World Academy of Science, Engineering and Technology
International Journal of Electronics and Communication Engineering
Vol:9, No:2, 2015

Excitonic Refractive Index Change in High Purity GaAs Modulator at Room Temperature for Optical Fiber Communication Network

Durga Prasad Sapkota, Madhu Sudan Kayastha, Koichi Wakita

***Abstract*—**In this paper, we have compared and analyzed the electroabsorption properties between with and without excitonic effect bulk in high purity GaAs spatial light modulator for optical fiber communication network. The eletroabsorption properties such as absorption spectra, change in absorption spectra, change in refractive index and extinction ration has been calculated. We have also compared the result of absorption spectra and change in absorption spectra with the experimental results and found close agreement with experimental results.

***Keywords*—**Exciton, Refractive index change, Extinction ratio.

I. Introduction

THERE has been considerable interest in the electric field dependence of optical properties in GaAs material with excitonic effect. The importance of exciton effects was cleared by Dow and Redfield [1] below and far above the bandgap. For the first time, a clear excitonic absorption peak was measured at room temperature in high purity GaAs [2]. The shift of electroabsorption near the band-gap to the lower energy was experimentally verified [3]. The studies of the advantages of exciton effects in the presence of electric field were increased in recent years. It is also important that the size of changes in refractive index due to electroabsorption is attractive for electro-optic devices. In this paper, we have compared electroabsorption properties with and without exciton effect and verified with experimental result. The change in absorption coefficient, change in refractive index and extinction ratio in the presence of electric field have been calculated.

II. Theoretical Models

The electroabsorption with exciton band and continuum band transition including Gaussian function and Sommerfield factor at RT can be defined [4]

$$\alpha(\hbar\omega) = \frac{4e^2\pi^2\hbar}{nmcd}\{\alpha_e(x) + \alpha_c(x)\} \quad (1)$$

with$\alpha_e(x) = G(x)$ and $\alpha_c(x) = f\delta(x) + S(x)$

$$\mathrm{x} = \frac{\hbar\omega - E_{ex}}{\hbar\Gamma} \quad (2)$$

D. P Sapkota is with the R&D of Nepal Telecom, Nepal(durga.sapkota@ntc.net.np).

M. S. Kayastha is with Kathford Engineering College, Nepal

K. Wakita is with the Electrical and Information Engineering Department, Chubu University, Japan.

$$G(x) = Q_X e^{-x^2/2} \quad (3)$$

$$\delta(x) = \frac{1}{1+e^{-2\pi x}} \quad (4)$$

$$S(x) = \frac{\pi e^{\frac{\pi}{\sqrt{x}}}}{\mathrm{x}\sinh\left(\frac{\pi}{\sqrt{x}}\right)} \quad (5)$$

$$f = \frac{2|M_{cv}|^2}{\pi m a_0{}^3\hbar\omega} \quad (6)$$

where is Planck constant, e is electron charge, n is refractive index, *m* is free electron mass, c is speed of light in vacuum, d is thickness of active layer, f is oscillator strength, $\delta(x)$ is delta function, $G(x)$ is Gaussian function, Q_X is exciton quenching factor, S(x) is Sommerfield factor, f is oscillator strength, M_{cv} is dipole matrix element, $E_{ex} = E_g + \Delta E$ is excition energy and $a_0$is bohrradus.

The exciton peak shift can be written for low field and high field, respectively as [4]:

$$\Delta\mathrm{E} = -6 \times 10^{-3}\frac{9}{8}f^2 \quad (7)$$

$$\Delta\mathrm{E} = -19 \times 10^{-3}\frac{9}{8}f^2 \quad (8)$$

where f is reduced electric field which is defined as $f = F/F_i$ where F_i is ionization field and F is electric field.

