Proc. QCTM, Fukui 1993
J. Phys. Soc. Jpn. 63(1994) Suppl. A pp. 236 – 243

Wave-Function Engineering for Advanced Semiconductor Devices

Hiroyuki SAKAKI
Research Center for Advanced Science and Technology,
University of Tokyo, Komaba 4-6-1, Meguro-ku, Tokyo 153, Japan

Several new attempts to control electron wavefunctions in mesoscopic and microscopic semiconductor structures for the advanced device functionality are described with emphasis on quantum-wire and quantum-box structures. The prospect and importance of reducing their feature sizes to 10nm scale by epitaxial growth methods are discussed.

1. Introduction

Owing to remarkable progresses in semiconductor technology, the fabrication of ultrathin layered structures such as quantum wells, tunnel barriers, and superlattices has become possible. Hence one can now control almost arbitrarily the potential profile $V(z)$ along the thickness direction z and thereby manipulate the electron wavefunction $f(z)$ while the two dimensional (2D) motion of electrons within the (x, y) plane remains free. As a result, a variety of new electronic phenomena have been discovered over the last two decades which have not only expanded the forefront of condensed-matter physics but also provided a number of new and advanced device functions in solid state electronics. Representative examples include the high-mobility electron transport in modulation-doped structures, the nonlinear and wavelength-selective transport in resonant tunneling structures and the intersubband-excitation induced photoconductivity in multi QW structures, where the controllability of $f(z)$ is ingenuinely used. In the area of interband optical transitions, the field-induced Stark effect of absorption spectra and the superior lasing properties of QWs due to the modified density of states has been studied and exploited[1)].

Some time ago, it was pointed out by the author that the further control of electron wavefunction by the use of in-plane quantum structures such as quantum wires and boxes and planar superlattices is theoretically very attractive in generating a whole series of new phenomena and device functions[1−8)]. Indeed a number of theoretical and experimental works on these systems have been done recently and shown to open new fields of physics and electronics. This whole field is called wavefunction engineering[1)]. As the length of this article is limited, we review in this paper some of these works recently done with emphasis on ours. For more extensive coverage of the subject up to 1991, the readers are recommended to read Refs[1-3].

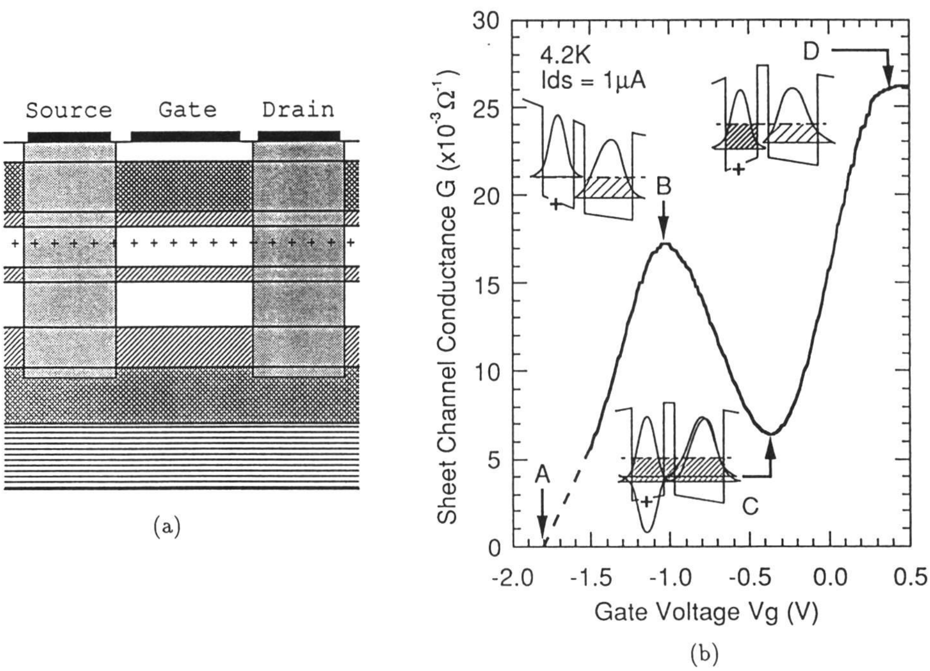


Figure 1: (a) A novel double-quantum well FET. (b) Its gate-voltage dependence of channel conductivity is affected by the resonant coupling of two levels[13].

