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THE EVOLUTION OF SEMICONDUCTOR QUANTUM STRUCTURES IN REDUCED DIMENSIONALITY - DO-IT-YOURSELF QUANTUM MECHANICS

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ABSTRACT - Following the past twenty-year evolutionary path in the interdisciplinary research of semiconductor superlattices and other quantum structures, significant milestones are presented with emphasis on experimental achievements in the physics of reduced dimensionality associated with technological advances.

I. INTRODUCTION - INCEPTION

In 1969, research on quantum structures was initiated with a proposal of an ''engineered'' semiconductor superlattice by Esaki and Tsu (1) (2). In anticipation of advancement in epitaxy, we envisioned two types of superlattices with alternating ultrathin layers: doping and compositional, as shown at the top and bottom of Fig. 1, respectively.

This was, perhaps, the first proposal of ''designed semiconductor quantum structures'': namely, we asserted that confined or miniband states could be produced if potential barriers and wells were created by means of successive deposition of different semiconductor layers with thicknesses smaller than the phase-coherent length of electrons. Since the electronic properties characteristic of semiconductor structures are mainly governed by such quantum states, it was predicted that new electronic materials can be designed and engineered to obtain desired transport and optical properties through tailoring the band structure with the control of the potential profile during the layer deposition.

It was thought that semiconductors and technologies developed with them, might be called for in order to demonstrate the quantum wave nature of electrons associated with the interference phenomena, since their small Fermi energies due to low carrier densities help make the de Broglie wavelength relatively large. Namely, the Fermi wavelength $\lambda_f = 2\pi/k_f$, where k_f is the magnitude of the Fermi wavevector, is given as a function of the carrier density n, as follows: $\lambda_f = (8\pi/3n)^{1/3}$ for a three-dimensional (3D) system; $(2\pi/n)^{1/2}$ for a two-dimensional (2D) system; $(4/n)$ for a one-dimensional (1D) system.

In this context, we first examined the feasibility of structural formation by heteroepitaxy for barriers and wells, thin enough to exhibit resonant electron tunneling through them (3). Figure 2 shows the calculated transmission coefficient as a function of electron energy for a double barrier. When the well width L, the barrier width and height, and the electron effective mass m^* are assumed to be 50Å, 20Å, 0.5eV and one tenth of the free electron mass m_o, respec-

Electronic Properties of Multilayers and Low-Dimensional Semiconductors Structures
Edited by J. M. Chamberlain *et al.*, Plenum Press, New York, 1990

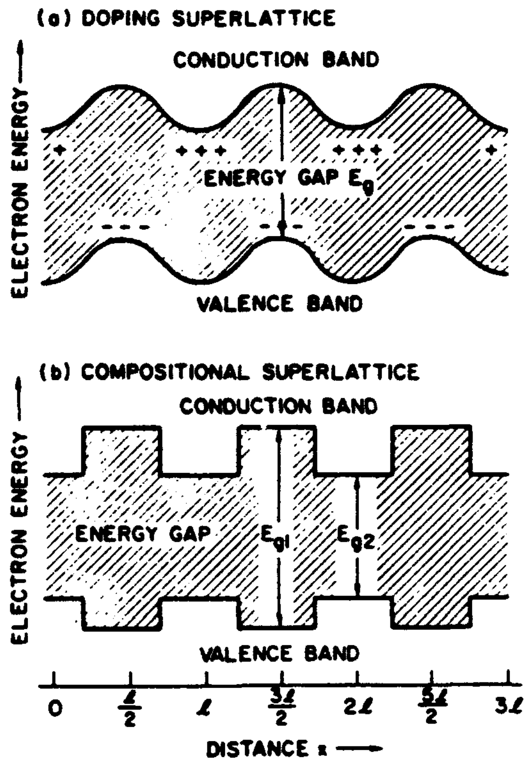

Fig. 1. Spacial variations of the conduction and valence bandedges in two types of superlattices: doping (top) and compositional.

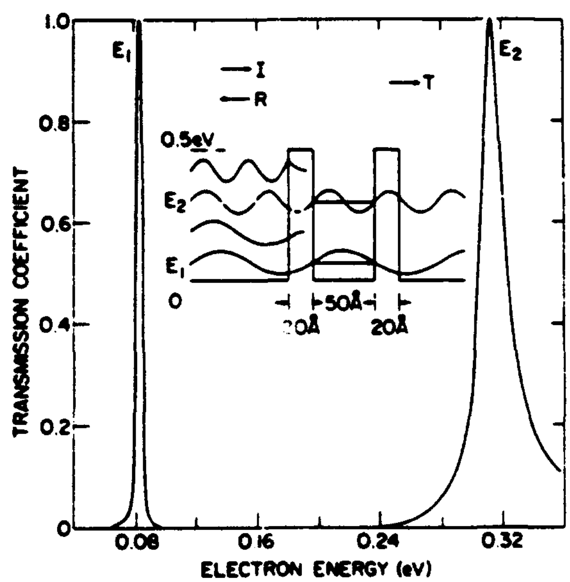

Fig. 2. Transmission coefficient versus election energy for a double barrier shown in the insert. At the resonant condition that the energy of incident elections coincides with one of those of the bound states, E_1 and E_2, the electrons tunnel through both barriers without attenuation.

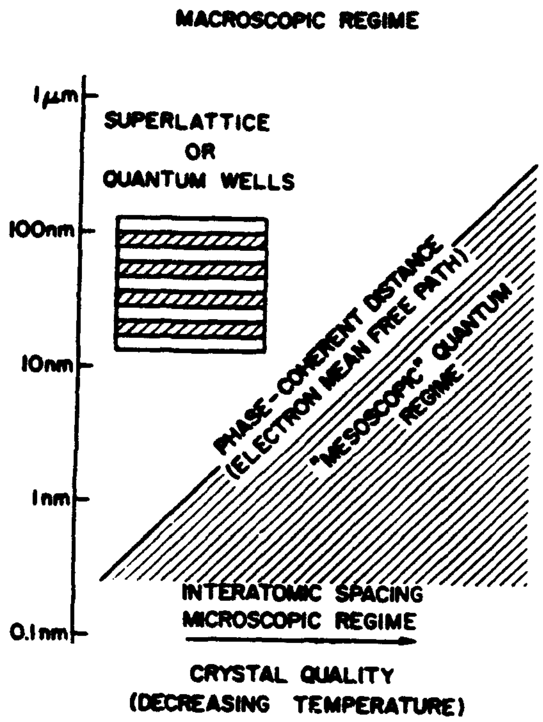

Fig. 3. Schematic illustration of a ''mesoscopic'' quantum regime (hatched) with a superlattice or quantum wells in the insert.

