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QUANTUM MICROSTRUCTURE DEVICES

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Recent developments in the study of nm-scale semiconductor micro-structures are reviewed with emphasis on their applications to advanced electronic and photonic devices. We describe, in particular, progresses in the use of quantum well structures for such new devices as several novel resonant-tunneling transistors, the Bloch oscillator, and a intersubband infrared laser. Also discussed are key developments to explore the use of nm-scale quantum wires and quantum boxes for injection lasers, transistors and other new devices. Importances of developing epitaxial methods for the fabrication of these in-plane quantum structures are emphasized

Keywords: A.heterostructures,quantum wells B. nanofabrications D.electron transport,optical properties

1 INTRODUCTION

Remarkable progresses in semiconductor technology such as epitaxial growth, and lithography have allowed one to fabricate a variety of semiconductor microstructures with a feature scale of 1-100nm, in which quantum mechanical natures of electrons play important roles. As a result, quasi-two-dimensional electrons tightly-bound in quantum wells or loosely confined in superlattices have been widely studied and their unique properties are used to create a class of devices with new functions or to upgrade the performance of existing devices [1]. The exploration has been further extended to quantum wires, quantum boxes(dots), and related structures, where the in-plane motion of electrons is controlled. A number of novel properties of one and zero-dimensional electron gas have been closed [2].

In this paper, we review some of recent works to exploit novel features of quantum microstructures for the creation and/or improvement of devices. In particular, we describe in section 2 work on transport devices including ultrafast heterostructure FETs, quantum-wire and quantum-dot devices, resonant-tunneling transistors and the Bloch oscillator. Then, we discuss in section 3 recent trends on photonic device research by reviewing quantum-wire and quantum-well lasers and intersubband infrared detectors and emitters. In section 4, we discuss the prospect of these devices and review briefly some attempts to prepare nanometer scale quantum wires to emphasize their importance for future progress of the field.

2 TRANSPORT DEVICES AND MICROSTRUCTURES

2.1 *Ultrafast heterostructure FETs*

Among various transport devices that make use of quantum microstructures, modulation-doped field-effect transistors (MOD-FETs) or high electron mobility transistors (HEMTs) are the simplest and yet most successful examples. As the gate length L_g is continually reduced, the cut-off frequency f_T of the device has been constantly raised, reaching more than 300GHz in an InGaAs MODFET with L_g of 50nm [3, 4]. As the saturation velocity v_s of electrons in InGaAs channels is estimated to be (1.5~2)x10^7cm/s, the intrinsic transit time $\tau_0(=L_g/V_s)$ is predicted to be (330~250) f_s, for which the intrinsic cut-off frequency $f_t(=1/2\pi\tau_o)$ should be in the range of 480~600 GHz. The sizable deviation of f_T from its intrinsic value can be ascribed to the series resistance and to the broadening of effective gate length, which is not negligible in very short channel devices. To clarify the ultimate frequency limit, one must elucidate also the contribution of velocity overshoot effect, which is not clear at present.

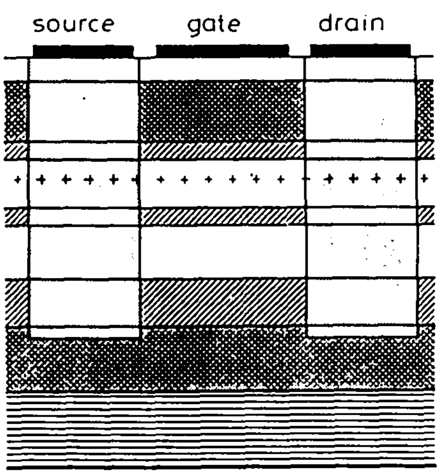
As the further shrinkage of gate length below 50nm gets exceedingly difficult, the exploration of an FETs channel that would allow a higher electron velocity becomes increasingly important. The single-mode quantum wire with a very high electron concentration is a suitable candidate as it has been predicted to suppress elastic scattering processes [5] and the optical phonon scattering [6], which may prevent the saturation of electron velocity. This point will be discussed in section 2.3.

