Semiconductor optical modulator by using electron depleting absorption control

PAPER

Semiconductor Optical Modulator by Using Electron Depleting Absorption Control

Minoru YAMADA†, *Member*, Kazuhiro NODA†*, *Nonmember*, Yuji KUWAMURA†, *Member*,
Hirohumi NAKANISHI†** *and* Kiyohumi IMAI†***, *Nonmembers*

SUMMARY Operation of a newly proposed semiconductor optical modulator based on absorption control by electron depletion around a p-n junction is demonstrated, forming preliminary structures of waveguide-type as well as panel-type (or surface-illuminated type) devices. The optical absorption is occurred at the intrinsic energy levels in the band structure not at the extended state into the band-gap. Performance of 35 dB on-off extinction ratio for 4 V variation of the applied voltage was obtained in a waveguide type device. Validity of the proposed mechanism were confirmed by getting large change of the absorption coefficient of around 5000 cm^{-1} over wide wavelength range of 30 nm.

key words: *optical modulator, optical switch, semicanductor*

1. Introduction

Progress of optical switches or modulators made of semiconductor materials is expected for further development of opto-electronics. For examples, waveguide type modulator with very wide modulation bandwidth is necessary for the optical communication, while panel type (or surface-illuminated) array modulator is required to realize an optical computer.

Mechanisms popularly used in the semiconductor optical modulator are based on the electro-optical effects induced by electric field, such as the Franz-Keldysh effect, quantum confined Stark effect and so on(1)-(19). The refractive index or the absorption coefficient is changed by these effect. Excellent operation with applied voltage less than 5 V and modulation bandwidth over 20 GHz have been reported(17),(18). Operation for very wide wavelength range of more than 0.5 μm was also obtained by changing the guiding mechanism of the propagating light(19).

Other mechanisms for the semiconductor optical modulator are to utilize direct variation of the carrier density. Large changes of the optical absorption coefficient due to screening or quenching effect on the exciton states with occupation of the carrier in the quantum well have been observed in modulators with a FET type configuration(20)-(23). Some diode type optical modulators, operating with the carrier injection to reduce absorption of incident light have also been proposed(24). Variation of the refractive index with depletion of the electron was also applied to an optical modulator(25),(26).

Investigation of different possible mechanism is also important to develop the optical switch or modulator, because various structure but unified material will be required to get monolithic integration or efficient coupling with other optical device such as a laser and a detector. In this paper, operation of a new type of semiconductor optical modulator is examined. The optical absorption is controlled through variation of thickness (or width) of the depletion layer around the p-n junction(27). The device was made of AlGaAs system forming waveguide-type as well as panel-type (or surface-illuminated) configurations, and is named as EDAC (electron depleting absorption control) optical modulator.

2. Mechanism of EDAC Optical Modulator

The basic idea of EDAC (electron depleting absorption control) optical modulator is schematically illustrated in Fig. 1. The optical absorption due to the electron transition from the valence band to the con-

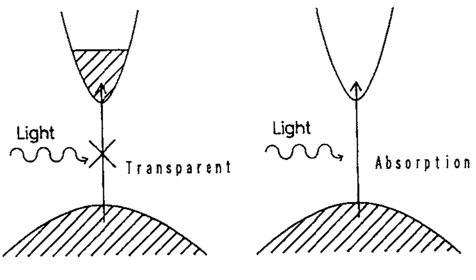

Fig. 1 Mechanism to control optical absorption. The optical absorption hardly occurs if the conduction band is filled with electrons as shown in (a), but occurs by sweeping out the electrons from the conduction band as shown in (b).

Manuscript received December 12, 1991.
Manuscript revised March 23, 1992.

† The authors are with the Faculty of Technology, Kanazawa University, Kanazawa-shi, 920 Japan.
* Presently, with Gunze Corp.
** Presently, with Yokokawa Electric Corp.
*** Presently, with PFU Corp.

