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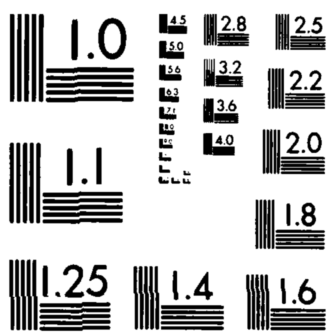

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InAs/GaSb and GaSb/AlSb superlattices, GaSb/InAs/GaSb quantum wells and GaAs/GaAlAs heterojunctions were prepared by MBE. Their electronic properties were investigated by optical and transport measurements including photoluminescence, far-infrared magneto-absorption, and the quantized Hall effect.

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INVESTIGATION OF QUANTUM EFFECTS IN HETEROSTRUCTURES

FINAL REPORT

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MARCH 20, 1985

U. S. ARMY RESEARCH OFFICE

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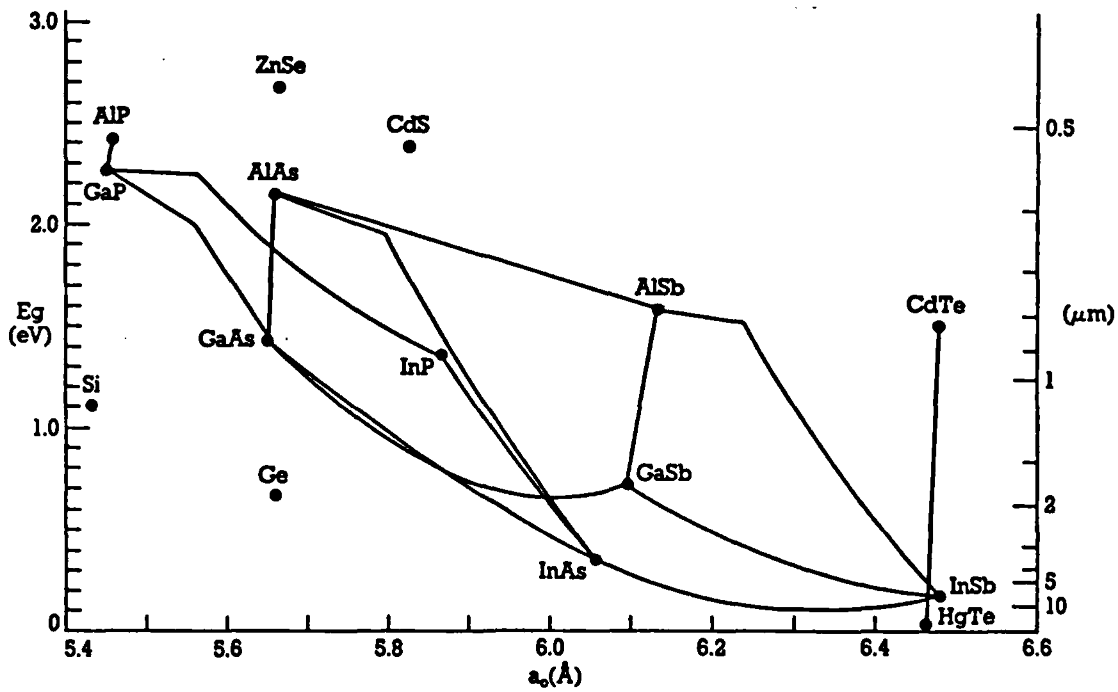
Introduction

Research on synthesized semiconductor superlattices and quantum wells was initiated with a proposal in 1969 by Esaki and Tsu: a periodic structure consisting of alternating ultra-thin layers with its period less than the electron mean free path. Our pioneering work in the early period is believed to have provided the foundation for subsequent progress, which proceeded rather rapidly in scope as well as in depth. Indeed, in recent years, considerable attention has been given to the engineering of such artificial structures. Obviously, the intriguing physics, particularly regarding the involvement of the reduced dimensionality in the electron gas system, has provided fuel for this advancement. Activities on this frontier of semiconductor physics, in turn, give immeasurable stimulus to device physics, leading to novel devices. We believe that efforts in this direction have opened up a new area of interdisciplinary investigations in the fields of physics, materials science and semiconductor devices. The subject appears to be one of the important topics at a number of conferences. For example, at the recent International Conference on the Physics of Semiconductors, San Francisco, 1984, about a quarter of the presented papers dealt with superlattices, quantum wells, and their related subjects, where Esaki gave a plenary talk. This talk (refer to Pub. 44) surveyed significant milestones in this area of research occurring over the past fifteen years, including our recent results which represent a part of this progress report.

