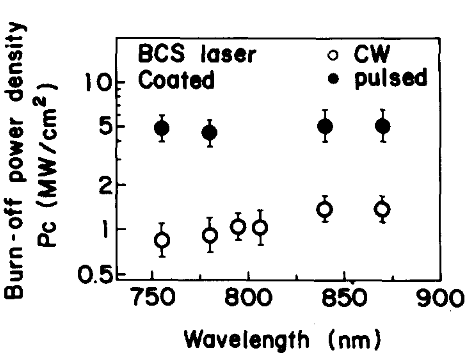

FIG. 3. Lasing wavelength dependence of burn-off power density P_c under cw (open circles) and pulsed (closed circles) operations.

with pulsed operations to P_c with cw operation became larger as the wavelength became shorter. This shows that the dependence of P_c on the pulse width of the current is different between visible and infrared lasers.[6,10,13] This difference is considered to be due to the difference in the Al composition of the active layer, that is, the difference in the temperature raise rate of the local region in the active layer where COD occurs.

In conclusion, we have studied the burn-off output power of the catastrophic failure of visible and infrared GaAlAs DH lasers. The burn-off output power increased with decreasing the active layer thickness of the laser. The burn-off power density P_c was obtained from this dependence on the thickness of the active layer. It was revealed that the value of P_c in visible GaAlAs lasers is quite the same as in infrared GaAlAs lasers in case of pulsed operation, and is a little smaller than in infrared lasers in case of cw operation.

The authors wish to thank T. Misugi, K. Dazai, and Y. Toyama with Fujitsu Laboratories Ltd. for their encouragement. We would also like to thank H. Nishi, S. Ohsaka, H. Imai, H. Ishikawa, and M. Yano for their useful discussions on this study.

[1] D. P. Cooper, C. H. Gooch, and R. J. Sherwell, IEEE J. Quantum Electron. **QE-2**, 329 (1966).
[2] C. D. Dobson and F. S. Keeble, Proc. Int. Symp. GaAs, Inst. Phys. Soc. London **68** (1967).
[3] H. Kressel and H. Mierop, J. Appl. Phys. **38**, 5419 (1967).
[4] D. A. Shew and P. R. Thornton, Solid-State Electron. **13**, 919 (1970).
[5] M. Ettenberg, H. S. Sommers, Jr., H. Kressel, and H. F. Lockwood, Appl. Phys. Lett. **18**, 571 (1971).
[6] P. G. Eliseev, J. Lumines. **7**, 338 (1973).
[7] P. A. Kirkby and G. H. B. Thompson, Appl. Phys. Lett. **22**, 638 (1973).
[8] B. W. Hakki and F. R. Nash, J. Appl. Phys. **45**, 3907 (1974).
[9] G. D. Henshall, Solid-State Electron. **20**, 595 (1977).
[10] H. Imai, M. Morimoto, H. Sudo, T. Fujiwara, and M. Takusagawa, Appl. Phys. Lett. **33**, 1011 (1978).
[11] C. H. Henry, P. M. Petroff, R. A. Logan, and F. R. Merritt, J. Appl. Phys. **50**, 3721 (1979).
[12] O. Ueda, H. Imai, T. Kotani, K. Wakita, and H. Saito, J. Appl. Phys. **50**, 6643 (1979).
[13] T. Kamejima and H. Yonezu, in Proc. of the 11th Conf. on Solid State Devices, Tokyo, 1979, Jpn. J. Appl. Phys. **19**, Suppl. 19-1, 425 (1980).
[14] K. Shima, K. Hanamitsu, T. Fujiwara, and M. Takusagawa, Appl. Phys. Lett. **38**, 605 (1981). K. Shima, K. Hanamitsu, K. Wakao, N. Takagi, H. Tabuchi, and M. Takusagawa, presented at Int. Conf. on Solid State Devices, Tokyo, Japan, 1982.
[15] K. Mizuishi, N. Chinone, H. Sato, and K. Aiki, IEEE J. Quantum Electron. **QE-16**, 728 (1980).
[16] T. Tsukada, J. Appl. Phys. **45**, 4899 (1974).
[17] M. Wada, K. Itoh, H. Shimizu, T. Sugino, and I. Teramoto, IEEE J. Quantum Electron. **QE-17**, 776 (1981).