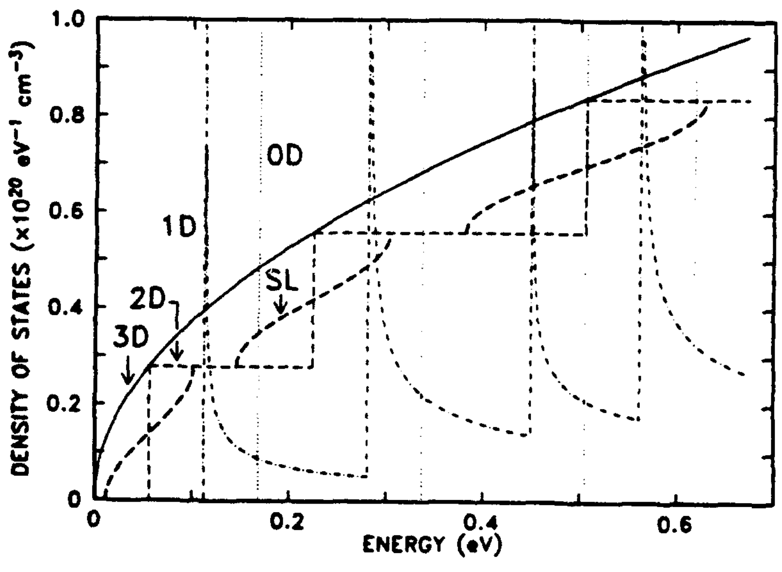

Fig. 4. Comparison of density of states in the three-dimensional (3D) electron system with those of a superlattice, and the two-dimensional (2D), one-dimensional (1D), and zero-dimensional (0D) electron systems.

tively, the bound energies, E_1 and E_2, in the quantum well are derived to be 0.08 and 0.32eV. As shown in the insert of the figure, if the energy of incident electrons coincides with such bound energies, the electrons tunnel through both barriers without attenuation. Such unity transmissivity at the resonant condition arises from the destructive interference of reflected electron waves from inside (R) with incident waves (I), so that only transmitted waves (T) remain.

The idea of the superlattice (SL) occurred to us as a natural extension of double- and multi-barrier structures where quantum effects are expected to prevail. An important parameter relevant to the observation of such effects is the phase-coherent distance or, roughly, the electron inelastic mean free path, which depends heavily on bulk and interface quality of crystals and also on temperature and values of the effective mass. As schematically illustrated in Fig. 3, if characteristic dimensions such as SL periods and well widths are reduced to less than the phase-coherent distance, the entire electron system will enter a ''mesoscopic'' quantum regime of reduced dimensionality, being placed in the scale between the macroscopic and the microscopic.

In the early 1970s, we initiated the attempt of the seemingly formidable task of engineering nanostructures in the search for novel quantum phenomena (4). It was theoretically shown that the introduction of the SL potential perturbs the band structure of the host materials, yielding unusual electronic properties of quasi-two-dimensional character (1) (2). Figure 4 shows the density of states $\rho(E)$ for electrons with $m^* = 0.067m_0$ in an SL with a well width of 100Å and the same barrier width, where the first three subbands are indicated with dashed curves. The figure also includes, for comparison, a parabolic curve $E^{1/2}$ for 3D, a steplike density of states for 2D (quantum well), a curve $\Sigma(E - E_m - E_n)^{-1/2}$ for 1D (quantum line or wire), and a delta function $\Sigma\delta(E - E_1 - E_m - E_n)$ for 0D system (quantum box or dot) where the quantum unit is taken to be 100Å for all cases and the barrier height is assumed to be infinite in obtaining the quantized energy levels, E_1, E_m and E_n. Notice that the ground state energy increases with decrease in dimensionality if the quantum unit is kept constant. Each quantized energy level in 2D, 1D and 0D is identified with the one, two and three quantum numbers, respectively. The unit for the density of states here is normalized to $eV^{-1}cm^{-3}$ for all the dimensions, although $eV^{-1}cm^{-2}$, $eV^{-1}cm^{-1}$ and eV^{-1} may be commonly used for 2D, 1D and 0D, respectively.

The analysis of the electron dynamics in the SL direction predicted an unusual current-voltage characteristic including a negative differential resistance, and even the occurrence of ''Bloch oscillations.'' The calculated Bloch frequency f is as high as 250 GHz from the equation $f = eFd/h$, for an applied field F and a superlattice period d of 10^3V/cm and 100Å, respectively.

Esaki, Chang and Tsu (5) reported an experimental result on a GaAs-GaAsP SL with a period of 200Å synthesized with CVD (chemical vapor deposition) by Blakeslee and Aliotta (6). Although transport measurements failed to show any predicted effect, this system probably constitutes the first strained-layer SL having a lattice mismatch 1.8% between GaAs and $GaAs_{0.5}P_{0.5}$.

Esaki et al. (7) found that an MBE (molecular beam epitaxy)-grown GaAs-GaAlAs SL exhibited a negative resistance in its transport properties, which was, for the first time, interpreted in terms of the above-mentioned SL effect. Although our early efforts focused on transport measurements, Tsu and Esaki (8) calculated optical nonlinear response of conduction electrons in an SL medium. Since the first proposal and early attempt, the field of semiconductor SLs and quantum wells (QWs) has proliferated extensively in a cross-disciplinary environment (9).

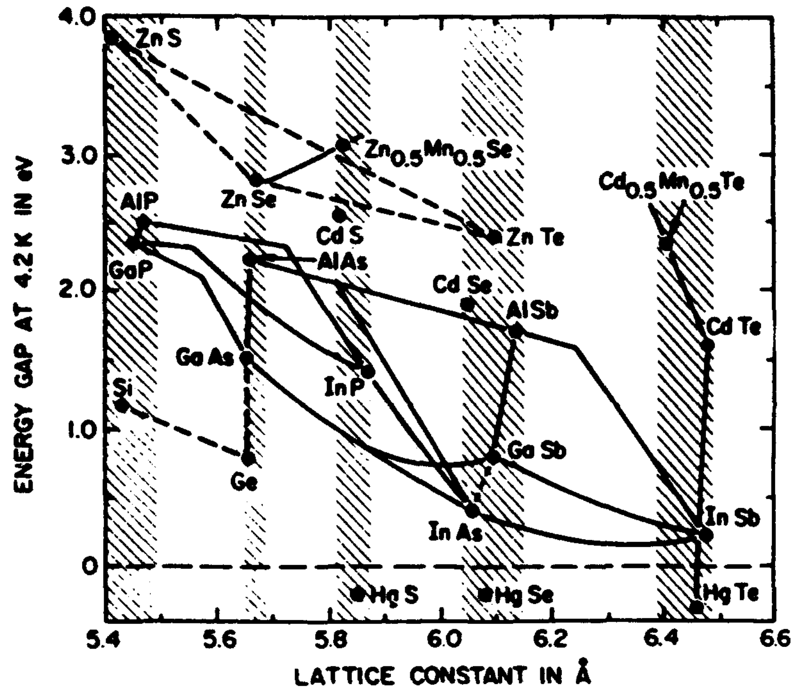

Fig. 5. Plot of energy gaps at 4.2K versus lattice constants.