2.2 *Resonantly-coupled double quantum well FETs and velocity modulation transistors*

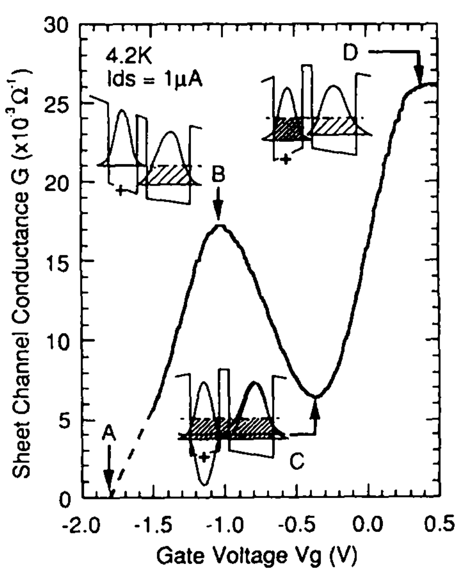
Two sheets of quantum wells(QWs), A and B, separated by a thin barrier such as shown in Fig.1(a) support usually the two ground subbands E_{1A} and E_{2B} of respective QWs. Their wavefunctions φ_{1A} and φ_{2B} are localized mostly in QW-A and QW-B, respectively, unless E_{1A} is resonant with E_{1B}. However, if the gate electric field is adjusted by applying, two level can be resonantly coupled to form the symmetric state E_S and the antisymmetric state E_{AS}, as shown in the inset of Fig.1(b). Under such a resonant condition, the wavefunctions φ_S and φ_{AS} of electrons spread over both QWs, as electrons move back and forth between two QWs with the typical frequency of Δ/h, where Δ is the splitting ($=E_{AS}-E_S$) of two levels.

The onset of resonant coupling has been extensively studied by optical spectroscopy as will be discussed in 2.5 [7]. This coupling can be studied also by measuring the current between the two QWs, as it increases sharply when the resonance is reached. Such measurements are made by using either a triple barrier resonant tunneling diode structure or a double QW channel FET structures with a separate Ohmic contact to each one of QWs [9]. By using the latter geometry, Eisenstein *et al.* has successfully detected a resonant increase of current at a particular gate voltage [9]. They found also that the width of a resonant peak is determined mainly by the roughness-induced level broadening rather than the coupling-induced splitting of levels.

Alternatively, the resonant coupling of two ground levels can be detected simply by measuring the average mobility of electrons [10, 14], or the conductivity along the double QW channel, if the channel is made in such a way that the scattering rate is highly dependent on the shape of the wave functions. Indeed, such a condition is satisfied in a double QW channel where ionized impurities are introduced into only one of the QWs, as shown in Fig. 1(a). In this geometry, the current is usually carried by high-mobility electrons flowing in the undoped QW. When the two ground levels coincide, however, the wavefunctions are coupled and extended almost equally over two QWs. Since all the electrons interact strongly with impurities, one expects both the mobility and the current to drop when the resonance is reached. Figure



(a)



(b)

Fig. 1. A novel double-quantum well FET (a). Its gate-voltage dependence of channel conductivity is affected by the resonant coupling of two levels (b).[11]

1(b). shows the conductance G of such a GaAs/AlGaAs double QW structure measured at 4.2K as a function of gate voltage V_g. When V_g is raised from its threshold, G increases initially as in the case of usual FETs, but G drops down to one third of its peak value and then recovers. This anomalous behavior is ascribed to the resonant enhancement of scattering events caused by ionized impurities.

This phenomenon was observed first by Palevski *et al.* [10] and later examined by Ohno *et al.* [11] to show that the modulation of channel conductivity can be quite large if the structure is optimized. Since this conductivity modulation is caused mainly by the change in the mobility or group velocity of electrons, this device is considered as one example of velocity-modulation transistors (VMTs), which were proposed earlier as a way to achieve ultrafast transistor operation and also novel functions [12]. Though the mobility modulation in this particular device is achieved only at low temperatures (up to 77K), VMT action at higher temperatures should be possible in principle, if the phonon scattering rate or the effective mass of electrons is efficiently modulated.

