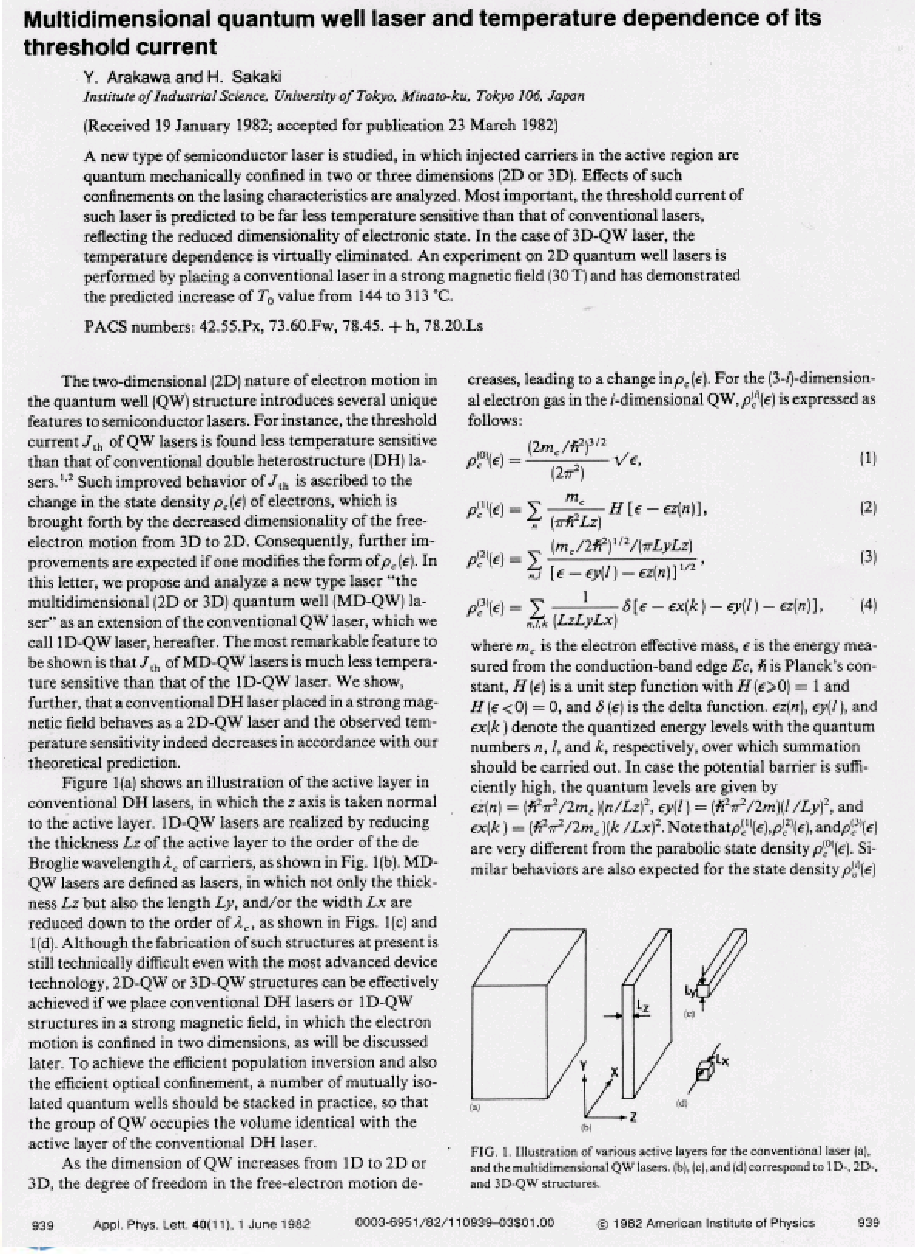
量子ドットの提案：30年前



Multidimensional quantum well laser and temperature dependence of its threshold current

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A new type of semiconductor laser is studied, in which injected carriers in the active region are quantum mechanically confined in two or three dimensions (2D or 3D). Effects of such confinements on the lasing characteristics are analyzed. Most important, the threshold current of such laser is predicted to be far less temperature sensitive than that of conventional lasers, reflecting the reduced dimensionality of electronic state. In the case of 3D-QW laser, the temperature dependence is virtually eliminated. An experiment on 2D quantum well lasers is performed by placing a conventional laser in a strong magnetic field (30 T) and has demonstrated the predicted increase of T_0 value from 144 to 313 °C.

