Super-radiant surface emission from a quasi-cavity hot electron light emitter

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The Hot Electron Light Emitting and Lasing in Semiconductor Heterostructure (HELLISH-1) device is a novel surface emitter which utilises hot carrier transport parallel to the layers of a $Ga_{1-x}Al_xAs$ p-n junction incorporating a single GaAs quantum well on the n-side of the junction plane. Non-equilibrium electrons are injected into the quantum well via tunnelling from the n-layer. In order to preserve the charge neutrality in the depletion region, the junction undergoes a self-induced internal biasing. As a result the built-in potential on the p-side is reduced and hence the injection of non-equilibrium holes into the quantum well in the active region is enhanced. The work presented here shows that a distributed Bragg reflector grown below the active region of the HELLISH device increases the emitted light intensity by two orders of magnitude and reduces the emission line-width by about a factor of 3 in comparison with the original HELLISH-1 structure. Therefore, the device can be operated as an ultrabright emitter with higher spectral purity.

1. Introduction

The operation of conventional semiconductor light emitters and lasers is, in principle, based on the transport of cold electron–hole pairs perpendicular to the junction plane in a forward biased p-n junction. The incorporation of quantum well(s) in the active region of the diode provides better carrier confinement leading to lower threshold currents and higher efficiencies [1, 2]. One of the drawbacks of heterojunction or quantum well lasers is the lack of compatibility in generic integration technology. This is because of the small spot size of the emitted light on the facet of the devices (edge emitters). Furthermore, both the fabrication and on-chip testing of such devices can be very expensive and time consuming.

The quest for devices that emit light from the surface has led to the discovery of vertical cavity surface emitting lasers (VCSEL) [3–5]. Recently single quantum well GaAs VCSEL'S with power efficiencies exceeding 55% [6] and (monomode) peak powers of about 5 mW are reported [7]. The improvement in VCSEL operation is largely due to the introduction of highly sophisticated but very complicated structural designs and fabrication techniques [6, 7]. Therefore, the quest for simpler surface emitting devices continues.

Research on surface emitting devices is further motivated by the need for large-scale two-dimensional arrays of light emitters for applications in optical signal processing. These include light logic, switching, interconnects, and optical computing [8].

Recently, we have demonstrated two such simple functional devices, HELLISH-1 and 2. Detailed description of the operation of both devices can be found elsewhere [9–13]. Briefly, it involves a delicate mechanism of heating electrons and holes in their respective channels in a p-n junction by the application of longitudinal electric fields, as shown in Fig. 1a. Hot electrons are captured by tunnelling in the quantum well in the depletion region. The accumulation of the negative mobile charge in the depletion region induces self-modification of the junction. In order to preserve the charge neutrality the device acts as if it were internally forward biased on the p side and reverse biased on the n side. This results in an increased potential barrier for the electrons and a reduced barrier for holes. The latter enables enhanced injection of holes into the quantum well where they recombine with the electrons.

The main features of HELLISH devices are:

(a) Only two diffused in contacts are required for the operation, therefore, fabrication of the device is extremely simple and cost effective.
(b) Light emission is due to carrier heating by the electric field, so emitted light intensity is independent of the input voltage polarity.
(c) As a result of these two features, fabrication of two-dimensional arrays of optical OR and NAND gates can be achieved easily [12].

Our previous work on HELLISH devices also indicated that a vertical cavity made up of two epitaxially grown reflectors could be incorporated into the device. It could, therefore, be operated as a VCSEL without having to pass the current through the mirrors because the charge injection is parallel to the p and n layers via diffused-in contacts. The aim of the current study is to investigate whether a vertical cavity surface emitting HELLISH-1 device with a high spectral purity and radiative power can be realised. In the first instance, we aimed at achieving emission from a 'quasi-cavity' by incorporating a Distributed Bragg Reflector (DBR) below the active layer. This DBR coupled with the lower reflectivity ($Ga_{1-x}Al_x$ As–Air) interface at the top is intended to define a quasi-vertical cavity similar to the structures studied by [14]. Hereafter we refer to this device as Ultrabright (UB) HELLISH device.