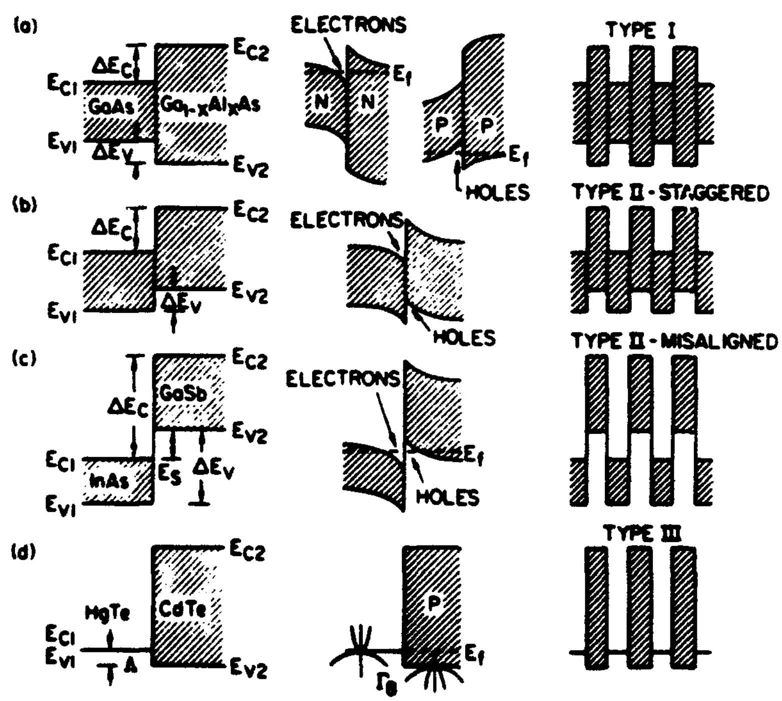

Fig. 6. Discontinuities of bandedge energies at four types of hetero-interfaces: band offsets (left), band bending and carrier confinement (middle), and superlattice (right).

II. EPITAXY AND SUPERLATTICE GROWTH

Heteroepitaxy is of fundamental interest for the SL and QW growth. Innovations and improvements in growth techniques such as MBE (10), MOCVD (metalorganic chemical vapor deposition) (11) and MOMBE or CBE during the last decade have made possible high-quality heterostructures. Such structures possess predesigned potential profiles and impurity distributions with dimensional control close to interatomic spacing and with virtually defect-free interfaces, particularly, in a lattice-matched case such as GaAs - $Ga_{1-x}Al_xAs$. This great precision has cleared access to a ''mesoscopic'' quantum regime.

The semiconductor SL structures have been grown with III-V, II-VI and IV-VI compounds, as well as elemental semiconductors. Figure 5 shows the plot of energy gaps at 4.2K versus lattice constants for zinc-blende semiconductors together with Si and Ge. Joining lines represent ternary alloys except for Si-Ge, GaAs-Ge and InAs-GaSb. The introduction of II-VI compounds apparently extended the available range of energy gaps in both the high and the low direction: that of ZnS is as high as 3.8eV and all the Hg compounds have a negative energy gap or can be called zero-gap semiconductors. The magnetic compounds, CdMnTe and ZnMnSe are relative newcomers in the SL and QW arena.

Semiconductor hetero-interfaces exhibit an abrupt discontinuity in the local band structure, usually associated with a gradual band-bending in its neighborhood which reflects space-charge effects. According to the character of such discontinuity, known hetero-interfaces can be classified into four kinds: type I, type II-staggered, type II-misaligned, and type III, as illustrated in Fig. 6(a)(b)(c)(d): band offsets (left), band bending and carrier confinement (middle), and SLs (right).

The bandedge discontinuities, ΔE_c for the conduction band and ΔE_v for the valence band, at the hetero-interfaces obviously command all properties of QWs and SLs, and thus constitute the most relevant parameters for device design. For such fundamental parameters, ΔE_c and ΔE_v , however, the predictive qualities of theoretical models are not very accurate and precise experimental determination cannot be done without great care. In this regard, the GaAs-GaAlAs system is most extensively investigated with both spectroscopic and electrical measurements. Recent experiments have reduced an early established value of $\Delta E_c/\Delta E_g$, 85 percent to somewhat smaller values in the range between 60 and 70 percent.

III. *RESONANT TUNNELING VIA QUANTUM WELLS*

Tsu and Esaki (12) computed the resonant transmission coefficient as a function of electron energy for multi-barrier structures from the tunneling point of view, leading to the derivation of the current-voltage characteristics. The SL band model previously presented, assumed an infinite periodic structure, whereas, in reality, not only a finite number of periods is prepared with alternating epitaxy, but also the phase-coherent distance is limited. Thus, this multibarrier tunneling model provided useful insight into the transport mechanism and laid the foundation for the following experiment.

Chang, Esaki and Tsu (13) observed resonant tunneling in GaAs-GaAlAs double-barriers, and subsequently, Esaki and Chang (14) measured quantum transport with local resonant tunneling for a GaAs-AlAs SL having a tight-binding potential. The current and conductance versus voltage curves for a double barrier are shown in Fig. 7. The energy diagram is shown in the inset where resonance is achieved at such applied voltages as to align the Fermi level of the electrode with the bound states, as shown in cases (a) and (c). The current and conductance versus voltage characteristics for an SL are shown in Fig. 8. The energy diagrams for band-type conduction, (a),

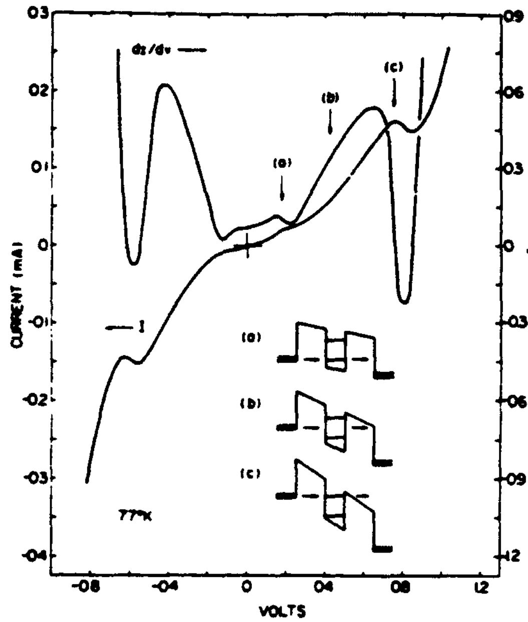

Fig. 7. Current- and conductance- voltage characteristics of a GaAs-GaAlAs double-barrier structure. Conditions at resonance (a) and (c), and at off-resonance (b), are indicated by arrows in the insert.

