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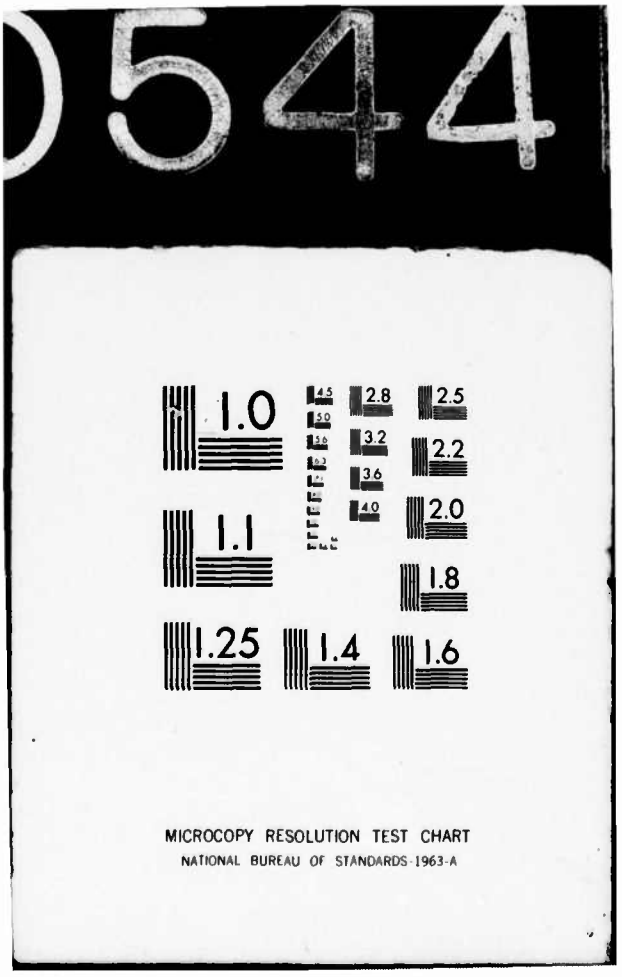
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THE SECOND INTERNATIONAL CONFERENCE ON THE "ELECTRONIC PROPERTIES OF 2-DIMENSIONAL SYSTEMS"

B.D. MCCOMBE *

12 April 1978

*Naval Research Lab., Washington, D.C.

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TRANSPORT PROPERTIES	MAGNETO-CONDUCTIVITY	

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The Second International Conference on the Electronic Properties of Two Dimensional Systems, 19-22 September 1977, is reviewed critically. Topics discussed include: Space charge layers in Si MOS structures; carrier localization, electric field subband spectroscopy and many-body effects, dc and high frequency magneto-conductivity, cyclotron resonance, charge density waves, surface 'superlattices'; electrons on liquid helium, bound state spectra and lifetimes, electron motion parallel to the surface, two

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dimensional plasmons, and Wigner crystallization; semiconductor superlattices; and other semiconductor MIS structures.

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THE SECOND INTERNATIONAL CONFERENCE ON THE "ELECTRONIC PROPERTIES OF 2-DIMENSIONAL SYSTEMS"

I. INTRODUCTION

The Second International Conference on the Electronic Properties of 2-D Systems was held in the Kongresshaus in Berchtesgaden, FRG. The first conference took place at Brown University in Providence, RI, USA, two years earlier. The beautiful setting in the German Alps, unfortunately, couldn't be appreciated until the final day because of the poor weather.

This was an extremely busy meeting with, in the writer's opinion, too many papers. There were no simultaneous sessions and the coffee breaks coincided with poster sessions. In three and a half days 86 papers were presented, 21 invited, and the remainder contributed of which 27 were presented in poster sessions. There were 108 registered participants representing nine countries, with the majority from FRG and the US.

The major topics of the Conference were the same as those at the previous one with the single substitution of semiconductor superlattices for layered compounds. The largest subject of discussion was quantum space-charge layers formed in the semiconductors of metal-insulator-semiconductor (MIS) structures. Again the dominant example of this class was the silicon metal-oxide-semiconductor (MOS) structure.

The mechanics of formation of a nearly two-dimensional quantum space-charge layer can be understood by examining the schematic energy diagram of Fig. 1. In the case shown, a p-type Si substrate, the application of a positive voltage to the metal-gate electrode lowers the potential energy for electrons in the semiconductor and the bands are bent down. For a sufficiently large voltage, and electric field across the thin oxide layer, the conduction band edge bends below the Fermi energy in the semiconductor leading to the formation of an inversion layer of mobile minority carriers (electrons). At low temperatures the strong potential causes the motion of these carriers to be quantized into a series of bands in the direction perpendicular to the interface; these are the so-called electric field subbands. For the situation shown [(100) Si] the many-valley nature of the conduction band leads to the formation of two sets of subbands for this orientation, as indicated. Additional systems exhibiting similar quantized nearly 2-D behavior, which were also discussed at the Conference, were electrons on the surface of liquid helium, and thin repeated semiconductor heterostructures (semiconductor superlattices). The latter are illustrated in Fig. 2.

The remainder of this report is subdivided into major topics as I perceive them. This choice and the details in the following sections are, of course, somewhat colored by my own personal prejudices and background.

II. Space-Charge Layers on Si (Si-MOS)

Much has been said in the past few years about the ideality of the Si MOS system for studying many-body effects in a nearly 2-D electron gas. This attitude was reflected at the Conference with many talks concerned with this system largely as a nearly ideal 2-D collection of charge carriers. Many of the effects due to the "real" interface and charges in the oxide were neglected or treated as a perturbation on the ideal system. It is my belief that this approach ignores much of the real physical situation, particularly at low space-charge layer densities in the so-called localized regime. This different "philosophy" was expressed by K.L. Ngai as well as by M. Pepper in invited papers on localization effects.

The remainder of the discussion of space-charge layers is divided into several sub-topics.

