many of the listed features likely involve some of the indicated bands, we think it is unwise to make specific v'–v'' assignments for most of these lines, as they probably involve circumstantial overlap of rotational lines in several bands of the various isotopic molecules. Furthermore, Kvasnik and King's high-v'' assignments are inconsistent with our reanalysis of this transition. These authors also concluded that the HgCl emission in the 5540–5730-Å region includes a significant broadband contribution, attributed to a bound-free transition. We think it unlikely that such a bound-free transition could involve any of the known states of HgCl for the following reasons. (1) The $B \rightarrow A$ transition should lie about 4000 cm^{-1} to the red of $B \rightarrow X$. (2) The $C \rightarrow A$ and $D \rightarrow A$ systems *may* occur in this region; however, if these systems are present, the $C \rightarrow X$ and $D \rightarrow X$ systems should occur strongly in the UV. To our knowledge strong emission in the latter systems has not been reported for typical laser excitation conditions. (3) The continuum of the $B \rightarrow X$ transition falls precisely in this region; however, the Franck–Condon properties of this system prohibit significant continuous emission from v' levels less than 11. At a typical operating temperature of 150 °C the Boltzmann factor for the sum of *all* levels greater than 10 is about 10^{-3}. Thus if vibrational thermalization is appreciable, the $B \rightarrow X$ continuum must be negligible. While we cannot rule out broadband emission from other species in Kvasnik and King's laser system, we think it possible that their continuum is simply the quasicontinuum of densely overlapped lines in the $B \rightarrow X$ discrete emission. Even in our high-resolution, single-isotope spectra the emission appears almost continuous in some regions.

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Low threshold InGaAsP/InP lasers with microcleaved mirrors suitable for monolithic integration

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Low threshold InGaAsP/InP injection lasers on semi-insulating InP substrates have been developed with mirrors fabricated by the microcleavage technique. Miniature suspended bridges containing the laser channels have been formed and then microcleavage has been accomplished by the use of ultrasonic vibrations. Lasers with current thresholds as low as 18 mA with 140-μm cavity length and with 35–45% differential quantum efficiency have been obtained.

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The cavity of a semiconductor injection laser is conventionally formed by cleaving the semiconductor substrate along one of the crystal cleavage planes. The two resulting parallel planes are the laser mirrors. This technique, which results in high quality mirror surfaces, is not ideally compatible with integrated circuit technology because of the severe limitations it imposes on the geometry and dimensions of the semiconductor wafer.

Several techniques have been explored to create integrated laser mirrors that do not rely upon opposite cleaved facets of the substrate and, consequently, can be located anywhere on the semiconductor wafer. These techniques include chemically etched mirrors,[1,2] grown mirrors,[3] and distributed Bragg reflectors.[4] Another approach recently demonstrated in the GaAlAs/GaAs system is the microcleaved facet (MCF) technique[5,6] that results in cleaved laser mirrors without the cleavage of the substrates. These papers demonstrated the microcleavage technique with oxide stripe lasers having relatively high current thresholds. However, for monolithic integration purposes low threshold lasers on semi-insulating substrates are of interest.

In this letter we report a low threshold InGaAsP/InP laser with two microcleaved mirrors on a semi-insulating (SI) InP substrate. The laser structure is similar to the groove

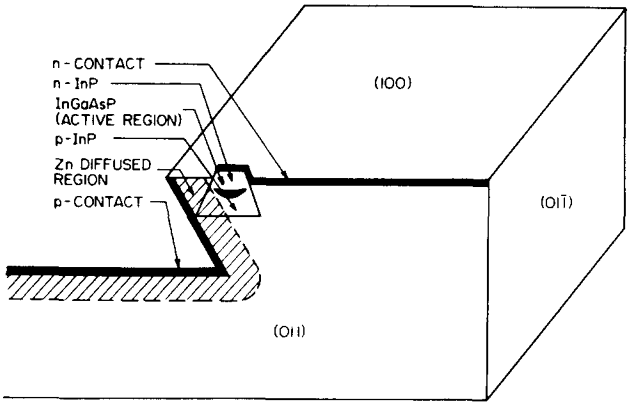

FIG. 1. Schematic cross section of the groove laser.