PACS numbers: 42.55.Px, 73.60.Fw, 78.45. + h, 78.20.Ls

The two-dimensional (2D) nature of electron motion in the quantum well (QW) structure introduces several unique features to semiconductor lasers. For instance, the threshold current J_{th} of QW lasers is found less temperature sensitive than that of conventional double heterostructure (DH) lasers.[1,2] Such improved behavior of J_{th} is ascribed to the change in the state density $\rho_c(\epsilon)$ of electrons, which is brought forth by the decreased dimensionality of the free-electron motion from 3D to 2D. Consequently, further improvements are expected if one modifies the form of $\rho_c(\epsilon)$. In this letter, we propose and analyze a new type laser "the multidimensional (2D or 3D) quantum well (MD-QW) laser" as an extension of the conventional QW laser, which we call 1D-QW laser, hereafter. The most remarkable feature to be shown is that J_{th} of MD-QW lasers is much less temperature sensitive than that of the 1D-QW laser. We show, further, that a conventional DH laser placed in a strong magnetic field behaves as a 2D-QW laser and the observed temperature sensitivity indeed decreases in accordance with our theoretical prediction.

Figure 1(a) shows an illustration of the active layer in conventional DH lasers, in which the z axis is taken normal to the active layer. 1D-QW lasers are realized by reducing the thickness Lz of the active layer to the order of the de Broglie wavelength λ_c of carriers, as shown in Fig. 1(b). MD-QW lasers are defined as lasers, in which not only the thickness Lz but also the length Ly, and/or the width Lx are reduced down to the order of λ_c, as shown in Figs. 1(c) and 1(d). Although the fabrication of such structures at present is still technically difficult even with the most advanced device technology, 2D-QW or 3D-QW structures can be effectively achieved if we place conventional DH lasers or 1D-QW structures in a strong magnetic field, in which the electron motion is confined in two dimensions, as will be discussed later. To achieve the efficient population inversion and also the efficient optical confinement, a number of mutually isolated quantum wells should be stacked in practice, so that the group of QW occupies the volume identical with the active layer of the conventional DH laser.

As the dimension of QW increases from 1D to 2D or 3D, the degree of freedom in the free-electron motion decreases, leading to a change in $\rho_c(\epsilon)$. For the (3-i)-dimensional electron gas in the i-dimensional QW, $\rho_c^{(i)}(\epsilon)$ is expressed as follows:

$$\rho_c^{(0)}(\epsilon) = \frac{(2m_c/\hbar^2)^{3/2}}{(2\pi^2)}\sqrt{\epsilon}, \tag{1}$$

$$\rho_c^{(1)}(\epsilon) = \sum_n \frac{m_c}{(\pi\hbar^2 Lz)} H[\epsilon - \epsilon z(n)], \tag{2}$$

$$\rho_c^{(2)}(\epsilon) = \sum_{n,l} \frac{(m_c/2\hbar^2)^{1/2}/(\pi Ly Lz)}{[\epsilon - \epsilon y(l) - \epsilon z(n)]^{1/2}}, \tag{3}$$

