Automating electrical characterization of bottom-emitting VCSELs

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Project Overview

Vertical-cavity surface-emitting lasers (VCSELs) are a type of semiconductor laser currently being developed for a variety of applications, including optical interconnects.

First developed in the late 1970s, VCSELs emit perpendicular to the semiconductor surface. They exhibit axial beam symmetry and low beam divergence, and unlike their predecessors, edge emitting lasers, are easier to incorporate into optoelectronic applications. They also can be fabricated in 2-D arrays, opening the possibility of massively parallel optical interconnects.

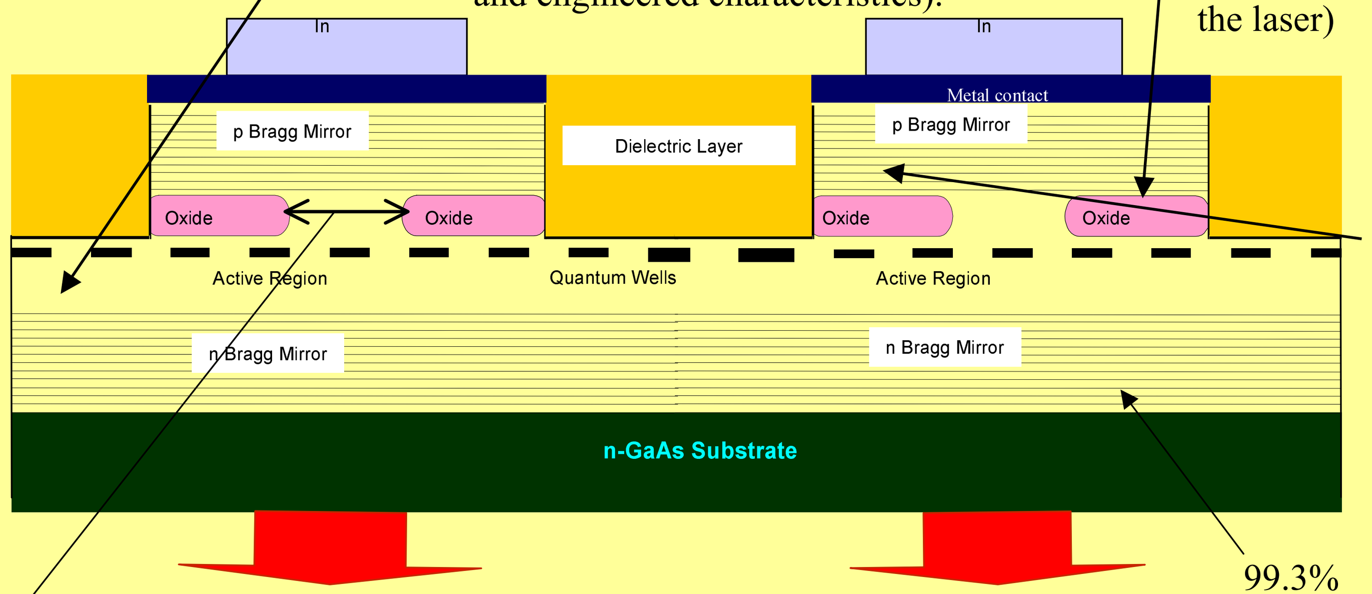
Another advantage of VCSELs is that they can be tested on the wafer early in the fabrication/ packaging process precluding further costs on defective devices. One important test is IVL characterization, where device voltage (V) and optical power (L) are plotted versus device current (I). We developed a compuer-controlled system for rapid IVL characterization of large numbers of VCSELs. These characterizations are a form of process monitoring, aiding in efficient fabrication processes, and providing information about VCSEL operating ranges.

VCSEL Heterostructure

This structure is grown epitaxially by Molecular Beam Epitaxy (MBE)

Active Region: This is the region where optical gain occurs. Photons are reflected off of the two mirrors and at the threshold current stimulated emission (lasing) occurs. The threshold current is dependent upon the optical gain of the cavity and its geometry (both material and engineered characteristics).