2.3 *Ballistic transport in quantum wires*

The use of quantum wires for transport devices can be divided into two categories, depending on the mean free path l being smaller or greater than the sample length L. As discussed in 2.1, when electrons in quantum wires are accelerated by high electric fields, they interact with optical phonons frequently enough to make the transport diffusive ($l<L$). Nonetheless, the use of a quantum wire array as an FET channel can be beneficial, since it will lead to the enhancement of both mobilities and saturation velocities [5, 6].

The ballistic and/or coherent transport of electrons in quantum wires has been studied extensively. Physics of such systems has been covered by Imry and Sivan in this volume. Here we discuss a few attempts to explore the possible device applications of this novel transport phenomena . As is well known, when the number of 1D subbands or modes is increased or deceased by the gate voltage, the channel conductivity will change by the quantized conductance (e^2/h). Ismail *et al.* have fabricated an FET channel consisting of a dense array of quantum wires with a typical period of 100nm or even less and have shown that the modulation of channel conductivity caused by the change of mode number can be quite high [13]. Though this scheme of modulating the ballistic transport works at present only in high quality wires at low temperatures, the development of higher quality wires with larger subband separations and higher purity may allow the similar operation at higher temperatures.

Another attempt to modulate the number of transverse modes and to control the electron transport in quantum wires has been made by using a Y-shaped electron waveguide structure. In this device, an electron wave packet is launched from one of the branches to reach the Y-junction and goes out through one of the two output branches. The selection of one branch out of two can be made by applying appropriate gate voltages in such a way that the number of transverse modes is unity for the selected branch and zero for the unselected. This type of device, however, has an inherent limitation in that both the current and voltage must be kept rather low not to spoil the ballistic nature of modal transport.

In the past several proposals have been made for a family of devices, in which the quantum interference of electron waves propagating in two different longitudinal modes is controlled by electrostatic fields or by magnetic fields. In principle, they are electron-wave versions of optical or microwave devices such as the Mach-Zehnder [15], the Michaelson interferometers [16], and a parallel-waveguide directional coupler [17]. All of these devices have a common drawback in that a clear interference with a good contrast can be obtained only when electrons are gently launched with a low excess energy at low temperatures. Otherwise, the phase breaking processes, particularly by electron-electron interactions, cannot be suppressed. Therefore both the maximum current for the on-state of such a device and the maximum voltage for its off-state will remain too low to allow a sufficient voltage gain or an ample current-drive capability needed for most of digital circuitries.

2.4 *Resonant tunneling diodes and transistors*

As is well known, a distinctive negative differential resistance with a very high peak-to-valley ratio can be achieved in double barrier resonant tunneling (RT) structures, even when a large voltage (>0.5V) is applied across the device at room temperatures. In addition, the density of current can be set quite high (>10^4A/cm^2), especially when the energy width dE of the transmission peak is sufficiently large. These facts indicate that resonant tunneling is a robust phenomenon and its device application is rather promising, as RT devices can handle both high currents and high voltages at room temperatures. In fact they are successfully applied to detect and generate mm and sub-mm electromagnetic waves and to hold voltage in a very fast sampling circuitry.

Several proposals have been made to prepare three terminal RT devices by adding the third electrode to control the current. These devices can be used to make novel digital circuitries or to disclose novel physics of RT through quantum wires and quantum boxes. In the following, we describe a few examples. The incorporation of a RT diode inside the emitter-to-base junction of hot-electron transistors (HETs) or hetero-bipolar transistors (HBTs) has been done successfully [18, 19, 20]. It is found that these devices exhibit novel input-output characteristics which can be used to achieve sophisticated logic functions with much smaller number of devices. The reduction factor can be as large as six. It is recently shown that even higher functionality can be achieved by placing two or more RT emitter electrodes in these resonant HET and HBT structures [20]. If two RT emitters are incorporated in a common base electrode of a HET structure and if a fixed voltage is applied across the two emitter electrodes, the base voltage can be bi-stable. Hence, this resonant HET with a multi-emitter geometry can be used as an advanced logic element and a memory cell.

