Invited Paper

850nm Oxide VCSEL Development at Hewlett-Packard

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ABSTRACT

Oxide confined VCSELs are being developed at Hewlett-Packard for the next-generation low cost fiber optics communication applications. Compared to the existing 850nm implant confined VCSELs, the oxide VCSELs have lower operating voltages, higher slope efficiencies, and better modal bandwidth characteristics. Preliminary data on epitaxy and oxidation control uniformity, device performance, and reliability will be discussed.

Keywords: VCSEL, oxide-confined, manufacturing, laser reliability.

1. INTRODUCTION

Large area gain guided 850nm vertical cavity surface-emitting lasers (VCSELs) using proton implantation have been widely used as light sources for fiber optic data communication applications. Low cost commercial manufacturing has been demonstrated with good epitaxial uniformity and wafer scale processing and testing.[1,2] Since its introduction several years ago, native oxide confinement in VCSELs has shown some very promising results.[3,4] Compared to implant VCSELs, oxide VCSELs have lower threshold currents and higher slope efficiencies. In addition, the strong index guiding of the oxide layer can give rise to very rich transverse mode structures that offer better modal bandwidth characteristics for multi-mode fibers. However, there are several manufacturing concerns that have prevented oxide VCSELs from being commercially manufactured in large quantities. First of all, since the oxidation rate of the oxide layer is very difficult to control, the oxide VCSEL aperture size variation is generally much larger than that of the photolithographically defined implant VCSEL aperture size. Secondly and more importantly, the strain and defects introduced by the oxide layer in the middle of the semiconductor stack close to the gain region could potentially cause reliability problems. Here we report the first commercially manufactured oxide VCSEL process at Hewlett-Packard. In addition to meeting or exceeding all the other performance criteria of the existing implant VCSELs, the oxide VCSELs also have lower forward voltages of less than 2V over the entire operating range, which is compatible with products using 3.3V power supplies.

Part of the SPIE Conference on Vertical-Cavity Surface-Emitting Lasers III • San Jose, California • January 1999
SPIE Vol. 3627 • 0277-786X/99/$10.00

2. EPITAXIAL GROWTH AND PROCESSING

The VCSELs are grown using a multi-wafer organometallic vapor-phase epitaxy (OMVPE) reactor. The epitaxial structure of the oxide VCSELs includes an n-type 40-pair AlGaAs DBR, a full wave cavity with three GaAs quantum wells in the center, a thin $Al_{0.97}Ga_{0.03}As$ layer for oxidation, and a p-type 25-pair AlGaAs DBR followed by a heavily-doped GaAs contact layer. The DBR interfaces are graded to reduce the series resistance of the devices. After the epitaxial growth, reflectivity spectra are taken across all the wafers and the Fabry-Perot wavelength is measured to characterize VCSEL thickness uniformity. Typically, the Fabry-Perot wavelength uniformity can be controlled to within ±0.6% over 80% area of a 2-inch diameter wafer, which translates into a lasing wavelength range of around 10nm. Wafer-to-wafer thickness variation from the same epi run and run-to-run thickness variation are even smaller. Epitaxial thickness uniformity like this is important in order to achieve a manufacturable process with high yield.

Another critical parameter that potentially has great impact on the process yield is the VCSEL aperture size uniformity. For implant VCSELs the current aperture size is very uniform and reproducible as it is defined by photolithography and proton implant. It is more complicated for oxide VCSELs, however, due to the wet oxidation step in the post-epi processing that defines the device aperture. The buried $Al_{0.97}Ga_{0.03}As$ oxidation layer is oxidized laterally in water vapor ambient in a furnace at around 450°C to form native oxide. Any variation in the oxidation depth across a wafer or from run to run will translate into variation in the oxide aperture size , which in turn leads to non-uniform device performance and difficulties in setting burn-in conditions later on. Currently, the oxide aperture sizes are controlled through the combination of oxidation rate and oxidation time. The aperture size variation across a 2-in wafer is typically within ±10%, and will further improve upon system optimization.

