(Review Article)

NANOLASERS
Lasing from Nanoscale Quantum Wires

Samuel S. Mao

Advanced Laser Technologies Group,
Lawrence Berkeley National Laboratory,
University of California,
CA 94720, Berkeley, U.S.A
E-mail: ssmao@lbl.gov

Abstract

Semiconductor lasers are in many ways second only to transistors as to their impact on today's high-tech industries. The unique characteristics, such as narrow emission wavelength, high frequency modulation, and device integratibility, make semiconductor lasers ideal photon sources for applications as diverse as telecommunication, signal processing, material characterization, and medical diagnostics. Advances in material growth technologies, particularly molecular beam epitaxy, metal-organic chemical vapor deposition, and a suite of chemical synthesis techniques, make the fabrication of high quality nanometer scale semiconductor structures possible. Thanks to the quantum size effects that drastically modify the energy spectra of confined electrons in reduced dimensions, the population inversion necessary for lasing action occurs more efficiently as the active semiconductor gain medium is scaled down from the bulk to the nanometer scale. Consequently, semiconductor lasers built with nanoscale active media are expected to exhibit extraordinary features such as great color range, high optical gain, and low lasing threshold. Indeed, miniaturized lasers using nanoscale semiconductor gain media . two-dimensional quantum wells, one-dimensional quantum wires, and zero-dimensional quantum dots . have shown significant improvements in device performance. This article provides an overview of the physics and technologies behind the rapid progress of miniaturization of semiconductor lasers, in particular the quantum wire lasers based on one-dimensional nanoscale optical gain media. Since the first report of lasing in quantum wires by Kapon and his co-workers [1], quantum wire lasers have evolved from .microlasers. in which the one-dimensional nanostructure is embedded in a micron size optical cavity, to .nanolasers. in which, as we recently demonstrated [2], the material gain and optical feedback are simultaneously achieved by individual nanoscale quantum wires. One-dimensional semiconductor fabrication technologies based on nanoscale lithography, selforganization, selective growth, and chemical synthesis will be reviewed along with recent advances of quantum wire lasers built upon each of these fabrication technologies.

Keywords: One-dimensional nanostructure; Quantum wire; Nanowire; Semiconductor laser; Quantum confinement

1 Introduction

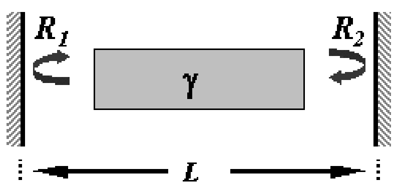
Miniaturization has often been a key word for modern integrated circuits built upon the concept that the smaller the device, the faster it operates. A similar line of thought is equally valid for semiconductor lasers that have been widely used in applications ranging from telecommunications to consumer electronics. Apparently, miniaturization will allow more lasers to be packed together and integrated with the shrinking integrated circuits.

The benefits of miniaturized semiconductor lasers are far beyond the capability of dense integration. In fact, size reduction results in improved device performance and new functionality. The basis of semiconductor laser operations [3–5] depends on the creation of nonequilibrium populations of energy carriers (electrons and holes, or excitons) in a semiconductor gain material, and coupling of electrons and holes to an optical field that stimulates radiative light emission. Quantum phenomena emerge when the dimension of a semiconductor material is scaled down to nanometer regime (< 100 nm); the resulting dramatic change of the physical properties of the nanoscale gain material has fueled global efforts to build high performance semiconductor 'nanolasers'.

1.1 Semiconductor laser cavities

Two basic elements necessary for realizing a semiconductor laser (Figure 1) include an *active gain medium* that provides optical gain by stimulated emission, and an *optical resonant cavity* that confines the photons to create positive optical feedback. Pumped by either an electrical or optical energy, electrons and holes within the semiconductor gain material can be excited to nonequilibrium energy levels so light radiation can be amplified (positive gain). If the resulting gain is sufficient to overcome the losses of the optical cavity that provides the necessary feedback of the radiation, lasing oscillation can be established at a well-established threshold. While the focus of this review is one-dimensional nanoscale structures – nanoscale quantum wires – as the active gain media of semiconductor lasers, it is beneficiary to take a brief look at different optical cavities that facilitate lasing action of nanoscale semiconductors.

Figure 1 Basic elements of a laser – gain medium and optical cavity



Conventional edge-emitting semiconductor lasers have an in-plane optical cavity with a cleaved facet mirror (Figure 2(a)). Light emission takes place from one side (edge) of the Fabry-Perot cavity typically a few hundred μm long (longitudinal) and 10 μm wide (lateral). Although the edge-emitting lasers have been used for many practical applications, the combination of edge emission and active layer geometry has several disadvantages. The long optical cavity results in typically multimode operation, by which the spontaneous emission of the active gain material is distributed over a large number of non-lasing modes. Because the active region is transversely thin (vs. laterally wide) for quantum dots) may provide additional mechanisms for realizing better performance semiconductor lasers.

While quantum well lasers are maturing toward commercial applications, semiconductor lasers based on one-dimensional (and zero-dimensional) nanoscale materials are still in their early development stage. The full promise of quantum wire (and quantum dot) lasers must await advances in device optimization, which has to be based on a thorough understanding of the physics of stimulated emission from nanoscale quantum structures. The understanding of semiconductor lasers based on nanoscale quantum wires (and quantum dots) is not complete, nor is their development, which is certain to continue.

Acknowledgements

This research has been supported by the U.S. Department of Energy under contract No. DE-AC03-76SF00098.

