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GaInAs/GaAs Micro-Arc Ring Semiconductor Laser

Satoshi Mitsugi, Junichi Kato, Fumio Koyama, Akihiro Matsutani
Toshikazu Mukaihara and Kenichi Iga

Tokyo Institute of Technology, Precision & Intelligence Lab.
4259 Nagatuta, Midori-ku, Yokohama 227, JAPAN

A micro-arc-ring cavity (MARC) laser is proposed to realize an in-plane micro-cavity laser for micro-photonic integrated circuits. This device consists of an etched concave reflector and two plane reflectors. The resonant optical wave can be tightly confined by a total internal reflection in the lateral microcavity. We present a basic design concept of a MARC laser for low threshold operation and for transverse mode control. We have fabricated a 0.98μm GaInAs/GaAs strained QW MARC laser by using direct electron beam lithography and reactive ion beam etching. The reflectivity of the etched reflector was ~74% estimated from the threshold of fabricated devices.

1. Introduction

Micro-cavity lasers, such as surface emitting lasers(1) and micro-disk lasers(2) are attractive as low power consumption light emitters in future optical interconnect systems. Also, etched facet ring lasers have been studied for in-plane photonic integrated circuits(3)(4). There have been difficulties in realizing miniatured ring lasers with controlled output optical coupling as well as transverse mode control. We have proposed a novel micro arc-ring cavity (MARC) laser(5) to realize a new type of in-plane microcavity which is applicable to large scale photonic integrated circuits. This structure consists of one etched concave reflector and two plane reflectors and can be formed by a full monolithic process technology. Resonant optical waves can be tightly confined in the MARC structure by using total internal reflection. Also, diffraction losses can be reduced with the help of a concave mirror. We expect a possibility of realizing an in-plane micro-cavity by using the MARC structure which will be useful for low threshold lasers as well as for wavelength filters.

In this paper, we present a design concept to realize a low loss micro-arc ring cavity. The analysis on the threshold and the transverse mode control has been carried out. Also, we demonstrate the lasing operation of 0.98μm GaInAs/GaAs strained quantum well MARC lasers fabricated by direct electron beam lithography and a reactive ion beam etching technique. The reflectivity of etched reflectors is a key issue to realize low threshold micro-arc ring lasers, which is evaluated from the experimental threshold.

2. Theory

The schematic structure of a MARC structure is shown in Fig.1. The cavity is an etched ring resonator with two plane reflectors and one concave reflector. This has no waveguide structure in lateral direction inside the cavity. The role of the concave reflector is to reduce the diffraction of the propagating mode and to control the higher order mode. We have calculated the resonator characteristic of the MARC.

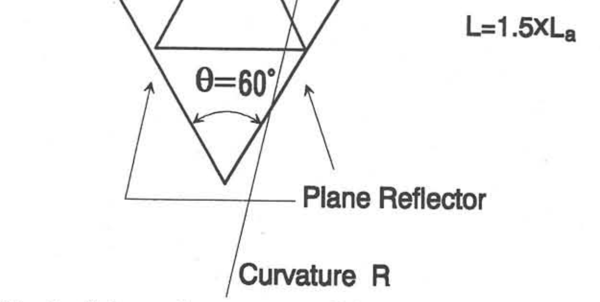

Fig.1 Schematic structure of the micro arc ring cavity. The curvature of a concave reflector is much larger than the arc length and cavity length can be approximated by $L=1.5xL_a$.

The MARC can been regarded as an equivalent Fabry-Perot cavity with finite apertures and concave reflectors. We assumed that the propagation mode can be approximated by a Gaussian function. The curvature of the phase front can be compensated by the concave reflector, resulting in the reduction of diffraction losses. The influence of Goos-Haenchen shifts is neglected. By using these approximations, we can calculate the one-round-trip-loss caused both by a finite aperture and by an imperfect total internal reflections. The curvature R of the concave reflector is determined from the resonant condition with a spot size w_0 of the resonant Gaussian mode. We calculated the one-round-trip loss of the MARC for λ=0.98µm. We have assumed 3 GaInAs/GaAs strained QW structures for the active region. The gain parameters were obtained from the experimental threshold current of fabricated edge-emitting lasers. We obtained the following relation among the threshold current density J_{th} and the one-round-trip loss α_m;