A. Subband Spectroscopy and Many-Body Effects

In the opening talk of the Conference, T. Ando reviewed theoretical work on many-body effects in semiconductor space-charge layers, concentrating predominantly on his own extensive work. He emphasized the role of many-body effects (exchange and correlation) in determining the electric-field subband energies. In this system the dimensionless parameter that characterizes the strength of the many-body interaction, r_s (the ratio of the average electron separation to the effective Bohr radius), can be continuously varied in the same sample (by simply changing the gate voltage) over a wide range, $0.6 \leq r_s \leq 4$. These studies have an interesting recent history. The early theoretical work by Stern treated the system in the self-consistent Hartree approximation. Infrared optical intersubband-resonance measurements somewhat later by Wheeler and students at Yale and then by Koch and co-workers in Munich, gave subband separations that were considerably larger than calculated. Many-body effects were taken into account by Vinter, Ohkawa, and Ando, each utilizing a different approach. All calculations showed exchange and correlation to be important, and the results were in reasonably good agreement with experiment. In the analysis of the IR experiments it had been assumed implicitly that the resonance occurred when the photon energy equaled the appropriate subband separation. However, at the Brown Conference it was shown (and not recognized until somewhat later) by Chen, Chen, and Burstein that the resonance energy is shifted by a depolarization effect (a resonant plasma screening). This was quantified later by Allen, Tsui, and Vinter, who showed that the shift could be of the order of the exchange/correlation effects and that the agreement with experiment might be fortuitous. Ando then showed that the depolarization shift itself is modified by exchange and correlation through final state, exciton-like, interactions. In fact, Ando has shown, in a certain approximation, that the two effects nearly cancel and the theoretical results are still in agreement with experiment. It is possible that with additional experiments the theoretical results may change again.

Since these various corrections cast at least some doubts on the magnitude of the theoretically calculated exchange/correlation contributions to the subband energies, it would be desirable to have an experimental determination of the subband energies that is independent of the depolarization and final state interaction corrections. One possible technique is surface channel tunnel spectroscopy which was suggested and described in a poster paper by Quinn, Kawamoto, and McCombe.

Ando also described work on cyclotron resonance, subbands in InSb, charge-density waves and several other topics. These are discussed in more detail in the appropriate sections.

The experimental results of subband spectroscopy were summarized by Kneschaurek with emphasis on the studies of the Munich group. Although mentioning work on other planes of Si, Kneschaurek concentrated largely on describing the work on electron inversion and accumulation layers on Si (100) surfaces. An apparent large discrepancy in the measured subband separations for inversion layers for this surface orientation as measured in absorption (transmission) experiments on MOS capacitors by the Munich group, and photoconductivity experiments on MOS transistors by Wheeler and co-workers at Yale, and emission measurements by Gornik and Tsui at Bell Labs on MOS transistors has been resolved in the past year. The discrepancy arises because the measurements on MOS transistors were carried out with essentially no background light on the samples and a nonequilibrium situation existed in which little or no fixed depletion charge was established. Since the potential at the interface depends (through Poisson's equation) on the total charge (inversion plus depletion), this nonequilibrium situation results in a weaker electric field and hence a smaller separation between subbands than the full equilibrium situation. This has now been demonstrated independently by the groups at Bell Labs, Munich, and Yale.

Another interesting point was also discussed by Kneschaurek. In temperature-dependent studies of the subband resonances the Munich group has found an additional resonance line at low gate voltages appearing at higher temperatures, and a shift to lower gate voltages of the main E $E_o \rightarrow E_1$ resonance. They interpret these results as follows: The "new" resonance at higher temperatures results from thermal population of the ground state of a series of subband levels associated with the 4-fold degenerate conduction band minima which have a light-effective mass perpendicular to the surface, and thus a lowest subband energy somewhat higher than that of the two-fold degenerate minima. This finding, two distinct resonances, is in apparent disagreement with temperature-dependent cyclotron-resonance results obtained on similar samples and discussed by J. Kotthaus in an invited paper. (The cyclotron resonance results are described in a later section.) The shifts to lower gate voltages (higher energies) with temperatures are expected from a self-consistent independent particle model (Hartree model) of the potential, but appear to be opposite to the dependence expected when many-body effects play a dominant role, as it appears they do. These two points remain to be resolved.

The photoresponse associated with the intersubband transitions was the subject of some controversy and considerable discussion at the Conference. Photoresponse was originally observed in 1970 by Komatsubara and co-workers and has since been most extensively investigated by Wheeler and students at Yale University. The sign of the photoresponse, a negative photoresistive signal, and the long response time remain a puzzle. In an invited paper Wheeler summarized recent work at Yale University. The absolute magnitude of the absorption coefficient for the $0 \rightarrow 1$ transition has been measured and compared with Stern's self-consistent Hartree calculation of the transition dipole moment for accumulation layers. Excellent agreement is obtained. In photoresponse measurements on extremely high effective mobility devices (μ_{eff}(peak) $\sim$ 25,000 cm^2/V-sec), intersubband transitions from E_o through E_7 have now been observed. In addition, Wheeler reported on a number of experiments that were carried out to elucidate further the nature of the photoresponse. Transient photoresponse measurements at 84 μm for the $0 \rightarrow 1$, $0 \rightarrow 2$, and $0 \rightarrow 3$ transitions yielded response times of approximately 1 msec with a systematic increase in response time of a factor of 2.5 in this sequence. With large negative substrate bias the response time decreases to less than 1 msec. Laser intensity and temperature dependence of the signal were also reported. Some controversy was stimulated by a "modest" proposal by Neppel, Kotthaus, Koch, Shiraki, and Dorda in a poster paper that the photoresponse is a sample heating or bolometric effect. This point was contested by Kamgar, who described time-resolved pulsed-laser measurements which gave response times in the microsecond regime. This point remains to be resolved since a conclusive experiment has not been carried out.

Other papers in which studies of the electric field subbands were described included an invited one by Gornik in which he reported some difficult experiments that observed the subband transitions via radiative decay of hot electrons. The total emitted intensity in these experiments was $\sim 10^{-11}$ w at 100 μm for typical device parameters.

B. DC and High Frequency Magnetoconductivity

There has been considerable effort devoted to oscillatory magnetoconductance studies of space-charge layers on Si since the pioneering work a decade ago by the group at IBM, and this was reflected at this Conference. Several years ago Smith and Stiles reported an effective mass determined from the temperature dependence of the amplitude of the Shubnikov-de Haas (magnetoconductance) oscillations. These data for electron inversion layers on Si (100) surfaces showed an effective mass that was larger than the appropriate bulk Si band mass and decreased with increasing density. These results were interpreted as "dressing" of the effective mass due to electron-electron interactions, and this has stimulated a large number of theoretical papers on the subject, the results of which are in semi-quantitative agreement with these experiments. However, at the Brown Conference two years ago, some concern was expressed by Hartstein, Fang, and Fowler, and others over the fact that some samples did not seem to exhibit the behavior described above.