References

1 Kapon, E., Hwang, D.M. and Bhat, R. (1989) *Phys. Rev. Lett*., Vol. 63, p.430.

2 Huang, M., Mao, S.S., Feick, H., Yan, H., Wu, Y., Kind, H., Weber, E.R., Russo, R.E. and Yang, P. (2001) *Science*, Vol. 292, p.1897; Mao, S.S., Russo, R.E. and Yang, P. (2001) *Proc. SPIE*, Vol. 4608, p.225.

3 Coldren, L.A. and Corzine, S.W. (1995) *Diode Lasers and Photonic Integrated Circuits*, Wiley, New York.

4 Zory Jr., P.S. (Ed.) (1993) *Quantum Well Lasers*, Academic, San Diego.

5 Verdeyen, J.T. (1995) *Laser Electronics*, 3rd ed., Prentice-Hall, Englewood Cliffs.

6 Jewell, J.L., Harbison, J.P., Scherer, A., Lee, Y.H. and Florez, L.T. (1991) *IEEE J. Quantum Electron*., Vol. 27, p.1332.

7 Soda, H., Iga, K., Kitahara, C. and Suematsu, Y. (1979) *Japan. J. Appl. Phys*., Vol. 18, p.2329.

8 Iga, K., Ishikawa, S., Ohkouchi, S. and Nishimura, T. (1984) *Appl. Phys. Lett*., Vol. 45, p.348.

9 Koyama, F., Kinoshita, S. and Iga, K. (1989) *Appl. Phys. Lett*., Vol. 55, p.221.

10 Kogelnik, H. and Shanks, C.V. (1972) *J. Appl. Phys*., Vol. 43, p.2327.

11 Lee, Y.H., Jewell, J.L., Scherer, A., McCall, S.L., Harbison, J.P. and Florez, L.T. (1989) *Electron. Lett*., Vol. 25, p.1377.

12 Huffaker, D.L., Graham, L.A., Deng, H. and Deppe, D.G. (1996) *IEEE Photon. Tech. Lett*., Vol. 8, p.974.

13 Schubert, E.F., Lu, L.W., Zydzik, G.J., Kopf, R.F., Benvenuti, A. and Pinto, M.R. (1992) *Appl. Phys. Lett*., Vol. 60, p.466.

14 Chalmers, S.A., Lear, K.L. and Killeen, K.P. (1993) *Appl. Phys. Lett*., Vol. 62, p.1585.

15 Peters, M.G., Thibeault, B.J., Young, D.B., Scott, J.W., Peters, F.H., Gossard, A.C. and Coldren, L.A. (1993) *Appl. Phys. Lett*., 63, 3411.

16 Hegblom, E.R., Babic, D.I., Thibeault, B.J. and Coldren, L.A. (1997) *IEEE J. Sel. Top. Quantum Electron*., Vol. 3, p.379.

17 Yablonovitch, E. (1987) *Phys. Rev. Lett*., Vol. 58, p.2059.

18 John, S. (1987) *Phys. Rev. Lett*., Vol. 58, p.2486.

19 Painter, O.J., Lee, R.K., Scherer, A., Yariv, A., O'Brien, J.D., Dapkus, P.D. and Kim, I. (1999) *Science*, 284, 1819.

20 Painter, O.J., Husain, A., Scherer, A., O'Brien, J.D., Kim, I. and Dapkus, P.D. (1999) *J. Lightwave Tech*., Vol. 17, p.2082.

21 Hwang, J.K., Ryu, H.Y., Song, D.S., Han, I.Y., Song, H.W., Park, H.K., Lee, Y.H. and Jang, D.H. (2000) *Appl. Phys. Lett*., Vol. 76, p.2982.

22 Hwang, J.K., Ryu, H.Y., Song, D.S., Han, I.Y., Park, H.K., Jang, D.H. and Lee, Y.H. (2000) *IEEE Photon. Tech. Lett*., Vol. 12, p.1295.

23 Song, D.S., Kim, S.H., Park, H.G., Kim, C.K. and Lee, Y.H. (2002) *Appl. Phys. Lett*., Vol. 80, p.3901.

24 McCall, S.L., Levi, A.F.J., Slusher, R.E., Pearton, S.J. and Logan, R.A. (1992) *Appl. Phys. Lett*., Vol. 60, p.289.

25 Gayral, B., Gerard, J.M., Lemaitre, A., Dupuis, C., Manin, L. and Pelouard, J.L. (1999) *Appl. Phys. Lett*., Vol. 75, p.1908.

26 Purcell, E.M. (1946) *Phys. Rev*., Vol. 69, p.681.

27 Benisty, H., Gerard, J.-M., Houdre, R., Rarity, J. and Weisbuch, C. (Eds.) (1999) *Confined Photon Systems*, Springer, Berlin.

28 Arakawa, Y. and Sakaki, H. (1982) *Appl. Phys. Lett*., Vol. 40, p.939.

29 Asada, M., Miyamoto, Y. and Suematsu, Y. (1986) *IEEE J. Quantum Electron*., Vol. 22, p.1915.

30 Nambu, Y. and Asakawa, K. (1995) *Appl. Phys. Lett*., Vol. 67, p.1509.

31 Eisler, H.J., Sundar, V.C., Bawendi, M.G., Walsh, M., Smith, H.I. and Klimov, V. (2002) *Appl. Phys. Lett*., Vol. 80, p.4614.

