Design of High-Power Electrically-Pumped VECSELs for the 3-4 µm Wavelength Range

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***Abstract*—We report the design of electrically-pumped high-power vertical-external-cavity surface-emitting lasers emitting at the mid-wave infrared wavelength regime. The device is designed with a monolithic configuration that can provide multiwatts of continuous-wave output power in a single transverse mode with an excellent beam quality.**

Keywords—mid-wave infrared, cw output power, vertical-external cavity surface-emitting laser (VECSEL), interband cascade laser, brightness

I. Introduction

Given that the mid-wave infrared (MWIR) region has a superior transmission through atmosphere and better penetration through fog, dust and smoke comparing to visible, and NIR wavelength regime [1], the development of MWIR lasers and the associated systems are of significant interests for advanced military operations. At the same time, there is also a pressing need to develop low-size, weight, power and cost (SWaP-C) lasers with a few watts of output power and high brightness for enabling a wide range of defense applications including countermeasure and night vision [2]. Among several types of semiconductor diode lasers, electrically-pumped (EP) vertical-external-cavity surface-mitting laser (VECSEL) is one the most suitable light sources that provide excellent beam quality and relatively high optical powers.

In order to obtain even more power that is not possible from a single emitter, two-dimensional (2D) arrays for this type of semiconductor lasers offer an attractive solution for power scaling without degrading the beam quality. Another important requirement of this defense application that needs to be met is that the high-power light source should involve minimal to no free-space optics in order to reduce the effects of shock, vibration and extreme temperature variations, necessitating a highly-integrated solution. Also, given that a VECSEL's cavity can be very well modeled by planar mirror and a spherical mirror spaced by many beam waists, its fundamental mode is given by a Gaussian, and thus it is natural to have $M^2 \sim 1.1$. As a consequence, its brightness can be ~3 times that of other schemes with $M^2 \sim 3$. That is, a VECSEL with an output of 4 Watts can have a brightness greater than a 10 Watt laser with an M^2 of 3.

In this work, we have studied the design, epitaxy, and fabrication process of high-power MWIR VECSELs with the objective of a few watts of output power and a circular near-diffraction limited (Gaussian) output beam at the same time. By varying the constituent semiconductor materials and the structural design parameters, the VECSEL emission wavelength can be varied from 3 µm to 4 µm. However, the overall design reported in this study is applicable for covering even wider wavelength ranges.

II. Device Design

The targeted wavelength range is accessible by the GaSb material system. Molecular beam epitaxy (MBE) is still considered to be the only viable growth technology for this material system required in such a very-long wavelength VECSEL structure. Figure 1 shows our proposed EP-VECSEL design for efficient, high brightness operation. Heat is extracted through the integrated Au-heat sink as well as through the top bonded sapphire substrate, which forms the external cavity, and serves as the external mode-controlling output coupler.

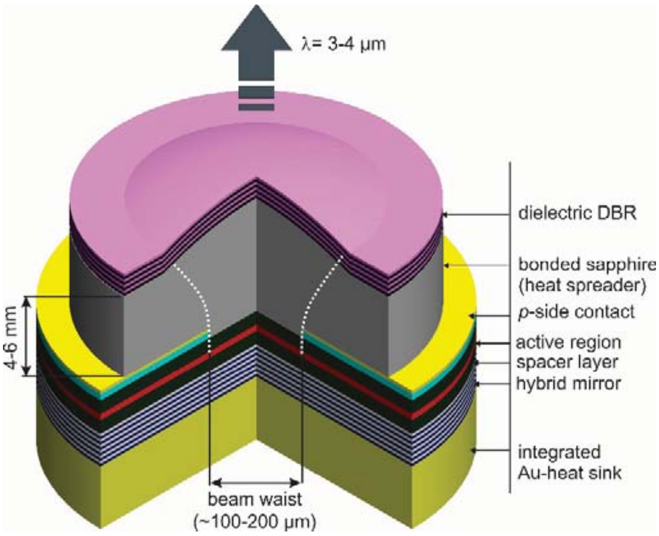

Fig. 1 Sketch of an electrically-pumped VECSEL with an epi-side down configuration for the 3-4 µm wavelength range. Several device components are indicated.

One could think of growing this either with the VECSEL-epitaxial DBR on top or on the bottom of the first growth. Here we consider that the epitaxial growth of the VECSEL-DBR is grown on top so that it is positioned at the bottom after removing the substrate and the device mesa is bonded face down to an integrated Au heat sink. We will then form the contacts to the laterally positioned contacts, attach the sapphire external-cavity chip to the top of the epi-stack on the GaSb wafer, and then remove the GaSb substrate, metalize the bottom DBRs for more reflection, and finally attach the heat sinks at the bottom. The gold layer thickness should be increased up to about 50-60 µm by electroplating. The electro-plated gold pseudo-substrate provides mechanical stability and serves as an excellent heat-sink.