Oxide Layer forces the current to the center of the cavity. It also functions to control aperture size of the laser. (Aperture size ultimately affects optical output power of the laser)



99.9% Reflectivity

99.3% Reflectivity

aperture size

DIRECTION OF LASING

We investigated six (6) properties that define VCSEL operation:

•Forward-Bias Diode turn-on Voltage (V_{to})

This voltage is defined as where a semiconductor is forward biased and permits current flow from the p- to n-terminals. (obtained for VI curve for the VCSEL device)

•Lasing Current Threshold (I_{th})

This is the current at which stimulated emission (lasing) begins to occur. This is obtained from the LI curve.

•Lasing Voltage Threshold (V_{th})

This is the corresponding voltage at the current threshold. It is approximately 2.8V in the devices we characterized during the duration of this project.

•Optical Output Power

This is the power output of the laser during the lasing mode of operation (typical values in the milliwatts range).
Output power is generally linearly related to photon number (P) for currents $I > Ith$.

•Power-conversion Slope-Efficiency (η_s)

This is defined as where L is the output optical power (W) and I_{th} is the current threshold (defined above)

•Power-conversion Wall-Plug Efficiency (η_{tot})

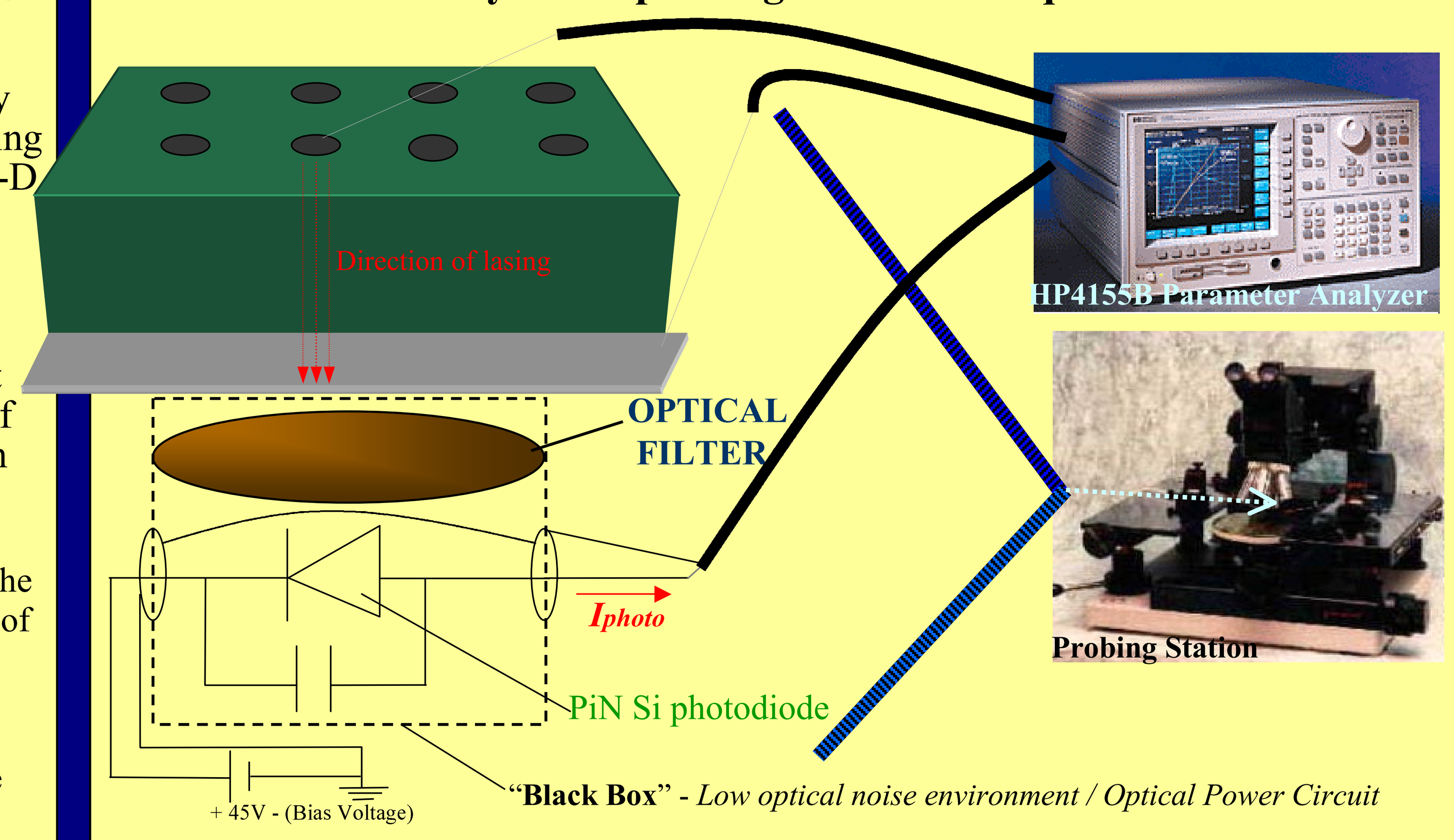
This value defines the overall efficiency (%) of the laser.

