Corrugated laser structures*

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GaAs–GaAlAs double-heterostructure injection lasers consist of several epilayers of GaAs and GaAlAs grown on a GaAs substrate. The need for cleaved end mirrors may be eliminated in these lasers by incorporating internal periodic corrugation which provide feedback. This distributed feedback relies on Bragg reflection from the periodic perturbation, and thus the lasing wavelength is directly proportional to the corrugation period. Such corrugated laser structures are compatible with the fabrication of monolithic optical circuits and seem to be most suitable as light sources for integrated optics. Our group prepared corrugated structures by ion milling or chemical etching through a photoresist mask which was generated by the interference of two laser beams. We observed laser emission from GaAs–GaAlAs double heterostructures with internal corrugation when pumped electrically at 77 °K. Theoretical considerations indicate that such lasers should have a very low threshold current and a good wavelength selectivity. Further experimental work on these devices is now in progress.

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INTRODUCTION

Recent advances in the area of fiber optics and the fabrication of glass fibers with low transmission losses enhanced the interest in fiber-optics communication systems. These systems require, for example, a modulated light source at one end of a fiber, a detector at the other end, and repeaters along the fiber. Such a system may be realized with discrete components, but it is hoped that the components would be integrated to form integrated optical circuits.[1] One of the promising materials for this purpose is GaAs, because it can be readily used to fabricate discrete components such as detectors, light guides, and modulated light sources. Moreover, the losses of the glass fibers are lower than 4 dB/km for the light emitted by GaAs sources ($\lambda \sim 0.9\ \mu m$). In this work, we were mainly interested in the fabrication of GaAs surface lasers, which could be used as light sources, and would be compatible with planar technology.

A homojunction *p–n* GaAs diode can be made to lase by passing sufficiently high current through it. This current can be modulated at very high frequencies, and the modulated emitted light can serve for the transfer of information. The performance of these junction lasers was much improved by incorporating one or two epitaxial layers of GaAlAs,[2] thus forming a single heterostructure (SH) or a double heterostructure (DH). Heterostructure junction lasers are usually grown by liquid-phase epitaxy (LPE), but may also be grown by vapor-phase epitaxy (VPE) or molecular-beam epitaxy (MBE). In these structures, the *p–n* junction between $Ga_{0.7}Al_{0.3}As$ and GaAs can lase like a regular homojunction. But, because of differences between the refractive indices and between the band gaps in the two materials, the free carriers and the radiation are better confined. Therefore, the heterostructures lase at low threshold currents and can be operated continuously at room temperature.

The lasers mentioned above consist of a sample (i.e., GaAs) with two end mirrors, which are either cleaved or polished. These mirrors form a Fabry–Perot arrangement, and provide the feedback required for laser oscillation. The problem is that the mirrors are hard to fabricate and susceptible to degradation, and are not compatible with planar technology.

A novel feedback mechanism was suggested by Kogelnik and Shank,[3] which is based on a periodic perturbation in the refractive index or in the gain (or loss) of the guiding medium. This perturbation may give rise to reflection and to lasing without end mirrors, and the laser thus formed is called distributed feedback (DFB) laser. Kogelnik and Shank[4] demonstrated laser action in a dye solution with DFB due to spatial modulation of the gain and the refractive index. It was pointed out[3] that a periodic perturbation in a waveguide height is, in effect, similar to a periodic change in the refractive index, and may also give rise to distributed feedback. In semiconductors such feedback may, therefore, be obtained by a periodic corrugation. Recently, the operation of GaAs–GaAlAs SH,[5] of GaAs

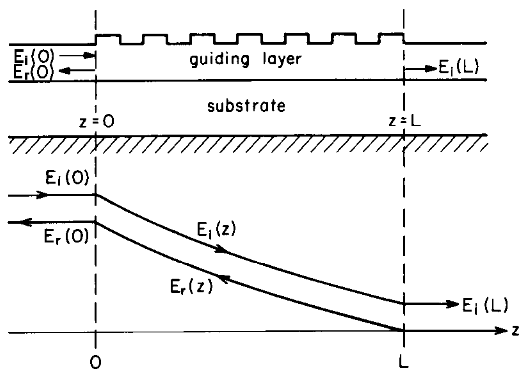

FIG. 1. The behavior of the incident (E_i) and reflected (E_r) waves in a passive periodic waveguide of length L. (The periodicity is represented here by a boundary perturbation.)

homostructure,[6] and of GaAs–GaAlAs DH[7] injection lasers with distributed feedback was demonstrated at 77° K. It is hoped that in the future these corrugated structures will operate at room temperature with high efficiency and stability.

