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Many-body Effects in a Semiconductor Microcavity Laser: Experiment and Theory

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Abstract

Many-body effects are observed in the threshold properties of selectively oxidized vertical-cavity surface-emitting lasers. These microcavity lasers represent the state-of-the-art in low threshold semiconductor injection lasers.

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Semiconductor microcavity lasers such as vertical cavity surface emitting lasers (VCSELs) are well suited for a number of important optoelectronics technologies such as data communication, optical data storage, laser printing and optical computing. Many of these technologies require high efficiency and ultra-low threshold semiconductor lasers with well understood threshold properties. In this paper, we describe a study of the underlying physical mechanisms governing the threshold properties of a VCSEL. In particular, we evaluate the mechanisms that effect the threshold properties as a function of emission wavelength . Other important issues, such as the dependence of the threshold properties on microcavity dimensions will be discussed.

We experimentally evaluate near-IR and visible VCSELs that have been defined by selective oxidation. The ability to define ultra-small (1-5 μm diameter) lasers with this process has recently enabled record low threshold currents and voltages [1, 2] and has led to a regime in which the intrinsic properties of the laser threshold are more accessible. We have measured the threshold current and threshold voltage of different size oxidized VCSELs across a 2 inch wafer. Due to non-uniformities in the materials growth, the cavity mode of the lasers shifts across the wafer which enables us to evaluate the threshold properties of the VCSELs at different emission wavelengths where the alignment of the peak gain and cavity mode is varied.

A microscopic laser theory based on the semiconductor-Bloch equations is used to analyze experimental results [3]. With this theory, bandstructure, band filling and many-body effects are treated in a consistent manner to determine the gain spectrum. The theory is anchored by comparison with experimental results. In Figure 1, we show threshold current density dependence on emission wavelength for a near-IR VCSEL with an InGaAs quantum well active region. Comparison of the experimental data (points) and the theory (solid curve) shows that the wavelength dependence of the threshold current density for a VCSEL can be accurately described by the microscopic theory. In Figure 2, we show the intrinsic bias voltages (points) for the same devices in which we have measured and subtracted out the series resistance contribution to the threshold voltage. The microscopic theory not only correctly predicts the voltage for a wide range of lasing wavelengths, but also indicates the importance of the many-body effects.

Results similar to those shown in Figure 1 and 2 will be presented for both near-infrared and AlGaInP based visible VCSELs. The ability to fabricate lasers with ultra-small, well-defined dimensions by selective oxidation enables us to extend our study to include the effects of the microcavity dimensions on device performance. As an example, in Figure 3 we show the threshold current density dependence on device area at the wavelength of minimum threshold current, showing a definite increase in threshold current density as the device size is reduced. This results in a redistribution of the contributions from many-body effects such as bandgap renormalization and Coulomb enhancement, and details of this analysis will be presented. Thus, the degrees of freedom afforded by our ability to fabricate devices with a range of gain structures and microcavity geometries allows us to perform a detailed parametric study of the above effects and their contributions to laser behavior.

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References

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Figure Captions

Figure 1: Dependence of threshold current density of InGaAs near-IR VCSELs on emission wavelength. The squares represent the experimental data measured from selectively oxidized VCSELs and the solid line is the result from the microscopic laser theory.

Figure 2: Dependence of intrinsic threshold voltage of InGaAs-GaAs near IR VCSELs on emission wavelength. The squares represent the experimentally measured threshold voltage minus the series resistance at threshold. The solid and dashed curves are the theoretical results with and without the many body contributions, respectively. The dotted line represents the photon energy at a given emission wavelength.

Figure 3: Dependence of the threshold current density of selectively oxidized AlGaInP-GaInP visible VCSELs on device area. The dashed line is a guide to the eye.

