Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp526-527

# Influence of Heterointerface Abruptness on Electrorefractive Effect in InGaAs/InAlAs Five-Layer Asymmetric Coupled Quantum Well (FACQW)

Yuji Iseri[1], Taro Arakawa[1], Kunio Tada[2], and Nobuo Haneji[1]

[1]Graduate School of Engineering, Yokohama National University
79-5 Tokiwadai, Hodogaya-ku, Yokohama 240-8501, Japan
Phone: +81-45-339-4143 E-mail: arakawa@ynu.ac.jp
[2] Graduate School of Engineering, Kanazawa Institute of Technology
1-3-4 Atago, Minato-ku, Tokyo 105-0002, Japan

## 1. Introduction

For high-performance semiconductor optical modulators and switches based on phase modulation such as Mach-Zehnder (MZ) modulators, five-layer asymmetric coupled quantum wells (FACQWs) have been studied [1-3]. The FACQW is one of the most promising candidates for producing a giant electrorefractive index change.

Because the FACQW is composed of ultra-thin layers, the thickness fluctuation of each layer may deteriorate the electrorefractive effect [4]. In addition, poor abruptness in heterointerfaces may also have bad influence on the characteristics of the FACQW. Improvements of abruptness of heterointerfaces for III-V compound semiconductors were theoretically and experimentally studied[5-7].

In this paper, we theoretically investigate the influence of heterointerface abruptness on electrorefractive effect in an $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ FACQW. We also propose an improved FACQW structure against the deterioration caused by poor abruptness of heterointerfaces.

## 2. Deterioration of electrorefractive effect

Figure 1 illustrates the calculation model used for investigating influence of abruptness in heterointerfaces of the FACQW on its electrorefractive effect[8]. A profile of Al composition $x$ in $In_{0.53-x/48}Ga_{0.47-47x/48}Al_xAs$ layers is shown. All InGaAlAs layers are assumed to be lattice-matched to an InP substrate. The dotted line describes the ideal FACQW structure with no transition region at heterointerfaces. It is composed of a 19-ML (mono layer) InGaAs well (QW1) and a 22 (=4+3+15)-ML well (QW2) with a 3-ML InAlAs layer inserted for potential modification. Both well layers couple with each other through an 8-ML InAlAs barrier layer. The solid line describes an Al composition profile of an "exponential model", that is, a structure with deteriorated abruptness in heterointerfaces. In the analysis, we assume that a composition $X$ ($z$) of Al at a position $z$=0 exponentially changes as

$$X(z) = X(0)\exp\left(-\frac{z}{L}\right),$$

where $L$ is a thickness constant of a transition layer. It is assumed for simplicity that $L$ for InGaAs/InAlAs interfaces is the same with that for InAlAs/InGaAs interfaces. Using this profile, absorption coefficient spectra with various $L$ were calculated by solving the Schrödinger equations utilizing the $k{\cdot}p$ perturbation theory with a 4 x 4 Luttin-

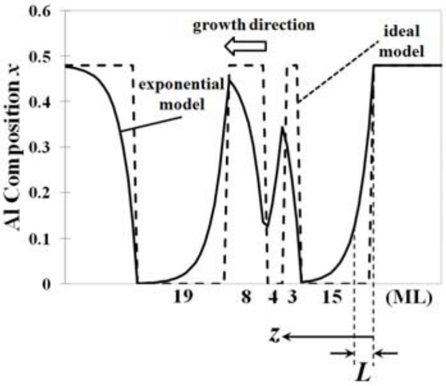
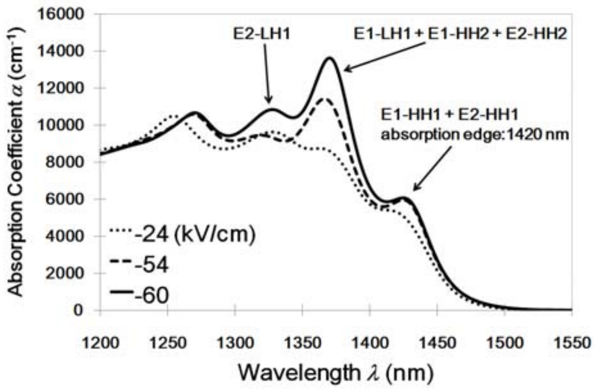
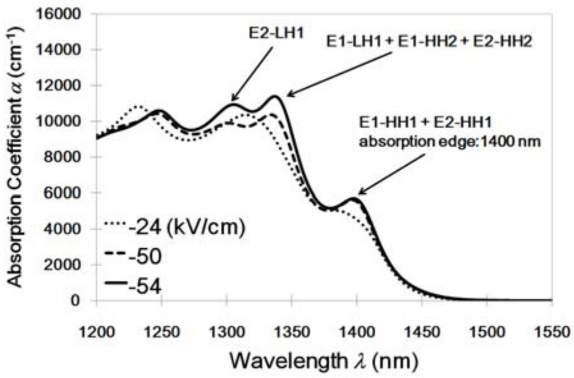



