The laser arrays described here are not individually addressable. Individually addressable laser arrays with 50-μm center to center spacings have been demonstrated.[10] A similar integrated circuit technology can be used to route conducting paths from the metal stripes over the active layers to bonding pads. To complete the wavelength multiplexed emitter the output from the array can be coupled to an optical fiber using a grating.[11,12]

In summary, we have demonstrated two techniques for wavelength multiplexing of laser arrays at 1.3 μm. Using an external cavity with a grating provides a linear dispersion of the wavelength with laser spacing. In the cleaved coupled cavity the wavelength is a function of the relative current in the two laser sections. The large optical cavity buried crescent geometry laser is particularly useful for arrays, since even at a center to center separation of 8 μm the lasers are optically uncoupled. In addition to the relative simplicity of wafer growth and high yields, the lasers are capable of emitting high power, have low current threshold, high quantum efficiency, and lowest order transverse mode operation.

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Selective low-temperature mass transport in InGaAsP/InP lasers

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A low-temperature mass transport process in InP was investigated. Mass transport of InP was achieved at 570–600 °C in a closed ampoule using iodine or InI as a catalytic transporting agent. Accomplishing the mass transport process at lower temperature has eliminated the problem of thermal etching and resulted in lasers with higher T_0.

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The fabrication of conventional buried heterostructure (BH) lasers requires a rather critical regrowth process in a liquid phase epitaxy (LPE) system. Recently developed mass transport techniques[1,2] offer simple alternative ways in which the regrowth step can be eliminated. The mass transport process provides an easy and elegant method to "bury" the active layer, thus reducing surface scattering loss,[3] yielding lasers with a more uniform far-field pattern. The thin mass transported InP region also serves as an excellent surface passivation and protection layer. Application of this technique has resulted in very low threshold lasers.[1,2] However, we have found that the threshold currents of mass transport lasers are rather sensitive to changes in ambient temperature, and these lasers are usually characterized by a low T_0 of 40–50 K. In recent studies on carrier leakage,[4,5] it was observed that heating the wafer at 675 °C prior to processing into the mesa laser structure in which any shunt leakage path has been eliminated,[3] the T_0 of the lasers degraded to 40–50 K as compared with 60–70 K of those processed from an unheated wafer. This strongly suggests that the low T_0 of mass transport lasers is due to the diffusion of zinc from the cladding into the active layer during the high-temperature ($\sim$675 °C) mass transport process, thereby reducing the doping concentration in the cladding layer and increasing the electron leakage current. Thus, the simplicity and other advantages offered by the mass transport process are somewhat offset by higher temperature sensitivities of the devices. In this letter, it is demonstrated that the low T_0 problem associated with the mass transport process could be overcome by accomplishing the mass transport of InP at low ($\sim$570–600 °C) temperature. Terrace lasers[2] fabricated with this new method have shown marked improvement in temperature sensitivities over those processed from the "ordinary" mass transport process without any sacrifice in threshold current and other characteristics.

In contrast to previous works,[1,2] where the mass transport was achieved in a LPE system using PH_3[1] or InP cover wafer,[2] experiments were conducted in a sealed evacuated

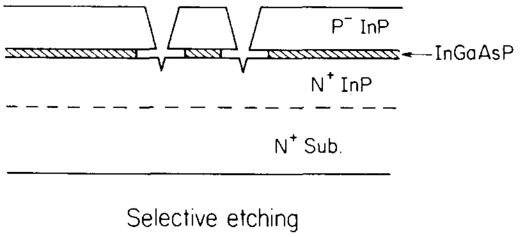

FIG. 1. Schematic drawing of the structure used for the study of the mass transport process. Two V grooves were etched, and the InGaAsP layer was then selectively removed, resulting in the undercut channels as shown.

