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# HELLISH-VCSEL: A Hot Electron Laser

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**Abstract**

Hot Electron Light emission and Lasing In Semiconductor Heterostructures (HELLISH-1) is a novel hot electron surface emitter consisting of a GaAs QW on the n side of an $Ga_{1-x}Al_x$As p-n junction. It utilises hot electron transport parallel to the junction plane. The injection of hot electron hole pairs into the QW is achieved via tunnelling and thermionic emission processes. Recently this structure has been modified by the incorporation of an upper and lower DBR defining a VCSEL (HELLISH-VCSEL). This has been shown to lase at room temperature with a Full Width at Half Maximum (FWHM) of 1.5 nm. In this work the operation of the device is demonstrated and compared to a conventional edge emitting QW laser. The emitted power is studied as a function of surface area. The spatial distribution of the light intensity over the surface of the device is also investigated.

## Introduction

Hot Electron Light Emitting and Lasing In Semiconductor Heterostructure (HELLISH) devices are surface emitters based on longitudinal transport. Currently, there are two device types are known as HELLISH-1 and HELLISH-2[1,2]. In this work the original HELLISH-1 structure has been modified by the inclusion of lower and upper Distributed Bragg Reflectors to form HELLISH-VCSEL[3].

## Experimental Results

The HELLISH-VCSEL and QW edge emitting laser were both grown by MOVPE on semi-insulating GaAs substrates and the structures are shown in Figure 1. The VCSEL (Figure 1a) consists of a HELLISH-1 cavity surrounded by upper and lower DBRs which have 17 and 27 periods, respectively, of AlGaAs layers with the Al concentrations indicated. The lower DBR provides a reflectivity in excess of 99% while the reflectivity of the upper DBR is slightly lower to allow an output from the top surface. The QW is centralised within the cavity so that it is aligned to the anti-node of the confined optical field and therefore maximises gain with each round trip[4].

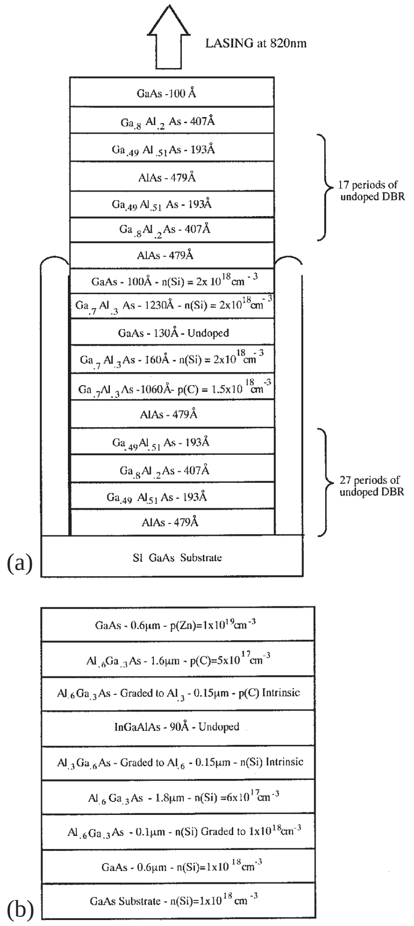


**Figure 1.** A schematic diagram of a) HELLISH-VCSEL and b) GRINSCH QW laser

The QW edge emitting laser is a GRINCSH structure (Figure 1b) consisting of a p-n junction with graded AlGaAs layers and a 90 Å InGaAs QW placed within the depletion layer at the junction. The QW has 9% Indium and 12% Aluminium content. This design is optimised for room temperature operation with a laser output at a wavelength of 812nm. Conventional stripe geometry lasers with cleaved facets were fabricated with typical dimensions of 1mm × 30$\mu$m. The dimensions of HELLISH-VCSEL varied between

100$\mu$m and 3.5mm. The upper DBR was selectively removed, down to the HELLISH cavity, so that the ohmic Au/Ge/Ni contacts could be evaporated onto the active region and then diffused throughout the cavity layers. The QW laser displayed the diode characteristics over 77-300K while the VCSEL contacts were ohmic at low applied voltages over this temperature range.