The half-width at half maximum of exciton $\hbar\Gamma$ can be defined as [4].

$$\hbar\Gamma = 26 \times 6.5 \times 10^{-3}\frac{1}{f}e^{-10/3f} \quad (9)$$

The relationship between change in absorption and refractive index change near the absorption edge for excitonic transitions is given by the Kramers-Kronigdispersion relation [5].

$$\Delta n = \frac{c}{\pi}\int_0^\infty \frac{\Delta\alpha dE}{\hbar\omega^2 - E^2} \quad (10)$$

where c is velocity of light, E is transition energy hw is photon energy.

III. Result and Discussion

For the simulation, the software based on Mathcad has been used in this work. The absorption coefficient with Coulomb interaction including exciton and continuum band at room temperature as well as associated with electric field in the presence of both exciton and continuum broadening has been considered in this work.

In Fig. 1, we have compared the structure of electroabsorption modulators which are waveguide type and surface-normal type. The waveguide has many disadvantages such as difficult to fabricate a 2D array, poor misalignment tolerance, and large size and fabrication complication whereas surface-normal type has also disadvantage such as short optical path length.

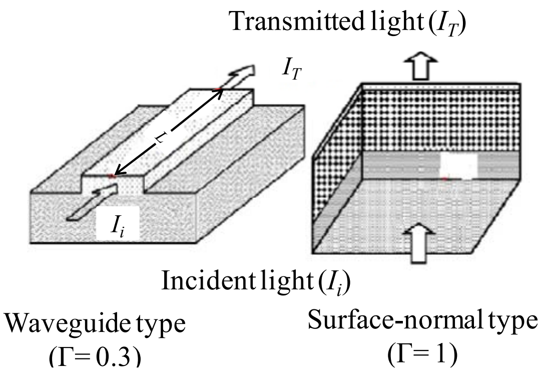

Fig. 1 Structure of electroabsorption modulator

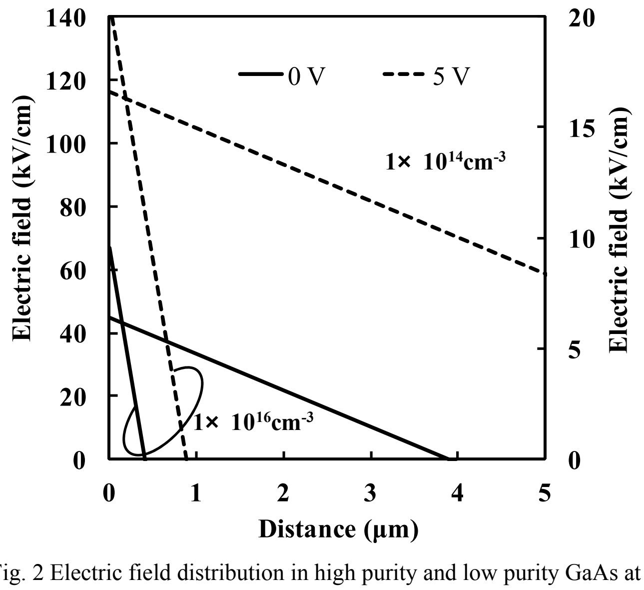

Fig. 2 Electric field distribution in high purity and low purity GaAs at two different voltages

The electric field distribution between high purity and low purity GaAs has been compared. Fig. 2 shows that the electric field at high purity GaAs has distributed widely than that of low purity GaAs.

Fig. 3 shows the absorption spectra with excitonic effects for high purity GaAs with 5µm thickness with impurity concentration of 10^{14} cm^{-3} at various electric fields. The linewidth broadening of exciton and stark energy shift with excitonic effect due to external applied voltage have been included in our calculation based on (8), (9), and (10) respectively. The linewidth broadening due to continumm band absorption is also included. In Fig. 3, the absorption spectra after exciton peak in experimental result at lower energy shows higher value than that of our result because this may be due to the reflection loss, coupling loss and substrate loss. The excitonic peak remains stable toward the lower energy having large red shift even at electric field of 70 kV/cm indicating that the electric field is uniform inside the active layer, which implies very high purity in active region. In the Fig. 3, the calculated absorption spectra without exciton effect at two different electric field is also shown.

