Microlens Integration with Diode Lasers and Coherent Phase Locking of Laser Arrays

Z.L. Liau, V. Diadiuk, and J.N. Walpole

■ Novel submillimeter-size lenses have been fabricated in compound semiconductor substrates by mesa etching and heat treatment. These precision large-numerical-aperture microlenses are well suited for diode lasers and laser arrays in miniaturized systems. A laser array has been efficiently coupled to an external cavity by a microlens array to achieve coherent phase locking. As part of a semiconductor substrate, these microlenses have the potential for monolithic integration with diode lasers and detectors to create reliable integrated optoelectronic systems.

Semiconductor diode lasers, because of their small size, generally have large beam divergences on the order of several tens of degrees. This divergence places a stringent requirement on the lenses needed for beam collimation. The lenses must have an aperture that is comparable to focal length (i.e., a large numerical aperture), similar to that of a microscope objective. Such lenses have a small focusing depth of only a few micrometers, and are also difficult to make. Conventional lenses, because of their size and expense, are cumbersome and incompatible with diode lasers or laser arrays in miniaturized system applications. For these reasons, a strong research interest has developed in arrays of submillimeter-size microlenses. Techniques such as ion-beam etching, ion exchange, photochemical etching, micromachining, molding, and assembly of graded-index rods have been employed to form refractive microlens arrays [1, 2]. Diffractive microlenses with multilevel Fresnel zones have also been widely investigated [3–5]. Highly efficient f/1 microlenses (i.e., a focal-length-to-aperture ratio equal to 1), however, have not been obtained by these techniques. In general, the f/1 lenses have high aspect ratios (i.e., thick lenses) and require high-refractive-index lens material with an accurate lens profile. A greater deviation from the planarity assumed in the diffractive lens design also exists.

Since 1986 we have developed a new technique in which a heat treatment (mass transport) smooths etched multistep mesas and forms high-quality precision microlenses [6, 7]. Monolithic arrays of f/1 microlenses made in compound semiconductors successfully collimated the output of a diode laser array in an experiment in which the laser array was coherently phase locked in an external cavity [8]. Monolithic integration of microlenses with diode lasers was also demonstrated [9]. This integration provides a permanent lens-laser alignment that removes a major practical problem of mechanical and thermal instabilities. In addition, the integrated devices are produced lithographically in a batch process that is potentially more economical.

Microlens integration is still in an early stage of development. Its ultimate success depends largely on a better understanding of mass transport, a relatively new material technique that involves high-temperature treatment under near-equilibrium conditions. Some initial studies of mass transport have been carried out, and a basic model has been developed [10]. Current efforts are directed to the investigation and prevention


(a)

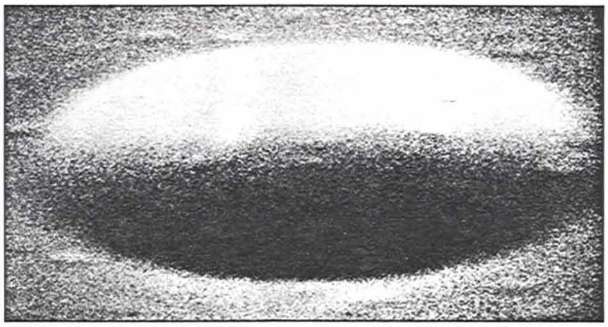
(b)

FIGURE 1. (a) Etched multistep mesa in a GaP substrate, and (b) its smoothing to form a microlens. The smoothing is due to a surface-energy-induced atomic migration (mass transport) that occurs in a heat treatment at 1000°C.

of material degradation that can be caused by the heat treatment.

Microlens Fabrication

Microlenses are formed by smoothing multistep mesa structures that are etched in a semiconductor substrate, as illustrated in Figure 1. The smoothing occurs in a heat treatment and is a combined effect of the surface energy associated with the etched steps and the surface atomic mobility at elevated temperature.

The fabrication begins with the design of the lens profile. Lenses for the collimation of point sources have simple profiles that can be expressed in exact algebraic formulas easily derived from optical path-length considerations. In ray optics, such a lens collimates a point source to an exact parallel beam. Because of the wave nature of light, however, and the resulting diffraction from the finite lens aperture, some beam divergence always occurs and is inversely proportional to the lens aperture. For a given lens profile the multistep mesa structure is designed by application of a simple mass-conservation rule, by which each volume to be eroded in mass-transport smoothing is equal to the corresponding volume filled. The mesa structure is then formed in the semiconductor substrate by repeated applications of photolithography and chemical etching.