32 Laude, J.-P. (2002) DWDM Fundamentals, Components, and Applications, Artech, London.

33 Murray, C.B., Norms, D.G. and Bawendi, M.G. (1993) *J. Am. Chem. Soc*., Vol. 115, p.8706.

34 Efros, A.L. and Rosen, M. (2000) *Annu. Rev. Mater. Sci*., Vol. 30, p.475.

35 Brus, L.E. (1984) *J. Chem. Phys*., Vol. 80, p.4403.

36 Brus, L.E. (1986) *J. Chem. Phys*., Vol. 90, p.2555.

37 Kapon, E. (1992) *Proc. IEEE*, Vol. 80, p.398.

38 Bernard, M.G.A. and Duraffourg, G. (1961) *Phys. Stat. Sol*., Vol. 1, p.699.

39 Liu, G.T., Stintz, A., Li, H., Malloy, K.J. and Lester, L.F. (1999) *Electron. Lett*., Vol. 35, p.1163.

40 Lester, L.F., Stintz, A., Li, H., Newell, T.C., Pease, E.A., Fuchs, B.A. and Malloy, K. (1999) *IEEE Photon. Tech. Lett*., Vol. 11, p.931.

41 Eliseev, P.G., Li, H., Stintz, A., Liu, G.T., Newell, T.C., Maloy, K.J. and Lester, L. (2000) *Appl. Phys. Lett*., Vol. 77, p.262.

42 Iga, K. (2000) *IEEE J. Sel. Top. Quantum Electron*., Vol. 6, p.1201.

43 Yariv, A. (1988) *Appl. Phys. Lett*., Vol. 53, p.1033.

44 Miyamoto, Y., Miyake, Y., Asada, M. and Suematsu, Y. (1985) *IEEE J. Quantum Electron*., Vol. 25, p.2001.

45 Asada, M., Miyamoto, Y. and Suematsu, Y. (1985) *Japan. J. Appl. Phys*., Vol. 24, p.L95.

46 Alferov, Z. (2000) *IEEE J. Sel. Top. Quantum Electron*., Vol. 6, p.832.

47 Ledentsov, N.N. (2002) *IEEE J. Sel. Top. Quantum Electron*., Vol. 8, p.1015.

48 Arakawa, Y. (2002) *Trans. IEICE*, Vol. E85, p.37.

49 Ledentsov, N.N. (1999) *Semicon*., Vol. 33, p.946.

50 Cho, A.Y. (1971) *J. Vac. Sci. Tech*., Vol. 8, p.S31.

51 Cho, A.Y. (1971) *Appl. Phys. Lett*., Vol. 19, p.467.

52 Manasevit, H.M. (1968) *Appl. Phys. Lett*., Vol. 12, p.156.

53 Dupuis, R.D., and Dapkus, P.D. (1977) *Appl. Phys. Lett*., Vol. 31, p.466.

54 Panish, M.B., Temkin, H. and Sumski, S. (1985) *J. Vac. Sci. Tech*., Vol. B3, p.657.

55 Osbourn, G.C. (1982) *J. Appl. Phys*., Vol. 53, p.1586.

56 Kash, K., Scherer, A., Worlock, I.M., Craighead, H.G. and Tamargo, M.C. (1986) *Appl. Phys. Lett*., Vol. 49, p.1043.

57 Gershoni, D., Temkin, H., Dolan, C.J., Dunsmuir, J., Chu, S.N.G. and Panish, M.B. (1988) *Appl. Phys. Lett*., Vol. 53, p.995.

58 Maile, B.E., Forchel, A., Germann, R., Grützmacher, D., Meier, H.P. and Reithmaier, J.P. (1989) *J. Vac. Sci. Tech*., Vol. B7, p.2030.

59 Kohl, M., Heitmann, D., Grambow, P. and Ploog, K. (1989) *Phys. Rev. Lett*., Vol. 63, p.2124.

60 Clausen Jr., E.M., Harbison, J.P., Florez, L.T. and Van der Gaag, B.P. (1990) *J. Vac. Sci. Tech*., Vol. B8, p.1960.

61 Izrael, A., Sermage, B., Marzin, J.Y., Ougazzaden, A., Azoulay, R., Etrillard, J., Thierry-Mieg, V. and Henry, L. (1990) *Appl. Phys. Lett*., Vol. 56, p.830.

62 Notomi, M., Naganuma, M., Nishida, T., Tamamura, T., Iwamura, H., Nojima, S. and Okamoto, M. (1991) *Appl. Phys. Lett*., Vol. 58, p.720.

63 Nunoya, N., Nakamura, M., Yasumoto, H., Tamura, S. and Arai, S. (1999) *Japan. J. Appl. Phys*., Vol. 38, p.L1323.

64 Nunoya, N., Nakamura, M., Yasumoto, H., Tamura, S. and Arai, S. (2000) *Japan. J. Appl. Phys*., Vol. 39, p.3410.

65 Yagi, H., Muranushi, K., Nunoya, N., Sano, T., Tamura, S. and Arai, S. (2002) *Appl. Phys. Lett*., Vol. 81, p.966.

66 Ils, P., Michel, M., Forchel, A., Gyuro, I., Klenk, M. and Zielinski, E. (1994) *Appl. Phys. Lett*., Vol. 64, p.496.

67 Cibert, J., Petroff, P.M., Dolan, G.J., Pearton, S.J., Gossard, A.C. and English, J.H. (1986) *Appl. Phys. Lett*., Vol. 49, p.1275.