The output of HELLISH-VCSEL is determined by both the gain spectra of the HELLISH cavity and reflectivity spectra of the DBRs. Electroluminescence (EL) spectra were obtained in the pulsed mode at temperatures between 77-300K. The reflectivity spectra were produced using a Varian Carey 5 spectrophotometer at room temperature.

The reflectivity and electroluminescence (EL) spectra of HELLISH-VCSEL are shown in Figure 2. It can be seen that the cavity resonance wavelength is at a wavelength of 816nm, the EL spectrum is therefore peaked at this wavelength with a FWHM of 1.5nm.

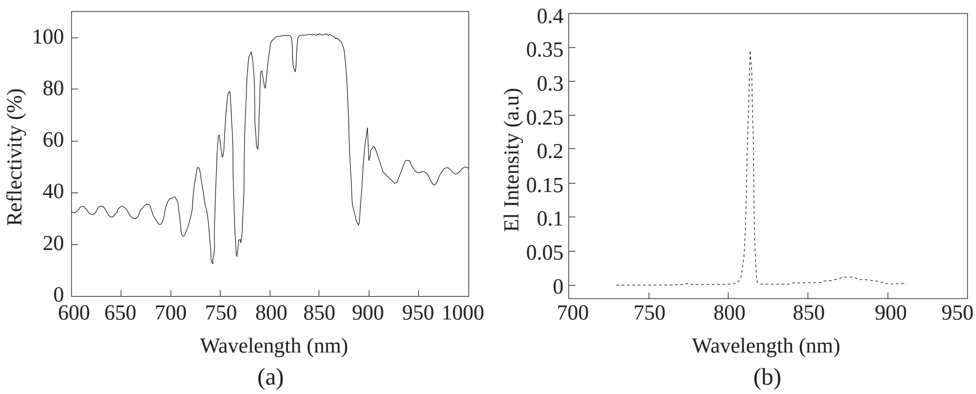


**Figure 2.** HELLISH-VCSEL a) reflectivity and b) EL spectra at 300K.

The peak wavelength on the wafer, from which the devices were fabricated, was found to shift by as much as ±20nm as a function of position. This is a common problem with MOVPE growth[4].

In order to analyse the growth errors from a device the reflectivity spectrum was measured from both ends of a 3×1mm simple bar as depicted in Figure 3. It is evident that the cavity resonance shifts by 1nm across the device length giving rise to a FWHM range of 1.5nm and corresponding to the FWHM observed in the EL spectrum.

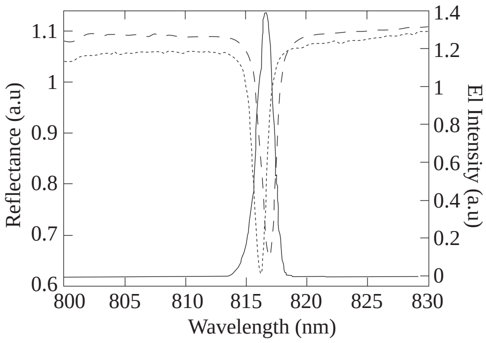


**Figure 3.** Reflectivity spectra (dashed lines) from the two end points of a 3×1mm HELLISH-VCSEL simple bar and corresponding EL spectrum (solid line) at 300K.

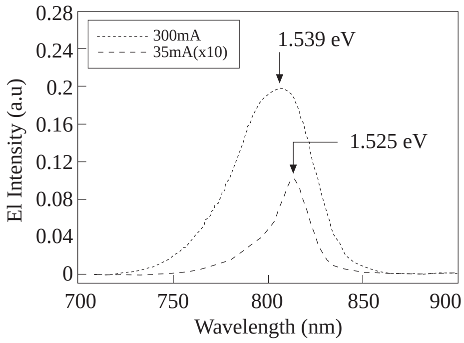


**Figure 4.** EL spectra for the QW laser at room temperature.

If the EL spectra of the QW laser is considered (Figure 4) then it can be seen that HELLISH-VCSEL (Figure 2) has an improved FWHM in comparison. To prevent device heating, and for a direct comparison to HELLISH-VCSEL, a pulsed current supply was used with a similar duty cycle. Figure 4 shows the EL spectra obtained and at 35mA the peak wavelength was 813nm which reduced to 805nm at 300mA and the overall shift was 8nm. Increasing current also gave rise to an enhanced high energy tail which indicated that the wavelength shift is not due to device heating , under pulsed conditions, but hot electron effects within the QW structure. It is also possible that this is a poor quality laser and therefore may not be lasing but only producing super-radiant emission. Therefore the EL spectra of this QW laser is very broad with a FWHM of 20nm, however the laser may not be fully operational, while HELLISH-VCSEL produces a 1.5nm FWHM (Figure 2).

