High efficiency single quantum well graded-index separate-confinement heterostructure lasers fabricated with MeV oxygen ion implantation

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Single quantum well AlGaAs/GaAs graded-index separate-confinement heterostructure lasers have been fabricated using MeV oxygen ion implantation plus optimized subsequent thermal annealing. A high differential quantum efficiency of 85% has been obtained in a 360-μm-long and 10-μm-wide stripe geometry device. The results have also demonstrated that excellent electrical isolation (breakdown voltage of over 30 V) and low threshold currents (22 mA) can be obtained with MeV oxygen ion isolation. It is suggested that oxygen ion implantation induced selective carrier compensation and compositional disordering in the quantum well region as well as radiation-induced lattice disordering in Al₈Ga₁₋₈As/GaAs may be mostly responsible for the buried layer modification in this fabrication process.

Fabrication of high quantum efficiency and low threshold semiconductor lasers has attracted considerable attention in recent years. One limit to device performance is the leakage current (current which bypasses the active region of the device). In addition to several conventional methods such as diffusion, etching, and burying insulation layer growth, all of which have been shown to have some technical difficulties, ion implantation may provide some advantages. It has been established that selected ion species may create insulating or semi-insulating layers in semiconductor crystals. Such high-resistivity layers placed in appropriate regions can block current flow through undesired leakage paths in semiconductor lasers. In the AlGaAs-GaAs material system, proton implantation, which utilizes the lattice damage mechanism, was first used to demonstrate this possibility. Oxygen ion implantation by chemical doping has been shown to result in a stable semi-insulating material and has previously been reported as a current confinement technique for planar stripe lasers. This is also a potentially promising technique for current confinement in AlGaAs/GaAs channeled substrate planar lasers. Some work on Be or Fe ion implantation into the InGaAsP/InP system for laser fabrication has also been reported. However, most of the above-mentioned investigations were carried out by preparing a semi-insulating layered substrate through ion implantation followed by liquid phase epitaxial (LPE) growth of active and cladding layers on top. We report in this letter the utilization of MeV oxygen ion implantation for direct fabrication of single quantum well (SQW) graded-index separate-confinement heterostructure (GRINSCH) AlGaAs/GaAs lasers. We have taken advantage of selective carrier compensation, chemical doping, and implantation-induced compositional disordering with Al interdiffusion to improve the device performance with respect to efficiency and threshold current, and obtain improved electrical characteristics.

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Figure 1 shows a sketch of the SQW-GRINSCH AlGaAs/GaAs layer structure. It was grown by the molecular beam epitaxy (MBE) method on an n-type Si-doped (100) oriented GaAs substrate. A 2 μm GaAs buffer layer with uniform composition was first grown on the substrate in order to reduce substrate-related defects. Following the growth of a Si-doped Al₀.₅Ga₀.₅As cladding layer, a 70 Å quantum well active layer was sandwiched between two graded-index AlGaAs waveguide layers of 1500 Å thickness, in which the Al mole fraction was varied from x = 0.5 to x = 0.2 towards the quantum well. These graded-index AlGaAs layers provide parabolic waveguide regions for vertical confinement both for electrical carriers and the optical field. The growth was then continued with a Be-doped Al₀.₅Ga₀.₅As upper cladding layer and a GaAs cap contact layer.

For lateral confinement, MeV oxygen ion implantation was employed, as indicated schematically in Fig. 2. The processing of the device began with delineating the mask stripes along the (110) direction on the surface by using photolithography. The mask stripe is 10 μm wide and consists of a 3500 Å gold film with a 4-μm-thick photoresist (AZ4400) layer on top. It defines the laser cavity width and provides

![Fig. 1. Sketch of the layer structure of a single quantum well GRINSCH AlGaAs-GaAs laser grown by the MBE method.](image-url)
FIG. 2. Cross-sectional views of (a) a masked and as-implanted single quantum well GRINSCH laser device chip and (b) an oxygen ion implantation fabricated laser device with such a structure.

enough material to prevent the 2 MeV oxygen ions from reaching the lasing region and causing implantation damage. Ion implantation was carried out at room temperature using the Caltech Tandem accelerator. The beam energy of 1.8 MeV was chosen according to our data on oxygen ion range versus beam energy in GaAs and photoresist as well as standard stopping power data. The best results were obtained when the implanted layer straddled the graded-index regions and the quantum well layer in the device. A dose of $2 \times 10^{13}/\text{cm}^2$ was found to be optimal with a beam flux under 1 $\mu\text{A/cm}^2$. A diagram of the masked and as-implanted sample is shown in Fig. 2(a).