68 Zarem, H.A., Sercel, P.C., Hoenk, M.E., Lebens, J.A. and Vahala, K.J. (1989) *Appl. Phys. Lett*., Vol. 54, p.2692.

69 Hsieh, K.C., Baillargeon, J.N. and Cheng, K.Y. (1990) *Appl. Phys. Lett*., Vol. 57, p.2244.

70 Cheng, K.Y., Hsieh, K.C. and Baillargeon, J.N. (1992) *Appl. Phys. Lett*., Vol. 60, p.2892.

71 Chou, S.T., Hsieh, K.C., Cheng, K.Y. and Chou, L.J. (1995) *J. Vac. Sci. Tech*., Vol. B13, p.650.

72 Chou, S.T., Cheng, K.Y., Chou, L.J. and Hsieh, K.C. (1995) *Appl. Phys. Lett*., Vol. 17, p.2220.

73 Chou, S.T., Cheng, K.Y., Chou, L.J. and Hsieh, K.C. (1995) *J. Appl. Phys*., Vol. 78, p.6270.

74 Francoeur, S., Hanna, M.C., Norman, A.G. and Mascarenhas, A. (2002) *Appl. Phys. Lett*., Vol. 80, p.243.

75 Fetzer, C.M., Lee, R.T., Jun, S.W., Stringfellow, G.B., Lee, S.M. and Seong, T.Y. (2001) *Appl. Phys. Lett*., Vol. 78, p.1376.

76 Twesten, R.D., Follstaedt, D.M., Lee, S.R., Jones, E.D., Reno, J.L., Millunchick, J.M., Norman, A.G., Ahrenkiel, S.P. and Mascarenhas, A. (1999) *Phys. Rev*., Vol. B60, p.13619.

77 Petroff, V.M., Gossard, A.C. and Wiegmann, W. (1984) *Appl. Phys. Lett*., Vol. 45, p.620.

78 Gaines, J.M., Petroff, P.M., Kroemer, H., Simes, R.I., Geels, R.J. and English, J.H. (1988) *J. Vac. Sci. Tech*., Vol. B6, p.1378.

79 Fukui, T. and Saito, H. (1990) *Japan. J. Appl. Phys*., Vol. 29, p.L731.

80 Hara, S., Ishizaki, J., Motohisa, J., Fukui, T. and Hasegawa, H. (1994) *J. Cryst. Growth*, Vol. 145, p.692.

81 Yamamoto, M., Higashiwaki, M., Shimomura, S., Sano, N. and Hiyamizu, S. (1997) *Japan. J. Appl. Phys*., Vol. 36, p.6285.

82 Higashiwaki, M., Ikawa, S., Shimomura, S. and Hiyamizu, S. (1999) *J. Cryst. Growth*, Vol. 201, p.886.

83 Chavez-Pirson, Ando, H., Saito, H. and Kanbe, H. (1993) *Appl. Phys. Lett*., Vol. 62, p.3082.

84 Nakashima, H., Kato, T., Maehashi, K., Nishida, T., Inoue, Y., Takeuchi, T., Inoue, K., Fischer, P., Christen, J., Grundmann, M. and Bimberg, D. (1998) *Mater. Sci. Eng*., Vol. B51, p.229.

85 Kapon, E., Tamargo, M.C. and Hwang, D.M. (1987) *Appl. Phys. Lett*., Vol. 50, p.347.

86 Bhat, R., Kapon, E., Hwang, D.M., Koza, M.A. and Yun, C.P. (1988) *J. Cryst. Growth*, Vol. 93, p.850.

87 Kapon, E., Kash, K., Clausen, E.M. Jr., Hwang, D.M. and Colas, E. (1992) *Appl. Phys. Lett*., Vol. 60, p.477.

88 Percival, C., Houston, P.A., Woodhead, J., Al-Khafaji, M., Hill, G., Roberts, J.S. and Knights, A.P. (2000) *IEEE Trans. Electron Dev*., Vol. 47, p.1769.

89 Simhony, S., Kapon, E., Colas, T., Hwang, D.M., Stoffel, N.G. and Worland, P. (1991) *Appl. Phys. Lett*., Vol. 59, p.2225.

90 Kim, T.G., Park, K., Kim, E.K., Min, S. and Park, J. (1997) *IEEE Photon. Tech. Lett*., Vol. 9, p.2.

91 Kim, T.G., Suzuki, Y., Shimiz, M. and Ogura, M. (1999) *Solid State Electron*., Vol. 43, p.2093.

92 Kim, T.G., Wang, X.-L., Komori, K., Hikosaka, K. and Ogura, M. (1999) *Electron. Lett*., Vol. 35, p.639.

93 Kim, T.G., Suzuki, Y. and Ogura, M. (2000) *IEEE Photon. Tech. Lett*., Vol. 12, p.104.

94 Kim, T.G., Wang, X.-L., Suzuki, Y., Komori, K. and Ogura, M. (2000) *IEEE J. Sel. Top. Quantum Electron*., Vol. 6, p.511.

95 Koshiba, S., Noge, H., Akiyama, H., Inoshita, T., Nakamura, Y., Shimizu, A., Nagamune, Y., Tsuchiya, M., Kano, H. and Sakaki, H. (1994) *Appl. Phys. Lett*., Vol. 64, p.363.

96 Akiyama, H., Koshiba, S., Someya, T., Wada, K., Noge, H., Nakamura, Y., Inoshita, T., Shimizu, A. and Sakaki, H. (1994) *Phys. Rev. Lett*., Vol. 72, p.924.

