Constant-temperature LPE growth and operation in an external-grating cavity," *IEEE J. Quantum Electron.*, vol. QE-13, pp. 637-642, Aug. 1977.

[9] P. D. Wright, E. A. Rezek, H. Holonyak, Jr., G. E. Stillman, J. A. Rossi, and W. O. Groves, "Multiple liquid phase epitaxy of $In_{1-x}Ga_xP_{1-z}As_z$ double heterojunction lasers: The problem of lattice matching," *Appl. Phys. Lett.*, vol. 31, pp. 40-42, July 1977.

[10] E. A. Rezek, N. Holonyak, Jr., B. A. Vojak, G. E. Stillman, J. A. Rossi, D. L. Keune, and J. D. Fairing, "LPE $In_{1-x}Ga_xP_{1-z}As_z$ ($X \sim 0.12$, $Z \sim 0.26$) DH laser with multiple thin-layer (<500 Å) active region," *Appl. Phys. Lett.*, vol. 31, pp. 288-290, Aug. 1977.

[11] P. D. Wright, E. A. Rezek, and N. Holonyak, Jr., "Lattice matching and dislocations in LPE $In_{1-x}Ga_xP_{1-z}As_z$-InP heterojunctions," *J. Crystal. Growth*, vol. 41, pp. 254-261, 1977.

[12] B. De Cremoux "First order theory of diffusion limited growth in LPE application to GaInAsP," presented at the 7th Int. Symp. on GaAs and Related Compounds, St. Louis, MO, Sept. 1978.

[13] V. Wrick, G. J. Scilla, L. F. Eastman, R. L. Henry, and E. M. Swiggard, "In situ In etching technique for LPE InP," *Electron. Lett.*, vol. 12, pp. 394-395, Aug. 1976.

[14] M. S. Abrahams and C. J. Buiocchi, "Etching of dislocations on the low-index faces of GaAs," *J. Appl. Phys.*, vol. 36, pp. 2855-2863, Sept. 1965.

[15] P. D. Wright and G. A. Antypas, unpublished.

[16] Y. Seki, H. Watanabe, and J. Matsui, "Impurity effect on grown-in dislocation density of InP and GaAs crystals," *J. Appl. Phys.*, vol. 49, pp. 822-828, Feb. 1978.

[17] A. Majerfeld, personal communication.

[18] D. Lubzens, "Photoetching of InP mesas for production of mm-wave transferred-electron oscillators," *Electron. Lett.*, vol. 13, pp. 171-172, Mar. 1977.

[19] J. P. Wittke, M. Ettenberg, and H. Kressel, "High radiance LED for single-fiber optical links," *RCA Rev.*, vol. 37, pp. 159-183, June 1976.

[20] M. Ettenberg and H. Kressel, "Interfacial recombination at (AlGa)As/GaAs heterojunction structures," *J. Appl. Phys.*, vol. 47, pp. 1538-1544, Apr. 1976.

GaInAsP/InP Double-Heterostructure Planar LED's

KENICHI IGA, MEMBER, IEEE, TOSHIO KAMBAYASHI, KIYOHIDE WAKAO,
CHIYUKI KITAHARA, AND KAZUNORI MORIKI

Abstract—$Ga_xIn_{1-x}As_yP_{1-y}$/InP **double-heterostructure wafers were grown on (100) InP substrates using a vertical LPE furnace. A new chemical etchant, named KKI-121, was developed to etch InP and GaInAsP into smooth surfaces and perpendicular facets. By using these techniques, new surface-emitting planar LED's with convex mirror-like windows were fabricated. The transparency of the InP substrate allows it to be used as a window. The emission peak was at 1.17 μm and the full width at half maximum was about 1000 Å.**

I. INTRODUCTION

RECENTLY, it has been recognized that optical fiber communication in the 1.0-1.7-μm wavelength region is very advantageous, because optical fibers exhibit very low transmission losses there [1]. $Ga_xIn_{1-x}As_yP_{1-y}$ quaternary alloys lattice-matched to InP substrates can be made with energy gaps from 0.73 to 1.35 eV. Therefore, lattice-matched GaInAsP/InP double-heterostructure diodes which emit light in the 0.92-1.65-μm wavelength range have been considered to be some of the most promising light sources. As for double-heterostructure (DH) LED's fabricated from this material, only a few types of edge-emitting diodes [2] and surface-emitting diodes [3]-[6] have been reported at this time. In this paper, we report the fabrication of a new surface-emitting planar LED, in which the transparency of the InP substrate allows it to be used as a focusing window. New chemical etching techniques for GaInAsP/InP system were developed and this structure was made by using the new etchant.

