FABRICATION OF GaAs/AlGaAs QUANTUM WELL LASERS WITH MeV OXYGEN ION IMPLANTATION*

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ABSTRACT

MeV oxygen ion implantation in GaAs/AlGaAs has been shown to provide a simple and very promising technique for quantum well laser fabrication. A 10μm stripe single quantum well (SQW) graded-index separation confinement heterostructure (GRINSCH) laser made in this way has achieved high performance with high quantum differential efficiency, low threshold current and good electrical isolation characteristics. MeV oxygen ion implantation with optimum thermal annealing produces a deep buried electrical isolation layer in n-type GaAs and reduces optical absorption in GaAs/AlGaAs quantum well structures. Ion implantation stimulated compositional disordering as well as implanted oxygen-related deep level traps may be considered as important effects for electrical and optical modification of interfaces in GaAs and AlGaAs.

INTRODUCTION

Ion beam processing of semiconductors with keV ions is a well-established technique for material surface modification and for electrical device fabrication. However, extending the beam energy to the MeV range in the processing offers the decided advantage of a greater ion range, which results deep implantation with minimum radiation damage at the sample surface. Thus, it allows many unique opportunities for the property modification of interfaces and deeply buried layers, and has high potential for three-dimentional device fabrication[1]. For III-V compound semiconductors, MeV ion beam processing has several promising applications since it has capabilities complementary to alternative methods such as thermal diffusion, chemical etching, liquid-phase and molecular-beam epitaxy. In this paper we present one example of an application of MeV ion beam processing in III-V optoelectrical device fabrication.

In semiconductor laser technology, considerable attention is still paid to injection current control and lateral optical confinement in order to gain high efficiency, low threshold current, and high power. In conventional fabrication processes, a complex procedure is commonly involved, in which the injection current is constrained by a SiO_2 stripe, which is thermally grown on top of the device, and the optical wave is guided by a cavity surrounded on all sides by the lower index $Al_xGa_{1-x}As$ heterostructures created through chemical etching and subsequent regrowth[2]. one popular laser incorporating such tranverse confinement with the buried heterostructure is presented in figure 1(a), taken from reference 2. Ion implantation has also

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been shown to provide a simple and very promising technique for this purpose. Ion-implantation-induced high resistivity layers placed in appropriate regions can block current flow through undesired leakage paths in semiconductor lasers. Bombardment with protons or deuterons was first used to demonstrate such a possibility[3,4]. Oxygen ion implantation as a means for generating stable high resistivity in GaAs was reported to be an effecient technique for current confinement in (Al,Ga)As planar stripe lasers[5,6]. Some work on Be or Fe ion implantation into an InGaAsP/InP system for laser fabrication has also been reported[7,8]. However, most of these investigations were carried out by preparing a semi-insulating layered substrate through keV ion implantation followed by epitaxial growth of active and cladding layers on top. Recently, we have undertaken an investigation to utilize MeV oxygen ion implantation to fabricate (Al,Ga)As lasers directly. A single quantum well (SQW) graded-index separate confinement heterostructure (GRINSCH) AlGaAs/GaAs stripe laser made in this way has shown high quantum efficiency, low threshold current, and good electrical characteristics[9].

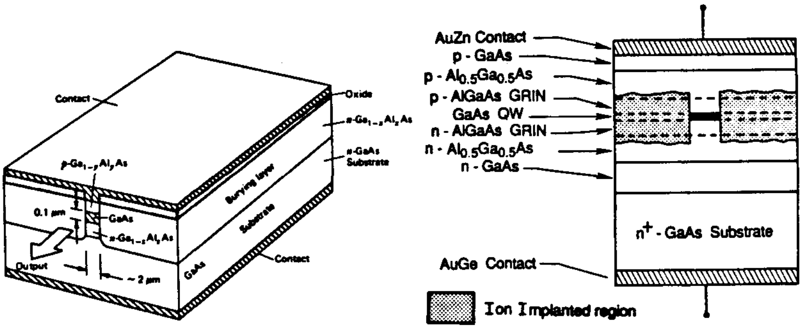
In this report, the effects of implanted oxygen in GaAs and AlGaAs will be summarized. The device fabrication with MeV ion implantation and the experimental results will be described in detail, along with a discussion about the mechanism involved.

