Integrated optical bent waveguide with grown 45° mirror by selective liquid-phase epitaxy of GaAs

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An integrated optical bent waveguide with as-grown 45° mirror is fabricated using nearly atomically smooth facets only. These facets are grown by single-step selective liquid-phase epitaxy of GaAs. The mirror orientation is automatically adjusted to the optimum angles since the waveguide on \{100\} substrate uses only the as-grown \{111\} and \{100\} crystal planes as waveguide walls and 45° mirrors. The technique for the mirror location control is described taking into consideration the growth rate anisotropy.

Bent waveguides for changing the propagation direction of light waves are essential in integrated optoelectronic circuits. Curved waveguides have been studied for this purpose, but the waveguides have large radiation losses due to bending, mode conversion, and reflection.\(^1\)\(^2\) Also, their losses are more sensitive to roughness of the walls than those of straight waveguides. In order to reduce the bending loss, an uncomfortably large bend radius of up to 1 cm is required for a weakly guiding structure.\(^3\)\(^4\) On the other hand, scattering loss becomes dominant as we try to reduce the bending loss and bend radius by confining the guided wave more tightly.\(^5\) Such difficulties can be relieved by using a 45° mirror as an edge (or corner) reflector, and recently the concept has been applied to GaAs/GaAlAs material system.\(^6\)\(^7\) The edge reflector takes advantage of the fact that the critical angle for total internal reflection at the GaAs/air interface is 17° which is much smaller than the incidence angle of 45°, and that the guided light is laterally well collimated within about 3°. Thus, compact direction change can be achieved by the total internal reflection. However, propagation loss of the 45°-mirror bent waveguide is very sensitive to the orientation and the location of the mirror,\(^8\) and additional scattering losses result from rough-etched walls and mirrors.\(^9\)\(^10\) The purpose of this work is to achieve automatic adjustment of the mirror orientation to the optimum angles and to achieve reduction of the scattering losses. This is achieved by using epitaxially grown facets as waveguide walls and 45° mirrors.

It is well known that selectively grown epitaxial crystals on small or narrow windows with low index direction edges and a large surrounding masked area show very smooth crystal facets.\(^9\)\(^10\) These grown facets have been used as resonator mirrors for semiconductor lasers.\(^9\)\(^11\) In selective liquid-phase epitaxy onto \{100\} GaAs, \{111\} and \{100\} facets are dominantly observed because of their local minimum growth rates. The growth is initiated by nucleation on crystal edges where nucleation barriers are low and As supersaturations are high, and proceed through Kossel's mechanism. Thus, nearly atomically clean facets are reconstructed by the layer-by-layer growth with sufficient As atoms available from the surrounding masked areas. The growth is surface kinetics limited\(^12\) rather than diffusion limited, contrary to conventional large area liquid-phase epitaxy. On the other hand, diffusion limited growth is dominant in large windows and the fact is utilized in fabricating the integrated optical tapers.\(^13\)

Thus, the walls of the epitaxial layers selectively grown on \{100\} substrates in the kinetically limited regime are mainly \{100\} and \{111\} planes. One of the \{100\} facets is exactly 45° to \{110\} straight waveguides and exactly vertical to the \{100\} substrate surface. Therefore, an integrated optical 45°-mirror bent waveguide with faceted walls can be fabricated by single-step selective liquid-phase epitaxy. Moreover, the waveguide has automatically optimized mirror orientation with \(\alpha = \beta = 0\), as schematically shown in Fig. 1 (a).

According to Buchman and Kaufmann,\(^8\) to have a power loss less than 1 dB, the GaAs rib waveguide must have the angle deviation \(\alpha\) and the displacement \(\Delta\) \(\approx\) Fig. (1b) less than 0.6° and 0.9 \(\mu\)m, respectively. Additional 1 dB loss re-

![FIG. 1. (a) Schematic diagram of the proposed 45°-mirror bent waveguide. (b) Nonideal behavior of the mirror fabricated by conventional etching.](image-url)
sults from about 2° tilt (\(= \beta\)) of the mirror from being vertical to the substrate surface. Thus, alignment during the fabrication will be very critical when conventional wet or dry etching is used. Moreover, the rough-etched walls and mirrors give additional scattering losses. With the proposed bent-waveguide fabrication technique, most of the above problems are solved even if we use nominally \{100\} GaAs substrates.

