Semiconductor Microlasers and Their Applications

BY R.E. SLUSHER

Advances in semiconductor materials growth and processing have resulted in major progress toward semiconductor microlasers with ultra-low thresholds and dimensions approaching a wavelength of the emitted light. These small dimensions and low operating powers may result in large, dense arrays of light sources operating at wavelengths from the near infrared well into the visible. The materials being used are InGaAs/InGaAsP in the wavelength range from 1.5-1 μm and the GaAs/AlGaAs for wavelengths near 0.8 μm. Arrays of these near infrared microlasers may be useful for high density, high speed optical interconnects down to the chip-to-chip level in computers or as high power phased arrays. There is also progress in visible microlasers using the InGaP/InAlGaP system and there is hope that the blue/green emitting II-VI compounds will improve in quality until they reach the regime of interest for microlasers. For many applications including displays, the sensitivity of the eye to wavelengths less than 670 nm makes arrays of visible microlasers especially interesting.

From a basic physics viewpoint, these small, low power lasers offer the simplicity of a single optical mode of the electromagnetic field that can, in principle, be largely isolated from the rest of the universe. This isolated mode can change the nature of the laser threshold[1,2] and can also allow the control of the quantum statistics of the light output.[3] The simplicity of a single mode may make it easier to study the dynamics of the dense, non-equilibrium electron-hole gas that typically is associated with semiconductor lasers. Many low dimensionality gain media for microlasers, including quantum wires and dots, remain largely unexplored. Finally, surfaces and interfaces play a major role in many microlasers and remain an important topic for basic microlaser research.

How Small Can A Microlaser Be?

Ideally, a semiconductor microlaser should be the optical equivalent of the single mode superconducting cavities used in the microwave region to achieve single atom masers.[4] The dimensions of an ideal cubic microresonator filled with a semiconductor should be λ/2n, where λ is the resonant wavelength and n is the index of refraction of the semiconductor. For example, for a wavelength of 1.5 μm and a typical semiconductor refractive index of n=3, the ideal dielectric microresonator is only 0.25 μm on a side. This ideal microresonator dimension limit can be relaxed in practice because the optical emission from the active medium in the cavity typically extends over a spectral range of only 5-10% of the central frequency. In this case, the cavity volume can be roughly 10 times larger than a cubic half-wavelength and still result in only one mode in the spectral region for optical emission. However, even at dimensions of the order of a micron, fabrication of these microcavities challenges the present processing techniques, especially when one realizes that non-uniformities of only a small fraction of λ/n will limit the Q of the cavity. The cavity Q is 2π times the number of optical cycles required for the cavity to lose 1/e of its energy due to radiative or nonradiative losses. Q values greater than 100, corresponding to effective cavity mirror reflectivities greater than 98%, are often required for microlasers since the small gain inherent in these microstructures requires high Q to achieve lasing at low threshold powers.

Several examples of semiconductor microlaser resonators are shown in Figure 1. A simple Fabry-Perot with a λ/n spacing between two distributed Bragg mirrors is shown in Figure 1(a). The mirrors for this structure are based on paired quarterwave semiconductor layers deposited by molecular beam epitaxy (MBE)[5] or organo-metallic chemical vapor deposition (OMCVD). For pairs of AlAs and $Al_xGa_{x-1}As$, where the difference in index is near 0.2, 15 pairs result in a mirror reflectivity near 98%. The gain medium in these structures is often one or several quantum wells of GaAs placed at the peak of the resonant mode electric field in the center of the λ/n layer. Selective etching of the mirror layers allows the spectacular scanning electron micrographs of these vertical cavity surface emitting lasers (VCSELs) shown in Figure 2. A major landmark in the microlaser field was achieved by Iga and his collaborators[6] in 1988 when they demonstrated

