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Evolution of New Device Concepts in Quantum-Well and Superlattice Structures

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Abstract: Recent progresses in the research activity on quantum-well (QW) and superlattice (SL) devices are summarized and examined to clarify how a variety of new device concepts have evolved. A special emphasis is placed on the importance of "wave function engineering (WFE)", as compared with the conventional "energy band engineering". Future prospects and impacts of QW and SL devices are also discussed and major technological problems to be solved are pointed out.

§1. Introduction

In the history of semiconductor electronics, one notices that many important inventions and discoveries were made when major physical concepts intersected with a new material technology or vice versa. For example, the bipolar transistor was born, when the concept of "minority carrier injection and collection" crossed with the Ge p-n junction technology, whereas the semiconductor laser came into existence, when the concept of "population inversion" or "stimulated emission" encountered the juction technology of direct-gap materials.

Another example of such a creative interaction can be seen in the recent research on ultrafine heterostructures. As illustrated in Fig.1,the recent developments of fine epitaxy technique such as MBE and MOCVD have enabled one to prepare various heterostructures, in which the quantum mechanical concepts of "size-quantization" and "tunneling" play very important role. By using such structures, a number of promising devices have been conceived and realized. Quantum-well (QW) lasers, and high-electron mobility transistors (HEMT and MISSFET) are good examples. In the following, we discuss how a variety of new devices have evolved in this area with the special attention to several key concepts which constitute a basis of these devices.[1]

§2. Key Concepts in QW and SL Devices

Although a variety of new device structures have been proposed, operating principles of these devices can be reduced to one (or more) of the following concepts: namely (A) the quantum confinement of carriers, (B) the spatial separation of electrons from holes and impurities, (C) the rapid transfer of carriers across the boundary and (D) the tunneling and associated resonance of de Broglie waves.

(A) Devices Based on Quantum Mechanical Confinement of Carriers

The most obvious function of QW structures is the quantum mechanical carrier confinement. In case of GaAs/AlGaAs QW structures which is shown in Fig. 2(A), the ground levels of such confined electrons and holes will be lifted from the band edges. This leads to the increase ΔEg of the effective energy gap, ΔEg being given by $\{(\hbar^2/2m_e) + (\hbar^2/2m_h)\}(\pi/L_z^*)^2$, in which L_z^* is the effective thickness of GaAs quantum wells. Such an increase of Eg provides a convenient method to shorten the lasing wavelength of QW lasers,[2] suggesting that QMCC is another effective way of energy-band engineering. In addition to this controllability of laser wavelengths, it was found recently that QW lasers possess such features as the greater temperature stability of the threshold current J_{th}, the superior mode stability to high-frequency modulation and also the lower threshold current. These features are now ascribed to the two-dimensionality of carrier states; note that the suppression of free motion of electrons in the direction normal to the layer plane leads to narrower gain spectrum and accounts for at least qualitatively the above improvements. These superior performances of the QW laser indicate the bright prospect of the QW laser.

Another consequence of quantum mechanical confinement is that the excitonic (attractive) interaction of electrons and holes can be enhanced in the quantum well, leading to the increase of the exciton binding egergy E_b. In the case L_z is much smaller than the usual radius of excitons, E_b is found to reach ~17meV, which is 4 times as large as its bulk value.[3] Hence the exciton contribution in QW is expected to be effective even at high temperatures; such a behavior has been indeed proven by the optical absorption study at room-temperature.[4] Furthermore, this exciton effect is shown to affect the refractive index of QW's and is used to achieve, for the first time, the optical bistability at room temperature.[5] These benefits of carrier confinements in QW film structures suggest that further improvements may be obtained if the carrier confinement is done in 2 or 3 dimensions. This point will be discussed in Section 3.

(B) Devices Based on The Spatial Separation of Electrons from Donor Impurities or Holes

Electrons in QW and SL structures are generally accumulated and confined in the potential-well layers, keeping the barrier layers unpopulated.[6] Hence, one can separate electrons completely from dopant impurities if one introduces dopants only into the barrier layers.[7] This modulation doping (MD) scheme is shown to be very effective in suppressing the coulomb scattering, resulting in the very high mobility of electrons at low temperatures ($\sim 10^6 cm^2/Vs$). As is well known, such a high-electron-mobility feature was readily applied to make very-high-speed transistors (HEMT[8] and MISSFET[9]), which can possibly be the core-device in ultrafast computers of the future.