Figure 2 illustrates how mass transport is carried out in a furnace system with a hydrogen and phosphine flow [11]. Phosphine thermally decomposes into phosphorus vapor that suppresses the decomposition of the compound semiconductor (InP or GaP). The presence of

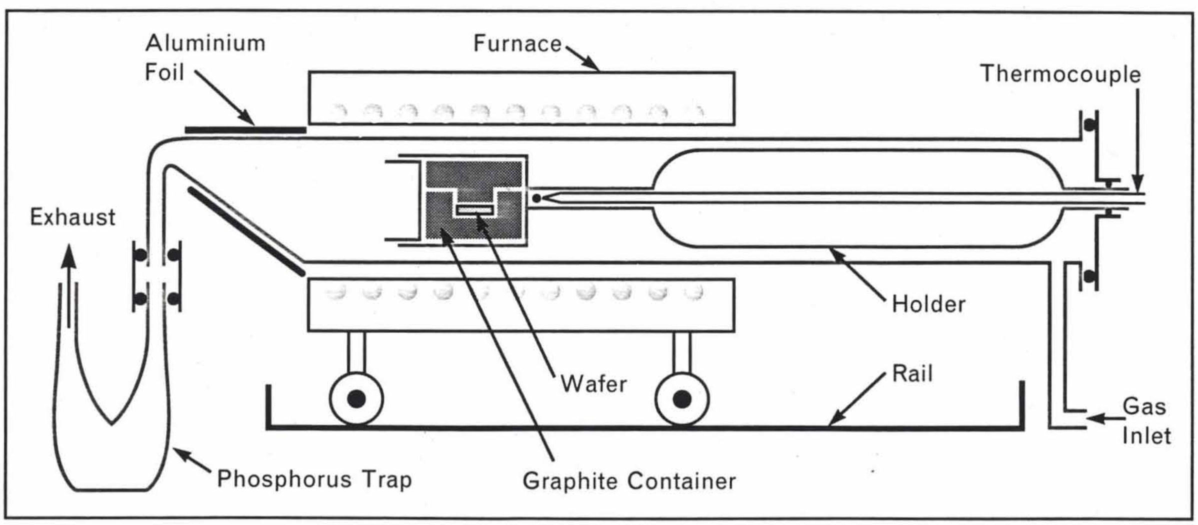

FIGURE 2. The furnace system specially designed for mass-transport processing of compound semiconductors. The gas flow, temperature distribution, and furnace movement were designed for high phosphorus vapor pressure along with minimum phosphine consumption and clean phosphorus disposition.

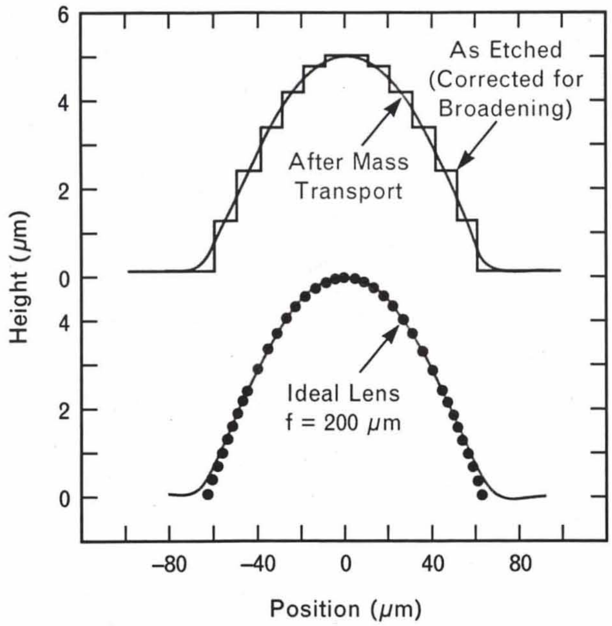

FIGURE 3. The profiles of the etched multistep mesa structure and the nearly ideal lens it formed after mass transport.

phosphorus vapor can result in phosphorus deposition in cooler regions, however, and the system has to be properly designed to prevent this problem. The wafer is further protected in a quartz/graphite container that prevents the slow evaporation of In or Ga. To make large-diameter microlenses, temperatures as high as 840°C for InP and 1000°C for GaP, and time as long as 80 hours, have been used to smooth wide mesa steps completely.

The smoothing of multistep mesas, which is evident in Figure 1, is more accurately studied by a surface profiling measurement, the results of which are shown in Figure 3. The measurement shows that the etched steps accurately control the lens profile, and the profile closely matches that of an ideal lens. As a result, we have obtained near-diffraction-limited beam collimation to divergences of 0.7° for 130-μm-diameter lenses.