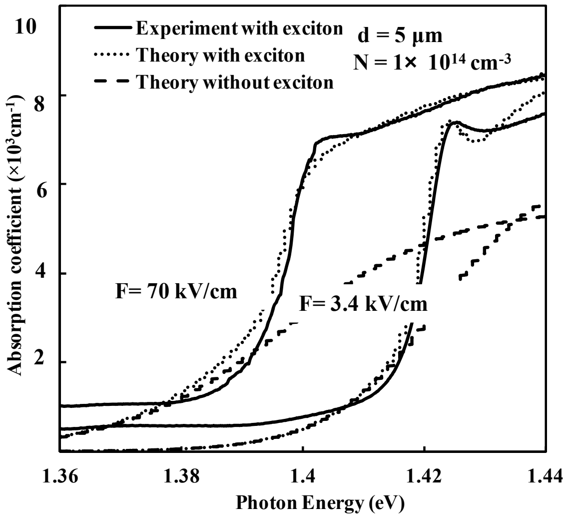

Fig. 3 Absorption spectra of theretical and experimental at two different electric field

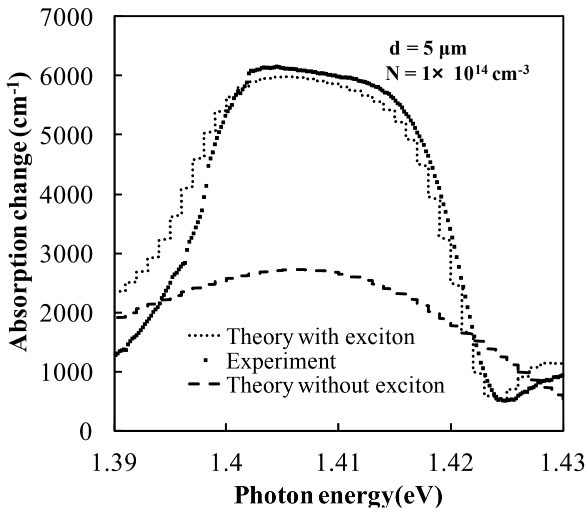

Fig. 4 Electroabsorption change of measured and theoretical results with and without exciton

Our numerical simulation discussed for GaAs bulk material with the thickness and carrier concentration of 5 µm of 1×10^{14}cm^{-3}, respectively as shown in Table I. The material dependence parameters such as reduced mass of electron and hole (μ) and bandgap E_g is taken as 0.069 m_0 and 1.425 eV respectively. The change in absorption coefficient as a function of photon energy with and without exciton absorption at the electric field of 70 kV/cm as well as measured absorption coefficient with exciton at the same electric field in shown Fig. 4. It is shown that the calculated change in absorption coefficient has closed agreement with the experimental ones. Our calculation shows that the change in absorption coefficient with exciton and without exciton was compared at photon energy of 1.406 eV. It is found that the change in absorption coefficient is 2.19 times higher with exciton effect than that of without exciton effect.

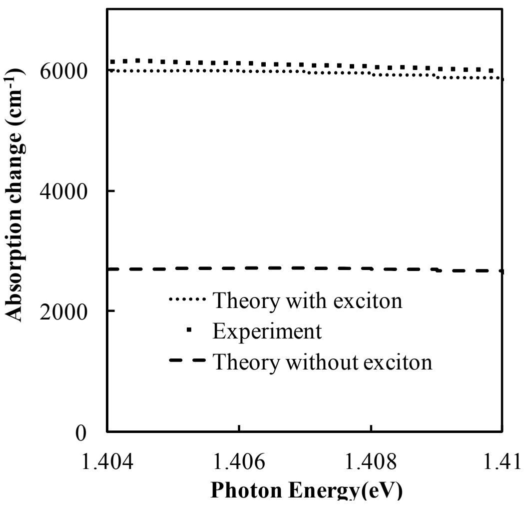

Fig. 5 Change in absorption spectra as a function of photon energy (in narrow range of photon energy)

Fig. 5 shows the change in absorption spectra as a function of photon energy in the required lasing wavelength of the device. The change in absorption spectra with exciton effect in this range is nearly coincide with the experimental result. In this range, the change in absorption spectra is about 2.19 times higher with exciton than that of without exciton effect.

