The Operation of a Novel Hot Electron Vertical Cavity Surface Emitting Laser

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ABSTRACT

The hot Electron Light Emission and Lasing in Semiconductor Heterostructure devices (HELLISH-1) is novel surface emitter consisting of a GaAs quantum well (QW), within the depletion region, on the n side of $Ga_{1-x}Al_xAs$ p-n junction. It utilises hot electron transport parallel to the layers and injection of hot electron hole pairs into the quantum well through a combination of mechanisms including tunnelling, thermionic emission and diffusion of 'lucky' carriers. Super Radiant HELLISH-1 is an advanced structure incorporating a lower distributed Bragg reflector (DBR). Combined with the finite reflectivity of the upper semiconductor-air interface reflectivity it defines a quasi-resonant cavity enabling emission output from the top surface with a higher spectral purity. The output power has increased by two orders of magnitude and reduced the full width at half maximum (FWHM) to 20nm. An upper DBR added to the structure defines HELLISH-VCSEL which is currently the first operational hot electron surface emitting laser and lases at room temperature with a 1.5nm FWHM. In this work we demonstrate and compare the operation of UB-HELLISH-1 and HELLISH-VCSEL using experimental and theoretical reflectivity spectra over an extensive temperature range.

Keywords: Hot electron laser, surface emitting device, longitudinal transport, Vertical Cavity Surface Emitting Laser(VCSEL).

1. INTRODUCTION

The Vertical Cavity Surface Emitting Laser (VCSEL) has become one of the most important devices in recent years. It was first realised in 1979 but did not come to fruition until growth systems such as Molecular Beam Epitaxy (MBE) and Metal Organic Vapour Phase Epitaxy (MOVPE) advanced sufficiently to cope with such stringent and precise requirements. (for a review see [1]). Since then the interest and research in this area has avalanched and the VCSEL has improved enormously in terms of power output and efficiency. In fact VCSELs with efficiencies up to 55% and powers of around 5mW single mode from GaAs quantum wells have been reported[2]. These devices can now rival conventional semiconductor lasers and are available commercially, VCSEL technology has also been extending into the visible wavelength range.

There have also been many advances in the direction of novel, light emitting devices based on longitudinal transport. One type of longitudinal transport light emitting device is known as CHINT[3]. In this structure hot electrons are transferred in real space between two separately conducting channels. If the second channel is a complementary layer then it has been shown that light emission occurs which has an intrinsic logic function with respect to the electrical inputs.

HELLISH (Hot Electron Light Emission and Lasing in Semiconductor Heterostructure) is another novel longitudinal transport device. This has been researched extensively resulting in two main types of devices; HELLISH-1 and 2.[4-6] HELLISH-1 consists of a 130Å GaAs SQW situated on the n-side of an AlGaAs p-n junction within the depletion region. Light emission is from the device surface, independent of the applied electric field and therefore exhibits an XOR function with respect to the applied voltage. HELLISH-2 has a similar material system but is a more complex structure as it includes an inversion layer and a multiple QW (MQW) structure with QW's of varying well widths. This has been shown to produce multi-wavelength operation and logic tasks which are discussed in detail elsewhere[7-8].

HELLISH-1 has been adapted and converted from an LED to a super radiant structure by the addition of a DBR grown under the original structure[6]. The DBR has been grown to provide over 99% reflectivity so that emission previously lost from the device edges and substrate is reflected back through the device. The GaAs-air interface has a reflectivity of approximately 30%, due to discontinuities in the refractive index, and forms a partial or 'quasi-cavity'. Although there are many losses from the upper surface (70%) the device is still able to maintain a high enough photon density to initiate stimulated emission. Therefore it is able to operate as a super radiant structure based on stimulated emission rather than spontaneous emission as in the original device.

Recently, a VCSEL device has been realised by incorporating an upper and lower DBR to the original structure. In this case the original HELLISH structure defines the cavity and this device is able to lase at room temperature. To date this is the first demonstration of a hot electron based VCSEL at room temperature.

2. RESULTS AND DISCUSSIONS

All three wafers were grown by MOVPE on semi-insulating GaAs substrates and the structures are given by Figure 1. As shown in the key, HELLISH-1 forms the cavity of HELLISH-VCSEL; and Super Radiant HELLISH consists of the lower and active region. The lower DBR has 27 periods of AlGaAs layers with varying Al concentration and provides a reflectivity better than 99%. The upper DBR is much thinner and only has 17 periods which allows an output from the top surface in the form of lasing. The QW is centralised within the active region in order to coincide with an anti-node of the confined optical field therefore increasing efficiency by maximising gain with each round trip through the cavity.