It is essential to consider the output power (Figure 5) for both devices. This was achieved by measuring the light emission using a power meter and then normalising with respect to the duty cycle in each case. The pulsed power output of the QW laser is linear (Figure 5a) with increasing current above the threshold current of 40mA. The device does not suffer any heating effects in either the spectra or power output and gives a maximum values of 1.1mW at 420mA. The pulsed output power of the QW laser (Figure 5a) can be directly compared to HELLISH-VCSEL results and it can be seen that the VCSEL has an increased output power of 2.6mW at 1.2KV$\text{cm}^{-1}$. From Figure 5b there is a distinct VCSEL threshold of 50V$\text{cm}^{-1}$ after which the light emission begins to increase linearly. After 150V$\text{cm}^{-1}$ the device exhibits heating effects and the output power is limited all the way up to the maximum fields. It has been shown that HELLISH-VCSEL is thermally stable up to 1.7KV$\text{cm}^{-1}$ with typical output power of 5.5mW[3].

However, the output power measurements may include errors as the power meter was designed for cw, had a response time of 300ms and an accuracy of ±5% for the nW-$\mu$W ranges. In order to confirm the validity of obtained results the output power was investigated as a function of applied voltage pulse width across the electric field range and is shown by Figure 5c.

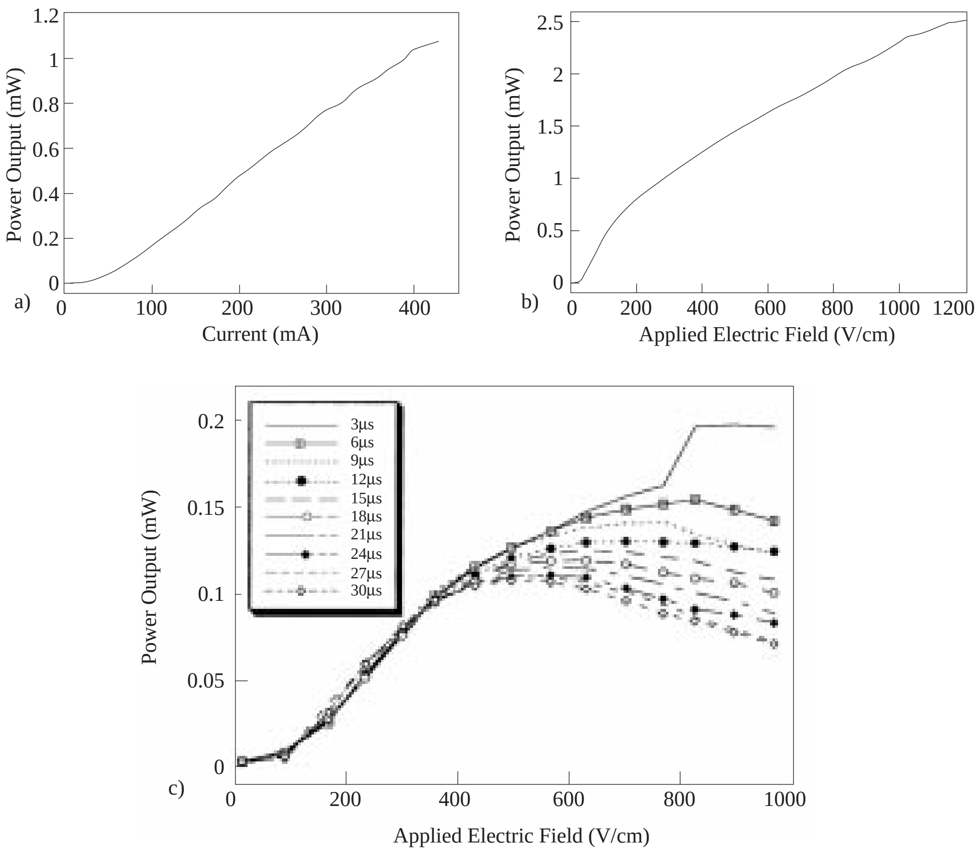


**Figure 5.** Output power of a) 1mmx30 $\mu$m QW laser using pulsed power supplies, b) 3×1mm HELLISH-VCSEL bar and c) HELLISH-VCSEL output power as a function of applied voltage pulse width, with a constant repetition rate of 10ms at 300K.

