AIP Applied Physics Letters

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Citation: Applied Physics Letters **51**, 886 (1987); doi: 10.1063/1.98844
View online: http://dx.doi.org/10.1063/1.98844
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/51/12?ver=pdfcov
Published by the AIP Publishing

GaAs-GaAlAs graded-index separate confinement heterostructure laser diodes selectively grown by molecular beam epitaxy on SiO_2-masked substrates

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(Received 7 May 1987; accepted for publication 20 July 1987)

The GaAs-GaAlAs graded-index separate confinement heterostructure was grown selectively by molecular beam epitaxy on a SiO_2-masked GaAs (100) substrate. The stripe windows on the SiO_2 mask were 10 μm in width and were oriented along $[01\bar{1}]$ direction. The laser diodes thus fabricated lased in a single longitudinal mode with a side mode suppression ratio of 95:1. Both the longitudinal mode and the single-lobe far-field pattern were stable up to $4I_{th}$.

Optoelectronic integrated circuits (OEIC's) have received attention due to their potential application to optical communication systems.[1,2] Over the past few years considerable progress has been achieved: four-channel optical receiver[3] and transmitter[4] have been demonstrated, respectively.

Selective growth by molecular beam epitaxy (MBE) on dielectric-masked substrates was first proposed to achieve simultaneously electric devices and isolation.[5] This selective growth method by MBE,[6,7] as well as by metalorganic chemical vapor deposition,[8] was later recognized to be potentially applicable to the fabrication of OEIC's. It was demonstrated that dislocation-free, optical-quality, epitaxial GaAs could be grown on SiO_2 windows as small as 5 μm.[6]

In this letter the performance of laser diodes fabricated with this selective growth method is reported. The diodes lase in a single longitudinal mode without intentional lateral guiding and exhibit essentially single-lobe far-field patterns. Both longitudinal mode and far-field pattern are very stable for pumping current up to at least as high as $4I_{th}$.

The processing procedure is the same as that reported earlier.[6] The basic features are described in the following. A thin layer of SiO_2 was first deposited on a Si-doped n^+-GaAs (100) substrate. Standard photolithography was employed to open stripe windows on this SiO_2 mask layer. These stripes had a width of 10 μm and were oriented along $[01\bar{1}]$ direction. The masked substrate was then loaded into a MBE system. The structure of the MBE layers grown was that of a graded-index separate confinement heterostructure (GRINSCH).[9] The order of growth was as follows: a 0.3-μm-thick n^+-GaAs buffer layer, GaAlAs/GaAs superlattice buffer layers, a 1.5-μm-thick N-$Ga_{0.5}Al_{0.5}As$ cladding layer, a 0.2-μm-thick N-GaAlAs composition-graded layer, a 10-nm-thick unintentionally doped GaAs active layer, a 0.2-μm-thick P-GaAlAs composition-graded layer, a 1.5-μm-thick P-$Ga_{0.5}Al_{0.5}As$ cladding layer, and a 0.3-μm-

