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Monolithic integration of a transparent dielectric waveguide into an active laser cavity by impurity-induced disordering

Robert L. Thornton, John E. Epler, and Thomas L. Paoli
Xerox Palo Alto Research Center, Palo Alto, California 94304

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In this letter we report the successful combination of a low-loss buried waveguide providing two-dimensional optical confinement with an active gain medium. We have thereby realized a planar and monolithic composite cavity laser where the laser cavity consists of distinct regions of optical gain combined with distinct regions of low-loss optical waveguide. The low threshold currents of these strucures (< 10 mA) confirm the low loss and waveguiding nature of the waveguide regions. The ability to make these types of structures has applications for window lasers, monolithic waveguides, and monolithic integration of electrical and optical components.

The integration of active laser devices with transparent waveguides is an important capability for the realization of III-V advanced optoelectronics. Much work has been done on the fabrication of low-loss ridge waveguides on GaAs for long wavelength (1.1 μm) optical signal processing.[1,2] It is much more difficult, however, to realize a two-dimensional waveguide (guiding in both directions orthogonal to the propagation direction) that is simultaneously buried beneath the surface and low in propagation loss at the emission wavelength of a laser fabricated in the same set of epitaxial layers. Such a structure is desirable in order to facilitate coupling of the waveguide to an active structure such as a laser, which is of necessity a subsurface structure. Coupling of a laser to a waveguide has been successfully achieved by having two parallel waveguides couple evanescently[3]; however, since the laser and waveguide were not coaxial in this case, there was considerable scattering (reflection) at the transition between laser and waveguide. Impurity-induced disordering (IID) has demonstrated its utility in the formation of buried heterostructure lasers,[4] and recently there has been work studying the optical waveguiding properties of waveguides formed by IID.[5,6] However, any section of the active region in the previous structures that is not electrically pumped will be highly absorbing at the laser emission wavelength. Previous workers have shown that the use of multiple quantum well active regions can significantly reduce the magnitude of this laser self-absorption,[7,8] but the emission wavelength is still sufficiently close to the absorption band edge that absorption loss is on the order of 100 cm^{-1}. In addition, due to the proximity of the band edge, any lasing wavelength shift due to band-filling effects would result in rapidly increasing absorption losses in the unpumped regions.

The lasers described in this study were fabricated from material grown by the metalorganic chemical vapor deposition technique. The active regions consisted of a four-well three-barrier active region, similar to previously reported multiple quantum well structures, with cladding layers of 40% Al. These devices have been fabricated using the silicon impurity-induced disordering (Si IID) process reported previously.[9,10] It has been shown that this technology can be used to make a planar waveguide for a window laser with a 100-μm-wide aperture.[11] However, as the laser emission aperture is made narrower, as is desirable for a low threshold buried heterostructure laser, increased diffraction losses necessitate either the fabrication of a two-dimensional waveguide or the ability to cleave the device so that the window region is only a few microns long.[12]

In Fig. 1 we show the basic technique used to fabricate the waveguide. The waveguide is achieved by narrowing the Si diffusion masking stripe in the desired waveguide region. In order to depict more clearly the alloy composition profiles that result in the waveguide, Fig. 2 represents the cross-sectional alloy profiles in three characteristic regions of the structure. The A curve shows the as-grown, nondisordered structure with the quantum well retained, as would be observed along the line indicated as A in Fig. 1(a). The curve B in Fig. 2 shows the resulting alloy profile along the section indicated as B in both Figs. 1(a) and 1(b), wherein the enhanced interdiffusion by Si doping has had the maximum amount of time to progress and the alloy profile therefore more closely approaches the uniform profile of the 40% Al

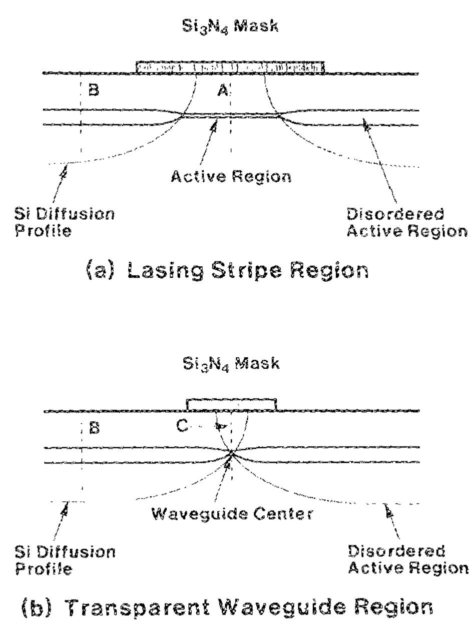

FIG. 1. Schematic diagram of the diffusion masking and diffusion profiles in the optically pumped (a) transparent waveguide and (b) sections of the composite cavity laser.