The basic method of our simulation is used for the calculation of refractive index change by using Kramers-Kronig dispersion relation. The change in refractive index has been calculated from the absorption cofficient change association with the applied electric field of 70 kV/cm below the bandgap as shown in Fig. 6. The refractive index change with exciton absorption is estimated to be about 2.08 times higher than that of without exciton effect at photon energy of 1.406eV.

Fig. 7 shows the extinction ratio as a function of photon energy with and without exciton effect. The extinction ratio with and without exciton effect has been calculated based on the relation $10log(e^{-\Delta\alpha d})$, where, $\Delta\alpha$ is the change in absorption coefficient and d is the thickness of active layer. The extinction ratio is same upto photon energy of 1.38 eV and the gap between the extinction ratio with and without exciton effect is increased up to 1.41 eV. The extinction ratio is higher with exciton effect than without exciton effect in the range of 1.38 eV to 1.41 eV and it is 2.06 times higher at photon energy of 1.406 eV. At this photon energy, the extinction ratio is estimated to be 13dB at 70 kV/cm.

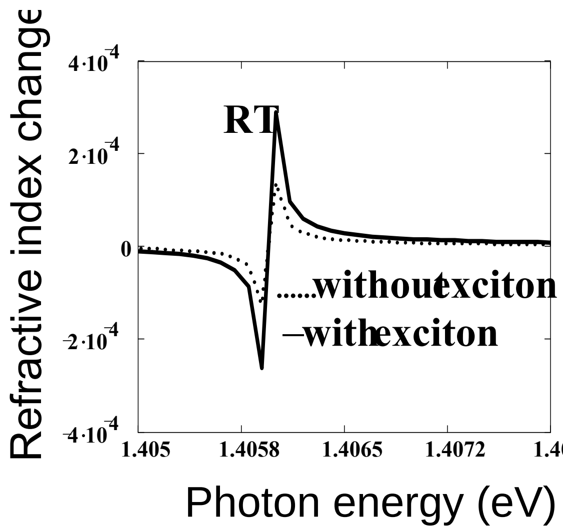

Fig. 6 Calculated refractive index change with and without exciton

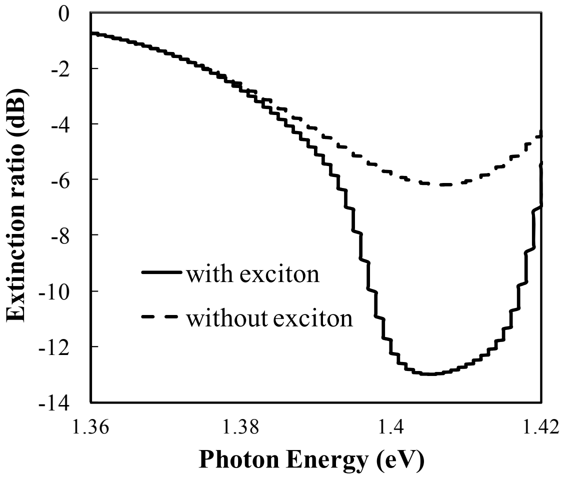

Fig. 7 Calculated extinction ratio with and without exciton effect

TABLE I
PARAMETERS USED IN THE CALCULATION

Parameters	Value	Units
active layer thickness (d)	5	μm
carrier concentration (N)	$1X10^{14}$	cm^{-3}
ionization field (F_i)	69	kV/cm
detuning energy (ΔE)	25	meV
bandgap (E_g)	1.429	eV

