VCSEL structure hot electron light emitter

N. Balkan a, A. Serpengüzel b,*, A. O’Brien-Davies a, I. Sökmen c, C. Hepburn a, R. Potter a, M.J. Adams a, J.S. Roberts d

a Department of Electronic Systems Engineering, University of Essex, Colchester, Essex CO4 3SQ, UK
b Department of Physics, Koç University, İstinye, Istanbul 80860, Turkey
c Department of Physics, Dokuz Eylül University, İzmir 35160, Turkey
d Department of Electronic and Electrical Engineering, Sheffield University, Sheffield, S10 2TN, UK

Abstract

The hot electron light emitting and lasing semiconductor heterostructure vertical cavity surface emitting lasers (VCSELs) are devices that utilise hot carrier transport parallel to the layers of the Ga xAl1−xAs p–n junction. The junction contains a GaAs quantum well (QW) in the depletion region. The fabrication of these devices is very simple, and requires only two top contacts that are diffused throughout the heterolayers. Light emission, being a hot carrier effect, is independent of the polarity of the applied bias. Pulsed operation of the device as a VCSEL has already been demonstrated at room temperature. An output power of 5.5 mW in a single longitudinal mode has been obtained. The doping and other structural parameters can be optimised for efficient injection of hot electron–hole pairs into the QW. In this work, we report our reflectivity, electroluminescence, and photoluminescence studies at room temperature. We also present the experimental results of emitted power measured as a function of the applied electric field. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Hot electron laser; Surface emitting device; Microcavity; Longitudinal transport; Vertical cavity surface emitting laser

1. Introduction

Over the past few years, quantum well (QW) GaAs vertical cavity surface emitting lasers (VCSELs) with efficiencies up to 55% and single mode peak powers of 5 mW have been reported [1]. The improved performance of VCSEL operation is primarily due to the introduction of very sophisticated and complicated structural design and fabrication techniques. To achieve surface emitting devices with simpler structures and fabrication requirements, there is need for more research, particularly concerning carrier injection mechanisms. A simple device of this kind is HELLISH-1 (hot electron light emitting and lasing semiconductor heterostructure). It was proposed by Balkan et al., and studied since the mid-1990s [2–4]. It is one of the two types of novel light emitters that utilise hot carrier transport parallel to the growth layers in an otherwise conventional p–n junction containing a QW [4,5].

Detailed description of the operation of the HELLISH-1 has been given elsewhere [2–5]. Briefly, it involves an electric field induced heating of the electrons and the holes in their respective channels of a Ga xAl1−xAs p–n junction containing a single GaAs QW in the depletion region, as depicted in Fig. 1. In this structure, hot electrons are captured primarily by tunnelling into the QW. However, other capture mechanisms may also be possible [6,7]. The accumulation of negative mobile charges (non-equilibrium electrons) in the QW in the depletion region induces a self-biasing of the junction. In order to preserve the charge neutrality, the potential barrier on the p-side is reduced. This enhances the injection of the holes into the QW, where they recombine with non-equilibrium electrons. The operation of the device can be optimised for electric field operation by designing the structure so as to keep the first electron sub-band–Fermi level separation around a few millielectronvolts. The application of a moderately high electric field should change the equilibrium, and therefore give rise to phonon assisted tunnelling into the QW. The optimisation can be achieved by a careful selection of the position of the
QW within the depletion region, and by changing the Fermi level via the n- and p-doping levels as depicted in Fig. 1. The electric field \( E \) is applied parallel to the layers. The injection of non-equilibrium carriers from the three-dimensional Ga\(_x\)Al\(_{1-x}\)As layer into the first sub-band of the GaAs QW is via \( I_t \) (thermionic) and \( I_t \) (tunnelling) currents. \( I_{de} \) and \( I_{dh} \) are the electron and hole drift currents in the QW, respectively. \( I_3 \) is the hot hole injection to the QW. The optimisation for the low electric field operation is achieved by reducing \( \Delta E \), either by changing the position of the QW with respect to the junction plane or by changing the doping parameters.