The accurate control of the lens profile is consistent with a recent study of the mass-transport phenomenon [10]. In this study the evolution of a surface profile is described by the exponential decay of its Fourier components; the decay lifetime is proportional to the fourth power of the spatial wavelength. Thus, once the small etched steps have been smoothed, any further change in the lens profile involves much longer spatial wavelengths and occurs on a time scale orders of magnitude longer. The lens formation is therefore essentially self-controlled and in good agreement with experimental observations.

One defect observed in these microlenses was a deviation from an exact circular symmetry with respect to the optical axes. The asymmetry was caused by the crystal-orientation dependence of etching rate in the fabrication of the multistep mesa. The etching mask was undercut anisotropically and the disks obtained were not exactly circular. Since the anisotropy increased with etching depth, it was reduced by increasing the number of steps to keep the step heights small. This procedure is particularly important for the fabrication of microlenses of extra-large numerical apertures. We typically required six to 10 steps for f/1 lenses. Other techniques such as ion etching (which is insensitive to crystallographic orientation) or compensations in the photolithographic definition of the disks can also minimize the problem.

Microlens arrays are easily obtained in this fabrication, because photolithography, chemical etching, and heat treatment all permit the simultaneous formation of identical elements in any desired pattern. Figure 4(a) shows an array of f/1 microlenses in InP. Figure 4(b) displays the formation of an array of images for a single object—the letter A. We can perform this demonstration by placing the microlens array under an ordinary microscope and positioning the character near the microscope light source. After a proper focusing adjustment, the image array is then visible in the microscope [6, 7]. The following section discusses how microlens arrays are needed for the collimation of light output from laser arrays.

Laser/Microlens Array: Coherent Phase Locking

Because the output power of a small single-mode diode laser is generally limited from 10 to 100 mW, considerable research interest has developed in diode laser arrays for high-power applications. A microlens array of a corresponding periodicity is required to concentrate the power from a laser array or to couple it efficiently to external optics. An external cavity (or, more precisely, extended cavity) can then be used to phase-lock the laser array coherently. In this application the microlenses also serve to increase the array fill factor (i.e., ratio of emission area to total area) so that the array can radiate in essentially a single beam. A coherent array of spot sources (i.e., low fill factor) has a multibeam radiation pattern similar to that of X-ray diffraction from a crystal lattice.

Basic diffraction theory shows that a coherent phase-locked laser array has a far smaller beam divergence than does an incoherent laser array. The coherent array output can also be focused to a tighter and hence brighter spot. This high brightness is important for many applications, such as frequency doubling or space communications. Although on-chip locking of mutually coupled multistripe diode lasers has been demonstrated, stable high-power operation with good phase control among stripes remains difficult [12–15]. Phase locking can also be achieved by operating the laser array in an external

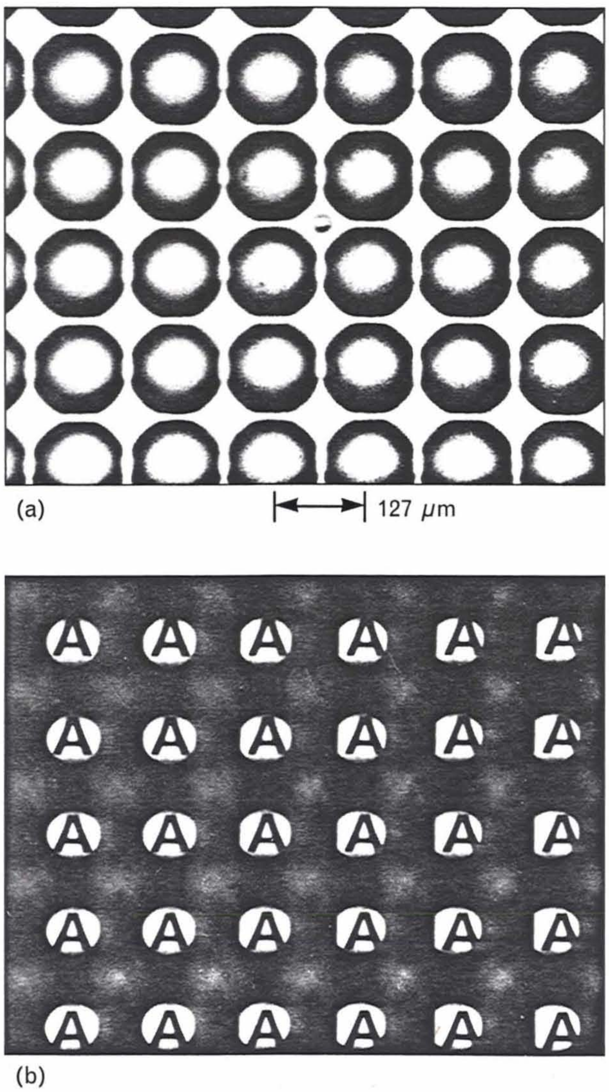

FIGURE 4. (a) An array of mass-transported f/1 microlenses in an InP substrate, and (b) the array of images the lens array formed from the letter A placed near the microscope light source.