97 Jiang, C., Muranaka, T. and Hasegawa, H. (2001) *Japan. J. Appl. Phys*., Vol. 40, p.3003.

98 Jiang, C. and Hasegawa, H. (2002) *Japan. J. Appl. Phys*., Vol. 41, p.972.

99 Chang, Y.C., Chang, L.L. and Esaki, L. (1985) *Appl. Phys. Lett*., Vol. 47, p.1324.

100 Akiyama, H. (1998) *J. Phys. Condens. Mat*., Vol. 10, p.3095.

101 Pfeiffer, L.N., West, K.W., Störmer, H.L., Eisenstein, J.P., Baldwin, K.W., Gershoni, D. and Spector, J. (1990) *Appl. Phys. Lett*., Vol. 56, p.1697.

102 Pfeiffer, L.N., Störmer, H.L., Baldwin, K.W., West, K.W., Goñi, A.R., Pinczuk, A., Ashoori, R.C., Dignam, M.M. and Wegscheider, W. (1993) *J. Cryst. Growth*, Vol. 127, p.849.

103 Gershoni, D., Weiner, J.S., Chu, G., S.N., Baraff, G.A., Vandenberg, J.M., Pfeiffer, L.N., West, K.W., Logan, R.A. and Tanbun-Ek, T. (1990) *Phys. Rev. Lett*., Vol. 65, p.1631.

104 Goñi, A.R., Pfeiffer, L.N., West, K.W., Pinczuk, A., Baranger, H.U. and Störmer, H.L. (1992) *Appl. Phys. Lett*., Vol. 61, p.1956.

105 Someya, T., Akiyama, H. and Sakaki, H. (1996) *J. Appl. Phys*., Vol. 79, p.2522.

106 Wegscheider, W., Pfeiffer, L.N., Dignam, M.M., Pinczuk, A., West, K.W., McCall, S.L. and Hull, R. (1993) *Phys. Rev. Lett*., Vol. 71, p.4071.

107 Wegscheider, W., Pfeiffer, L.N., West, K.W. and Leibenguth, R.E. (1994) *Appl. Phys. Lett*., Vol. 65, p.2510.

108 Wagner, R.S. and Ellis, W.C. (1964) *Appl. Phys. Lett*., Vol. 4, p.89.

109 Hiruma, K., Yazawa, M., Katsuyama, T., Ogawa, K., Haraguchi, K., Koguchi, M. and Kakibayashi, H. (1995) *J. Appl. Phys*., Vol. 77, p.447.

110 Yang, P., Wu, Y. and Fan, R. (2002) *Int. J. Nanosci*., Vol. 1, p.1.

111 Hu, J., Odom, T.W. and Lieber, C.M. (1999) *Acc. Chem. Res*., Vol. 32, p.435.

112 Wu, Y. and Yang, P. (2000) *Chem. Mater*., Vol. 12, p.605.

113 Morales, A.M. and Lieber, C.M. (1998) *Science*, Vol. 279, p.208.

114 Duan, X.F., Wang, J.F. and Lieber, C.M. (2000) *Appl. Phys. Lett*., Vol. 76, p.1116.

115 Trentler, T.J., Hickman, K.M., Geol, S.C., Viano, A.M., Gibbons, P.C. and Buhro, W.E. (1995) *Science*, Vol. 270, p.1791.

116 Martin, C.R. (1994) *Science*, Vol. 266, p.1961.

117 Braun, E., Eichen, Y., Sivan, U. and Ben-Yoseph, G. (1998) *Nature*, Vol. 391, p.775.

118 Vayssieres, L. (2004) *Int. J. Nanotech*., Vol. 1, Nos. 1/2, pp.1–41.

119 Mayers, B., Gates, B. and Xia, Y. (2004) *Int. J. Nanotech*., Vol. 1, Nos. 1/2, pp.86–104.

120 Maiman, T.H. (1960) *Nature*, Vol. 187, p.493.

121 Basov, N.G., Krokhin, O.N. and Popov, Y.M. (1961) *JETP*, Vol. 40, p.1320.

122 Hall, R.N., Fenner, G.E., Kingsley, J.D., Soltys, T.J. and Carlson, R.O. (1962) *Phys. Rev. Lett*., Vol. 9, p.366.

123 Nathan, M.I., Dumke, W.P., Burns, G., Dill, F.H. Jr. and Lasher, G.J. (1962) *Appl. Phys. Lett*., Vol. 1, p.62.

124 Holonyak Jr., N. and Bevacqua, S.F. (1962) *Appl. Phys. Lett*., Vol. 1, No. 82.

125 Quist, T.M., Rediker, R.H., Keyes, R.J., Krag, W.E., Lax, B., McWhorter, A.L. and Zeiger, H.J. (1962) *Appl. Phys. Lett*., Vol. 1, p.91.

126 Kroemer, H. (1963) *Proc. IEEE*, Vol. 51, p.1782.

127 Kroemer, H. (1963) *Semiconductor Laser with Electric Pumping*, U.S. Patent 3309553, August 16.

128 Alferov, Z.I. and Kazarinov, R.F. (1963) *Semiconductor Laser with Electric Pumping*, Inventor's Certificate 181737, March 30.

129 Alferov, Z.I., Andreev, V.M., Korolkov, V.I., Portnoi, E.L. and Tretyakov, N. (1969) *Sov. Phys. – Semicond*., Vol. 2, p.1289.

130 Alferov, Z.I., Andreev, V.M., Korolkov, V.I., Nikitin, V.G. and Yakovenko, A.A. (1971) *Sov. Phys. – Semicond*., Vol. 4, p.481.