2. Reduction and Resonant Enhancement of Electron Scattering in Double Quantum Well and Its FET Application

The separation of electron wavefunction $f(z)$ from ionized impurity potential $V_{imp}(\mathbf{r})$ in a modulation doped GaAs QW channel is quite effective in reducing the impurity scattering[9]. Hence this scheme is now commonly employed in field-effect transistors(FETs) for superior high frequency characteristics. If this impurity-election distance (or their overlap) is efficiently controlled, for example, by gate voltage V_g in a FET configuration, this should affect the scattering rate or drift velocity of electrons and result in the change dG of channel conductivity. This novel FET concept was proposed by the author and named as velocity modulation transistor (VMT)[10], Since VMTs are conceptually new, they may exhibit various functions that can not be realized in conventional FETs. The question exists, however, as to what device structure is to be to modulate the electron velocity most efficiently. It has been pointed out[11,12] that double-quantum well (DQW) structures such as shown in Fig.1(a) are most suited for this purpose. It is because the wavefunctions $f(z)$ of the two lowest states can be efficiently modulated between the coupled and uncoupled pairs, as illustrated in the insets of Fig.1(b), and should influence the conductivity. Indeed, it has been demonstrated recently that the impurity scattering can be enhanced drastically by bringing the two lowest levels into resonance in a novel DQW structure, where only the top QW is doped with donor impurities[13]. Figure 1(b) shows its channel conductance G measured at 4.2K as a function of gate voltage V_g. Note that G rises

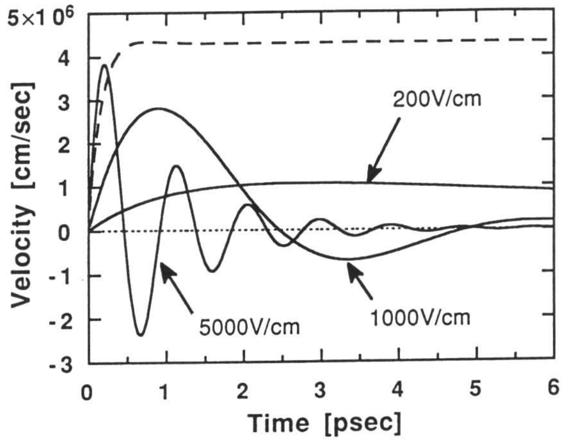


Figure 2: Time evolution of electron velocities at 300K in coupled quantum box structures[7)].

first linearly with V_g, which represents the normal FET behavior as it reflects the increase of high-mobility electrons in the undoped (bottom) channel. Upon further increase of V_g, however, G drops dramatically to one third of its peak value and then recovers. This extraordinary behavior results from the gate-induced resonance of two ground levels. It is because the wavefunctions of resonantly coupled electronic states spread over both QWs and interact strongly with impurities, which are intentionally introduced in the top QW, leading to the reduction of channel conductivity. Although this VMT action is achieved so far only when the electron temperature T_e is low, this mechanism is expected to be extended to the case of high T_e if the effective mass and/or the phonon scattering rate can be modulated at a higher temperature.

In a sense, this VMT action has a conceptual similarity to the quantum confined Stark effect in which the field-induced deformation of wavefunctions is used to modulate the interband optical absorption process. These examples indicate clearly that the modulation of $f(z)$ in QW structures by gate voltage V_g is quite effective in controlling fundamental properties of semiconductors.