Extensive work on a large number of samples of the effective mass vs density for different amounts of net fixed positive oxide charge in the SiO_2 were described in a contributed paper by Fang. These results are interesting and perplexing since they show an unexpected systematic dependence of the S-dH mass on oxide charge density. Measurements were made as a function of oxide charge, oxide thickness, substrate bias, substrate doping, and device geometry. The apparent effective masses were found to be dependent to some degree on all these parameters; with many results in disagreement with many-body considerations and previous measurements. Particularly interesting were the studies of oxide-charge dependence of the effective mass. Oxide charge was varied systematically in single samples by doping with Na^+ ions and drifting controlled amounts to the interface. At low values of oxide charge the mass increased with decreasing electron density, in agreement with previous results; but at large values of oxide charge the opposite behavior was observed, and at low-electron densities mass values below the band mass were observed. It appears from these results that scattering due to interface charges affects the S-dH mass, and that interpretations based on many-body effects in a homogeneous 2-D electron gas must be viewed with some care.

Since the first report of the observation of cyclotron resonance of 2-D electrons on Si (100) Si MOS structures in *Physical Review Letters* (simultaneously by groups at Bell Labs and the Technical University of Munich) in 1974, there has been considerable effort in this area. J. Kotthaus reviewed much of this work in an invited paper concentrating on the results obtained in Munich. There has been a controversy over the frequency dependence of the cyclotron resonance mass since the previous conference at Brown. A decreasing mass with increasing frequency was observed in several samples by Kennedy and co-workers at NRL in 1975; they suggested that many-body effects manifested through the inhomogeneous distribution of scattering centers could explain these results qualitatively, and theoretical work has since lent credence to this idea. However, in similar experiments Koch and co-workers have found little or no frequency dependence of the mass. It now appears that there are real differences in samples, perhaps in the nature of the interface scattering.

Kotthaus also described some interesting temperature and uniaxial stress-dependence results in which the Si (100) cyclotron effective mass was found to vary continuously from a value of about 0.2 m_o to $\sim$ 0.4 m_o as a function of increasing temperature or stress. Two distinct cyclotron masses (expected from thermal population of the higher, heavier mass subbands, E_o') were not observed. This implies some form of coupling between the E_o and E_o' subbands, such as might be provided by the "charge density wave" ground state discussed below. However, this is in disagreement with the intersubband results discussed by Kneschaurek (Sect. II A) and also with cyclotron resonance results discussed by McCombe in which little increase in the mass above 0.2 m_o was found at temperatures up to 90 K.

Gornik, in an invited paper, reported on the observation of cyclotron resonance by radiative emission. A frequency-dependent effective mass was found in these studies. Several contributed papers on the theory of cyclotron resonance line shape and position were also presented.

It is clear that additional work is required to clarify the role of the interface and scattering centers in influencing the effective mass measured by these techniques, particularly at low carrier densities.

C. Charge Density Waves on Si Surfaces

For a number of years various experiments have been at odds qualitatively with the conventional theories (self-consistent Hartree approximation and its extensions which include many-body exchange and correlation) of the quantum space-charge layers on various surfaces of Si. In particular, for the Si (111) surface, all six conduction band minima are equivalent, and the conventional theories predict a single series of 6×2 (spin) = 12-fold degenerate electric field subbands for this orientation. S-dH experiments and others have found a degeneracy of the ground state subband of $2 \times 2 = 4$. Similarly the (110) surface should have $4 \times 2 = 8$-fold degenerate ground state; a degeneracy of $2 \times 2 = 4$ is observed. Similar interesting observations have been made on the Si (100) surface under uniaxial stress.

In the usual models for a (100) surface orientation as described in the introduction and shown in Fig. 1, the lowest subband, E_o, is formed by the valleys with the highest effective mass perpendicular to the surface; thus the E_o, E_1, E_2, ... subbands are 2×2 (spin)-fold degenerate with a cyclotron mass of $\sim 0.2\ m_o$. The other subbands, E_o', E_1', E_2', ... are 4×2-fold degenerate, lie higher in energy, and have a cyclotron mass of $0.42\ m_o$. Uniaxial stress in the [010] direction splits the degeneracy of the upper (primed) valleys moving one pair of valleys down in energy and one pair up; in addition, the lower (2×2-fold degenerate, unprimed) valleys are moved up in energy. At reasonable values of stress the lower valleys can be made to cross one pair of the upper valleys at which point the degeneracy should be (4×2). Similarly, when the valleys are close together in energy, it should be possible to populate thermally both a set of light cyclotron mass subbands (E_o') and a set of heavy cyclotron mass subbands (E_o'), which should lead to two distinct cyclotron resonances.

Experimentally, S-dH measurements by Eisele, Gesch and Dorda and others, always yield a valley degeneracy of 2×2 for all values of uniaxial stress. In addition, the temperature- and stres-dependent cyclotron resonance studies of Kotthaus and others in Munich show a single cyclotron resonance with a mass value that shifts from $m_c^* \approx 0.2\ m_o$ to $m_c^* \approx 0.4\ m_o$ with increasing stress/temperature at low surface electron densities.

In an invited paper M. Kelley reviewed theoretical studies that he and L. Falicov have carried out in an attempt to explain some of these perplexing results. They have constructed a model Hamiltonian for this system in the unrestricted Hartree-Fock approximation, in which phonon-mediated intervalley exchange interactions are included which couple the upper (primed) valleys with the lower (unprimed) valleys. The strength of this interaction is characterized by a parameter U. This concept was used previously by these authors to explain the "anomalous" degeneracy

factors observed for (111) and (110) Si surfaces. Under the proper conditions the coupling leads to a lowest energy ground state which is not the usual Hartree (paramagnetic) state but is rather a charge-density wave state whose wave function is composed of linear combinations of wave functions from the coupled valleys.

This model calculation is able to achieve "agreement" with some of the experiments on the (111) Si surface when very large values of the parameter U are used (such large values have not yet been shown to be justified). In particular, the stress and temperature results described above are explained by increased coupling between valleys (through a decreased energy denominator in the case of applied stress) which leads to a transition from the usual paramagnetic ground state to the charge-density wave ground state. Since the valleys are coupled, the E_o and E_o' levels never cross under stress, and this explains the observed degeneracy factor. The coupling also qualitatively explains the single cyclotron resonance observed by Kotthaus and co-workers, and the shift in mass with stress observed by them and also by Eisele and others in S-dH measurements. Stress-dependent field-effect mobility and other transport measurements by Eisele, Gesch and Dorda have also been interpreted on this basis; this work was reviewed by Eisele.