For all three structures the devices investigated were simple bars and Hall bars fabricated over a 100μm to 3.5mm range. Au/Ge/Ni contacts were evaporated directly onto the top layer then diffused through all layers for the devices without the upper DBR. With HELLISH-VCSEL the upper DBR had to be selectively etched in order to evaporate contacts directly onto the n region after which they were diffused through the active layers. Contacts were tested for each of device layers and were ohmic over 70K<T<300K, which is the usual operating range.

The operation of the device is based on the heating of electrons and holes in their respective channels in the $Ga_{0.7}Al_{0.3}As$ p-n junction by the application of longitudinal electric fields[4]. Due to their lower effective mass the electrons heat up more readily than the holes and occupy higher energy levels. Non equilibrium electrons injection into the quantum well may occur through the following injection mechanisms: The occupation of the higher 3-D states in the n-layer is in

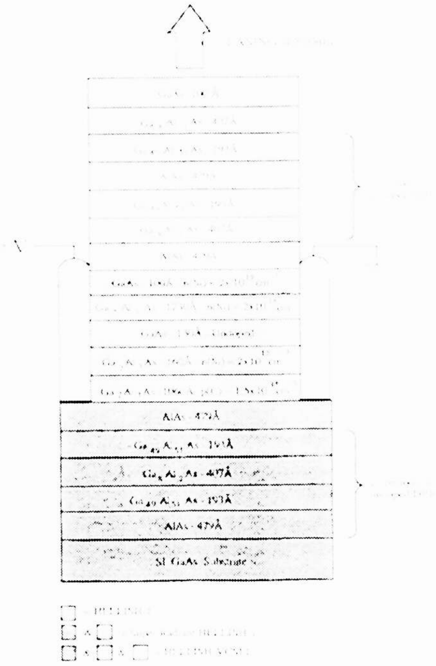

Figure 1: A schematic diagram of HELLISH-1, Super Radiant HELLISH and HELLISH-VCSEL.

effect identical to the lowering of the built-in potential by the application of a forward bias in a conventional p-n junction device. Therefore, effective lowering of the potential barrier should enhance both the tunnelling and the thermionic injection of hot electrons into the quantum well as depicted in figure 2 and as described in (4-6). The dominant mechanism at low fields is expected to be the tunnelling process. The accumulation of excess negative charge in the depletion region induces a self modulation of the junction. The n-side potential barrier increases, while the p-side depletion region and potential barriers decrease enhancing hot hole diffusion into the QW. Another mechanism that may contribute to the overall injection, particularly at intermediate and higher electric fields , is associated with the well-known 'lucky drift' model[9]. The hot carriers drifting towards the appropriate contact in their respective channels suffer collisions with phonons which lead to relaxation of momentum and/or energy. In the 'lucky drift' model the carrier velocity is determined by momentum-relaxing collisions without there being in the same period any significant energy relaxation. Whilst this lucky drift is occurring in the transverse direction, the carriers can also diffuse in the orthogonal direction towards the opposite side of the junction (i.e. hot electrons go towards the p-side and hot holes towards the n-side). Thus these carriers can gain sufficient energy from the field to be captured by the quantum well. Since the holes have to gain considerably more energy than the electrons (as a consequence of the position of the quantum well with respect to the junction), it follows that the region of the device where the recombination of carriers in the well is maximised is offset towards the cathode. Infra-red photographs of the near-field emission indicate that much of the radiation is generated near the cathode, in agreement with this qualitative theory. More quantitative estimates of the device performance based on this model will be the subject of future work.

Radiative recombination takes place in the QW. Because the operation of the device is based purely on electric field heating of carriers, the resultant light emission is independent of the polarity of applied bias.