Our activity in the period between 1981-1984 is covered here. The report is rather brief and concise, since all results have been published in detail in journals and conference proceedings, as shown in the attached list of publications. Our major studies are summarized, classifying them into nine categories according to materials used and structures prepared. All of these structures were prepared by the MBE technique. Two MBE systems were available: Riber 1000 for InAs/GaSb/AlSb; and Varian GEN-II for GaAs/GaAlAs.

The figure shown below (taken from VG Semicon) illustrates the energy gap (in eV and μ m) vs. the lattice constant at 300K for a variety of semiconductors. The materials involved in our studies are GaAs, GaAlAs, InAs, GaSb, AlSb, Si and Ge.



1) *InAs/GaSb/AlAs Heterostructures*

(refer to Pub. 1, 9, 24)

In 1981, a triple-constituent heterostructure, InAs/GaSb/AlSb was proposed and its significance was emphasized.[1,9] Transport measurements[24] were made on InAs-AlSb-GaSb multi-heterojunctions prepared by MBE. The result was analyzed in terms of electron tunneling across a thin AlSb layer.

2) *InAs/GaSb Superlattices*

(refer to Pub. 3, 5, 6, 7, 8, 11, 15, 16, 18)

Optical absorption measurements[3] with and without magnetic fields have been performed on semiconducting InAs-GaSb superlattices to demonstrate the effect of spatial separation of electrons and holes. Luminescence[5] of band-to-band radiative recombination from such superlattices were observed as a function of temperature, indicating the existence of a low-energy tail. It was noticed that the luminescence peak shifts toward high energy under strong pulsed-excitation. Recently, this result was interpreted in terms of the layer-to-layer transient photovoltage as was observed in doping GaAs superlattices.

Far-infrared magneto-absorption experiments[6] were carried out in semimetallic InAs-GaSb superlattices at magnetic fields up to 20T. The spectra exhibited extensive oscillations of cyclotron resonance and interband absorptions from valence to conduction subbands. Transitions at both the center and the boundary of the superlattice zone were observed, from which the width of the ground conduction subband was obtained, demonstrating directly its three-dimensional character. Extensive experiments on Shubnikov-de Haas oscillations under tilted magnetic fields[7] were performed on InAs-GaSb superlattices with layer thicknesses of 500 and 1000Å

The structural investigation on (100)-oriented InAs-GaSb superlattices[18] was made with the techniques of high-energy helium backscattering and channeling. Oscillatory structure on the backscattering spectra confirmed the superlattice periodicity. Channeling measurements revealed higher dechanneling along <110> directions than along the [100] growth direction. An interface relaxation and contraction model based on average bond-length changes was proposed.

3) *GaSb/AlSb Superlattices*

(refer to Pub. 12, 26, 30, 44)

The study was initiated with the MBE growth of AlSb[12], and subsequently the formation of a GaSb-AlSb superlattice[26] was demonstrated metallurgically from X-ray diffraction and optically from electroreflectance and photoluminescence measurements. The absorption spectra[30] in high-quality superlattices[44] exhibited the two-dimensional density of states and free-exciton peaks. The effect of strain induced by the 0.65% lattice mismatch was manifested by the shift of the absorption edges and the reversal of the heavy- and light-hole exciton peaks.