laser reported earlier[7] except that here both sides of the groove are masked by Si_3N_4 during epitaxy so that crystal growth occurs only inside the groove. The schematic cross section is shown in Fig. 1. Three layers are grown inside the groove: *p*-InP (Zn doped, $2\times10^{17}cm^{-3}$), InGaAsP (undoped), and *n*-InP (tin doped 2×10^{18} cm^{-3}). The *p* contact is obtained by Zn diffusion through an etched window in a Si_3N_4 mask (Fig. 1) followed by AuZn/Au metallization. The *n* contact is formed by an AuGe/Au layer covering the top *n*-type InP layer. This structure does not require epitaxial growth on the sides of the groove so that the original SI InP substrate remains intact and protected by Si_3N_4 mask during the liquid phase epitaxy. This is especially suited for monolithic integration with ion implanted field-effect transistors which can be fabricated on the SI InP substrate.

The microcleavage technique that is used here is somewhat different from those reported earlier[5,6] which were based on selective etching. Here, miniature bridges are formed by etching beneath a 15-μm-wide Si_3N_4 stripe which covers the grooved laser channel using 10% iodic acid etchant. This etching was done in the original SI InP substrate and does not intersect any grown layers, so that sharp, well-defined, dovetail-shaped directional etching is obtained on both sides of the Si_3N_4 stripe. When the etchings from both sides join, triangular suspended bridges which are confined by stop-etch planes are formed. Microcleavage is then accomplished by the use of ultrasonic vibrations.

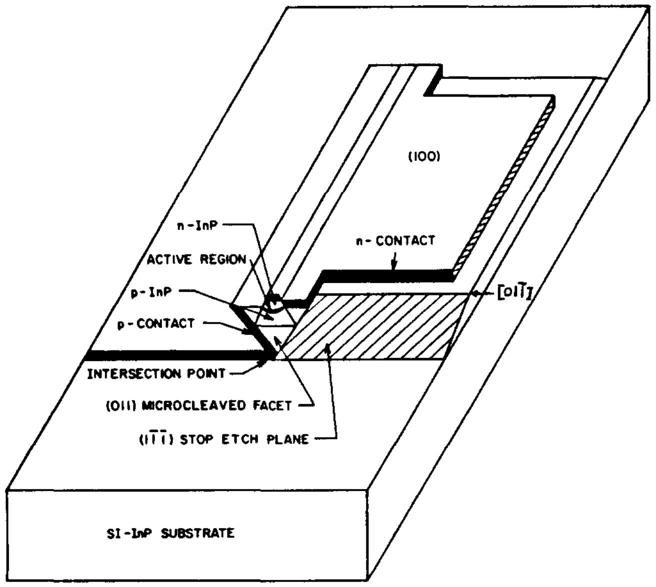

FIG. 2. Schematic description of the microcleaved section of the laser.

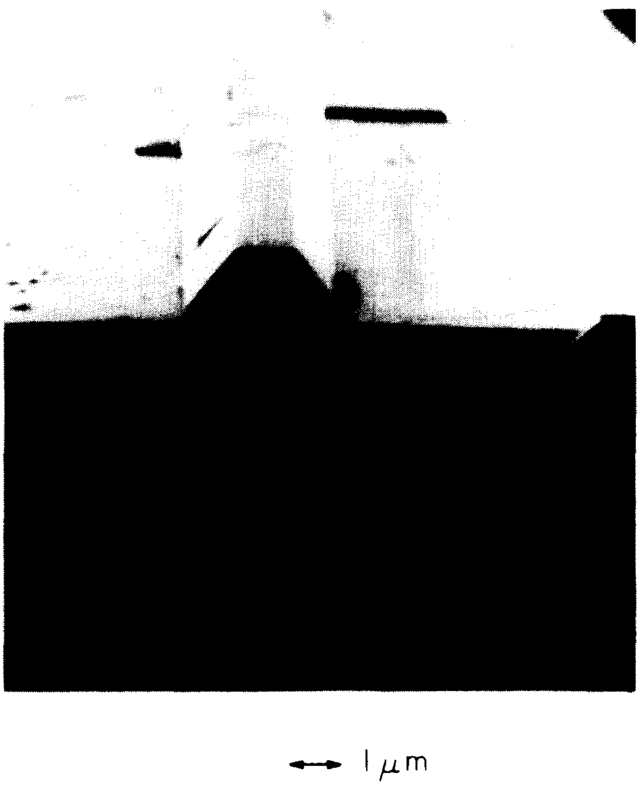

FIG. 3. SEM photomicrograph of the microcleaved mirror.