Another promising aspect of the "spatial separation" is seen in InGaAs/GaSbAs SL[10] and GaAs nipi SL structures,[11] where electrons can be separated from holes as shown in Figs.2(c) and 2(d). In such a configuration (which we call the type II superlattice), one readily sees that the effective energy gap can be made very small or even negative (semi-metallic state) even when the constituent materials have wide energy gap. This suggests the possible device applications of such materials for light sources and devices in long-wavelength range. Especially in the case of nipi structures, where the potential profiles V(z) are gradual, the energy gap is found to be modulated by the electric field, indicating the unique feature of band-gap tunability.

Another interesting use of "electron-hole separation scheme" has been proposed to apply this concept to construct low-noise avalance photo diodes.[12,13] When carriers in type II superlattices (A/B/A/B) are accelerated parallel to the layer plane, electrons flow in one film (say "A"), while holes drift in film B. If one chooses the energy gap Eg_B of film B to be much larger than the gap Eg_A of film A, then the avalanche effect of holes can be suppressed, resulting in the drastic increase of the ionization rate ratio α/β. In the case of InGaAs/AlSbAs SL, which is lattice matched to InP substrates, α/β is expected to reach as high as 10^3, suggesting the possible use of such system for low-noise APD's.

(C) Devices Based on Rapid Transfer of Carriers Across The Interfaces

Device concepts described up to now have dealt mainly with carriers which are confined in the well layers. If one considers the situation, where carriers cross the hetero-interfaces, a number of new and useful phenomena are expected to occur. If electrons transfer from the barrier layer to the well layer, then a beam of high-energy electrons will be generated, since the potential energy difference ΔEc at the interface is tranformed to the kinetic egergy of electrons. The most obvious use of such high-energy electrons is its application to high-speed FET's, in which the reduction of transit time is of prime importance. Such a hot-electron injector can be also used as the emitter of ballistic injection transistors, in which the potential barrier at reverse-biased collector junction can be surmounted by hot electrons and yet the junction blocks effectively the flow of thermal electrons.

Another use of hot electron injenction is seen in its application to avalanche photo diodes (APD's) having either the superlattice or the stair-case structures.[14,15] One may expect that the impact ionization rate can be increased by the hot carrier generation at the heterointerface. Since the band edge discontinuity ΔEc of electrons in GaAs/AlGaAs superlattices is much larger than ΔEv of holes, the enhancement of avalanche effect is expected to occur predominantly in the conduction band. Hence, it was both predicted and demonstrated that the ionization rate ratio α/β in GaAs/AlGaAs SL's is much greater than unity.

The backward transfer of electrons from the wells to the barriers becomes important when hot electrons are generated in the well by electric fields parallel to the layer. When the electron mobility in the barrier layers is set much lower than the mobility in the well layers, then this real-space transfer (RST) will result in the negative differential resistance, which is somewhat similar to the Gunn effect.[16] Although the process of carrier transfer across the interface is not strictly a quantum effect, there could be a variety of applications, including the velocity modulation transistor[17] which will be described in section 3.

(D) Devices Based on Resonance and Tunneling of de Broglie Waves

The most well known device proposal of this category is the negative differential resistance device of Esaki and Tsu,[18] which makes use of the negative-mass region of the E-k relationship in SL structures. The operating principle of this device is basically the Bragg resonance of de Broglie waves with the periodic SL potentials. Hence, the successful demonstration of this effect requires the fabrication of the nearly ideal (coherent) SL potential as well as the relatively long coherence length of electron waves. This device, therfore, can be regarded as one of the final targets of technological developments.

Resonant tunneling devices[19] are another example of the device applications of tunneling. Since the I-V characteristics in such structures exhibit strong non-linearities and negative differential resistances, this structure may find important applications as high-speed mixers and other non-linear devices.

The tunneling base transistor[20] which consists of p-GaAsSb/n-InGaAs/p-GaAsSb is based on the scheme of controlling the tunneling current of holes through the InGaAs barrier layer by applying the voltage to the barrier layer. It should be noted that the InGaAs barrier layer remains always conductive for electrons because of the peculiar band offset situation.