Following implantation the mask was removed by etching the sample in HCl acid for 1 min for the photoresist layer, followed by etching in a commercial gold etchant for the Au film. The sample was then annealed in a graphite heater at 650 °C for 10 min in N$_2$ ambient gas. This optimum condition was determined in a test of the annealing procedure for oxygen-implanted n-type and p-type GaAs, where we observed the effect of selective carrier compensation as we will discuss below. Finally, the AuZn was deposited to contact the surface p-type GaAs, and AuGe was evaporated on the backside to contact the n-type GaAs substrate. These metal contacts were alloyed at 450 °C for 20 s. The individual laser chips were then cleaved without subsequent coating for testing. A schematic diagram of a fabricated device is shown in Fig. 2(b).

For comparison, a SiO$_2$ stripe geometry laser was also fabricated from the same MBE-grown wafer as that used for implantation fabricated devices. The SiO$_2$ layer was 2000 Å thick and was thermally grown on the sample surface. The laser stripe was 10 $\mu$m wide and the cavity was 420 $\mu$m long.

Optical characterization of the fabricated lasers was performed at room temperature under a probe station. For a typical device of cavity length 360 $\mu$m, the lasing emission wavelength is 0.842 $\mu$m. The output power per facet versus the pulsed injection current is shown in Fig. 3. One finds that the threshold current is about 22 mA. A total slope efficiency (both as-cleaved facets combined) associated with this particular laser is about 1.25 W/A. A total external quantum efficiency over 85% was obtained. As a comparison, the output characteristic curve of a SiO$_2$ stripe laser has also been plotted in Fig. 3, where it is shown that the threshold current in this 10-$\mu$m-wide and 420 $\mu$m stripe laser is about 65 mA and the total external quantum efficiency is about 51%.

The electrical characteristics of the implanted laser diode were also measured. A typical current-voltage curve is presented in Fig. 4. A low leakage current and a high and sharp reverse breakdown voltage of over 30 V have been obtained.

Oxygen ion implantation as a means of creating semi-insulating layers in GaAs was first reported by Favennec et al. Recently, it has also been reported that a similar result can be achieved in AlGaAs. In contrast to proton bombardment, where the insulating effect is mainly due to lattice damage, oxygen ion implanted n-type GaAs and AlGaAs remain insulating after annealing above 600 °C. As damage due to bombardment normally disappears at this temperature, the insulating properties are ascribed to chemical doping with oxygen in the restored lattice. However, a different effect has been found in p-type GaAs material. It exhibits a feature similar to the proton implanted samples. It is believed that the electrical isolation in oxygen ion implanted GaAs is due to oxygen associated deep levels in GaAs, which trap electrons but not holes. Our experiments in testing samples have further confirmed this phenomenon. If n$^+$ and p$^+$-type GaAs samples are implanted with 1 MeV oxygen ions and annealed at temperatures under 600 °C, both samples were insulating, which was mainly due to residual
In summary, single quantum well GRINSCH lasers have been fabricated using high-energy oxygen ion implantation in combination with optimized thermal annealing. High external quantum efficiency, low threshold current, and excellent electrical characteristics were obtained. This technique requires fewer critical processing steps than those previously employed. It is shown that oxygen ion induced selective electrical compensation in n-type GaAs and AlGaAs as well as implantation-induced lattice disordering around the quantum well layer provides good electrical isolation for lateral current confinement. Oxygen ion bombardment can also induce Al composition interdiffusion in AlGaAs/GaAs superlattices, giving the desired effect of compositional disordering in the quantum well layer and graded-index regions, thus providing lateral optical confinement and reduced optical loss. A detailed investigation of this effect is under way.

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