Reprinted from Trans. IEICE. Electron., Vol. E75-C, No. 9, pp. 1063~1070 (1992)

duction band is controlled by the number of electrons located in the conduction band in the direct transition type semiconductor materials. The optical absorption hardly occurs if the conduction band is filled with electrons as shown in Fig. 1(a), but occurs by sweeping out the electrons from the conduction band as shown in Fig. 1(b). Then, two states of transmission (or "on") and cut off (or "off") are switched by changing the electron density in the conduction band. The n-type bulk material is considered to be state (a), and whose depleted portion around a p-n junction is in condition of state (b). The width of the depleted portion is varied with applied voltage on the p-n junction.

The change of the optical absorption with the number of carriers is more effective in n-type material than in p-type material, because the effective mass and density of states of the conduction electrons are much smaller than those of the holes in the valence band. The device is designed to utilize variation of the depletion layer in n-side region.

3. Waveguide-Type EDAC Optical Modulator

3. 1 Device Structure and Fabrication

The structure and the operating mechanism of a waveguide-type EDAC optical modulator are illustrated in Figs. 2 and 3. The optical beam propagates in a n^+-$Al_{0.09}Ga_{0.91}As$ waveguide layer having small band gap and high refractive index noted with n_1. The p-n junction is located at the boundary between n^+-$Al_{0.09}Ga_{0.91}As$ waveguide layer and p^+-$Al_{0.2}Ga_{0.8}As$ cladding layer. The reason why we put slight Al in the waveguide instead of GaAs is to examine operation for various wavelength of the light source.

The optical beam suffers absorption loss in the n^+-side part of the depletion layer as illustrated with the painted area of the field distribution in Fig. 3. When the p-n junction is reverse biased, the thickness (or width) of the depletion layer is increased, resulting in

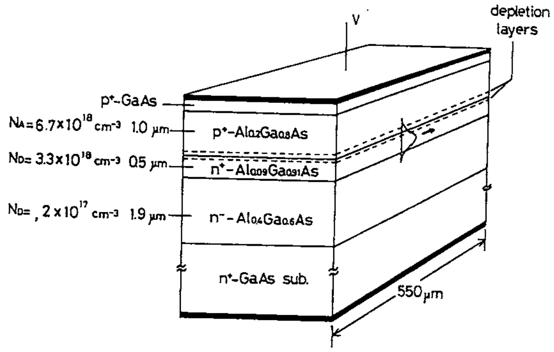

Fig. 2 Schematic illustration of the waveguide-type optical modulator.

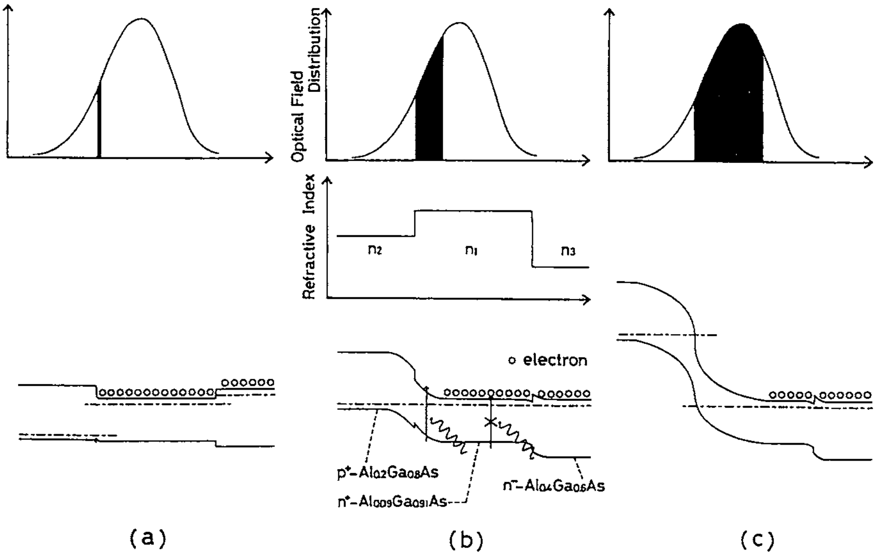

Fig. 3 Band gap profile and optical field distribution. Bias voltage is in forward direction (a), zero(b), and in backward direction (c). The depletion layer is widened by the backward bias giving large absorption loss.

larger absorption as shown in Fig. 3 (c), while inverse change occurs with forward bias shown in Fig. 3(a).