Another scheme to control the RT transport is to prepare a very small cylinder-shaped double barrier (DB) diode by selective etching and then to form a doughnut-shaped gate electrode surrounding the DB part of the diode By applying a negative voltage to the gate, the diameter of a conducting region of the cylindrical diode is continually squeezed, resulting in a novel structure in current voltage-characteristics [21, 22]. These structures stem from such mechanisms as the Coulomb blockade, and RT transport through a donor state and/or a laterally-quantized state in the narrow part of the quantum well, but thier relative importance depends on the detail of sample geometry. Similarly, a very thin wall-shaped RT diode was fabricated with an array of gate electrodes sitting near the DB part of the diode to control the thickness of a conducting region of the diode [23]. When separate voltages are applied to these gates to adjust the magnitude of the current, logic functions to build neural circuits are found to be realized.

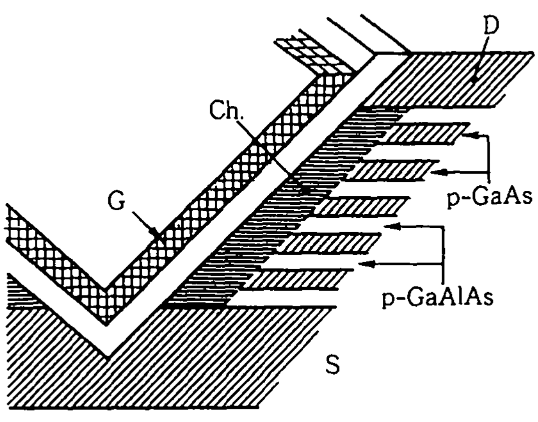


Fig. 2. A planar superlattice structure consisting of coupled edge-quantum-wire structures (proposed by Sakaki[1]).

Some years ago, proposals were made to expose an edge surface of undoped quantum well structures and to overgrow an n-AlGaAs structure on its top to form modulation-doped quantum wires, planar superlattices, and double barrier resonant tunneling diodes [2, 5, 24]. Figure 2(a) shows the geometry of a planar superlattice with control gate, proposed by the author [2, 24]. When the number of barriers is decreased to two, the structure is reduced to a gate-controlled resonant tunneling diode, proposed by Luryi *et al.* [25]. Very recently, such structures have been successfully made and found to exhibit a gate-controlled negative differential resistance caused by the resonant tunneling of 2D electrons through a quantum wire state [26, 27].

2.5 *Bloch oscillations in layered superlattices and possible improvements in coupled quantum box arrays*

The Bloch oscillation was predicted to occur in a periodically modulated potentials, when electrons are accelerated to the edge of the Brillouin zone with negligible influence of scatterings [28, 29]. Such a condition is satisfied when the mean interval of scattering events is far longer than the period $T(=mh/edF)$ of the Bloch oscillation, where F is the field for the acceleration, d is the spatial period of the potential modulation, and all other symbols have their conventional meanings. Although the use of a superlattice structure or a medium with a longer period d did greatly increase the possibility of satisfying this condition, an experimental proof of the Bloch oscillation was not accomplished until recently. It is primarily because of the lack of a method to excite and detect the ultrafast oscillation of about THz in frequency which decays very rapidly with a typical time constant of about one picosecond or even less. With the advent of femtsecond laser technology, however, it has now become possible to introduce photo-generated carriers almost instantly (0.1ps) into a specific quantum well and follow their motion with sub-picosecond time resolution [7, 30]. By using such techniques, oscillatory motions of electrons , though being quite damped, were successfully detected at low temperatures both in a coupled double quantum well structure [7] and a coupled multi-quantum well structure [30] or a superlattice. Oscillations in the former system result from the quantum beat of the two coupled ground levels, whereas those in the latter correspond to the Bloch oscillation or a kind of beat in the Wannier-Stark ladder system, as an electric field used in the experiment was strong enough to localize the wavefunction within a few to several periods of a superlattice.

One valuable challenge on the Bloch oscillator is to find a way to suppress the rapid damping of oscillations. This is particularly important, if the Bloch oscillator is ever to be used for a practical application. It is proposed that the use of a linear or planar array of coupled quantum boxes with appropriate parameters can be quite effective to suppress the optical phonon scatterings of electrons and prolong the oscillation [31]. It is because both the intrasubband and intersubband scatterings by optical phonons can be eliminated, when the miniband of the system is narrower than the optical phonon energy E_{op} (-36meV) and its first minigap is wider than E_{op}, respectively. Figure 3 shows the time evolution of electron velocities calculated for such a system at room temperature. Note that distinct oscillations are predicted to occur in this system even at 300K, where the damping is dominated only by acoustic phonon scatterings, whereas no oscillation is seen once the miniband is set wider than E_{op}.