THEORY

In order to understand the basic principles of DFB lasers, let us first discuss a passive waveguide with surface corrugation of period Λ, as shown in Fig. 1. Consider an incident wave of amplitude $E_i(0)$ at $z=0$ and wavelength λ_0/n in the waveguide, where λ_0 denotes the wavelength in vacuum and n the refractive index of the medium. It can be shown[8] that the passive waveguide will act as a grating filter if

$$\lambda_0/n \approx 2\Lambda/m \text{ (Bragg condition)}, \tag{1}$$

where m is an integer. The incident wave would then be strongly attenuated, while a large part of the energy would be reflected by the periodic structure in a manner similar to the Bragg diffraction of x rays from crystal planes. The amplitudes of the incident and of the reflected beams are also shown in Fig. 1.

Next, consider a corrugated active waveguide, i.e., a case where the waveguide medium provides gain. In this case, the incident wave no longer decays: instead, it increases and reaches a larger value $E_t(L)$ upon leaving the corrugated region ($z=L$). The reflected wave also increases and it leaves the corrugated region at $z=0$ with an amplitude $E_r(0)$, as shown in Fig. 2. Let α be the amplitude gain of the medium, $\Delta\beta=2\pi n/\lambda_0-2\pi/\Lambda$ the deviation from Bragg condition, and $\gamma^2=\kappa^2+(\alpha-i\Delta\beta)$,[2] where κ depends on the nature of the periodic perturbation. It can be shown[9] that if

$$(\alpha-i\Delta\beta)\sinh(\gamma L)=\gamma\cosh(\gamma L), \tag{2}$$

then both $E_t(L)/E_i(0)$ and $E_r(0)/E_i(0)$ are infinite. This means that the corrugated active waveguide acts as an oscillator, since it gives a finite output $E_t(L)$ and $E_r(0)$ with no input $[E_i(0)=0]$. This type of laser oscillator is the DFB laser mentioned earlier, and Eq. (2) gives the oscillation condition.

DFB lasers must oscillate near Bragg condition ($\lambda_0 \approx 2n\Lambda/m$), which means that the lasing wavelength can be selected by choosing a certain corrugation period Λ. This is in contrast to regular Fabry–Perot-type semiconductor lasers, where the oscillation frequency cannot be predetermined. Moreover, theoretical calculations[10] show that by properly designing the laser structure the DFB lasers could have a threshold which is lower than that of regular lasers.

FABRICATION OF CORRUGATED STRUCTURES

The oscillation wavelength of a distributed feedback laser is determined approximately by Eq. (1). For GaAs at 77° K, lasing can occur at $\lambda_0 \sim 0.82$ μm, and the refractive index is $n\sim 3.6$. Therefore, a corrugation of period $\Lambda\sim 0.11$ μm is required for $m=1$, or of period $\Lambda \sim 0.34$ μm for $m=3$. The most widely used technique for fabricating gratings of such a small period consists of etching of the crystal through a periodically slotted mask.[11]

The mask can be generated by holographic techniques in a thin (~1000 Å) photoresist film (Shipley AZ1350B) which was spun coated on a polished GaAs sample. For that purpose Ar^+ or He–Cd lasers may be used. The laser beam is first split in two. Each partial beam passes through a spatial filter (a lens and pin-hole combination), and then reflected from a mirror so that the two beams meet at an angle 2α. A spatial interference pattern is thus formed, with a period which is given by

$$\Lambda=\lambda/2\sin\alpha, \tag{3}$$

where λ is the wavelength of the laser. When the photoresist film is exposed to the interference pattern, the pattern is recorded, and after development a photoresist grating is formed on the GaAs sample. The grating period Λ can be varied by varying λ or α, and for a small period we need a small λ. The shortest wavelength available at present is $\lambda=0.3250$ μm from the He–Cd laser, and by taking $\alpha\approx 90°$ we can make gratings of period $\Lambda=0.1625$ μm. As mentioned, a period $\Lambda=0.11$ μm is required for fundamental gratings ($m=1$) in GaAs. We found that the period can be decreased by adding a quartz prism and some index matching oil on top of the photoresist layer, as shown in Fig. 3. The grating period was now $\Lambda=\lambda/(2n_Q \sin\alpha)$,

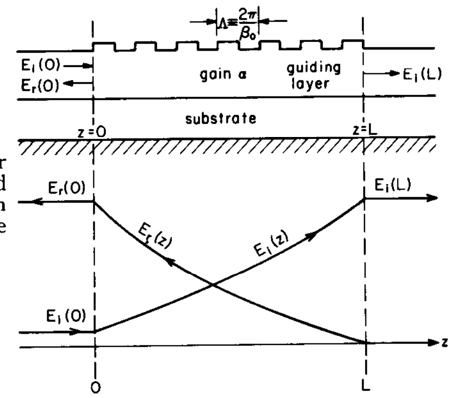

FIG. 2. The behavior of the incident and reflected wave in a periodic waveguide with gain.