Design parameters Al composition x in Al_xGa_{1-x} As system and thickness of each grown layer are determined theoretically to get suitable field distribution as discussed in later. Impurity concentrations in p^+ and n^+ layers are chosen to get heavy doping as possible. Since the cladding layer in n-side need not have heavy doping, the doping level of n^- was chosen in order of $10^{17}\,cm^{-3}$.

Liquid-phase epitaxy was used for the crystal growth on Si-doped GaAs substrate. The dopants were Te and Zn for n-type and p-type impurities, respectively. Metals of Au-Ge and Au-Zn were evaporated as the electrodes for n-type side and p-type side, respectively.

3. 2 Operating Characteristics

Transmission characteristics of the waveguide-type device were measured with an experimental set-up shown in Fig. 4. The light source was a semiconductor laser diode. For the wavelength dependence measurement, laser diodes with different wavelengths were used.

Variations of the transmitted light with the applied voltage and the device length are shown in Figs. 5 and 6, respectively. The device was operated in range from −3 V to +1 V. More reverse bias than −3 V caused the break down of p-n junction, while larger forward bias than 1 V induced remarkable current flow. The device length was changed by cutting the waveguide of an identical sample from 550 to 200 μm. Scales in the vertical axes were given by eliminating the connecting loss of 21 dB which is estimated by taking extrapolation of the data to $L=0$. Guiding loss inside of the device at wavelength of 811 nm was estimated to be $50\,cm^{-1}$ for "on" state with +1 V bias in Fig. 6. This guiding loss may be due to optical absorption at the depletion layer, which still exists even at "on" state. 35 dB extinction ratio with voltage variation from −3 V to +1 V was obtained in 550 μm-long sample.

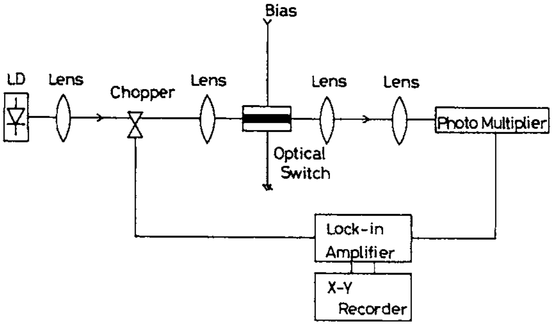

Fig. 4 Experimental set-up for the measurement of the transmitted light on the waveguide-type device.

The curved lines in Fig. 5 are by theoretical calculation. By putting change of the local absorption coefficient to be $\Delta\alpha$, field confinement factor in the n-side depletion layer to be $\xi(V)$, the device length to be L, and intensity of the incident light to be T_o, the intensity T of the transmitted light is given by

$$T = T_o \exp\left[-\Delta\alpha\xi(V)L\right] \qquad (1)$$

One feature of this device is that the confinement factor $\xi(V)$ in the n-side depletion layer is varied with the applied voltage V, while the change of the local absorption coefficient $\Delta\alpha$ is independent from strength of the applied voltage. While other devices based on the electro-optical effect are under the counter situa-

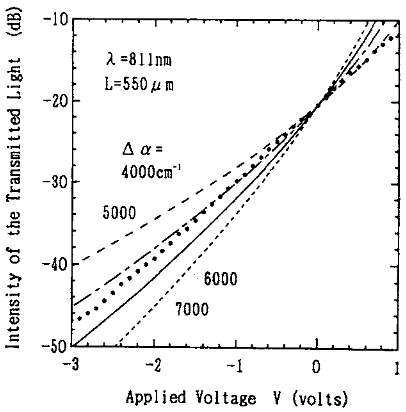

Fig. 5 Variation of the transmitted light with applied voltage. Scale of the vertical axis was given by subtracting the connecting loss of 21 dB. 35 dB variation of the transmitted light was observed with 4 V change of the applied voltage.