There are several experiments, however, that appear to conflict with this interpretation. These are: 1) The temperature-dependent intersubband resonances reported by Kneschaurek which show two distinct resonances $E_o \rightarrow E_1$ and $E_o' \rightarrow E_1'$ at higher temperatures, and 2) the temperature dependent cyclotron resonance studies of Kennedy *et al.* and van Deursen on samples from Bell Labs, in which a single resonance was observed with mass near 0.2 m_o which did not shift to higher mass at temperatures up to 90 K.

It appears that some of these effects are sample dependent, and that a coupling between valleys that is related to interface properties (and thus could be different for different samples) might be more appropriate than the large intervalley exchange interaction evolved by Kelley and Falicov. These points await further experimentation before the final verdict is in.

D. Surface "Superlattices"

Less than a year ago, P.J. Stiles and co-workers at Brown University reported in *Physical Review Letters* anomalous behavior of channel conductance and magnetoconductance measurements on n-channel MOSFETs fabricated on vicinal planes of Si; these are planes such as (811) whose normals are tilted by small angles away from the [100] direction toward the [111]. These results were interpreted in terms of a one-dimensional superlattice potential formed at the $Si-SiO_2$ interface; this additional periodic potential introduces new Brillouin zone boundaries and modifies the energy band structure in the superlattice direction by opening up "minigaps" in the energy-momentum relation. This original series of experiments stimulated a number of other studies, and much of this work was reported at the Conference.

A. Lakhani of the Univeristy of Sherbrooke reviewed the transport studies which were carried out largely at Brown University. He outlined a simple Kronig-Penney model of a one-dimensional superlattice and calculations of the size of the minigap, surfaces of constant energy, the density of states, as well as the conductance vs gate voltage curves parallel and perpendicular to the superlattice direction. The latter exhibit characteristic structure near voltage that corresponds to the Fermi energy's being in the vicinity of the minigap. Lakhani then described the samples and transport experiments in the light of this model. Several samples [(811), (23,2,2) and (511) orientations] were studied, and the qualitative trends were as expected from the superlattice model. From analysis of the data, values of the superlattice constant and the minigap were obtained; for the (811) sample these values were 104 Å and 4 meV, respectively. Lakhani also mentioned an alternative model (the Fermi surface projection model) that was suggested by L. Sham of the University of California, San Diego, and was described in more detail by S.J. Allen in another invited talk concerned with high frequency conductivity studies. Among other things, Allen discussed far infrared transmission measurements on a (911) sample. An absorption peak was observed for the IR electric field polarized parallel to the "superlattice" direction but not for perpendicular polarization; this is attributed to interband absorption across the minigap. From analysis of the absorption peak the gap was found to be 4 meV and the "superlattice" period 110 Å. Observation of a minigap via emission in (911) samples was also reported by Gornik.

Sham's Fermi surface projection model also appears to be consistent with all the reported data, and none of the reported experiments were able to distinguish between the models.

E. Localization

Several years ago it was suggested by Mott and independently by Stern that the quasi 2-dimensional electron gas formed at the Si-SiO_2 interface of Si MOSFETs is a system in which localization of carriers in the surface channel takes place due to random static potential fluctuations, and an Anderson transition from thermally activated to metallic conductivity is observed. These concepts have received considerable attention in 3-dimensional amorphous semiconductors. Since these original suggestions, there have been a number of experimental studies of the Si MOS system in the region of low surface-carrier densities where such effects should be dominant. It has now been well established that something like an Anderson transition does indeed take place, and some of the experimental results on certain types of samples agree well with the predictions of the Mott-Anderson model. These results include: 1) The observation of a thermally activated conductivity, with the activation energy dependent on density (excitation from the Fermi energy to a mobility edge), and a transition to metallic behavior above a certain critical density; 2) a low temperature region in some samples where ln (conductivity) α (temperature)$^{-\frac{1}{3}}$ (a variable range hopping regime); and 3) the observation of a constant minimum metallic conductivity with values near 0.1 e^2/h (independent of sample parameters), again for some sets of samples. However, there have been a number of observations of "anomalous" behavior

in certain types of samples; these observations do not conform to the Mott-Anderson model of random static potential fluctuations. Two invited papers were largely concerned with understanding some of these "anomalies."

M. Pepper reviewed the work that he and others at Cambridge University (the strongest proponents of the Mott-Anderson model) have carried out on electron and hole localization in Si MOS devices. His talk, as did that of K.L. Ngai which preceded it, took the point that localization behavior can be used to obtain information about charges at the $Si-SiO_2$ interface; this was, however, the only substantive point of agreement between the two.

Pepper described measurements on certain samples that show that the so-called mobility edge, which should be fixed in the Mott-Anderson picture, moves as a function of carrier density. This behavior had been previously observed by Tsui and Allen at Bell Labs. The usual means of characterizing interface charge in MOS devices is through capacitance-voltage measurements, which Pepper emphasized measure net charge; this is found to be always positive. On the other hand, the density of localized states (as determined from the density of carriers required to reach the Anderson transition from thermally activated to metallic conductivity) lies generally in the range $2 \times 10^{11} cm^{-2}$ to $2 \times 10^{12} cm^{-2}$, while the net positive charge is always substantially smaller, typically between $10^{10} cm^{-2}$. This implies extensive charge compensation; the above results can be rationalized if the localization depends on the total charge which is much larger than the net charge. Pepper cited as additional evidence for this picture the fact that typical thermal activation energies are always less than a few meV, considerably smaller than the binding energies measured for isolated positive charges (Na^+ ions) drifted up to the interface ($\sim$18 meV). He inferred from this that the dominant compensated charges form static pairs whose dipolar fields lead to much weaker binding. Pepper also described a series of experiments in which substrate bias was used to move the average position of charge in the inversion layer away from the interface. These results reproduced earlier studies on different samples by the Bell Labs group in that the "constant" value of minimum metallic conductivity could be increased and could depend on carrier density. In order to salvage the Mott-Anderson picture, Pepper presented a qualitative model in which the range of the fluctuating potential increases as carriers are moved away from the interface owing to the diminishing influence of the compensated charges that form dipolar fields. The longer range fluctuations cause the average energy of localized states to drop further from the unperturbed subband edge and also modify the considerations which lead to the prediction of a constant minimum metallic conductivity.