The only remaining problem is the mirror location control to have the displacement \(\Delta\) equal to zero. Since the \{100\} planes are metastable, i.e., they have higher growth rate than the \{111\} planes, the \{100\} mirror location control is closely related to the growth rate anisotropy. Therefore, the larger the growth rate ratio, the longer the section of the window edge preferable to the \{100\} facet growth should be made for the control. The location control is possible by a proper choice of growth time and window shape when the desired waveguide thickness and growth rate data are given, as schematically shown in Fig. 2. A tentative value of 2.2 for the growth rate ratio between \{100\} and \{111\} plane is used. As is evident, the control may be difficult for a material of very large growth rate ratio. But the control is possible for GaAs, as experimentally shown in Fig. 3, in spite of the relatively strong growth rate anisotropy. Note that, in spite of the irregular details of the window shapes such as ragged and rounded edges and slight misorientations in Fig. 3(a), clear facets are developed in Fig. 3(b). This is due to the reconstruction of the singular facets by the layer-by-layer growth.

![Figure 2](image2.png)

**FIG. 2.** Schematic diagram showing the shapes of the 45°-mirror with growth time for two different window shapes. Note that the crystals become pyramids as growth time elapses sufficiently, irrespective of the window shapes. \(r\) is the growth rate.

![Figure 4](image4.png)

**FIG. 4.** Fabricated devices with 90° and 180° direction changes, respectively, which have been selectively grown on \{100\} GaAs substrate with SiO\(_2\) mask. The growth time and temperature are 20 min and 800 °C, respectively.
and is a distinguished advantage over dry- or wet-etching techniques, where irregularities of mask edges are directly transferred to result in rough surfaces.

Figure 4 shows the fabricated bent waveguides with 45° as-grown mirrors, which were grown for 20 min with a cooling rate of 0.2 °C/min at 800 °C. About 500-Å-thick rf sputtered SiO2 films were used as epimask. Conventional horizontal sliding technique was used for the epitaxy. The device has very smooth and clear surfaces and the automatically optimized mirror orientation is achieved, although the mirror location is slightly displaced. Thus, with the optimized $\alpha$, $\beta$, and $\Delta$ and very smooth waveguide walls and mirrors, propagation loss of the 45°-mirror bent waveguide can be minimized.

Apart from considerations on the fabrication, additional factors on optical mode control should be considered. The displacement $\Delta$ should be zero at a height of peak intensity of the guided lightwave considering the slanted {111} side walls of the straight guides. Either single or double heterostructure with additional AlGaAs layers may be used for further confinement of light energy inside the selectively grown epitaxial layers.

In summary, the fabrication of the 45°-mirror bent waveguide by single-step selective liquid-phase epitaxy has been described with corresponding experimental results. The device uses only very smooth crystal facets for both straight guide walls and 45° mirrors, therefore, the mirror orientation is automatically adjusted to the optimum angles. Thus, propagation losses are expected to be reduced significantly while using only a small chip area. Also, irregularities of the window edges or slight misorientations produced during photolithography processes do not give any harmful effect on the waveguide characteristics in contrast to the conventional etching techniques. Additional design considerations including the mirror location and the optical mode control have been presented. The bent-waveguide structure presented can be useful for integrated optical laser applications because it can solve the resonator formation problem.


Fe-C film formation by dual ion beam sputtering

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Fe-C films are formed by dual ion beam sputtering in which an ion beam irradiates the substrate during film formation. The magnetic properties and film structure of the resulting Fe-C films are investigated. As the acceleration voltage of the substrate beam increases, C concentration in the Fe-C films decreases, thereby changing the magnetostriction constant of the film from positive to negative. When films formed at an acceleration voltage of 0, 200, and 400 V are heated at 100, 300, and 400 °C, respectively, the relative permeability of each film reaches a maximum. The Fe-C film with 8 at. % C has a room-temperature saturation magnetic flux density of 2.2 T, a relative permeability of 900, and a magnetic threshold constant near zero.

The parameters in ion beam sputtering can be changed more independently than in other methods such as rf sputtering, making ion beam sputtering an excellent technique for investigating the mechanism of film formation. In recent years, magnetic films such as Fe, Fe3N, and permalloy have been formed using this method in an attempt to develop better materials for magnetic recording. The magnetic properties and film structures of these films have also been investigated. \(^5\) Magnetic properties are known to vary depending on the ion beam irradiating the substrate while the film is deposited by ion beam sputtering (dual ion beam sputtering method). \(^6\)

In this study, Fe-C films which have a high saturation magnetic flux density are investigated. The relation between the film forming conditions in ion beam sputtering and the magnetic properties and film structure of the Fe-C films are reported. The Fe-C film is heat treated in order to determine the effect of annealing on the magnetic properties and film structure.

A dual ion beam sputtering apparatus manufactured by...