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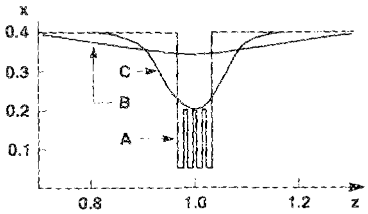

FIG. 2. Profiles of the estimated alloy compositional variation (x) along cross sections indicated in Fig. 1 as a function of depth from the surface (z).

cladding layers. In curve C of Fig. 2, we show the profile along the line bisecting the core of the transparent waveguide, along the line labeled C in Fig. 1(b). Since the enhanced interdiffusion has had the shortest amount of time to occur along this center line, the profile here will be intermediate between that of the as-grown active region layers and the more fully interdiffused layers that form the cladding of the waveguide. As a result, there is a maximum in Ga composition, and therefore refractive index, along this line, yielding a two-dimensional waveguide that is coaxial to the original active region.

Figure 3 shows scanning electron microscope (SEM) cross sections of facets cleaved through the two regions of the laser depicted in Fig. 1. Both facets have been heavily stained with an AB etch solution[13] to enhance the weak contrast due to variations in alloy composition in the transparent waveguide. As a result, the composition in the waveguide core [as reflected in the brightness of the central subsurface ellipse in Fig. 3(b)] appears comparable to the composition of the nondisordered active region in Fig. 3(a). This false perception is not observed when viewing the samples unstained; however, the unstained contrast is not sufficient in the waveguide case to provide for good photographic reproduction.

In Fig. 3(a), it should first be noted that in the region above the active region layer, there is a delineation of the edges of the Si diffusion profile. This is a result of p-n junction contrast from the n-type Si diffusion into the p-type upper cladding layers. It should further be noted in Fig. 3(a) that even in the low (~ 20 nm) resolution of a SEM photo, interfacial blurring of the active region greater than 20 nm can be observed starting at the p-n junction. It follows directly that the 12 nm quantum wells have been interdiffused to an extent greater than 20 nm up to the p-n junction. We use this fact in interpreting the SEM photograph in Fig. 3(b). Here we have allowed the lateral diffusion beneath the mask to proceed to such an extent that the two silicon diffusion fronts cross, eliminating all of the p-type material underneath the nitride masking stripe. Since the disordering has been observed to initiate at the point where the p-n junction intersects the active region, we can infer with complete certainty that the quantum well fine structure is destroyed in the waveguide region.

In Fig. 4 we compare the performance of lasers with and without two-dimensional waveguiding. Figure 4(a) shows

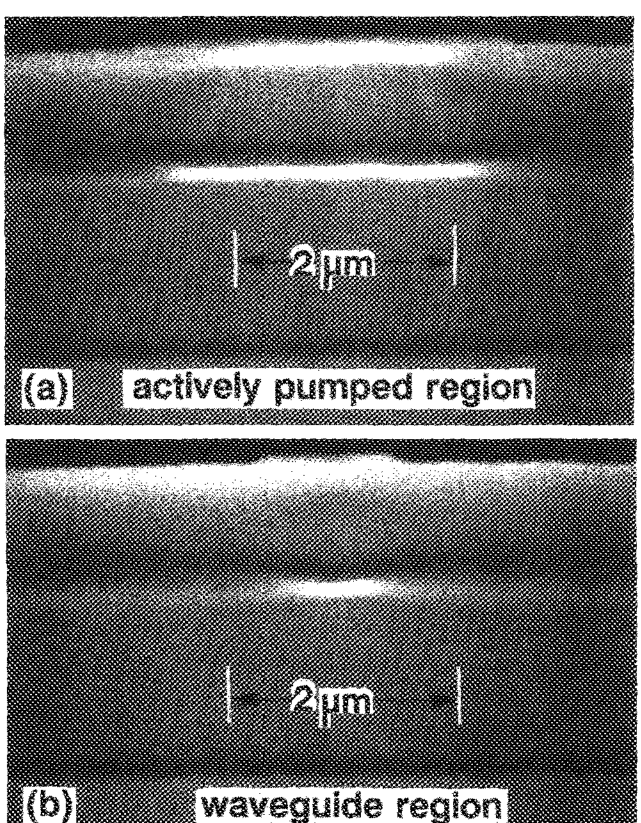

FIG. 3. SEM cross sections showing the buried heterostructure laser section of (a) the transparent optical waveguide section and (b) the composite laser cavity.