3. DEVICE CHARACTERIZATION

The uniformity in epitaxial thickness and oxide aperture size gives rise to good device yield in DC testing. Excellent device performance has been achieved with low operating voltage, high power, and fast modulation speed. Because of the intrinsic geometry of VCSELs, tens of thousands of devices on a wafer can be tested in wafer form. Fig. 1 shows the LIV curves of a typical oxide VCSEL device from such a test over a range of substrate temperatures. For the vast majority of the device population, the threshold currents are between 3mA and 5mA, and the slope efficiencies are between 0.35W/A and 0.45W/A. The threshold change is minimal and the slope efficiency drops slightly when the substrate temperature is raised up to 90°C. The typical series resistance of the devices is around 30ohms and reduces slightly at higher temperatures. Because the VCSELs are intended for 3.3V applications, the forward operating voltage is also an important parameter. The threshold voltage of the device shown in Fig. 1at room temperature is around 1.65V. Fig. 2 also plots the output powers of the same device at a fixed forward voltage of 2V at different substrate temperatures. From room temperature up to 90°C, the power at 2V stays between 3mW to 5mW for most of the devices.

After DC testing, some of the VCSEL dice are built into standard TO-46 header cans to test their modulation speed. Fig. 3 shows the typical eye diagram of an oxide VCSEL operating at 1.25Gbps. The wide open eye pattern indicates good speed performance of the oxide VCSELs.

Another important difference between oxide VCSELs and implant VCSELs is the transverse mode guiding mechanism. The gain-guided implant VCSELs generally have higher optical loss, lower efficiency, and larger noise due to effects such as mode hopping. On the other hand the strong index guiding in oxide VCSELs leads to very different transverse mode characteristics. Fig. 4 shows the near- and far-field intensity patterns of a typical oxide VCSEL. At currents slightly above threshold, the near-field shows symmetric and well-defined NxN mode patterns. As the current increases smaller bright mode patterns quickly fill up the whole oxide aperture. The intensity patterns are very stable and reproducible. The far-fields intensities of the lasers are always concentrated in four off-axis beams and the divergence angle increases quickly at higher pump currents. Fig. 5 shows the numeric aperture (NA) behavior of the a typical oxide VCSEL at different pump current levels. Also shown is the corresponding behavior a similar implant VCSEL that is gain-guided. The much higher NA values of the oxide VCSEL indicates the large transverse lasing mode components due to the strong index-guiding of the native oxide. This is also confirmed by the fact that the spectral line-widths of the oxide VCSELs are measured to be much wider than those of similar implant VCSELs. The highly multi-mode nature of these oxide VCSELs have been shown to reduce the modal noise in multimode fiber link systems.

4. RELIABILITY

One of the greatest concerns of developing oxide VCSELs is the reliability. The transformation of high Al content AlGaAs into native oxide is known to introduce strain and defects in the VCSEL structure. Preliminary reliability of the oxide VCSELs is studied here by stressing the devices at a constant output power of 2mW at 70°C ambient. This condition was chosen to simulate actual product operation where a monitor diode feedback is used to maintain a constant output power. The elevated stress temperature represents the upper ambient temperature limit of the product specifications. Fig. 6 shows the operating current at 2mW, 70°C over a period of more than 2000 hours for more than 460 units, resulting in ~1 million cumulative device hours. All these units have remained stable. We are also conducting long-term wearout tests at various currents and temperatures to determine the activation energy.

5. SUMMARY

In summary, a commercially manufacturable oxide VCSEL process has been demonstrated. Good uniformity control in epitaxial thickness and oxide aperture is found to be important in achieving high yield. The manufactured VCSELs have superior performance with operating voltage less than 2V. Preliminary results show that oxide VCSEL reliability compares favorably with that of proton-implanted VCSELs.