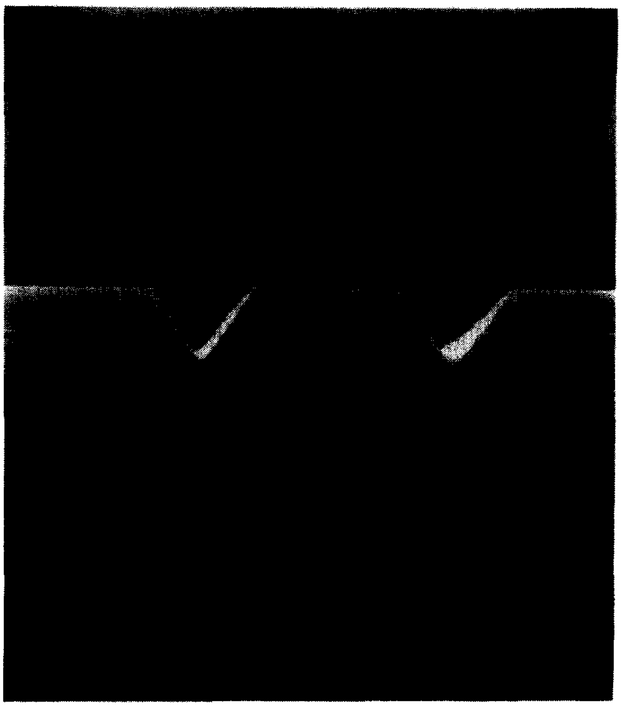

FIG. 2. SEM picture of the structure shown in Fig. 1 after heating at 690 °C for an hour in an ampoule with InP at the hot (730 °C) end. The dark regions are the InGaAsP layers, and the undercut channels (see Fig. 1) were filled with mass transported InP (scale = 1 μm).

ampoule placed in a furnace with a temperature gradient of ~ 2 °C/cm along the axis of the ampoule. The structure used in the study is shown in Fig. 1. Two etching windows 4 μm wide were impressed on an Si_3N_4 etching mask on the wafer in the $(01\bar{1})$ crystallographic direction. The wafer was then immersed in a solution of 2.5% Br in methanol, and two V grooves were etched. The InGaAsP layer was then selectively removed with a solution of $KOH{:}K_3Fe(CN)_6{:}H_2O$ (2:1:6), resulting in the desired 1–2-μm-wide undercut channels. The purpose of using this structure for studying the mass transport process is that the center region gives rise automatically to a BH laser (Fig. 1).

Various schemes for accomplishing mass transport of InP were then investigated, and results of the improved methods which enable the mass transport of InP to proceed at low temperature will be briefly described. The prepared wafer is positioned at the cold end of the ampoule, and different "source" materials are used at the hot end. Comparisons will be made for the three different source materials used: InP, InP + I, and InP + InI. Using InP as source at the hot end (~ 730 °C), mass transport similar to that described in Ref. 2 was observed. Full filling of the etched channels was achieved at 690 °C (wafer temperature) after one hour, as shown in Fig. 2. It can be seen that the corners remained sharp and the filling stopped at the (111) crystal planes. However, when the temperature at the hot end was reduced below 690 °C, no mass transport was observed. This is therefore an inherently high-temperature process, and is not satisfactory as it leads to lasers with low T_0's. Next, a small amount (1 mg) of iodine was added to the InP source, and the mass transport process was found to be accelerated. In this case, heating for 30 min at 600 °C was sufficient to fill in the entire undercut channel of about 2 μm in length. However, regions of the wafer not covered by Si_3N_4 were found to be etched. This is attributed to the high chemical activity of iodine. To prevent this etching, the chemical activity of iodine was reduced by using InI instead of pure iodine, and a "clean" mass transport was obtained with no observable etching on the wafer.

At 600 °C, the width of the mass transported region resulted using InI was found to be $\sim 20\%$ of that using pure iodine. This reduced rate of transport is advantageous as very thin passivation layer can be conveniently obtained, thus avoiding the undesirable addition of a parasitic junction due to a wide mass transported region. At 570 °C, the amount of mass transport was about half that at 600 °C (using InI). However, at 570 °C, a small amount of etching was observed on the wafer, and the temperature of 600 °C was found to be the optimum.

To ascertain that InP was transported from the source to the wafer, further experiments were conducted. Two identical wafers with undercut channels as shown in Fig. 1 were placed at the hot and cold ends of an ampoule respectively. After heating, the undercut channels of the cold wafer were filled with InP, while the hot wafer was found to be etched (Fig. 3), indicating that during the heating period, InP was indeed transported from the hot to the cold wafer, filling up the channels of the latter. The etching on the hot wafer was very pronounced, as shown in Fig. 3. The dark regions in the figure are the InGaAsP layers, which show the original thickness of the etched channels. It can be seen that InP was removed from the undercut channel, and the channel was etched to about four times wider. Similar results were observed at lower temperature with shorter heating duration in the presence of iodine or InI.