Fig.1. Profile of Al composition $x$ in InGaAlAs layers used for investigating influence of abruptness in heterointerfaces.




(a) $L$=0 ML




(b) $L$=3 ML

Fig.2. Calculated absorption spectra of InGaAs/InAlAs FACQW (TE mode). (a) $L$=0 ML, (b) $L$=3 ML. For $L$=0 ML and 3 ML, absorption coefficient change $\Delta\alpha$ is maximum at $F$= −60 and -54 kV/cm, respectively.

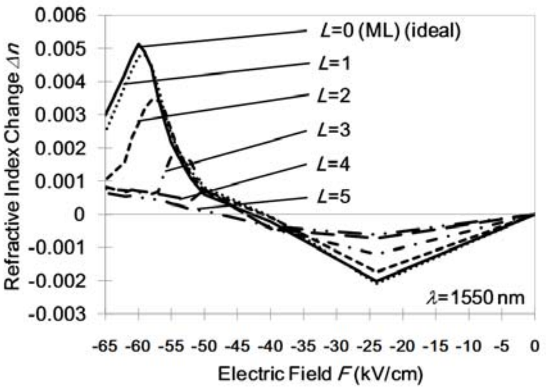
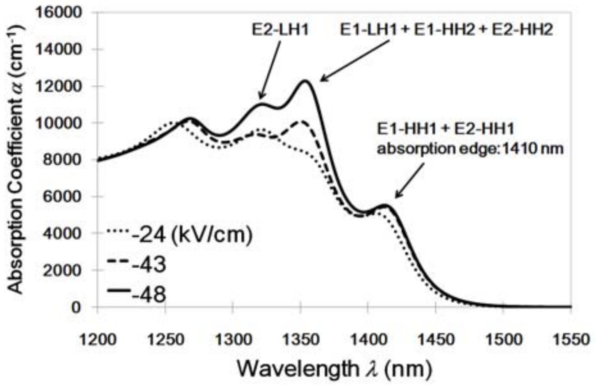



Fig.3. Calculated electrorefractive index change $\Delta n$ (TE mode) of FACQW with various $L$.




$L$=3 ML after redesign

Fig.4. Calculated absorption spectra of the redesigned FACQW (TE mode) with $L$=3 ML. Absorption coefficient change $\Delta\alpha$ is maximum at $F$= −48 kV/cm.

ger-Kohn Hamiltonian[9] The exciton effect was calculated using non-variational approach.

Figure 2 shows the calculated absorption coefficient spectra of the FACQW for $L$=0 and $L$=3 ML. The large electrorefractive index change is caused by the increase of the peak at around 1370 nm. However, in the case of $L$=3 MLs, the increase of the peak becomes small, resulting in small electrorefractive index change.

Figure 3 shows the theoretical refractive index changesat the wavelength of 1550 nm with various $L$ as functions of an applied electric field. When $L$ is equal or more than 3 MLs, the decrease of the electrorefractive index change at 50-60 kV/cm is remarkable. The main reason for this deterioration of the electrorefractive index change is that due to the poor abruptness of heterointerfaces, the height of the thin barrier layers for coupling (the 8ML-InAlAs layer) decreases and localization of carriers in the FACQW becomes weakened.