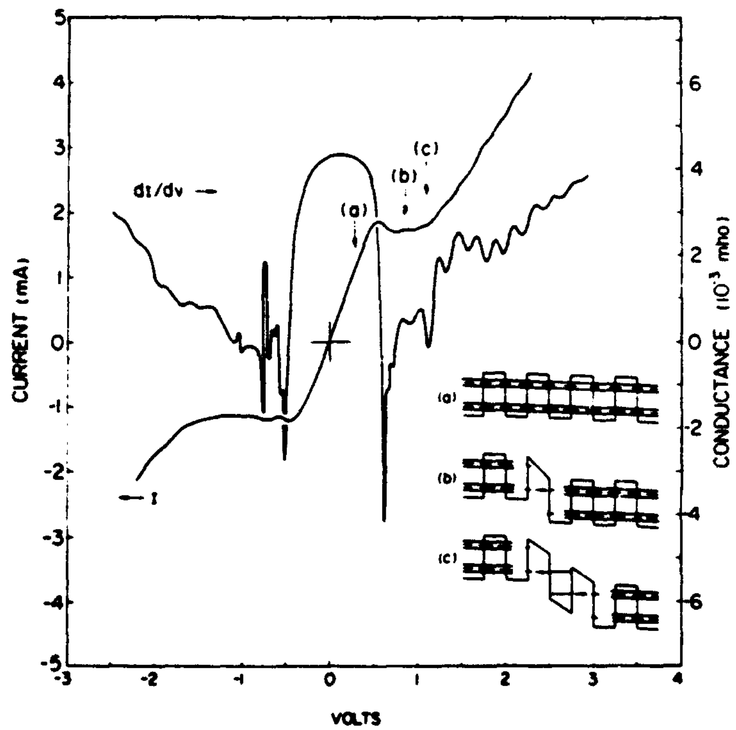

Fig. 8. Current- and conductance- voltage characteristics of a GaAs-AlAs superlattice. Band-type conduction (a) and resonant tunneling at an expanding high-field domain (b) and (c), are indicated in the insert.

and resonant tunneling at an expanding high-field domain, (b) and (c), are shown in the inset. Both of those quantum transport measurements, probably constitute the first observation of man-made bound states in both single and multiple QWs.

The technological advance in MBE for the last decade resulted in dramatically-improved characteristics in resonant tunneling, as shown in Fig. 9, as well as in SL transport, which spurred renewed interest in such structures (15). The observation of resonant tunneling in p-type double barrier structures (16) revealed fine structure corresponding to each bound state of both heavy and light holes. The existence of optical phonon-assisted resonant electron tunneling in the valley current region was found (17), (18), for which a theoretical approach was proposed (19). Discrete electronic states in a three-dimensionally confined quantum well (quantum dot) were observed in double-barrier heterostructures which had been shaped into slender columns of less than 2500 Å in diameter by advanced processing techniques (20).

A variety of tunneling heterostructures have been developed with a combination of materials other than GaAs/AlAs, such as InGaAs/InAlAs (21) and InAs/AlSb (22). Research in polytype heterostructures of InAs/AlSb/GaSb (23), (24), has been rejuvenated with the observation of a substantial negative differential resistance based on resonant interband tunneling in GaSb/AlSb/InAs/AlSb/GaSb (25) and InAs/AlSb/GaSb/AlSb/InAs (26). Those multi-heterojunctions, indeed, correspond to a portion of the proposed polytype superlattices (23). The emerging studies on one- and two- dimensional electron tunneling in lateral structures will be discussed in section IX.

A great deal of engineering interest in resonant tunneling, obviously, has arisen from its potential application to high-speed semiconductor devices. Picosecond bistable operation has been observed in a double-barrier resonant tunneling diode, where a rise time of 2 ps is said to be the fastest switching yet measured for an electronic device (27). The high-speed performance of this device is apparently related to the lifetime of the quasibound-state in the quantum well (28). The evidence of sequential tunneling due to intersubband scattering was also observed (29).

IV. OPTICAL ABSORPTION, PHOTOCURRENT SPECTROSCOPY, PHOTOLUMINESCENCE AND STARK EFFECT

Optical investigation on the quantum structures during the last two decades has revealed the salient features of quantum confinement. Dingle et al. (30) (31) observed pronounced structure in the optical absorption spectrum, representing bound states in isolated and double QWs. In low-temperature measurements for such structures, several exciton peaks, associated with different bound-electron and bound-hole states, were resolved. The spectra clearly indicate the evolution of resonantly split, discrete states into the lowest subband of an SL. van der Ziel et al. (32) observed optically pumped laser oscillation from GaAs-GaAlAs QW structures at 15K. Since then, the application of such structures to semiconductor laser diodes has received considerable attention because of its superior characteristics, such as low threshold current, low temperature dependence, tunability and directionality (33). Advanced graded-index separate-confinement single quantum well heterostructure lasers (GRIN-SCH) with high performance have been developed (34) (35).

Tsu et al. (36) made photocurrent measurements on GaAs-GaAlAs SLs subject to an electric field perpendicular to the well plane with the use of a semitransparent Schottky contact. The photocurrents as a function of incident photon energy are shown in Fig. 10 for samples of three different configurations, designated A (35Å GaAs - 35Å GaAlAs), B (50Å GaAs - 50Å GaAlAs), and C (110Å GaAs - 110Å GaAlAs). The energy diagram is shown schematically in the upper part of the

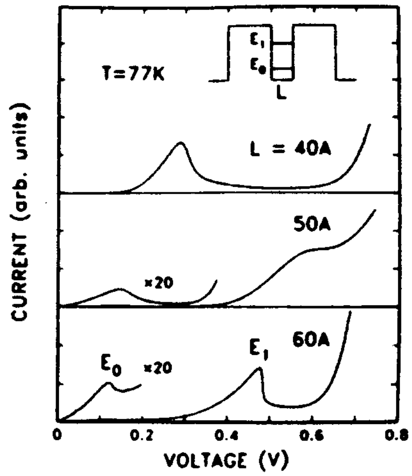

Fig. 9. Current-voltage curves for three double-barriers with well widths, L, of 40Å, 50Å, and 60Å. The bound energies, E_1 and E_2, are shown in the energy diagram of the upper part.