EFFECTS OF IMPLANTED OXYGEN IN GaAs-AlGaAs

Creating buried insulating or semi-insulating layers in GaAs and AlGaAs by ion implantation has attracted considerable attention for many years. Oxygen ion implantation plus subsequent thermal annealing has been shown to be the most promising method to generate stable high resistivity (up to $10^8 \Omega/\text{cm}^2$) layers in n-type GaAs [10] and in n-type AlGaAs [11]. In contrast to proton bombardment where the lattice damage mechanism is responsible for the electrical isolation, oxygen ion implanted samples preserve thermal stability at temperture up to 950°C. As damage due to bombardment normally recovers at temperatures higher than 600°C, the insulating property is ascribed to chemical doping with oxygen in the restored lattice[11,12]. It is proposed that this method relies on the formation of an oxygen-related deep acceptor-like level that traps the electron charge carriers, instead of holes, in the material, resulting in a selective carrier compensation effect[13]. We have investigated its dose-dependence by *in situ* resistivity measurement during the implantation[14]. In as-implanted samples, a dramatic resistivity change was found at a dose level of 10^{12}ions/cm^2, and the resistivity becomes relatively stable at doses over 10^{14}ions/cm^2, since a continuous amorphous layers forms. The selective carrier compensation was comfirmed by I-V measurement on 1 MeV oxygen ion implanted and annealed n- and p- type GaAs single crystals, where n-GaAs was shown to be insulating, but p-GaAs was conducting[9].

Oxygen-ion-induced compositional lattice disordering or mixing is another interesting effect, which provides a method to tailor optoelectrical device geometries[15]. In an AlGaAs/GaAs superlattice system, interdiffusion of Al causes a mixing of AlGaAs with GaAs, which leads to an increase in the AlAs mole fraction in the GaAs layers, resulting in an up-shift of the energy bandgap and an effective decrease of the refractive index in those layers. Ion-implantation-induced lattice disordering in superlattices has been observed for Si, Zn, Al, Ar, Kr, and F ions[15−18]. It is comfirmed that ion implantation is a more effective, selective, and maskable method. Recently, our preliminary work[19] by secondary ion mass spectrametry profiling and cross-sectional transmission electron microscopy imaging has revealed that oxygen ions implanted into AlAs/GaAs superlattices can also induce lattice disordering. This evidence shows that significant Al interdiffusion can take place in the implanted region; a detailed investigation of this effect with MeV ions is in progress.

In optoelectrical applications, the effects of oxygen in ion implanted samples discussed here would provide some unique and controllable functions, which make the device fabrication procedure simple and promising.

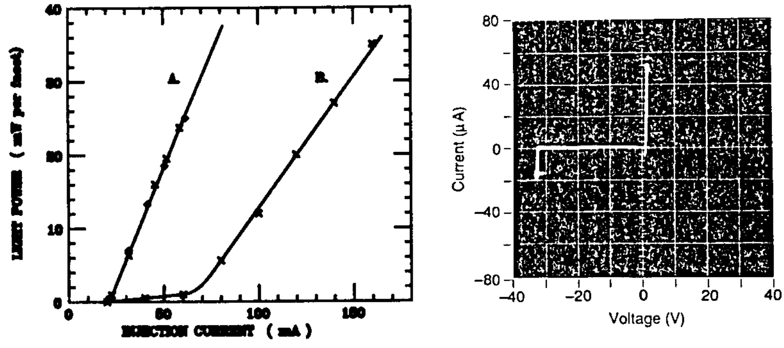


(a) (b)

Figure 1. **(a)** A conventional buried heterostructural laser (taken from reference 2). **(b)** A cross-sectional view of a single quantum well graded-index separation confinement heterostructural laser fabricated with ion implantation.

DEVICE FABRICATION AND RESULTS

The SQW-GRINSCH (Al,Ga)As laser chips used in this study were grown by the MBE method on an n-type Si-doped < 100 > oriented GaAs substrate. A quantum well with active layer 70 Å thick was sandwiched between two graded-index $Al_xGa_{1-x}As$ waveguide layers 1500 Å thick, with $Al_{0.5}Ga_{0.5}As$ cladding layers on both sides. In the GRIN layers, the Al mole fraction value was varied from 0.5 to 0.2 towards the quantum well edges. They provide parabolic waveguide boundaries for vertical confinement both for the electrical carriers and the optical wave. A cross-sectional view of such a structured laser is shown in Figure 1(b) along with an indication of the oxygen ion implanted regions. MeV oxygen ion implantation was employed for lateral confinement with the associated effects discussed above. To define a laser cavity stripe, a set of 10 μm wide masks, which consist of a 3500 Å thick gold film and a 4 μm thick potoresist layer, were delineated parallel to the (110) direction on the sample surface to protect the active lasing area from implantation damage. Oxygen implantation with a beam energy of 1.8 MeV, carried out with the Caltech Tandem accelerator, was performed at room temperature with a dose of 2×10^{15}ions/cm^2. These parameters were optimized in order to let the implanted layer straddle the quantum well and the graded-index layers and completely compensate the original electrical conducting carriers in the desired isolation region. The device was then annealed optimally at 650°C for 10 min to remove the damage produced by the implantation. Metallization was placed onto both surfaces for ohmic contacts. The resulting device was finally cleaved to obtain the reflecting end facets.