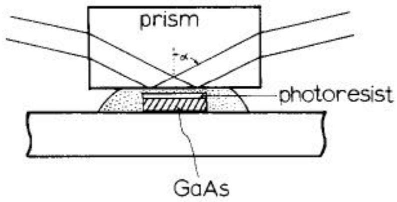

FIG. 3. A schematic drawing of the photoresist exposure method for short period interference. He–Cd laser; 3250 Å.

where $n_Q \sim 1.5$ is the refractive index of quartz. Thus, using a He–Cd laser we were able to fabricate $\Lambda = 0.11$ μm gratings. But, it should be mentioned that the fabrication of such gratings is rather difficult, and in most cases 0.34-μm gratings have been used [corresponding to $m=3$ in Eq. (1)], although the lasing threshold is higher for the 0.34-μm ones.

A computer-programmed scanning electron microscope (SEM) may also be utilized to write grating patterns of period $\Lambda \geq 0.3$ μm in a masking material.[12,13] The advantages of the SEM are its high resolution and programmability, but the complexity and cost involved, and the small field of view (~1×1 mm), limit its use.

The grating pattern formed in the photoresist may be transferred onto the GaAs by ion-beam etching or chemical etching. Ion-beam etching is usually[11] carried out with 2-keV-Ar^+ ions, as shown in Fig. 4. Selective chemical etching in bromine–methanol solution can be utilized to make V-groove gratings.[14] In principle, the chemical etching may result in deeper grooves, while introducing less defects into the corrugated structure.

The growth of GaAlAs on GaAs corrugated surface by liquid-phase epitaxy is an important step in the fabrication of GaAs–GaAlAs double heterostructures with DFB. This growth presents special problems, because the corrugations may either be wiped out by meltback or interfere with the growth of the top layers. It was found[15] that good results could be obtained if the growth temperature was kept in the range 700°–670°C (see also Fig. 6).

CORRUGATED LASER STRUCTURES

Distributed-feedback (DFB) laser oscillations in corrugated structures were first observed in thin optical waveguides attached to corrugated substrates.[16,17] Gain in these waveguides was due to doping with organic

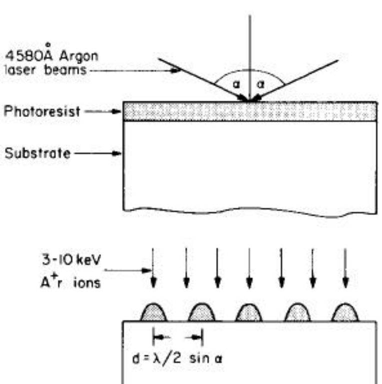

FIG. 4. (a) Holographic exposure of photoresist. (b) Ion-beam etching of substrate after developing photoresist.

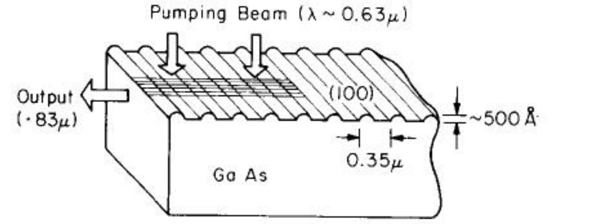

FIG. 5. Schematic structure of a GaAs distributed-feedback laser.

dye, and they were optically pumped by pulsed nitrogen or neon lasers. Shortly afterwards,[18–20] our group demonstrated laser oscillations in corrugated semiconductor structures which were optically pumped at 77° K using pulsed ruby laser ($\lambda \sim 0.69$ μm) or dye laser ($\lambda \sim 0.63$ μm). At first we studied GaAs with surface corrugation (produced by ion-beam etching) of period $\Lambda = 0.35$ μm and depth 500 Å, as shown in Fig. 5. Lasing was observed in this structure when the pumping intensity exceeded a threshold of about 2×10^5 W/cm². The wavelength λ_0 of the emitted light, and the period Λ, were found to obey Bragg condition [Eq. (1)] with $m=3$. Lasing was then observed in corrugated epilayers of insulating GaAs which were grown over n-type GaAs, or over an epilayer of $Ga_{0.7}Al_{0.3}As$, thus forming a single heterostructure (SH). The threshold pumping intensity was found to be lower (~10^4 W/cm²) for these structures, due to a better confinement of the radiation. By varying the period Λ in the range 0.345–0.348 μm we were able to tune the emitted laser wavelength in the range 0.826–0.832 μm. Later we observed lasing in a similar structure with a corrugation period $\Lambda = 0.11$ μm, i.e., the fundamental grating ($m=1$). Double heterostructure (DH) GaAs with DFB was investigated by Shank *et al.*[21] They also used a structure with a period $\Lambda = 0.11$ μm, and demonstrated that at 77° K the threshold pumping intensity was lower than that observed for SH.