Pepper also discussed some interesting experiments on radiation effects on localization, and he related observed shifts in device thresholds to measured thermal activation energies in the localized regime as well as speculating on the microscopics of the interface that lead to the observed behavior. A final point discussed by Pepper was the question of localization in the presence of large magnetic fields (contributed

papers by Nicholas *et al* and Kawaji *et al* were also concerned with this point), and some controversy was generated by his remarks on a qualitative explanation of how magnetoconductance oscillations can be seen in a region of density where localized behavior is observed at zero magnetic field. His explanation, basically in terms of large regions of potential variations of very long range which do not effectively localize electrons when the cyclotron orbit size (at high fields) is much less than this range, was contested by S.J. Allen of Bell Labs.

An earlier invited paper by K.L. Ngai also addressed this point among many others. Ngai also presented strong arguments on the side of utilizing low-temperature inversion layer measurements in the region of localization to achieve a better understanding of microscopic properties of the interface. However, he presented a considerably different picture of localization with a description of a new concept (originally introduced by him and T.L. Reinecke in *Phys. Rev. Lett.* in 1976) of dynamic pair localization. In addition to the usual static random potential fluctuations (which lead to single particle localization) Ngai presented strong phenomenological arguments, making analogies between the $Si-SiO_2$ interface and amorphous semiconductors and also models of surface reconstruction, to support the view that two-electron and two-hole states exist at and near the strongly disordered and nonstoichiometric interface region which can play a strong role in localizing carriers. Such pair states have been shown to be effective localization centers in amorphous semiconductors. Ngai was particularly concerned with explaining some of the anomalies discussed previously: 1) An apparently density-dependent mobility edge, 2) large variations in some samples in the supposedly constant minimum metallic conductivity, 3) a decrease in the thermal activation energy with increasing negative substrate bias, and 4) the observation of well-defined magnetoconductance oscillations in a region of density which is localized at zero magnetic field.

Ngai described results obtained from detailed calculations utilizing three related models of the pair localization states:

1. A generalized random pair-attractive interaction model (random negative U model).
2. A simplified dangling bond/reconstruction model (in analogy to Si surface reconstruction) in contact with a Fermi gas, and
3. A more general random reconstruction model equivalent to the random negative U model.

A qualitative understanding of the "anomalous" behavior described above is a natural outgrowth of the pair localization models. One simple example is the puzzling observation of magnetoconductance oscillation in the localized regime, which was the subject of some controversy. This can be understood on the basis of pair localization since high magnetic fields tend to break-up (delocalize) the spin up/spin down pairs because of the Zeemann energy. Additional experiments would be desirable to establish unambiguously the importance of the pair states in MOS structures.

Another interesting series of studies in the general category of localization were those described in an invited talk by A. Fowler. In addition to "fixed" positive charge in the SiO_2 there is also (generally undesirable) mobile positive charge owing to, e.g., Na^+ ions. Fowler described transport measurements in which Na^+ ions were introduced purposely via deposition of NaCl under the metal gate of the MOS structure. The resulting Na^+ ions can be drifted to the $Si-SiO_2$ interface in controlled and measurable amounts by temperature-gate voltage bias treatments, and then "frozen" in place by quenching to low temperatures with the bias applied. There is evidence that these ions collect in the oxide at a rather well defined distance ($\sim$ 3 - 4 Å) from the $Si-SiO_2$ interface. These ions form nearly two-dimensional centers for the binding of carriers confined to the electric field subbands in the Si. Fowler described the transport measurements that A. Hartstein and he had carried out at low temperatures; they observed maxima in curves of channel conductivity vs gate voltage and a dependence of the peak on the measured oxide charge (concentration of Na^+ ions) and temperature. The peak is interpreted as resulting from thermal activation from an "impurity band" associated with the Na^+ centers to a mobility edge. From temperature dependence studies they were able to determine the energy difference between the impurity band peak and the mobility edge ($\sim$ 18.5 meV). This is related to the binding energy of the Na^+ impurities. The thermal activation energy was found to increase with increasing negative substrate bias, which moves the electrons in the Si closer to the Na^+ ions, as expected. Fowler also described lower temperature thermal activation measurements, in a region where the conductivity is dominated by nearest neighbor hopping, from which an estimate of the bandwidth ($\sim$ 3.3 meV at $N_{(NA^+)}=5 \times 10^{11} cm^{-2}$) was obtained. Both binding energy and bandwidth were found to decrease with increasing $N_{(NA^+)}$.

The experimental data were compared with calculations of Kramer, Martin and Wallis (whose more recent results were presented in a contributed paper). These authors calculated the binding energy of electrons to isolated Na^+ ions as a function of electric field in the context of an effective mass hydrogen atom model. Measured values of thermal activation energy were somewhat smaller than the values of binding energy calculated with the Na^+ ions located precisely at the interface; however, as discussed by R.F. Wallis, the binding energies are reduced somewhat for the Na^+ ions moved into the oxide by several Å. This brings the calculated binding energies and experimental thermal activation energies into substantially better agreement; and considering approximations in the calculation and the fact that the thermal activation energy is not identical to the binding energy, it does not seem fruitful to push the comparison any further at present. Optical experiments would provide more precise numbers for comparison with theory.

Another very interesting topic, which can be considered to be a type of localization and which received some attention at the Conference, is the subject of Wigner crystallization of 2-D electrons in MOS structures, particularly in high magnetic fields. Wigner first discussed the possibility

of the crystallization of electrons from a gas to an ordered lattice in 1934. Simply stated, this transition results from a competition between Coulomb and kinetic energy, with the Coulomb energy dominating at low densities and temperatures and the lowest free-energy state being the ordered lattice. Theoretical calculations were presented by several authors, one of which included the effects of random static potential fluctuations in high magnetic fields. In addition, some experimental results were described that were interpreted in terms of Wigner crystallization. The experimental results are only speculative at the moment, and a definitive experiment remains to be done in this fascinating area.

F. Miscellaneous

A number of other interesting experimental and theoretical studies of Si MOS structures were presented that do not fit into the above categories. Two of the more extensively discussed were: warm and hot electron-effects in Si MOSFETs and optical (far-IR) observations of 2-D plasmons by groups at Bell Labs and Munich. Studies of plasmon dispersion and magnetoplasmon modes are just beginning, and this will probably be a topic of some interest at the next conference.

II. Electrons on Liquid Helium

Although the number of papers on this topic was small because of the parallels and contrasts with the Si MOS system and the relatively small number of "dirt" effects, electrons on the surface of liquid helium are an extremely interesting system for physical studies.

