Thermal Management of Vertical External Cavity Surface Emitting Laser Grown on GaAs Substrate

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In a VECSELs, it seems that most of the heat comes from the pumping mechanism which is the external laser that is exciting the active medium. The pump photons have higher energy than the emitted photons and thus the energy difference is dissipated as heat in the active medium. As the temperature increases in the active medium the excited carriers star escaping the quantum wells until the laser gain is depleted and the power output decreases. Thermal management is crucial for VECSEL power performance and it is usually addressed by using heat spreader plates and heat sinks as will be explained next.

Keywords: VECSEL; Semiconductor laser; Thermal management; Quantum devices
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1. Introduction

Since 1960, the LASER which is an acronym for Light Amplification by Stimulated Emissions of Radiation has been used for several applications. It has been used in military applications as a rangefinder and for painting targets for smart bombs. Civilian uses include anything from laser pointers to leveling devices to alignment of optical systems. These applications are possible because of a laser's properties of having highly monochromatic light that is light of one wavelength and having light that is highly collimated meaning that the photons are very close together while they propagate through the air or the medium they happen to be in.

It was Albert Einstein in 1917 who first theorized about the process that makes lasers possible called "stimulated emission" [1,2]. Before the laser was the maser which is acronym for Microwave Amplification by Stimulated Emission of Radiation. This works on the same principles as the laser but emits no light photons; it was mainly used to amplify radio signals. The men who invented the maser, Charles Townes and Arthur Schawlow, were at Columbia University [1,2]. In 1960, Theodore Maiman invented the first optical laser. It was called the ruby laser because it used a ruby rod doped with chromium to emit light in a beam. However it was pulsed and had few applications [1,2]. Ali Javan, in 1960, invented the first gas laser which was the Helium-Neon which outputs visible light at 632.8 nm wavelength (red). These Helium-Neon lasers are widely used today. There are even Helium-Neon lasers that emit a green light at around 532 nm wavelength. In 1962, a new kind of laser was invented by Robert Hall. This new laser was a semiconductor laser made of gallium arsenide at General Electric Labs [1,2]. This was followed closely by the first continuous wave solid state laser.

The lasers mentioned here all have one thing in common, that is that they are all very inefficient when it comes to power use (which is power out over power in). The best that most lasers can hope for is about 10-30% especially in gas and solid state lasers. Semiconductor lasers are about 50% efficient with some high power semiconductor lasers having 60-70% efficiency. The reason that lasers are so inefficient is that the energy that is not emitted as light is converted into heat. Therefore, elimination of this heat is crucial to improve laser efficiency. It is especially true for semiconductor lasers where excessive heat can lead to structural break down. For most lasers (gas and solid state) the problem of heat is solved by simply designing a heat exchange system around the active medium using circulating water from the city or from water cooling tower; some lasers come with or one can have ordered for it a system that has a refrigerated water cooling system. The cooling system usually includes cooling the power supply also since so much power is required to excite the lasers; this is normal practice because most power supplies are made with semi-conductors and they create large amounts of heat while in operation. The cost of, all of these solutions is very expensive and are all external solutions to the problem of controlling heat in lasers. So it makes sense to engineer the laser so that the creation of heat is at a minimum.

2. Background

2.1 Definition of a VECSEL

The vertical external cavity surface emitting laser (VECSEL) is a type of semiconductor laser. Its name is an acronym for VECSEL. Figure (1) shows the major components of this laser [3]. The bottom mirror is a highly reflective mirror usually a distributed Bragg's reflector (DBR). A DBR is composed of multiple layers of materials with different refractive index which allows up to 99.9% reflectivity. The active region that can be composed of quantum well, quantum dashes, or quantum dots, is band gap engineered to absorb the pumped photons and emit photons at a desired wavelength

[4]. The external cavity is formed between the active region and the external mirror. The external mirror, also call an output coupler, is partially reflective spherical mirror that defines the laser transverse mode [4] and allows the extraction of a portion of the laser beam from the cavity.

Figure (2) shows the basic functions of the VECSEL components. High energy incident pump photons are absorbed into pump absorbing region [4]. Carriers diffuse to the quantum wells where electrons are excited and relaxed emitting photons with energy equal to the quantum well band-gap energy [4]. The generated photons travel back and forth in the cavity. These photons stimulate more electrons in high energy levels to drop to lower energy levels and generate more photons with same wavelength and phase emitting coherent light as shown in Fig. (3) [5].