§3. Prospects of QW and SL Devices and Possibilities of Wave-Function Engineering

As descibed in Section 2, the encounter of quantum mechanical concepts with the ultrafine heterostructure technology has already resulted in a number of new devices. Some of them, such as QW lasers and heterojunction FET's (HEMT and MISSFET), have already given great impacts on the existing devices, since their performances are in some sense far superior to those of conventional devices and match very well with the urgent need of high-quality devices. In section 2, we have shown that various operating principles of these quantum-effect devices are based on the four key concepts. One should note here that these basic concepts have one common feature in the sense that the positional co-ordinate $\mathbf{r}$ play the vital role in generating these new properties; the potential profile $V(\mathbf{r})$, the wavefunction $\varphi(\mathbf{r})$, the charge distribution $\rho(\mathbf{r})$ and the average electron velocity $v(\mathbf{r})$ are all position dependent and this dependence is responsible for most of the phenomena. In this context, this new field of device physics should be given a new name of "Wave-Function Engineering" to make a distinction from the conventional "Energy-Band Engineering", in which the manipulation of band structures in the k-space is the main concern.

Finally, a few remarks should be made on the future prospects of this field. In addition to the further developments of quantum well lasers, (modulation doped) high-electron-mobility transistors, and other existing devices, there will be further exploration in new branches of "Wave-Function Engineering". One of such branches is the branch of quantum-well wire (QWW) structures[21] and planar superlattice structures[22] (which is but a coupled-wire structure). Although the first proposals and the device analysis of these structures were made several years ago (QWW in 1980, P-SL in 1975), it was only recently that material technology has advanced enough to think about the experimental exploration of this field.[23] The recent theoretical study has predicted various advantages of using QWW structures; they include:

(a) extremely high electron mobility in QWW structures,[21]
(b) improved temperature stability of laser performances,[24]
(c) gate-controlled superlattices and so on.

Whether a family of such QWW and P-SL constitutes a fertile branch of new devices depends totally on the future developments of material and device technology.

1次元 約4万 cm²/V·s 約10Ω/μm

Another important branch of QW and SL device to be explored in the future is a group of devices, in which the wave functions or energy levels electrons are controlled by external fields in such a way that macroscopic quantities such as the conductivity or the light output can be modulated. The velocity modulation transistor (VMT) is one of the first examples of such kind,[17] where the electron mobility in FET channels is changed by the gate field. Since the conductivity change ΔG in VMT is not associated with the change of carrier density, VMT is in principle free from the transit time limitation and is expected to be a promising candidate for ultrafast transistors. A similar scheme is also applied to the modulation of semiconductor lasers, in which the light output is modulated by changing the spatial overlap of electron-and hole wavefunctions.[25] This scheme is expected to be effective in extending the maximum modulation frequency beyond its conventional limit.

In conclusion, we have shown that a variety of ultrafine heterostructure devices are based on a small number of key concepts. Moreover, these key concepts are shown to be integrated to the more general concept of wave-function engineering. Importances and prospects of these quantum-effect devices are clarified.

