnold Tongues map: a comparison of theory with experimental results

- $f_{in}/1$ - when the injected wireless signal is at the same frequency as the natural oscillation frequency

- $f_{in}/2$ - when the injected wireless signal is twice the frequency of the natural oscillation

- The y axis is the amplitude of the injected wireless signal
Adler’s equation – the short version of Arnold’s tongues

\[ \Delta f = \frac{f_0}{2Q} \sqrt{\frac{P_{\text{inj}}}{P_0}} \]

\( \Delta f \) – locking range
\( f_0 \) – oscillator frequency
\( P_{\text{inj}} \) – power of injected signal
\( P_0 \) – output power of oscillator
\( Q \) – oscillator quality factor
The optoelectronic interface includes the RTD-LD electric-to-optic (E/O) converter and patch antenna for RF broadcasting.

- The RTD-LD responds to the wireless electromagnetic radiation which is amplified by the negative conductance.
- The optical fibre delivers microwave broadcasted signals.

Microwave to optical conversion

- RF generator
- 1.4 V
- Patch antenna
- Wireless RF Emission
- 3 GHz
- d. c. bias
- Shunt Capacitor
- RTD
- Microstrip line
- Au
- Laser Diode
- Printed Circuit Board
- Measurement Setup
- SCOPE/Spectrum Analyzer
- RF output
- 50 Ω
- Optical Signal
- PD
- 50 Ω
Analogue Phase Modulation

- The laser diode output, locked with a broadcasted signal, shows the same modulation features of the injected signal with the same sidebands at 1 MHz offset of the radio frequency sub-carrier.

- Most digital wireless signals are phase shift keyed (PSK) and so, because of the fixed phase relationship, the phase synchronization of the RTD-LD can be used to translate the digital information from the wireless to the optical domain.
RoF network based on W-O RTD-LD

In the Radio over Fiber (RoF) network the pico-cell base station consists of a microwave-optical interface circuit combining an electric-to-optic (E-O) converter, the RTD-LD.

Base Station (BS)

RTD-LD (E/O)

Control Station (CS)

Up-link RF in

E/O: Electric-to-Optic Converter

Optical Signal

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The Wireless/Optical interface
Embedding a RTD within an optical waveguide core we obtained an electro-absorption modulator/photo-detector (RTD-EAM/RTD-OWPD).

**Wafer structure**

**Energy-band diagram**

**Current voltage characteristic**

**Operation as photo-detector (RTD-OWPD)**
RTD-PD optical-to-RF interface

- The RTD-PD interface characterization setup includes patch antennas for directional wireless emission-reception.
Optical to wireless synchronisation

RTD-OW free-running oscillation and locking to a 1530 nm optical signal modulated by an RF signal at 600 MHz.
The driven RTD-LD – chaos generation

(a) Coupling strength, $V_{ac}/V_p$

(b) Largest Lyapunov exponent, $\lambda_1$

Frequency ratio, $f_{in}/f_0$

Frequency ratio, $f_{in}/f_0$
Phase maps and spectra the driven RTD-LD
Steganography – camouflage for signals – just add chaos.

• At source chaos generator is modulated but chaos > modulation so signal looks like noise

• Deterministic chaos can be removed by receiver and signal recovered
Summary and Conclusion

- Introduction to the RTD the fastest electronic device
- The RTD-LD can be monolithically integrated
- The hybrid RTD-LD has allowed as to verify the Lienard’s oscillator model
- Modulation of the phase of the radio frequency sub-carrier was demonstrated in the laser output.
- First demonstration of wireless to optical conversion and optical to wireless with the RTD-PD - using synchronization of a nonlinear oscillator.
- Chaos generation

http://userweb.elec.gla.ac.uk/i/ironside/RTD/RTDOpto.html