Extended Abstracts of the 1995 International Conference on Solid State Devices and Materials, Osaka, 1995, pp. 446-448

D-5-3

InGaAs/GaAs Strained Quantum Well Lasers with Etched Micro-Corner Reflectors

Junichi KATO, Fumio KOYAMA, Akihiro MATSUTANI, Toshikazu MUKAIHARA and Kenichi IGA

Precision and Intelligence Laboratory, Tokyo Institute of Technology
4259 Nagatsuta, Midori-ku, Yokohama 226, Japan

The design and the fabrication of etched corner reflectors are presented for future semiconductor based photonic integrated circuits. A corner reflector terminating an optical waveguides is formed by two etched facet mirrors orthogonal to each other. We present the theoretical modal reflectivity of miniature corner reflectors. Also, we demonstrate InGaAs/GaAs strained quantum well short cavity lasers with corner reflectors fabricated by reactive ion beam etching.

1. INTRODUCTION

Monolithic integration of semiconductor photonic devices is attractive for future optical communication or optical information processing systems. Size reduction of photonic devices including semiconductor lasers may be one of important issues for large scale integration. The use of total internal reflections would be one of solutions for this purpose. The total internal reflection have be used for ring lasers[1-2], micro disk lasers[3], 90° turning waveguides[4], corner reflectors[5] and so on. Among of them, a corner reflector terminating an optical waveguide can be easily fabricated by two etched facet mirrors orthogonal to each other. This monolithic mirror is a very compact and may play a role of an extremely high reflectivity mirror, which can be applicable to low loss resonators. Etched corner reflectors have been demonstrated in semiconductor lasers[5),6)], which have been fabricated by dry etching techniques such as reactive ion etching (RIE)[5),6)], reactive ion beam etching (RIBE) and chemical assisted ion beam etching (CAIBE)[7]. Some optical properties of corner reflectors were discussed and also a phase coupled array using corner reflectors was demonstrated[6]. However, the quality of the reflectors has been insufficient and it is unclear how we reduce the lateral size of the corner reflector.

In this work, we present the design and the fabrication of etched corner reflectors. The modal reflectivity of miniature corner reflectors is examined. Short cavity lasers with corner reflectors formed by an RIBE technique have been demonstrated and the quality of the 100% mirror is evaluated from laser threshold. In addition, we present a novel corner reflector array laser using a self-imaging effect.

2. THEORY

We carried out a 2-D analysis of a corner reflector shown in Fig. 1. The corner reflector consist of two plane mirrors orthogonal to each other. It is easily expected that the reflectivity of the corner reflector will be nearly 100% when the waveguide width is sufficiently large. However, the reflectivity is deteriorated by diffraction and imperfect total internal reflection with reducing the waveguide width. The cause of deteriorated reflectivities would be two physical phenomena, that are an optical diffraction and a phase shift at total internal reflection mirrors. We have considered these two phenomena for calculation.

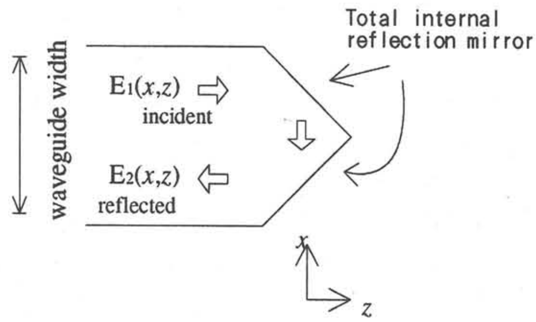

Fig. 1 Schematic model for 2-D analysis

We assumed fundamental and first ordered Gaussian functions as input beams for calculations. We denote $E_1(x,z)$ and $E_2(x,z)$ as the electric fields of incident and reflected beams, respectively. For a diffraction propagation analysis, we use the Fresnel-Kirchoff integral. Also, we consider the phase shift at total internal reflection mirrors by expressing the input lightwave as a set of plane waves with various wave vectors.

The calculated modal reflectivity is shown in Fig. 2 The results are plotted for fundamental and first ordered modes as a function of the waveguide width. From the results, we can see that a high reflectivity more than 99% can be expected when the waveguide width is more than 10 μm. Also, the deference in modal reflectivity between fundamental and first ordered modes can be clearly seen. The first-ordered mode takes a higher reflectivity than the fundamental mode. The obtained results have been used for a device design.