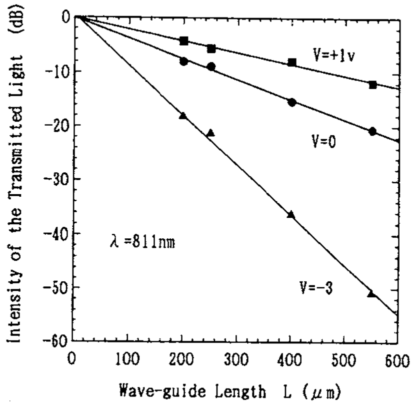

Fig. 6 Variation of the transmitted light for different waveguide length. Guiding loss in the waveguide is $50\,cm^{-1}$ for 1 V bias.

tion that ξ is constant but $\Delta\alpha$ is changed with the applied field. As an increase of the reverse bias, the confinement factor $\xi(V)$ increases, resulting in large amount of absorption.

The field distribution was analyzed to be a guided mode in a three layer dielectric waveguide by assuming that the refractive index n is changed with the Al composition x in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ alloy system in relation of Ref.(28).

$$n(x)=3.59-0.071x+0.091x^2 \qquad (2)$$

but is not changed with the depleting of the electrons. The confinement factor $\xi(V)$ was analyzed from this field distribution and the thickness of the depletion region obtained by analyzing the Poisson's equation. Value of $\xi(V)$ in the structure of Fig. 2 was theoretically estimated to change from 0.015 to 0.0466 for voltage variation from +1 to −3 V.

The curves in Fig. 5 are drown with two fitting parameters of T_o and $\Delta\alpha$. The former parameter gives parallel shift of the curve in vertical direction and is adjusted to fit the data at $V=0$. While the latter one gives slope of the curve and several values are substituted as in the figure. The experimental data fit roughly with theoretical curves for $\Delta\alpha=5000\sim6000\ \mathrm{cm}^{-1}$. This value seem to be reasonable by comparison with data of the absorption coefficient in n type bulk GaAs which were measured for different doping densities(28).

Wavelength dependence of the extinction ratio for the 250 μm-long sample is shown in Fig. 7 with painted circles, where wavelength of the incident light was changed by using laser diodes with different wavelength. The extinction ratio of this figure is defined by next equation.

$$\delta=(1-T_{\min}/T_{\max})\times100(\%) \qquad (3)$$

Here, $T_{\min}$ and $T_{\max}$ are the minimum and the maximum intensities of the transmitted light, respectively, under the voltage variation from −3 to +1 V. The dotted line in Fig. 7 is a profile of the spontaneous emission caused by current injection with forward bias larger than +1 V. Wavelength at the peak of the extinction ratio, about 810 nm, is almost the same as that of the spontaneous emission. This correspondence indicates that both phenomena are caused by the change of the electron density in the conduction band but not by the tailing states extending into the band gap.

Optical bandwidth of the modulation getting sufficient extinction ratio more than 90% (10 dB) was around 30 nm as given in Fig. 7.

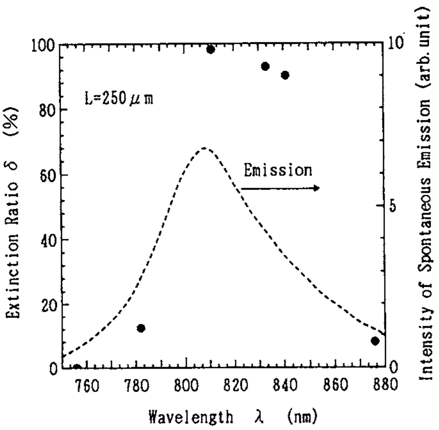

Fig. 7 Wavelength dependence of the extinction ratio and the spontaneous emission in the waveguide-type device. The most efficient wavelength for the absorption change is 811 nm, which almost coincides with the peak wavelength of the spontaneous emission.

4. Panel-Type EDAC Optical Modulator

4. 1 Device Structure and Fabrication

Since thickness of the depletion layer around a single p-n junction is only several tens of nm, a large number of p-n junctions is required to get sufficient extinction ratio in a panel-type device. Here, we fabricated a preliminary device consisting of a p-n-p-n junction as shown in Fig. 8 to examine the modulation effect in a panel-type device, where the optical beam is incident perpendicular to the p-n junction planes. Liquid phase epitaxy was used for the crystal growth, where the duplicated forming of the p-n junction was done by repeating the back and forth movement of the carbon boat in the furnace. After evaporation of the electrode metals for p-type side and n-type side electrodes, windows of 200×200 $\mu\mathrm{m}^2$ area were opened by chemical etching.