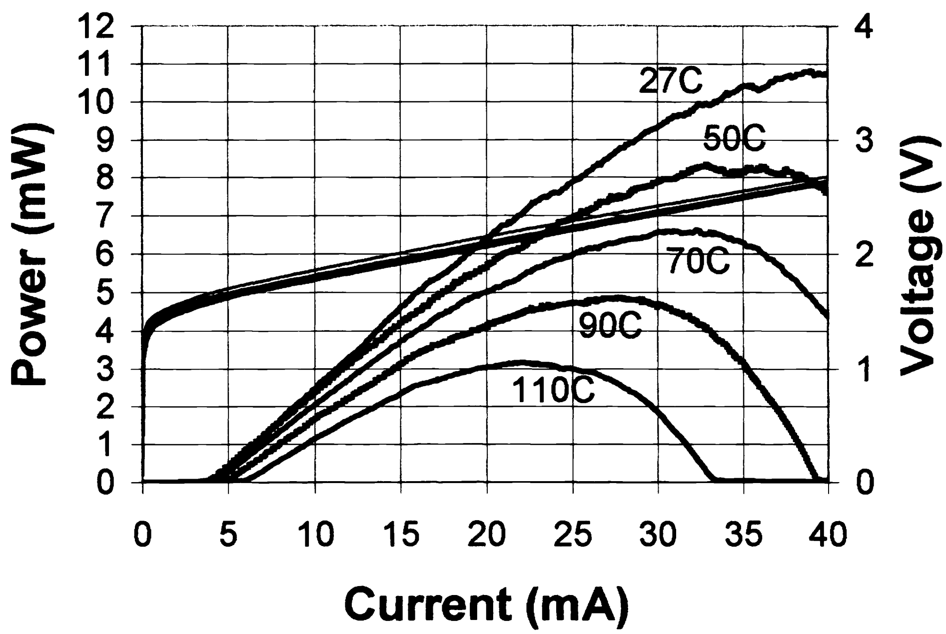

Fig. 1. LIV curves of a typical oxide VCSEL at different substrate temperatures.

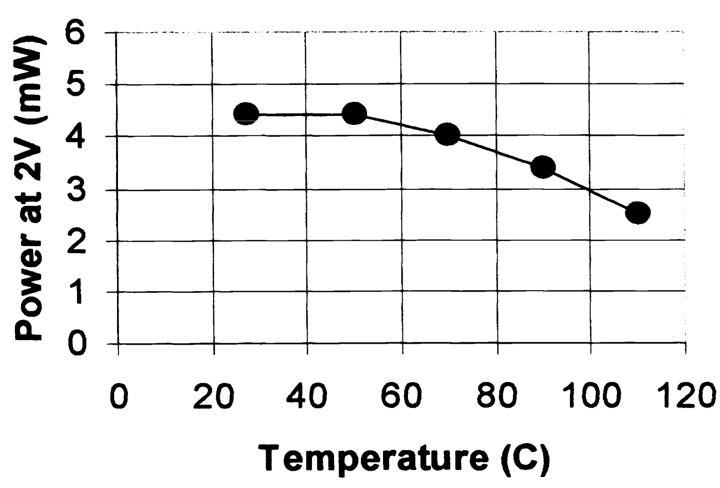

Fig. 2. Output power of a typical oxide VCSEL with bias voltage at 2V at different temperatures.

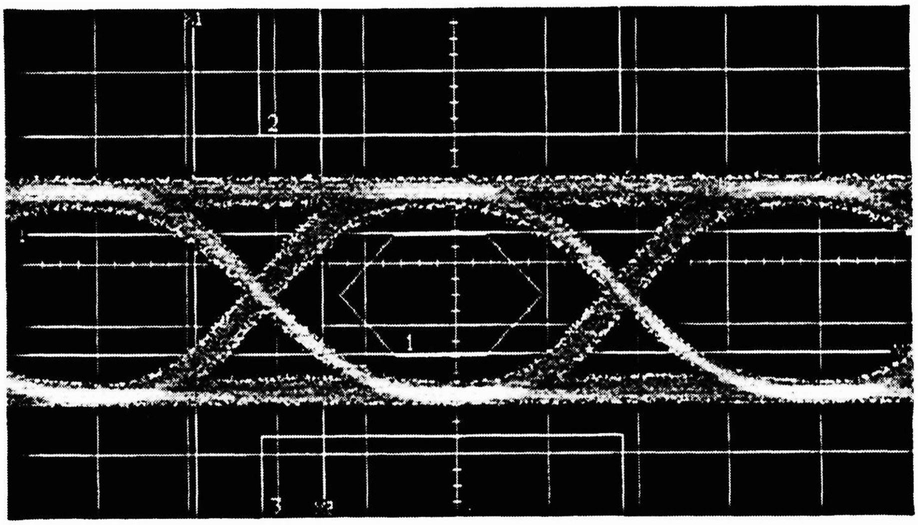

Fig. 3. Eye diagram of an oxide VCSEL operating at 1.25 Gbps.

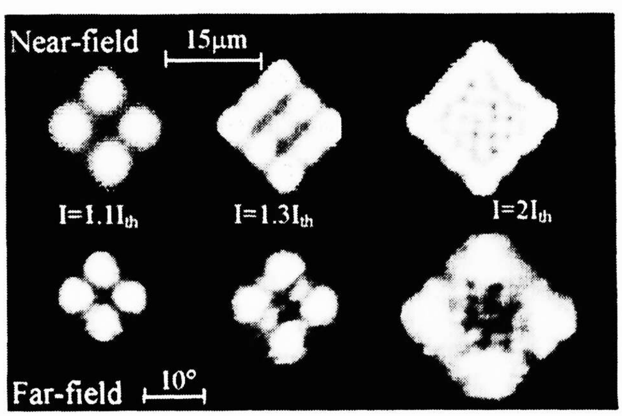

Fig. 4. Near-field and far-field intensity patterns of an oxide VCSEL at different pump levels.