3. EXPERIMENT

InGaAs/GaAs strained quantum well lasers with a corner reflector were fabricated. A base wafer containing

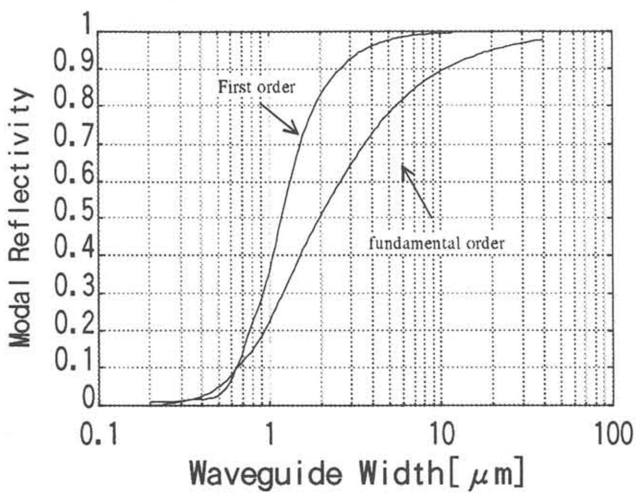

Fig. 2 Calculated modal reflectivity as a function of waveguide width.

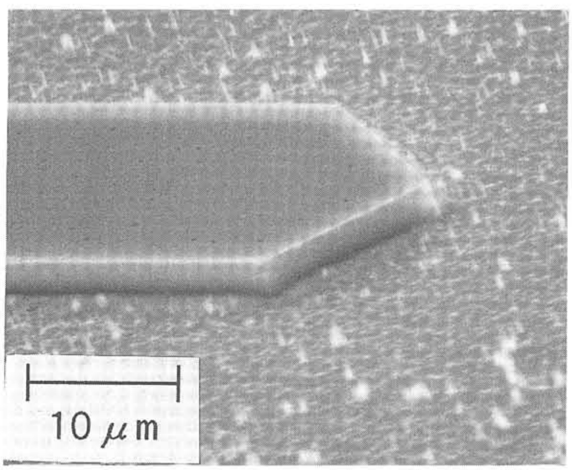

Fig. 3 SEM photograph of fabricated corner reflector

three quantum wells was grown by low pressure metal-organic chemical vapor deposition(LP-MOCVD). The resist mask was patterned by direct EB lithography followed by Cl_2-RIBE. The wafer was lapped to be 100μm thick and Au/Zn/Au and AuGe/Au electrodes were evaporated for both p- and n-type contacts. After the evaporation, we patterned the resist mask for RIBE using a negative EB resist. Before Cl_2 based RIBE was carried out , we etched the electrode using accelerated Ar ion beam for 2 minutes to avoid side wall roughness caused by the electrode. Then we carried out the Cl_2 based RIBE using ECR plasma. The Cl_2 gas pressure was 8×10^{-4} torr and the accelerated voltage was 400V. The etching time was 13 minutes, resulting in the etched depth of 2.5μm.

Figure 3 shows the SEM photograph of fabricated corner reflectors. Almost vertical etched sidewalls were successfully fabricated. The other side was cleaved to form a Fabry-Perot cavity. The laser was measured under room

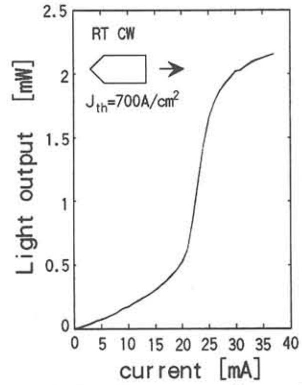

Fig. 4 I-L characteristic of corner reflector laser.

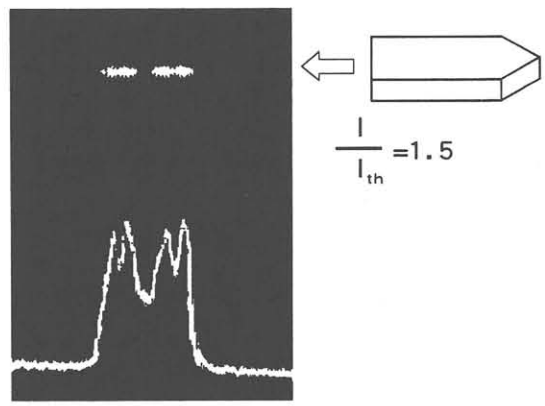

Fig. 5 Near field emission pattern observed from the side of the cleaved facet.

temperature cw conditions. The measured device was 20μm wide and 160μm long. The I-L characteristic was shown in Fig. 4. The threshold current was 21mA. Fig. 5 shows the near-field emission pattern observed from the side of the cleaved facet. One can see that the first ordered transverse mode mainly oscillates. From this fact, we can understand that the transverse mode was strongly selected by the corner reflector. This is in good agreement with the theoretical result in Fig. 2.