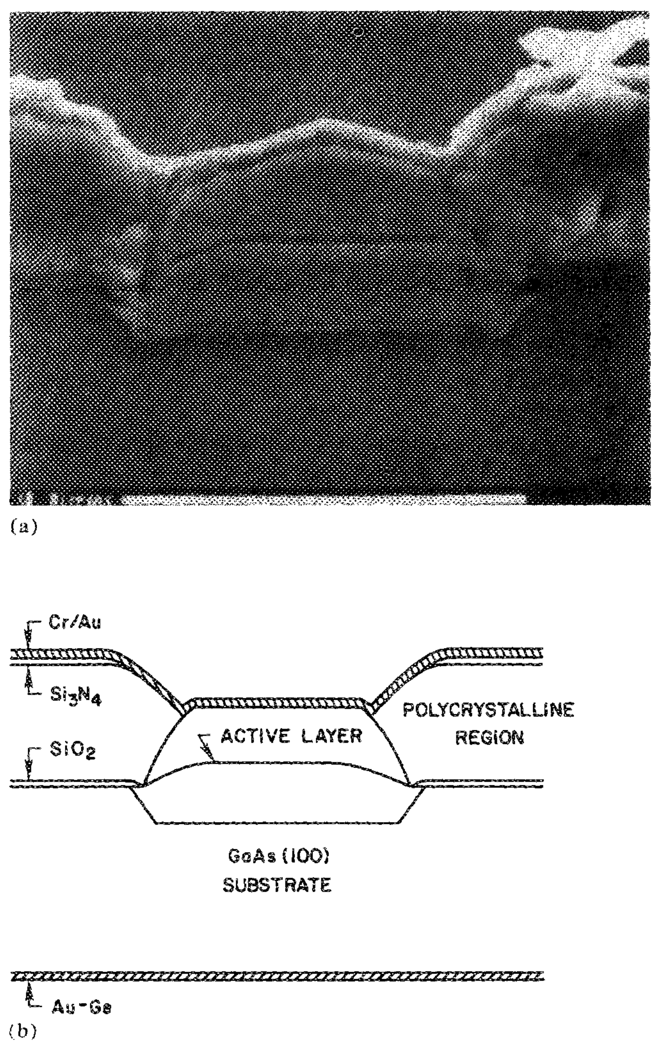

FIG. 1. (a) Scanning electron micrograph and (b) the corresponding schematic drawing of a $(01\bar{1})$ oriented laser facet. The length of white bar beneath the micrograph equals to 10 μm. Epitaxial layers were grown on the window, whereas polycrystalline materials were deposited on the SiO_2 mask.

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thick p^{+}-GaAs cap layer. The scanning electron micrograph and the corresponding schematic drawing of a $(01\bar{1})$ oriented laser facet are shown in Figs. 1(a) and 1(b), respectively. As in the previous cases[5,6] epitaxial semiconducting layers were grown on the windows, whereas columnar, polycrystalline high-resistivity materials were deposited on the SiO_2 mask. Post-growth processing included the deposition of a thin layer of thermal silicon nitride on the wafer, opening of contact windows of 10 μm in width, formation of contact layers, and cleaving of the wafer into individual laser diodes. It was noticed that, since the substrate was much thicker than the films grown, the presence of polycrystalline materials did not have a noticeable effect on the cleaving process.

The laser diodes were operated at room temperature under pulsed condition. The laser power output versus pumping current of a typical diode is shown in Fig. 2. The threshold current was 50 mA. The curve does not show any kink. The lasing spectrum at the injection current of 80 mA is shown in Fig. 3. The diode lased essentially in a single longitudinal mode at a wavelength of 846.2 nm. The side mode suppression ratio was calculated to be 95 to 1 at this pumping current. The same longitudinal mode was maintained up to $4I_{th}$, the maximum pumping current used.

The far-field radiation pattern parallel to the *p-n* junction is shown in Fig. 4. It consists of one dominant and symmetric mode and one smaller mode on one side of the dominant mode. The full width at half-maximum of the dominant mode at 200 mA ($=4I_{th}$) is 9.6°. As shown in Fig. 1(a) the width of the straight part of the active layer, W, is 5 μm. The corresponding diffraction angle ($\simeq$ lasing wavelength λ/W) is 9.7°. This value agrees very well with the measured value

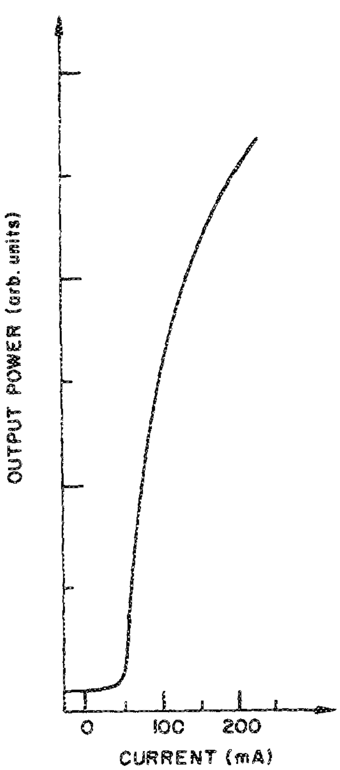

FIG. 2. Power output vs pumping current of a typical laser diode. The threshold current was 50 mA.