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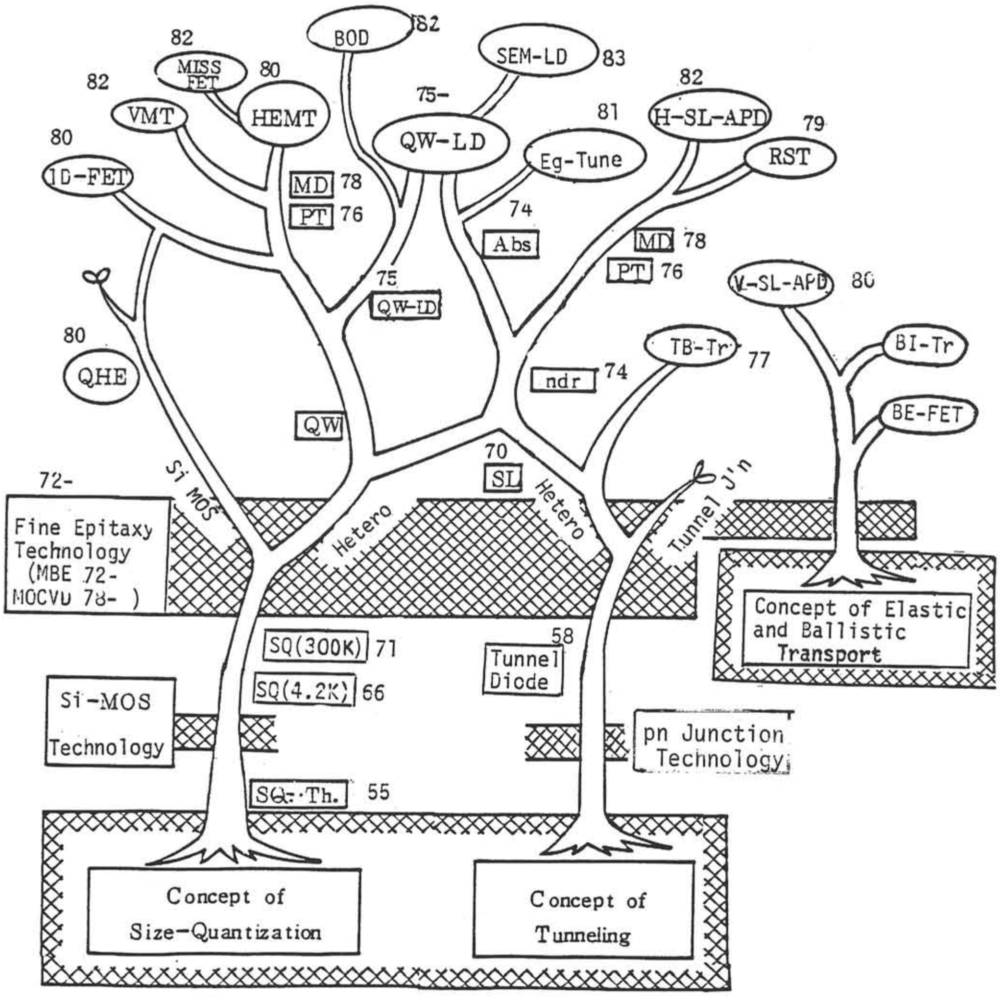

Fig. 1 A tree diagram to represent the evolution of QW and SL devices. A tree on the left shows the root of size- or surface-quantization SQ which was predicted in 55(=1955), and proved both at 4.2K and 300K by using MOS technology[1]It lead to QHE(quantized Hall effect) and was extended to heterostructures, where the study of PT(parallel transport)[6]and MD(modulation doping)[7]resulted in various transistors such as HEMT[8],MISSFET[9], VMT[17], and 1D-FET[21]. SQ has also lead to QW-LD (laser diode)[2], BOD(bistable optical device)[3], and SEM(size-effect modulation)LD[25]. The tree in the center represents the tunneling study and resulted in tunnel base transistor(TB-Tr)[20]and ndr(negative differential resistance)[18]using SL concept. From SL, born were horizontal-SL-APD[12, 13],RST[16], and Eg(energy gap) tuning by nipi SL [11]. The tree on the right represents the quasi-elastic or ballistic transfer, which has lead to BE(ballistic electron)FET,BI-Tr(ballistic injection transistor and vertical(V)-SL-APD[14,15].

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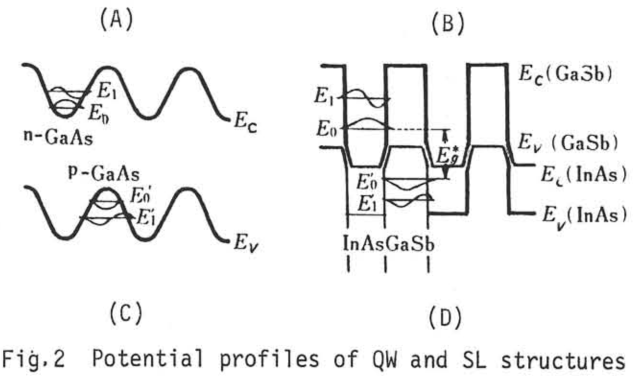

Fig.2 Potential profiles of QW and SL structures