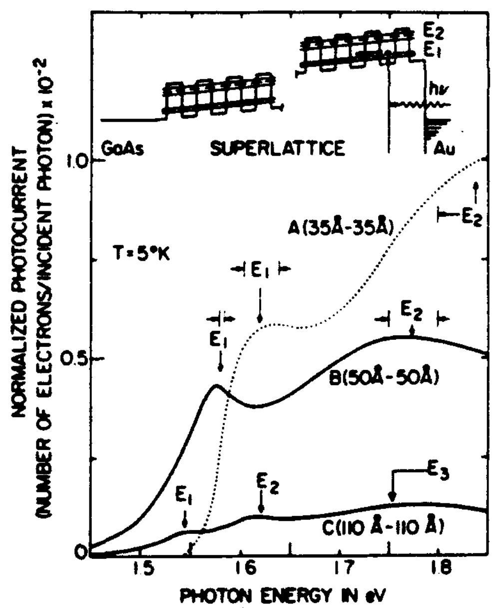

Fig. 10. Photocurrent versus photon energy for three superlattice samples A, B, and C. Calculated energies and bandwidths are indicated. The energy diagram of a Schottky-barrier structure is shown in the upper part.

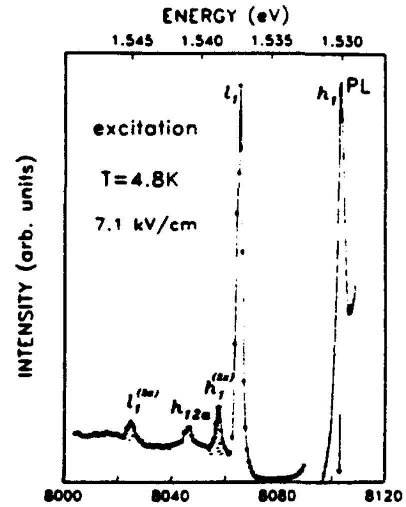

Fig. 11. Excitation spectrum with the photoluminescence of the heavy-hole exciton for a 160-Å quantum well at 7.1 kV/cm, where h_1 , $h_1^{(2s)}$, l_1 and $l_1^{(2s)}$ denote the ground and excited states of the heavy- and light-hole excitons, respectively, and h_{12a} corresponds to an exciton related to the n=1 conduction and n=2 heavy-hole valence bands.

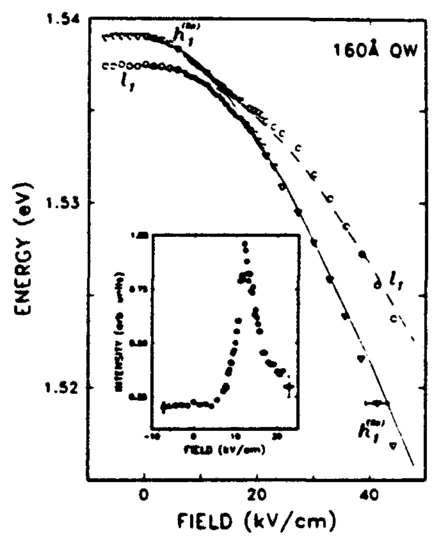

Fig. 12. Stark shifts of the light-hole exciton (open circles) and excited states of the heavy-hole exciton (open triangles), exhibiting strong coupling (solid circles) between them. The integrated intensity of $h_1^{(2s)}$ normalized to l_1 is shown as a function of electric field in the insert.

figure where quantum states created by the periodic potential are labeled E_1 and E_2. These states are essentially discrete if there is a relatively large separation between wells, as is the case in sample C, but broaden into subbands in samples A and B owing to an increase in overlapping of wave functions. Calculated energies and bandwidths for transitions shown in the figure are found to be in satisfactory agreement with the observation. Recently, Deveaud et al. (37) made transport measurements of 2D carriers in SL minibands by subpicosecond luminescence spectroscopy. Schneider et al. (38) studied the dynamics of electron transport along the growth direction of tight-binding GaAs-AlAs SLs by electrical and optical time-of-flight experiments.

In undoped high-quality GaAs-GaAlAs QWs, the main photoluminescence peak is attributed to the excitonic transition between 2D electrons and heavy holes. Mendez et al. (39) studied the field-induced effect on the photoluminescence in such wells: when the electric field, for the first time in luminescence measurements, was applied perpendicular to the well plane, pronounced field-effects, Stark shifts, were discovered. More recently, Vina et al. (40) studied such shifts on the excitonic coupling as indicated in Figures 11 and 12. Figure 11 shows excitation spectrum with the photoluminescence of the heavy-hole exciton, where h_1, $h_1^{(2x)}l_1$ and $l_1^{(2x)}$ denote the ground and excited states of the heavy- and light-hole excitons, respectively, and h_{12a} corresponds to an exciton related to the n=1 conduction and n=2 heavy-hole valence bands. Figure 12 shows Stark shifts of the light-hole exciton (open circles) and excited states of the heavy-hole exciton (open triangles), exhibiting strong coupling (solid circles) between them. Chemla et al. (41) observed Stark shifts of the excitonic absorption peak, even at room temperature; Miller et al. (42) analyzed such electroabsorption spectra and demonstrated optical bistability, level shifting and modulation.

Although electric field-induced effects on a crystal such as Bloch oscillations and Stark ladder, have been studied since the early days of quantum mechanics, experimental verification was hardly possible. Semiconductor SLs, however, with their versatility in design, have provided a unique opportunity for this study. Recently it was theoretically shown (43) and experimentally observed (44) that the application of an electric field F along the growth direction of a semiconductor SL indeed induces the Stark localization of the eigenstates resulting in a blue shift of the optical-absorption edge and the presence of oscillations. The energy diagrams in Fig. 13 illustrate the localization process of the states with increase in applied electric fields.

V. RAMAN SCATTERING

Manuel et al. (45) reported the observation of enhancement in the Raman cross section for photon energies near electronic resonance in $GaAs - Ga_{1-x}Al_xAs$ SLs of a variety of configurations. Both the energy positions and the general shape of the resonant curves agree with theoretical values. Later, it was pointed out that resonant inelastic light scattering yields separate spectra of single particle and collective excitations which will lead to the determination of electronic energy levels in QWs as well as Coulomb interactions. Subsequently, this was experimentally confirmed and the technique has now widely been used as a spectroscopic tool to study electronic excitations (46).

Meanwhile, Colvard et al. (47) reported the observation of Raman scattering from folded acoustic longitudinal phonons in a GaAs(13.6Å)-AlAs(11.4Å) SL. The SL periodicity leads to Brillouin zone folding, resulting in the appearance of gaps in the phonon spectrum for wave vectors satisfying the Bragg condition, whereas Raman scattering for the optical modes revealed quasiconfined behavior (48).

