Extended Abstracts of the 22nd (1990 International) Conference on Solid State Devices and Materials, Sendai, 1990, pp. 1-4 **A-1-1**

Invited

Towards High Speed Optoelectronics

Yasuharu SUEMATSU
Tokyo Institute of Technology
2-12-1, O-okayama, Meguro-ku, Tokyo 152

Present day optoelectronics depends quite heavily on quantum size effects, which provides quite attractive features such as high gain, low loss for high efficiency, high speed lasers and high refractive index variation for high speed optical switches. Moreover quantum size effect is also becoming very important to explore novel high-speed electronic devices. This paper will deal about such quantum size effect devices for high speed optoelectronics.

1. Introduction:

Optoelectronic technology possess the potentiality for high density information transmission and storage, both in the time and the space. In-land trunk communications and transoceanic submarine cable systems, for examples, have recently started to be used widely for public services. However, the ultimate speed of information transmission is believed to be far beyond the present technology, which is limited mainly by the photonic and electronic devices. Similar limitation exists for optical disk memory, in which the writing and read out speed is determined by the optical power of light sources.

State of art photonic and electronic technologies have mainly been developed utilizing bulk materials. Some efforts have been carried out to find the possibility of attaining superior device performances with novel material systems, such as the quantum size effect material. The photonic devices require superior optical properties, such as, the smaller relative optical loss against the gain to increase the laser efficiency as well as the laser stability, and higher field induced refractive index variation for high speed optical switches, which are difficult to obtain with bulk materials.

Meanwhile, Dingle measured the quantum state in thin semiconductor film[1], Van der Ziel[2] and Holonyak[3-5] demonstrated quantum well lasers by optical pumping and current injection respectively, Capasso showed the possibility of reducing the detector noise by semiconductor superlattice[6], and Asada pointed out the possibility of field induced higher refractive index variation in quantum structure for high speed photonic switch[7] and Sakaki showed the potentiality of improving the laser performance with quantum wire effects[8]. Fabrications toward the quantum wire and box structures were made[9-17]. Recently preliminary experiments to realize quantum wire lasers have been carried out successfully[15,16].

Also in the area of electronic devices, effects of the quantum confinement and the quantum interference of the electron in a structure as small as the electron-wavelength have been investigated to explore novel high-speed devices[18-22].

In this paper, recent researches on some quantum size effect lasers and photonic switches are mainly reviewed in the context of the high speed information system. In relation with this, some basic researches on ultra-high-speed electronics based on quantum size effect are also reviewed.

2. Theoretical background of optical properties in quantum size structures:

The density of states of a quantum size effect structure is sharper than the parabolic-like density of states of a bulk structure, i.e. stair-case-like for quantum film structure and δ-function like for quantum box structure[23]. Thus the optical gains of electronically injected quantum film, wire, and box are much larger than that of bulk, raising from film to box. This attractive feature is leading to the exploration of quantum size effect lasers. The output efficiency of these laser was theoretically estimated to be larger, because the loss factor originated from the active region is smaller due to reduced space factor of active region.

The instability of a laser resonator indicated by Henry's α-parameter[24], which is the ratio of fractional variation of refractive index to that of gain with injected carrier density decreases, with the increase of quantization and becomes zero for quantum box[25]. Thus with quantum size structure, stable laser performance can be expected against the variation of injection current.

Theoretical limit of direct modulation frequency of a laser diode is inversely proportional to the square root of the fractional laser gain, i.e. Henry's αparameter. The dynamic wavelength shift or the wavelength chirp of a modulated laser is theoretically proportional to Henry's αparameter. Thus the speed of direct modulation and the wavelength chirp of laser diode are expected to be improved with the increase of quantization[26].

The electronic polarization formed with electron and hole pair is deformed when the electric field is applied to a quantum size effect structure, because electron and hole shift in opposite directions with the applied field. Thus the refractive index of the medium decreases with applied field[7]. This property is very much attractive for optical switch. However the absorption loss also increases with the applied field due to the Kramers-Kronig relation. The ratio of field induced index variation to loss variation α_p[27] specifies the performance of these devices. For an example for low loss reflection type optical switch, α_p should larger than about ten and moreover this should be in the low fundamental absorption region. This condition i.e. larger α_p in low absorption region was shown to be attainable in quantum box structure[28].

Because of the facts that the optical switch utilizing quantum size effect is small and the index variation follows the electronic relaxation time, high speed operation is expected for such optical switches and modulators.

3. Quantum wire and box lasers:

Quantum well, or quantum film, lasers now look like to be in rather established stage showing excellent properties of the high power[29], high efficiency[30], and low chirp[31].

A new type of quantum size structure, i.e. the strained superlattice structure where the wavelength can be artificially manipulated without degradation in the device characteristics was proposed[32,33] and good device characteristics were realized[34,35].

