

**Highly Uniform and Reproducible Vertical-Cavity Surface Emitting Lasers Grown by  
Metalorganic Chemical Vapor Deposition**

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We show that the uniformity of the lasing wavelength of vertical-cavity surface emitting lasers (VCSELs) can be as good as  $\pm 0.3\%$  across a entire 3" wafer in MOCVD growth with a similar run-to-run reproducibility.

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## Highly Uniform and Reproducible Vertical-Cavity Surface Emitting Lasers Grown by Metalorganic Chemical Vapor Deposition

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Metalorganic chemical vapor deposition (MOCVD) technology is increasingly recognized as a superior platform for growth of vertical cavity surface emitting lasers (VCSELs) because of its high throughput, low surface defect density, continuous compositional grading control, and the flexibility for materials and dopant choices. In this paper, we show that it is also capable of extremely high wafer uniformity and run-to-run reproducibility.

The growth was performed on an Emcore GS3200 MOCVD reactor. The reactor pressure and growth temperature are typically 60 torr and 750 °C, respectively for 770- and 850-nm VCSEL growth. Growth rates of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  in the mirror and active layers using TMG, TMA, and 100%  $\text{AsH}_3$  were calibrated *in situ* by a normal-incidence reflectance setup.<sup>[1]</sup> This setup using a W-halogen lamp and a silicon detector through a 10 nm interference filter provides a simple, robust, and accurate measurement of the growth rate. Group-V flow, total reactor flow, and the gas-flow distribution along the radial direction of the top flange were carefully optimized for 4" and 3" wafers through measurements of the distributed Bragg reflector (DBR) center wavelength. The VCSEL structure for this uniformity study consists of a 36.5 period *n*-type bottom DBR mirror, 3 GaAs/ $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$  quantum wells embedded in the center of a one-wave cavity, and a 23 period *p*-type top DBR mirror doped with  $\text{CCl}_4$ . There are two DBR periods for oxide current apertures<sup>[2]</sup>, one on each side of the optical cavity.

Shown in Fig. 1 is the wavelength of the cavity mode for the 840-nm VCSEL structure as a function of the distance from the center of the wafer. Excellent uniformity was achieved to  $\pm 0.05\%$  in the center 2" area of the 3" wafer, and to  $\pm 0.2\%$  over of the entire 3" wafer. This uniformity was achieved

with an AsH<sub>3</sub> flow of 248.5 sccm in a total reactor flow of 32.6 slm and a top-flange gas-flow partition of 7%:78%:15% between the inner, middle and outer injection zones.

This structure was processed into VCSELs with 9×9  $\mu\text{m}^2$  oxide apertures on both sides of the cavity. The lasing wavelength and threshold current of VCSEL devices are plotted as a function of the distance from the center of the wafer. Even with fabrication nonuniformity, the lasing wavelength uniformity is still  $\pm 0.3\%$  over nearly the whole wafer. The threshold current variation is less than  $\pm 10\%$  in the 2" area of the 3" wafer. Oxide-confined VCSELs with 1×1  $\mu\text{m}^2$  oxide apertures show threshold current as low as 26  $\mu\text{A}$ , the lowest reported to date for 840-nm VCSELs.

The MOCVD growth runs are also highly reproducible. We typically reconfirm the growth rate with a calibration growth run using the *in situ* reflectance setup before growing a series of VCSEL wafers. Shown in Figure 3 are the cavity wavelengths for 770- and 850-nm VCSELs plotted as a function of run number. We obtained wavelength run-to-run reproducibility of  $\pm 0.3\%$  for both 770- and 850-nm VCSELs over the course of about 100 runs.

In summary, we have demonstrated an optimized MOCVD technique for highly uniform and reproducible VCSEL growth, enabling high performance VCSELs with uniform lasing characteristics. This work is supported by the DOE under contact No. DE-AC04-94AL85000.

[1]. W.G. Breiland and K.P. Killeen, *J. Appl. Phys.* (to be published).

