E-2-4
Extended Abstracts of the 2014 International Conference on Solid State Devices and Materials, Tsukuba, 2014, pp632-633

Non-destructive Mapping of Doping and Structural Composition of High Current Density Resonant Tunnelling Diodes Grown by Metal-Organic Vapour Phase Epitaxy Through Photoluminescence Spectroscopy

K.J.P. Jacobs[1], B.J. Stevens[2], T. Mukai[3], D. Ohnishi[3], R.A. Hogg[1]

[1] *Department of Electronic & Electrical Engineering, University of Sheffield, Centre for Nanoscience & Technology, North Campus, Broad Lane, Sheffield, S3 7HQ, United Kingdom*
[2] *EPSRC National Centre for III-V Technologies, Department of Electronic & Electrical Engineering, University of Sheffield, Centre for Nanoscience & Technology, North Campus, Broad Lane, Sheffield, S3 7HQ, United Kingdom*
[3] *Sensing Technology R&D Project, R&D Headquarters, Rohm Co. Ltd., 21 Saiin Mizosaki-cho, Ukyo-ku, Kyoto 615-8585, Japan*
Corresponding author: k.jacobs@shef.ac.uk

We report on the optical spectroscopy of metal-organic vapour phase epitaxy (MOVPE) grown high current density (~700 kA/cm^2) InGaAs/AlAs/InP based resonant tunnelling diodes (RTDs) for terahertz emission. The low temperature photoluminescence (PL) measurements we describe allow the non-destructive determination of doping level, ternary alloy composition, and quantum well thickness. Furthermore, mapping of these parameters over a full wafer allows the uniformity to be analysed and details of the growth processes to be deduced. This rapid non-destructive mapping of the epitaxy by PL is highly advantageous, and promises a route to future growth optimisation.

Research into terahertz (THz) technology is now receiving an increasing amount of attention as the region between 0.1-30 THz finds use in a wide variety of applications, including ultra-broadband wireless communications [1]. High-speed electronic devices including resonant tunnelling diodes (RTDs) are used to develop high-frequency room-temperature emitters operating in this spectral region. Resonant tunnelling devices were first demonstrated by Chang *et al.* in 1974 [2]. InGaAs/InP is a material system of choice for high-speed devices due to the high electron mobility of InGaAs and excellent lattice matching to InP. In 2011, Mukai *et al.* demonstrated wireless transmission at 1.5 Gbit/s using a RTD oscillator at 300 GHz [3]. Fundamental oscillation up to 1.37 THz has also been recently reported [4]. The QW perfection and uniformity, ternary alloy composition and uniformity, and doping uniformity of the emitter and collector layers across the wafer are important parameters, as high peak and low valley currents are required, with low device variability and high yield in volume manufacture, to make RTD based THz emitters commercially viable.

In this work, we report on the optical spectroscopy of high current density (~700 kA/cm^2) InGaAs/AlAs/InP based RTDs, grown by metal-organic vapour phase epitaxy (MOVPE). Fig.1 shows schematics of (a) an n+ InGaAs doping test-structure, (b) the full RTD structure.

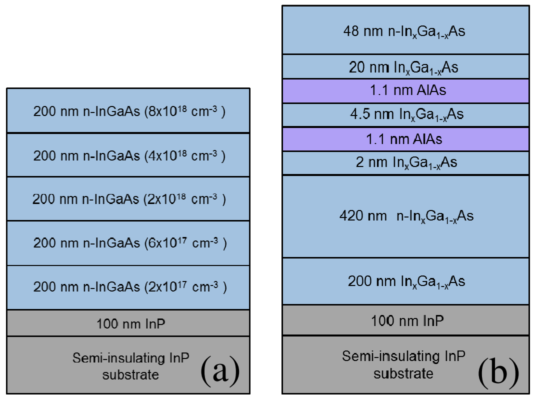

Fig. 1. Schematic of (a) n+ InGaAs test-structure (b) RTD layer structure.

We demonstrate how photoluminescence (PL) mapping at low temperatures allows the non-destructive determination of a range of structural, and electrical parameters such as; doping level and uniformity, ternary alloy composition and uniformity, and uniformity of the quantum well thickness.

PL as a function of doping was measured for InGaAs test-layers and the emission, dominated by the Moss-Burstein effect, was correlated to secondary-ion mass spectroscopy (SIMS) and electrochemical capacitance-voltage (eCV) to give a direct, accurate measurement of the doping of the emitter and collector layers. Fig. 2 shows the spatial variation of doping, non-destructively mapped using PL over a full 2” wafer. Our optical measurements are in good agreement with SIMS and eCV. This measurement technique is therefore not only advantageous in being non-destructive, but we also find that the measurement is more reproducible than eCV. The measurement of doping via this low temperature photoluminescence technique can be accurate to ~3%. For these test structures a 16% variation of the doping concentration was observed and mapped.