C.C. Grimes presented an excellent review of the recent experimental and theoretical advances in this area, particularly the extensive work carried out at Bell Labs. He compared and contrasted the case of electrons on the surface of liquid helium with the MOS case on Si. In contrast, the energy levels for motion and to the surface of electrons on liquid helium can be treated as a one electron problem. In this case the binding is due to the classical image potential of the electron (in the He dielectric) and the short-range repulsive barrier of the interface. The band states turn out to be quite like s-states of the hydrogen atom but with a very small binding energy ($\sim$0.7 meV) because of the tiny polarizability of liquid He and the resulting minute image charge.

A comparison of the two cases is presented in Table I, which is a modification of that presented by Grimes. As can be seen the most striking differences are: Smaller binding energies, <u>much</u> lower densities (<u>much</u> smaller Fermi energies), and the larger spatial extent of the wave function for the case of electrons on the surface of helium. This leads to what is largely a classical, nondegenerate 2-D system for motion parallel to the surface. The mobilities are also much higher, and the system is simpler, cleaner and easier to study (in some respects).

	bind. Energy (meV)	<z> (Å)	n_s (cm^{-2})	E_{Fermi} (meV)	m^*/m_o	τ_{scatt} (sec)	Mobility
Si MOS	5-50	∿30	10^{11}-10^{13}	1-50	0.2-.5	10^{-12}	10^{-3}-10^{4}
Electrons on He	0.7	114	10^{5}-10^{9}	10^{-4}-10^{-2}	1.0	10^{-7}	10^{-7}

Grimes discussed several major topics, highlights of which are presented in the following.

A. Bound State Spectra and Lifetimes

Several years ago Grimes and Brown first measured the splitting of the bound states of electrons on liquid helium by Stark tuning the levels into resonance with the mm-wave source frequency. Extrapolating these data to zero-applied electric field yielded values of 0.52 and 0.61 meV for the 0↦1 and 0↦2 level splittings; this is in rather good agreement with values of 0.49 and 0.58 meV, respectively, calculated in the infinite barrier approximation. Later experiments have revealed transitions through the seventh excited state. Subsequent finite barrier and graded barrier calculations have improved agreement to within about 10%. Further work is required here. Grimes also mentioned that a challenging problem is calculation of the width of the bound state transitions, a point that was addressed in a contributed paper by Ando, who considered He gas atom scattering and ripplon (surface waves on liquid helium) scattering as possible broadening mechanisms.

Recently Zipfel *et al* have utilized linewidth measurements in the presence of a magnetic field parallel to the surface to measure the auto-correlation time of surface electrons as a function of surface electron density, n_s. At low electron densities there is a component of linewidth owing to coupling of the parallel and perpendicular motion of electrons that results from the presence of the parallel magnetic field. At high densities this component of linewidth is "motionally" narrowed because of electron-electron scattering, and the velocity auto-correlation time for electron-electron scattering can be determined from these measurements. The results show that the velocity auto-correlation time decreases by a factor of 6 as the density increases by a factor of 10; in this region of densities and temperatures the ratio of potential energy to kinetic energy of the surface electrons increases from 9 to 36. At high densities the motion becomes that of a highly correlated liquid; this in conjunction with the fact that the measured auto-correlation times are close to those expected for a harmonic oscillator about a lattice site in a triangular electron lattice indicates that this system may be close to Wigner crystallization. This is a subject of considerable interest and effort here as well as in the Si MOS system.

B. Electron Motion Parallel to the Surface

Motion of electrons parallel to the surface is impeded by two scattering mechanisms—1) scattering by He gas atoms in the vapor at the interface, and 2) scattering by thermally excited surface waves in the liquid helium (ripplons). The effects of scattering have been studied theoretically by several workers. Results show that He gas atom scattering becomes negligible in limiting the mobility at sufficiently low temperatures, and that the low temperature mobility should increase rapidly as temperature is decreased (as a result of lowering the He vapor pressure) and then saturate at a value allowed by ripplon scattering. Experimental measurements by several techniques are in qualitative agreement with this. The results demonstrate that He gas atom scattering dominates above $\sim$0.8 K and ripplon scatterdominates below $\sim$0.6 K. However, two measured values of the ripplon limited mobility differ substantially (by a factor of $\sim$5), and further experimental work is required here.

Because of the very large mobilities and slow energy relaxation of the surface electrons, it is very easy to heat the electron gas. Grimes reviewed studies of warm and hot electron effects and presented some unpublished results of plasmon standing wave resonance line-shapes obtained at Bell Labs. These studies showed dramatic changes in the line shape with only about 12% increase in the amplitude of the rf electric field indicating how sensitive the scattering is to electron temperature.

C. Two-Dimensional Plasmons

Because of the long scattering times (narrow lines) and the fact that the areal density of electrons can be varied over several orders of magnitude, this is an ideal system for the study of 2D plasmons. In two dimensions the plasmon dispersion relation is $\omega \propto k^{\frac{1}{2}}$ to lowest order (rather than $\omega \propto$ const. in 3-D).

Several years ago Grimes and Adams carried out a series of experiments with a swept rf spectrometer; plasmon standing wave resonances in a rectangular cell were excited and detected, and the dispersion relation, $\omega_p^2 = 2\pi n_s e^2 k/m$, was verified for $10^7 < n_s < 3 \times 10^8 cm^{-2}$.

D. Wigner Crystallization

The question of Wigner crystallization for electrons on liquid helium has received a great deal of theoretical attention as has the same question for Si MOS. The major difference between the two cases is that electrons on liquid helium are a nondegenerate 2-D system and crystallization should occur at the highest achievable areal densities; whereas inversion layer electrons on Si form a degenerate system at low temperatures and crystallization is predicted to occur at the lowest densities achievable (and measureable).

Thus far the studies have been largely theoretical and, as is the case for Si MOS, no direct experimental evidence for crystallization has been found.

In summary, Grimes suggested that several more years effort, particularly experimental work, would be required to achieve a detailed understanding of this system.

Two additional talks on this subject were presented, both by Russians. Shikin described cyclotron resonance studies; and a very interesting talk, which was not on the program, was given by Khaikin. Entitled "Birth, Life, and Death of Bubbles: Instabilities of Charged He Surfaces", this included some fascinating motion pictures of the dynamics of charged He surfaces.

III. Semiconductor Superlattices

The development of computer-controlled ultra-high vacuum molecular-beam-epitaxial (MBE) techniques during the past several years has made possible the growth of repeated thin semiconductor heterostructures (semiconductor superlattices) with the alternating layers as thin as a single monolayer. The predominant heterostructure system that has been grown by this technique is the GaAs-$Ga_{1-x}Al_xAs$ system, primarily because of the excellent lattice match. Due to the band line-up between GaAs and $Ga_{1-x}Al_xAs$ in the vicinity of the fundamental energy gap (at the Brillouin zone center), a series of "one-dimensional" potential wells is formed in the superlattice direction (Fig. 2). Similar to the case of MOS inversion layers, quantum subbands are formed in these potential wells, with the subband energy spacing and degree of dimensionality dependent upon the well depth, width, and the separation between adjacent wells (the carrier width of the $Ga_{1-x}Al_xAs$).