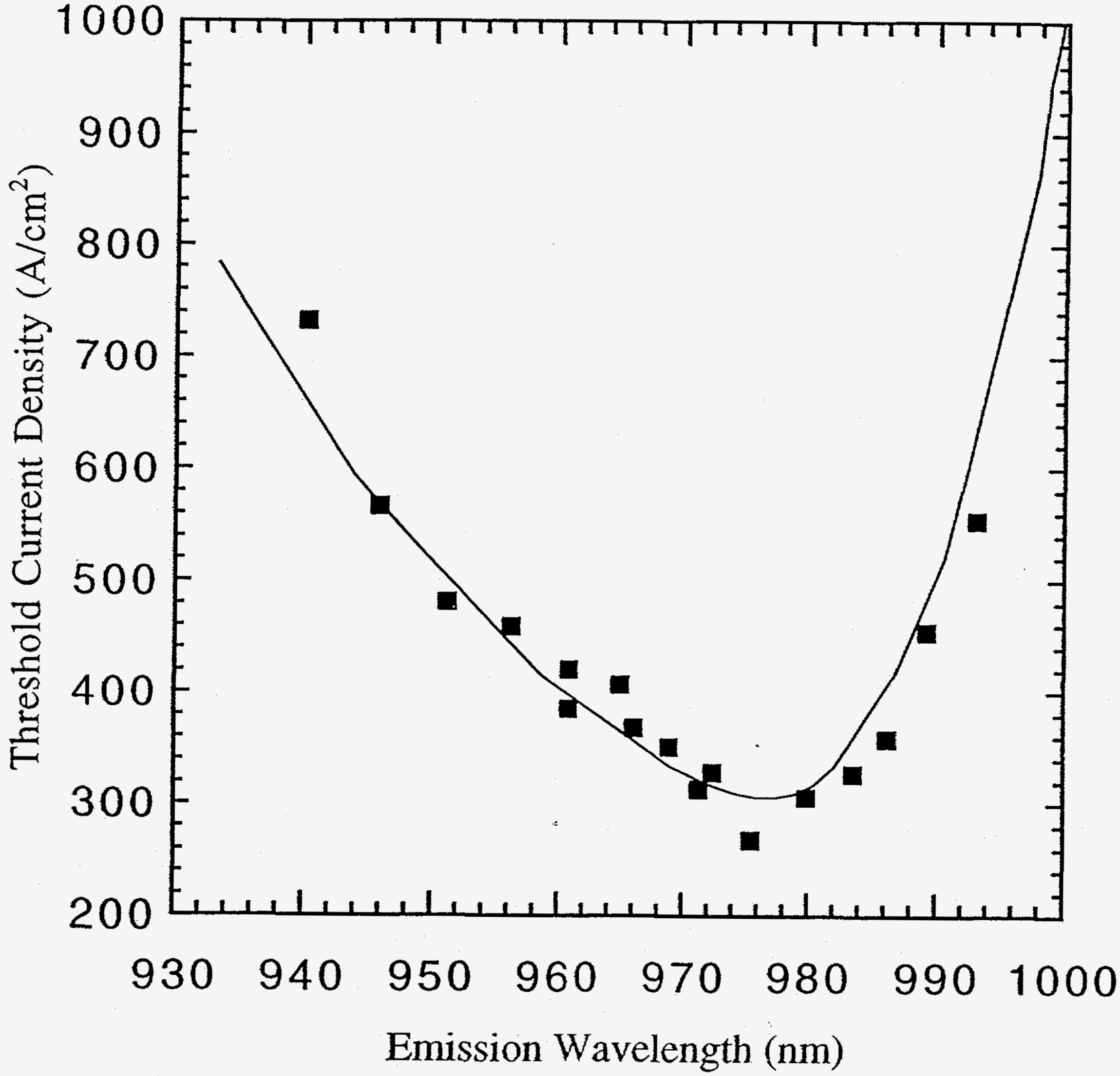

Fig. 1, Crawford et. al.