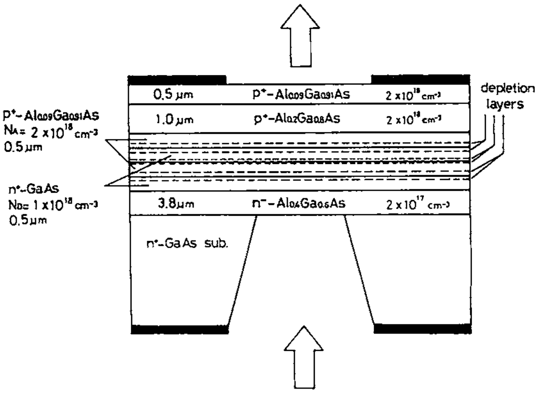

Fig. 8 Cross section of the panel-type optical modulator.

4. 2 Operating Characteristics

Measuring set up is shown in Fig. 9. The optical source of this measurement is a tungsten-halogen lamp radiating incoherent light and whose wavelength was selected by monochromator. The light was guided into the panel-type device with a multi-mode fiber.

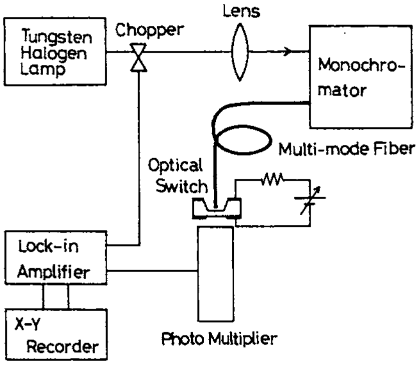

Fig. 9 Experimental set-up for the measurement of the transmitted light on the panel-type device.

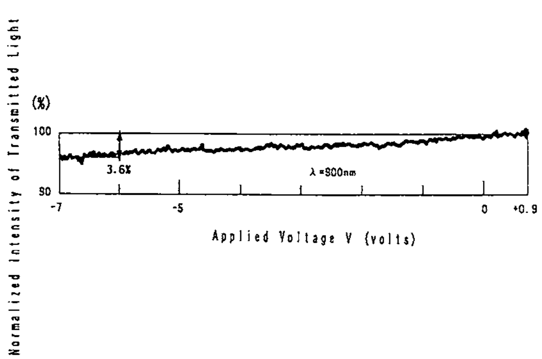

Fig. 10 Normalized intensity of the transmitted light with variation of the applied voltage.

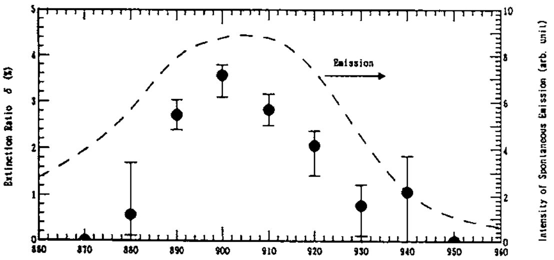

Fig. 11 Wavelength dependence of the extinction ratio and the spontaneous emission in the panel-type device. Good correspondence was obtained between profile of the extinction ratio and that of the spontaneous emission.

Intensity variation of the transmitted light with variation of the applied voltage is shown in Fig. 10. The extinction ratio was 3.6% at wavelength of 900 nm for the voltage change from -7 V to $+0.9$ V. Wavelength dependence of the extinction ratio is shown in Fig. 11 with painted circules. Profile of the spontaneous emission of same sample with larger forward bias than 1 V is also shown in the figure with a broken line. Good correspondence between the absorption and the emission characteristics were confirmed.