(a)

(b)

Figure 2. **(a)** A characteristic curve of the output light-power per facet versus the pulse injection current; A): an oxygen ion implantation fabricated SQW GRINSCH (Al,Ga)As laser; B): a laser fabricated by a SiO_2 stripe with the same layerd structure. See the text for the details. **(b)** I-V characteristic curve of an oxygen ion implantation fabricated SQW GRINSCH (Al, Ga)As laser.

Optical characteristic measurements were performed at room temperature under a probe station. For a typical cavity geometry of 10 μm ×360μm, the lasing emission wavelength is 0.842 μm. The light outputs from two end facets were tested to be nearly the same. The characteristic curve of the output light power per facet versus the pulsed injection current (Curve A.) is plotted in figure 2(a). For combined two facet output the curve slope associated with this device is about 1.25 W/A. A total external quantum efficiency of over 85% was obtained. The corresponding current threshold is about 22 mA. For a comparison, Curve B in figure 2 was taken from a device fabricated by a 10 μm width SiO_2 stripe window with the same layered structure, where a threshold current of 65 mA and an efficiency of 51% are obtained. In addition, the oxygen ion implanted device has also shown exellent electrical characteristics. Its current-voltage characteristic curve is shown in figure 2(b). A high and sharp reverse bias breakdown voltage of over 30 volts has been obtained.

DISCUSSION

As pointed out earlier, high performance of semiconductor lasers requires crucial current control and lateral electrical and optical confinement, the same as for vertical confinement. Compared to conventional processes for buried heterostructure laser fabrication, oxygen ion implantation provides a simple and promising technique with fewer critical steps. The mechanism of improved performance in oxygen ion implantation fabricated lasers is rather complex. It takes advantages of all effects produced by implantation. First, the deep-level-associated high resistivity in the implanted region gives directly a precise injection current control around the laser active region, which minimizes the device threshold current. Selective carrier compensation insures protection of the surface p-GaAs layer and reduces the requirement for the mask thickness. Ion-implantation-induced compositional lattice disordering may be main features responsible for high lasing quantum efficiency. Intermixing of the GaAs quantum well layer with surounded GRIN AlGaAs layers results in an Al mole fraction increase, and, in turn, in a bandgap energy change and a refractive index change, which serve for electrical carrier confinement and optical wave guiding in the GaAs lasing area. High efficiency in the implantation fabricated lasers also indicates that the optical absorption by residual damage and implantation-induced deep traps is very low. In addition, oxygen ion implanted lasers have better thermal resistance and stability than for a SiO_2 stripe laser, since the SiO_2 layer forms a significant thermal barrier because of the very low thermal conductivity of SiO_2 (about 1 percent of the thermal conductivity of GaAs)[20].

Formation of insulating or semi-insulating layers by ion implantation into semiconductors and its application to device fabrication have been exploited in modern device technology. One technique is to prepare a semiconductor-on-insulator structure (SOI) material by ion implantation with candidate ions; the material then serve as a substrate for further device processing. Another method is to introduce high resistivity into desired regions in a structured device, providing a current blocking layer for better device performance; that is the case we present in this paper. In the III-V compound semiconductor materials, only a moderate dose is required. This makes the implantation technique promising for use. It is noted that this method can be also applied to the InP laser system. We have found that MeV nitrogen ion implantation can generate high resistivity in n-type InP crystals[21]. Two different laser structures with ion implantation have been proposed[21]; the device processing work is underway.

CONCLUSIONS

In conclusion, we have investigated the fabrication of SQW-GRINSCH AlGaAs/GaAs stripe lasers by high energy oxygen ion implantaion. This technique minimizes the critical processing steps required by conventional processes, and gains high device performance, i.e. high efficiency, low threshold current and good electrical characteristics. It also suggests the possibility of MeV ion beam processing for other III-V semiconductor device applications.

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