The QW can also be placed in the depletion region on the p-side of the junction plane. In this type of device, the carrier injection mechanism is the same, but the charge neutrality is initially disturbed by hot hole injection into the QW via tunnelling. Hence, hot electrons are induced to diffuse through a reduced barrier into the QW [8,9].

The main features of the HELLISH devices are as follows.

1. Only two diffused-in contacts are required for the operation; therefore, the fabrication of the device is simple and cost effective.
2. Light emission is due to carrier heating by the applied electric field; therefore, the operation of the device as a light emitter is independent of the polarity of the applied bias.
3. The fabrication of a two-dimensional array of optical OR and NAND gates can be achieved easily.
4. VCSEL structures based on HELLISH devices do not require top and bottom contacts, as the current is injected into the active layer without having to pass through the distributed Bragg reflector (DBR) layers.

The aim of the current work is to study the intensity and spectrum of light emitted from HELLISH VCSEL structures pumped either electrically or optically at room temperature.

2. Results and discussions

Fig. 2 shows the cross-section of the device grown by metal–organic vapour phase epitaxy (MOVPE) on a semi-insulating GaAs substrate. HELLISH-1 is composed of the Ga\(_x\)Al\(_{1-x}\)As p–n junction with the GaAs...
QW on the n-side of the depletion region. The QW is placed at the centre of the active region in order to coincide with the antinode of the confined optical field, therefore providing an optimum condition for amplification. The lower DBR of the VCSEL microcavity has 27 periods of undoped GaAlAs layers with varying Al concentration, and provides a reflectivity of better than 99%. The top DBR of the VCSEL microcavity has 17 similar layers to allow the light output from the surface. In order to make contacts to the active layer, the top DBR is selectively etched, and Au–Ge–Ni contacts were directly evaporated onto the n-layer, and consequently diffused through the active layers. External bias of either polarity is applied in the pulsed mode between these contacts of the bar shaped device. Therefore, the current is injected into the active region without having to pass through either of the DBR layers. Since both the n- and the p-layers of the active region are heavily doped, contacts to both layers are expected to be ohmic at room temperature. Therefore, the total current in the active region is due to the flow of both electrons and holes in their respective parallel channels [6,7]. If the contacts to either of the layers is not ohmic, however, then forward biasing of the device may occur in the vicinity of the anode (for positive biasing), or the cathode (for negative biasing). Forward biasing will reduce the built-in potential, enabling the hot electrons flowing along the n-layer to transfer into the QW at lower fields. As a result, a more intense light is expected to be emitted near the cathode [8,9].

The optical quality of the mirrors and the microcavity resonance wavelength of the device were determined using conventional double beam reflectivity spectroscopy [6,7]. Fig. 3 shows the reflectivity spectrum of the VCSEL recorded at room temperature, from a point close to the centre of the wafer with a resolution of about 1 mm², as determined by the optical beam diameter. It is evident that there is a microcavity resonance at a wavelength of \( \lambda = 823 \) nm. The linewidth of the microcavity resonance is 1.5 nm. The resonance wavelength was observed to shift by ±20 nm as a function of the position on the wafer. The variation is accounted for by the non-uniformities in the DBR, and the microcavity layer thicknesses common to the MOVPE growth. The shift in the microcavity resonance with position may imply lower efficiencies for VCSEL operation. It will also give rise to linewidth broadening as discussed later.

The microcavity resonance wavelength of the calculated spectrum (shown in Fig. 4) is at approximately the same wavelength as the experimental wavelength of 823 nm. It has, however, a much smaller linewidth than the resonance linewidth of the experimental spectrum. This is also attributed to the monolayer fluctuations in the microcavity length within the spatially resolved beam diameter of 1 mm² [7]. The calculated spectrum does not include the absorption effects, which are observed on the high-energy side of the experimental spectrum, and therefore, has more prominent short wavelength lobes.