cavity in which spatial filtering precisely selects the fundamental coherent lasing mode with a definite phase relationship among array elements [4, 16]. The external-cavity approach has the additional advantages of direct application to two-dimensional arrays and a wider spacing between lasers. Wider spacing greatly improves heat dissipation, which is of great practical importance for efficient, stable, and reliable operation of the laser array.

Earlier work has demonstrated external-cavity coherent phase locking of diode laser arrays either by using spatial filters in the Fourier-transform plane [8, 16] (as shown in Figure 5), or by using diffraction coupling via the Talbot self-imaging effect [3, 4, 17]. In the former case, an interference pattern that exactly matches the spatial filter can be produced only when the array elements emit the same wavelength with the same phase. Thus only that mode gets good feedback in the external cavity, and it can therefore continue to be amplified by the gain region and reach the lasing condition. A microlens array with near-unity fill factor renders the Fourier transform to nearly a single spot and makes the spatial filter essentially a single hole or, for a one-dimensional array, a single slit. Using a single wire at the first node of the desired Fourier transform further simplifies the scheme. This wire simplification, adopted in our experiment described below, makes the alignment of the spatial filter considerably easier, because the effect of wire position on the behavior of the laser array is more easily monitored.

For simplicity, we used a one-dimensional laser array in the form of a bar cleaved from a mass-transported GaInAsP/InP buried-heterostructure laser wafer [18]. A buried-heterostructure laser consists of a micronwide active stripe—GaInAsP in this case—that is totally buried in a single-crystal cladding material—InP—to form a stable single-mode waveguide. The waveguide was typically 300 μm in length and had a cleaved mirror facet on each end for optical feedback and light output. Figure 5 illustrates a one-dimensional array that consists of five lasers with 127-μm spacing. Because the cleaved mirror facet facing the external cavity was antireflection coated, the optical feedback was predominantly from the external cavity. The microlens array also had a 127-μm periodicity (see Figure 4) and was antireflection coated as well. The microlens and laser arrays were mounted