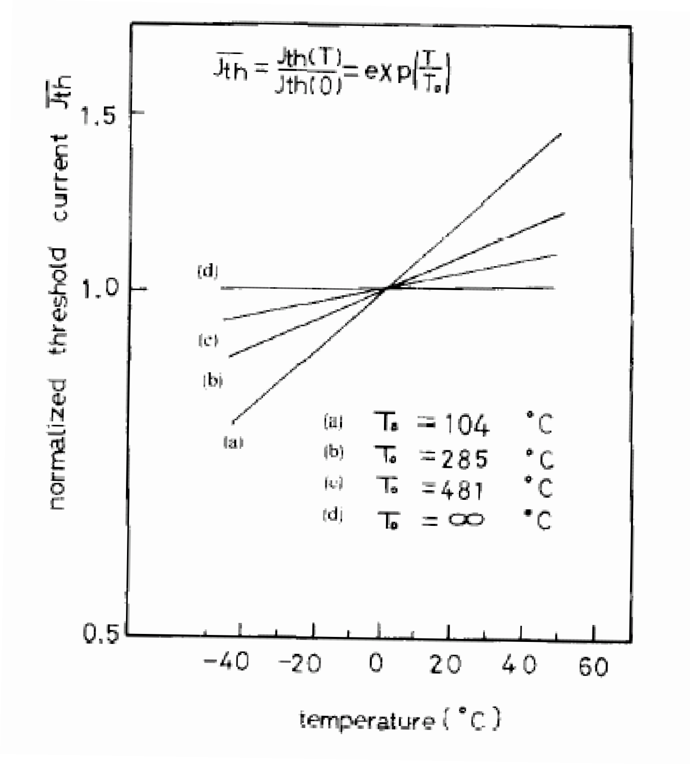
$$\rho_c^{(3)}(\epsilon) = \sum_{n,l,k} \frac{1}{(LzLyLx)} \delta[\epsilon - \epsilon x(k) - \epsilon y(l) - \epsilon z(n)], \tag{4}$$

where m_c is the electron effective mass, ϵ is the energy measured from the conduction-band edge Ec, $\hbar$ is Planck's constant, $H(\epsilon)$ is a unit step function with $H(\epsilon > 0) = 1$ and $H(\epsilon < 0) = 0$, and $\delta(\epsilon)$ is the delta function. $\epsilon z(n)$, $\epsilon y(l)$, and $\epsilon x(k)$ denote the quantized energy levels with the quantum numbers n, l, and k, respectively, over which summation should be carried out. In case the potential barrier is sufficiently high, the quantum levels are given by $\epsilon z(n) = (\hbar^2\pi^2/2m_c)(n/Lz)^2$, $\epsilon y(l) = (\hbar^2\pi^2/2m)(l/Ly)^2$, and $\epsilon x(k) = (\hbar^2\pi^2/2m_c)(k/Lx)^2$. Note that $\rho_c^{(1)}(\epsilon)$, $\rho_c^{(2)}(\epsilon)$, and $\rho_c^{(3)}(\epsilon)$ are very different from the parabolic state density $\rho_c^{(0)}(\epsilon)$. Similar behaviors are also expected for the state density $\rho_v^{(i)}(\epsilon)$

FIG. 1. Illustration of various active layers for the conventional laser (a), and the multidimensional QW lasers. (b), (c), and (d) correspond to 1D-, 2D-, and 3D-QW structures.

939 Appl. Phys. Lett. 40(11), 1 June 1982 0003-6951/82/110939-03$01.00

- 半導体量子ドットとそのレーザ応用を提案
- 閾値電流の温度無依存性を理論予測



Appl. Phys. Lett . 40, 939 (1982)
被引用回数 > 2,300 回

1980年代における量子ドットレーザ研究

理論

- The first proposal : Arakawa (1982)
- Reduced temperature dependence: Arakawa (1982)
- Higher speed modulation : Arakawa (1984)
- Zero-α-parameter, low-chirping : Arakawa (1984)
- Lower threshold current density : Asada/Suematsu (1986)
- p-doping: Arakawa (1982, 1991)
- Tunneling injection: Arakawa (1992)