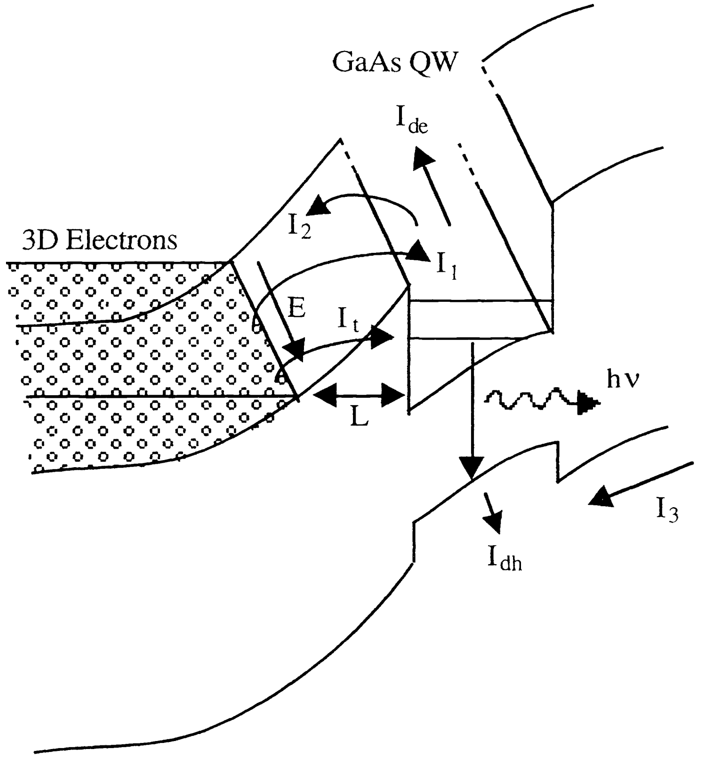

Figure 2: The carrier dynamics involved with HELLISH-1 operation. E is applied longitudinal electrical field, I_1 and I_t are injection of excess electrons into the well by thermionic emission and tunnelling respectively. I_2 is the total (thermionic emission and tunnelling) reverse current from the well. Ide and I_{dh} are electron and hole drift currents, respectively, and I_3 is hot hole diffusion into the quantum well.

With the two advanced structures the operating principles are exactly the same and only difference is that the DBR reflectivity spectra determines the quantity of light emission from the sample surface. It is not just the intrinsic hot electron effects that are responsible for the emission spectrum, but the combination of HELLISH EL spectra (gain spectra) and DBR reflectivity spectra. The room temperature reflectivity spectra for Super Radiant or Ultra Bright (UB) HELLISH) is given by Figure 3. In the UB device all emission normally lost through the substrate in HELLISH is reflected back through the device via the lower DBR so increasing the photon density. Although the reflectivity spectra does limit the light emission, there is no distinctive cavity resonance, so a large degree of stimulated emission will be emitted. In the case of HELLISH-VCSEL, however, there is a definite cavity and resonance wavelength at 816 nm as also shown in figure 3. Therefore the majority of photons are confined to the cavity, losses are low so lasing is possible on a single longitudinal mode at the resonant wavelength.

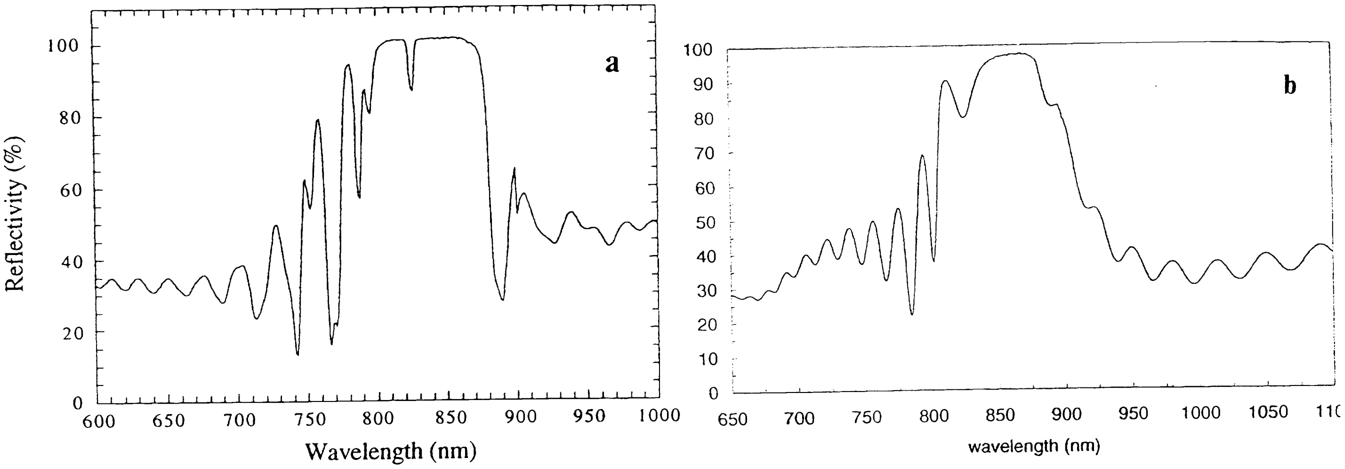

Figure 3: (a) The reflectivity spectra for HELLISH-VCSEL and (b) Super Radiant HELLISH at room temperature.