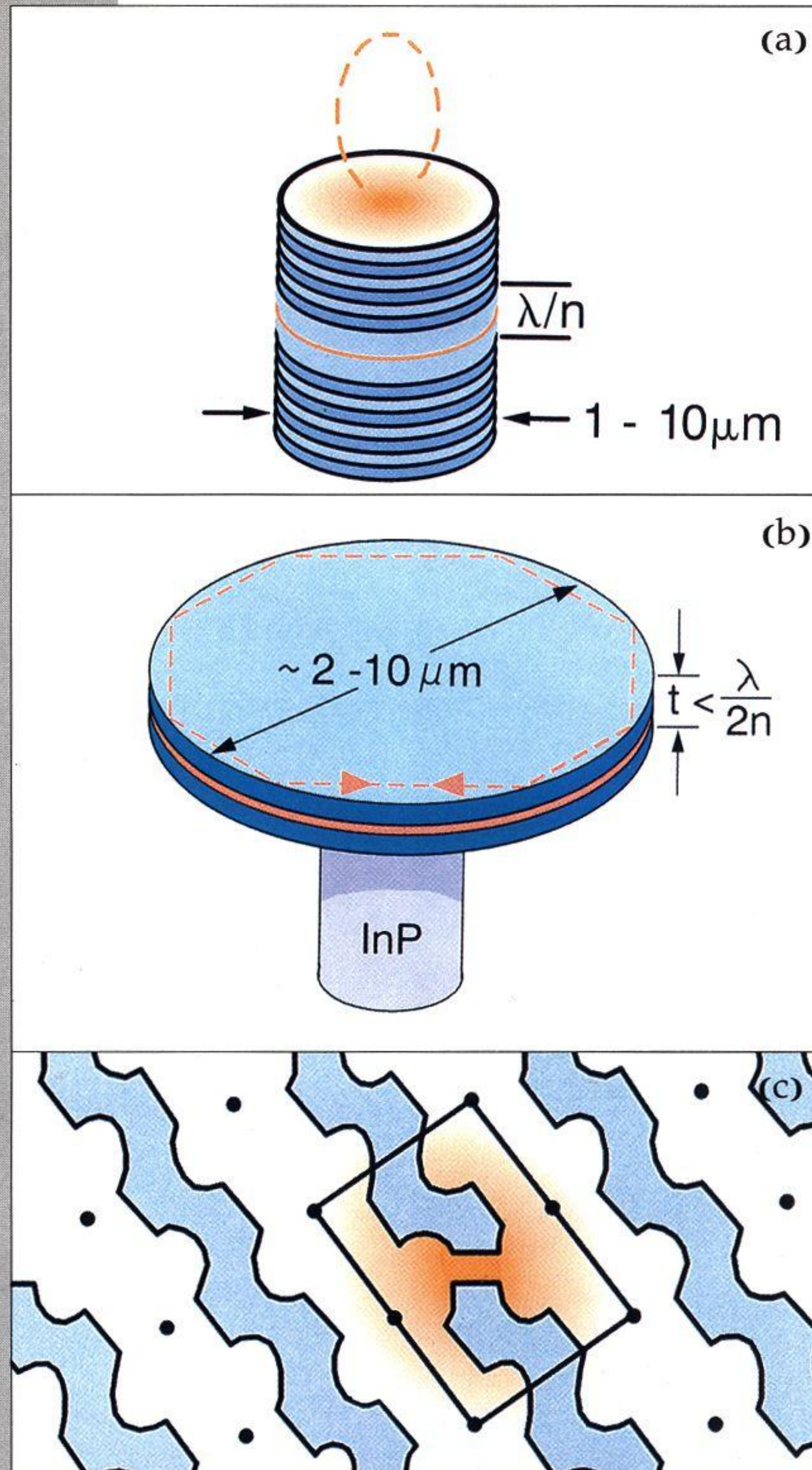

Figure 1. Semiconductor microlaser structures are shown schematically for (a) a vertical Fabry-Perot microcavity with distributed Bragg mirrors separated by a L/n spacer containing the gain material shown as a red line, (b) a microdisk whispering-gallery mode structure with the gain material shown as a red layer in the plane of the disk, and (c) a local acceptor mode in a photonic bandgap dielectric array shown here in cross-section. Emission from the vertical cavity in (a) is dominantly into a Gaussian mode indicated by the dashed red line. The gain region in microdisk is typically an InGaAs quantum well enclosed by InGaAsP barriers. The whispering-gallery mode Q is high due to total internal reflection indicated schematically by the dashed red rays in (b). The local mode around the acceptor state in the photonic bandgap material is indicated by the red glow in (c).

continuous, room temperature operation of an electrically pumped VCSEL. The high efficiencies, high densities, and planar integration required for most applications can only be achieved with electrical pumping. A number of further important advances followed in the late 1980s[7-9] so that efficient operation at room temperature is now achieved.

Typical dimensions for these tiny Fabry-Perots are 5-10 μm in diameter and several microns in height. They have only one high Q mode within the gain spectral bandwidth, but there are other modes in the plane of the λ/n spacer. Spontaneous emission from the gain region occurs with the appropriate spectral weighting factor into any of these modes. The fraction β of the spontaneous emission that is discharged into the dominant lasing mode at low excitation is often used to characterize how closely the structure approaches the ideal case of a single mode. For the Fabry-Perot microresonators, the lateral modes in the plane of the gain region can reduce β to the range between 0.001 and 0.1.[10]

As β approaches one, the rate of spontaneous emission $1/\tau_s$ can be dramatically decreased or enhanced depending on the position of the emitter in the microcavity. For example, a small quantum dot, 10-20 nm on a side, could be used as an emitter and placed near the center of the cavity at the maximum field of a single high Q mode where the spontaneous emission rate from excitons in the dot would be strongly enhanced. This could lead to a fast response light emitting diode (LED). If the quantum dot is moved to a position near a mirror where the field is weak, the spontaneous emission rate will be sharply reduced. Note that the rate at which radiation enters the lasing mode is proportional to β/τ_s. This ratio can remain nearly constant if the size of a microcavity is decreased toward the single mode limit, since both τ_s and β increase as the number of modes decreases. Clever cavity and emitter designs can be used to optimize β and tailor τ_s for particular applications.[11]