Up to 350Vcm$^{-1}$ all measurements are within experimental error which indicates that the response time of the power meter is sufficient to detect the emission from the device. Above 350Vcm$^{-1}$ the power begins to saturate with increasing pulse width and duty cycle. This is attributed to the device heating as the duty cycle increases.

If the devices are producing a coherent light source, therefore lasing, it should be possible to detect plane polarised emission. This was achieved by placing a polariser in between the device and detector and investigating EL intensity as a function of polariser angle over 360°. The results for HELLISH-VCSEL are compared with a conventional edge emitting QW laser (Figure 6). If the QW laser results are considered (Figure 6a) then it can be seen that this also exhibits polarisation with a ratio of 3.75:1 above threshold at 250mA and a ratio of 3.4:1 below threshold at 30mA. However, if the current was decreased too far below threshold then it is reasonable to assume that there will be some degree of stimulated emission, and therefore polarisation before the lasing threshold is achieved. HELLISH-VCSEL was tested at $1\text{KVcm}^{-1}$ but could not be investigated below threshold (Figure 6b). The EL intensity was low and close to the noise floor of the detector so it was very difficult to interpret the results. At $1\text{KVcm}^{-1}$ the light emission from HELLISH-VCSEL is clearly polarised and has a ratio of 2:1 (max:min). The low extinction ratio may be due to the quality of the device, which has already been shown to be questionable, (Figure 3) and because the structure is not optimised. Currently, both devices exhibit plane polarised light emission above the threshold currents/electric fields and may be considered to be lasing at room temperature. For future optimised structures of both the QW laser and VCSEL it should be possible to see narrower FWHM and a higher extinction ratio from the plane polarised results.

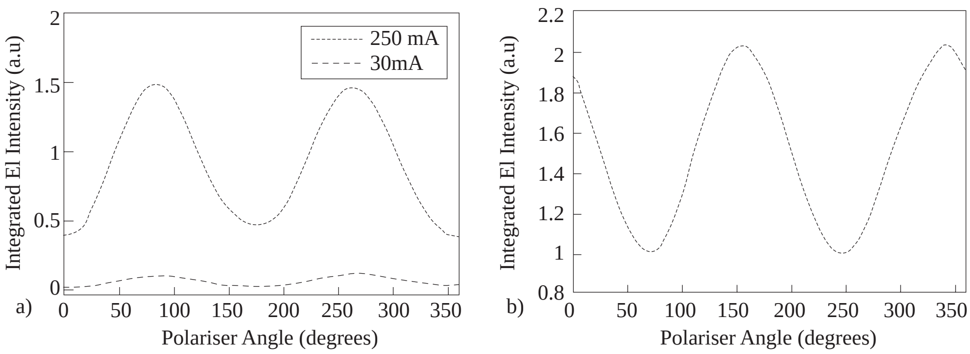


**Figure 6.** A comparison of light output polarisation for a) edge emitting QW laser above and below threshold current and b) HELLISH-VCSEL with $1\text{KVcm}^{-1}$ at 300K.

To determine the uniformity of HELLISH-VCSEL EL emission several device configurations were considered with surface areas covering three orders of magnitude as shown in Figure 7. The total detectable emission integrated over $0\text{-}1\text{KVcm}^{-1}$, as a function of surface area (Figure 7) was investigated. Although the data is quite scattered it is clear that the emitted light increases with surface area. The increase is not linear and indicates that the light emission has a non-uniform distribution across the device.