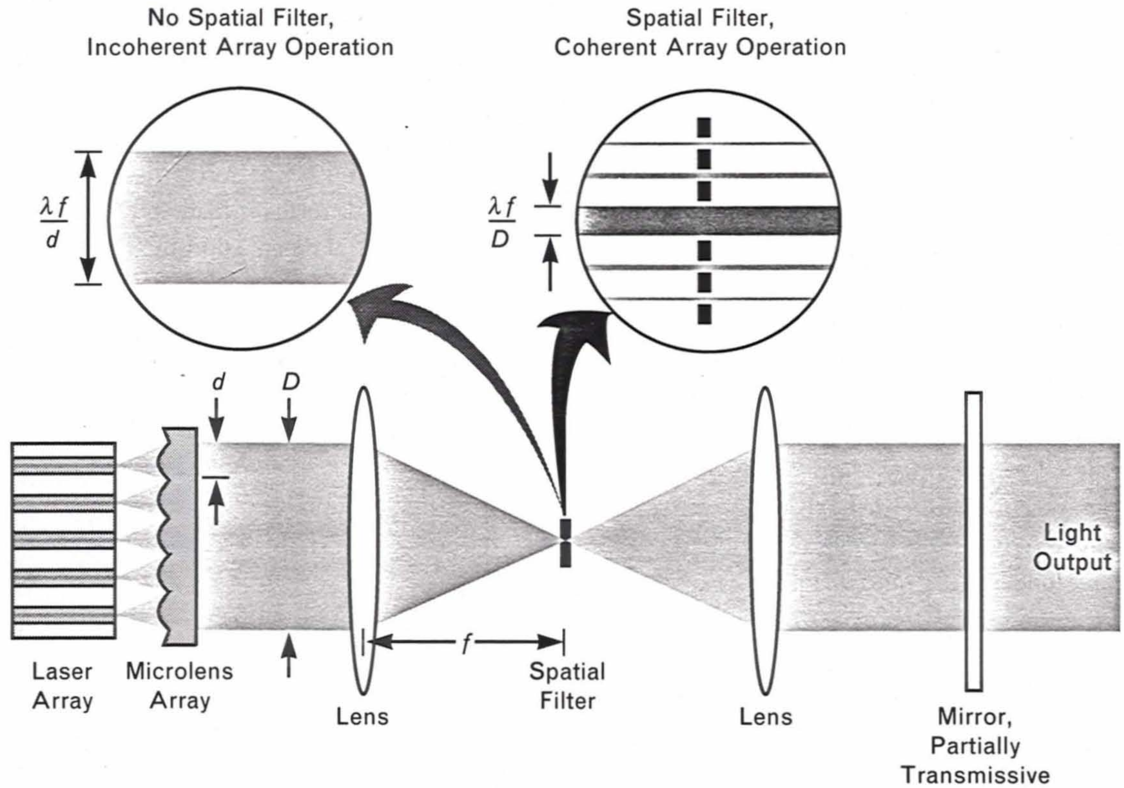

FIGURE 5. Coherent phase locking of a laser array in an external cavity. The dimensions in the actual experimental system are d = 127 μm, D = 635 μm, f = 6.25 cm, and λ = 1.3 μm.

on an alignment stage equipped with mechanical and piezoelectric micromanipulators for accurate positional and angular alignment between the two arrays [19]. The entire lens-laser assembly was mounted on another micromanipulator stage for alignment to the optical axis of the external cavity.

Figure 6 shows that coherent phase locking of the laser array was indeed achieved. Before the spatial filter was applied, the lasers lased independently of each other, as can be seen in Figures 6(a) and 6(b). The far-field emission pattern in Figure 6(a) shows a divergence of 1.3 mrad (0.76°), which corresponds to that of a single microlens (i.e., a single laser). The emission spectra shown in Figure 6(b) are also independent of each other. After the spatial filter was aligned in place, narrow peaks (approximately one-fourth of the original width) developed in the far field (Figure 6[c]) and all the stripes except one emitted identical longitudinal modes (Figure 6[d]). This result clearly shows that four of the five lasers in the array—lasers 2 through 5—were coherently phase locked. The higher side lobes in the far-field radiation pattern indicate an effective fill factor of only 65%, which can be explained by the less-than-uniform illumination of the microlenses due to the angular intensity distribution of the waveguide output.

Coherent phase locking of a laser array is simple in principle; at the present stage, however, it is far from practical. One major challenge is the difficult and critical alignment between the laser and microlens arrays. There are six degrees of freedom (three rotational and three translational) in this alignment, and the depth tolerance for f/1 lenses is only a few micrometers. Once the arrays are aligned, mechanical and thermal instabilities are additional major concerns. An elegant solution to these problems is monolithic integration of lasers and microlenses in a single chip in which the lasers and microlenses are lithographically aligned during fabrication and remain permanently aligned. This topic is the subject of the following discussion.

Monolithic Lens-Laser Integration

The development of high-quality semiconductor microlenses and the earlier development of miniature mirrors and beam deflectors bring within reach the monolithic integration of diode lasers with microlenses [18]. Such an integration is highly desirable for all diode laser applications in general and for the coherent array application in particular. The monolithic integration offers not only optimum mechanical stability but also potential manufacturing economy, because it would allow thousands of aligned lens-laser pairs to be fabricated at the same time.

Figure 7 illustrates a possible integration scheme in which a 45° mirror deflects the light from the waveguide gain region (the GaInAsP active layer) to a microlens on the other side of the wafer. The outer portion of the microlens has a smaller curvature and is designed as a spherical mirror to focus the light back to the waveguide to provide feedback for the laser oscillation. The inner portion of the microlens forms the collimating lens. Such a *bifocal* microlens is made possible by the accurate profile control described in the section "Microlens Fabrication." To achieve good optical coupling, the 45° mirror must be centered to the optical axis of the microlens to within a micron, since that is the size of the waveguide mode.