The intensity of the transmitted light is given by next equation for the panel-type device

$$T = T_0 \exp\left[-\Delta\alpha \sum_i d_i\right] \qquad (4)$$

where, d_i is thickness of each n-side depletion layer and $\sum_i d_i$ is total thickness of the n-side depletion layers. As an increase of the reverse bias, the total thickness of the n-side depletion layers increase, resulting in large amount of absorption. Change of d_i was measured through the capacitance measurement of the device. Then we can estimate the change in the absorption coefficient $\Delta\alpha$ from the data in Fig. 11. Estimated $\Delta\alpha$ is shown in Fig. 12. The largest change occurred at wavelength of 900 nm with value of $\Delta\alpha = 4000 \sim 5000$ cm^{-1}. Estimated values of $\Delta\alpha$ almost coincides with that in the waveguide type modulator at the peak change. The wavelength width getting sufficient change in absorption coefficient $\Delta\alpha$ more than 2000 cm^{-1} was about 40 nm in this device.

To obtain larger extinction ratio, we piled up

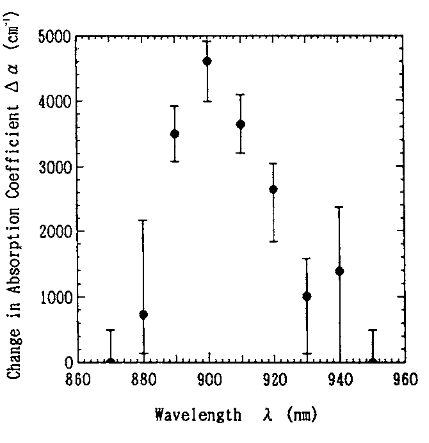

Fig. 12 Wavelength dependence of the change in the absorption coefficient by electron depleting around p-n junction. The largest change of the absorption coefficient was estimated to be 4000~5000 cm^{-1} at wavelength of 900 nm.

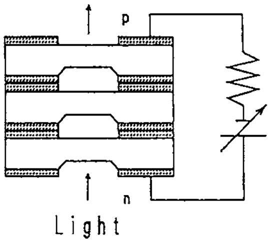

Fig. 13 A combined device by piling up three chips.

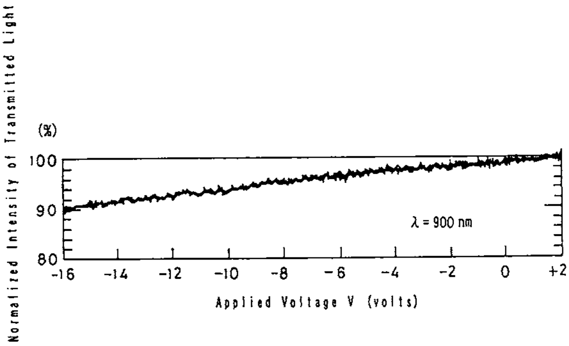

Fig. 14 Normalized intensity of transmitted light with variation of the applied voltage on the combined device. Performance of 10% extinction ratio was obtained.

three chips making a combined device as shown in Fig. 13. Performance of 10% (0.45 dB) extinction ratio with 18 V variation of the applied voltage was obtained for the combined device as shown in Fig. 14.

By increasing the number of the p-n junctions, larger extinction ratio will be obtained. With increasing layer number, the required voltage is also increased. However, this problem may be resolved if we can support the bias voltage along horizontal direction by forming a comb-like structure made by Horikoshi et al. to be a photodetector$^{(29)}$. Fabrication of the modulator with the comb-like structure is at moment a subject for authors.

5. Conclusion

Operation of optical modulators based on the electron depleting absorption control (EDAC for short) were examined forming both waveguide-type and panel-type devices. Performance of 35 dB (99.97%) extinction ratio was observed with 4 V variation of the applied voltage in a waveguide-type device. Total absorption or guiding loss in the waveguide was estimated to be 50 cm^{-1}. While, performance of 0.45 dB (10%) extinction ratio was observed with 18 V variation of the applied voltage in a panel-type device. Large change of the absorption coefficient reaching $\Delta\alpha \cong 5000$ cm^{-1} and wide wavelength range of $\Delta\lambda > 30$ nm were confirmed. Excellent features of our EDAC optical modulator may be to have high saturation level of the absorption for the incident light inensity and having possibility to integrate with other optical devices easilly, because same band energy levels can be used in those devices. Disadvantage of the EDAC modulator is the high absorption loss at "on" state. However, this disadvantage may be canceled with above mentioned excellent features in some application fields like as the optical computer by improvement of the device structure.