II. FABRICATION OF DH WAFERS

$Ga_xIn_{1-x}As_yP_{1-y}$/InP DH wafers were epitaxially grown by a two-phase solution technique using a vertical LPE furnace [7]. The carbon boat is a rotary-type structure, so that the horizontal temperature distribution along the sliding plane could be made uniform and the temperature variation during the movement of solution holders could be reduced. Fig. 1 shows the temperature program. Four layers of GaInAsP/InP were grown. The substrate used was (100)-oriented InP and was cleaned with an $H_2O:H_2SO_4:H_2O_2$, 1:3:1 etchant in volume ratio. After soaking the melts at 665°C for about 40 min, four layers were grown on the substrate successively. Crystal growth of each layer was done using two-phase solutions with excess InP. The cooling rate and starting temperature for the quaternary layer were set at 0.8°C/min and 635°C, respectively. The quaternary layer was grown thicker

---

Manuscript received November 27, 1978; revised February 5, 1979.

The authors are with Tokyo Institute of Technology, Research Laboratory of Precision Machinery and Electronics, 4259, Nagatsuta, Midoriku, Yokohama, Japan.

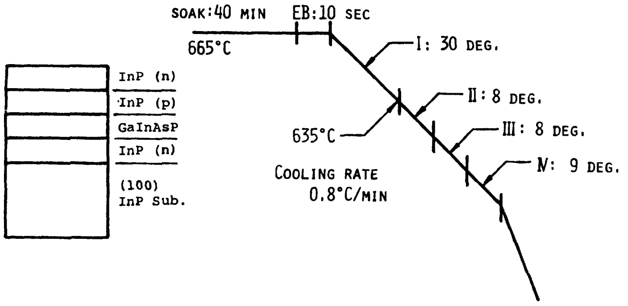

Fig. 1. The temperature program of LPE growth.

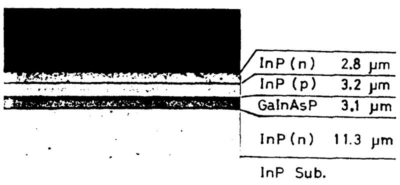

Fig. 2. The cross-sectional view of a grown wafer.

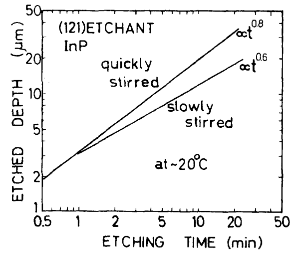

Fig. 3. The relation between the etched depth and etching time.

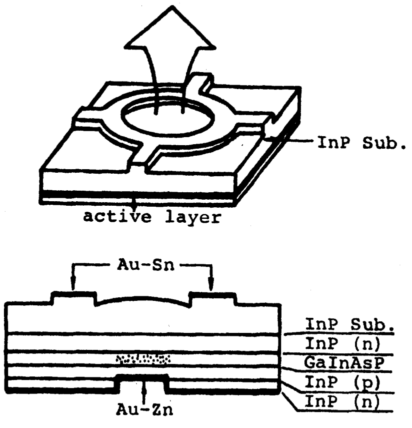

Fig. 4. Surface-emitting planar LED.

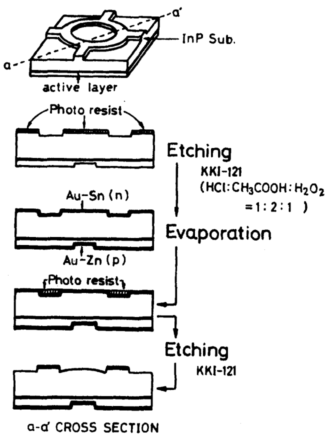

Fig. 5. The fabrication process of a convex mirror.

than in the case of wafers for laser diodes. Fig. 2 shows a stain-etched cross section of the wafer with the four epitaxial layers: n-type InP, GaInAsP, p-type InP, and n-type InP. The GaInAsP active layer was usually grown about 3 μm thick, and its nominal composition was $Ga_{0.2}In_{0.8}As_{0.46}P_{0.54}$. The active layer carrier concentration may be equal to or less than $2 \times 10^{18} cm^{-3}$. The p-type and n-type dopants were Zn and Te, respectively.