EP-VECSELs require larger gain and incorporate as many quantum wells as practical, consistent with the resonant periodic gain principle [3]. To maximize overlap between the quantum wells and the optical standing wave, the cavity can be extended to a few wavelengths in length with the quantum wells clustered around the standing wave peaks.

A. Current Aperture

In conventional EP-VECSELs with a large-area, current injection from the top annular *p*-contact and uniform current distribution around the active region is always a big concern. Due to non-uniform current injection from annular contact and the resulting spatial hole burning, EP VECSELs are much rarer. This problem can be naturally overcome by incorporating the cascaded active region typically used in lasers for $\lambda > 3$ µm. As a matter of fact, EP-VECSELs are improved by interband cascade laser (ICL) active regions with short-period superlattices (SLs) at several stages that induces 100-200 µm of current spreading, which is highly advantageous unlike edge emitters. Current spreading along the transverse plane (i.e. perpendicular to growth direction) is very significant in a cascaded structure with thousands of thin layers that magnify resistance anisotropy [4]. In other words, a large ratio between in-plane and vertical conductivity in the cascaded layer structure ensures excellent lateral carrier injection through metal contacts with the intra-cavity configuration.

Excessive lateral current spreading in such cascaded structures also creates a problem in making current confinement of the devices. As it is known that V(E)CSELs require an aperture close to the active region for current confinement. Unfortunately, the buried tunnel junction (BTJ) concept [5] cannot be used to confine the current at the center of EP-VECSELs with a multi-stage ICL active region. Even monolithic aperture-VECSELs based on the selective, lateral under-etching of the tunnel-junction to define carrier confinement cannot solve the problem in VECSELs with multi-stage ICL active region [6]. Most importantly, the apertureless device becomes power-hungry since they experience higher optical loss due to the interaction between top annular contact and transverse modes emerging from the resonator. The *n*-mirror is probably the place to form a potential aperture. Ion implantation is one possibility to explore [7].

B. Highly-Reflective Mirror

The bottom epitaxial Bragg reflector consists of a few-pairs of ¼-λ thick *n*-doped AlAsSb/GaSb layers grown on an *n*-doped GaSb substrate. Unlike GaSb-based VCSELs with 24-26 layer pairs to get reflectivity approximately >99.8%, we consider to utilize a hybrid mirror that consists of a combination of only 10.5-12.5 pairs of AlAsSb/GaSb layers with refractive index contrast $\Delta n = 0.6$ at 4 µm, a GaSb phase matching layer and a terminating Au layer, yielding reflectivity ~99.98%. With these extreme high reflectivites, this kind of mirror is qualified as a substrate-side mirror of the VCSEL, where no light is coupled out. The mirror structure will be followed by an *n*-type GaSb current spreading layer and an active region. The growth will be continued by depositing a phase adjustment *n*-type current spreading layer and a contact layer. The components were processed on the wafer by etching a mesa structure and fabricating necessary passivation layers and metal contacts as shown in Figure 1.

The top dielectric DBR consists of only 5-pairs of ZnS and Ge layers. These two dielectric mirror materials can be deposited by e-beam evaporation on the sapphire spacer which contains the spherical mirror. Despite of the poor thermal conductivity of these dielectric materials, the peak reflectivity of this mirror can be as high as 99.8% by considering Δn between these two materials to be approximately ~2.0 at around 4 µm.

C. Active region

Type-II QWs based active region utilized in GaSb based VECSELs with $\lambda > 3$ µm. A single-stage (non-cascaded) active region consists of type-II QWs can be used [8]. This can be made of a $Ga_{0.9}In_{0.1}Sb$ hole confining QW sandwiched between two InAs electron confining QWs, as commonly used in ICLs. The photon energy corresponding to the lasing wavelength can be changed by changing the thickness of the constituent QWs. The thickness of the AlGaSb barriers between the QWs can be chosen in a way that prevent excess energy broadening of the mini-bands and allow homogeneous filling of the QWs by tunneling at the same time. A multi-stage type-II QW-based active region can also be employed [9]. Such a higher stage multiplicity in these VCSEL devices assures sufficient gain to overcome the cavity loss. The layering and right doping configurations of the active stages with carrier rebalancing may be important to significantly reduce the threshold current density of the device [10].

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