Vertical Cavity Surface Emitting Laser (VCSEL) considerations for Atomic Clocks

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University of Glasgow

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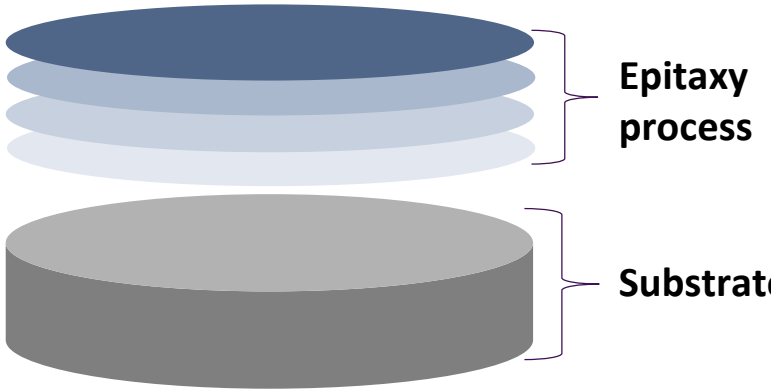
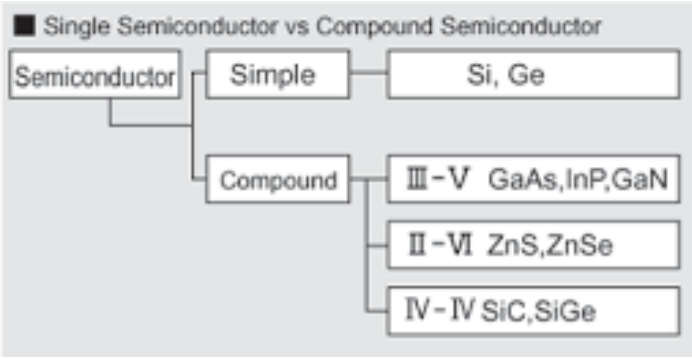
CSC Overview

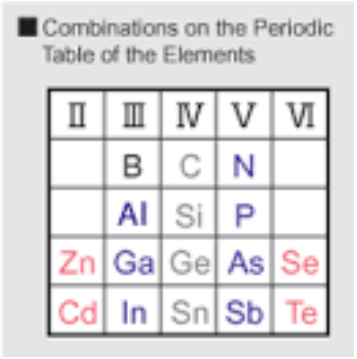
- **Formal JV – 50:50 Cardiff University:IQE Plc**
- **Co-located with IQE @ St Mellons**
  - Extensive MOCVD (Metal Organic Chemical Vapour Deposition) capability, multiple reactors
- **Epitaxy focus:**
  - GaAs, InP photonics, GaN RF/Power
- **Primary delivery mechanisms:**
  - Collaborative R+D programmes, Contract epitaxial materials supply, Exploitation of CRD outcomes

Epitaxy - engineering advanced materials

Atomically engineered epitaxial films of compound semiconductors (*up to 300 films*)