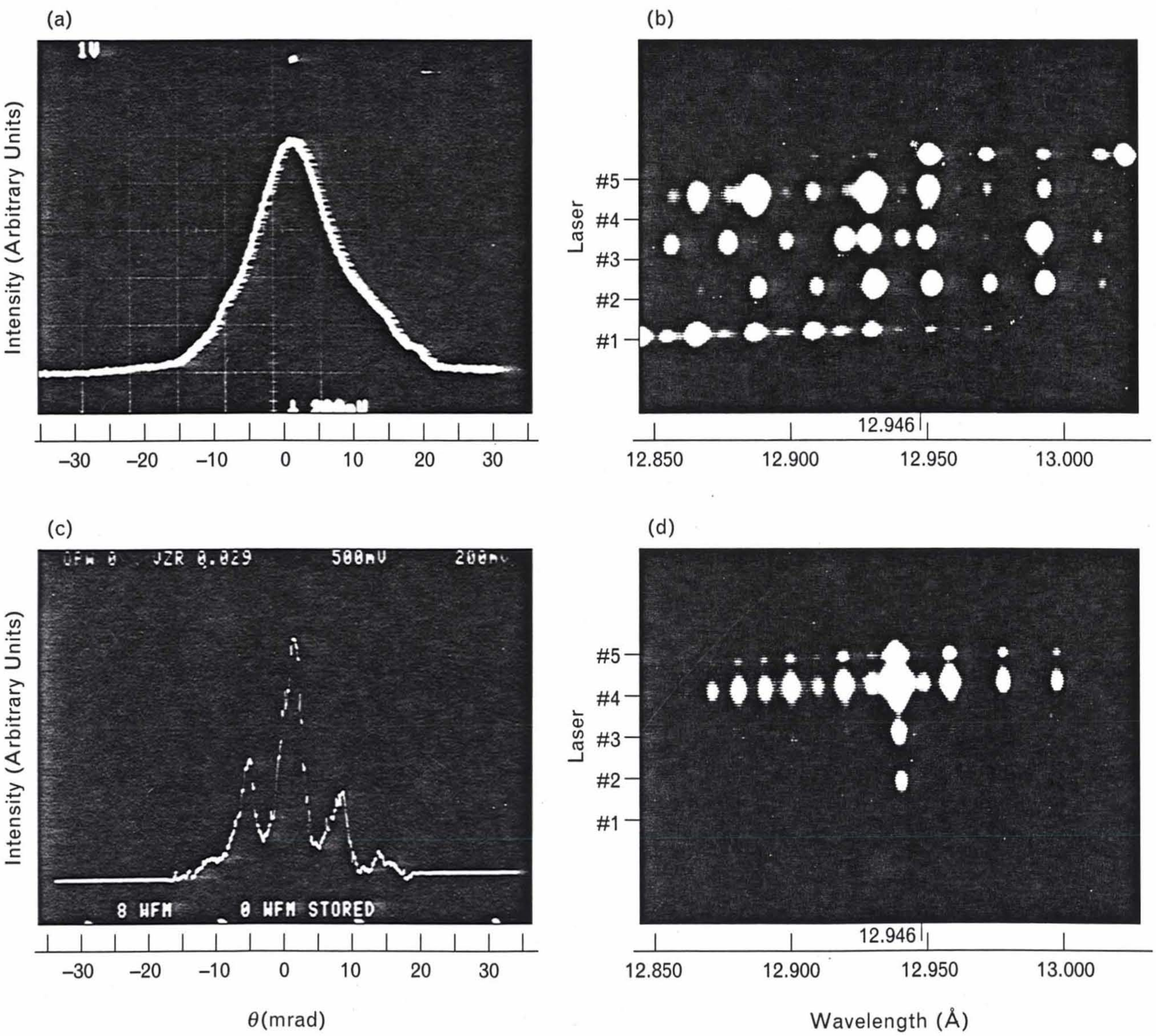

FIGURE 6. Far-field pattern (left) and emission spectra (right) of the linear laser array before (upper) and after (lower) the coherent phase locking. The locking is clearly demonstrated by the narrower peaks in the far-field pattern in (c) and by the identical emission spectra in (d).