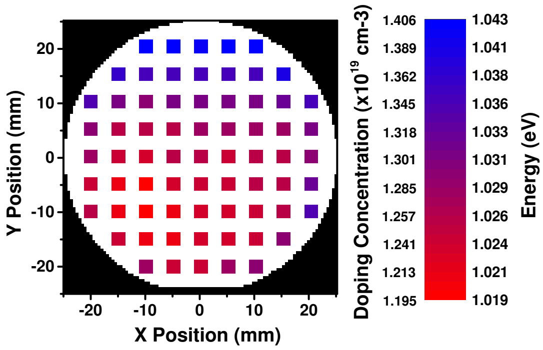

Fig. 2. PL map of doping concentration of n+ InGaAs layers determined from PL at 15 K.

For the RTD structures, we utilised eCV as an accurate selective etch, to identify the origin of low temperature PL emission from the QW and the highly doped emitter/collector layers. Fig. 3 shows temperature dependent PL spectra of a 4.5 nm QW RTD structure from 15 to 300 K, indicating that both emission peaks are only clearly resolved when the sample is cooled below 50 K. From a manufacturing perspective, the uniformity of the layer thicknesses and alloy composition of the QW are also important parameters for low device variability and high yield in volume manufacture.

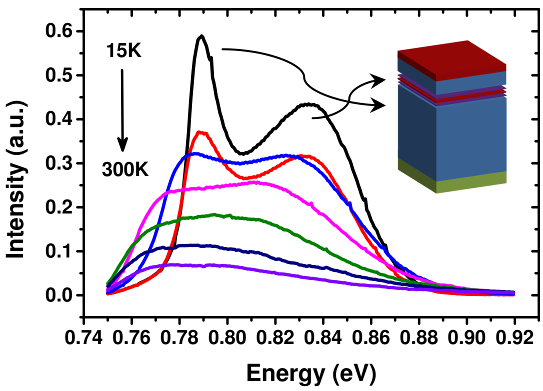

Fig. 3. Temperature dependent PL spectra of the full RTD structure indicating emission from QW and emitter/collector layers.

We investigate the InGaAs alloy composition and QW thickness over a full 2” wafer by measuring PL at low temperatures, and confirm our observations with high resolution X-ray diffraction (HRXRD) crystallography. Fig. 4 shows a wafer map measured over a full 2” RTD wafer with a 5 mm resolution (68 points) at 15 K. The difference in peak energy ΔE, with respect to the wafer center, for the QW emission is plotted as a function of position. The observed profile of the QW peak emission is attributed to both alloy and layer thickness non-uniformity over the wafer. This is confirmed with HRXRD and modeling. InGaAs alloy composition fluctuations of less than 0.6%, QW thickness variation of less than 0.5% were all deduced from this non-destructive mapping technique. The origin of these fluctuations in doping, alloy composition and thicknesses, with regard to the growth process will be discussed.

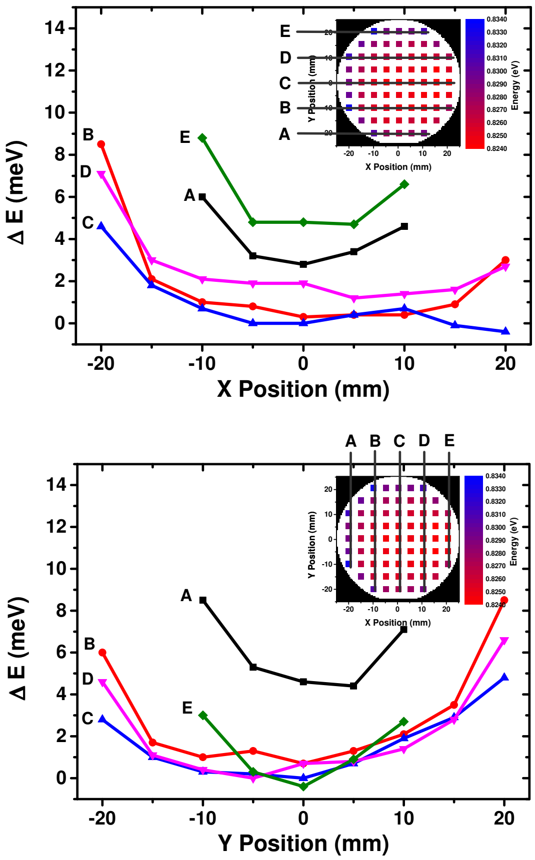

Fig. 4. (a) horizontal and (b) vertical line-scans of the QW peak wavelength shift determined by PL at 15 K. Insets show origin of line-scans with regard to the wafer map.

In summary, we have shown how doping, alloy and QW non-uniformity and perfection of high current density RTD structures may be non-destructively mapped over a full wafer with low temperature PL.

We gratefully acknowledge D. T. D. Childs and Prof. O. Wada for fruitful discussions and the U.K. Engineering & Physical Sciences Research Council for financial support.

[1] M. Tonouchi, Nature Photonics, **1**, 97, (2007).
[2] L. L. Chang, L. Esaki, R. Tsu, Appl. Phys. Lett. **24,** 593, (1974).
[3] T. Mukai, M. Kawamura, T. Takada, T. Nagatsuma, Tech. Dig. Optical Terahertz Science and Technology Meeting, MF42, Santa Barbara, (2011).
[4] M. Asada, S. Suzuki, ICECOM 21st International Conference on Applied Electromagnetics and Communications, Croatia, (2013).