Journal of the Optical Society of Korea, Vol. 1, No. 1, March 1997, pp. 48~51

Field-induced refractive index variations in GaAs/AlGaAs multiple quantum well waveguide modulator

Wook-Rae Cho, Seung-Han Park, and Ung Kim
Department of Physics, Yonsei University, Seoul 120-749, Korea
Kyung-Hyun Park
Division of Electronics and Information Technology, Korea Institute of Science and Technology, Seoul 130-650, Korea

(Received; January 20, 1997)

A quantum well electroabsorption waveguide modulator utilizing a field-induced refractive index change was designed and fabricated. The *on/off* ratios of the device were investigated as a function of wavelength over the spectral range of 850 nm to 910 nm for the various reverse biases. The field-induced refractive index variations associated with quantum-confined Stark effect was theoretically obtained based on the measured *on/off* ratios. The resulting maximum refractive index change (Δn) of $\sim 7.5\times 10^{-4}$ at -8 V was estimated.

I. INTRODUCTION

Multiple quantum well (MQW) electroabsorption modulators have been extensively studied for the use of future optical modulators and switching devices[1-3]. When an electric field is applied perpendicular to MQW, the optical electroabsorption spectrum near the bandedge is shifted to lower energies without destroying the strong exciton resonance peak. This effect, known as the quantum-confined Stark effect (QCSE)[4,5], can be utilized to modulate the intensity of light propagating either parallel or perpendicular to the quantum well layers.

In this paper, the *on/off* ratios of MQW electroabsorption waveguide modulator were investigated as a function of wavelengths over the spectral range of 850 nm to 910 nm for various reverse biases. The MQW electroabsorption modulator of the strip-loaded waveguide type was specially designed and fabricated. In addition, the field-induced refractive index changes (Δn) associated with the QCSE were obtained by using a Kramers-Kronig transformation[6] based on the electroabsorption changes ($\Delta\alpha$) from the measured *on/off* ratios. The resulting maximum refractive index change (Δn) of $\sim 7.5\times 10^{-4}$ at -8 V was estimated.

II. EXPERIMENT

The waveguide structure was designed for single-mode guiding at 875 nm, far below the exciton peak for the light polarized perpendicular to the MQW layers. The epitaxial layer structure was designed to have a single guided mode in a direction perpendicular to the layers. The refractive indices of $Al_xGa_{1-x}As$ for the different wavelengths and the aluminum mole fractions were calculated from the empirical formula of Adachi[7]. Also, the index of refraction of the MQW structure was obtained by using the thin film approximation of Van der Zeil and Gossard[8], *i.e.*,

$$n_{i-MQW} = \sqrt{(a\, n_w^2 + b\, n_b^2)/(a+b)} \quad (1)$$

where a and b were well and barrier thicknesses and n_w and n_b were well and barrier bulk indices, respectively. The effective index method[9] was employed to design the strip-loaded structure that provided transverse single-mode confinement. A schematic diagram of the designed waveguide structure of MQW field-induced optical modulator is shown in Fig. 1(a).

The epitaxial layer structure was grown on a [100] oriented n-type GaAs substrate by molecular beam epitaxy (MBE). The guiding layer consisted of a MQW structure of 60 periods with 100-Å GaAs wells and 100-Å $Al_{0.3}Ga_{0.7}As$ barriers. The $Al_{0.3}Ga_{0.7}As$ cladding layer below the MQW structure served to isolate the guiding region from the GaAs substrate. The upper cladding $Al_{0.13}Ga_{0.87}As$ layer was of 1 μm in thickness and doped with $p = \sim 2\times 10^{18}$ cm^{-3}. The AlGaAs layers above and under MQW region confine the light in the vertical direction.

Also, lateral confinement was achieved by etching the region outside the core from the upper cladding. Conventional contact microlithography was used to pattern the sample. The strip-loaded waveguide was fabricated by wet etching process to get 3 μm in width and 0.8 μm in depth of the top AlGaAs layer. Etching was performed by means of a solution of H_3PO_4:H_2O_2:H_2O(16:9:75) with a photoresist mask. Ohmic p contacts of Pt(100Å)/Ti(100Å)/Pt(300Å)/Au(2000Å) were deposited on the etched region using the E-beam evaporation. Ohmic n contacts were obtained from Ge/Au/

Ni/Au evaporation. A proton implantation[10] with an energy of 140 KeV and a dose of 2×10^{14} cm^{-2} was carried out to convert the core region between the gold plated electrodes into the semi-insulating material. Thus, the voltage applied on both sides of the core resulted in a strong field beneath the electrodes and a relatively very weak field under the ridge, indicating an increased refractive index under the region outside the ridge relative to the core region due to QCSE[11-13]. Fig. 1(b) shows a scanning electron microscope (SEM) micrograph of the fabricated field-induced optical modulator. The direction of the waveguide was chosen in the $[1\bar{1}0]$ direction. Device length was ~500 μm.