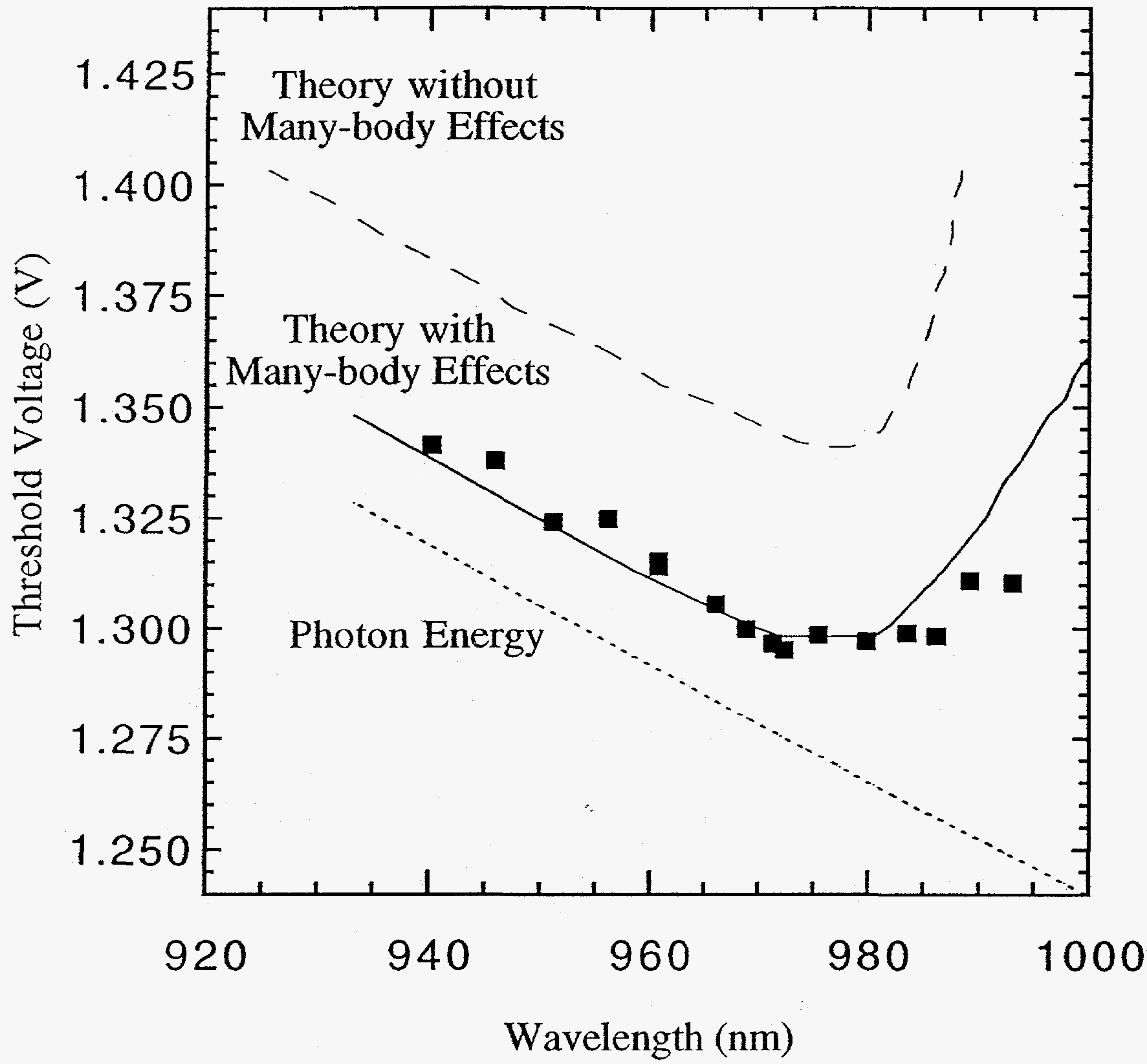

Fig. 2, Crawford et. al.