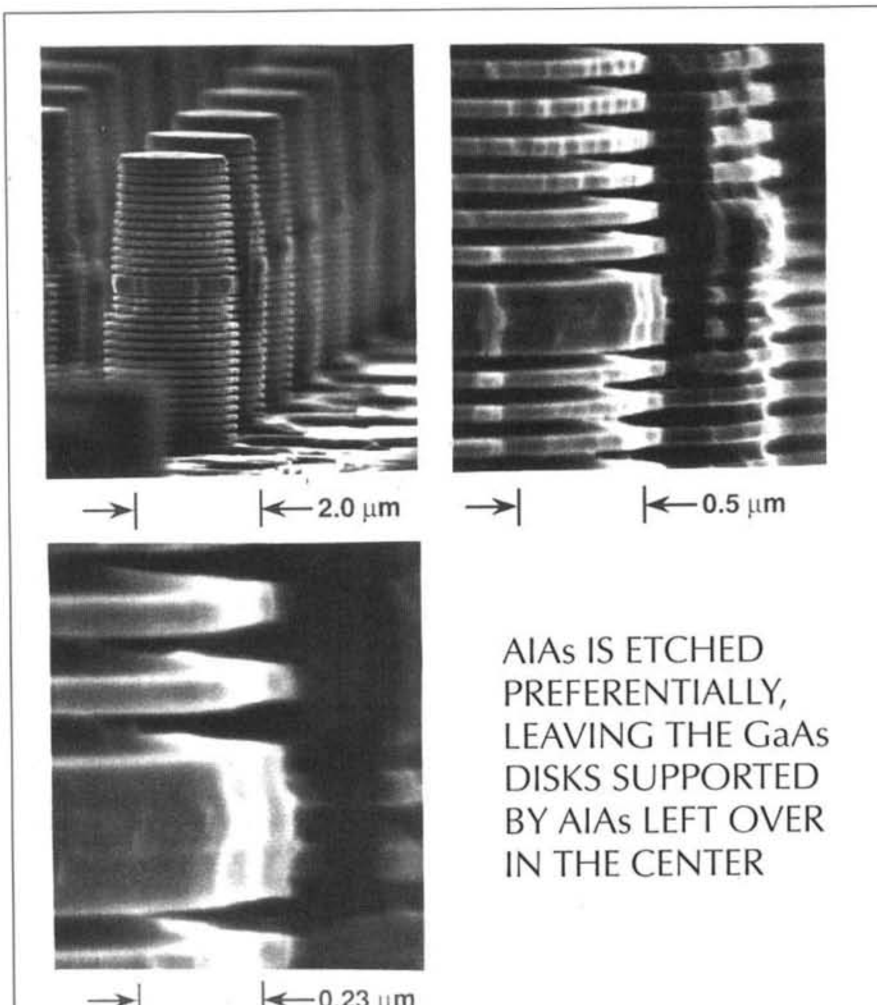

FIGURE 2. SCANNING ELECTRON MICROGRAPHS OF VERTICAL CAVITY SURFACE EMITTING LASERS ARE SHOWN ETCHED TO REVEAL THE DISTRIBUTED BRAGG MIRRORS ABOVE AND BELOW THE EMITTING GaAs REGION. LASING IN THESE STRUCTURES IS IN THE VERTICAL DIRECTION, BETWEEN THE TWO BRAGG MIRRORS.

Semiconducting microdisks[12] shown in Figure 1(b) form high Q resonators without requiring the multiple layer dielectric mirrors of the Fabry-Perot structure. These microdisks have volumes of less than a cubic wavelength, several hundred times smaller than semiconductor ring layers[13,14,15] with volumes in the range near 100 μm. The dominant resonant mode is called a whispering-gallery mode. It propagates around the edge of the disk with very low loss due to total internal reflection at the boundary between the high index semiconductor and its surrounding medium, either air or glass. This high index contrast also serves to isolate emitters in the optically thin disk from external modes propagating orthogonally through the disk. The Q for these microdisks increases exponentially with radius and exceeds 100 for radii greater than 1 μm. The emission from the ideal whispering-gallery mode is into a narrow range of angles around the plane of the disk. Coupling into a specific direction, either vertically or in the plane of the disk, must be accomplished with additional coupling structures.[16]

An electrically pumped microdisk laser[17] can be formed, as shown in Figure 3. The microdisk in the figure is 0.25 μm thick, less than a half-wavelength in the semiconductor, and is composed of six 100Å wide InGaAs quantum wells with InGaAsP barriers. The disk is supported below by a n-type InP post. The pin structure is completed by a p-type InP post and a metallic contact pad. An advantage of the disk geometry is the strong overlap of the gain material and the resonant mode, since the mode is strongly confined to the semiconductor disk and the gain material nearly fills the plane of the disk. Overlap factors as large as 0.5 are obtained for the microdisks, while the VCSEL overlap factors are in the range near 0.01 due to the small overlap of the gain region with the vertical mode that extends a considerable distance into the distributed Bragg mirrors. However, unless the disk radius is less than 1 μm or the gain and pumping can be confined to the outer edge of the disk, there is a loss in efficiency for the microdisk due to emission from the central region of the disk.