131 Hayashi, I., Panish, M.B., Foy, W. and Sumski, S. (1970) *Appl. Phys. Lett*., Vol. 17, p.109.

132 Alferov, Z.I., Andreev, V.M., Korolkov, V.I., Tretyakov, D.N. and Tuchkevich, V.M. (1968) *Sov. Phys. – Semicond*., Vol. 1, p.1313.

133 Dingle, R., Wiegmann, W. and Henry, C.H. (1974) *Phys. Rev. Lett*., Vol. 33, p.827.

134 van der Ziel, J.P., Dingle, R., Miller, R.C., Wiegmann, W. and Nordland Jr., W.A. (1975) *Appl. Phys. Lett*., Vol. 26, p.463.

135 Dupuis, R.D., Dapkus, P.D., Holonyak, N. Jr., Rezek, E.A. and Chin, R. (1978) *Appl. Phys. Lett*., Vol. 32, p.295.

136 Chow, W.W., Choquette, K.D., Crawford, M.H., Lear, K.L. and Hadley, G.R. (1997) *IEEE J. Quantum Electron*., Vol. 33, p.1810.

137 Towe, E., Leheny, R.F. and Yang, A. (2000) *IEEE J. Sel. Top. Quantum Electron*., Vol. 6, p.1458.

138 Geels, R.S., Corzine, S.W., Scott, J.W., Young, D.B. and Coldren, L.A. (1990) *IEEE Photon. Tech. Lett*., Vol. 2, p.234.

139 Geels, R.S. and Coldren, L.A. (1990) *Appl. Phys. Lett*., Vol. 57, p.1605.

140 Levi, A.F.J., Slusher, R.E., McCall, S.L., Tanbun-Ek, T., Coblentz, D.L. and Pearton, S.J. (1992) *Electron. Lett*., Vol. 28, p.1010.

141 Levi, A.F.J., Slusher, R.E., McCall, S.L., Pearton, S.J. and Hobson, W.S. (1993) *Appl. Phys. Lett*., Vol. 62, p.2021.

142 Slusher, R.E., Levi, A.F.J., Mohideen, U., McCall, S.L., Pearton, S.J. and Logan, R.A. (1993) *Appl. Phys. Lett*., Vol. 63, p.1310.

143 Baba, T., Fujita, M., Sakai, A., Kihara, M. and Watanabe, R. (1997) *IEEE Photon. Tech. Lett*., Vol. 9, p.878.

144 Baba, T. (1997) *IEEE J. Sel. Top. Quantum Electron*., Vol. 3, p.808.

145 Faist, J., Capasso, F., Sivco, D.L., Sirtori, C., Hutchinson, A.L. and Cho, A.Y. (1994) *Science*, Vol. 264, p.553.

146 Scamarcio, G., Capasso, F., Sirtori, C., Faist, J., Hutchinson, A.L., Sivco, D.L. and Cho, A.Y. (1997) *Science*, Vol. 276, p.773.

147 Kazarinov, R. and Suris, R.A. (1971) *Sov. Phys. – Semicond*., Vol. 5, p.707.

148 Capasso, F., Gmachl, C., Paiella, R., Tredicucci, A., Hutchinson, A.L., Sivco, D.L., Baillargeon, J.N., Cho, A.Y. and Liu, H.C. (2000) *IEEE J. Sel. Top. Quantum Electron*., Vol. 6, p.931.

149 Capasso, F., Tredicucci, A., Gmachl, C., Sivco, D.L., Hutchinson, A.L., Cho, A.Y. and Scamarcio, G. (1999) *IEEE J. Sel. Top. Quantum Electron*., Vol. 5, p.792.

150 Cao, M., Miyake, Y., Tamura, S., Hirayama, H., Arai, S., Suematsu, Y. and Miyamoto, Y. (1990) *Trans. IEICE*, Vol. E73, p.63.

151 Cao, M., Daste, P., Miyamoto, M., Miyake, Y., Nogiwa, S., Arai, S., Furuya, K. and Suematsu, Y. (1988) *Electron. Lett.*, Vol. 24, p.824.

152 Kojima, T., Tamura, M., Nakaya, H., Tanaka, S., Tamura, S. and Arai, S. (1998) *Japan. J. Appl. Phys.*, Vol. 37, p.4792.

153 Yagi, H., Muranushi, K., Nunoya, N., Sano, T., Tamura, S. and Arai, S. (2002) *Japan. J. Appl. Phys.*, Vol. 41, p.L186.

154 Nunoya, N., Yasumoto, H., Midorikawa, H., Tamura, S. and Arai, S. (2000) *Japan. J. Appl. Phys.*, Vol. 39, p.L1042.

155 Nunoya, N., Nakamura, M., Morshed, M., Tamura, S. and Arai, S. (2001) *IEEE J. Sel. Top. Quantum Electron.*, Vol. 7, p.249.

156 Nakamura, M., Nunoya, N., Yasumoto, H., Morshed, M., Fukuda, K., Tamura, S. and Arai, S. (2000) *Electron. Lett.*, Vol. 36, p.639.

157 Yoshida, J. and Kishino, K. (1995) *IEEE Photon. Tech. Lett.*, Vol. 7, p.241.

158 Chou, S.T., Wohlert, D.E., Cheng, K.Y. and Hsieh, K.C. (1998) *J. Appl. Phys.*, Vol. 83, p.3469.

159 Wohlert, D.E. and Cheng, K.Y. and Chou, S.T. (2001) *Appl. Phys. Lett.*, Vol. 78, p.1047.

160 Asada, M., Miyamoto, Y. and Suematsu, Y. (1985) *Japan. J. Appl. Phys.*, Vol. 24, p.L95.

161 Tsuchiya, M., Petroff, P.M. and Coldren, L.A. (1989) *IEEE Trans. Electron. Dev.*, Vol. 36, p.2612.

162 Hu, S.Y., Miller, M.S., Young, D.B., Yi, J.C., Leonard, D., Gossard, A.C., Petroff, P.M., Coldren, L.A. and Dagli, N. (1993) *Appl. Phys. Lett.*, Vol. 63, p.2015.