2. Experimental results and discussion

A schematic structural diagram of the device is illustrated in Fig. 1b. It is grown by MOVPE on semi-insulating GaAs substrate. A distributed Bragg reflector, comprising 27 periods of AlAs/GaAlAs layers, with a reflectivity better than 99.6%, is grown at the bottom of HELLISH-1, which is a $Ga_{0.69}Al_{0.31}As$ p-n junction with a 130 Å GaAs quantum well placed on the n-side in the depletion region. Refractive index discontinuity at the top $Ga_{0.69}Al_{0.31}As$–Air interface translates into a top mirror with approximately 30% reflectivity. The structure is tailored to ensure that the GaAs quantum well is centred within the $Ga_{0.69}Al_{0.31}As$ material to coincide with the antinode of the optical field in the

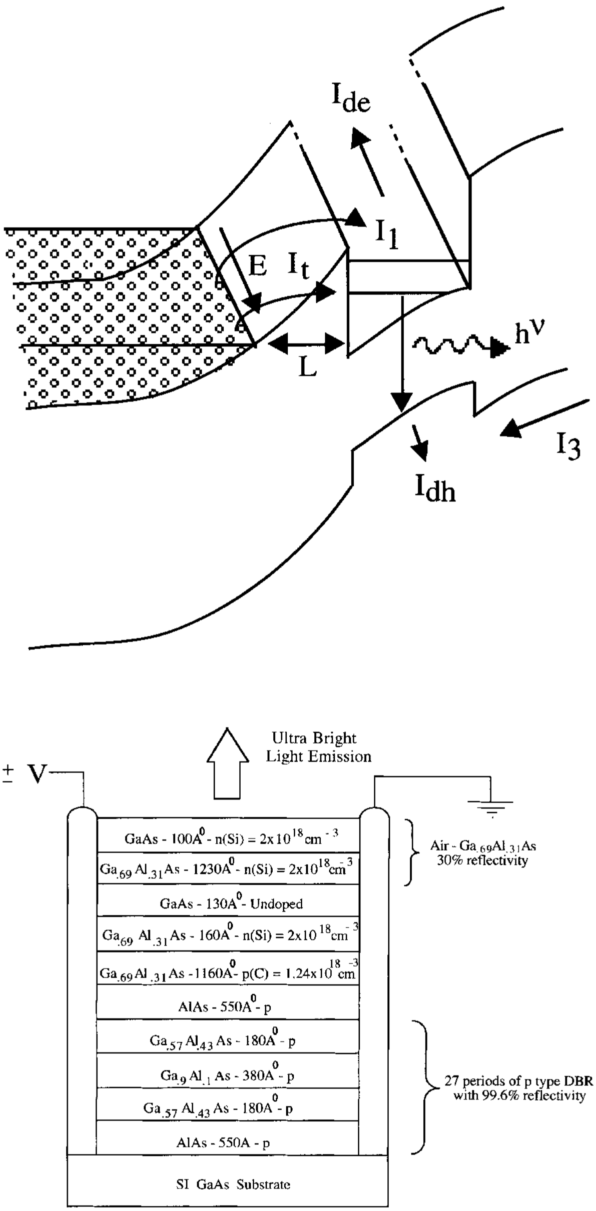

Figure 1 (a) Operation of the basic device HELLISH-1. *E* is the applied longitudinal field. The injection of non-equilibrium electrons from the 3-D $Ga_{1-x}Al_xAs$ layer is via I_1 (thermionic) and I_t (tunnelling) currents. I_{de} and I_{dh} are the electron and hole drift currents respectively. I_3 is the hot hole injection into the well. (b) Schematic diagram of the device structure for ultrabright emission.

cavity. This provides optimum amplification and enhancement of spontaneous emission [15].

The devices investigated were fabricated in the form of simple bars with lengths ranging between 100 μm and 3.5 mm. Electrical contacts were formed by diffusing Au/Ge/Ni alloy. Contacts were tested for each of the HELLISH-1 layers (p and n $Ga_{0.69}Al_{0.31}As$ layers and GaAs quantum well) by selective etching and were shown to be ohmic at temperatures where the devices are commonly operated ($70\,K < T < 300\,K$). All the measurements were carried out on both devices, one with and the other without the cavity (simple HELLISH-1).