Low threshold InGaAsP terrace mass transport laser on semi-insulating substrate

T. R. Chen,[a] L. C. Chiu, K. L. Yu, U. Koren, A. Hasson, S. Margalit, and A. Yariv
California Institute of Technology, Pasadena, California 91125

(Received 10 August 1982; accepted for publication 29 September 1982)

Very low threshold InGaAsP terrace lasers on semi-insulating (SI) InP substrate have been fabricated using the mass transport technique. The fabrication process involves a single-step liquid phase epitaxial (LPE) growth followed by a mass transport of InP at ~675 °C in the presence of an InP cover wafer. Lasers operating in the fundamental transverse mode with smooth far-field patterns and threshold currents as low as 9.5 mA have been obtained.

PACS numbers: 42.55.Px

The recently discovered mass transport phenomenon[1] provides an innovative technique for fabricating low threshold quaternary lasers. In certain laser structures, such as the buried heterostructure, this technique eliminates the critical regrowth step, and the entire fabrication process is thereby greatly simplified. This novel technique also opens a new field for investigation and application in other InP based semiconductor devices. In the present work, we report on a very low threshold current InGaAsP/InP laser (T-MT) on

---

[a] Permanent address: Chengdu Institute of Radio Engineering, People's Republic of China.

SI InP substrate which was fabricated using this new technique.

The structure reported here is that of a terrace laser on SI InP substrate. Schematic representation of the three basic layers is shown in Fig. 1(a). These are grown by conventional liquid phase epitaxy (LPE) on an Si_3N_4 masked terrace-shaped SI InP substrate.[2,3] The terrace was etched either along the (011) or the $(01\bar{1})$ crystallographic direction. In both cases, high quality growth and lasing action had been achieved. The three LPE layers are n^+-InP cladding layer, undoped InGaAsP active layer, and p-InP cladding layer, respectively. Following deposition of a new Si_3N_4 etching mask on the grown wafer, windows for chemical etching were opened with one side parallel to and approximately 5 μm away from the edge of the original terrace. The p-InP cladding layer underneath the windows was then removed selectively with a solution of hydrochloric acid and water (1.5:1). The quaternary InGaAsP layer was etched next, either with a solution of $KOH:K_3Fe(CN)_6:H_2O$ or $H_2SO_4:H_2O_2:H_2O$, resulting in a desired undercutting into the InGaAsP active layer as shown in Fig. 1(b). The etching rate of the quaternary layer was found to depend on the thickness of the active layer, and the amount of undercutting is controllable for each wafer. After etching, the Si_3N_4 mask was removed. The wafer was cleaned and reintroduced into the LPE system for mass transport.

The mass transport of InP was accomplished without using PH_3.[1] Instead, the LPE system was only flushed with H_2, and the wafer was covered with an SI InP cover wafer and a thick graphite plate. The system was then heated to 670–680 °C and maintained at that temperature for about 45 min. The InP cover wafer furnished the phosphorus vapor for the mass transport. This may be more convenient than purging the system with PH_3. InP mass transport had been found to be very reproducible. The width of the mass transported region was found to depend on the thickness of the active layer, the temperature, and the time duration of heating. A terrace laser structure after mass transport is shown in Fig. 1(c). A scanning electron micrograph of the structure is shown in Fig. 2.

It was discovered that mass transport also took place in the absence of an InGaAsP layer, which resulted in our case in an InP homojunction. A detailed study of the InP mass transport effect and the characteristics of the junction will be presented elsewhere.