Considerable experimental work has been done on this system by the groups at IBM and Bell Labs. Studies include optical absorption and photoconductivity, x-ray scattering, transport measurements, light scattering, and infrared lattice vibration studies. The most direct experimental evidence of the subbands has been the optical absorption studies of Dingle *et al.* at Bell Labs. Until very recently, theoretical studies of this system had been limited to simplified Kronig-Penney model calculations. During the past year there have been several theoretical band structure calculations of the superlattice structures utilizing pseudopotential and tight binding techniques.

Several papers were presented at the Conference on studies of superlattice structures. In an invited talk L. Esaki reviewed some of the past experimental work on the GaAs-$Ga_{1-x}Al_xAs$ superlattices, concentrating on the IBM work. He then described the most recent studies at IBM on oscillatory magnetoresistance with the current in the superlattice planes. A series of n-doped samples was studied at 4.2 K in magnetic fields up to 18 Tesla (at the National Magnet Laboratory) with the magnetic field direction varied from perpendicular to parallel to the superlattice planes. Magnetoresistance oscillations were observed in all samples investigated. For a sample with deep, separated wells, clear oscillations were observed for the magnetic field perpendicular to the planes that shifted to higher fields and gradually disappeared as the magnetic field direction was rotated toward the superlattice plane. The shift in the oscillations with magnetic field angle (φ) measured from the superlattice planes obeyed the $\sin\varphi$ relationship expected for a 2-D band. (For a 2-D electron gas the

period of oscillation depends only on the component of magnetic field perpendicular to the planes, i.e., H sin(φ.) For samples with narrower or shallower wells there was very little observed dependence on magnetic field orientation indicating an approach to 3-D behavior. Results were compared with the subband energies and with those calculated from a Kronig-Penney model with generally good agreement.

Esaki also described similar results on a new superlattice structure formed from alternating layers of InAs and GaSb. The major difference between this and the GaAs-$Ga_{1-x}Al_xAs$ system is the relative location of the zone-center conduction and valence-band energies; in the present case the GaSb valence-band edge lies above the InAs conduction-band edge. This requires more sophisticated theoretical treatment, but again nearly 2-D quantum subbands are formed and similar magneto-oscillatory behavior to that reported above is also observed.

In another invited talk R. Dingle described magnetoabsorption measurements in Grenoble on GaAs-$Ga_{1-x}Al_xAs$ superlattices carried out in very high magnetic fields . Similar field tilting experiments were performed, and the very complex spectra also showed nearly 2-D behavior or more 3-D behavior depending on the well parameters.

IV. Other Semiconductor MIS Structures

In spite of considerable effort relatively little progress has been made since the last Conference in the study of space-charge layers on semiconductor surfaces other than Si. This is primarily because of the difficulty in producing insulator-semiconductor interfaces with adequate electrical properties. The most success has been achieved by workers in Munich in studies of InSb space-charge layers.

Beinvogel *et al* reported the observation of intersubband resonances in n-inversion layers on p-type InSb where the gate insulator was provided by a 2-μm thick layer of a lacquer. There are several qualitative differences in the properties of space-charge layers on small-mass, narrow-gap semiconductors such as InSb or InAs and those of Si. In particular, the subband separations are much larger (due to the small mass) for a given n_s, and can be comparable to the energy gap; for reasonable values of n_s more than one subband is populated; and finally, the parameter r_s, characterizing the importance of many-body effects, is small indicating that they do not play a significant role. The comparability of the subband splitting and fundamental energy gap in InSb means there is strong admixture of valence-band edge wave functions into the "conduction band" subband states. This is probably the explanation for the observation of Beinvogel *et al.* of strong intersubband transitions with the IR electric field polarized parallel to the surface.

Additional oscillatory magnetoconductivity sutdies on InSb were reported by Dörr *et al* and cyclotron resonance by Kotthaus in his invited paper. The situation is somewhat complicated by the fact that several subbands are simultaneously populated, several beating oscillations are seen in the magnetoconductivity measurements, and several overlapping resonances are observed in the cyclotron resonance experiments.

In addition, there were reports of oscillatory magnetoconductance and/or cyclotron resonance of space-charge layers (generally accumulation layers) on InAs, PbTe and Te; and transport studies of very thin crystals of $Bi_2 (Te_{1-x}S_x)_3$ and accumulation layers on ZnO.

It is clear that these studies are in their infancy, and considerable work both experimental and theoretical is required to understand these properties in detail. Hopefully, additional effort will also provide better interface properties on other semiconductors that will also become amenable to space-charge layer studies.

V. Summary

It is clear from the excitement at the Conference, the variety of interesting work, and the energetic way it is being carried out, reported, and discussed, that the study of electronic properties of these nearly 2-D systems will be an active area for several years to come. It was announced at the Conference Banquet that the next conference will be held in Japan in 1979.

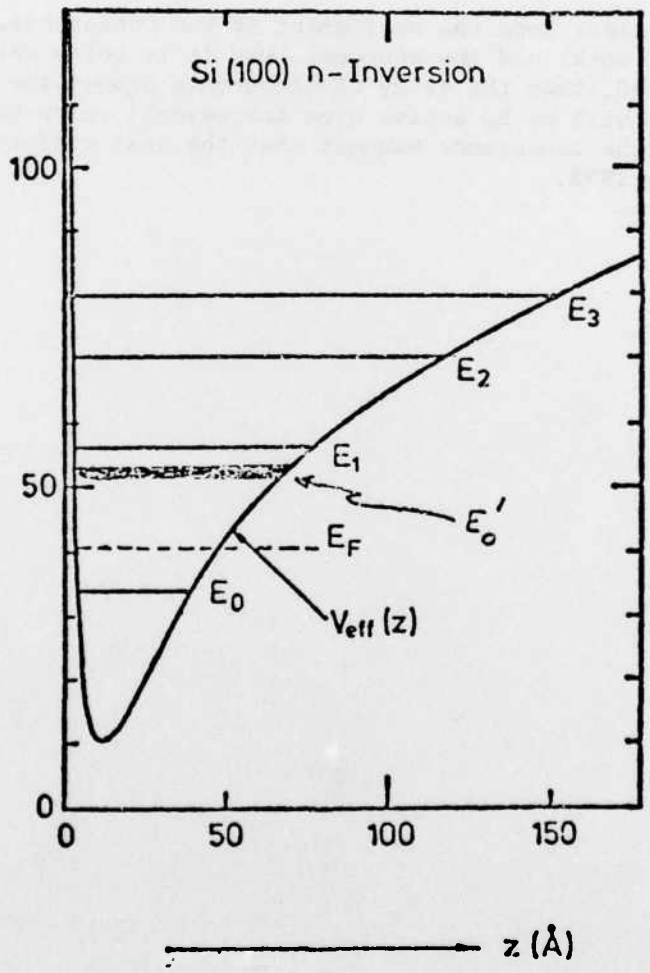


Figure 1.