$$J_{th} = J_0 \exp\left(\frac{\alpha_i + \alpha_m}{A}\right) \qquad (1)$$

where $J_0 = 150 A/cm^2$, $\alpha_i = 10 cm^{-1}$ and $A = 35 cm^{-1}$. Figure 2 shows the threshold current versus the arc length for the fundamental mode and the 2nd higher order mode. The curvature R is chosen as R=4xL_a. In this condition, the cavity loss for the fundamental mode is minimized. We can expect sub-mA low threshold operations as well as single transverse mode operations by reducing the size in several micron ranges. The one-round-trip loss can be increased for higher order transverse modes by changing the curvature R of the concave reflector, resulting in transverse mode control.

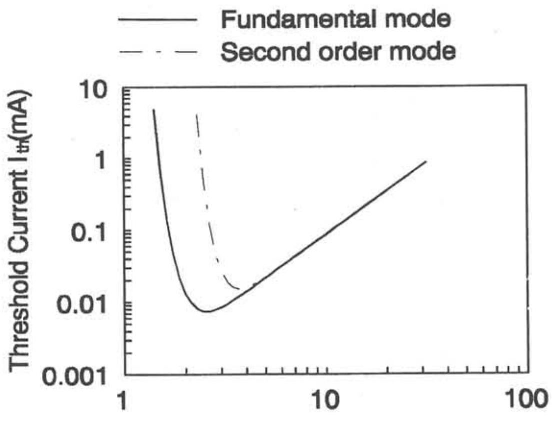

Fig.2 Calculated threshold current I_{th} versus arc-length L_a. The angle of the MARC is θ=60° and the curvature R is chosen as R=4xL_a

3. Experiment

We fabricated MARC lasers with arc lengths of L_a=100 and 50 µm. The etched reflectors were formed by an electron beam (EB) lithography and reactive ion beam etching (RIBE) process[6] by using GaInAs/GaAs 3QW-SCH (λ=0.965µm) wafers grown by low-pressure metal-organic chemical vapor deposition (LP-MOCVD).

At first we thinned the GaAs wafer to be 150µm thick and Au/Zn/Au and AuGe/Ni/Au were evaporated for electrodes on the p-side and the n-side of the wafer, respectively. We carried out the following self-align process. The ring cavity patterns were formed by an electron beam (EB) exposure using a negative-type EB resist. The RIBE was carried out with a Cl_2 plasma to obtain vertical and smooth etched surfaces. We etched the p-side electrode and the wafer at the same time with a mask of the EB resist. The etching time was 17 minutes resulting in the etching depth of 3µm. The resist was removed by reactive ion etching (RIE) with O_2 plasma. After these processes, the wafer was annealed in a H_2 atmosphere at 440 ℃ for 3 minutes.

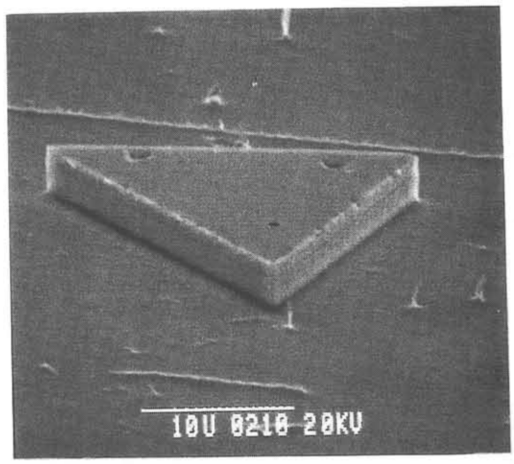

Fig.3 SEM photograph of the fabricated MARC.