This description is summarised by Figure 4 which shows the electroluminescence (EL) spectra for each device. These experiments were performed by applying electrical pulses with a duration of 3μs and duty cycle less than 1% parallel to the device layers. By comparing the spectra of all devices it is possible to see the development of a HELLISH LED to VCSEL.

HELLISH-1 has a broad EL spectrum with peaks at around 1. 46 eV and 1.54 eV. The light emission extends over a 110 nm range, from 780-890 nm, and has a FWHM of 70 nm. With UB-HELLISH the EL intensity has increased by two orders of magnitude. Note that the HELLISH EL spectrum has to be increased forty times to fit onto the same graph. UB-HELLISH spectrum has a main peak at 820 nm (1.52 eV) and a reduced FWHM of 20 nm as defined by the quasi-cavity resonance of reflectivity spectrum in 3(a). The high energy tail of the HELLISH -1 is also modulated by the reflectivity spectrum to give the small hihg energy peaks in the UB spectrum. With HELLISH-VCSEL the EL spectrum has a peak at 816 nm (1.52 eV) with the FWHM is reduced to 1.5 nm as defined by the cavity resonance in figure 3(b). For both the UB and VCSEL structures the resonant wavelength was observed to shift by ±20 nm as a function of position on the wafer. This variation is accounted for by the non-uniformities in DBR layer thickness commonly obtained with MOVPE grown material[12].

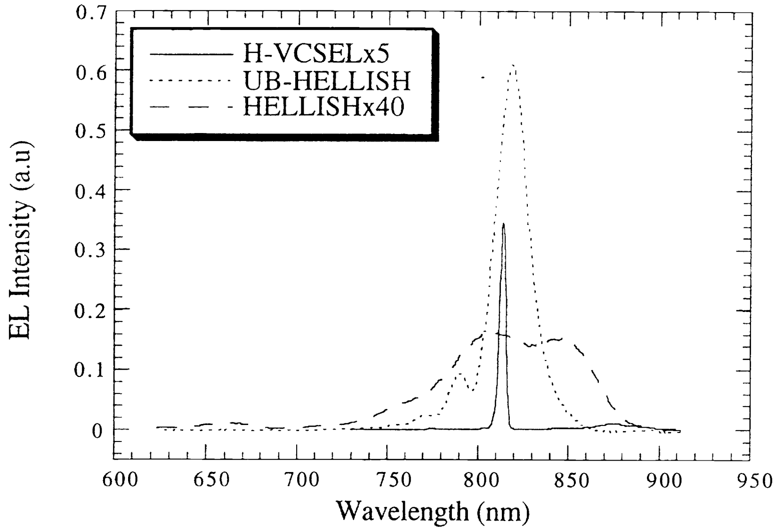

Figure 4: A comparison of EL spectra for HELLISH-1, UB-HELLISH and HELLISH-VCSEL at room temperature.

If the reflectivity spectrum of a HELLISH-VCSEL 3x1 mm device is considered , shown in Figure 5, then it can be seen that the resonance wavelength shifts by at least 1 nm across the length of the device. Therefore this coupled with the 1 nm resolution of our monochromator results in a resonant frequency width of 1.5 nm and hence explain why the observed FWHM of VCSEL spectra is 1.5 nm. This could be improved by reducing the non-uniformities during growth and optimising device design for example by reducing the size of the surface area.