Beta factors for the microdisk laser are expected to be from 0.1-0.3 for disk diameters near 2 μm. Low Q modes in the disk interior that overlap the emission spectrum compete with the lasing mode for spontaneous emission. Weak interaction of the emitters with modes outside the disk and the degeneracy of the two possible counter-propagating modes at the disk edge also degrade the β value. However, due to the exponential increase in the whispering-gallery mode Q with radius and the wide spectral spacing of these modes, there is only one dominant mode within the emission spectrum for 2 μm diameter InGaAs disks.

Complete isolation of a single mode of the field can, in principle, be obtained in a photonic bandgap material,[18] as shown schematically in Figure 1(c). A three-dimensional periodic dielectric array, shown in cross-section, forms a photonic bandgap where no modes of the electromagnetic field can propagate. A single mode is then introduced into the structure by a dielectric defect where a local "acceptor" or "donor" mode is formed.[19] Periodic dielectric arrays can be formed by etching patterns into a semiconductor and the defect state can be formed by microprocessing techniques. This approach to semiconductor microcavities promises greater control of spontaneous emission processes and a closer approach to the ideal β=1 limit. However, fabricating these structures is difficult and no laser structures of this form have been demonstrated to date.

It is interesting to compare the semiconductor microresonators shown in Figure 1 with semiconductor lasers in general use today—for example, in a compact disk player or a fiber optic communication system. Typical semiconductor "stripe" lasers are nearly 200 μm in length and the lateral mode area is approximately a square micron. This results in nearly 100 longitudinal modes within the spectral bandwidth of the laser gain medium and a β value between 10^{-4} and 10^{-5}. In other words, several hundred microlasers will fit into the "grain of salt" dimensions of semiconductor lasers in use today. Since the gain-length product is relatively large in the present lasers, they do not require high reflectivities. A cleaved face with a reflectivity of only 30% is often sufficient, unless very low thresholds are required.

How Low Can A Microlaser Threshold Be?

Semiconductor laser thresholds at present tend to scale with the volume of the active region. Much of the threshold reduction obtained by using quantum wells instead of thicker gain material is simply a matter of reducing the gain volume. The much smaller optically active region in a microlaser promises correspondingly lower thresholds. We can hope to reduce microlaser threshold currents to the 1-10 μA regime. Of course, the small gain-length product for microlasers means that much higher reflectivities, often above 99%, are required. The record for VCSELs at room temperature is 700 μA[20] at a wavelength of 0.8 μm; for room temperature microdisk lasers, it is 950 μA at a wavelength of 1.5 μm.[17] At lower temperatures where the emission spectrum narrows and the peak gain increases by as much as a factor of 50, the microlaser thresholds are down in the tens of microwatts range. These thresholds are roughly consistent with the semiconductor electron-hole recombination gain mechanism, the gain volume, and the resonator Q values. The room temperature thresholds for microlasers achieved to date are not as low as the 500 μA thresholds that can