Figure 3 shows the scanning electron microscope (SEM) photograph of one of fabricated MARC lasers. The current output characteristic and the lasing spectra of the device were measured under room temperature pulsed operations. In the present device structure , the laser light can be observed only by light scattering due to imperfect etched surfaces. The scattered light from the etched reflector was detected by a power meter through a multi-mode fiber. We confirmed the laser operation by observing narrow lasing spectra as shown in Fig. 4. As a result, the threshold current is 50mA under pulsed operations for L_a=100µm. The longitudinal mode spacing was measured to be 2.5nm for L_a=50μm, which is in good agreement with theory, assuming ring cavity modes. The threshold of the MARC laser is increased by the scattering loss in the etched reflector, although the ideal reflectivity of the mirror is nearly 100%. We have calculated the threshold of the MARC laser with taking the effective reflectivity R_e deferiorated by the scattering into account as show in Fig. 5. We used eq. (1) to calculate

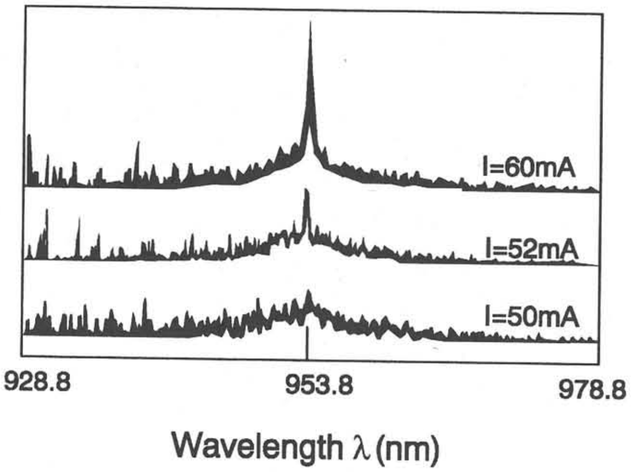

Fig.4 Spectra of fabricated MARC with L_a=100μm under room temperature pulsed operations.

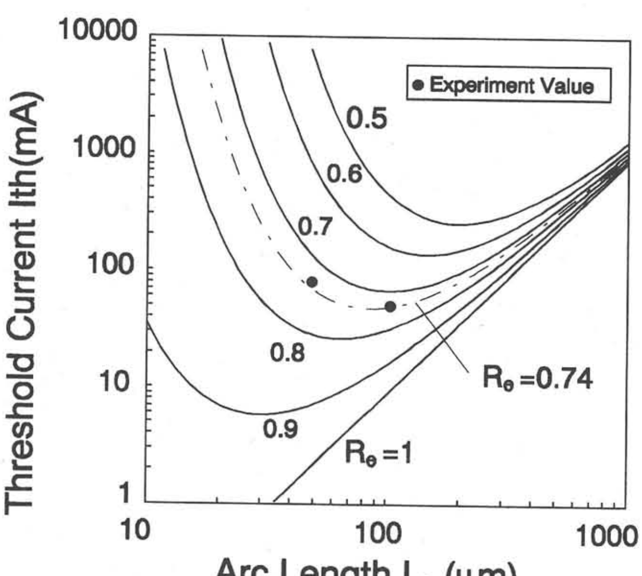

Fig.5 Threshold versus cavity size with a parameter of effective reflectivity of etched reflectors. Closed circles show the experiment value. The gain parameter for the culculation was obtained from the measured thresholds of striped lasers.

the threshold. We estimate the etched reflectivity from the relation among the threshold current density versus the excess scattering loss. By fitting the experimental result with the theory, the reflectivity is estimated to be 74%. Further improvement on etched mirror qualities may enable us to make smaller ring cavities, resulting in ultra low threshold operations. Another important issue is the coupling of light output from the closed cavity. One way is to use an evanescent coupling with an external waveguide. A calculation shows that the formation of a sub-micron air gap enables the efficient coupling of the MARC with an enternal output waveguide.

4. Conclusion

In conclusion, we have demonstrated a novel semiconductor ring laser fabricated by using EB fine lithography and dry etching. Low threshold and single transverse mode operations can be expected by optimizing the concave etched reflectors. The proposed concept might be helpful for realizing ultra low threshold in-plane microcavity lasers as well as for the size reduction in large scale integrated photonics.

Acknowledgemt

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