The most qualitative analysis of surface emission can be obtained by taking infra red photographs of HELLISH-VCSEL at $1\text{KVcm}^{-1}$ for both polarities (Figure 8). The effective exposure time is 0.18s and shows that the EL emission extends across the device length. The light emission appears to be relatively uniform and there are no areas of high intensity (hot spots) visible. However, this may be due to the long exposure time required to capture the pulsed EL emission. If the polarity is changed then the emission distribution and EL intensity remains the same.

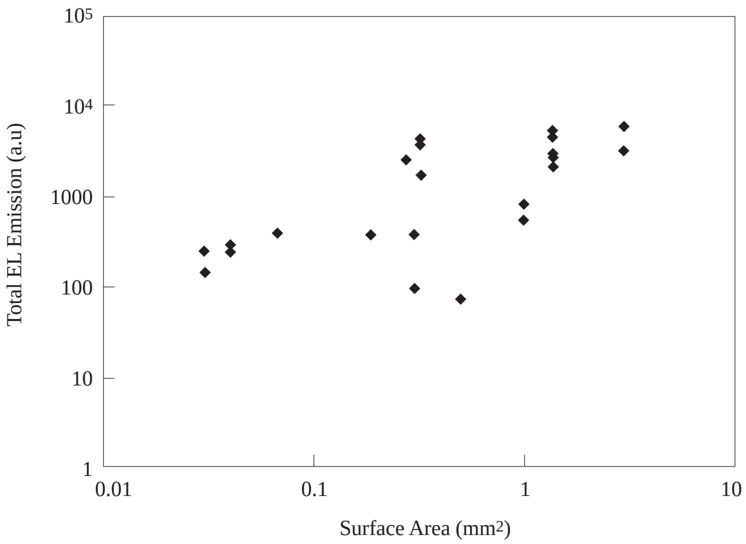


**Figure 7** Total EL intensity as a function of device surface area at 300K for HELLISH-VCSEL.

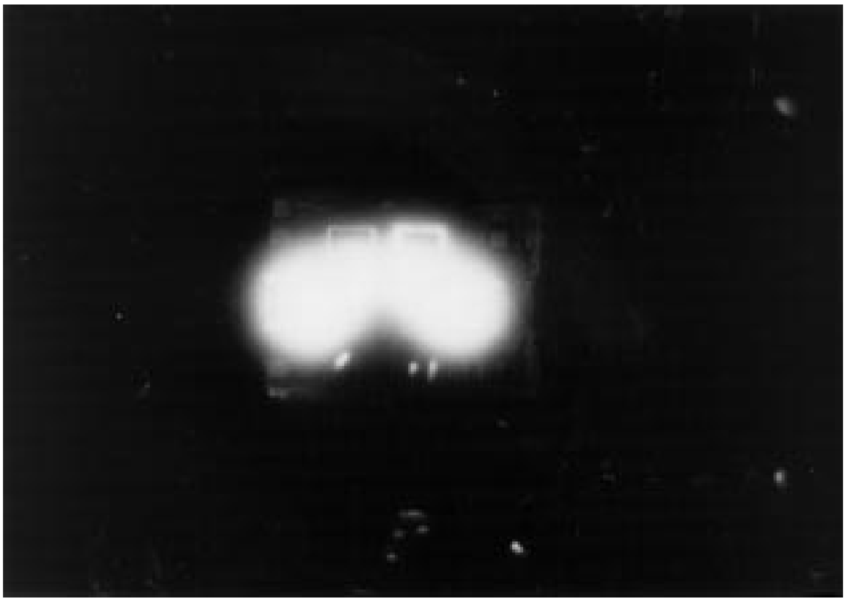

**Figure 8.** An infra red photograph of a 3.5mm HELLISH-VCSEL Hall bar at 300K. This was taken using $1\text{KVcm}^{-1}$ and an exposure time of 10 minutes.

## Conclusions

The comparison of HELLISH-VCSEL to a conventional QW laser has demonstrated that HELLISH-VCSEL may be lasing at room temperature. The emission has a peak wavelength of 816nm, with a FWHM of 1.5nm at room temperature. It also displays optical XOR logic functions. The FWHM is better than the QW laser, as power output is 5.5mW at room temperature, double that from the conventional laser, and the light from both structures are plane polarised. Additionally, HELLISH-VCSEL has all the advantages of HELLISH devices including intrinsic logic functions and minimal temperature dependence.

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