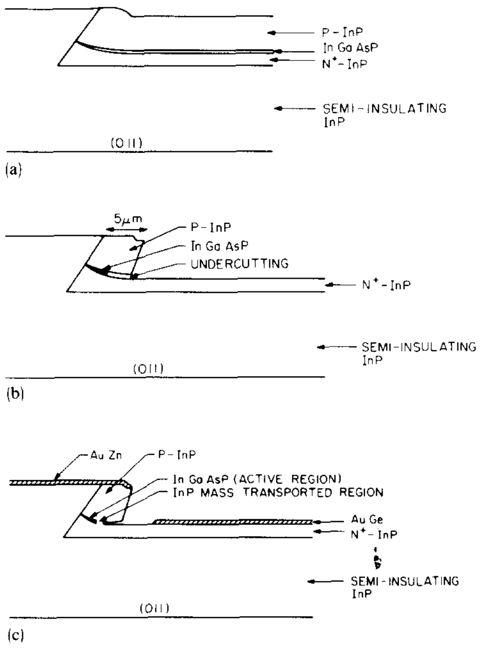

FIG. 1. (a) Schematic cross section of the three basic layers of the T-MT laser on semi-insulating InP along the (011) direction. (b) Schematic cross section of the T-MT laser after the selective undercutting into the active layer. (c) Schematic cross section of the fabricated T-MT laser.

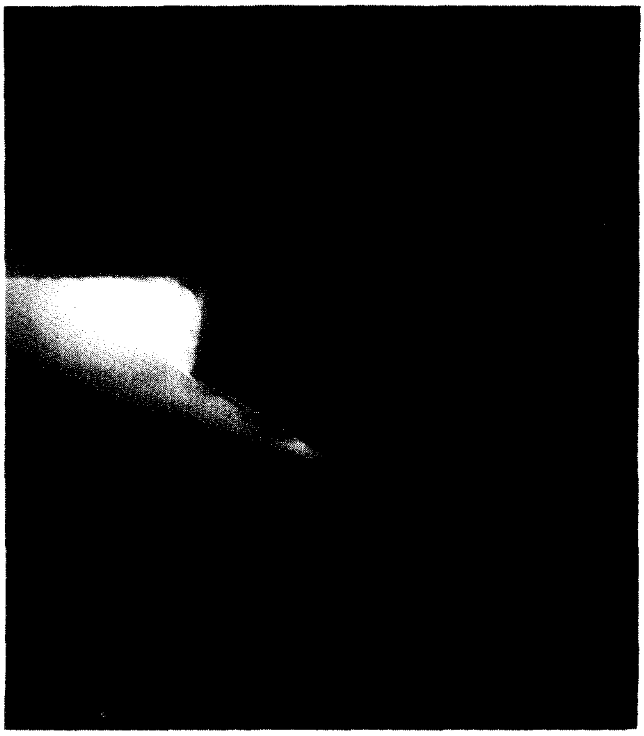

FIG. 2. SEM photograph of the T-MT laser after mass transport.

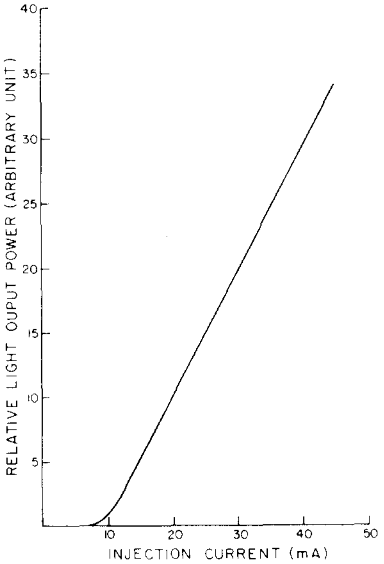

FIG. 3. L-I characteristics of a T-MT laser, I_{th} is 9.5 mA.