163 Hu, S.Y., Yi, J.C., Miller, M.S., Leonard, D., Young, D.B., Gossard, A.C., Dagli, N., Petroff, P.M. and Coldren, L.A. (1995) *IEEE J. Quantum Electron.*, Vol. 31, p.1380.

164 Saito, H., Uwai, K. and Kobayashi, N. (1993) *Japan. J. Appl. Phys.*, Vol. 32, p.4440.

165 Hara, S., Motohisa, J. and Fukui, T. (1998) *Electron. Lett.*, Vol. 34, p.894.

166 Ando, C.-P.H., Saito, H. and Kanbe, H. (1994) *Appl. Phys. Lett.*, Vol. 64, p.1759.

167 Ohno, Y., Kanamori, H., Shimomura, S. and Hiyamizu, S. (2002) *Physica*, Vol. E13, p.892.

168 Kapon, E., Simhony, S., Bhat, R. and Hwang, D.M. (1989) *Appl. Phys. Lett.*, Vol. 55, p.2715.

169 Tiwari, S., Pettit, G.D., Milkove, K.R., Legoues, F., Davis, R.J. and Woodall, J.M. (1994) *Appl. Phys. Lett.*, Vol. 64, p.3536.

170 Qian, Y., Xu, Z.T., Zhang, J.M., Chen, L.H., Wang, Q.M., Zheng, L.X. and Hu, X.W. (1995) *Electron. Lett.*, Vol. 3, p.102.

171 Piester, D., Bönsch, P., Schrimpf, T., Wehmann, H.-H. and Schlachetzki, A. (2000) *IEEE J. Sel. Top. Quantum Electron.*, Vol. 6, p.522.

172 Kim, T.G., Son, C.S. and Ogura, M. (2001) *IEEE Photon. Tech. Lett.*, Vol. 13, p.409.

173 Sirigu, L., Oberli, D.Y., Degiorgi, L., Rudra, A. and Kapon, E. (2000) *Phys. Rev.*, Vol. B61, p.R10575.

174 Kim, T.G., Wang, X.-L., Kaji, R. and Ogura, M. (2000) *Physica*, Vol. E7, p.508.

175 Watanabe, S., Koshiba, S., Yoshita, M., Sakaki, H., Baba, M. and Akiyama, H. (1998) *Appl. Phys. Lett.*, Vol. 73, p.511.

176 Watanabe, S., Koshiba, S., Yoshita, M., Sakaki, H., Baba, M. and Akiyama, H. (1999) *Appl. Phys. Lett.*, Vol. 75, p.2190.

177 Sorba, L., Schedelbeck, G., Wegscheider, W., Bichler, M. and Abstreiter, G. (2000) *Phys. Stat. Sol.*, Vol. A178, p.227.

178 Hayamizu, Y., Yoshita, M., Watanabe, S., Akiyama, H., Pfeiffer, L.N. and West, K.W. (2002) *Appl. Phys. Lett.*, Vol. 81, p.4937.

179 Fons, P., Iwata, K., Yamada, A., Matsubara, K., Niki, S., Nakahara, K., Tanabe, T. and H.Takasu (2000) *Appl. Phys. Lett.*, Vol. 77, p.1801.

180 Bagnall, D.M., Chen, Y.F., Zhu, Z., Yao, T., Koyama, S., Shen, M.Y. and Goto, T. (1997) *Appl. Phys. Lett.*, Vol. 70, p.2230.

181 Yu, P., Tang, Z.K., Wong, L., G.K., Kawasaki, M., Ohtomo, A., Koinuma, H. and Segawa, Y. (1998) *J. Cryst. Growth*, Vol. 184, p.601.

182 Cao, H. *et al.* (2000) *Phys. Rev. Lett.*, Vol. 84, p.5584.

183 Yang, P., Yan, H., Mao, S.S., Russo, R.E., Johnson, J.C., Saykally, R.J., Morris, N., Pham, J., He, R. and Choi, H.J. (2002) *Adv. Func. Mater.*, Vol. 12, p.323.

184 Johnson, J.C., Yan, H., Schaller, R.D., Haber, L.H., Saykally, R.J. and Yang, P. (2001) *J. Phys. Chem.*, Vol. B105, p.11387.

185 Johnson, J.C., Choi, H.J., Knutsen, K.P., Schaller, R.D., Yang, P. and Saykally, R.J. (2002) *Nature Mater.*, Vol. 1, p.106.

186 Duan, X., Huang, Y., Agarwal, R. and Lieber, C.M. (2003) *Nature*, Vol. 421, p.241.

187 Kirstaedter, N., Ledentsov, N.N., Grundmann, M., Bimberg, D., Ustinov, V.M., Ruvimov, S.S., Maximov, M.V., Kopev, P.S. and Alferov, Z.I. (1994) *Electron. Lett.*, Vol. 30, p.1416.

188 Hirayama, H., Matsunaga, K., Asada, M. and Suematsu, Y. (1994) *Electron. Lett.*, Vol. 30, p.142.

189 Michler, P., Imamoglu, A., Mason, M.D., Carson, P.J., Strouse, G.F. and Buratto, S.K. (2000) *Nature*, Vol. 406, p.968.