In addition to computer analysis of IVL data sets, we need to develop a low-noise optical environment for microprobing. We designed and implemented a probing setup incorporating a "black box" optical power meter circuit and a parameter analyzer to simultaneously measure IV and IL characteristics of VCSEL devices.

We have successfully demonstrated that rapid IVL characterization is possible for bottom-emitting VCSELs in a self-contained setup.

Experimental Setup

I. 2-D VCSEL Array Microprobing and Data Acquisition



"**Black Box**" - *Low optical noise environment / Optical Power Circuit*

Steps in microprobing and analysis:

1. User places a bare VCSEL wafer onto the probing station. The wafer has been mounted to a glass slide via silver paint, which functions as the ground for the device. The device is then probed using micromanipulators. After electrical contacts are made the user then sends a current sweep via the HP4155B parameter analyzer.

2. The user then configures the parameter analyzer to complete the appropriate type of sweep (usually current) across the device. Typical sweeps range from 0 - 7.5mA. Three values are read into the parameter analyzer: ***device voltage (V_{dev}), device current (I_{dev}), and photo current (I_{photo})***. The photo current is converted into optical power by using the known responsivity of the photodiode in the power meter (conversion completed in EXCEL). The values are then transferred via .txt file for subsequent data analysis on the computer.

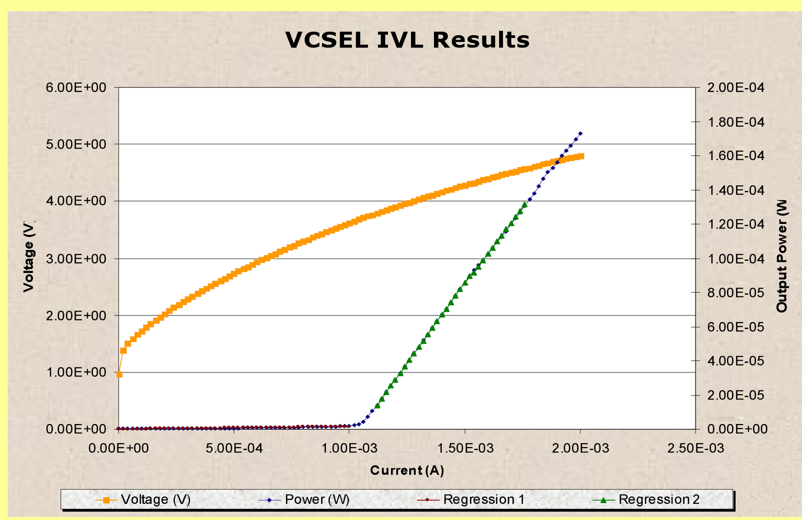
II. IVL Parameter and Statistical Analysis / Data Management

3. After the user puts the three sets of data from the parameter analyzer into Excel, the process of analyzing VCSEL data is handled automatically. Using Microsoft's Visual Basic for Applications, code was developed that determines the two linear regions for the VCSEL data, uses that to find our target parameters and plots the data in meaningful ways.