Optical characterisation of devices were performed using conventional photoluminescence (PL) and double-beam photoreflectance (PR) spectral techniques. For the PL measurements the 647 nm line of a Kr ion laser, and for the PR measurements a monochromated white light source were used for excitation. Figure 2a shows a typical room temperature PR spectra recorded from the central region of the wafer. The high reflectance band of the DBR between $\lambda = 800$ and 900 nm is clearly visible, as is the dip at $\lambda = 820$ nm, caused by the resonant cavity mode. Both the DBR reflectivity band and cavity resonance maintained their shape but shifted in wavelength by as much as ± 20 nm in the PR spectra when viewed from several different points across the wafer. This observation is in accord with the expected spectral change due to a variation in material growth thickness across the wafer that occurs commonly in MOVPE grown material [16]. Fig. 2b shows the spectrum for the ideal structure calculated by using a computer programme based on the transmission matrix formulation [17]. The calculated spectrum does not include absorption effects which are observed in the experimental plot on the short wavelength side. Otherwise the agreement between the calculated and the measured PR spectra is excellent.

In an ideal VCSEL structure with highly reflecting cavity boundaries the passive linewidth of the cavity resonance (i.e., in the absence of current injection) is expected to be in

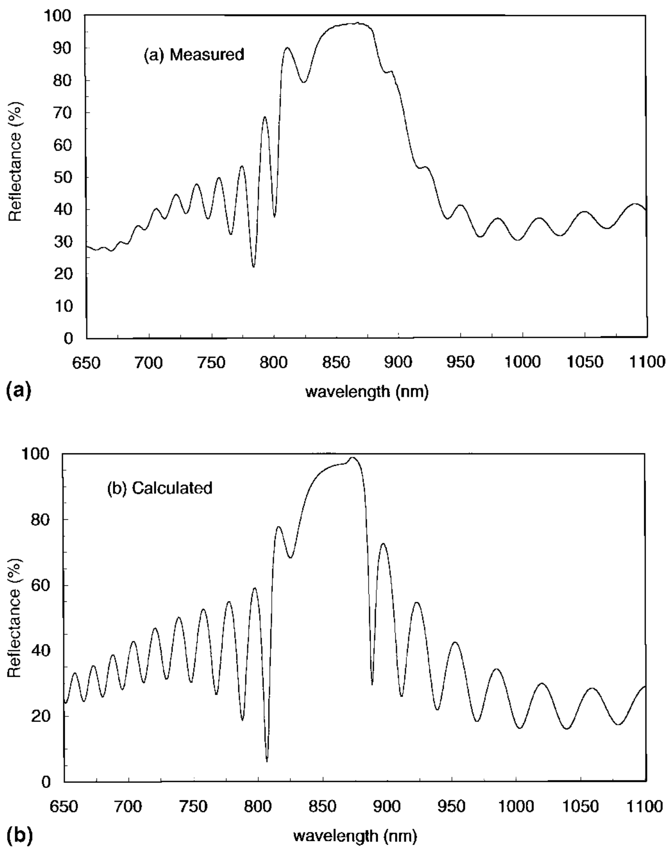

Figure 2 (a) Measured reflectivity spectrum of the device, and (b) calculated reflectivity spectrum plotted as described in the text.

the range of 1–2 nm. In our structure, however, we have a quasi-cavity where the reflectivity of the top mirror is only 30%. The line-width is about 20 nm, as expected [17]. Room temperature PL spectra from the simple HELLISH device (without a cavity) and from the UB-HELLISH, are shown in Figs. 3a, b respectively. It is obvious that the spectral line-width is reduced from about 75 nm for the simple structure, to 20 nm for the resonant cavity structure. The PL spectrum of the simple structure peaks at an energy $E1 = 1.47$ eV, which corresponds to the e1–hh1 transition, and has a broad shoulder at $E2 = 1.51$ eV which is the e2–hh2 transition energy in the 130 Å quantum well. The position of the peak of the UB-HELLISH spectrum is however, determined by the cavity resonance and occurs at 820 nm as expected from Fig. 2.

The electroluminescence (EL) and I–V characteristics of the devices were measured in the pulsed mode. Voltage pulses of about 3 μs duration with a period of 10 ms were applied along the layers via the diffused-in contacts. Measured I–V characteristics were symmetrical with respect to the polarity at all temperatures and were non-linear at high electric fields as expected from hot electron effects. Emitted light pulses were collected and dispersed in synchronisation with the voltage pulses.