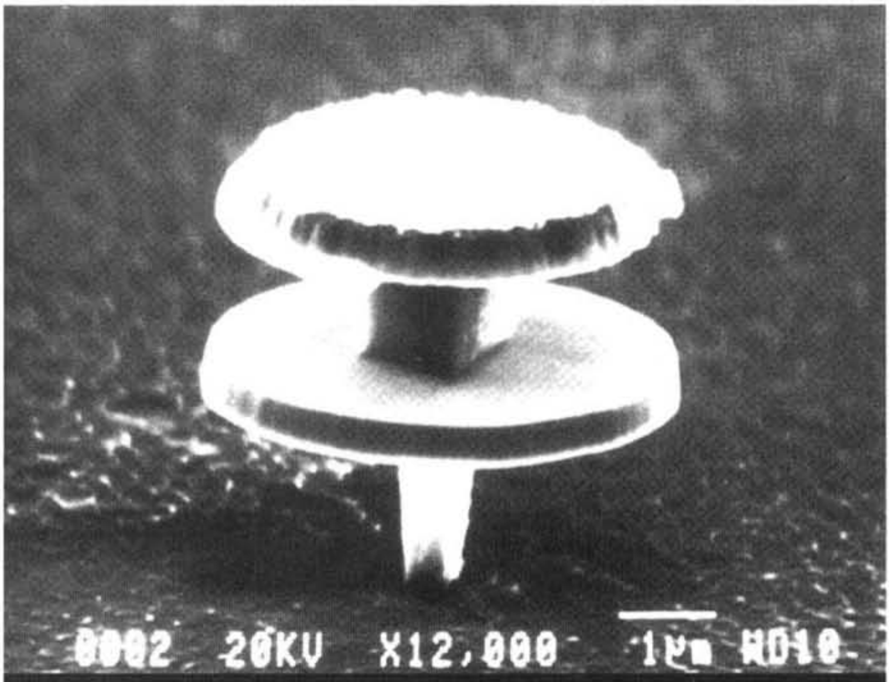

FIGURE 3. SCANNING ELECTRON MICROGRAPH OF AN ELECTRICALLY PUMPED MICRODISK LASER. THE 5 μM DIAMETER DISK IS SUPPORTED ON AN N-TYPE INP POST AND CONTACTED ABOVE BY A P-TYPE INP POST AND A METALLIC DISK CONTACT.

be achieved with the larger stripe lasers using high reflectivity mirrors. Higher Qs, gain-length products, and efficiencies must be achieved for microlasers to fulfill their promise of ultra low thresholds. Before speculating on where the microlaser thresholds will be in 10 years, it is good to consider some of the basic physics expected for microcavity lasers.

An ideal microcavity with $\beta=1$ is expected to emit all photons, either spontaneous or stimulated into the "lasing" mode. In this limit, the light output into the single mode simply increases nearly linearly with pump power without the typical sharp increase at a threshold exhibited in lasers with $\beta<1$. Kobayashi *et al.*[1] and DeMartini *et al.*[2] have termed this limiting behavior a "thresholdless" or "zero-threshold" laser. What exactly do we mean by laser threshold? Several definitions[11] lead to interesting insights into the threshold region for a microlaser. For example, one can define the threshold at the point where the stimulated emission rate equals the spontaneous emission rate or where the average number of photons in the lasing mode is unity. At pumping powers well below this point, the light output statistics are clearly similar to those of thermal light and above this point they approach coherent state statistics. In a low beta laser, there is a strong analogy of the laser threshold with a second order phase transition[21] between these two light output states. This transition can be quantified by studying the ratio of the square of the variance of light amplitude fluctuations divided by the mean amplitude. This ratio is unity for the Poisson statistics that approximately describes both thermal light and the coherent state. In a low β laser, there is a large increase in the ratio of the variance to the mean near threshold, characteristic of a phase transition. Recent simulations[22] using quantum rate equations for a microlaser indicate that this fluctuation peak is very broad and weak in the limit where $\beta=1$ and there is no absorption at low pump powers. Deviations from this limit toward more realistic microlasers brings back the fluctuation peak; however, it can be considerably broader and weaker than in very low β lasers. Several initial experiments[1,23] have addressed the microlaser threshold issue, but much work remains to be done.

Semiconductors have the advantage of very high internal quantum efficiency for gain media in microlasers. Recent experiments[24] have measured internal quantum efficiencies for GaAs as high as 99.7%. At low pumping powers, a semiconductor absorbs and reemits light at the microcavity resonance frequency. In effect, a coupled oscillator system is formed between the cavity mode and the semiconductor excitation. The semiconductor excitation is well characterized as an exciton at low pumping powers. The modes of this coupled exciton-cavity system are expected to split into a doublet with a spacing proportional to the strength of the interaction. This splitting has recently been observed[25] for approximately 10^4 excitons in a Fabry-Perot microcavity. This splitting has previously been observed in atomic systems and can be explained as a cavity quantum electrodynamic (QED) effect.[26] These efficient reabsorption effects must be taken into account when measuring spontaneous emission rates in cavities. They allow one to speculate about new regimes in microlasers, such as lasing without inversion at β values very close to one.[11]

As the pump power is increased toward the threshold region, the electron and hole concentrations become so large that excitons are no longer a good description of the system unless the electron and hole are very tightly bound, as in the higher bandgap or lower dimensionality semiconductors. In GaAs and InGaAs at room temperature, the electron-hole gas is best described as a dense, nonequilibrium system.[27] Spatial and spectral hole burning[27] may play important roles in these microlasers. Recently, the understanding of the temperature dependence of semiconductor laser thresholds has undergone a revolution. Subthreshold fluctuations appear as a major contributor to the large increases in threshold powers found near and above room temperature.[28] The reduced mode density in microlasers may reduce these lossy subthreshold fluctuations. There is much work to be done to improve our modeling of semiconductor lasers.

There is still a great deal of hope for reducing the thresholds of microlasers to the region near 10 microwatts at room temperature. In part, this will rely on fabricating very high Q microstructures. Improved heat sinking and reduced resistive losses must be achieved. Also important is the minimization of gain reduction due to surfaces and interfaces. For example, as the diameter of VCSELs is reduced below 5 μm, the threshold downscaling with gain volume is lost due to high surface recombination velocities at the GaAs quantum well boundaries.

