generation by large signal modulation of a solitary laser diode and by active mode locking. In the former case, each optical pulse builds up from essentially spontaneous emission noise and therefore pulse to pulse coherence is very poor. In the latter case, each pulse builds up (at least partially) from stimulated emission of the previous optical pulse which returns from a round-trip tour of the external cavity, and hence the optical pulses should be coherent to one another. However, the autocorrelation traces of Figs. 3(a) and 3(b) show that pulse to pulse coherence is quite poor in the output of these very high rate actively mode-locked lasers. This is most likely due to (1) the large amount of frequency chirping due to variations in the refractive index of the laser material at such high modulation frequencies[6,7] and (2) the relatively small feedback from the external cavity.

In general, when attempting to actively mode lock a laser diode at very high repetition rates one has several avenues of approaches. One approach is to completely antireflection coat one facet of the laser and couple it to an external cavity. All the cavity submodes of the laser diode are suppressed, and lasing takes place soley between the laser facet and the external mirror. The difficulty is that this laser now has a much longer photon lifetime than a typical solitary laser diode, which aggravates the already difficult problem of driving the laser diode at frequencies of tens of gigahertz. It appears that a better approach would be the one described above—applying a relatively small amount of feedback to an unaltered ultrafast laser diode so that the high speed capability of the laser diode is not compromised. A second dilemma is that it is generally observed that active mode locking of laser diodes is achieved most easily when the laser is biased only slightly above threshold. An intuitive explanation for this result is that it is easier to fully modulate the output of the laser diode and force it into the large signal regime when the laser is only slightly above threshold. Since the modulation speed of the laser decreases with decreasing bias level, this approach also encounters difficulty when attempting to mode lock at tens of gigahertz. In our experiment, the laser was biased at a very high level at 10 mW so that the intrinsic speed of the laser can be maintained. The microwave drive power required to bring the optical output to full modulation is consequently high. This, however, should not be regarded as a penalty since the available optical power is correspondingly high.

In conclusion, we have demonstrated that suitably constructed high speed laser diodes can be used as narrowband signal transmitters in the Ku band frequency range (12–20 GHz). The modulation efficiency can be increased over limited bandwidth by a weak optical feedback. A stronger optical feeback enables one to actively mode lock the laser diode at a very high repetition rate up to 17.5 GHz, producing pulses ~ 12 ps long.

This research was supported by the Defence Advance Research Project Agency, the National Science Foundation under the Optical Communication Program, and by the Army Research Office.

[1]K. Y. Lau, N. Bar-Chaim, I. Ury, and A. Yariv, Appl. Phys. Lett. **45**, 316 (1984).
[2]C. Lin, C. A. Burrus, G. Eisenstein, R. S. Tucker, P. Besomi, and R. J. Nelson, paper WJ4, Optical Fiber Communication Conference, New Orleans, 1984.
[3]R. C. Alferness, G. Eisenstein, S. K. Korotky, R. S. Tucker, L. L. Buhl, I. P. Kaminow, and J. J. Veselka, paper WJ3, Optical Fiber Communication Conference, New Orleans, 1984.
[4]R. S. Tucker, G. Eisenstein, and I. P. Kaminow, Electron. Lett. **19**, 552 (1983).
[5]L. Figurroa, K. Y. Lau, H. W. Yen, and A. Yariv, J. Appl. Phys. **51**, 3062 (1980).
[6]J. E. Bower and C. A. Burrus, paper M-1, Ninth International Semiconductor Laser Conference, Rio de Janeiro, 1984.
[7]R. A. Linke, paper M-4, Ninth International Semiconductor Laser Conference, Rio de Janeiro, 1984.

Cd diffused mesa-substrate buried heterostructure InGaAsP/InP laser

M. B. Yi,[a] L. T. Lu, E. Kapon, Z. Rav-Noy, S. Margalit, and A. Yariv
California Institute of Technology, Pasadena, California 91125

(Received 22 October 1984; accepted for publication 4 December 1984)

A new type of buried heterostructure InGaAsP/InP lasers grown by a single-step liquid phase epitaxy on Cd diffused mesa substrate is described. These lasers exhibit excellent current and optical confinement. Threshold currents as low as 15 mA are achieved for a laser with a 2-μm-wide active region.