Acknowledgment

The authors acknowledge Dr. S. Akiba and Dr. K. Utaka of KDD R & D Laboratories for providing the growing system of the material, Prof. M. Suzuki and Prof. T. Hata of Kanazawa University for convenience of the experiment, and Mr. Y. Kakimoto and Mr. H. Yamamoto for helpful assistance. This research is partly supported by Grand in Aid for Scientific Research by Ministry of Education, Culture and Science, Japan.

References

(1) Keldysh L. V.: "The effect of a strong electric field on the optical properties of insulating crystals", Sov. Phys. JETP, **34**, pp. 788-790 (Nov. 1958).

(2) Callaway J.: "Optical absorption in an electric field", Phys. Rev., **134**, pp. A998-A1000 (May 1964).

(3) Seraphin B. O. and Bottka N.: "Franz-Keldysh effect of the refractive index in semiconductors", Phys. Rev., **139**, pp. A560-A565 (July 1965).

(4) Reinhart F. K.: "Electroabsorption in Al$_y$Ga$_{1-y}$As-Al$_x$Ga$_{1-x}$As double heterostructures", Appl. Phys. Lett., **22**, pp. 372-374 (Jan. 1973).

(5) Stillman G. E., Wolfe C. M., Bozler C. O. and Rossi J. A.: "Electroabsorption in GaAs and its application to waveguide detectors and modulators", Appl. Phys. Lett., **28**, pp. 544-546 (May 1976).

(6) Döhler G. H., Künzel H. and Ploog K.: "Tunable absorption coefficient in GaAs doping superlattice", Phys. Rev. B, **25**, pp. 2616-2626 (Feb. 1982).

(7) Van Eck T. E., Walpita L. M., Chang W. S. C. and Wieder H. H.: "Franz-Keldysh electrorefraction and electroabsorption in bulk InP and GaAs", Appl. Phys. Lett., pp. 451-453 (Feb. 1986).

(8) Takeuchi H., Kasaya K. and Oe K.: "Low-switching-voltage InGaAsP/InP waveguide interferometric modulator for integrated optics", Photon. Technol. Lett. **1**, pp. 227-229 (Aug. 1989).

(9) Wood T. H., Burrus C. A., Tucker R. S., Weiner J. S., Miller D. A. B., Chemla D. S., Damen T. C., Gossard A. C. and Wiegmann W.: "100 ps waveguide multiple quantum well (MQW) optical modulator with 10 : 1 on/off ratio", Electron. Lett., **21**, pp. 693-694 (Aug. 1985).

(10) Koren U., Miller B. I., Koch T. L., Eisenstein G., Tucker R. S., Bar-Joseph I. and Chemla D. S.: "Low-loss InGaAs/InP multiple quantum well optical electroabsorption waveguide modulator", Appl. Phys. Lett., **51**, pp.

1132-1134 (Oct. 1987).

(11) Wood T. H., Carr E. C., Burrus C. A., Miller B. I. and Koren U.: "Large electroabsorption effect in GaInAs/InP multiple quantum well (MQW) optical modulator grown by OMVPE", Electron. Lett., **24**, pp. 840-841 (July 1988).

(12) Suzuki M., Tanaka H., Akiba S. and Matsushima Y.: "Superior characteristics of buffer layer loaded InGaAsP electroabsorption modulator for mW-range operation", IOOC '89, **2**, 20B1-19, 1 (1989).

(13) Soda H., Furutsu M., Sato K., Okazaki N., Yamazaki S., Nishimoto H. and Ishikawa H.: "High-power and high-speed semi-insulating BH structure monolithic electroabsorption modulator/DFB laser light source", Electron. Lett., **26**, pp. 9-10 (Jan. 1990).

(14) Kikugawa T., Ravikumar K. G., Shimomura K., Izumi A., Matsubara K., Miyamoto Y., Arai S. and Suematsu Y.: "Switching operation in OMVPE grown GaInAs/InP MQW intersectional optical switch structures", IEEE Photon. Technol. Lett., **1**, pp. 126-128 (June 1989).