4) *GaSb/InAs/GaSb Quantum Wells*

(refer to in Pub. 13, 33, 37, 42, 45)

MBE-grown GaSb-InAs-GaSb quantum wells have been investigated, where the unique bandedge relationship allows the coexistence of electrons and holes across the two interfaces. Before an experimental approach, the electronic properties for such quantum wells, were studied by self-consistent calculation.[13] This theory predicted the existence of a semiconductor-to-semimetal transition as a result of electron transfer from GaSb to InAs when the InAs quantum-well thickness reaches a threshold, somewhat similar to the mechanism in the InAs-GaSb superlattices. Such a transition was

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confirmed experimentally[33] : The threshold was found to be 60Å. Measurements of magnetoresistance and the Hall resistance[37,42,45] were made over the wide range of magnetic fields: A large magnetoresistance at low fields suggests a two-carrier conduction mechanism; prominent Shubnikov-de Haas oscillations at middle fields arising from electrons provide the electron density; Hall plateaus in the quantized Hall effect at high fields give the difference in the electrons and hole densities. Such imbalance in the carrier densities implies the existence of positively charged centers of the extrinsic origin in the neighborhood of the interface. Typical data for the carrier densities and mobilities with 100Å quantum wells are $10^{12}cm^{-2}$ and $2.6x10^5 cm^2/V \bullet sec$ for electrons and $2x10^{11}cm^{-2}$ and $1.7x10^4 cm^2/V \bullet sec$ for holes, respectively, at 4.2K: the highest mobilities ever reported for InAs.

5) AlSb/InAs/AlSb Quantum Wells

(refer to Pub. 35 and 38)

MBE-grown AlSb-InAs-AlSb quantum wells[35,38] similar to GaSb-InAs-GaSb, have been studied: The electron concentration appears to be susceptible to the exposure of moisture; its mobility is smaller than that in the GaSb-InAs-GaSb case by, at least, an order of magnitude; and no evidence of the existence of holes is found. A serious doubt about the integrity of the grown structure prevented the derivation of any conclusion from experimental results at this time.

6) p GaAs/GaAlAs Quantum Wells

(refer to Pub. 34, 41, 43, 47)

In modulation-doped p GaAlAs-GaAs heterojunctions,[47] the temperature dependence of the mobility was investigated, discovering that it reaches $2.34 \times 10^5 cm^2/V \bullet sec$ at 1.9K, the highest value reported for holes in III-V compound semiconductors. From the effect of the GaAlAs spacer thickness on the hole density,[43] a valence-band offset of 210 ± 30meV was deduced for $Ga_{0.5}Al_{0.5}$ As-GaAs heterojunctions, corresponding to the result that the fraction of the conduction-band offset to the energy gap difference is 0.62 ± 0.05. Notice that this value substantially differs from 0.85 ± 0.03 given earlier by Dingle. The fractional quantum Hall effect[34,41] was extensively studied in this two-dimensional hole system.

7) n GaAs/GaAlAs Quantum Wells

(refer to Pub. 14, 23, 32, 39, 46)

Photoluminescence measurements[14,23] have been performed on GaAs quantum wells under an electric field perpendicular to them. With an increasing field, the intensity decreased and became completely quenched at an average field of a few tens of kV/cm. This was accompanied by a shift to lower energies of the peak positions. The results were interpreted as caused by the field, which induces a separation of electrons and holes and modifies the energies of the quantum states. Recently, time-resolved photoluminescence for excitons[46] was observed in such quantum wells.

For a dilute two-dimensional electron gas with a concentration of $6 \times 10^{10}cm^{-2}$ in a GaAs-GaAlAs heterojunction, magnetotransport measurements have been carried out at 0.5IK[32] (later 68mK)[39] and up to 28T. The magnetoresistance indicated a substantial deviation from linearity above 18T and exhibited no additional features for filling factors beyond 1/5, which suggested a transition to a (Wigner) crystalline state.

8) Ge/GaAs Superlattice Growth

(refer to Pub. 2, 4, 10, 21, 27)

An exploratory study for the MBE growth of Ge-GaAs superlattices was made with the structural examinations by X-ray diffraction and Rutherford backscattering. Satisfactory results were obtained in both surface morphology and crystalline quality aspects.

9) Si/GaAs Growth

(refer to Pub. 36)

We have grown GaAs and GaAlAs on (100) oriented Si substrates by molecular beam epitaxy. Low-temperature photoluminescence, Raman scattering, and scanning electron microscopy were used to characterize the epitaxial layers. It is shown for the first time that antiphase disorder could be suppressed. The doped GaAlAs grown directly on Si substrates exhibited photoluminescence efficiency similar to that of GaAlAs grown on GaAs substrates. The technique developed in this study is now widely accepted and used in the technical community.

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