InGaAsP/InP double heterostructure lasers are used as light sources for optical fiber communications in long-wavelength range because of lower losses and dispersion of optical fiber in this range.[1-4] Low threshold current and a stable single transverse mode are necessary for such applications. Among the lasers developed to date the buried heterostructure lasers are very promising, owing to their very low threshold currents. However, the growth of conventional

[a] On leave from Jilin University, Changchun, Jilin, China.

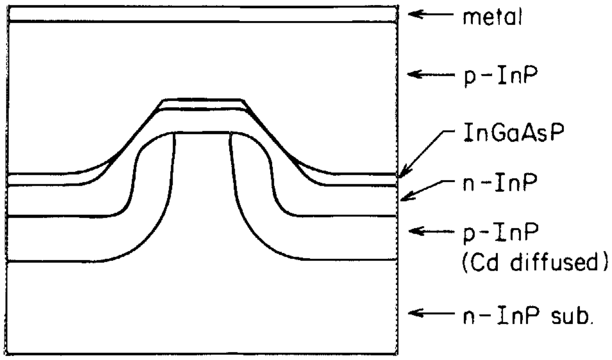

FIG. 1. Schematic cross section of the Cd diffused mesa substrate buried heterostructure.

buried heterostructure lasers requires a two-step liquid phase epitaxial growth process which is not desirable since degradation is originated in the exposed surfaces in the high-temperature H_2 ambient before the melt contact during the second liquid epitaxial growth process.

Some attempts to fabricate the buried heterostructure by single-step crystal growth were reported.[5-7] The mesa substrate buried heterostructure[6] is one of the more promising schemes, but it suffers from considerable current leakage due to the lack of effective current confinement. Additionally, since the current confinement in that structure is achieved by a narrow oxide stripe, the contact resistance is relatively high. In this letter, we report on a Cd diffused mesa substrate buried heterostructure InGaAsP/InP laser which is fabricated by a one-step epitaxy. Cd diffusion was used for the formation of the p-InP internal current confinement channel.

A schematic view of the Cd diffused mesa substrate buried heterostructure is shown in Fig. 1. Mesas were formed on the substrate by etching through stripe windows in Si_3N_4 using the HCl-H_3PO_4 solution. Stripes were parallel to [011] direction on a (100) n-InP. The mesas were $\sim 7\,\mu m$ wide and $\sim 4\,\mu m$ high. With Si_3N_4 as the mask on the top of mesas, Cd diffusion was then used for the formation of the p-InP internal current confinement channel. CdP_2 was used as a source and the diffusion was carried out in a closed quartz ampoule at 615 °C.[8] After 1.5 h of diffusion, the thickness of the diffusion layer was about 2.5 μm. Figure 2 shows the cross section of the Cd diffused mesa substrate wafer. After removing the Si_3N_4, approximately half of the Cd diffused layer was etched away to eliminate the thermal damaged and high concentration layer near the surface.[8] Then, four layers, InP ($n \sim 5\times 10^{17}$ cm^{-3}), GaInAsP (undoped active layer), InP($p \sim 1.5\times 10^{18}$ cm^{-3}), and an Zn p^+-InGaAsP contact were grown consecutively. The first layer was grown with a supersaturated solution in order to have 0.5–1 μm thick buffer layer on the top of the mesas. The super cooling degree was 14 °C. The other two layers were grown by a two-phase solution technique. As shown in the scanning electron microscope photograph of the cross section of such a structure (Fig. 3), the active layer above the mesa is fully pinched off from the same layer between the mesas, and below the active layers the vertical current channels are formed by Cd diffusion layers. In order to measure the I-V characteristics of the

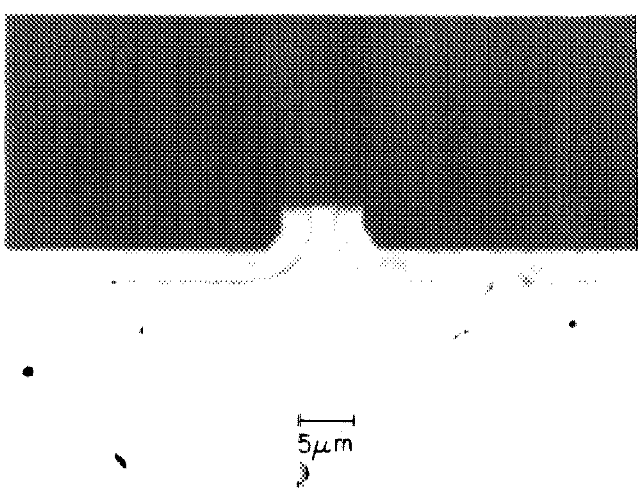

FIG. 2. Etched cross section of Cd diffused mesa substrate.