3. Control of Tunneling, Scattering, and Energy Relaxation in Quantum Boxes

When electrons are confined three-dimensionally in quantum box structures, they form a series of discrete levels. This situation will significantly affect electron transport as well as inter-level relaxation processes. In this section, we describe three specific examples in which the tunneling, the phonon scattering, and the energy relaxation process are to be controlled to achieve desirable device functions.

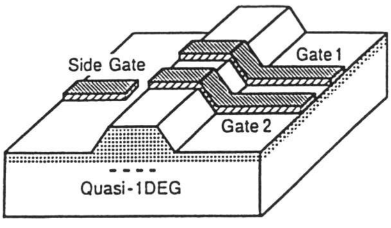
3.1 Suppression of optical phonon scattering and the Bloch oscillation

It was pointed out by the author[7)] that the intersubband scattering by optical phonons can be virtually eliminated in quantum box (CQB) structures when the minigaps or the energy spacings between adjacent subbands exceeds the energy $\hbar\omega_{opt}$ of optical phonons ($\sim$ 36meV in GaAs). Similarly, if the width of the first miniband of a CQB structure is chosen to be less than $\hbar\omega_{opt}$ ($\sim$ 36meV), all the intra-subband scattering by optical phonons can be also inhibited. Hence, when these two conditions are met simultaneously, electron transport in a CQB structure will be almost free from optical phonon scattering and is affected only by acoustic phonon scattering, so long as impurities, interface roughness and other structural disorders are negligibly small. The high field transport under such a circumstance is investigated theoretically[7)]. It is found that electrons are accelerated by DC fields of 1-10kV/cm to the edge of the mini-Brillouin zone and exhibit the Bloch oscillation even at room temperature (as shown in Fig.2). If the bandwidth exceeds $\hbar\omega_{opt}$, however, the phonon scattering become too frequent to observe the oscillation at 300K.

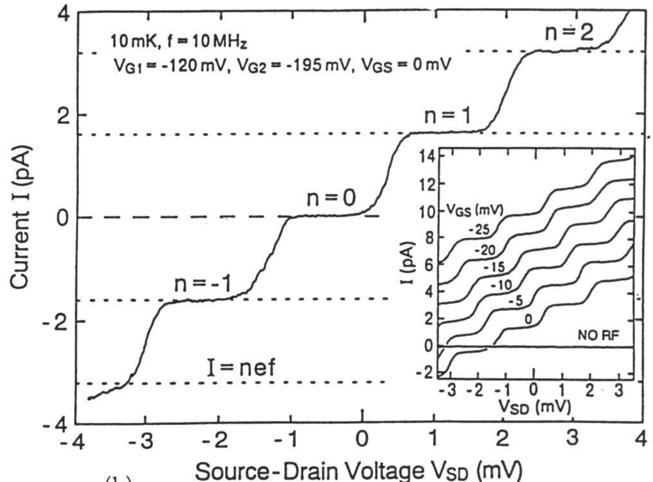
3.2 Transfer of single electron via quantum-box and isolated island structures

The injection of a single electron into a small and nearly isolated island of a metal or semiconductor is known to influence the in-flow of subsequent electrons when the presence of the first electron raises appreciably the electrostatic energy of a capacitor and/or increase the local Fermi energy of the quantum box[14)].