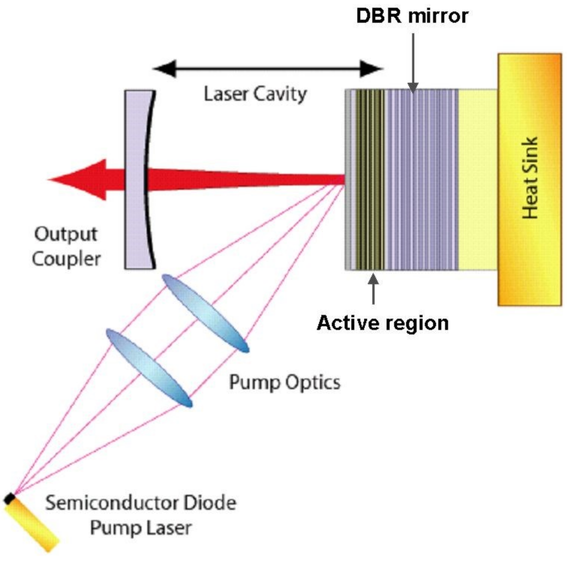

Fig. (1) Configuration of an optically pumped vertical external cavity surface emitting laser (VECSEL)

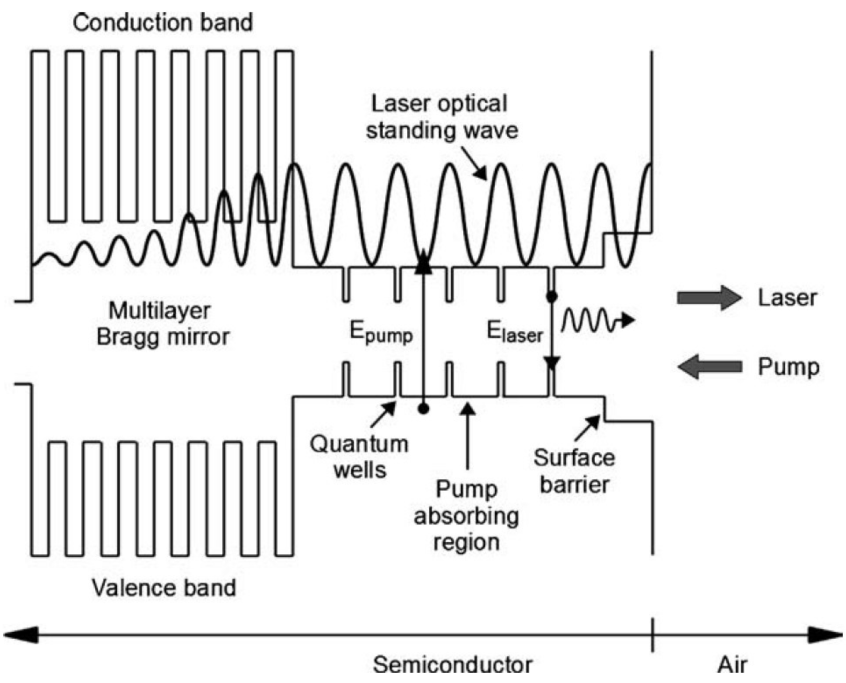

Fig. (2) Operating principles of optically pumped vertical external cavity surface emitting lasers (VECSELs) [4]

As it can be seen in Figure 3 in order to produce a considerable amount of photons by stimulated emission, population inversion must be maintained hence the use of an external pump laser [4-6]. Eventually, enough photons will be generated and they will escape the cavity through the output coupler.

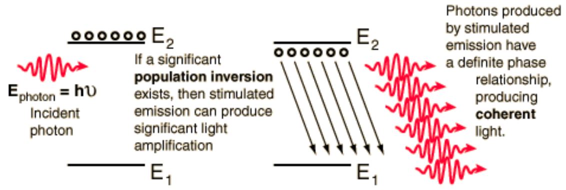

Fig. (3) Schematic diagram of the stimulated emission processes in lasers [5]

3. Experimental Procedure

Previous experiments have shown that an etch stop layer is unnecessary for the substrate removal of GaAs in GaSb/GaAs systems. Now, the goal of this study is to optimize a substrate removal technique to obtain the smoothest surface possible. The GaSb layers used in this experiment were grown by means of molecular beam epitaxy (MBE). A 3μm thin GaSb film was grown at a rate of 0.50 μm/hr at temperature of 510°C with a V-to-III ratio of Sb to Ga of 6.6 on GaAs substrate.