III. Chemical Etching Techniques for the GaInAsP/InP System

For the fabrication of lasers, LED's, and monolithic integrated circuits, photolithography and chemical etching techniques are considered to be good ones, because they are simple, speedy, safe, and highly developed. Furthermore, chemical etching does not damage the wafer crystal. In order to find a good chemical etchant for InP, we examined several tens of test etchants and found some new chemical etchants. For the fabrication of the mirror-like windows of LED's, the most favorable etchant was a mixed solution of hydrochloric acid, acetic acid, and hydrogen peroxide with a volume ratio of 1:2:1, which we have named KKI-121. Fig. 3 shows the relation between the etched depth and etching time for (100) InP at about 20°C. The etched depth was proportional to the etching time to the 0.8th power and 0.6th power for the cases in which the etchant was stirred quickly and stirred slowly, respectively. Not only does this etchant etch InP, but it etches GaInAsP and deposited Au/Zn or Au/Sn. The etching speed of GaInAsP is higher than that of InP, and the etching rate is about 0.1 μm/min for Au/Zn and Au/Sn at about 20°C. The etched bottom surface was smooth and mirror-like, and the etched sides became almost perpendicular. In this etching process, photoresist can be used as the mask.

IV. Fabrication of the Surface-Emitting Planar LED

The structure of the LED, consisting of four layers grown on an n-type InP substrate, is schematically illustrated in Fig. 4. The p contact was formed on the third, p-type, InP layer after etching off the n-type InP top layer. The substrate side was polished and etched with KKI-121 etchant in order to form a smooth mirror surface. By etching the surface twice, a convex mirror surface was made. Fig. 5 illustrates the fabrication process of the convex mirror surface. First, we made a photoresist mask, except in the circular portion, and etched with KKI-121 etchant for a few minutes. After removing the photoresist, Au/Sn and Au/Zn were evaporated on the substrate side and the grown layer side, respectively, and annealed at about 400°C. Next, we again made a photoresist mask on the etched portion and etched with KKI-121 etchant for a few minutes. By this procedure, the convex mirror surface was formed. Fig. 6 shows a cross section of a processed wafer. It can be seen that the etched surface becomes a convex

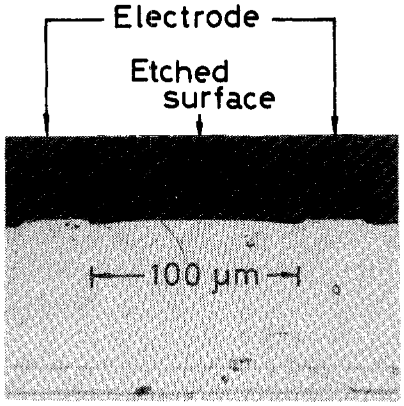

Fig. 6. The cross-sectional view of an LED.

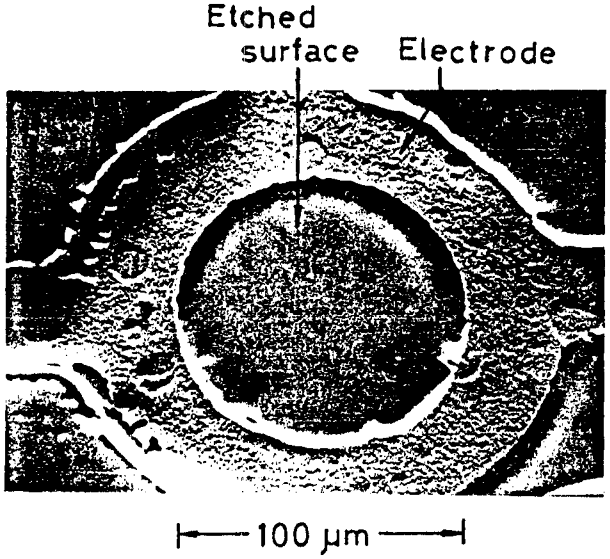

Fig. 7. An SEM view of an LED's surface.

surface. The focal length of the focusing window corresponds to 0.7 mm. Fig. 7 shows an SEM view of the wafer. The circular ring is the electrode and the central circular part is the etched convex surface. The emission can be taken out through this 100-μm diameter window, because the bulk InP is transparent at the emission wavelength. The absorption coefficient of InP ($n \simeq 2 \times 10^{18}\,\mathrm{cm}^{-3}$) was measured to be $\simeq 5\ \mathrm{cm}^{-1}$ in the 1.2-1.5-μm wavelength region.