Several ways have been tried to form the quantum wire structures. Quantum wires are grown on a slant angled crystal[10]and on a grooved surface of crystal[9,12]. Quantum wires and boxes were fabricated by lithography from thin film by successive process of electron beam lithography, wet or dry etching, and crystal regrowth[11,16,17]. In the latter case, the wire width of 28nm to 30nm was formed, and the electron cyclotron resonance (ECR)[36] reactive ion beam dry etching at low pressure and with low ion extraction voltage was shown to be applied for low damage etching[37,14].

Lasing action in quantum wire lasers prepared from crystal growth on slanted angled crystal[15] and prepared from lithography[16] were demonstrated. Emission from quantum box laser was also demonstrated[11].

4. Optical waveguide switch utilizing quantum size effects:

Absorption type waveguide modulator with quantum confined Stark effect[38] of quantum film was fabricated and high speed operation of 10 to 40GHz was demonstrated[39,40]. These type of modulators are also integrated together with laser diode[41].

Reflection type optical switch was fabricated and the switching operation with the application of reverse bias voltage was confirmed [42,43]. Several other types of waveguided switch were also considered[44–46].

The field induced refractive index variation was measured for quantum wire with fairly good agreement with theory[14].

5. High-speed electronic devices by quantum effect:

Demand for high speed performance of the transistor is increasing. For example, future photonic devices/systems require ultrafast drivers for photonic devices, ultrafast amplifiers for the detected signal and ultrafast digital devices in the transmitter, the repeater and the receiver systems.

Quantum effect is attractive also for electron devices;there are possibility to invent new principles for ultrafast devices. Three-terminal devices have been proposed using resonant tunneling phenomena;the resonant tunneling hot electron transistor as a functional device[18] was demonstrated already in a form of the integrated circuit, a novel metal-insulator material system was proposed to reach upto Tera-Hz operation[19]. Bragg reflection of the electron wave in the planar superlattice have been proposed to apply to FET[20]. Aharonov-Bohm effect transistor has been proposed[21]. It has been proposed to attain subpicosecond switching operation by using the high-velocity hot electron and the transport control on the wave principle[22].

The above efforts to explore new principles are quite important and present techniques of fine crystal epitaxy and nanometer fabrication provide good chance to realize them.

6. Conclusion:

Development of advanced photonic devices utilizing the quantum size effect depends heavily on the development of advanced fine material processings. The success of quantum well laser would be a mile stone of a chain along this direction. However there are more basic field still remain to be explored especially in quantum wire and quantum box devices. Development of ultra-high speed electronic devices are also essential for the high speed optoelectronics.

References:

1. R.Dingle: *Festkorper Probleme XV (Advances in Solid State Physics)*, H.J.Queisser, Ed. New York:Pergamon, (1975) 21.
2. J.P.Van der Ziel, R.Dingle, R.C.Miller, W.Wiegmann and W.A.Nordland Jr: *Appl.Phys.Letts.*, 26 (1975) 463.
3. E.A.Rezek, N.Holonyak,Jr., B.J.Vojak, G.E.Stillman, J.A.Rossi, D.L.Keune and J.D.Fairing: *Appl.Phys.Letts.*,31 (1977) 288.
4. R.D.Dupuis, P.D.Dapkus, N.Holonyak,Jr., E.A.Rezek and R.Chin: *Appl.Phys.Letts.*,32 (1978) 295.
5. N.Holonyak, R.M.Kolbas, R.D.Dupuis and P.D.Dapkus: *IEEE J. Quantum Electron..*,QE-16 (1980) 170.
6. F.Capasso, W.T.Tsang and G.F.Williams:*IEEE Trans Electron. Devices*, ED-30 (1983) 381.
7. H.Yamamoto, M.Asada and Y.Suematsu: *Electron. Letts..*,21 (1985) 579.
8. H.Sakaki: *Japan J. Appl. Phys.*,19 (1980) L735.
9. P.M.Petroff, A.C.Gossard, R.A.Logan and W.Wiegmann:*Appl. Phys. Letts.*, 41 (1982) 635.
10. E.Kapon, S.Simhony, R.Bhat and D.M.Hwang: *Appl. Phys. Letts.* 55 (1989) 2715.
11. Y.Miyamoto, M.Cao, Y.Shingai, K.Furuya, Y.Suematsu, K.G.Ravikumar and S.Arai: *Japan J.Appl. Phys.*, 26 (1987) L225.
12. T.Fukui and H.Saito: *Appl. Phys. Letts.*,50 (1987) 824.
13. A.Scherer, B.P.Van der Gaag, E.D.Beebe and P.S.D.Lin: *J. Vac. Sci. Technol.*,B8 (1990) 28.
14. K.G.Ravikumar, T.Kikugawa, T.Aizawa, S.Arai and Y.Suematsu: *48th Annual Device Research Conf.*, USA, June 1990.
15. M.Tsuchiya, L.A.Coldren and P.M.Petroff: *Proc. IOOC'89*, Japan, 19C1-1, 104.
16. M.Cao, Y.Miyake, S.Tamura, H.Hirayama, S.Arai, Y.Suematsu and Y.Miyamoto: *Trans. IEICE Japan*, E73 (1990) 63.
17. A.Izrael, B.Sermage, J.Y.Martin, A.Ougazzaden, R.Azoulay, J.Etrillard, V.Thierry-Mieg and L.Henry: *Appl. Phys. Letts.*,56 (1990) 830.
18. N. Yokoyama, K. Imamura, S. Muto, S. Hiyamizu, and H. Nishi: *Jpn. J. Appl. Phys.*, 24 (1985) L853.
19. Y. Nakata, M. Asada and Y. Suematsu: *Electron. Lett.*, 22 (1986) 58.
20. H. Sakaki, K. Wagatsuma, J. Hamasaki and S. Saito: *Thin Solid Films*, 36 (1976) 497.
21. S. Datta, M. R. Melloch, S. Bandyopadhyay and M. S. Lundstrom: *Appl. Phys. Lett.*, 48 (1986) 487.
22. K. Furuya: *J. Appl. Phys.*, 62 (1987) 1492.
23. M.Asada, Y.Miyamoto and Y.Suematsu: *IEEE J.Quantum Electron.*, QE22 (1986) 1915.
24. C.H.Henry: *IEEE J.Quantum Electron.*,QE-18 (1982) 259.
25. Y.Miyake and M.Asada: *Japan J. Appl. Phys.*, 28, (1989) 1280.
26. Y.Arakawa and A.Yariv: *IEEE J. Quantum Electron.*,QE-22, (1986) 1887.
27. K.Shimomura, Y.Suematsu and S.Arai: *IEEE J.Quantum Electron.*, QE-26 (1990)
28. K.Matsubara, K.G.Ravikumar, M.Asada and Y.Suematsu: *Trans. IEICE of Japan*, E72 (1989 1179.
29. H.Asano, S.Takano, M.Kitamura and I.Mito: *Natl. Conv. Rec. IEICE Japan* C-150, (1990). (In Japanese)
30. A.Kasukawa, Y.Imajo and T.Makino: *Electron. Letts.*, 25 (1989) 104.
31. H.Yamazaki, T.Sasaki, M.Kitamura, N.Kida and I.Mito: *Natl. Conv. Rec. IEICE Japan* C-15 (1990). (In Japanese)
32. W.T.Tsang: *Appl. Phys. Letts.*,38 (1981) 661.
33. G.C.Osbourn: *Phys. Rev.B*,27 (1983) 5126.
34. H.Temkin, T.Tanbun-Ek and R.A.Logan: *Appl. Phys. Letts.*, 56 (1990) 1210.
35. M.Okayasu, T.Takeshita, M.Yamaka, O.Kogure, M.Horiguchi, M.Fukuda, A.Kozen, K.O and S.Uehara: *Electron. Letts.*, 25, (1989) 1163.
36. Asakawa K and Sugata S: *Japan J. Appl. Phys.*, 22 (1983) L653.
37. K.G.Ravikumar, K.Kudo, S.Arai and Y.Suematsu *Third Optoelectron. Conf.* Japan. (1989).
38. D.A.B.Miller, D.S.Chemla, T.C.Damen, A.C.Gossard, W.Weigmann, T.H.Wood and C.A.Burrus: *Phys. Rev. Letts.*, 53 (1984) 2173.
39. T.H.Wood, C.A.Burrus, D.A.B.Miller, D.S.Chemla, T.C.Damen, A.C.Gossard and W.Weigmann: *IEEE J.Quantum Electron.*, QE-21 (1985) 117.
40. O.Mitami, I.Kotaka, K.Wakita, K.Kawano, Y.Kawamura and H.Asai: *Natl. Conv. Rec. IEICE Japan* C-237, (1990). (In Japanese)
41. Y.Kawamura, K.Wakita, Y.Itaya Y.Yoshikuni and H.Asahi: *Electron. Letts.*,22 (1986) 242.
42. K.G.Ravikumar, K.Shimomura, T.Kikugawa, A.Izumi, S.Arai, Y.Suematsu and K.Matsubara: *Electron. Letts.*, 24 (1988) 415.
43. T.Kikugawa, K.G.Ravikumar, K.Shimomura,A.Izumi, K.Matsubara, Y.Miyamoto, S.Arai and Y.Suematsu *Photonics. Tech. Letts.*,1 (1989) 126.
44. J.E.Zucker, K.L.Jones, M.G.Young, B.I.Miller and U.Koren: *Appl. Phys. Letts.*, 55 (1989) 2280.
45. J.E.Zucker, K.L.Jones, B.I.Miller and U.Koren:*IEEE Photonics Technol. Letts.*, 2 (1990) 32.
46. J.E.Zucker, K.L.Jones, G.R.Jacobovitz, B.Tell, K.Brown-Goebeler, T.Y.Chang, N.J.Sauer, M.Wegener and D.S.Chemla:*CLEO '90*, CPDP16-1/631, USA, 1990.