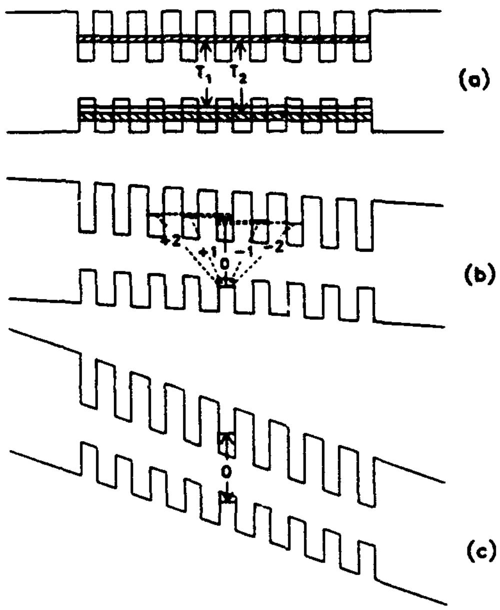

Fig. 13. Sketches of the conduction- and valence- band potential profiles for GaAs - $Ga_{1-x}Al_xAs$ superlattice under a (a) small, (b) moderate, and (c) high electric field, clad by thick $Ga_{1-x}Al_xAs$ regions. The diagrams are approximately scaled for a 30-35-Å superlattice with x=0.35, and fields of $2x10^3$, $2x10^4$, and $1x10^5$ V/cm, respectively.

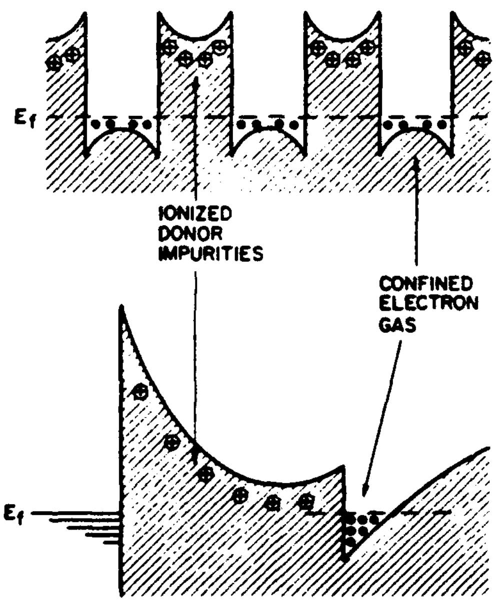

Fig. 14. Modulation doping for a superlattice and a heterojunction with a Schottky junction.

Fasolino et al. (49) claimed that folded modes appear in the frequency range where the bulk dispersions of the two constituents overlap as in the longitudinal acoustical region, while modes confined in one layer and evanescent in the other, arise from the situation of no overlap as in the optical region of GaAs and AlAs.

VI. MODULATION DOPING

In SLs, in order to prevent usual impurity scattering, it is possible to spatially separate free carriers from their parent impurity atoms by doping impurities in the region of the potential hills. Though this concept was expressed in the original article, Esaki and Tsu, (1), Dingle et al. (50) successfully implemented such a concept in modulation-doped GaAs-GaAlAs SLs, as illustrated at the top of Fig. 14, achieving unprecedented electron mobilities far exceeding the Brooks-Herring predictions. Subsequently, the similar technique was used to form the high- mobility 2D hole gas. Recently, low-temperature electron mobilities as high as 5×10^6 cm^2/Vs at a carrier density of $1.6\times10^{11} cm^{-2}$ (51), and subsequently, 10^7 cm^2/Vs at a density of $2.4\times10^{11} cm^{-2}$ (52) have been reported at modulation-doped GaAs heterostructures: the latter, obviously, constitutes the highest ever measured in a solid.

The modulation-doping technique has exerted profound impact on the course of the evolution of the quantum structures in low dimensionality. The achievement of the high-mobility 2D carriers with long phase-coherent lengths has opened up the new genre of lateral quantum structures in dimensionality less than two, leading to further ramification in this research. The availability of such high-mobility 2D carriers has prompted the development of a high-speed field-effect transistor called HEMT (high electron mobility transistor); its band energy diagram is shown at the bottom of Fig. 14 (53).

VII. MAGNETOTRANSPORT, QUANTIZED HALL EFFECT AND FRACTIONAL FILLING

Chang et al. (54) observed Shubnikov-de Haas oscillations associated with the subbands of the nearly 2D character in GaAs-GaAlAs SLs. The oscillatory behaviors agreed well with those predicted from the Fermi surfaces derived from the SL configurations and the electron concentrations.

v. Klitzing et al. (55) demonstrated the interesting proposition that quantized Hall resistance could be used for precision determination of the fine structure constant α, using 2D electrons in the inversion layer of a Si MOSFET. Subsequently, Tsui and Gossard (56) found modulation-doped GaAs-GaAlAs heterostructures desirable for this purpose, primarily because of their high electron mobilities, which led to the determination of α with a great accuracy.

The quantized Hall effect in a 2D electron or hole system is observable at such high magnetic fields and low temperatures as to locate the Fermi level in the localized states between the extended states. Under these conditions, the magnetoresistance ρ_{xx} vanishes and the Hall resistance ρ_{xy} goes through plateaus. This surprising result can be understood by the argument that the localized states do not take part in quantum transport. At the plateaus, the Hall resistance is given by $\rho_{xy} = h/e^2\nu$ where ν is the number of filled Landau levels; h, Planck's constant; and e, the electronic charge.

Tsui, Stormer and Gossard (57) discovered a striking phenomenon, an anomalous quantized Hall effect, exhibiting a plateau in ρ_{xy}, and a dip in ρ_{xx}, at a fractional filling factor of 1/3 in the extreme quantum limit at temperatures lower than 4.2K. This discovery has spurred a large number of experimental and theoretical studies.

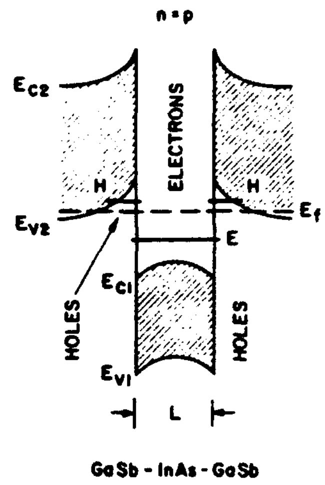

Fig. 15. Energy-band diagram of ideal GaSb-InAs-GaSb quantum wells for electrons and holes.