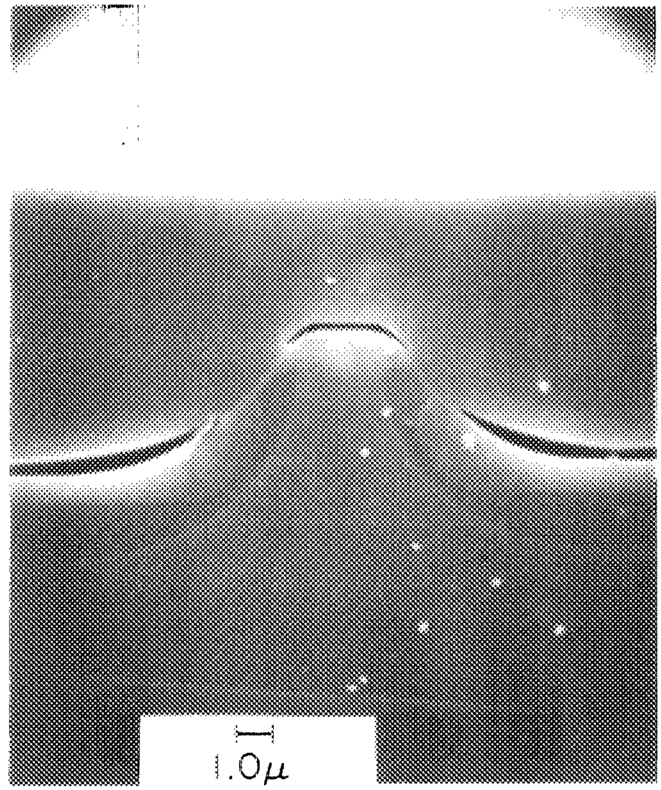

FIG. 3. SEM photograph of the Cd diffused mesa substrate BH laser.

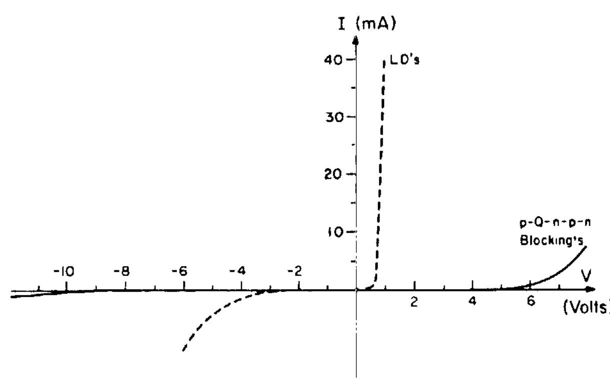

FIG. 4. I-V curves of p-Q-n-p-n blocking structure and Cd diffused mesa substrate BH laser diode.

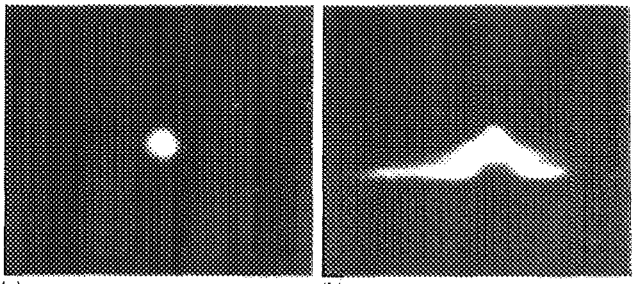

FIG. 5. Near-field patterns of Cd diffused mesa substrate BH laser: (a) normal near-field pattern and (b) luminescence on both sides of the mesa by the current leakage through the quaternary layer.

blocking layers, ohmic contacts were applied to the blocking p-Q-n-p-n layer regions, and devices that do not contain the lasers mesa region were cleaved. These control devices could be separately tested on a curve tracer and compared to the laser I-V characteristics. Figure 4 shows the I-V characteristics of the p-Q-n-p-n (where Q is the undoped GaInAsP layer) blocking structure and Cd diffused mesa substrate buried heterostructure laser diodes. With 6-V forward bias voltage, the current flowing through the blocking structure is less than 1 mA. It is evident that good current confinement is achieved.