IV. CONCLUSION

In conclusion, we have calculated the change in absorption coefficient, change in refractive index and extinction ratio associated with exciton effect at two different electric fields. We obtained the good agreement with experimental results. We have concluded that the performance characteristics such as refractive index change, extinction ratio of bulk high purity GaAs layer for spatial light modulator can be enhanced with exciton effect. It is found that the change in absorption coefficient is almost double with exciton effect which consequently doubles the change in refractive index in exciton effect than in without exciton. The refractive change in this work is reached nearly to the refractive change of quantum well structured external modulator. The extinction ratio has been estimated to be about 2.06times higher with exciton effect than without.

REFERENCES

[1] J. D. Dow and D. Redfield, “Electroabsorption in semiconductors: the excitonic absorption edge,” Phys. Rev. B, vol. 1, pp. 3358-3371, 1970.

[2] M.S.Kayastha, M. Takahashi, and K. Wakita, “High-extinction ratio and low-driving-voltage spatial light modulator by use of ultrahigh-purity GaAs,” Jpn. J. Appl. Phys,vol. 49, pp. 102201-102205, 2010.

[3] M. S. Kayastha, D. P.Sapkota, M. Takahashi and K.Wakita, “Effect of electric field on exciton in high-purity GaAs epilayer measured at room temperature,” Electronic Lett.,vol. 49, pp. 57-59, 2013.

[4] D. P. Sapkota, M. S. Kayastha, M. Takahashi and K. Wakita, "Proposed Model of Electric Field Effects inHigh-Purity GaAs at Room Temperature," Optics and Photonics Journal, vol. 4, pp. 99-103, 2014

[5] T. Hiroshima," Electric field induced refractive index changes in GaAsAlxGa1-xAs quantum well," Appl. Phys. Lett., vol. 50, pp.968-970, 1987.

Durga Prasad Sapkota was born in Sept. 1972. He received his M. Sc. Degree in Mathematics from Tribhuvan University, Kathmandu, Nepal, in 1998. He received Ph.D. degree from the Graduate School of Electrical and Electronics Engineering of Chubu University. Aichi, Japan in 2012. His research interests are related with multiple quantum well and bulk optoelectronic devices for optical fiber communication. He joined Nepal Telecom in 1994 and has continued till this date as a responsibility of research task in research and development of Nepal Telecom.

M. S. Kayastha was born in Jan 1980. He received his B.E degree in Electronics and Communication Engineering from Pokhara Engineering College, Pokhara, Nepal in 2004 and his M.E and Ph. D degree from Chubu University, Aichi, Japan in 2007 and 2011, respectively. He had been engaged in research and development of high efficiency spatial modulator using high purity GaAs by liquid phase epitaxy method. He had also been engaged in synthesis and characterization of graphene film by ME-SWP-CVD and thermal CVD. He is a member of Nepal Engineers Association (NEA) and Nepal Engineering Council (NEC). He joined Kathford Int’l College of Engineering and Management on June, 2014 as a Senior lecturer and Head of Department in Department of Computer and Electronics & Communication Engineering. He is also affiliated to Kathmandu Institute of Applied Science.

Koichi Wakita received his B. S. degree in Electronics Engineering from the Nagoya Institute of Technology in 1968 and his M. S. and Dr. Eng. degree from Nagoya University in 1970 and 1976, respectively. In 1973, he joined NTT Electrical Communication Laboratories, Japan. He had been engaged in research and development of semiconductor lasers and multiple quantum well optical modulators for the optical fiber communication. In 1997, he joined the Department of Electronics and Information Engineering in Chubu University, Aichi, Japan, as a professor. He is a member of the IEICE of Japan, the Institute of Electrical Engineers of Japan, and the Japan Society of Applied Physics.