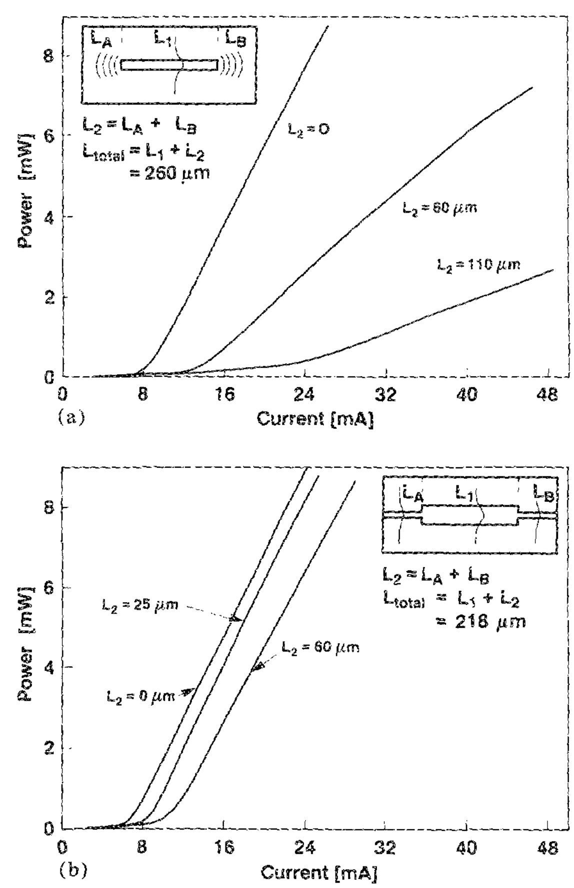

FIG. 4. Pulsed power vs current characteristics for the window lasers (a) without and (b) with two-dimensional waveguiding, showing the effect in both cases of increasing the length of unpumped regions in the laser cavity.

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the characteristics for lasers with increasing lengths of one-dimensional waveguide regions (which will result in one-dimensional diffraction) and Fig. 4(b) shows the characteristics for lasers with increasing lengths of two-dimensional waveguide regions. The insets in these two figures show the geometries of the devices for comparison purposes. The dramatically reduced dependence of slope efficiency on threshold for the devices in Fig. 4(b) is an indication that the diffraction and scattering losses in the two-dimensional waveguide case are low, and the only slight increase in threshold with increasing length of unpumped region in the two-dimensional waveguide case is an indication in addition that the propagation loss in the waveguide is also low. Since the waveguide regions are proton bombarded and therefore not electrically pumped, we would expect considerable absorption in these regions if they did not in fact consist entirely of material with wider band gap than the as-grown active region.

We have developed an estimate of the magnitudes of both the scattering loss at the active/waveguide region transitions and the propagation loss in the waveguide regions. By using several devices of varying waveguide and total cavity lengths,[14] we have solved for estimates of the scattering loss to be in the range of $\approx 7\%$, and for the waveguide propagation loss to be on the order of $\approx 10\ \mathrm{cm}^{-1}$. This value of propagation loss is of an appropriate magnitude to be consistent with free-carrier absorption in the $\approx 7\times 10^{18}$ n-type disordered waveguide region, but is too low to be consistent with band to band absorption if the lasing photon energy were higher than the band gap of the alloy composition of the waveguide, and the waveguide region were not electrically pumped. We therefore conclude that the propagation loss is indeed free-carrier absorption in a wide band-gap alloy that is substantially transparent at the lasing energy. It should be noted, however, that the numbers presented here are order of magnitude estimates only, and substantial error is possible due to the relatively small contribution that scattering loss and propagation loss make to the total threshold current.

In conclusion, we have successfully fabricated low-loss optical waveguides in the AlGaAs alloy system by impurity-induced disordering. These waveguides are novel in that they can be fabricated in a monolithic and planar fashion, are subsurface structures that are easily made coplanar and coaxial with buried regions of gain (such as the active region of a semiconductor laser), and they exhibit relatively low propagation loss at the wavelength at which such an active region would emit radiation. Although the propagation loss levels are not yet competitive with the low-loss waveguides fabricated in $LiNbO_3$ or undoped AlGaAs at longer wavelengths, the fact that optical gain elements are readily available to amplify signals will greatly ease the constraint on tolerable levels of propagation loss. These structures will therefore be of great interest in future realizations of integration of optical and electronic components.

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