A plot of threshold current density as a function of the cavity length was shown in Fig. 6. We can now estimate the reflectivity of the micro-corner reflector, in comparison with the threshold of two cleaved laser. The threshold current density can be expressed as follow;

$$J_{th} = J_0 \exp\left[\left\{\alpha_{in} + \frac{1}{L}\ln\left(\frac{1}{R}\right)\right\} / G\right] \qquad (1)$$

J_0, α_{in}, G are fitting material parameters, which are 108A/cm^2, 10cm^{-1}, 25cm^{-1}, respectively. Then the reflectivity of the corner reflector R was evaluated with a

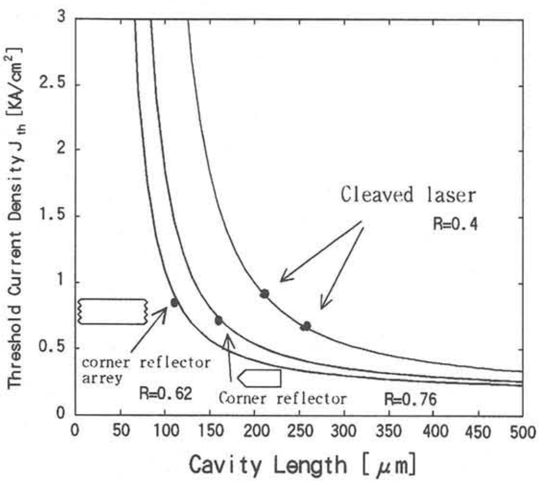

Fig. 6 Threshold current density as a function of cavity length to estimate the reflectivity of corner reflector.

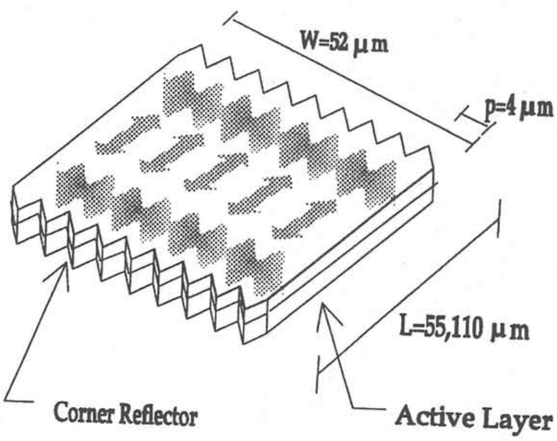

Fig. 7 Schematic view of corer reflector array laser using Talbot self-imaging effect.

fitting procedure. The reflectivity was estimated to be 76%. Further improvements on etched mirror qualities enable us to make higher efficiency, lower threshold operation that will be suitable for investigation.

We have also fabricated a monolithic Fabry Perot cavity laser using corner reflector arrays as shown in Fig.7. The cavity length was carefully designed to use a Talbot self imaging effect. In this structure, we do not need any waveguiding structure in a lateral direction. The cavity length L and array pitch p was defined in the following so that a Talbot self imaging effect can be used.

$$L = \frac{m \times p^2}{\lambda_p} \times n_{eff} \quad \text{(m : integer)} \qquad (2)$$

where λ_p was the laser emission wavelength and n_{eff} was the effective refractive index of the laser waveguide.

The fabrication process was the same as that of the previous single stripe device. We obtained room temperature pulsed operations of this novel array structure. The threshold current density was 840A/cm^2 for 110μm long InGaAs/GaAs QW devices. The effective reflecting of the array mode is estimated to be ~62% as shown in Fig. 6. This configuration might be interesting high power for phase locked laser arrays.

4. CONCLUSION

We have challenged to realize miniature corner reflectors fabricated by semiconductor microfabrication. The key issue is to develop nanometer semiconductor fabrication processes with low induced damages. High quality corner reflectors might provide functionalities in future large scale integrated photonics.

ACKNOWLEDGMENTS

The authors acknowledge Prof. Emeritus Y. Suematsu, the former president of Tokyo Institute of Technology for his encouragement.

References

1) A. Behfar-red, S. S. Wong, J. M. Ballantyne, B. A. Soltz and C. M. Harding, Appl. Phys. Lett., **54** (1989) 493.
2) S. Mitsugi, J. Kato, F. Koyama, A. Matsutani, T. Mukaihara and K. Iga, Jpn. J. Appl. Phys., **11B** (1994) 6201.
3) A. F. J. Levi, S. L. McCall, S. J. Pearton and R. A. Logan, Electron. Lett., **29** (1993) 1666.
4) John E. Johnson and C. L. Tang, IEEE Photon. Tech. Lett., 4 (1992) 24.
5) M. Hagberg, A. Larsson and S. T. Eng, Appl. Phys. Lett., **56** (1990) 1934.
6) G. M. Smith, D. V. Forbes, J. J. Coleman and J. T. Verdeyen, IEEE Photon. Tech. Lett., 5 (1993) 873.
7) Robert M. Spencer, Sean S. O'Keefe, Glenn H. Martin, William J. Schaff, Lester F. Eastman, IEEE Photon. Tech. Lett., 7 (1995) 20.