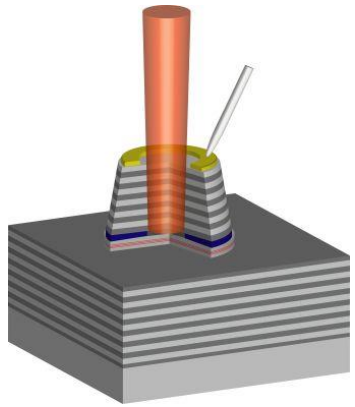


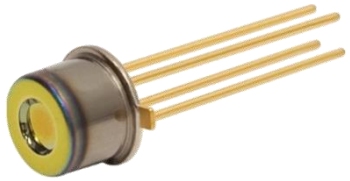


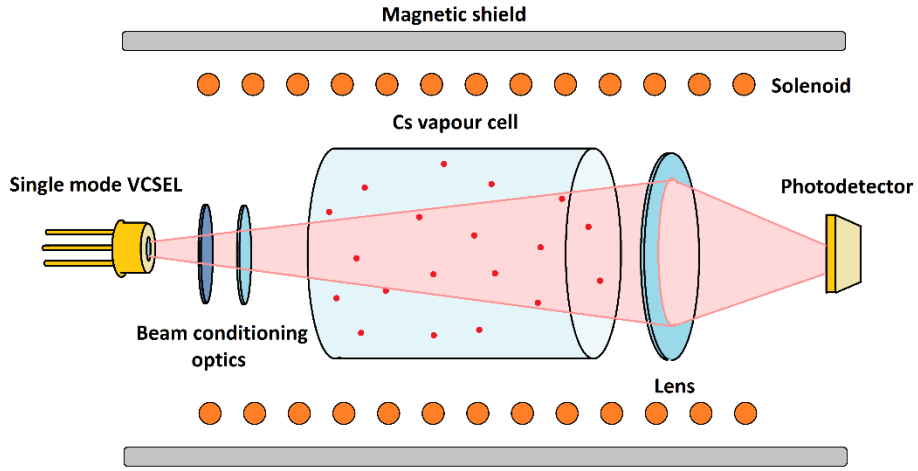


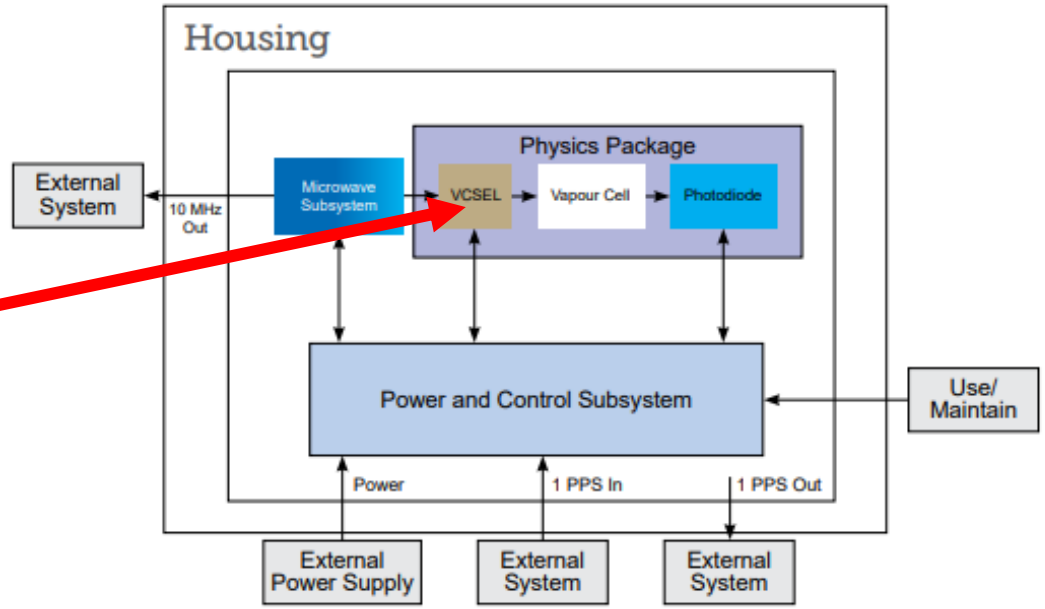
VCSEL focus – D1 Cs 894.6nm

- Narrow laser linewidth (spectral purity)
  - Reducing aperture size
  - Lower loss gain region and Bragg mirrors
- High optical output power
- Laser RIN (intensity noise)
  - Improved gain and mirror sections
  - Reducing technical noise contributions









Iterative development for 894.6nm single mode VCSELs

5 iterations of epi design ⇨ epi growth ⇨ fabrication ⇨ packaging ⇨ characterisation

Epitaxial Design	Epitaxial Growth	Fabrication	Packaging / Assembly	Validation & Reliability Testing
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD		ICS Integrated Compound Semiconductors	ALTER TECHNOLOGY	ICS Integrated Compound Semiconductors NPL National Physical Laboratory

VCSEL performance

KAIROS VCSEL against best-in-class commercially available 894nm VCSELs.