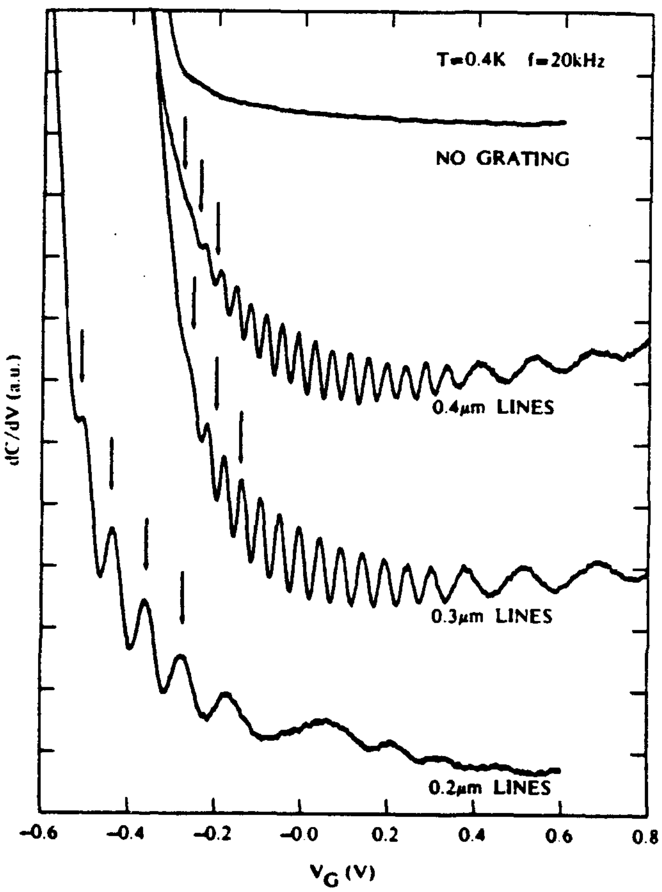

Fig. 16. The derivative of the capacitance versus gate voltage for three quantum wire samples and a control sample.

VIII. InAs-GaSb and GaSb-AlSb SYSTEMS

Since 1977, the InAs-GaSb system was investigated because of its extraordinary bandedge relationship at the interface, called type II-''misaligned'' in Fig. 6(c). The band calculation for InAs-GaSb SLs (58) revealed a strong dependence of the subband structure on the period: The semiconducting energy gap decreases when increasing the period, becoming zero at 170Å, corresponding to a semiconductor-to-semimetal transition. The electron concentration in SLs was measured as a function of InAs layer thickness, (59); it exhibited a sudden increase of an order-of-magnitude in the neighborhood of 100Å. Such increase indicates the onset of electron transfer from GaSb to InAs which is in good agreement with theoretical prediction. Far-infrared magneto-absorption experiments (60) were performed at 1.6K for semimetallic SLs which confirmed their negative energy-gap.

MBE-grown GaSb-InAs-GaSb have been investigated, where the unique bandedge relationship allows the coexistence of electrons and holes across the two interfaces, as shown in Fig. 14. Prior to experimental studies, Bastard et al. (61) performed self-consistent calculations for the electronic properties of such QWs, predicting the existence of a semiconductor-to-semimetal transition as a result of electron transfer from GaSb at the threshold thickness of InAs; this is somewhat similar to the mechanism in the InAs-GaSb SLs. Such a transition was confirmed by experiments carried out by Munekata et al. (62), although the electron and hole densities are not the same, probably because of the existence of some extrinsic electronic states. Analysis (63) for such a 2D electron-hole gas elucidated, for the first time, the fact that the quantum Hall effect is determined by the degree of uncompensation of the system.

The GaSb-AlSb system, which belongs to type I in the relative position of the band gaps at the interface, has been studied. Optical absorption measurements in GaSb-AlSb SLs revealed the effect of strain induced by a lattice mismatch of 0.65%, resulting in the reversal of light and heavy valence subbands (64): Raman scattering confirmed the magnitude of the strain (65). More recently, photoreflectance and photoluminescence studies under hydrostatic pressure at cryogenic temperature have been performed for GaSb-AlSb multiple QWs (66).

The polytype heterostructures and SLs involving InAs, GaSb and AlSb, were proposed on the consideration that the differences in lattice constants (6.058Å, 6.095Å and 6.136Å) are not excessive, and yet their band parameters are significantly differing among them (23).

IX. LATERAL QUANTUM STRUCTURES

It is of significance that the extraordinary high mobility, μ, for a 2D carrier density, n, at modulation doped GaAs heterostructures has made the elastic mean-free-path length, ℓ, greater than the pattern dimensions of small devices accessible with the present-day microfabrication technique (67), where $\ell = h/e\mu(n/2\pi)^{1/2} = 1.65\times10^{-15}\mu n^{1/2}$. Namely, if $n = 2.5\times10^{11}cm^{-2}$ ($\lambda_f = 50nm$), the magnitude, ℓ, reaches 0.8, 8, and 80 μm for $\mu = 10^5$, 10^6 and 10^7 cm^2/Vs, respectively. Although these large ℓ values are derived, assuming no introduction of damages or scattering centers during the processing, it is now feasible to fabricate such devices that phase coherence of electrons is maintained on the length scale of whole structures. On the background of the remarkable advances in MBE, dry-etching and electron-beam lithography, the physics of ''coherent small devices'' has gained a great deal of attention in the past several years, including studies on quantum interference (68), the Aharonov-Bohm effect (69), and quenching of the Hall effect (70).

In most cases, quasi ID and OD electronic systems were achieved with lateral confinement by depleting a high-mobility 2D gas in the surrounding area through a means, or simply by forming a small mesa through dry etching. A clear manifestation for spatial quantization

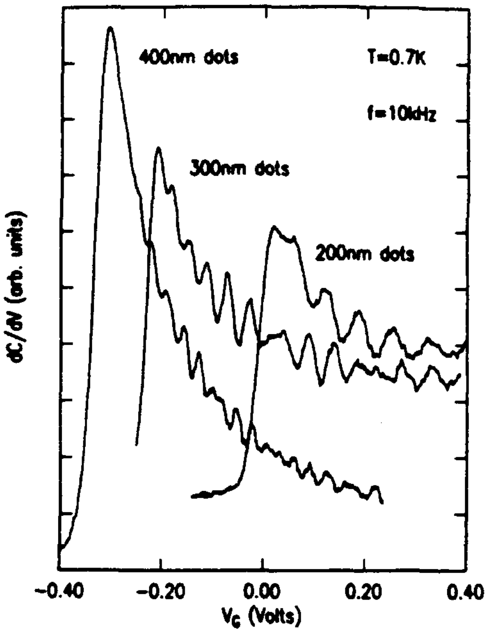

Fig. 17. The derivative of the capacitance versus gate voltage for three quantum dot samples. The main peak in the derivative is due to turn-on of the capacitors.