Microlaser Applications

Potential applications of microlasers include laser printers, read/write sources for optical memories, displays, optical interconnects, and high power phased arrays. Arrays of low power microlasers could speed printers and optical memories. The requirement of visible microlasers with vertical emission for displays has stimulated recent work on visible VCSELs. Optical interconnects provide a good example of the possible utility of microlasers. Microelectronic systems have advanced to the point where their performance is limited by interconnects between boards and multichip modules, and even between individual chips.

There are many advantages for optical interconnects in complex high speed electronic systems.[29,30] Optical interconnects offer lower crosstalk, high interconnect density, lower noise, and—most important—reduced impedance mismatch when compared with electrical interconnects. Optical interconnects will probably be the preference for interconnect distances longer than a few millimeters. Of course, cost is the limiting factor at present. Efficient, low power light sources will be a key to the success of optical interconnects. Data rates in the range from 1-10 Gbs are of interest for the immediate future. Coupling 1 mW of power into an optic fiber allows logic level voltages to be generated by a simple, low cost optical receiver. Higher densities can be achieved by decreasing the coupled power to the hundred microampere range at the expense of receiver complexity. Microlaser arrays are approaching the speeds, densities, and powers required for this important optical interconnect technology, but have not yet demonstrated all of the many system requirements, including reliability and cost.

Photonics applications in general require devices and couplers that can be cheaply produced at high densities and high efficiencies. Semiconductor microlasers do have promise for being cheap and high density because of their small size and low power consumption. Wafer scale testing is another advantage for microlasers. The cleaving and individual handling of each laser typically required today for stripe lasers is not necessary. An entire wafer of microlaser arrays, like the one shown in Figure 4, can be tested in a short time with an appropriate multiprobe configuration. This can result in higher yields and lower cost per element. Efficient coupling of symmetric mode patterns and the stable single mode operation of microlasers are also important advantages when compared with the larger stripe lasers.

MOVING FROM PROMISE TO REALITY

Several problems remain to be solved before widespread microlaser applications will become a reality. Heating is a major concern at the present threshold levels in the milliampere regime. If the thresholds are reduced, heat sinking is improved, and parasitic resistances are reduced, then this problem can be solved. A second area for improvement is efficiency. High efficiency means both the "wall plug" efficiency and the optical coupling efficiency. It is hoped that both of these efficiencies will reach the 50% range. It is often important for the photonics to be compatible or integrable with VLSI silicon circuitry and this has been a problem for III-V semiconductors. Growth of III-V materials on Si results in defects at the interface between the materials that eventually cause device failure. Growth and fabrication of III-V semiconductors devices and circuits are not as cheap as one would hope. Semiconducting organic polymers[31] are a very promising new direction since they can be cheaply spun on Si substrates. However, the polymer electroluminescent efficiencies and aging effects need to be improved before widespread applications of conducting polymers can be realized.

Planar integration of electrically pumped VCSELs has been progressing at a good pace. An important parameter for most applications is the wall plug efficiency,

$$\eta_w = \eta_d (I_o - I_t) V_g / I_o (V_g + I_o R) \qquad (1)$$

where η_d is the differential pump efficiency for light output, I_o is the operating pump current, I_t is the threshold current, V_g is the pin junction voltage at the operating current, and R is the series resistance. For present VCSELs, η_w is 8-10%. The goal is to reach the 20-50% range. Reduction of the threshold current and the series resistance in the mirrors both need to be achieved. New diode designs are being studied[32] to reduce the series resistance, as shown in Figure 5. These microlasers are fabricated in the GaAs/AlGaAs system using MBE growth of the mirror layers and an GaAs active layer. Current is forced to flow through a 10 µm diameter region where the gain defines the lateral extent of the vertical mode. Light is coupled out at the top into a symmetric Gaussian profile mode through a hole in the p-type ohmic contact. In Figure 5(a), the top contact is through the n-doped, MBE grown multi-layer mirror. It is the resistance of these mirror contacts that reduces the wall plug efficiency by increasing the total voltage across the device. The threshold voltage for the design in Figure 5(a) is near 3V. A design to reduce the series resistance is shown in Figure 5(b), where the top contact is through a p-doped conductive layer. A high reflectivity dielectric mirror has been evaporated onto the top of the struc-