Figure 4 shows a typical EL spectrum at $T = 300$ K. The EL spectrum peaks at about the same energy as the PL spectrum and has a line-width of about 20 nm. Both the EL peak energy and line-width agree with the cavity resonance features as shown in the reflectivity spectra in Fig. 2. EL intensity integrated over wavelength from the

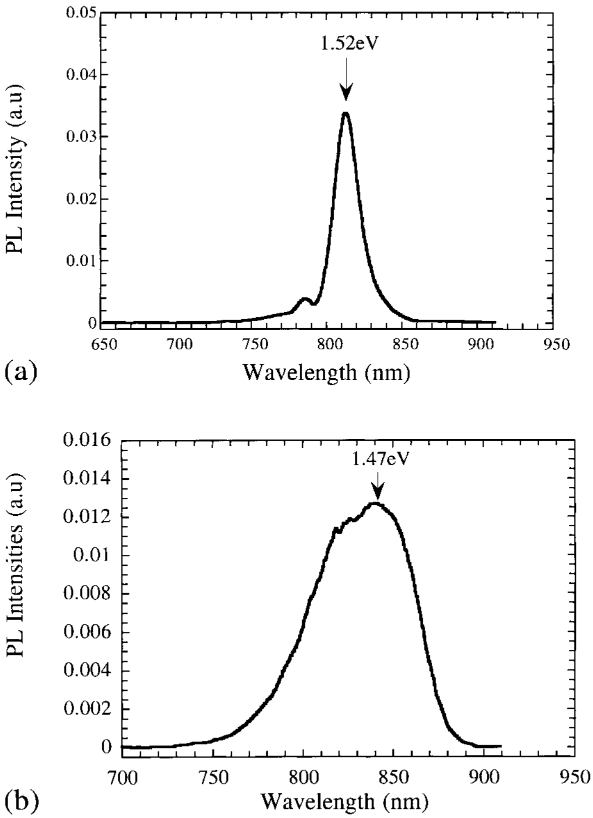

Figure 3 (a) PL spectra from the device with the quasi-cavity at $T = 300$ K. (b) PL spectra from an identical sample without the cavity.

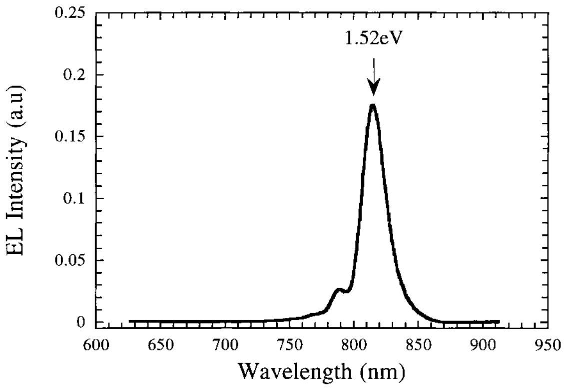

Figure 4 EL spectra from the device at $T = 300\,K$ at an applied electric field of $E = 1100\,V\ cm^{-1}$.

UB-HELLISH-1 is plotted at $T = 300\,K$, against the applied electric field in Fig. 5a. Figure 5b shows the integrated EL intensity from the identical structure without the cavity. It is clear from the figures that the emitted light intensity is between two and three orders of magnitude higher than the simple device without the cavity, suggesting strongly that the photon density is amplified in the cavity. This observation is similar to the work concerning the enhancement in the spontaneous emission from InGaAs/GaAs quantum

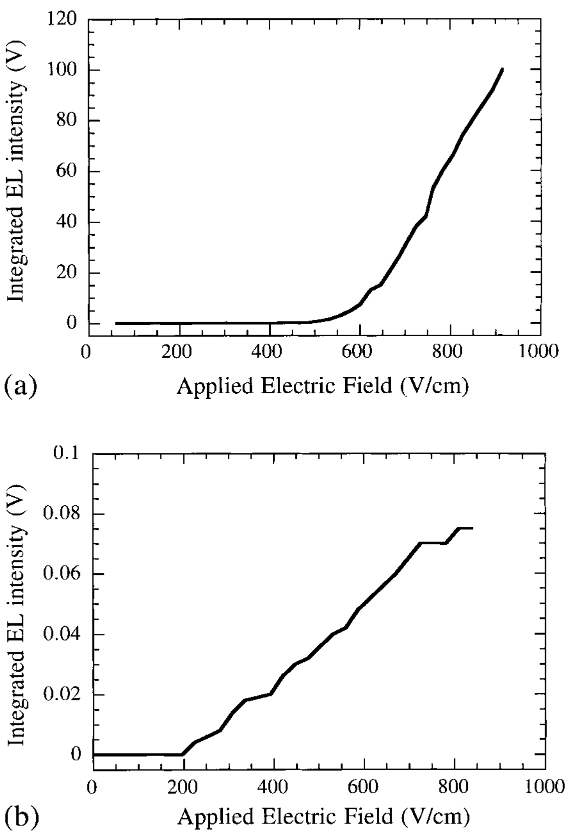

Figure 5 (a) EL intensity integrated over wavelength versus applied electric field for the UB-HELLISH. (b) The same plot for the identical device without the cavity.

well with only a single DBR reflector at the bottom where several orders of magnitude enhancement is observed [14].