The experimental setup used to measure the *on*/*off* ratios of the fabricated device is shown in Fig. 2. A Ti: sapphire laser was employed as a light source. The output of the laser was end-fire coupled into one facet by a ×40 microscope objective. Various reverse biases were applied to the field-induced optical modulator. The light was linearly polarized perpendicular to the growth direction (TE polarization). The output light intensity exiting the other facet was captured by an avalanche photo diode (APD) to measure the *on*/*off* ratio, *i.e.*, the ratio between the output power with and without the applied electric field to the modulator. A part of the light reflected by a beamsplitter was sent to the charge-coupled device (CCD) for alignment purposes.

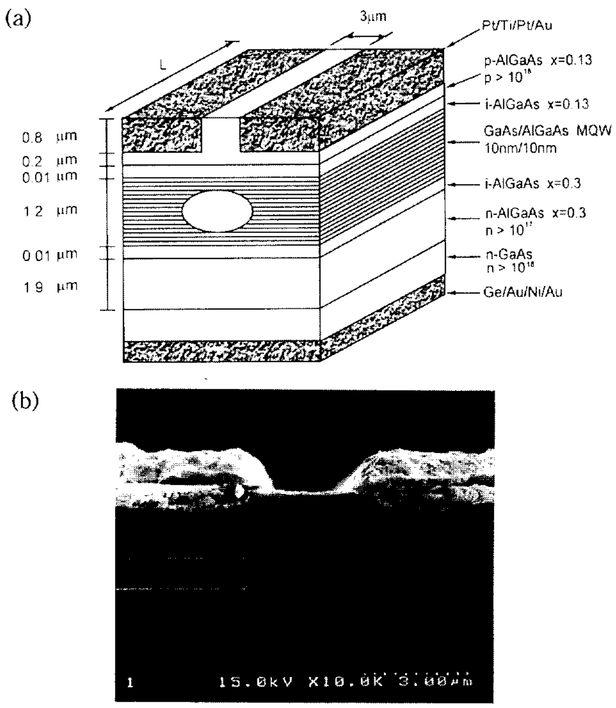

Fig. 1. (a) Designed electric field-induced electroabsorption modulator, (b) SEM micrograph of MQW modulator.

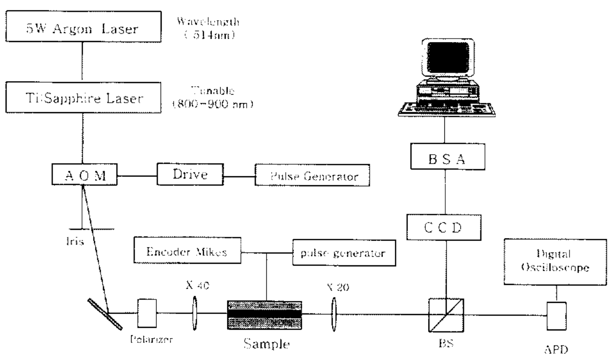

Fig. 2. Experimental setup for measuring *on*/*off* ratio.

III. RESULTS AND DISCUSSION

The observed single-mode pattern of the strip-loaded waveguide near wavelengths of 875 nm is shown in Fig. 3. It was confirmed by careful examination of the near-field pattern with small displacement of the insertion light beam to the waveguide that no higher order modes could be excited near wavelengths of 875 nm, as designed.