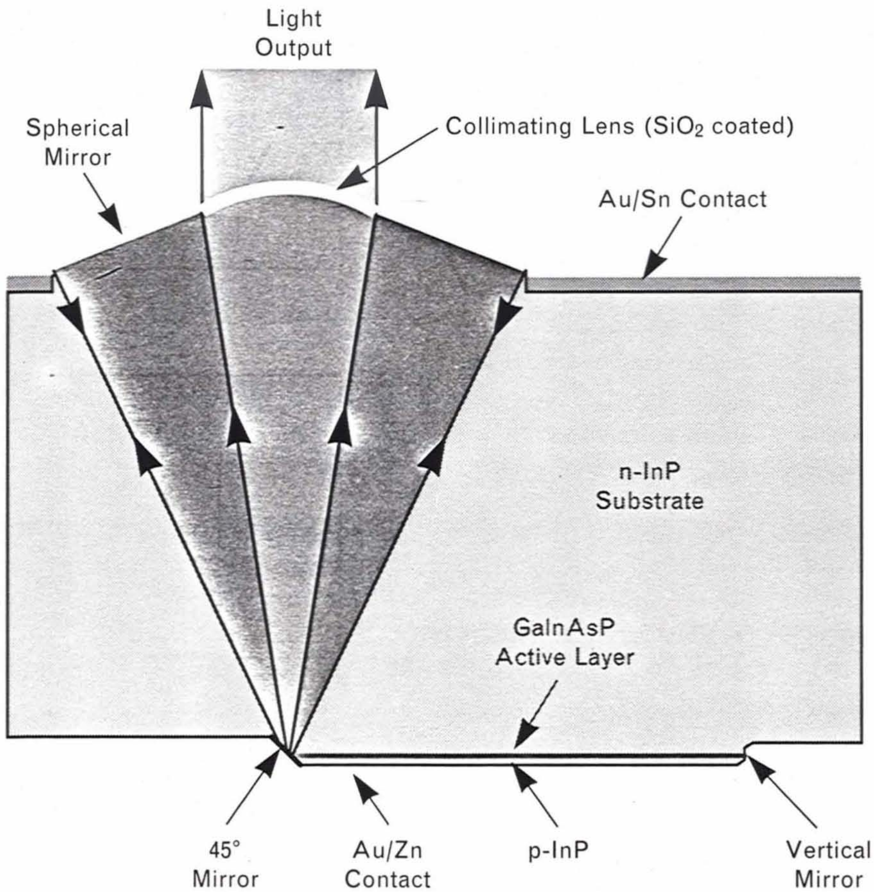

FIGURE 7. A diode laser with a monolithic integrated microlens. The longitudinal cross section shows the laser cavity formed by the spherical mirror, the active layer (a buried-heterostructure waveguide gain region), and the vertical mirror at the far end of the waveguide. The central portion of the microlens collimates the laser output.

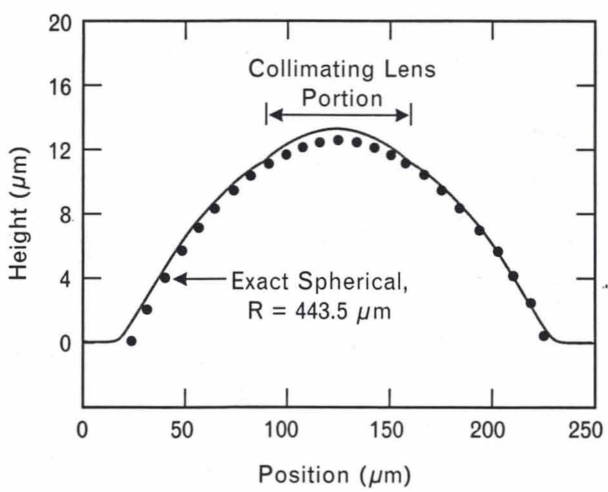

FIGURE 8. Bifocal microlens for monolithic integration with a diode laser. The two distinct curvatures shown correspond to the two lens portions.

The fabrication started with an n-type substrate (which has lower free-carrier absorption than p-type) with both sides polished. The measured substrate thickness, after some minor adjustments, became the focal length of the microlens. A 10-step mesa structure was then designed, etched, and mass transported to form the bifocal microlens. Figure 8 clearly shows the two distinct curvatures in the lens profile.

The double heterostructure (i.e., an active layer sandwiched between two wider-bandgap cladding layers [18]) gain region was then formed on the other side of the wafer by epitaxial growth. The beam deflector and the vertical mirror were formed by etching and mass transport; the beam deflector was precisely centered to the optical axis of the underlying microlens. The optical axis was accurately located by shining infrared light through the substrate and observing the concentrated spot of light produced by the microlens. The buried-heterostructure waveguide was then formed, again by etching and mass transport. Figure 9 shows the integrated lens-laser structure. After metallization and coatings were applied, the device as illustrated in Figure 7 was completed.

Figure 10 illustrates how lasers have been obtained with collimated light output. This result describes the first demonstration of a monolithic lens-laser integration. Although the laser exhibits high threshold currents and poor efficiency, we believe considerable improvement can be made by further perfecting the fabrication technology. Questions concerning possible material degradation or diffusion during the high-temperature treatment in the lens and mirror fabrications must also be addressed. Recent studies show the need for better wafer protection during mass transport [11]. Slow cooling may also be needed to anneal out the crystalline vacancies generated at high temperatures.