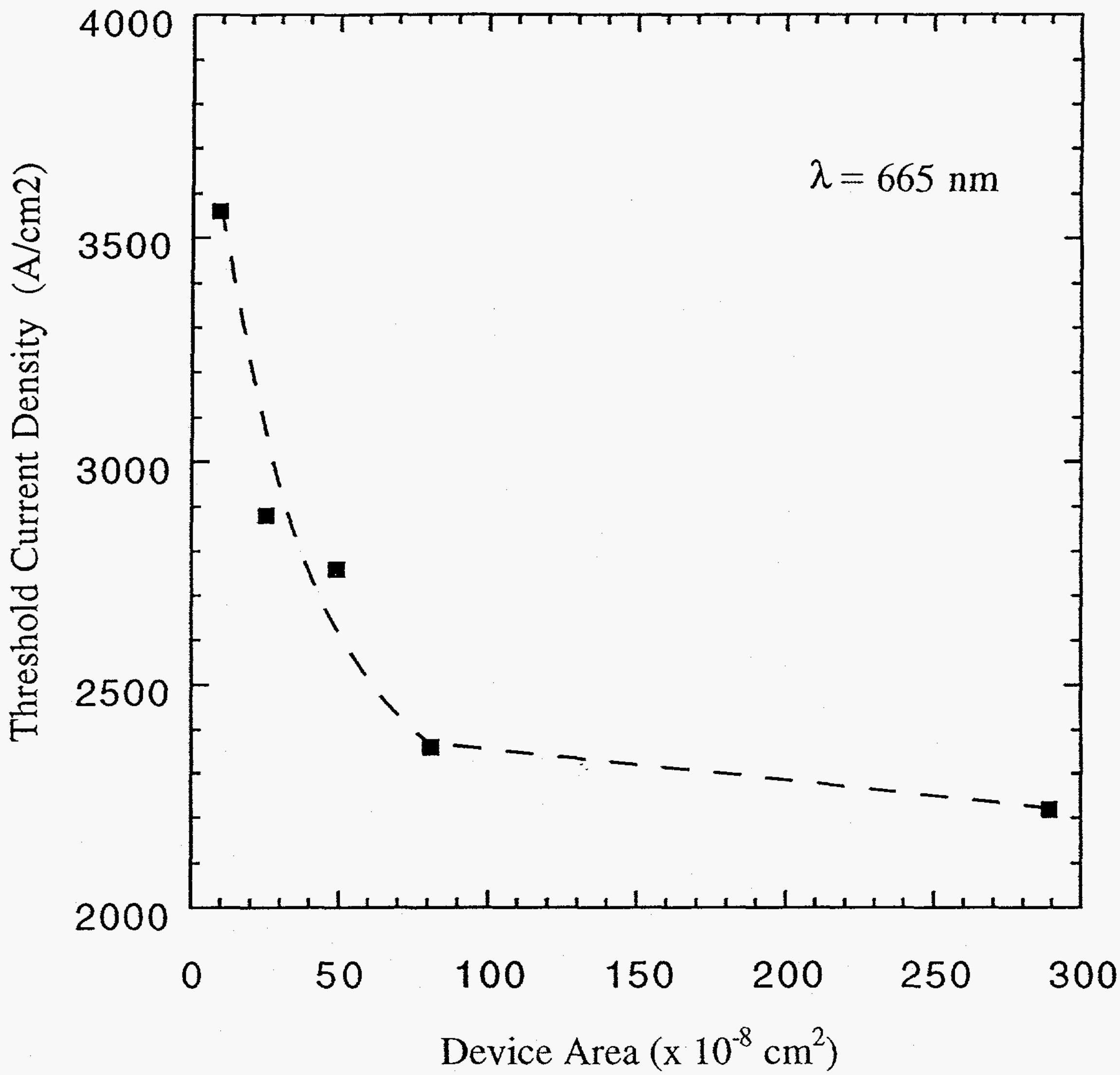

Fig. 3, Crawford, et. al.