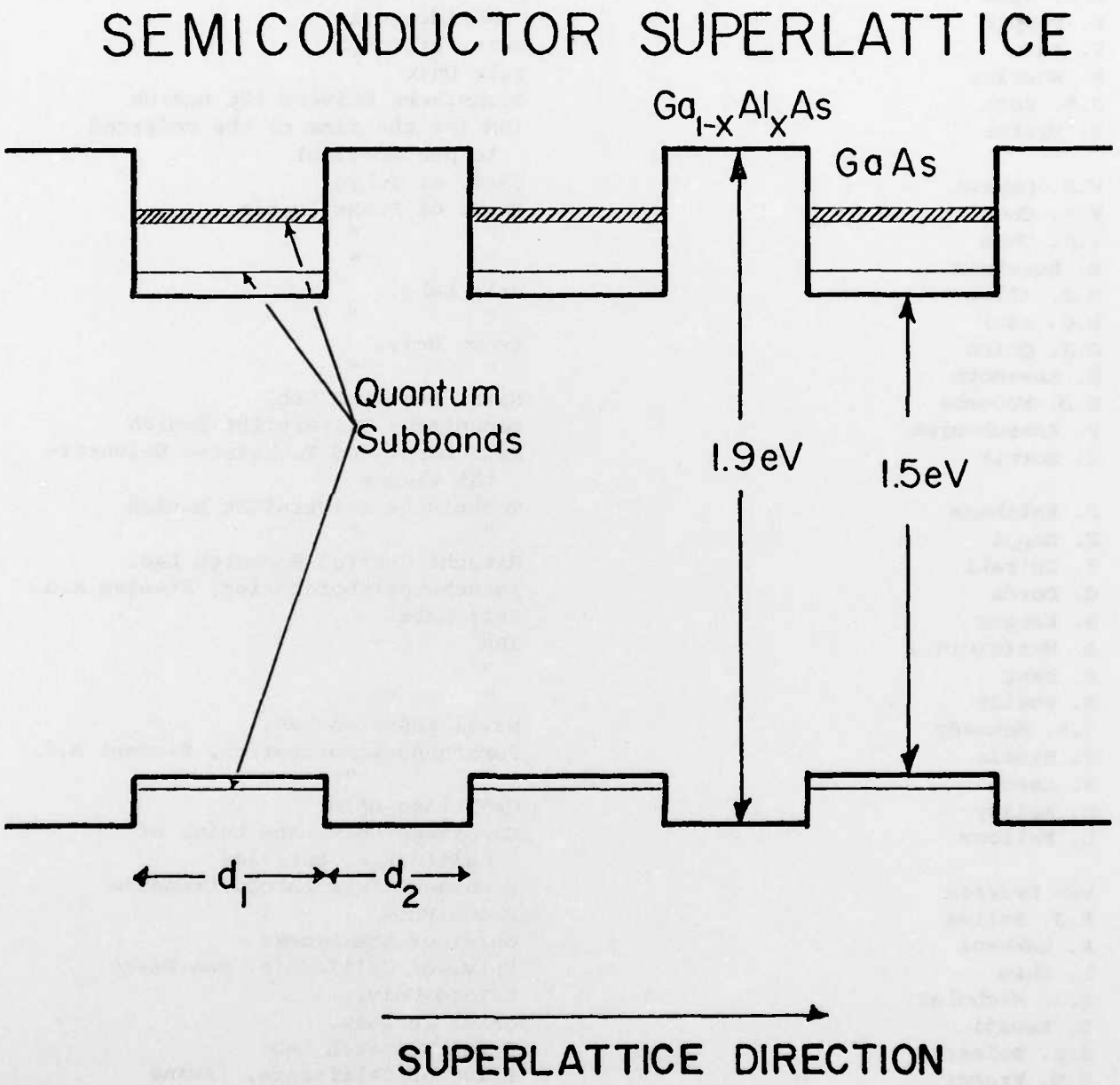
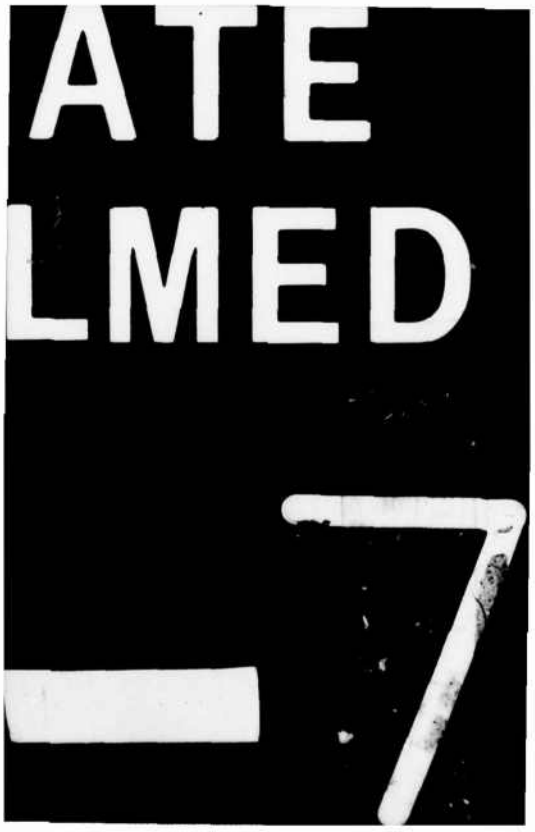

SEMICONDUCTOR SUPERLATTICE
$Ga_{1-x}Al_xAs$
GaAs
Quantum
Subbands
1.9eV
1.5eV
d_1
d_2
SUPERLATTICE DIRECTION

Figure 2.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