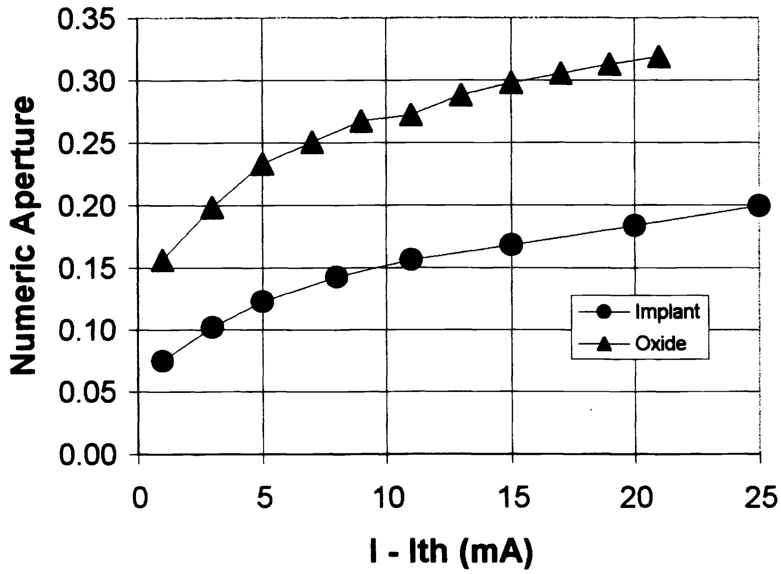

Fig. 5. Numeric apertures of a typical oxide VCSEL and a similar implant VCSEL.

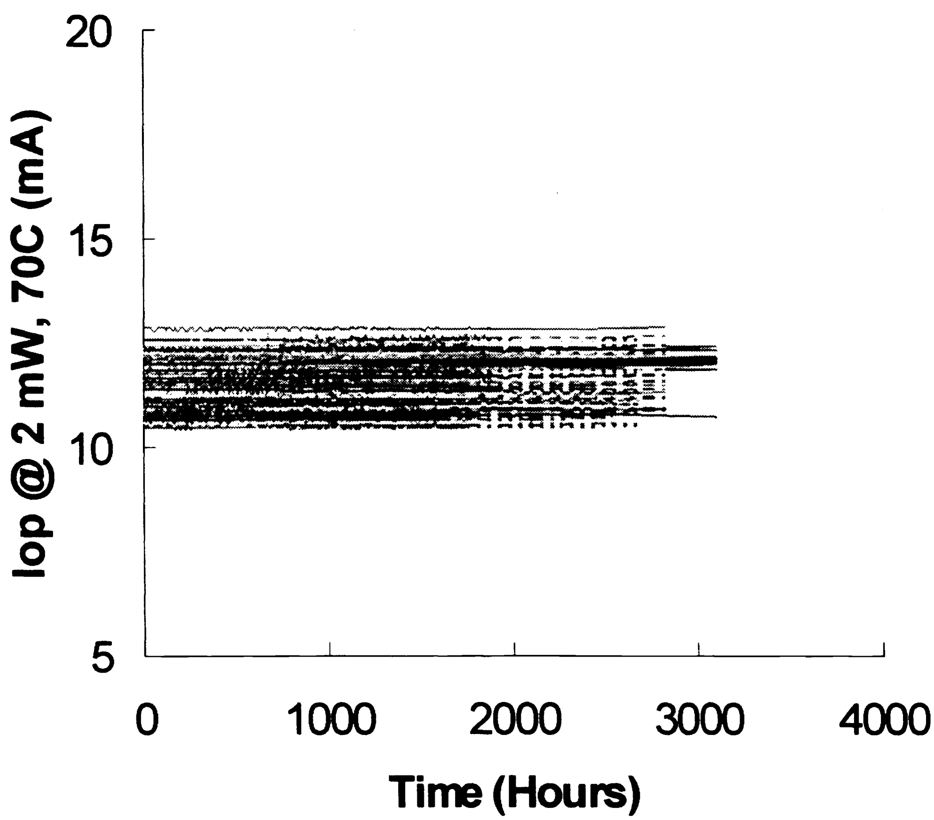

Fig. 6. Constant power stress of 460 oxide VCSEL devices at 2mW and 70°C ambient.