The two linear regions are found using the second derivative of the data, which is determined by performing linear regression around each point, and again around each slope. Places where the second derivative exceeds the standard deviation are then marked as regions of rapid change in the data, which define the endpoints of the linear regions of the data.

The user is also allowed to edit the endpoints of the linear regions manually. Slope efficiency and threshold current and voltage are found using these regions. Turn-on voltage and series resistance are found through linear regressions on IV data sets.

IVL and Efficiency Plots



I-V-L Plot:

The orange plot (to the left) shows the standard diode IV characteristics of the VCSEL. The resistance is the slope of a linear regression of this data. The turn-on voltage is the y-intercept.

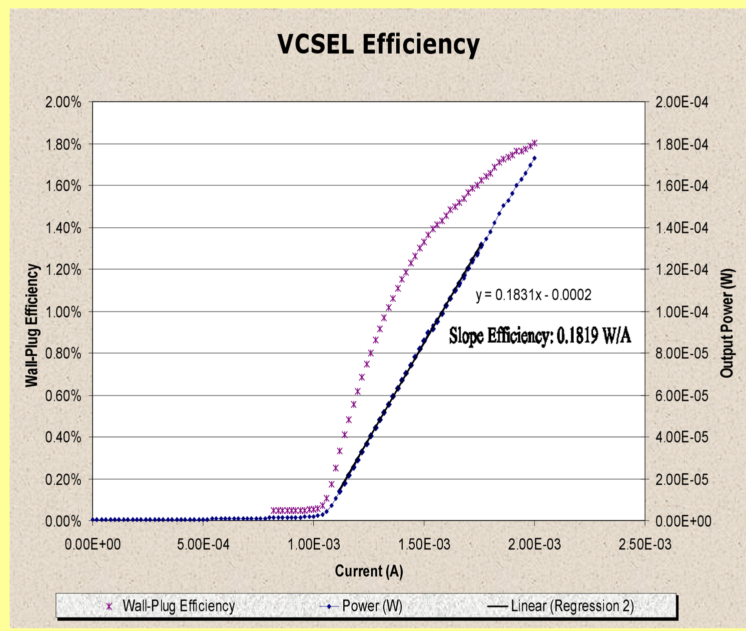
The green plot (same graph) shows the optical output power of the VCSEL. The lasing current threshold is the intersection of the two linear regions of this plot. The corresponding voltage at that current value is the threshold voltage. Were the device run to higher currents the optical power would eventually level off and begin to fall. The maximum value of this plot is the maximum output power.

Methods for determining efficiency:

The "*Wall-Plug*" efficiency of a VCSEL is the ratio between optical power out and electrical power in, and varies for different current values. The graph to the right shows the Wall-Plug efficiency plotted against current. Were the data to continue, the Wall-Plug Efficiency would level out and start falling. The point at which it reaches its maximum shows the most efficient current to operate a particular VCSEL device.

The slope efficiency is the slope of the second linear part of the IL data (lasing region). It is proportional to the quantum efficiency, which indicates the percentage of the electrons traveling through the active region which cause emission of a photon.

These two parameters are used to judge the performance of VCSELs, and indicate areas of design that need improvement.



Conclusions

- Rapid on-wafer IVL characterization with a single setup is feasible and efficient for bottom-emitting VCSELs.
- On-wafer device testing saves time and data acquisition and limits packaging efforts to known functional devices.
- Computer-based analysis of IVL parameters of VCSEL arrays will provide more rapid feedback on device performance, design processes, and packaging with increases of VCSEL development by the Army.
- Greater attention must be provided towards improving wall-plug efficiency and lowering voltage threshold.
- An improved system of cataloguing VCSEL wafers must be instituted to better analyze spatial variance in VCSEL properties across a wafer.

Future Work

- Integrate LabVIEW control of the HP4155B parameter analyzer into the hierarchy of the EXCEL data analysis program.
- Complete development of rapid IVL characterization platform for top-emitting VCSELs
- Perform high-volume analysis (both electrical parameters and statistical) on wafers to determine spatial trends of properties within design.