- ✓ New supply chain established and in-spec VCSELs delivered in 33 months through 5 iterations
- ✓ Improvement on a number of parameters compared to commercially available VCSELs (specific to atomic clock applications)

Parameters	KAIROS VCSEL	Nearest competitor
Single/Multi mode	Single mode	Single mode
Wavelengths	894.59 nm	894.59 nm
Max Power output (per VCSEL)	**1 mW**	0.5 mW
Linewidth	**30 MHz**	60 MHz
Power consumption	5 mW	5 mW
Package style	Flexible	Chip / carrier / TO46 / TO56
Stable linear polarisation	Yes	Yes

Clock performance

TELEDYNE e2V Everywhereyoulook™

MINAC™ clock has demonstrated 5x better short-term frequency stability (<5e10^{-12} up to 10s avg time)

MADE IN BRITAIN

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Aircraft carrier to trial quantum technology on Arctic exercise

11 March 2022 | Topic: Fighting arms | Surface Fleet

Storyline: HMS Prince of Wales

The world's first atomic clock of its kind has been fitted to Britain's biggest warship to help ensure pinpoint accuracy wherever she goes.

Aircraft carrier HMS Prince of Wales received the state-of-the-art piece of quantum technology before sailing for Norway on Monday to take part in the largest military exercise in a generation in the Arctic.

The technology – about the size of a typical laptop – provides a highly-accurate time signal which will allow the ship's complex combat systems to synchronise should the more traditional GPS signal fail.

Time signals are crucial for warships and having precise information helps the ship's company stay safe while at sea on operations.

cs connected

Commercial in Confidence

Lack of ***robust, reliable*** *and* ***volume supply*** of quantum photonic components present a major barrier to commercialising quantum technologies (computing, communication, imaging, sensing/metrology/timing)

Pressing need for proven foundry platform technologies for photonic quantum components:

Cost to taxpayer of CRD

Majority of UK QT programmes include semiconductor device manufacturing, each amounting to ~20-30% of total project cost

Cost-driven market traction

Significant R&D is required to improve reliability and reproducibility of quantum components. Upfront scale-up costs prevent market traction for QPCs

Lack of data for R&D studies

Semiconductor industry needs mid-volume data for understanding material and process related parameters that influence performance and reliability

QFoundry brings together UK's most established supply chains for quantum photonic components to address critical challenges in manufacturing and deliver a National (and World's first) open-access Quantum Photonic Component foundry

Delivering key technology platforms for accelerating uptake of quantum applications:

Vertical Cavity Surface Emitting Lasers

VCSELs enable miniaturisation of quantum technologies, such as rf quantum magnetometers and atomic clocks, potentially unlocking numerous quantum applications

Single-Photon Devices

Single-photon detectors (including mid-IR) & quantum light emitters are critical to realising viable applications for situational awareness, secure comms and optical computing.

Addressing key barriers to adoption

Q-Manufacturability

- Full wafer processing
- On-wafer and wafer-to-wafer process reproducibility
- Parametric design optimisation
- Robust testing and characterisation

Q-Reliability

- Baselining devices against industry standards
- Understanding reliability drivers for quantum applications
- Defining new test protocols

Q-Supply chains

- Customised quantum photonic components via foundry platforms
- Commercial viability through proven expertise and assets along supply chains

UK National Foundry for Quantum Photonic Components - QFoundry

AMETHYST RESEARCH

ICS Integrated Compound Semiconductors

MICROCHIP

The University Of Sheffield.

CS connected

TOSHIBA

CATAPULT Compound Semiconductor Applications

UNIVERSITY OF CAMBRIDGE

IQE

NPL National Physical Laboratory

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

bay photonics

Targeting wide range of applications, driven by **need for situational awareness, security, non-destructive evaluation and position, navigation & timing,** including quantum key distribution, sensing, LiDAR, atomic clocks and magnetometers

Target specifications for QFoundry VCSELs, in development

Parameters	QFoundry VCSELs
Single/Multi mode	Single and multi
Wavelengths	Any in the range of 700 – 950 nm, with specific focus on: **LiDAR and data/telecom** • 940nm and 850nm **Atomic clocks and quantum magnetometers:** • 795nm (Rb), 844nm (422nm, Sr+), 894nm (Cs), 935nm (Yb+)
Max Power output	Single-mode discrete: • Up to 10 mW per VCSEL Single-mode array: • Up to 100s of mW Higher for multi-mode devices
Linewidth	10-40 MHz (typ. 30 MHz)
Package style	Flexible – please enquire
Stable linear polarisation	Yes

If you have any specific requirements for your application, we would like to hear from you