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Prospect of Quantum Heterostructure Materials and Devices

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Abstracts: While quantum-well lasers and high electron mobility transistors are advanced enough to find some practical applications, most of other quantum-heterostruture (QHS) devices and materials are still subjects of exploratory research. This paper evaluates significant contributions of the past QHS research, particularly in the field of fine epitaxial growth, and then discuss prospects of both developmental and exploratory efforts on QHS materials and devices, including resonant tunneling, quantum Stark effect, and quantum wires.

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1. Introduction-Targets and Phases

It has been well accepted that semiconductor hetero-structures exhibit a variety of new properties when the thicknesses of constituent films become comparable with (or less than) de Broglie wavelength of electrons. Since such properties result mainly from quantum mechanical interaction of electrons with artificial potential V(z) introduced by epitaxy, most of the properties are new and scarcely found in bulk semiconductors. Using such unique features, devices with new concepts and functions have been proposed and demonstrated. Quantum well (QW) lasers and high-electronmobility transistors (HEMT) are good examples.

To present an overview of the field, I show in Fig. 1 a 3x3 matrix, in which three phases of QHS research are illustrated in three sub-areas of the field, namely, material-science, electron-physics, and device(or function)-synthesis aspect of QHS. Note that in each sub-area, phases of research may vary from exploratory (and risky) phase to (re-)production phase via developmental phase, in which the main target is the full disclosure of newly discovered (or invented) materials, physics, and devices. One should make clear distinction between these different phases and targets. In the following I pick up several topics from various location of the matrix.

2. Development of FETs and Lasers Using QHS

The wide recognition of technological importance of QHS relies strongly on its successful application to FETs and lasers, which are two key elements in semiconductor electronics. Hence, the full development of HEMTs and QW lasers are extremely important. In the following, I discuss the prospect of these devices. Fortunately, the supremacy of HEMTs[1] in lownoise microwave receiver application has been well established, and has permitted the first commercial utilization of HEMTs in 1985. This is the 9th year since the first parallel taransport experiment in GaAs/AlGaAs QHSs[2], the 7th year since the first demonstration of highmobility effect in modulation-doped QHSs[3], and the 5th year since the advent of HEMTs[1], which shows a typical example of time lag from exploratory to production phase.





When it comes to high speed digital applications, the real potential of HEMTs and other heterostructure FETs is yet to be demonstrated[4]. Although the switching speed of 5.8 ps achieved by 0.35-micron-gate HEMT ring oscillator circuit [5] proves extremely-highspeed capability of HEMTs in simple circuits, the switching in more practical circuits is generally much slower since it is primarily dominated by the time delay associated with the charging process of capacitive loads. The only way to speed up this process is to increase the current drive capability or equivalently the maximum electron concentration Nmax in the channel. Since Nmax in standard HEMT structures is generally limited, one should pursue serious efforts to increase Nmax by utilizing selectively-doped double heterostructures [4] or/and some material systems such as InGaAs/InAlAs.[6]

Among various features of QW lasers, their capability to reduce the threshold current Jth over conventional lasers appears to be the most attractive. This low threshold together with high differential quantum efficiencies has allowed the fabrication of high-power AlGaAs lasers with typical output of 100mW[7]. Since such lasers are important in the expanding field of optical data recording, serious effort should be directed for their development. The phase-locked array of such lasers has allowed already the laser output in excess 2.5 to 4W[7]. Although one should establish efficient method of heat sinking and the better control of phase locking, semiconductor lasers with this power level may revolutionize the power application of lasers. QW lasers of other material system are not so well developed; more efforts should be made to exploit these advantages in other wavelength regions.

3. Epitaxial Growths and QHS Materials

- Achievements and Challenges -

Ultrathin layered structures needed for QHS research have strongly promoted systematic efforts to develop molecular beam epitaxy (MBE), organo-metallic vapor phase epitaxy (OM-VPE), and other epitaxial technologies to their ultimate capabilities. In MBE, one can now control precisely the number of atomic layers deposited by the in-situ measurement of RHEED intensity

oscillation[8]. Moreover, the roughness of MBEgrown AlGaAs-GaAs heterointerfaces, which is typically one atomic layer in amplitude, is found to be reduced to less than 0.2 atomic layer by the interruption of Ga (or Al) deposition for tens of seconds prior to the interface formation, since this process enhances the atomic diffusion along the growth fronts[9].