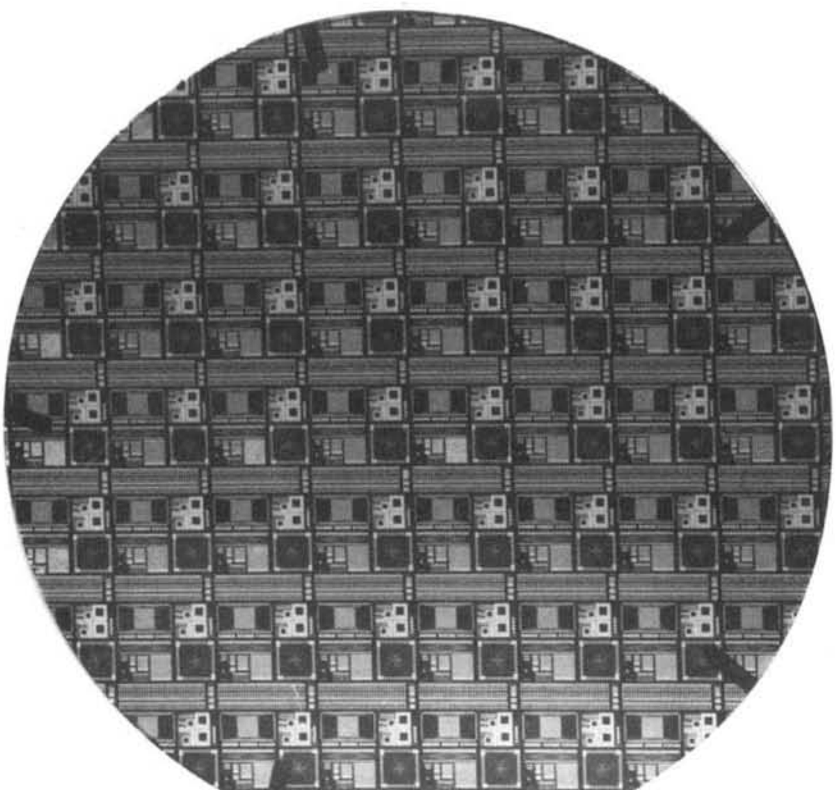

FIGURE 4. A TWO-INCH DIAMETER WAFER FILLED WITH ONE- AND TWO-DIMENSIONAL VCSEL ARRAYS. THE 1-D ARRAYS CONTAIN 64 VCSEL ELEMENTS AND THE 2-D ARRAYS INCLUDE 4×12 AND 32×64 ELEMENTS.

ture. The threshold voltage for this improved design is reduced to 1.7 V. Both of the structures in Figure 5 have current thresholds near 3 mA. It is hoped that the wall plug efficiencies can be significantly increased with designs of this type.

A major advantage of the VCSEL microlasers for a number of applications is the ability to fabricate large, dense two-dimensional arrays. Moderately large arrays are being studied. Individually addressable 32×32 arrays have been demonstrated by a group at Bellcore[33] and 8×18 arrays have been demonstrated by D. Vakshoori and coworkers at AT&T Bell Laboratories.[34] The Bellcore array is matrix addressable, requiring only 64 electrical contacts for individual addressing of each laser. The threshold currents in this 32×32 array are between 6-8 mA. Laser threshold currents for the 8×18 array from AT&T are all very near 4 mA, the threshold voltages are near 2.65 V, and the array does not exhibit any degradation after overdriving the lasers, *i.e.*, there is no current annealing. The VCSELs in the AT&T array each operate at a bit-rate of 450 Mbs, making the net potential throughput 65 Gbs. Operation for over 1,000 hours has been achieved without significant degradation in performance; however, complete reliability studies over a range of termperatures remain to be demonstrated. Each element of the array emits a symmetric Gaussian pattern with a relatively low divergence angle that allows efficient coupling into optical fibers or other low numerical aperture optics. One of the next steps in this array technology is to incorporate smart pixels at each microlaser position. Possible applications for these arrays include laser printers, optical memory read/write heads, 2-D optical scanners, and optical interconnects.

Coherently coupled VCSEL arrays have the potential to generate large power outputs, at least up to the one watt range. A large area laser or an array of unlocked lasers can also produce high powers, but the emission angle will be broad and difficult to focus. A narrow, focusable beam results when an array of many small elements is coherently phase locked. It may also be possible to electrically adjust the relative phasing across the array, resulting in a rapidly steerable beam over a broad angular range. A regularly spaced, coherently locked array produces a diffraction pattern in the far field similar to that of a two-dimensional grating. If the entire array is oscillating in the lowest order Gaussian mode, the output beam has a narrow central lobe with an angular width that varies inversely with the size of the array. Recently, 8×8 VCSEL arrays have been demonstrated with total power outputs from 0.5 W[35] to over 1 W.[36]

Visible light VCSELs have recently been demonstrated[37] with wavelengths between 670-630 nm. Previous operation of this type of microlaser was limited to wavelengths greater than 770 nm. The active region of the visible laser is MOCVD grown InGaP strained quantum wells with InAlGaP barriers. The distributed Bragg mirrors are formed from AlGaAs and InAlGaP. Only pulsed optical pumping at room temperature has been achieved to date. If these visible microlasers can be improved to work continuously as diodes, the many advantages of VCSEL arrays will make them attractive for numerous applications, including ultrafast