190 Michler, P., Kiraz, A., Becher, C., Schoenfeld, W.V., Petroff, P.M., Zhang, L., Hu, E. and Imamoglu, A. (2000) *Science*, Vol. 290, p.2282.

191 Santori, C., Pelton, M., Solomon, G., Dale, Y. and Yamamoto, Y. (2001) *Phys. Rev. Lett.*, Vol. 86, p.1502.

192 Bauer, E. and Poppa, H. (1972) *Thin Solid Films*, Vol. 12, p.167.

193 Eaglesham, D.J. and Cerullo, M. (1990) *Phys. Rev. Lett.*, Vol. 64, p.1943.

194 Leonard, D., Krishnamurthy, M., Reaves, C.M., Denbaars, S.P. and Petroff, P.M. (1993) *Appl. Phys. Lett.*, Vol. 63, p.3203.

195 Moison, J.M., Houzay, F., Barthe, F., Leprince, L., Andre, E. and Vatel, O. (1994) *Appl. Phys. Lett.*, Vol. 64, p.196.

196 Shchukin, V.A., Ledenstov, N.N., Kopev, P.S. and Bimberg, D. (1995) *Phys. Rev. Lett.*, Vol. 75, p.2968.

197 Rossetti, R., Nakahara, S. and Brus, L.E. (1983) *J. Chem. Phys.*, Vol. 79, p.1986.

198 Alivisatos, A.P., Harris, A.L., I.evinos, N.J., Steigerwald, M.L. and Brus, L.E. (1988) *J. Chem. Phys.*, Vol. 89, p.4001.

199 Steigerwald, M.L. and Brus, L.E. (1989) *Ann. Rev. Mater. Sci.*, Vol. 19, p.471.

200 Bawendi, M.G., Carroll, P.J., Wilson, L. and Brus, L.E. (1992) *J. Chem. Phys.*, Vol. 96, p.946.

201 Murray, C.B., Norris, D.J. and Bawendi, M.G. (1993) *J. Am. Chem. Soc.*, Vol. 115, p.8706.

202 Katari, J.E.B., Colvin, V.L. and Alivisatos, A.P. (1994) *J. Phys. Chem*., Vol. 98, p.4109.

203 Murray, C.B., Kagan, C.R. and Bawendi, M.G. (2000) *Annu. Rev. Mater. Sci*., Vol. 30, p.545.

204 Alivisatos, A.P. (1996) *Science*, Vol. 271, p.933.

205 Bimberg, D., Grundmann, M. and Ledentsov, N.N. (1999) *Quantum Dot Heterostructures*, Wiley, New York.

206 Rennon, S., Avary, K., Klopf, F., Reithmaier, J.P. and Forchel, A. (2001) *IEEE J. Sel. Top. Quantum Electon*., Vol. 7, p.300.

207 Saito, H., Nishi, K., Ogura, I., Sugou, S. and Sugimoto, Y. (1996) *Appl. Phys. Lett*., Vol. 69, p.3140.

208 Lott, J.A., Ledentsov, N.N., Ustinov, V.M., Egorov, A.Y., Zhukov, A.E., Kopev, P.S., Alferov, Z.I. and Bimberg, D. (1997) *Electron. Lett*., Vol. 33, p.1150.

209 Yoshie, T., Shchekin, O.B., Chen, H., Deppe, D.G. and Scherer, A. (2002) *Electron. Lett*., Vol. 38, p.967.

210 Michler, P., Kiraz, A., Zhang, L., Becher, C., Hu, E. and Imamoglu, A. (2000) *Appl. Phys. Lett*., Vol. 77, p.184.

211 Young, D.K., Zhang, L., Awschalom, D.D. and Hu, E.L. (2002) *Phys. Rev*., Vol. B66, p.R81307.

212 Sellin, R., Ribbat, C., Grundmann, M., Ledentsov, N.N. and Bimberg, D. (2001) *Appl. Phys. Lett*., Vol. 78, p.1207.

213 Kim, H.J., Motohisa, J. and Fukui, T. (2002) *Appl. Phys. Lett*., Vol. 81, p.5147.

214 Ogawa, T. and Takagahara, T. (1991) *Phys. Rev*., Vol. B44, p.8138.

215 Nojima, S. (1994) *Phys. Rev*., Vol. B50, p.2306.

216 Grundmann, M. and Bimberg, D. (1997) *Phys. Rev*., Vol. B55, p.4054.

217 Rossi, F., Goldoni, G. and Molinari, E. (1997) *Phys. Rev. Lett*., Vol. 78, p.3527.

218 Sarma, S.D. and Wang, D.W. (2000) *Phys. Rev. Lett*., Vol. 84, p.2010.

219 Kuther, A., Bayer, M., Gutbrod, T., Forchel, A., Knipp, P.A. Reinecke, T.L. and Werner, R. (1998) *Phys. Rev*., Vol. B58, p.15744.

220 Constantin, C., Martinet, E., Oberli, D.Y., Kapon, E., Gayral, B. and Gerard, J.-M. (2002) *Phys. Rev*., Vol. B66, p.165306.

221 Vuckovic, J., Pelton, M., Scherer, A. and Yamamoto, Y. (2002) *Phys. Rev*., Vol. A66, p.23808.

222 Yamamoto, Y., Tassone, F. and Cao, H. (2000) *Semiconductor Cavity Quantum Electrodynamics*, Springer, Berlin, 2000.