V. Emission Characteristics

Emission characteristics were measured with current pulses. Fig. 8 shows the near-field pattern of an LED, when the pulse current was 40 mA (2 kA/cm^2). The emission area was about 50 μm in diameter which was in agreement with the p-contact area. The curved line shows the luminance distribution along the center line. Fig. 9 shows the emission spectrum at room temperature. The emission peak was at 1.17 μm and the full width at half maximum was about 1000 Å. The oscillation wavelength of a laser made from the same composition but with a thinner active layer was 1.22 μm. The difference of the lasing wavelength and LED peak seems to be caused by composition grading in the active layer, which was thicker in the case of the LED. The light output versus current is shown in Fig. 10. It can be seen that the LED exhibited linear output versus input current up to about 350 mA. The external quantum efficiency was not so high in the present stage. It can be considered that it is due to the leak of current through the isolation layer. The efficiency may be improved by increasing the thickness and impurity concentration of the isolation InP layer.

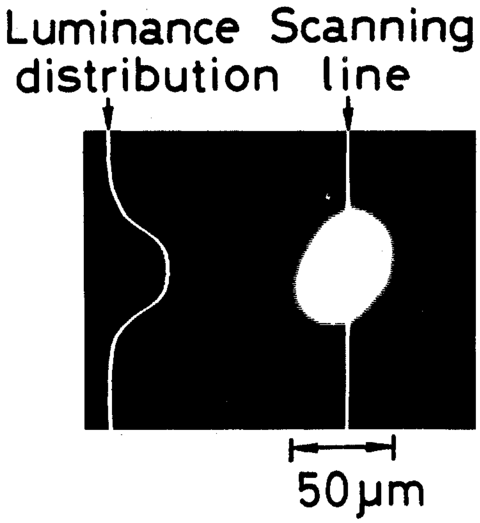

Fig. 8. A near-field pattern of an LED.

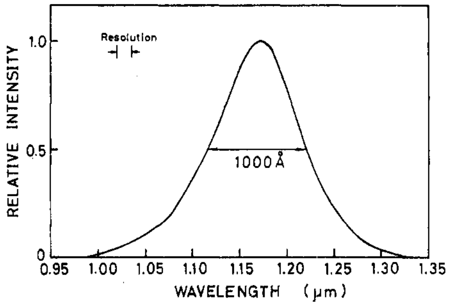

Fig. 9. Emission spectrum at room temperature.

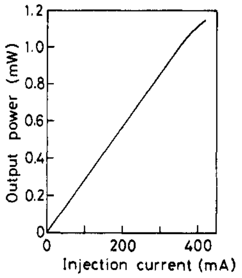

Fig. 10. Light output versus current characteristics.

VI. Conclusion

$Ga_{0.2}In_{0.8}As_{0.46}P_{0.54}/InP$ DH wafers were fabricated on (100) InP substrates by a two-phase solution technique using a vertical LPE furnace. Several etchants were examined for fabricating the special structure of InP and GaInAsP, and KKI-121 was found to be the best etchant at present. By using these techniques, surface-emitting planar LED's with convex mirror windows were fabricated. The peak emission wavelength was 1.17 μm and the full width at half maximum was about 1000 Å. The *I-L* characteristics exhibited fairly good linearity.

ACKNOWLEDGMENT

The authors wish to thank Prof. Y. Suematsu, Prof. H. Fukuyo, and Prof. S. Furukawa, as well as Associate Prof. N. Oura, Tokyo Institute of Technology, and T. Yamamoto, KDD Research Laboratory, for helpful discussion of this work.

REFERENCES

[1] H. Osanai, T. Shioda, T. Moriyama, S. Araki, M. Horiguchi, T. Izawa, and H. Takata, "Effect of dopants on transmission loss of low-OH-content optical fibers," *Electron. Lett.*, vol. 12, pp. 549–550, Oct. 1976.