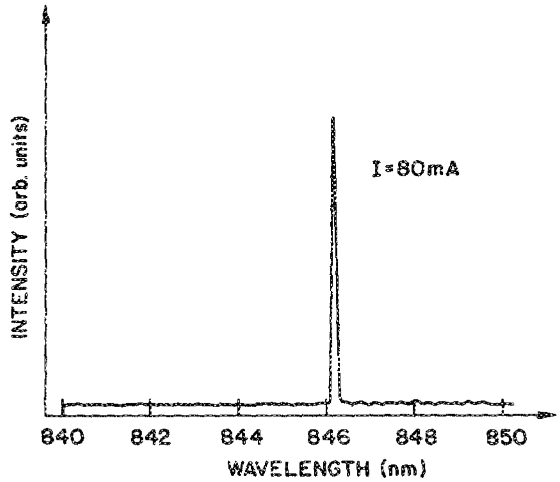

FIG. 3. Lasing spectrum of the same diode shown in Fig. 2. The side mode suppression ratio was 95 to 1 at this pumping current of $1.6I_{th}$.

above. The occurrence of the side mode is due to the asymmetry of the active layer (Fig. 1), which results from the off-normal incidence of the molecular beams on the masked substrate.[10] The far-field pattern is stable in the range of the pumping current used.

Both longitudinal mode behavior and far-field pattern indicate the presence of index guiding in the lateral direction. One possible source of the index guiding is the bending of the active layer at regions close to the polycrystalline materials. One can regard the epitaxial region as one large grain embedded in other smaller grains. During the MBE growth the three joining interfaces among the epitaxial grain, its neighboring grain, and the vacuum would assume an equilibrium configuration whose geometry depended on the relative magnitude of the three interfacial energies.[7] This required the growth front of the epitaxial grain close to the joint of the three interfaces to assume an orientation other than the (100) orientation. However, in the center region of the epitaxial grain the growth front was not affected, and it assumed the (100) orientation of the substrate. Consequent-

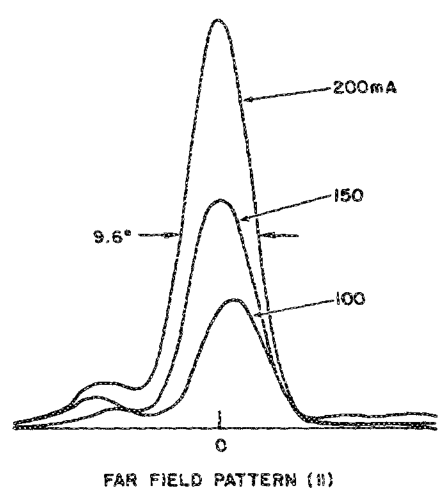

FIG. 4. Far-field pattern parallel to the *p-n* junction of a laser diode.

ly, the epitaxial layers were flat in the center but were bent at the two ends adjacent to the polycrystalline regions.

To study further the isolation properties of the polycrystalline regions the near-field pattern of the laser diode was measured. For the epitaxial region grown on the windows, the pattern showed uniform luminescence along the bent active layer below threshold current. When the current was gradually increased to above threshold, the diode began to lase near the center. On the other hand, no luminescence was observed from the adjacenet polycrystalline regions within the current range employed, even though the contact window (10 μm wide) was wider than the epitaxial stripe region.

Another set of laser diodes grown at the same time but with 15-μm-wide SiO_2 stripe windows was also studied. The near-field pattern showed the presence of two lasing filaments. One of them was located near the center of the straight section of the active layer. The other was at the smoother of the two bent sections. This was further evidence of the asymmetric growth across the $[01\bar{1}]$ oriented stripes. To improve the laser performance it was desired to have symmetric and smooth growth fronts. One approach was to employ substrate rotation during the MBE growth. Another was to grow the laser structure over the $[0\bar{1}\bar{1}]$ oriented stripes. Previous study[7] had shown that the epitaxial regions near the polycrystalline regions exhibited smoother profile for growth over $[0\bar{1}\bar{1}]$ oriented stripes.

In summary, GaAs-GaAlAs GRINSCH laser diodes have been fabricated using the selective growth method by MBE on SiO_2-masked GaAs (100) substrates. The diodes lased in a single longitudinal mode with a side mode suppression ratio of 95 to 1. Both the lasing longitudinal mode and the essentially single-lobe far-field pattern are stable for pumping current up to as high as $4I_{th}$.

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