## 3. Redesinged FACQW structure against the deterioration

In actual crystal growth processes, deterioration of heterointerface abruptness especially in metal organic vapor phase epitaxy (MOVPE) is inevitable. To overcome this problem, we redesigned the FACQW structure on the assumption that there exists some deterioration in abruptness of heterointerfaces. For example, when $L$=3 ML, 19-ML

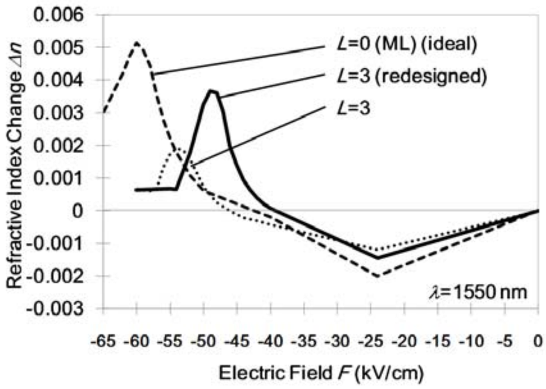



Fig.5. Calculated electrorefractive index change $\Delta n$ (TE mode) of FACQW (ideal, $L$=3 ML before redesign, and $L$=3 ML after redesign).

InGaAs, 8-ML InAlAs and 15-ML InGaAs layers are thickened by 1, 2, and 1 ML, respectively.

Figure 4 shows the calculated absorption coefficient spectra of the redesigned FACQW structure. Comparing with Fig. 2.(b), the increase of the absorption peak at around 1370 nm is recovered. Figure 5 shows the theoretical refractive index change of the re-designed FACQWs with $L$=3 ML as a function of an applied electric field. Though the peak height at around $F$=50 kV/cm is slightly decreased, the electrorefractive index change is greatly recovered even with $L$=3 ML. This result shows that the FACQW structure is still a promising structure for low-voltage and high-speed optical modulators and switches even with non-abrupt heterointerfaces.

## 4. Conclusions

The influence of heterointerface abruptness on electrorefractive effect in InGaAs/InAlAs FACQW was studied. Transition layers of composition at heterointerfaces in the FACQW will deteriorate the electrorefractive index change. This problem can be overcome by changing the thicknesses of a few critical layers.

## Acknowledgements

This study is partly supported by the Strategic Information and Communications R&D Promotion Program (SCOPE), Ministry of Internal Affairs and Communications, and by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology, Japan. The authors are also grateful to Dr. J. Hashimoto, Dr. M. Murata, and Dr. K. Sakurai, Sumitomo Electric Industries, Ltd., for discussion.

## References

[1] H. Feng, J. P. Pang, M. Sugiyama, K. Tada, and Y. Nakano, IEEE J. Quantum Electron. **34** (1998) 1197.
[2] T. Suzuki, T. Arakawa, K. Tada, Y. Imazato, J.-H. Noh, and N. Haneji, Jpn. J. Appl. Phys. **43** (2004) L1540.
[3] M. Fukuoka, T. Hariki, S. Tajitsu, T. Toya, T. Arakawa, and K. Tada, Euro. Conf. Optical Comm. (ECOC 2008) P.2.22.
[4] K. Tada, T. Arakawa, K. Kazuma, N. Kurosawa, and J. H. Noh, Jpn. J. Appl. Phys. **40** (2001) 656.
[5] S. Sudo, Y. Nakano, M. Sugiyama, Y. Shimogaki, H. Komiyama, and K. Tada, Proc. 10th Intern. Conf. Indium Phosphide and Related Materials (IPRM 1998) 485.
[6] Y. Takeda, M. Tabuchi, R. Oga, I. Yamanaka, and A. Nakamura, Tech. Report of IEICE, 2004-50 (2004) 53. (Japanese)
[7] T. Nakano, T. Shioda, E. Abe, M. Sugiyama, N. Enomoto, Y. Nakano, and Y. Shimogaki, Appl. Phys. Lett. **92** (2008) 112106.
[8] Y. Sawai, T. Toya, R. Hasegawa, T. Arakawa, and K. Tada, 55th JSAP Spring Meeting 2008, 29a-ZG-6 (in Japanese).
[9] C. L. Chuang, Phys. Rev. B. **43** (1991) 9649.