Inspired by these extremely fine controllabilities of MBE, OM-VPE has been also advanced to permit the film thickness control of comparable accuracy[10]. More conventional VPE using halides is also shown to give a similarly high controllability, when the reaction chamber is properly modified. Furthermore, the concept of atomic-layer epitaxy originally proposed for II-VI compounds [11] is extended or somewhat modified to III-V compounds.

Using these epitaxial technologies, a number of new material possibilities have been demonstrated. In addition to quantum wells and modulation doped structures, I name here just a few examples; device-quality Si/SiGe superlattices grown on Si[12] represent the potential of strained-layer superlattices, and the elimination of DX centers by the substitution of n-AlGaAs with n-GaAs/AlAs short-period superlattices[13] is also another interesting example.

In spite of these impressive achievements of fine epitaxial technology, there remain many unresolved (or incompletely solved) problems yet to be challenged. They include the growth and preparation of (a) high quality epi-layers on highly-lattice-mismatched substrates such as GaAson-Si and (b) high-quality overlayers and interfaces on processed crystal surfaces, (c) high quality semiconductor layered structures containing ultrathin metals or insulators, (d) high quality II-VI films with controled conduction type. All of these systems are highly needed for a variety of applications, but their properties are still strongly affected or dominated by uncontrollable defects of various origins. Hence, systematic efforts should be made to tackle these defectrelated problems.

From Exploratory To Practical Devices Resonant Tunneling and Quantum Stark Effect

Although the early interest in resonant tunneling (RT) was directed mainly to the spectroscopic study of quantum levels[14], the recent interest appears to have shifted more toward the better understanding of tunneling current and the possible applications of its negative differential resistance (NDR) characteris tics[15,16]. Indeed, NDR is used for the generation and the detection of extremely high frequancy electromagnetic waves[15]. For such purposes, it is essential to clarify the transport mechanisms and to establish methods to design and prepare diodes with high peak-to-valley (p/v)ratio. By a series of work[16], we have demonstrated that the use of high-and-thin potential barriers is effective in suppressing the thermally-excited excess current Jex and at the same time enhancing the RT current Jrt. By utilizing AlAs barrier**s** of 8-atomic-layer in thickness and a 50A thick GaAs quantum well, we have achieved a p/v ratio as high as 10 at 80K and 3.0 at room temperature, the highest values ever reported[16]. Note that the observation of NDR was limited to at low temperatures and the 300K NDR was realized only recently in 1985. Now that a breakthrough has been made to achieve excellent NDR characteristics, the RT diode may well find more wide-spread applications, particularly in those area where the unique controllability of the diode impedance and the maximum current level can be well exploited.

In the area of QHS optical devices, one of the most hot topics is the quantum Star k effect[17], where the fundamental absorption edges of QWs shifts appreciably toward the longer wavelength upon the application of electric fields Ex normal to the heterointerfaces. This electro absorption has been successfully used to realize the absorption-type optical modulators and other novel devices[17]. Since this modulator is fast, small, and readily integrable with QW lasers, it may find various applications. Another important effect of Ex on QW optical properties is an appreciable change of its refractive index[18,19,20]. The first experimental demonstration of such effect was made by the author's group in multi-layer reflector configuration, whose reflection spectra was shown to be red-shifted by the application of Ex[18]. The use of similar effect in the total-reflectiontype cross-waveguide configuration was also proposed[19]. Various possibilities of device applications have been also discussed[18]. Recent study of Yamanishi et al has accounted for the large change of n observed experimentally[20].

5. Explorations Towards Lower Dimensions

-QW Wires, QW Boxes, and Planar Superlattices-In 1976, the author proposed and analysed planar superlattices, in which the two-dimensional electron gas interacts with periodic potentials to yield novel transport properties[21]. In 1980, the QW wire was first discussed by the author as a novel system to achieve extremely high electron mobilities in excess of 10⁷ cm²/Vs[22]. In 1982, Arakawa and Sakaki proposed and analysed novel QW lasers with quantum wires and boxes[33]. Although these proposals and predictions were made a little topearly to be taken seriously, the recent development in ultrafine lithography appears to be generating more favorable atmospheres to them. Indeed, an increasing number of experimental attempts have been made towards the fabrication of planar superlattices [24], quantum wires[25,26], and quantum boxes. However, the characteristic dimensions of structures fabricated so far are still in the range of 400 to 500A at the shortest. Since this is not small enough, one should continue efforts to achieve the quantum limit condition where most of the drastic quantum effects are predicted.

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