In collaboration with the Technical University of Delft, we have recently studied the electron transport via a novel small island structure which is formed by introducing two tunnel barriers (B_1 and B_2) into a narrow wire of n-AlGaAs/GaAs heterojunction[15)](See Fig.3(a)). These barriers are formed by depositing two 200nm-long metallic gates (G_1 and G_2) on the wire structure with the geometrical spacing of 200-300nm. Despite its simplicity, this structure allows the precise transfer of a single electron. In this device, gate voltages are initially chosen to make both barriers B_1 and B_2 high enough to prevent the flow of electrons. When the barrier B_1 of entrance gate is appropriately reduced, a single electron tunnels from the emitter into the central island. The entrance of the second electron, however, can be prevented because the additional increase of electrostatic energy stored in a small capacitor B_1 is too large to be fed by the external power supply. After closing the entrance gate G_1, the barrier B_2 of exit gate G_2 is lowered for a while to let the single electron leave from the island to the collector electrode. Since the end result is the transfer of a single electron from the emitter to the collector, one can generate a current ef by modulating the gate voltages with frequency f. Such a measurement has been performed at 10mK with the rf signal of 10MHz. A series of step structures are observed in I-V characteristics (as shown in Fig.3(b)) which corresponds precisely to nef. Note that clear step structures appear only when the in-plane potential is designed in a way that the small barrier capacitance and the control of tunnel resistance over a wide range are simultaneously achieved.



(a)



(b)

Figure 3: A schematic drawing (a) and quantized I-V characteristics (b) of a turnstile device with two controlling gates G_1 and G_2 on an n-AlGaAs/GaAs quantum wire. Gates G_1 and G_2 are modulated with 10MHz to allow the transfer of single electron per cycle.

3.3 Energy relaxation in quantum boxes: problems and possibilities

As stated in 3.1, both upward and downward transitions between two subbands by the absorption and emission of optical phonons will be suppressed significantly in quantum box (QB) structures, unless the spacing of energy levels is close to the optical phonon energy $\hbar\omega_{opt}$. It is because the density of available states in QB structures is nearly zero anywhere except the point of their energy eigenvalues. This reduction of intersubband process produces a quite attractive situation in realizing the Bloch oscillator. This situation is favorable also for the possible realization of light emitters based on the intersubband process, since the non-radiative relaxation by phonon emissions, which is quite harmful, can be practically eliminated.

Recently it has been pointed out that this phonon bottle-neck effect is detrimental in making injection-type QB lasers, since the efficiency of interband light emission process is reduced unless carriers injected to the QB relax quickly to their ground levels[6,16)]. We have investigated this issue in detail by considering the electron relaxation by two-phonon processes (LO+LA) and (LO−LA), in which the emission or the absorption of longitudinal acoustic phonons(LA) takes place in addition to the emission of longitudinal optical phonons(LO)[17)]. It is found that this two-phonon process offers a rather fast (sub-nanosecond) relaxation path, so long as the level separation is set within ±3meV of $\hbar\omega_{opt}$. Recently it is further pointed out by Bockelmann that the electron relaxation by Auger process can be quite efficient if the two dimensional electrons are present in the surrounding area of QBs[18)]. Since the tuning of quantum levels with the accuracy of 6meV is not unrealistic and also the introduction of 2D-elections can be easily done, QBs designed with optimized structures can be considered as potentially attractive system as the active layer of semiconductor lasers.

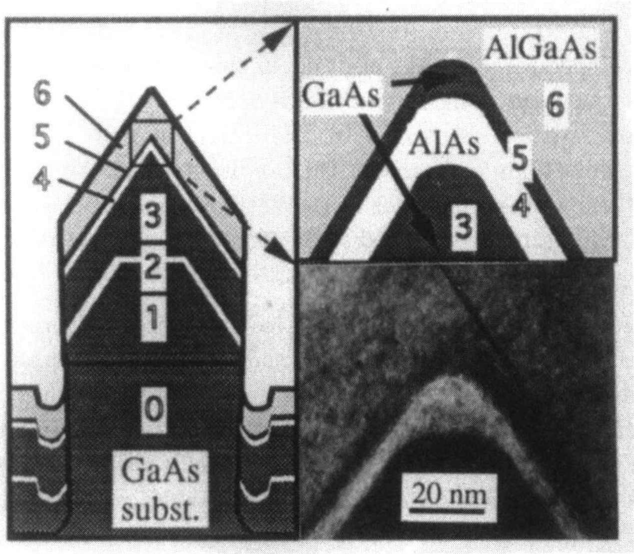


Figure 4: Ridge-type quantum wire formed on a patterned substrate; (a) and (b) show the schematic structure whereas (c) is the TEM image of the ridge top.