The study of a negative-effective-mass dispersion and negative differential resistance in multi-layered superlattices has been continually pursued. It has been found that observed characteristics are well explained by transport theories if scatterings by phonons, impurities, and interface roughness are all taken into account

3. PHTONIC DEVICES AND MICROSTRUCTURES

3.1 *Quantum well and quantum wire lasers*

Advantages of using quantum wells in the active region of semiconductor lasers and light emitting devices have been widely recognized. They originate from several different factors; for example, (1) the size-reduction of active regions leads to a smaller current for pumping, (2)

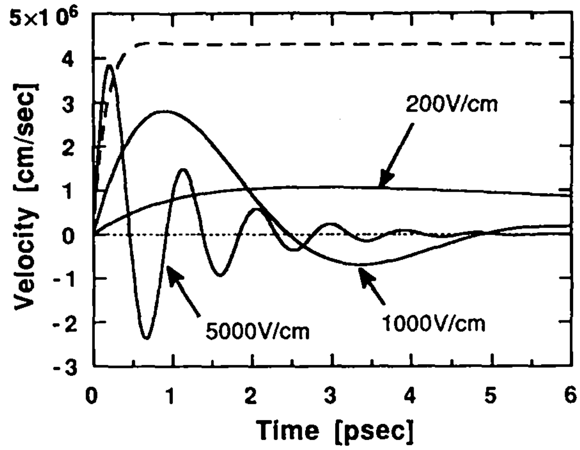


Fig. 3. Electron velocities at 300 K in coupled quantum box structures calculated as functions of time after a step-like voltage is applied.[31]

The same gain can be achieved by smaller density of carriers as the gain spectrum is sharpened, (3) thin active layers allow us to use lattice mismached materials.

Recently, successful developments have been reported on ZnSe-based quantum well lasers and InGaN-based quantum well light-emitting diodes, which have converted current-injected carriers into blue photons for the first time [32, 33]. In these device structures, pseudomorphic layers are cleverly used to form active layers with specific compositional profiles which are needed for the confinement of carriers and photons.

The use of high quality quantum wires and quantum boxes to form active regions of lasers and LEDs is known to give additional advantages not only over bulk semiconductors but also over quantum wells, as they provide the sharper densities of states and also the larger binding energy of excitons [34]. These advantages can be obtained only when their energy level separation is larger than kT and the level broadening is far smaller than kT. Hence, one must prepare these 1D structures with feature sizes less than typically 25nm and roughness-induced level broadening of 10meV or even less.

Several different approaches have been made to satisfy these requirements. For example, the selective growth of GaAs either in the bottom region of sharp V-groove structures or in the top portion of sharp ridge structures has been used to form nm-scale quantum wires. In these structures, the one-dimensionality of confined excitons has been demonstrated by measuring such quantities as the blue shift of photoluminescence (PL) [35], the anisotropy in diamagnetic shifts of PL spectra [36], and the reduced variation of PL decay time with temperatures [37]. The lasing from groove quantum wires has been demonstrated first by Kapon *et al.* by incorporating a vertical stack of wires into a standard double-heterostructure structure that can be pumped by current injection [35]. In addition, a planar array of groove quantum wires has been successfully incorporated into an optical microcavity structure, which is sandwiched by a pair of multi-layered Bragg reflectors [38]. By pumping the structure optically, a surface-emitting lase operation has been observed at low temperatures. In these experiments, however, no substantial improvements have been found in laser performances; this is probably due to the roughness-induced level broadening in narrow quantum wires and to the lack of level separation in the case of wide quantum wires.

Another kind of quantum wires that have been incorporated successfully into a DH structure are edge-quantum wire structures, one example of which is schematically shown in Fig. 2. As discussed earlier, electrons and/or excitons can be confined in the edge region of undoped quantum wells (QWs), if the local potential near the edge surface is lowered by overgrowing an n-AlGaAs layer or a GaAs/AlGaAs double layer onto the edge surface of original QWs. By using the latter scheme, Wegscheider *et al.* have grown an array of edge quantum wires on the cleaved surface of multi QWs and prepared a waveguide structure [39]. Laser oscillations have been observed, when the structure was pumped either optically or electrically. In this device, the position of emission peak was found to be almost unchanged even when the pumping was varied from a very low level to the point of stimulated emission. This unique feature has been tentatively ascribed to the possible enhancement of exciton binding energy, on which a further study is certainly needed.