[2] T. P. Pearsall, B. I. Miller, R. J. Capik, and K. J. Bachmann, "Efficient lattice-matched double-heterostructure LED's at 1.1 μm from $Ga_xIn_{1-x}As_yP_{1-y}$," *Appl. Phys. Lett.*, vol. 28, pp. 499–501, May 1976.

[3] A. G. Dentai, T. P. Lee, C. A. Burrus, and E. Buehler, "Small-area, high-radiance c.w. InGaAsP L.E.D.s emitting at 1.2 to 1.3 μm," *Electron. Lett.*, vol. 13, pp. 484–485, Aug. 1977.

[4] K. Oe, S. Ando, and K. Sugiyama, "Surface emitting LED's for the 1.2-1.3 μm wavelength with GaInAsP/InP double heterostructures," *Japan. J. Appl. Phys.*, vol. 16, pp. 1693–1694, Sept. 1977.

[5] H. Nagai and Y. Noguchi, "$InP/Ga_xIn_{1-x}As_yP_{1-y}$ double-heterostructure for 1.5 μm wavelength," *Appl. Phys. Lett.*, vol. 32, pp. 234–236, Feb. 1978.

[6] I. Umebu, O. Hasegawa, and K. Akita, "InGaAsP/InP D.H. L.E.D.s for fiber-optical communications," *Electron. Lett.*, vol. 14, pp. 499–500, Aug. 1978.

[7] K. Wakao, K. Moriki, T. Kambayashi, and K. Iga, "GaInAsP/InP DH laser grown by newly designed vertical LPE furnace," *Japan. J. Appl. Phys.*, vol. 16, pp. 2073–2074, Nov. 1977.

Comparison of Surface- and Edge-Emitting LED's for Use in Fiber-Optical Communications

DAN BOTEZ, MEMBER, IEEE, AND MICHAEL ETTENBERG, SENIOR MEMBER, IEEE

***Abstract*—The performance of state-of-the-art double-heterojunction (DH) surface and edge emitters are compared with respect to their use in high-data-rate fiber-optical communication systems. Thick-window (20–25-μm) surface emitters with 2–2.5-μm thick active layers and emitting up to 15-mW optical power at 300 mA have been fabricated. For edge emitters, we use very-high-radiance-type devices with ≃ 500-Å thick active layers. For these two types of LED's we examine differences in structure and light coupling efficiency to fibers of various numerical apertures (NA). For typically good devices we compare the diodes' output power capabilities, the powers coupled into step- and graded-index fibers of various NA, and their respective frequency response. For the same drive current level, we find that edge emitters couple more power than surface emitters into fibers with NA ≲ 0.3. The edge emitters also have ≈5 times larger bandwidths. We estimate that an edge emitter can couple 5–6 times more power into low numerical aperture (NA ≲ 0.2) fibers than a surface emitter of the same bandwidth. We conclude that edge emitters are preferred to surface emitters for optical data rates above 20 Mbits/s.**

Manuscript received January 2, 1979; revised January 30, 1979. This work was supported in part by the Department of the Air Force, Rome Air Development Center, Hanscomb Air Force Base, MA, and in part by RCA Laboratories, Princeton, NJ.

The authors are with RCA Laboratories, Princeton, NJ 08540.

I. INTRODUCTION

HIGH-RADIANCE light-emitting diodes (LED's) have been the subject of intensive research and development for fiber-optical communications, due to their linearity, small temperature sensitivity, and inherently small sensitivity to gradual degradation (compared to injection lasers). As a result of these efforts, two basic types of diodes have emerged: surface-emitting LED's [1] and edge-emitting LED's [2]. We present in this paper a comparison between state-of-the-art surface and edge emitters fabricated in our laboratory. The edge emitters are of the "very-high-radiance" type on which we reported previously [3]. The surface emitters are "thick-window" type diodes whose structure and performance are presented below.

The two types of diodes are first compared from a general point of view; differences in structure, emission angular distribution, and the consequent differences in coupling efficiency to optical fibers. For typically good diodes we compare the optical powers emitted into air, the powers coupled into optical fibers of various numerical apertures (NA), as well

0018-9383/79/0800-1230$00.75 © 1979 IEEE