4. Nanometer-Scale Quantum Wires: Properties and Fabrication

A number of new and attractive phenomena have been predicted to appear in quantum wire(QWI) structures and partly demonstrated[2–8]. New phenomenon in quantum wire structures include the quantization of conductance in ballistic regime[8], the possible reduction of both elastic and inelastic scatterings of electrons in single mode QWIs[5,19], the reduction of thermal broadening of carrier energy[20], the enhancement of exciton binding energy, and the novel situation of electron-electron scattering, which may lead to the spin polarization[21] as well as the unique hot electron distributions.

Although quite attractive, many of these properties are expected to appear only when the majority of electrons or excitons are accommodated in the ground subband of lateral quantum structures. This means that one must operate medium-sized quantum structure devices at low temperatures on alternatively aim for room temperature operations by preparing high-quality quantum wires of 5-30nm-scale cross-section, in which the interface roughness (or the size fluctuation of their cross-section), the impurity concentration, and other defects are kept negligibly small. Various attempts have been made to satisfy these conditions.

As a specific example, we explain a method to form a GaAs ridge-type quantum wire, which is schematically shown in Fig.4[22]. In this approach, we formed first, by selective etching, stripes of 1-2mm wide mesa structures on (001) GaAs substrate and then deposited GaAs and/or AlAs by molecular beam epitaxy. On such a patterned substrate, the growth proceeds in such a way that a sharp ridge-like structure is finally formed. Figure 4(b) and (c) show the cross-section views of the ridge that consists of two (111) planes. Note that the ridge top has a width of only about 10nm. We deposited on this ridge a 7nm-thick GaAs/AlAs quantum well and found by luminescence spectroscopy that excitons in this system are confined not only along the thickness direction but also along the width direction since the quantum well on the (111) planes are thinner and function as barriers for the lateral motion. The effective size of the ridge wire in Fig.4 is 9nm$\times$16nm and satisfies the conditions mentioned earlier. The successful formation of GaAs QWIs with similar sizes in the bottom region of sharp V-groove structures by MOCVD method have been also reported[23,24]), indicating again the effectiveness of selective growth approach.

Another epitaxy approach which has recently enabled the successful formation of high-quality QWI structure is to expose first the edge surface of undoped GaAs/AlGaAs multi-quantum well structures and then deposit on the edge surface an n-AlGaAs layer, which produces the accumulation layer of electrons at the interface. Indeed the formation of one-dimensional electrons confined both by QW potential and by the space-charge fields was demonstrated[25,26]). In these works wire structures were prepared by exposing the edge surface of QWs by cleavage or facet growth. In addition, the growth of thin GaAs on the edge surface followed by the deposition of AlGaAs layer is found to yield a QWI structure which confines both electrons and holes and its lasing action has been demonstrated[27]). These findings indicate that novel epitaxial growth approaches are quite promising for the formation of nanometer scale QWI structures.

References

1) For a review, see for example H.Sakaki: *Proc. of 1st Int. Symp. on Foundation of Quantum Mechanics*, Tokyo, 1983 (published by Phys. Soc. of Japan) (1984) 94 and also L. Esaki, in *Recent Topics in Semiconductor Physics*, ed. by H. Kamimura (World Scientific 1983) 1.

2) For a review on application of quantum wires and boxes, see for example, H. Sakaki: Surf. Sci. **267** (1992) 623.

3) For a review on physics of quantum wires and boxes, see all the articles in *Nanostructure Systems*, ed. by M. Reed (Academic Press 1992).

4) H. Sakaki, K. Wagatsuma, J. Hamasaki, and S. Saito: Thin Solid Films **36** (1976) 497.

5) H. Sakaki: Jpn. J. Appl. Phys. **19** (1980) L735.