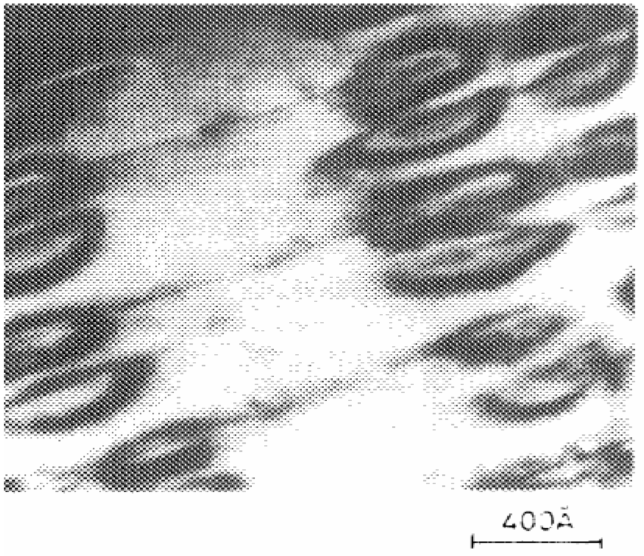
量子ドットの自己組織化形成

Growth by molecular beam epitaxy and characterization of InAs/GaAs strained-layer superlattices

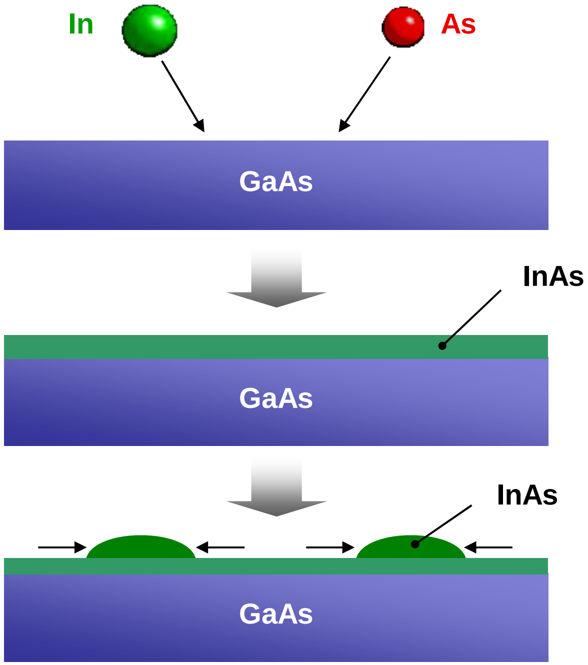
L. Goldstein, F. Glas, J. Y. Marzin, M. N. Charasse, and G. Le Roux
Centre National d'Etudes des Telecommunications, 196 rue de Paris, 92220 France

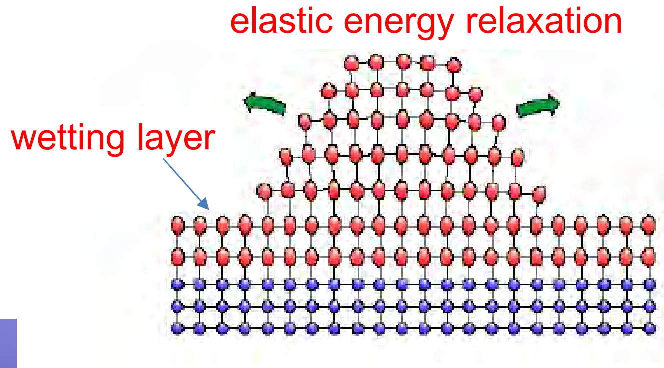
(Received 26 July 1985; accepted for publication 4 September 1985)

Appl. Phys. Lett. 47 (1985) 1099.