The etchings on the side of the Zn diffusion of the laser channel (shown on the left in Fig. 1) are continuous and uninterrupted through the longitudinal laser axis. On the right-hand side of the laser channel a directional etch is performed through square openings in a Si_3N_4 mask. The exposed squares define the suspended bridges which are then microcleaved, while the unexposed squares define the remaining laser channel and *n*-contact mesa. The resulting structure after microcleavage is shown schematically in Fig. 2.

An SEM photomicrograph of the microcleaved facet is shown in Fig. 3. The location of the microcleaved facet on the longitudinal axis is determined by the intersection point of the two stop-etch planes confining the triangular bridge and the (1$\bar{1}\bar{1}$) stop-etch plane that is etched at the [01$\bar{1}$] side of the Si_3N_4 square openings as shown in Fig. 2. The microcleaved facet always starts cleaving from this intersection point. This is an advantage of the present technique because previously reported techniques required a smooth line termination of the undercutting selective etching to achieve a good microcleaved facet.[5] A top view of the groove laser showing a complete laser device with two microcleaved mirrors and showing the laser channel and the *n*-contact mesa is shown in Fig. 4.

Lasers with two microcleaved mirrors have been operated cw with threshold currents as low as 18 mA for 140-μm

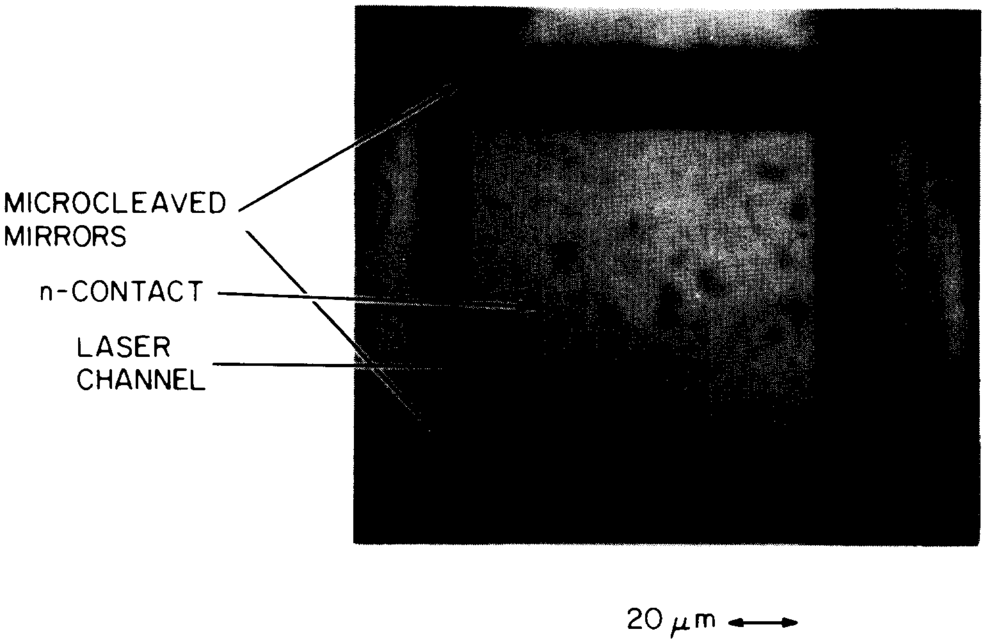

FIG. 4. Top view photomicrograph showing a complete laser device on the SI InP substrate.

cavity length. The lasers operate at a wavelength of 1.3 μm and with differential quantum efficiency of 35–45% per both facets. These results are statistically similar to those obtained for conventionally cleaved lasers of this type. The yield for operating lasers with two microcleaved mirrors on a 1.2×0.7 cm^2 wafer was about 15%. This relatively low yield is due mainly to defects in the processing steps which are not inherent to the microcleavage technique. It is expected that much higher yields can probably be obtained with this technique.

In conclusion, low threshold InGaAsP/InP injection lasers have been fabricated on SI InP substrate using a microcleavage technique to form the laser mirrors. The microcleavage technique is based on directional etching of the SI InP substrate to form miniature bridges which are defined by stop-etch planes. Laser with microcleaved mirrors are well suited for integration with other optoelectronic devices. This technique may also prove useful for fabrication of very short cavity lasers and for batch processing fabrication technology.

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