(15) Huang T. C., Chung Y., Dagli N. and Coldren L. A.: "GaAs/AlGaAs multiple quantum well field-induced optical waveguide" Appl. Phys. Lett., **57**, pp. 114-116 (July 1990).

(16) Mukaiyama K., Yamanishi M., Kan Y., Ohnishi T., Okuda M.. and Suemune I.: "High-speed intensity modulation by quantum-confined field effect combined with modulation of injection current in light-emitting triodes", Jpn. J. Appl. Phys., **29**, pp. L967-L970 (June 1990).

(17) Wakita K., Kotaka I., Mitomi O., Asai H., Kawamura Y. and Naganuma M.: "High-speed InGaAlAs/InAlAs multiple quantum well optical modulators", J. Lightwave Technol., **8**, pp. 1027-1031 (July 1990).

(18) Mak G., Rolland C., Fox K. E. and Blaauw C.: "High-speed bulk InGaAsP-InP electroabsorption modulators with bandwidth in excess of 20 GHz", IEEE Photon. Technol. Lett., **2**, pp. 730-733 (Oct. 1990).

(19) Haung T. C., Dagli N. and Coldren L. A.: "A novel intensity modulator with high on/off ratio over a large optical bandwidth", in technical digest of Conference on Lasers and Electro-Optics (CLEO'91), CMA6 (May 1991).

(20) Chemla D. S., Bar-Joseph I., Klingshirn C., Miller D. A. B., Kuo J. M. and Chang T. Y.: "Optical reading of field-effect transistors by phase-space absorption quenching in a single InGaAs quantum well conducting channel", Appl. Phys. Lett., **50**, pp. 585-587 (March 1987).

(21) Kastalsky A., Abeles J. H. and Leheny R. F.: "Novel optoelectronic single quantum well devices based on electron bleaching of exciton absorption", Appl. Phys. Lett., **50**, pp. 708-710 (March 1987).

(22) Sakaki H., Yoshimura H. and Matsusue T.: "Carrier concentration dependent absorption spectra of modulation doped n-AlGaAs/GaAs quantum wells and performance analysis of optical modulators and switches using carrier induced bleaching (CIB) and refractive index change (CIRIC)", Jpn. J. Appl. Phys., **26**, pp. L1104-L1106 (July 1987).

(23) Abeles J. H., Chan W. K., Colas E. and Kastalsky A.: "Junction field-effect transistor single quantum well optical waveguide modulator employing the two-dimensional Moss-Burstein effect", Appl. Phys. Lett., **54**, pp. 2177-2179 (May 1989).

(24) Okada Y., Yan Ran-Hong, Coldren L. A., Merz J. L. and Tada K.: "The effect of band-tails on the design of GaAs/AlGaAs bipolar transistor carrier-injected optical modulator/switch", J. Quantum Electron., **25**, pp. 713-719 (April 1989).

(25) Mendoza-Alvarez J. G., Coldren L. A., Alping A., Yan R. H., Hausken T., Lee K. and Pedrotti K.: "Analysis of depletion edge translation lightwave modulators", J. Lightwave Technol., **6**, pp. 793-808 (June 1988).

(26) Lee S. S., Ramaswamy R. V. and Sundaram V. S.: "Analysis and design of high-speed high-efficiency GaAs-AlGaAs double-heterostructure waveguide phase modulator", J. Quantum Electron., **27**, pp. 726-736 (March 1991).

(27) Yamada M., Noda K., Nakanishi H., Kuwamura Y. and Kawabata T.: "A semiconductor optical switch utilizing optical absorption in depletion layer", in technical digest of Conference on Laser and Electro-Optics (CLEO'91), CTuT6 (May 1991).

(28) Casey H. C., JR. and Panish M. B.: "Heterostructure Lasers PartA" ACADEMIC PRESS, pp. 45-47 (1978).

(29) Horikoshi Y., Fischer A. and Ploog K.: "New long-wavelength photodetector based on reverse-biased doping superlattices", Appl. Phys. Lett., **45**, pp. 919-921 (Nov. 1984).