Stranski-Krastanov
成長モード



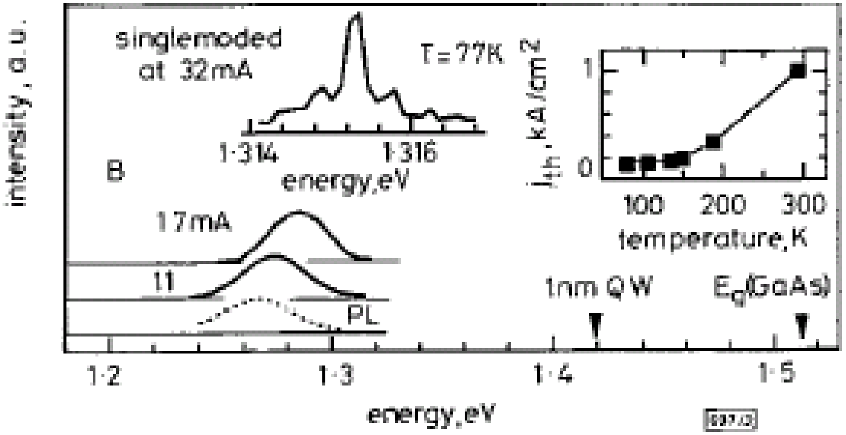


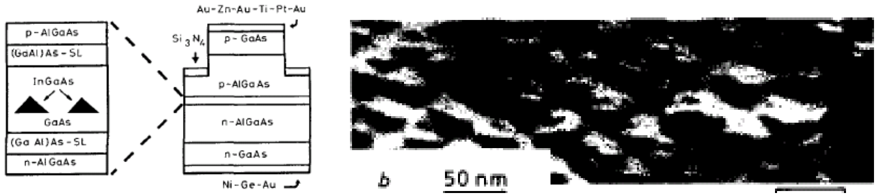
- Goldstein *et al* 1985
- Petroff *et al* 1993
- Ledentsov *et al* 1994
- Arakawa *et al.* 1994

量子ドットレーザ作製の試み

Low threshold, large T_0 injection laser emission from (InGa)As quantum dots

N. Kirstaedter, N.N. Ledentsov, M. Grundmann,
D. Bimberg, V.M. Ustinov, S.S. Ruvimov,
M.V. Maximov, P.S. Kop'ev, Zh.I. Alferov,
U. Richter, P. Werner, U. Gösele and J. Heydenreich





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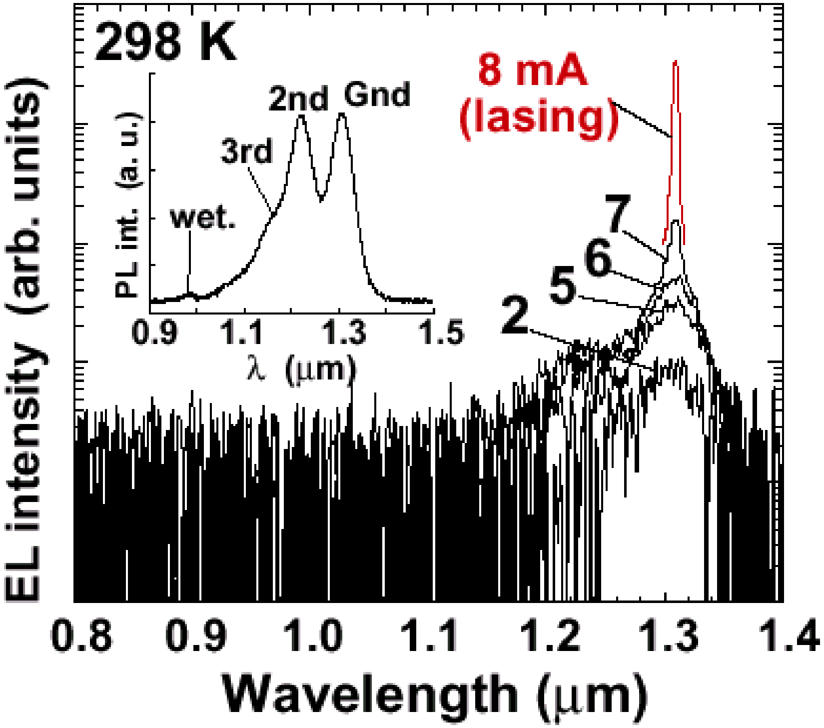

■CW operation at R.T.

K. Mukai, *et al.*, Fujitsu
IEEE Phot. Tech. Lett. 11, 1205-1207 (1999).

大型国家プロジェクトが量子ドット研究を飛躍させた

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