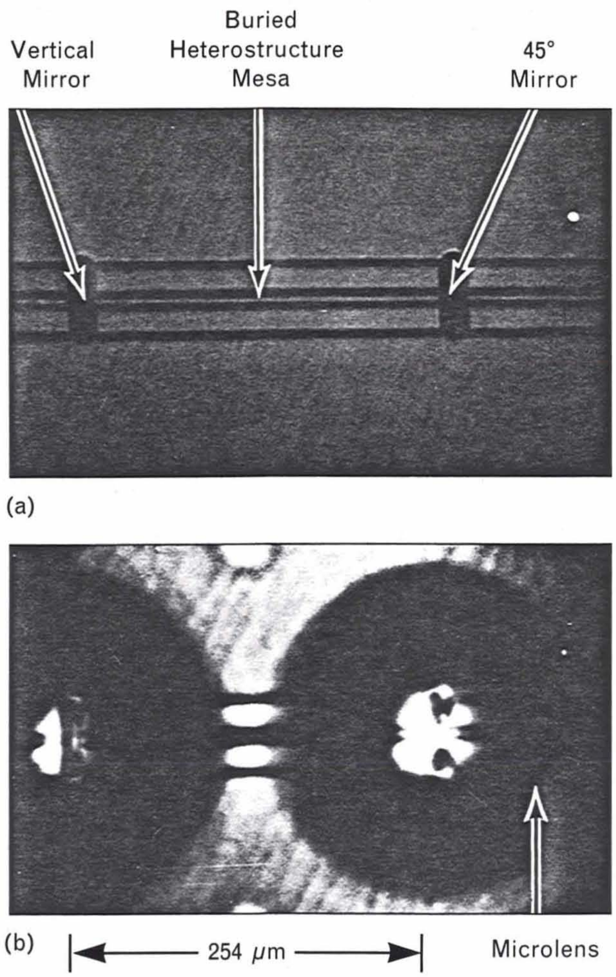

FIGURE 9. (a) A micrograph of the integrated lens-laser structure as viewed from the laser side. (b) An infrared photograph makes the substrate transparent so that the underlying microlens becomes visible. The 45° mirror and BH waveguide are centered on concentrated spots of light produced by the microlenses.

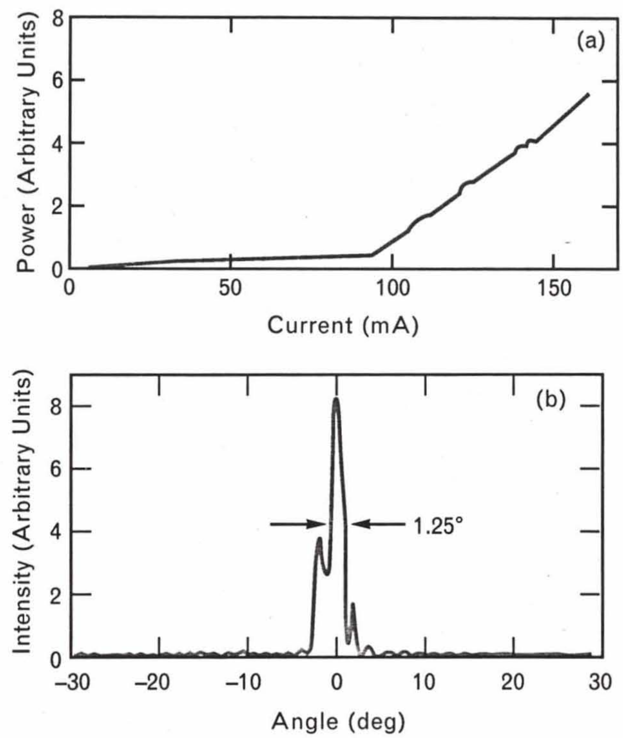

FIGURE 10. A monolithic lens laser: (a) the characteristic light output versus drive current, and (b) the far-field radiation pattern.

Finally, the device described in this article is a new type of surface-emitting diode laser (i.e., emission is perpendicular to the wafer surface). The device is well suited for junction-side-down mounting on a heatsink or bonding on other integrated circuitry for optical interconnections, transmission, or computing. Monolithic two-dimensional arrays, fabricated without spherical mirrors but with antireflection-coated collimating lenses, can be easily operated in an external cavity for coherent phase locking.

Conclusion

The mass-transported microlenses are well suited for beam collimation and other basic micro-optical functions that diode lasers and laser arrays require. Because of their large refractive index, accurate profile, and smooth surface, these microlenses are expected to have performance and efficiency that compare favorably with other microlenses. Although they require multistep lithography, these microlenses are fabricated in batch process and are therefore potentially economical. More work is needed to further basic understanding, especially the possible detrimental effect of heat treatment on material quality and bulk diffusion. This understanding is particularly important for creating reliable monolithic integrated optoelectronic systems. One immediate example is the coherent phase-locked diode laser arrays that can be made into efficient high-power lasers with high brightness.

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