6) Y. Arakawa and H. Sakaki: Appl. Phys. Lett. **40** (1982) 893.

7) H. Sakaki: Jpn. J. Appl. Phys. **28** (1989) L314 and also H. Noguchi, J. P. Leburton and H. Sakaki: Phys. Rev. B**47** (1993) 15593.

8) B. J. Van Wees, H. Van Houten, C. W. Beenakker, J. G. Williamson, J. P. Kouwenhoven, D. Van der Marel, and C. T. Foxon: Phys. Rev. Lett. **60** (1988) 848.

9) R. Dingle, H. L. Stormer, A. C. Gossard, and W. Wiegmann: Appl. Phys. Lett. **33** (1978) 665 and also T. Mimura, S. Hiyamizu, T. Fujii, and K. Nanbu: Jpn. J. Appl. Phys. **19** (1980) L225.

10) H. Sakaki: Jpn. J. Appl. Phys. **21** (1982) L381 and also K. Hirakawa, H. Sakaki and J. Yoshino: Phys. Rev. B**54** (1985) 1279.

11) A. Palevski, F. Beltram, F. Capasso, L. Pfeiffer, and K. W. West: Phys. Rev. Lett. **65** (1990) 1929.

12) M. Tsuchiya, T. Noda, H. Kano, and H. Sakaki: Inst. Phys. Conf. Ser. **112** (1990) 339.

13) Y. Ohno, M. Tsuchiya, and H. Sakaki: Appl. Phys. Lett. **62** (1993) 1952.

14) See for example, Single Charge Tunneling, (ed. by H. Grabert, J. M. Martinis and M. H. Devoret, Plenum Press) (1991).

15) Y. Nagamune, H. Sakaki, L. P. Kouwenhoven, L. C. Mur, C. J. P. M. Harmans: to be published in Appl. Phys. Lett. (1994).

16) H. Benisty, C. M. Sotomayor-Torres, and C. Weibuch: Phys. Rev. B**44** (1991) 10945, and U. Bockelmann and G. Bastard, Phys. Rev. B**42** (1990) 8947.

17) T. Inoshita and H. Sakaki: Phys. Rev. B**46** (1992) 7260.

18) U. Bockelman and T. Egeler: Phys. Rev. B**46** (1992) 15574.

19) T. Yamada and J. Sone: Phys. Rev. B**40** (1989) 6265.

20) See for example, T. Ogawa, and T. Takagahara: Phys. Rev. B**43** (1991) 14325 and B**44** (1991) 8138.

21) G. Fasol and H. Sakaki: Phys. Rev. Lett. **70** (1993) 3643.

22) S. Koshiba, H. Noge, H. Ichinose, H. Akiyama, Y. Nakamura, T. Inoshita, T. Someya, K. Wada, A. Shimizu, and H. Sakaki: Appl. Phys. Lett. (Jan.10 Issue, 1994) and Workbook of 6th Int. Conf. on Modulated Semicond. Structures (Garmisch 1993) 281, to be published in Solid State Electronics.

23) E. Kapon, D. M. Hwang, and R. Bhat: Phys. Rev. Lett. **63** (1989) 430.

24) S. Tsukamoto, Y. Nagamune, M. Nishioka, and Y. Arakawa: J. Appl. Phys. **71** (1992) 533.

25) H. L. Stormer, L. N. Pfeiffer, K. W. Baldwin, K. W. West, and J. Spector: Appl. Phys. Lett. **58** (1991) 726.

26) Y. Nakamura, M. Tsuchiya, J. Motohisa, H. Noge, S. Koshiba, and H. Sakaki: Workbook of 6th Int. Conf. on Modulated Semicond. Structures (Garmish, 1993) 60, and to be published in Solid State Electronics (1994).

27) W. Wegsheider, W. Kang, L. N. Pfeiffer, K. W. West, H. L. Stormer, and K. W. Baldwin, *ibid* 26 and to be published in Phys. Rev. Lett. (1994)