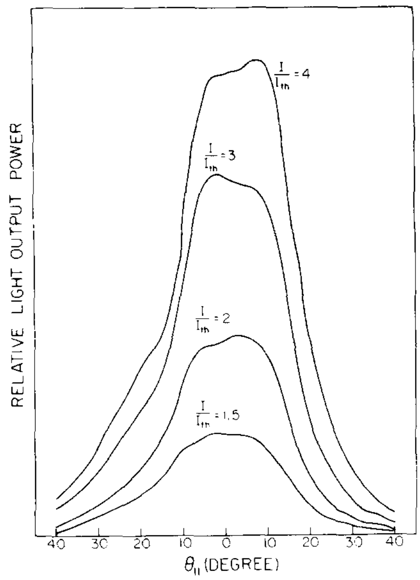

FIG. 4. Far-field pattern at pulsed operation of a T-MT laser.

Since the etching of the active layer was performed from one side only, the overhanging top layer was supported on one side and no problems with its collapse were encountered. Also, the undercutting process was quite controllable, since the other side of the active layer was well defined by the terrace wall. Thus, very narrow active regions with uniform widths could be realized. Furthermore, contacts and separation of the two contacts were easily achieved in the present case, since both were made on a broad area. All these resulted consistently in low threshold and high performance lasers over the entire wafer. For further improvement of the p contact, a shallow Zn diffusion over the P-InP top layer was performed. Alternatively, a thick p^+-InGaAsP cap layer could be grown on the p-InP cladding layer. The performance of the T-MT laser depends on the structure parameters. With an active layer of ~0.1–0.2 μm thick and ~2 μm wide, and a mass transported region of ~1 μm wide, the threshold currents cluster tightly around 20 mA (for a cavity length of 250 μm). The lowest obtained is 9.5 mA. cw operation is also achieved, with threshold current only 10% higher than that of pulsed operation. The light versus current characteristics for the lowest threshold current laser are shown in Fig. 3. Light output increases linearly with injection current till four times threshold current. Differential quantum efficiency is about 50% for both facets.

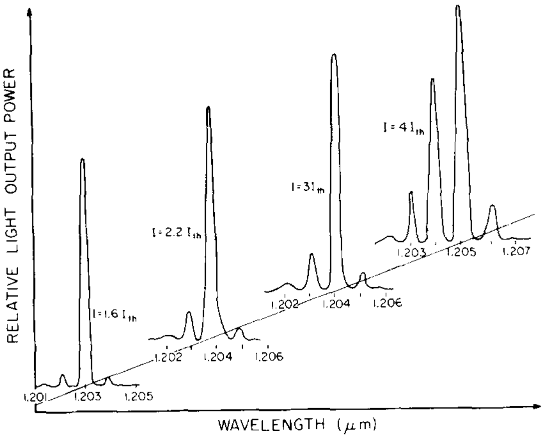

FIG. 5. Spectra of a T-MT laser at different injection levels.

One of the noticeable feature of the T-MT lasers is their ability to operate in a stable single transverse mode. A typical far-field pattern of the laser is shown in Fig. 4. The laser exhibits smooth far-field pattern with a beam divergence of ~30° (full width at half-maximum). Single mode operation is maintained above four times threshold current. Spectra of the laser output at different injection levels are shown in Fig. 5. The spectra show predominant single longitudinal mode operation up to $3I_{th}$. The measured temperature dependence of the threshold current showed a T_0 of 40–50 °K in the temperature range of 10–40 °C.

In conclusion, a very low threshold InGaAsP/InP terrace laser has been fabricated on SI InP substrate using InP mass transport effect. The laser operates in a stable single mode with linear L-I characteristics and smooth far-field pattern.

This work is supported by the National Science Foundation, the Office of Naval Research, and the Air Force Office of Scientific Research.

The authors are thankful to Dr. P. C. Chen for the invaluable discussion regarding the mass transport process.

[1] Z. L. Liau and J. N. Walpole, Appl. Phys. Lett. **40**, 568 (1982).

[2] T. R. Chen, K. L. Yu, U. Koren, A. Hasson, S. Margalit, and A. Yariv, J. Appl. Phys. **53**, 7215 (1982).

[3] T. Matsuoka, Y. Suzuki, Y. Noguchi, and H. Nagai, Electron. Lett. **18**, 359 (1982).