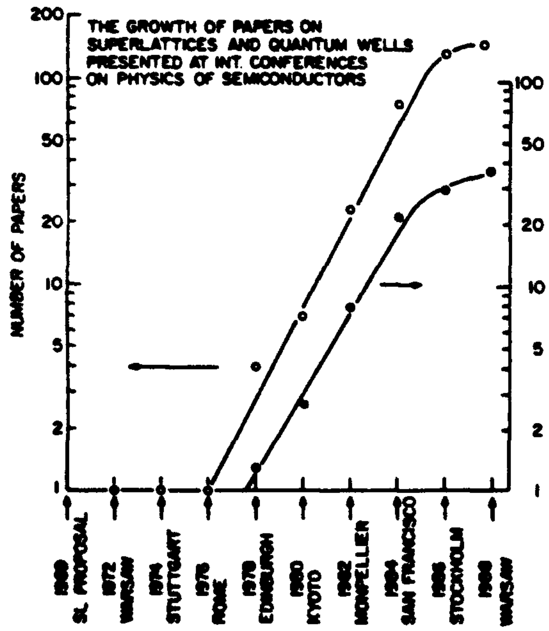

Fig. 18. Growth in the number of papers on SLs and QWs and the percentage of those to the total presented at the International Conference on the Physics of Semiconductors being held every other years.

was the capacitance measurements of the density of states of such ID and OD systems (71) (72). Figures 16 and 17 show capacitance spectra for samples with three different wire widths and three dot diameters, respectively, where the period of the oscillations duly decreases with increase in the size. With capacitance spectroscopy for the dot samples, Hansen et al (73) observed a pronounced magnetic-field-induced split of quantum levels into surface states and bulklike Landau states, indicating that spacial quantization effects become negligible with the magnetic length much smaller than the size of the confining potential.

With the ''coherent small devices'', the study of ballistic electron transport or 2D electron optics has been a rapidly growing field of research, which is in contrast with the traditional transport study in the diffusive regime where length scales are large in comparison with the electron mean-free-path. Recently, van Wees et al. (74), and subsequently Wharam et al. (75), clearly demonstrated a quantized conductance of $2e^2/h$ per occupied subband or wave guide mode in observing electron transport through a short pathway with a variable width of the order of the Fermi wavelength. The studies of magnetic focusing in such electron system have been reported (76) (77). ID electron resonant tunneling has been attempted through the OD state defined in a 0.42 μm square box (78). With reduction to ID, it is speculated that higher mobilities would be achieved because of the suppression of scattering (79), and also exciton binding energies and oscillator strengths could be enhanced (80) (81).

For the purpose of the development of novel field-effect transistors, a variety of lateral structures with grating-gate and grid-gate (82), and dual-gate (83) configuration have been explored, including the observation of 2D electron resonant tunneling through the ID state defined by the dual-gate. In principle, with reduction in dimensionality, the current-voltage characteristic should be sharpened in the consideration of the energy and parallel momentum conservation rule in resonant tunneling.

X. OTHER SUPERLATTICES

Since the inception of the superlattice, the major part of research has been centered on compositional structures. Nevertheless, GaAs doping SLs have exhibited an interesting optical property, i.e., tunability in emission wavelength as well as absorption coefficient, arising from long recombination lifetimes of photoexcited electrons and holes which are separated in the superlattice potential (84). The advent of the δ-doping technique (85) has contributed to the growth of high quality doping SLs (86). Recently, Schubert et al. (87) achieved tunable, stimulated emission of radiation from such a doping SL confined between GaAlAs barriers.

It is certainly desirable to select a pair of materials closely lattice-matched in order to obtain stress- and dislocation- free interfaces. Lattice-mismatched heterostructures, however, can be grown with essentially no misfit dislocations, if the layers are sufficiently thin, because the mismatch is accommodated by uniform lattice strain (88). On the basis of such premise, Osbourn and his co-workers (89) prepared strained-layer SLs from lattice-mismatch pairs, claiming the versatility in the choice of layer materials. A number of strained-layer SLs have been explored in the past several years.

Gossard et al. (90) achieved GaAs-AlAs epitaxial structures with alternate-atomic-layer composition modulation by MBE. Recently, there is a great deal of interest in optical properties of ultra-short-period SLs associated with their band structure (91): the direct-indirect (type I - type II) transition occurs with the varying of layer thickness (92) (93).

Kasper et al. (94) pioneered the MBE growth of Si-SiGe strained-layer SLs, and Manasevit et al. (95) observed unusual mobility enhancement in such structures. The growth of high-quality Si-SiGe SLs (96) attracted much interest in view of possible applications as well as scientific investigations. In short period Si-Ge SLs, the band structure is strongly influenced by induced strain due to a lattice mismatch of more than 4% and also predicted zone folding (97) resulting in the observation of new optical transitions (98). Resonant tunneling of holes with a negative differential resistance has been observed in Si-SiGe structures with unstrained (99) and strained (100) Si double-barriers.

Dilute-magnetic SLs such as CdTe-CdMnTe (101) (102) and ZnSe-ZnMnSe are contemporary additions to the superlattice family, and have already exhibited unique magneto-optical properties.

XI. CONCLUSION

We have witnessed remarkable progress of an interdisciplinary nature on this subject. A variety of ''engineered'' structures exhibited extraordinary transport and optical properties; some of them, such as ultrahigh carrier mobilities, semimetallic coexistence of electrons and holes, resonant tunneling and large Stark shifts on the optical properties, may not even exist in any ''natural'' crystal. Thus, this new degree of freedom offered in semiconductor research through advanced material engineering has inspired many ingenious experiments, resulting in observations of not only predicted effects but also totally unknown phenomenon. The growth of papers on the subject for the last decade is indeed phenomenal. For instance, the number of papers and the percentage of those to the total presented at the International Conference on the Physics of Semiconductors (ICPS) being held every other year, increased as shown in Fig. 18. After the incubation period of several years, it really took off, with a rapid annual growth rate, around ten years ago. It says that, currently, more than one third of semiconductor physicists in the world are working in this field.

Activities in this new frontier of semiconductor physics, in turn, give immeasurable stimulus to device physics, leading to unprecedented transport and optoelectronic devices or provoking new ideas for applications. Figure 19 illustrates a correlation diagram in such interdisciplinary research where beneficial cross-fertilizations are prevalent.

I hope this article, which cannot possibly cover every landmark, provides some flavor of the excitement in this field. Finally, I would like to thank the many participants in and out of superlattice research for their contributions, as well as the ARO's partial sponsorship from the initial day of our investigation.

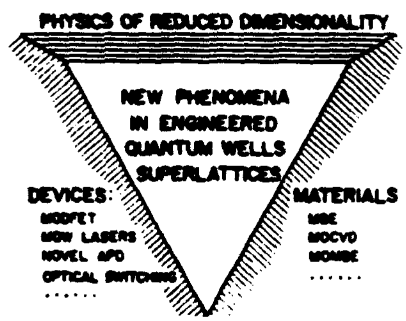

Fig. 19. Correlation diagram in a cross-disciplinary research environment.

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