The operation of DFB GaAs injection lasers was demonstrated first by Scifres *et al.*[5] in a single heterostructure, and by Stoll and Seib[5] in a homostructure. In both cases corrugations with period $\Lambda \sim 0.35$ μm were fabricated by ion-beam etching, and the lasers were pumped at 77° K by short current pulses. Scifres *et al.* showed that devices made from the same substrate exhibit good uniformity in wavelength, and that the wavelength did not change much with changes in the pumping current.

We observed[22,23] lasing in the GaAs–GaAlAs double heterostructure shown in Fig. 6. The structure consists of a 3-μm n-type $Ga_{0.7}Al_{0.3}As$ layer and a 1-μm p-type

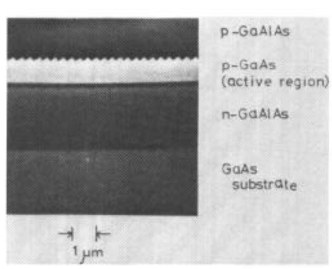

FIG. 6. A SEM photograph of the cross section of a distributed-feedback laser along the direction of light propagation. The corrugation period is 3470 Å.

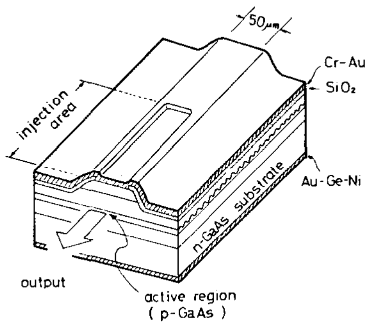

FIG. 7. The schematic structure of the distributed-feedback laser.

GaAs which were grown by the LPE method on an *n*-type substrate. The *p*-type layer was corrugated, and a 3-μm *p*-type $Ga_{0.7}Al_{0.3}As$ and 1-μm *p*-type GaAs were grown on top of the corrugated layer. Diodes were formed, as shown in Fig. 7, and pumped at low temperatures by short current pulses. The threshold current density was found to depend on the method of etching used in making the corrugation: for ion-beam etching the threshold was $\sim 10^4$ A/cm^2 at 77° K, and for chemical etching $\sim 10^3$ A/cm^2. This fact, combined with photoluminescence measurements, indicate that the number of nonradiative recombination centers produced by chemical etching is less. As to the spectral characteristics of the emitted light it was found that the laser emitted a single longitudinal mode, as shown in Fig. 8. The lasing wavelength variation with temperature was found to be 0.5 Å/°K in the range 80°–145°K, which is much lower than that observed in Fabry–Perot-type lasers. The variation of the wavelength upon increasing the pumping current was also small. Recently,

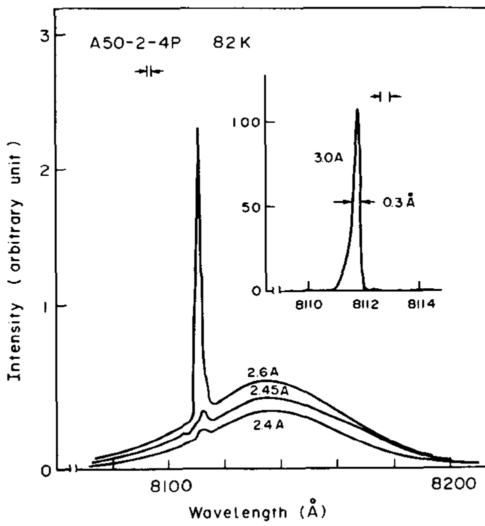

FIG. 8. The emission spectra of a typical laser. The period and the depth of the corrugation is 3470 and 1800 Å, respectively. The threshold current density is 750 A/cm^2 at 80° K.

Anderson *et al.* observed lasing[24] in GaAs–GaAlAs DFB DH injection lasers with fundamental gratings ($\Lambda = 0.11$ μm).

SUMMARY

In this work we described the fabrication of corrugated laser structures, and the operation of some of them under optical or electrical pumping. The GaAs–GaAlAs distributed feedback double heterostructure injection lasers studied at 77°K were found to have a threshold current density of $\sim 10^3$ A/cm^2 and to oscillate in a single longitudinal mode. The variations of the lasing wavelength with temperature and with current were relatively small.

The future of corrugated laser structures as practical light sources for optical communication depends on their ability of operating at room temperature. This aim could be achieved by using structures with fundamental gratings, and with separate confinement of the radiation and of the carriers.

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