We also studied the emission intensity as a function of the surface area. This involved the measurement of the integrated intensity from devices with lengths between 100 μm and 3.5 mm, and widths between 200 μm and 2.2 mm corresponding to a 3 orders of magnitude variation in the surface area as shown in Fig. 6a. Although the data is rather scattered it is clear that the emitted light increases with increasing surface area. The increase is, however, by no means linear. This indicates that the light emission does not have uniform distribution on the surfaces of some, or all, the samples studied, but is more intense in some regions of devices (hot spots/areas) than the others. Figure 6b shows an infrared photograph of the surface emission from a 3.5 mm device at $F = 1200\ \mathrm{V\ cm^{-1}}$. The picture is taken by using Kodak High speed IR film (HIE 135-136) with an effective exposure time of 270 μs. It is obvious that for this particular device most of the emission is from the cathode half of the device. In some devices studied the light intensity has a more uniform distribution. The reason for this variation is currently under investigation and will be reported in the future.

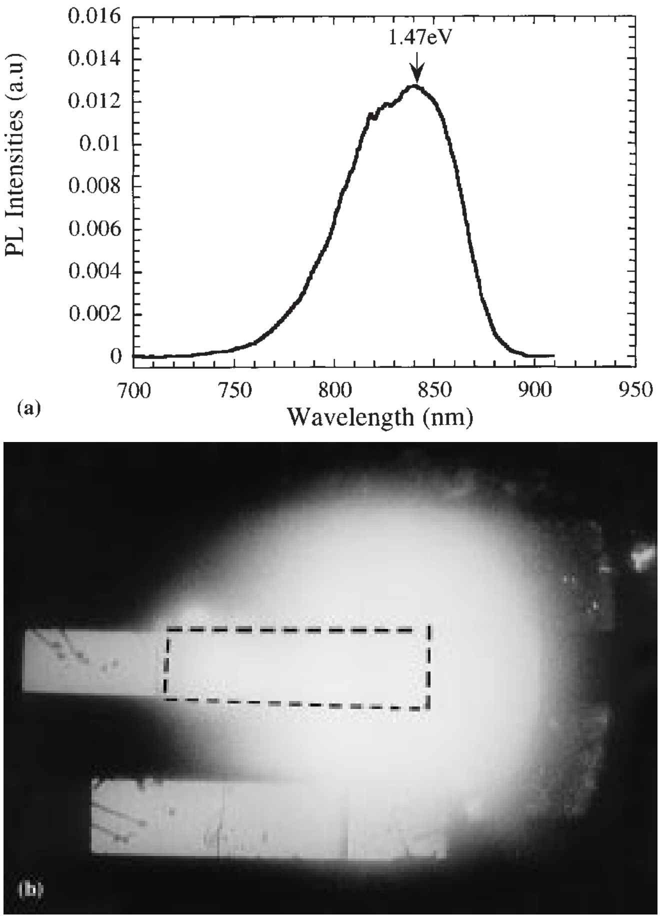

Figure 6 (a) Integrated intensity versus the surface area of the UB-HELLISH devices. (b) Infrared picture of the surface emission from a 3.5 mm device which is indicated with the broken lines.

The output power of the UB HELLISH is 4.7 mW at room temperature at a working field of 1 kV cm^{-1} (which translates into 10 V across a 100 μm device). Although the wall plug power efficiency of the current device ($\eta < 1\%$) is considerably lower than conventional superluminescent structures, it has a better heat dissipation and, therefore can deliver much higher powers at higher applied fields.

3. Summary

We have demonstrated the operation of the HELLISH-1 structure placed in a quasi-vertical cavity. A two order of magnitude photon amplification with a reduced line-width is indicative of super radiant emission from the device. In order to operate the device as a true vertical cavity surface emitting laser, however, a second mirror (DBR or dielectric) with high reflectivity needs to be placed on the top of the HELLISH-1 structure. This work is currently under way and will be reported in the near future.

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