3.2 *Intersubband photonic devices*

Quite some time ago, it was pointed out by Esaki and Sakaki that a multilayered superlattice with appropriate parameters can be used as an infrared detector if some of the electrons tightly bound in the ground subband E_1 are excited by infrared radiation into the second subband E_2 of a looser confinement, where electrons can flow along the z-direction normal to the layers [40]. Levine *et al.* have carried out a series of extensive work and demonstrated that this type of device indeed allows the detection of infrared in the wavelength region of 4-11μm [4]. In this device, the transit time T_t of electrons should be chosen preferably comparable with or shorter than the lifetime T_e of electrons in the second subband, as the collection efficiency of photoexcited carriers is proportional to T_e/T_t. Though T_e depends on a number of parameters, it is typically in the range of 1-10ps when the level separation is larger than the optical phonon energy. Hence, the device length is usually set at about 1μm so that photoexcited electrons in the ground subband reach the collector electrode within a few tens of ps, resulting in a reasonable quantum efficiency. For a detailed account on this subject, see an excellent review by Levine [41].

When an appropriate electric field is applied across a multi-quantum well structure, the ground level $E_1(n)$ of the n-th quantum well can be brought almost or exactly on resonance with the second level $E_2(n+1)$ of the (n+1)th quantum well. In such a case, electrons in the $E_1(n)$ level can flow into $E_2(n+1)$ and then relax to the $E_1(n+1)$ level, resulting in a transfer from the n-th quantum well to the neighboring one. Some time ago, Kazarinov and Suris considered such a cascade transport for the first time [42] and pointed out that it may lead to the emission of infrared radiation. They have shown that the emission should occur if $E_1(n)$ is biased slightly above $E_2(n+1)$ so that the tunnel transport takes place is compensated by the emission of photons and/or phonons to compensate their energy level separation. Although quite weak, the predicted infrared radiation was detected by Helm *et al.* successfully [43].

Several refined geometries have been proposed to improve carrier injection processes [44, 45] and to achieve the population inversion for intersubband lasers. Indeed, Faist *et al.* has observed for the first time an intersubband laser action at the wavelength of 4.2μm by feeding the current of about 1A (or 15kA/cm^2) through a 25 periods of a novel InGaAs/InAlAs triple quantum well (TQW) structure [45]. In this TQW structure, each period contains an n-type injector layer and three quantum wells (QWs-A, B, and C) whose thicknesses are 0.8nm, 3.5nm, and 2.8nm, respectively. When a bias voltage of about 350meV is applied across an each period, which corresponds to the total voltage of 8V across the diode, electrons are first injected through a tunnel barrier into the ground level (#3) of QW-A and then relaxed by inelastic tunneling to the ground subband (#2) of a neighboring well (QW-B), which is about 300meV below the level #3. Although this relaxation process is dominated by the emission of optical phonons with its time constant of about 4ps, a small fraction (0.1-0.03%) of the relaxation takes place via the emission of photons with the rate of about $(13\text{ns})^{-1}$ and gives rise to an optical gain required for the laser action. To achieve the population inversion, the density N_s of electrons in #3 is increased by current injection to the level about $2\times10^{11}\text{cm}^2$, while N_s in #2 is kept almost zero. This evaluation is done by transferring electrons via phonon assisted tunneling from level #2 to the ground level (#1) of neighboring QW-C and further to the outside collector layer. The laser emission of 8mW is observed for the input of 8W which gives the overall efficiency of 0.1%. The use of quantum box structures should be useful in enhancing this efficiency, as the non-radiative relaxation path by optical phonon emission can be suppressed in quantum boxes, as discussed earlier. In fact, this phonon bottle neck effect is pointed out to be a problem for the use of quantum boxes for injection lasers [46] to this effect precisely, one must consider both multiphonon process [47] and the Auger process [48].