The *on*/*off* ratios were measured as a function of wavelength over the spectral range of 850 nm to 910 nm for the various reverse biases, as shown in Fig. 4. As mentioned above, the refractive index under the region outside the ridge relative to the core region was increased mainly due to QCSE when a reverse bias was applied[11-13]. As the applied voltage was increased, the lateral refractive index difference between the core and cladding was decreased, the single mode became less confined, and the loss was greatly increased. Thus, the *on*/*off* ratio was enhanced as the voltage was raised due to the decreasing confinement of the light under the core. The largest *on*/*off* ratio was ~20.3 for a

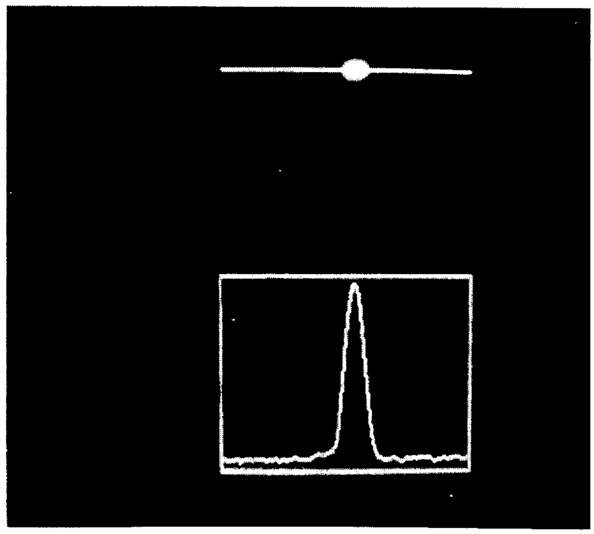

Fig. 3. Observed single mode near-field pattern.

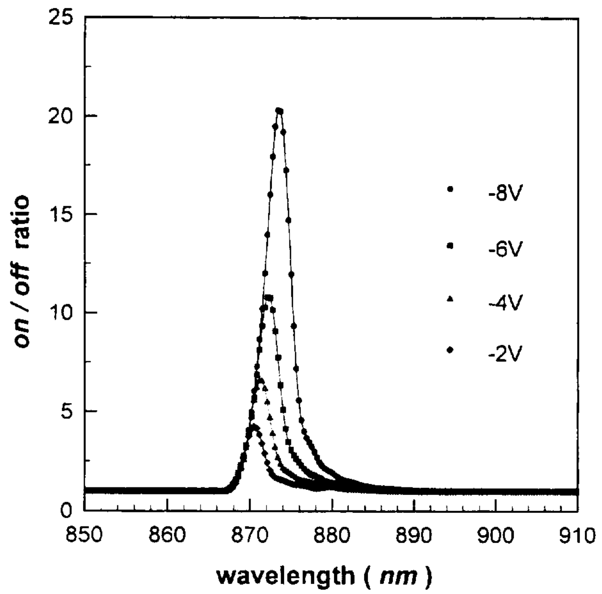

Fig. 4. *on/off* ratios as a function of wavelength for -2 V, -4 V, -6 V, and -8 V.

reverse bias voltage of 8 V at a wavelength of 876 nm.

The field-induced refractive index changes (Δn) were calculated by using a Kramers-Kronig transformation based on the obtained electroabsorption changes ($\Delta\alpha$) from the measured *on/off* ratios[6]. Δn and $\Delta\alpha$ are related by

$$\Delta n(\omega) = \frac{c}{\pi} P\int_{-\infty}^{\infty} \frac{\Delta\alpha(\omega')\,d\omega'}{\omega'^2 - \omega^2}. \qquad (2)$$

The *on/off* ratio (D_m) is described by $D_m = e^{\Gamma\Delta\alpha L}$, where Γ is the filling factor[12] and L is the waveguide length. The spectra of electroabsorption changes $\Delta\alpha(\omega)$, for the various reverse biases, were obtained from the measured *on/off* ratios, as shown in Fig. 5(a). Note that the peak of $\Delta\alpha(\omega)$ was shifted to the lower energy side due to QCSE.

Fig. 5(b) shows the calculated values of $\Delta n(\omega)$ from the numerical integration of Eq. (2). The peak values of the refractive index changes (Δn_{max}) for the reverse bias voltages occurred near 875 nm significantly below the exciton peak. Δn for the longer wavelengths over 900 nm was almost linearly increased with increasing the applied voltage like bulk GaAs. However, the variation of refractive index near 875 nm was drastically increased with increasing voltage due to the quadratic electro-optic effect associated with QCSE. The maximum refractive index change was estimated to be $\sim 7.5\times10^{-4}$ for the 8 V reverse bias applied at 876 nm. This well agrees with other published results[10,13].