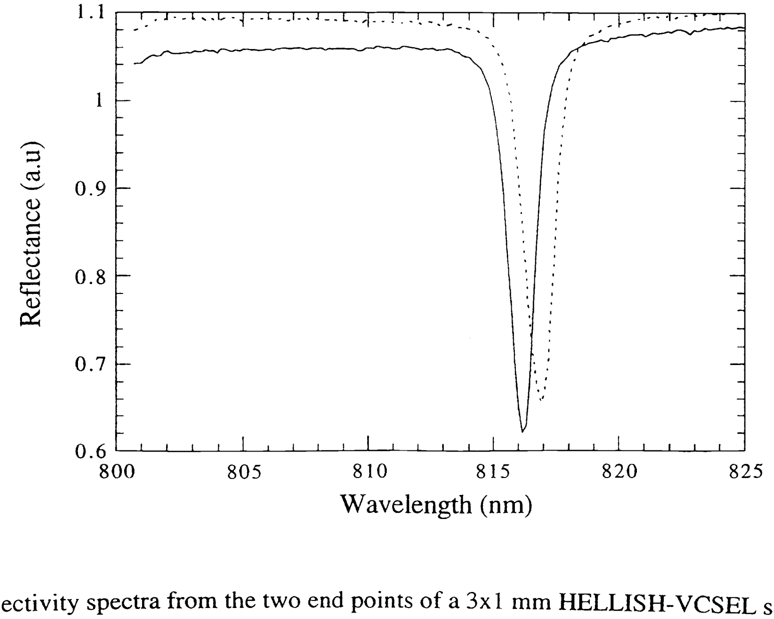

Figure 5: Reflectivity spectra from the two end points of a 3x1 mm HELLISH-VCSEL simple bar at room temperature.

Although this structure is far from optimised a whole range of device configurations have been tested and all have emitted light with the expected characteristics. In figure 6 we show an infra-red photograph of the surface emission from a 3 mm HELLISH-VCSEL at F=700 V/cm. The effective exposure time is of the order of one second. Despite the large size of the device the intensity is remarkably uniform. In devices with comparable lengths , however, the emission is not always uniform but tends to concentrate nearer to the cathode. Currently the smallest operational device is a 100x25 µm HELLISH-VCSEL which requires 10V to achieve an applied electrical field of 1 kV/cm. If a 10µm structure can be realised then this will only require 1V to obtain an electric field of 1KV/cm which is comparable to conventional VCSELs.

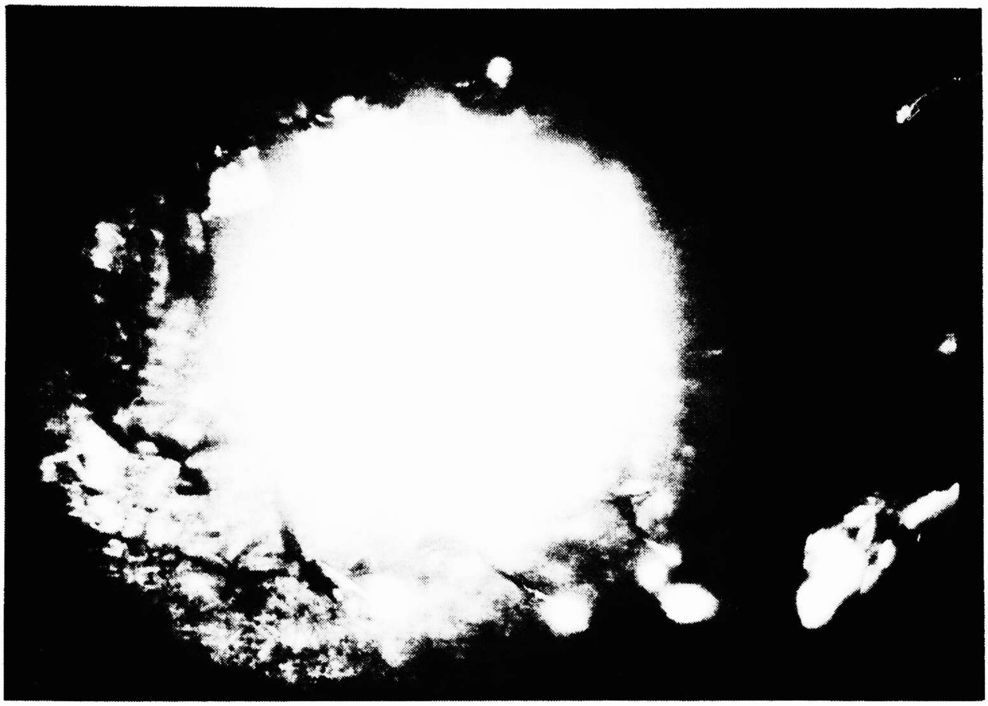

Figure 6: Infra-red photograph of the surface emission from a 3.5 mm HELLISH-VCSEL at F=700V/cm