In the presence of iodine vapor, a chemical transport process took place. The iodine vapor acted as transport agent, reacting with the source material to give gaseous products.[6] During the growth reaction, the transporting agent was dissociated from the gaseous compound and diffused back to the source. The dominant chemical reaction involved is

$$2InP + InI_3 \rightarrow 3InI + \tfrac{1}{2} P_4.$$

The driving force for the transport of InP is the temperature gradient between the source and the wafer. The chemical agents (iodine and InI) merely act as catalysts and accelerate the transport process.

The transport process in Refs. 1 and 2 appears to be a

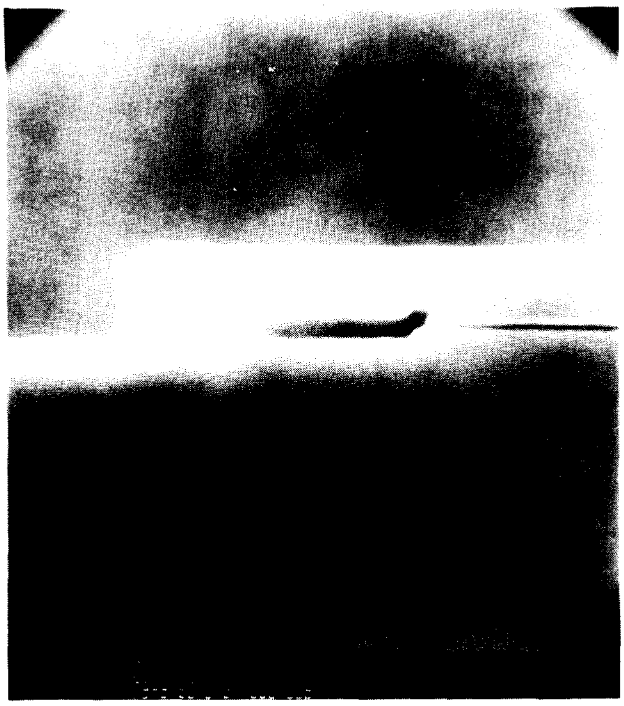

FIG. 3. SEM picture showing a magnified view of the etched channel of the wafer placed at the hot end of an ampoule after heating. The dark thin region on the right is the InGaAsP layer. The region to the left of the InGaAsP layer is the etched undercut channel (see Fig. 1), which is seen to be etched to about four times its original thickness (scale = 1 μm).

local rearrangement of InP molecules under phosphorus overpressure, while in the present case both indium and phosphorus are evidently supplied from the hot wafer. This is one of the advantages of the present method as the required materials are supplied from another wafer, and this prevents etching of the original wafer. Moreoever, it has been found that phosphorus overpressure alone may not lead to mass transport.[7]

Lasers fabricated with the low-temperature mass transport technique have threshold current densities and characteristics (except the T_0) comparable to the mesa lasers.[3] The advantage of using iodine or InI is that mass transport can be obtained at a temperature lower than the wafer growth temperature, and the undesirable diffusion of zinc mentioned above can be prevented, yielding lasers with higher T_0's. The width of the mass transported region varies directly as the heating time, amount of chemical agent present, and the temperature gradient. These parameters can be calibrated so that any desired width of mass transported region can be obtained reproducibly.

The mass transport technique is an excellent way to passivate and protect the surface. This is essential in the long term stability and reliability of the lasers. Burying the active layer also resulted in less surface scattering loss and better far-field pattern.[3]

In summary, low-temperature mass transport of InP has been achieved in a sealed evacuated ampoule containing InI as transport agent. An advantage of achieving the desired mass transport at relatively low temperature is that the process does not lead to any undesirable thermal etching of the original structure, which usually occurs when the transport process proceeds at high temperature (see Figs. 2 in Ref. 1). The greatest advantage, however, lies in the fact that this method has resulted in lasers with higher T_0 than those fabricated by executing the transport process at higher temperatures.

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