In Fig. 5, the emitted optical power is plotted as a function of the applied electric field at room temperature for a device with the QW on the p-side of the junction plane [8]. The electric field was applied in the pulsed mode with a pulse width of a few microseconds and a duty cycle of smaller than 0.01%. The emitted light power increases rapidly at above a threshold field of 300 V cm\(^{-1}\), which is a signature of stimulated emission. Therefore, in a device with an ideal microcavity, lasing with a single longitudinal mode is possible. However, because of the large dimensions of the device investigated, there will be many transverse modes. The power emitted from the device at a typical operating field of 1000 V cm\(^{-1}\) is about 5 mW. Considering that HELLISH-1 is a single QW VCSEL, and despite the non-ideal DBR uniformity, 5 mW optical power com-
Fig. 5. The emitted optical power versus the applied electric field for the device with the QW on the p-side of the junction plane at room temperature.

Fig. 6. (a) The EL spectrum of a 3.0 × 1.0 mm device driven above the threshold field at room temperature. (b) The reflectivity spectra measured from the two ends of the same device.

Fig. 7. The PL spectrum of the HELLISH VCSEL at room temperature.

pares favourably with the conventional multiple QW GaAs VCSELs [9].

The EL spectrum measured at room temperature, above the threshold field, and in the pulsed mode is shown in Fig. 6. The EL emission peaks at 816 nm. This is about 7 nm shorter than the resonance wavelength in Fig. 3, and is due to the non-uniformities in the DBR layer and microcavity layer thickness as already pointed out. The linewidth of the EL spectra is about 1.5 nm. In the EL experiments, the light is collected from a large surface area device (3.0 × 1.0 mm). The EL spectrum, therefore, represents emission from a large volume of the VCSEL. Indeed, in the reflectivity spectra of the device of Fig. 6(a), the resonance wavelength shifts by at least 1 nm across the length of the device. This gives rise to a total linewidth of about 1.5 nm, as observed in the EL spectrum.

In order to demonstrate the optically pumped operation of HELLISH VCSEL, we have also performed photoluminescence (PL) measurements at room temperature. The excitation source was a continuous wave argon ion laser at a wavelength of 514.5 nm and an optical power of 400 mW. The laser beam was focused on the sample using a cylindrical lens of 15 cm. The PL spectrum of the HELLISH VCSEL at room temperature is shown in Fig. 7. The emission peaks at 824 nm. This is about 1 nm longer than the resonance wavelength in Fig. 3, and is again due to the non-uniformities in the DBR layer and microcavity layer thickness, as pointed out previously. However, the linewidth of the PL spectra is 0.7 nm. This PL linewidth is much narrower than the experimentally measured reflectivity and EL linewidth of 1.5 nm. This narrow linewidth is understandable, because in the PL measurements, the light is collected from a small surface area (1.2 × 0.04 mm), since the excitation laser is focused on the sample with a 15 cm focal length cylindrical lens. The PL spectrum, therefore, represents emission from a small volume of the VCSEL.
3. Conclusions

The operation of the HELLISH VCSEL has been demonstrated in both electrical and optical injection modes. Despite problems associated with the growth of the DBR layers, and the microcavity thicknesses, the device emits greater than 5 mW power (with a wall-plug efficiency less than 1%) at room temperature. In common with the other VCSELs, in the HELLISH VCSEL, true single-mode operation can only be achieved by improving the growth techniques and, hence, the layer quality (free of non-uniformities), and by reducing the active surface area of the devices. Further improvement to the device performance can be achieved by placing the QW into a waveguide structure for better photon confinement. This work is currently underway and will be reported in the near future.

Acknowledgements

We are grateful to EPSRC for funding the project (GR/L35034) and to the British Council for the Academic Link Grant.

References