In figure 7(a) and (b) we show the temperature dependence of the emitted light intensity for HELLISH-1 and HELLISH- VCSEL. It is evident from the figure that the VCSEL efficiency has a much stronger temperature dependence than the simple device. It is reduced by about a factor of 7.5 when the temperature is increased from T=77 K to room temperature. This reduction can be partly due to the disparity in the temperature dependencies of the cavity resonance wavelength and GaAs QW band gap, and hence the gain peak. This is illustrated in figure 8 where the calculated band gap and the cavity resonance wavelength are plotted against temperature. In figure 8 we also plot the experimental results of temperature dependence of the resonance mode of HELLISH-VCSEL and gain peak (EL peak) of the HELLISH-1 device. Both the theoretical and the experimental result show that the difference between the resonance mode and the gain peak increases with temperature giving rise to reduced efficiency at high temperatures as observed.

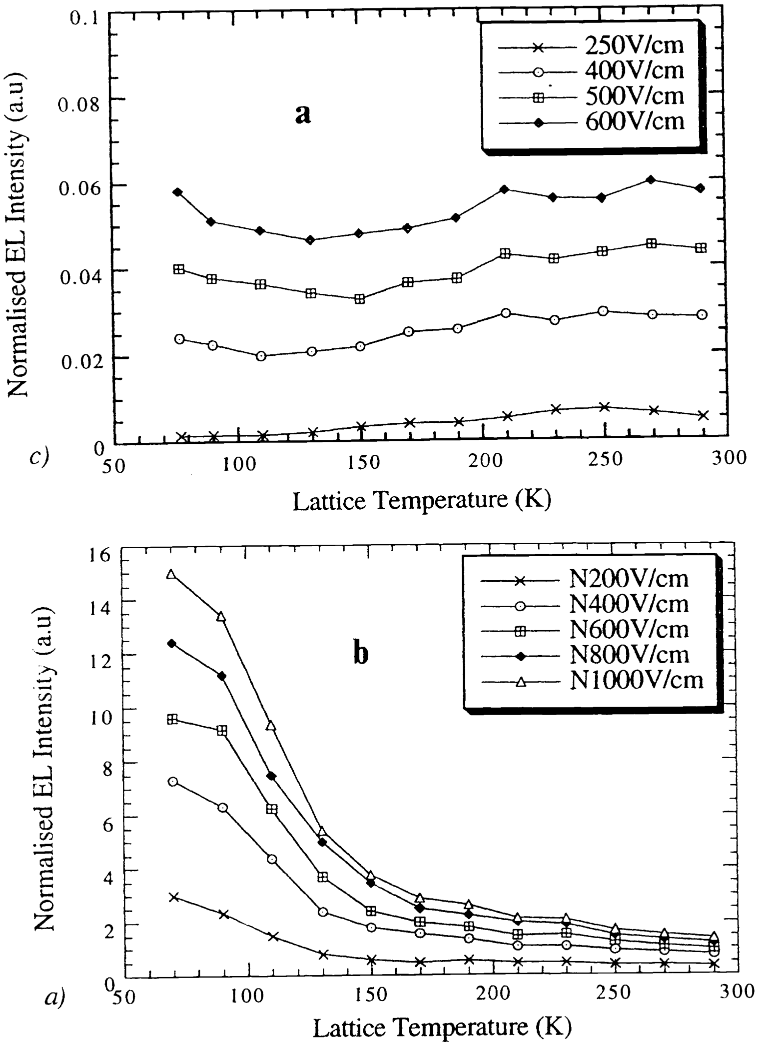

Figure 7: Temperature dependence of the emitted light as a function of temperature. (a) HELLISH-1 device and (b) HELLISH-VCSEL

In order to compare these structures with conventional devices it is necessary to consider the output power of a 3x1 mm device for each structure at room temperature, as given by Figure 9. HELLISH-1 and UB-HELLISH were analysed up to an electrical field of 1.2 KV/cm and gave 2.1 mW and 4.7 mW respectively. HELLISH-VCSEL was also investigated for thermal stability and tested up to 2.7 KV/cm. Increasing the electrical field to 1.8 KV/cm gave an output power of 5.5 mW but after this point the device began to heat and the power saturated. In all structures emitted power was independent of the applied electrical field. HELLISH-VCSEL is currently an unoptimised structure and produces 5.5 mW single longitudinal mode emission but has many transverse modes due to the large dimensions of the devices investigated

The efficiency is estimated to be around 1%, however, by optimising device design, growth and by fabricating smaller devices this should be improved.