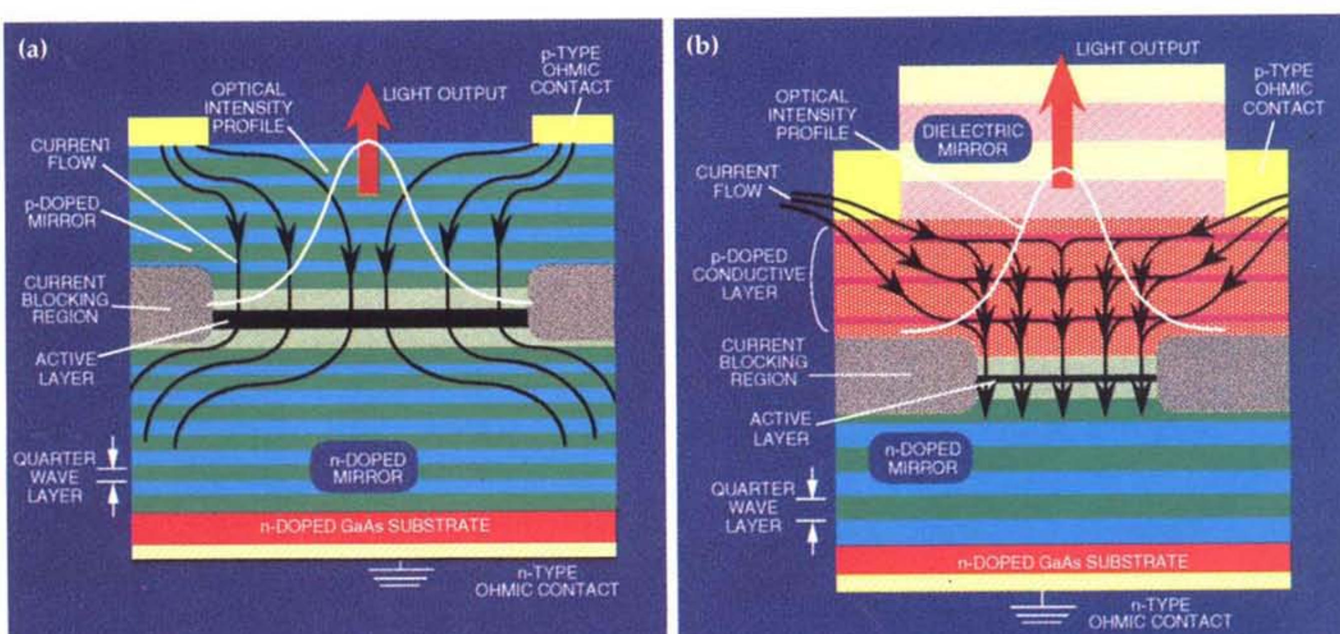

FIGURE 5. ELECTRICALLY PUMPED VCSEL DESIGNS FOR HIGH EFFICIENCY LIGHT OUTPUT. ELECTRICAL CONTACTS THROUGH BOTH MIRRORS IN (a) RESULTS IN A THRESHOLD CURRENT OF 3 MA AND A THRESHOLD VOLTAGE OF 3 V. REPLACING THE UPPER CONTACT WITH A CONDUCTING LAYER AND A DEPOSITED MIRROR, AS SHOWN IN (b), REDUCES THE THRESHOLD VOLTAGE TO 1.7 V DUE TO THE DECREASED SERIES RESISTANCE.

holographic memories, laser projection displays, plastic fiber-optics communication, and applications where HeNe lasers are used at present.

Whispering-gallery mode microlasers have a number of unique advantages for applications. The microdisk has an advantage in electrical pumping efficiency when compared with the VCSEL geometry, because the electrical contact is made through low resistance p and n contact posts instead of the relatively high resistance layered VCSEL mirror contacts. Recently microcylinders[38] have been made to lase at room temperature with thresholds in the 5 mA range. When compared with disks, the cylinders are easier to fabricate with planar contacts to the top electrode. In principle, couplers can be designed to couple light from a microdisk or microcylinder either vertically or horizontally. The key challenge for this type of microlaser is to accomplish this coupling with high efficiency. Initial experiments[16] show that tabs or gratings at the edge of the disk or cylinder can couple light out into a specific direction; however, efficient coupling has yet to be demonstrated. High index contrast waveguides formed by techniques similar to those used for the microdisks should allow bending interconnecting waveguides in distances of only a few wavelengths without significant bending losses. This is an important feature for complex, high density photonic circuits.

The world of very small, low power lasers is growing rapidly. New materials and new resonator structures promise even further advances toward ultra-low power microlasers. As the limit of a single mode of the field is approached, interesting threshold fluctuations and squeezed light sources are topics for basic research. In the applied area, the low powers, small dimensions, and large microlaser arrays offer many opportunities. Several companies, including Photonics Research Inc. and AT&T, are searching for microlaser markets and systems applications. It is hoped that there will be significant commercial applications within the next five years.

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