4. CONCLUSION AND FUTURE PROSPECTS

As described in Secs. 2 and 3, the use of two-dimensional electron gas in quantum wells and other layered structures for the advancement of device functions has become a standard practice especially for compound semiconductor devices. It is because the technological cost for the growth of such structures is continually reduced, while the gain in device performances is found to be quite large. The best example is the recent advent of blue lasers and LEDs, which have become possible only when thin strained layers of ZnSSe and InGaN are grown and used as their active layers [32, 33]. This trend will continue and is being extended to new material systems, such as Si-SiGe, NiAl-AlAs and other systems.

In contrast, the use of quantum wires and quantum boxes for the realization of advanced devices has been explored mainly in theoretical analyses and the experimental work has progressed relatively slowly. It is mainly due to the technological difficulty of preparing high-quality quantum wire structures. Hence, the prospect of devices based on quantum wires and boxes depends critically on whether the reliable nano-fabrication technology can be developed or not. Fortunately, we have seen over the last few years several significant developments in epitaxial technology, by which nm-scale wires and dots can be fabricated. Since this subject is addressed in a separate paper by Gossard in this issue, we list up in the following several representative approaches and describe their features.

As stated earlier, the selective growth of quantum wire structures on the top of sharp ridges or in the bottom of V-grooves has been successfully accomplished by several groups [35-37]. Though the confinement energy is shown to be controlled over a wide range, the broadening of quantized levels is found to be large (10-30meV), indicating that the further reduction of the size fluctuation is necessary. The most promising way to minimize the size fluctuation of nm-scale wires is to employ edge quantum wire (E-QWI) structures [1, 5, 39, 49, 50]. As discussed earlier, carriers in E-QWIs are confined along the z-axis by the usual quantum well potential $V(z)$ and are bound along the y-axis by an additional potential $V(y)$, which is introduced by the overgrowth of an n-doped barrier layer or a quantum well layer onto the edge surface of the original QWs. To expose clean and flat edge surfaces of QWs, cleavage and facet growth has been mainly used [39, 49, 50]. In near future, the edge exposure will be also achieved by ultra-clean etching process [5]. A very sharp luminescence, laser action, and FET action have been all observed, which have indicated the one-dimensional nature of carriers. Although the prospect of this E-QWI approach is bright, it has a drawback in that the planar feature of wafer surfaces is usually lost as a result of the edge exposure, which makes the subsequent device processing rather difficult. A solution to this problem is quite important.

It has been pointed out by Petroff *et al.* that a planar array of quantum wires or a tilted superlattice can be formed, when a half-mono-layer of GaAs and that of AlAs are alternately deposited on a vicinal substrate. It is because GaAs and AlAs deposited on such a surface may be incorporated selectively at the edge of each atomic step, which may be evenly spaced [51]. Although the compositional modulation was achieved, the amplitude of modulation was found to be weaker than expected [51-53]. This is partly because GaAs molecules on the surface are too mobile to be all incorporated selectively at the step edges and partly because AlAs molecules are too strongly bonded to the substrate to reach the step edges. Hence, surface chemistry during the growth must be modified to improve the quality of tilted superlattices.

As discussed up to now, the formation of quantum wires and boxes are usually done by using various templates. It is recently found, however, that, if a very thin InAs or InP layer is deposited on a lattice-mismatched GaAs substrate, the spontaneous formation of nm-scale quantum dot structures will be realized [54, 55]. Their lateral size depends critically on the growth condition and can be controlled down to 15nm or so, although some amount of size fluctuation is found unavoidable. In addition, though dots are usually located randomly, the registration of their position is found to be controllable, if the substrate surface is modified selectively by a focused ion beam prior to the vapor phase growth of InP dots [55]. It has been also found that the alternate deposition of thin layers of GaP and InP on a GaAs substrate leads to the spontaneous formation of nm-scale quantum wire structures and the laser action with a strong polarization dependence has been demonstrated [56].

Finally, I conclude this review by emphasizing the importance of stimulating interactions among three related fields of research: *i.e.*, physics of low-dimensional systems, material science of nano-scale structures, and advanced electronics based on quantum structure devices. A mutual stimulation and cross-fertilization among them will be the main source of thrust for future progress in this fascinating area of solid-state science.

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