[2]. K.D. Choquette, R.P. Schneider, Jr., K.L. Lear, K.M. Geib, *Electron. Lett.* **30**, 2043 (1994).

Figure 1. Wavelength uniformity of the optical cavity mode across a 3" 840-nm VCSEL wafer.

Figure 2. Lasing wavelength and threshold current uniformity across a 3" 840-nm VCSEL wafer for 9×9  $\mu\text{m}^2$  devices with oxide apertures on both sides of the cavity.

Figure 3. Cavity wavelength of 770- and 850-nm VCSEL structures versus the growth run number. The typical reproducibility is  $\pm 0.3\%$ .

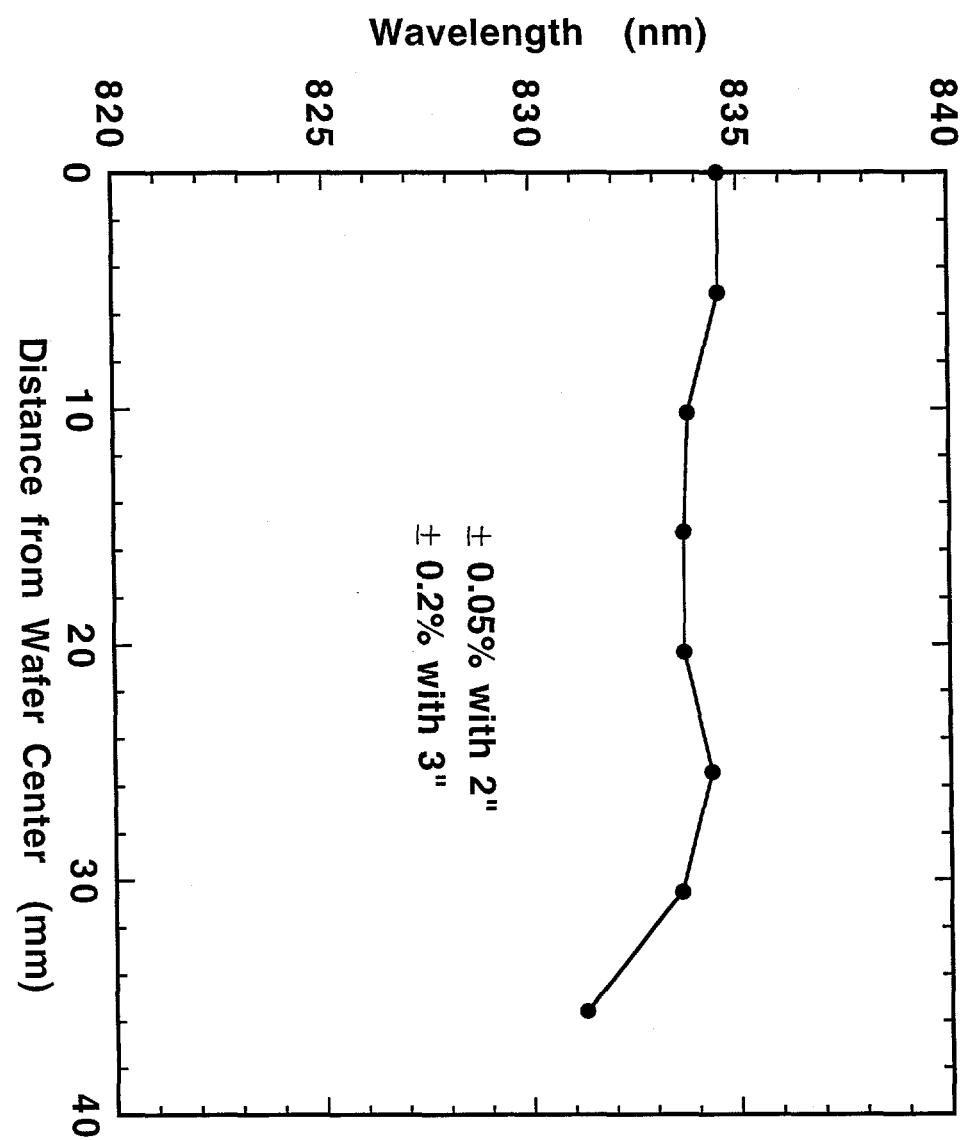


Fig. 1

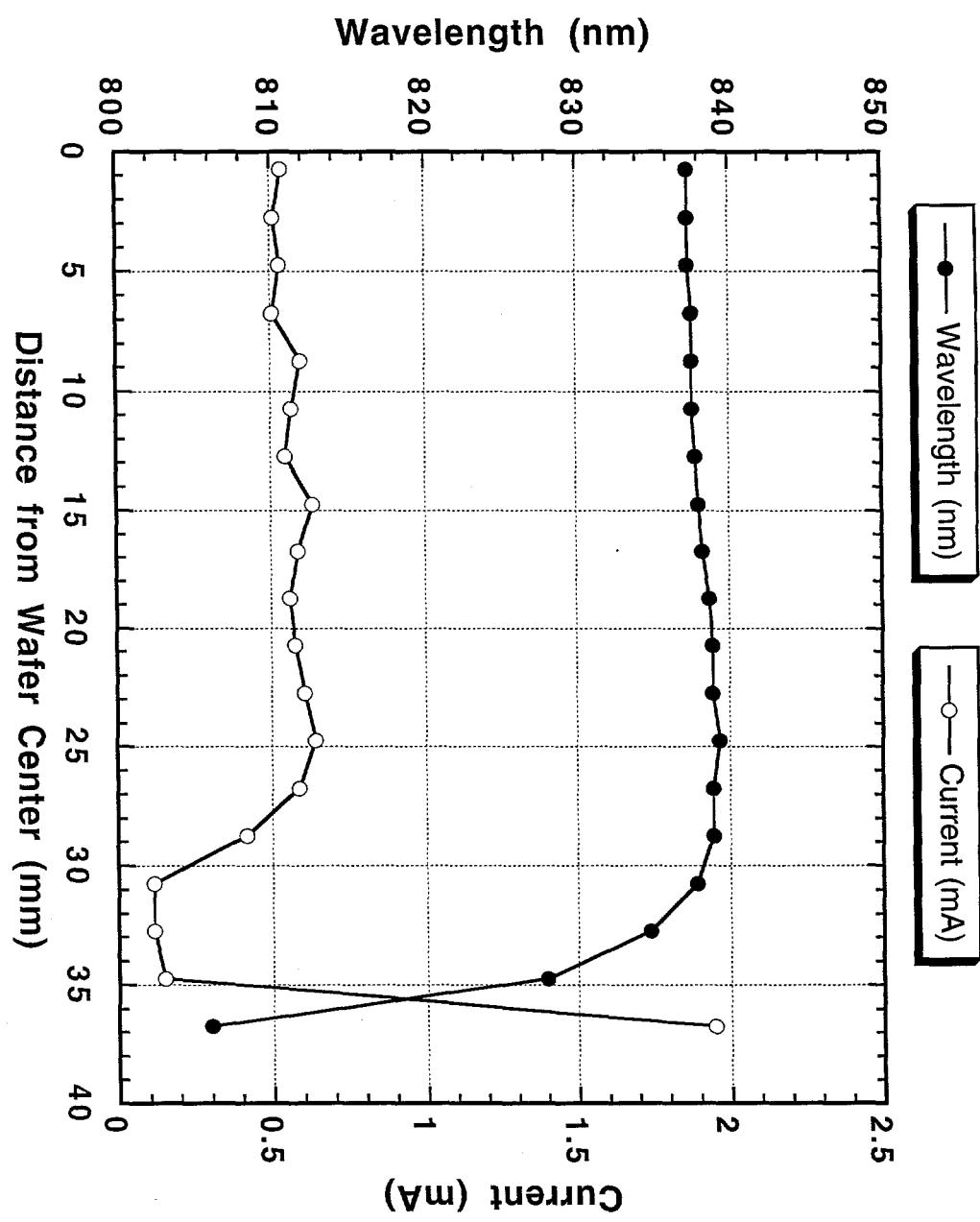


Fig. 2

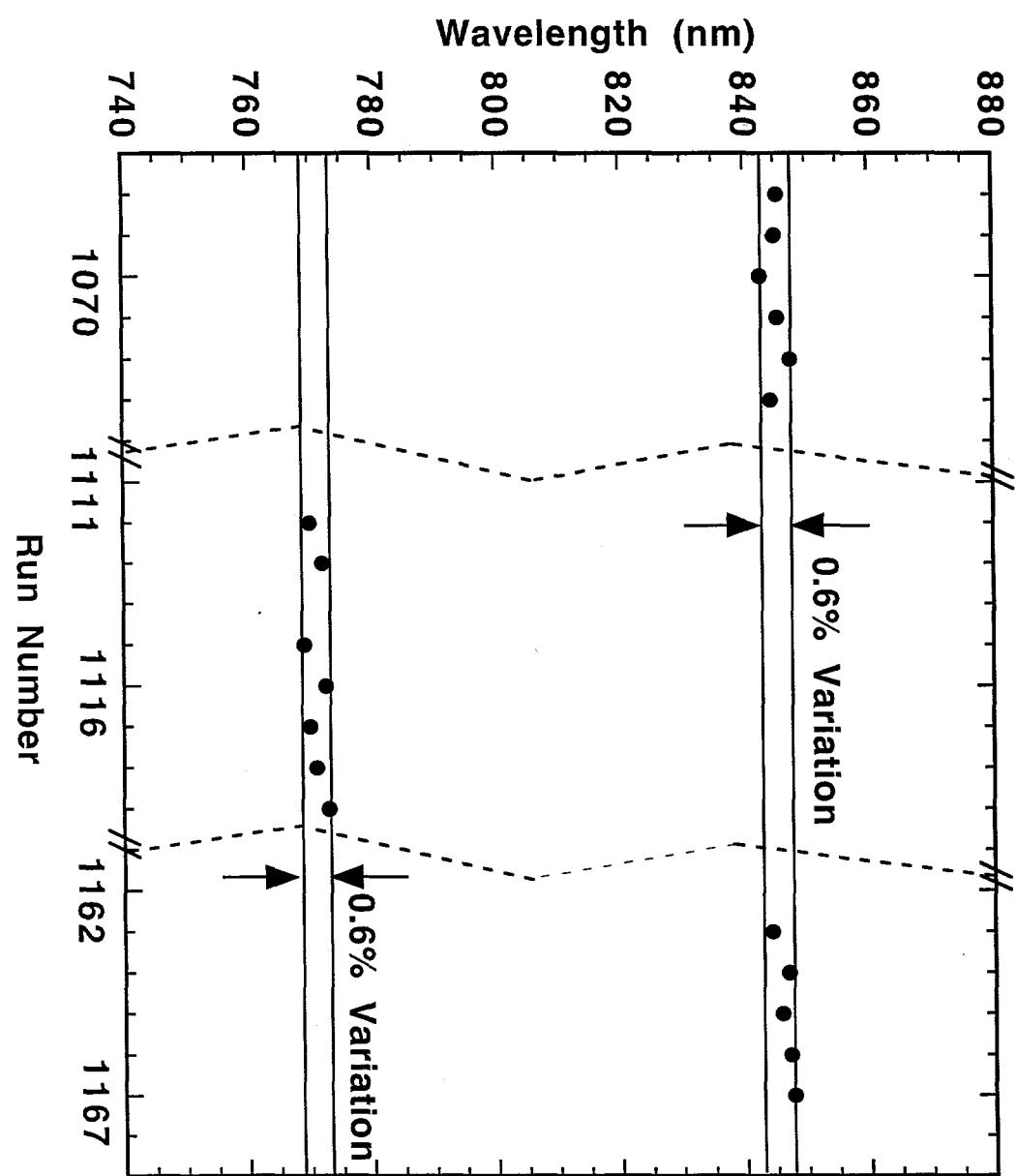


Fig. 3