The samples were cleaved in squares of 1x1 cm^2 for easy handling. Cleaving is performed using a diamond scriber. The wafer is placed epitaxial side up on a clean room wipe sheet. With a ruler on the straight side of the sample 1 cm is measured and marked by scribing a small line. Then the wafer is placed over a straighten out paper clip so that the scribe line aligns with the paper clip and by applying equal pressure to both sides of the wafer with the ends of two tweezers the sample fractures in a straight line. The same procedure is repeated until the maximum possible 1cm^2 chips are obtained from one wafer.

The next step is to chemically clean the sample to remove any impurities that may reside on the wafer surface. Each sample was soaked in acetone, isopropanol, and methanol for 2 minutes in each solution. Then the sample was rinsed with deionized (DI) water and dried with a Nitrogen gun. Nomarski images of the clean surface were taken before the bonding procedure.

Microscope glass slides were cut into three pieces. A pinch of ApiezonW® wax was placed on top of the glass slide and then the slide was placed on a hot plate at a temperature of 150°C. Once the wax was melted, the sample was placed on the wax with the GaSb layer facing down. Slight pressure was applied on the sample to assure even contact, free of air bubbles, with the wax. Then the sample was removed and allowed to cool.

4. Results and Discussion

In VECSELs, it seems that most of the heat comes from the pumping mechanism which is the external laser that is exciting the active medium. Less than 100% of the energy pump into the laser is converted to effective radiative power and hence the rest is converted to heat. This is due to the difference in energy between the incident pump photons and emitter laser photons. The pump photons have higher energy than the emitted photons and thus the energy difference is dissipated as heat in the active medium. As the temperature increases in the active medium the excited carriers star escaping the quantum wells until the laser gain is depleted and the power output decreases. Hence, thermal management is crucial for VECSEL power performance and it is usually addressed by using heat spreader plates and heat sinks as will be explained next.

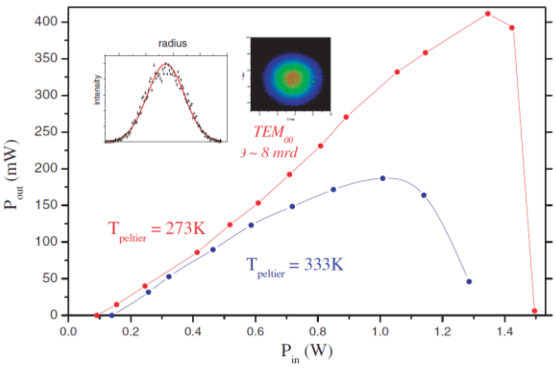

Fig. (4) Output power from a 1 μm VECSEL with an unprocessed InGaAs/GaAs gain as a function of incident pump power at two different temperature settings

Several VECSEL designs had been developed to remove the undesired heat from the active region. The ones most mentioned in literature [4,6-8] are shown in Fig. (5). The first one, figure (5a), is the most simple design. The VECSEL is directly bonded to a heat sink exactly as it is grown. This design is not too efficient due to the substrate thermal impedance. In addition to the poor thermal conductivity of the substrates, (33 W/m.K for GaSb [7] and 45 W/m.K for GaAs [8]), they are too thick, up to 500μm.

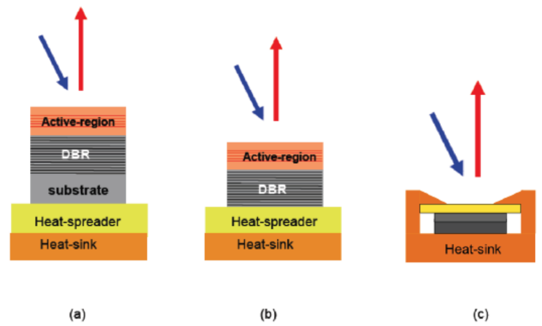

Fig. (5) VECSEL structure designs for thermal management

The second design, figure (5b), the substrate is removed hence improving heat removal. However, this design can only be used when etch chemistry permits a good selectivity between the substrate and an etch stop layer as it will be described in the subsequent sections. For this design, the VECSEL structure is grown in reverse order. The active medium is grown close to the substrate and the DBR is grown last. In this way the heat is extracted through the DBR and even though DBR's thermal conductivity could still be low, (11 W/m.K for $Al_{0.5}Ga_{0.5}As$ DBR [6]), thermal diffusion length is much less than with the presence of the substrate. In the third design, Figure (5c), heat is extracted directly from the active region. The active region is bonded to heat spreader plate. Thus, the substrate can be either removed or kept depending of its etch chemistry. However, the heat spreader must be transparent such as transparent diamond, sapphire or silicon carbide.

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