After growth a layer of chemical vapor deposited silicon dioxide was deposited over the entire wafer, and contact stripes (7–15 μm) were opened photolithographically. Au-Zn contacts were evaporated and alloyed at 420 °C. The wafer was lapped down to 75 μm on the substrate side and Au-Ge was evaporated to form the n contact. Bars of 200–300 μm long lasers were cleaved and tested with 100 ns current pulse. No difference in threshold current was found between lasers with double current confinement (oxide stripe on the top) and single current confinement (broad area p contact) which again indicates the effectiveness of p-Q-n-p-n blocking structure.

For the active regions with ~ 2-μm width and ~ 0.2-μm thickness, the pulsed threshold current varied between 15 and 30 mA. The near-field patterns of Cd diffused mesa substrate buried heterostructure lasers are given in Fig. 5. Figure 5(a) shows a normal pattern and Fig. 5(b) shows the luminescence on both sides of the mesa due to current leakage through the quaternary layer caused by intentionally etching off the Cd diffused layer on part of the wafer while the blocking is provided by a 7-μm SiO_2 stripe. In the latter case the threshold was 75 mA. The far-field patterns are shown in Fig. 6. Stable fundamental transverse mode is the feature of such a structure. The far-field and near-field patterns were displayed on a monitor by using an infrared vidicon camera.

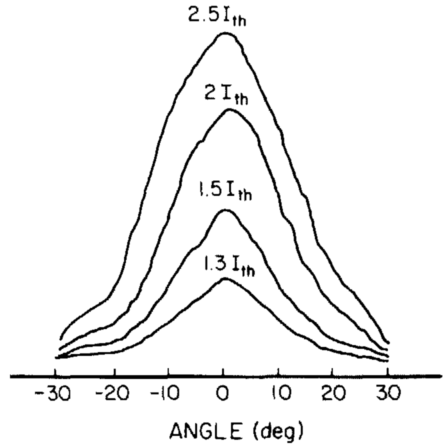

FIG. 6. Near-field pattern parallel to the junction of Cd diffused mesa substrate BH laser.

In conclusion, Cd diffused mesa substrate buried heterostructure type lasers were demonstrated. Fabrication of the lasers is simple, and good current and optical confinement have been achieved by single-step growth. Stable single transverse mode operation and low threshold are demonstrated.

The research discussed in this paper is supported by the National Science Foundation and the Office of Naval Research and the Air Force Office of Scientific Research. The authors wish to thank T. Venkatesan of Bell Laboratories for taking the SEM picture.

[1] J. J. Hsieh, Appl. Phys. Lett. **28**, 283 (1976).
[2] T. Yamamoto, K. Sakai, S. Akiba, and Y. Suematsu, IEEE J. Quantum Electron. **QE-14**, 95 (1978).
[3] M. A. Pollack, R. E. Nahory, J. C. DeWinter, and A. A. Ballma, Appl. Phys. Lett. **33**, 314 (1978).
[4] R. Hirano, E. Osmura, H. Higuchi, Y. Sakakibara, H. Namisaki, W. Susaki, and F. Fujikawa, Appl. Phys. Lett. **43**, 187 (1983).
[5] P. C. Chen, K. L. Yu, S. Margalit, and A. Yariv, Appl. Phys. Lett. **38**, 301 (1981).
[6] M. Oron, N. Tamari, H. Shtrickman, and C. A. Burrus, Appl. Phys. Lett. **41**, 609 (1982).
[7] H. Ishikawa, H. Imai, I. Umsbu, K. Hori, and M. Takusagawa, J. Appl. Phys. **53**, 2851 (1982).
[8] Y. Matsumoto, Jpn. J. Appl. Phys. **22**, 1699 (1983).