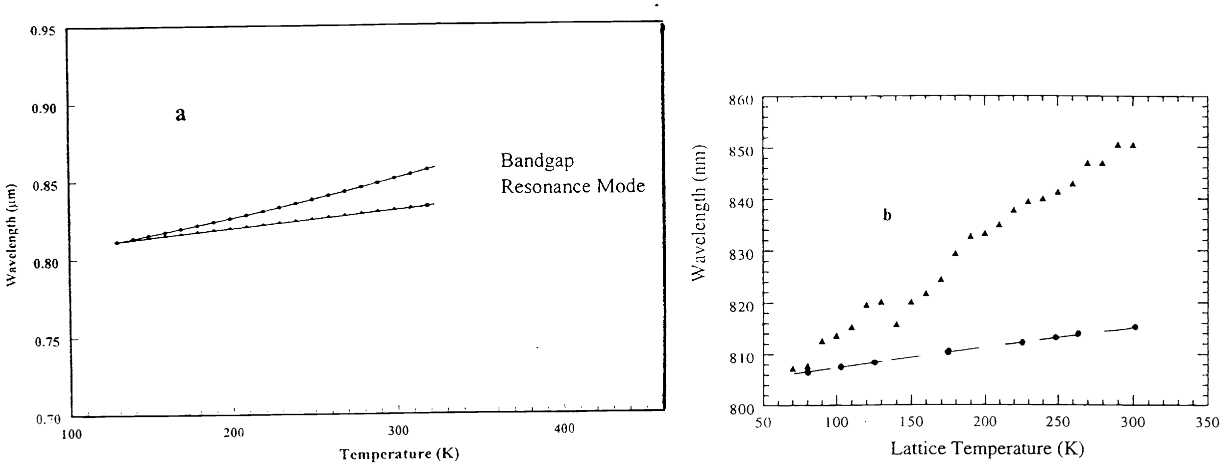

Figure 8: (a) Calculated temperature dependence of the band gap (upper line) and the cavity resonance wavelength
(b) Experimental temperature dependence of the HELLISH EL (gain) peak wavelength (triangles), and HELLISH - VCSEL Emission peak (as modulated by the cavity resonance)

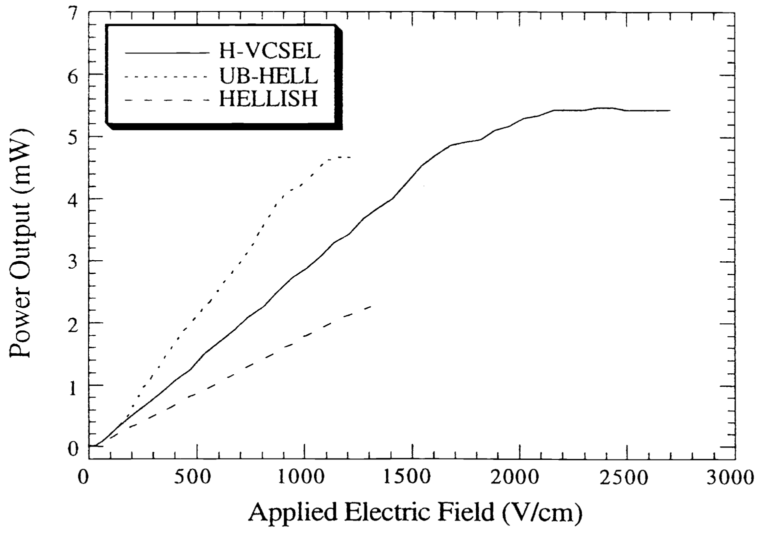

Figure 9: Output power for 3x1 mm bars of all devices with high electrical fields at room temperature.

3. CONCLUSIONS

The operation of a novel hot electron light emitter has been demonstrated. With the introduction of a lower DBR the device is shown to emit ultra bright light with enhanced spectral purity. When the device is placed into a vertical resonant cavity consisting of a couple of BDR mirrors, it lases with an output power of 5.5 mW in single longitudinal mode. The device is very simple to fabricate in 2-D arrays with only two diffused-in point contacts required. The operation of the device is determined by the applied electric field and therefore, light emission is independent of the polarity of bias voltage.

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