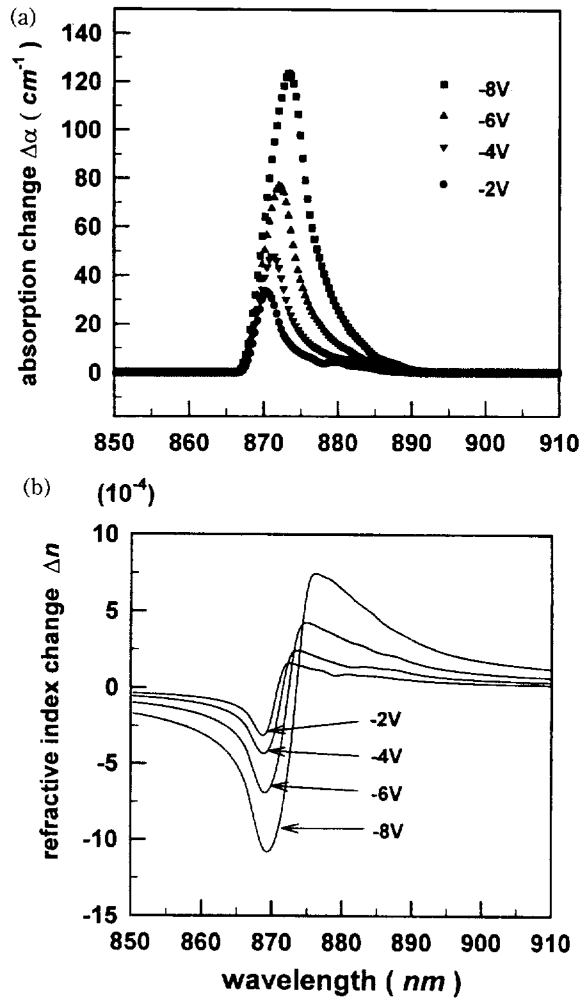

Fig. 5. (a) Electroabsorption changes obtained from the measured on/off spectra, (b) Refractive index changes calculated from the electroabsorption changes.

IV. SUMMARY

We have demonstrated that the *on/off* ratio can be utilized to find the electric field-induced refractive index changes of MQW. The *on/off* ratios of MQW strip-loaded electroabsorption waveguide modulator were measured as a function of wavelength over the spectral range of 850 nm to 910 nm for the various reverse biases. The field-induced refractive index variations associated with QCSE were theoretically calculated based on the spectra of electroabsorption changes obtained from the measured *on/off* ratios. The maximum refractive index change (Δn) of $\sim 7.5\times10^{-4}$ at -8 V was estimated.

V. ACKNOWLEDGMENTS

This work was supported by the Atomic-scale Surface Science Research Center of Excellence Program at

Yonsei University (1996), the Basic Science Research Institute Program of the Ministry of the Education (1996), and ADD (EO-15).

REFERENCES

[1] T. H. Wood, A. Burrus, D. A. B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, and W. Wiegann, Appl. Phys. Lett. **44**, 16 (1984).
[2] S. Tarucha and H. Okamoto, Appl. Phys. Lett. **48**, 13 (1986).
[3] D. A. B. Miller, J. S. Weiner, and D. S. Chemla, IEEE J. Quanum Electron. **QE-22**, 1816 (1986).
[4] D. A. B.Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, W. Wiegmann, T. H. Wood, and C. A, Burrus, Phys. Rev. Lett. **53**, 2173 (1984).
[5] D. A. B.Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, W. Wiegmann, T. H. Wood, and C. A, Burrus, Phys. Rev. **B**. **32**, 1043 (1985).
[6] J. S. Weiner, D. A. B. Miller, and D. S. Chemla, Appl. Phys. Lett. **50**, 842 (1987).
[7] S. Adachi, J. Appl. Phys. **58**, Rl (1985).
[8] J. P. van der Zeil and A. C. Gossard, J. Appl. Phys. **49**, 2919 (1978).
[9] M. Warren, W. Gibbons, K. Komatsu, D. Hendricks, H. M. Gibbs, and M. Sugimoto, Appl. Phys. Lett. **51**, 19 (1987).
[10] T. C.Huang, Y. Chung, N. Dagli, and L. A. Coldren, Appl. Phys. Lett. **57**, 114 (1990).
[11] M. Glick, F. K. Reinhart, G. Weimann, and W. Schlapp, Appl. Phys. Lett. **48**, 14 (1986).
[12] T. H. Wood, R. W. Tkach, and A. R. Chraplyvy, Appl. Phys. Lett. **50**, 798 (1987).
[13] R. W. Wickman, A. L. Moretti, K. A. Stair, and T. E. Bird, Appl. Phys. Lett. **58**, 690 (1991).