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Research on

New Kinds of Quantum Wells

First Annual Report
on
ONR Grant N00014-90-J-1413
Covering the period 1 Dec. 1989 – 30 Nov. 1990

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Abstract

The research concentrated almost exclusively on the InAs/AlSb quantum well system, with some supporting work on the GaSb/AlSb system. Many advances were made. The overall quality of the quantum wells improved, now routinely yielding room-temperature mobilities of 30,000cm^2/Vs for 15nm wide wells. A new two-donor model explains the electron concentrations, in terms of a deep EL2-like bulk donor and a mysterious interface donor near the bottom of the well, below the lowest quantum state. A first systematic study of transport properties vs. well widths was undertaken, showing a steep drop in mobility for well widths below 10nm. Cyclotron resonance data taken at the University of Munich give quantitative evidence of non-parabolicity under the combined effect of quantization and band filling. Field effect transistors and photoluminescence data continue to present difficulties. Tilted superlattices (TSLs) from the GaSb/AlSb system were demonstrated, with very promising properties, as were InAs quantum wells that incorporate GaSb/AlSb TSLs either as corrugated barriers or as periodic center loading. A record electron mobility for InAs (613,000cm^2/V·s) was obtained in the corrugated barrier well.

1) INTRODUCTION

The two-year grant that is the subject of this report is a follow-up to the earlier ONR Contract # N00014-87-K-0297. The two projects had overlapping subject matter, and the present Annual Report naturally includes research that was *initiated* already under the predecessor contract.

Essentially all our work during the one-year reporting period concerned itself with the improvement and study of InAs/AlSb quantum wells and related structures.

As was the case under the predecessor contract, our work stimulated great interest on the part of others, which led to several fruitful cooperations in which some of the individuals were supported by sources other than this ONR grant. To give a meaningful picture of the research done, the P. I. felt it necessary to include such mixed-sponsorship work in this report whenever there was at least one individual whose contribution to the work had been supported by this ONR grant, even if the P. I. himself was the only such individual. A complete list of participants and their sources of support is given at the end.

In addition to extensive mixed-sponsorship work, the P. I. was also involved in three projects that involved the InAs/GaSb/AlSb system, and which drew on the results of the ONR-supported research to an extent that they would never even have been attempted without that research, but for which none of the participants was supported under this ONR grant. Progress on those projects is not reported here. The first such project is DARPA-sponsored research on the use of InAs/AlSb quantum wells as superconducting weak links between superconducting Nb electrodes. The second project is Rockwell-sponsored research (under the UC-MICRO program) towards the realization of a P-n-P double heterostructure AlSb-InAs-AlSb bipolar transistor. The third project is a new cooperation with Los Alamos on strained-layer superlattices involving the InAs/InSb combination, for infrared detector applications. In all three cases the flow of benefits is two-way.

2) REPORT ON THE RESEARCH

2.1) Materials Preparation and Evaluation

2.1.1) Growth Procedure (C. Bolognesi)

Our "standard" growth procedure for InAs/AlSb quantum wells[1] was refined, leading to noticeably better transport properties. All previous growths had been initiated by nucleating a 50nm AlSb buffer layer directly upon the (polished and de-oxidized) GaAs substrate surface, followed by 1μm of GaSb buffer layer to accommodate the 7% lattice mismatch, followed by another 1μm of AlSb to act as the lower barrier to the InAs quantum well. Structures grown in this fashion typically exhibited room-temperature mobilities no higher than 25,000 cm^2/Vs. In the new growth scheme, the AlSb nucleation is preceded by a first 200nm GaAs buffer, followed by a 10-period $Al_{0.35}Ga_{0.65}As$-GaAs smoothing superlattice (2.5nm+2.5nm), followed by another 100nm of GaAs. Using this scheme, room-temperature mobilities ≥30,000cm^2/Vs for 15nm wide wells are now routinely achieved (**Fig. 1**).

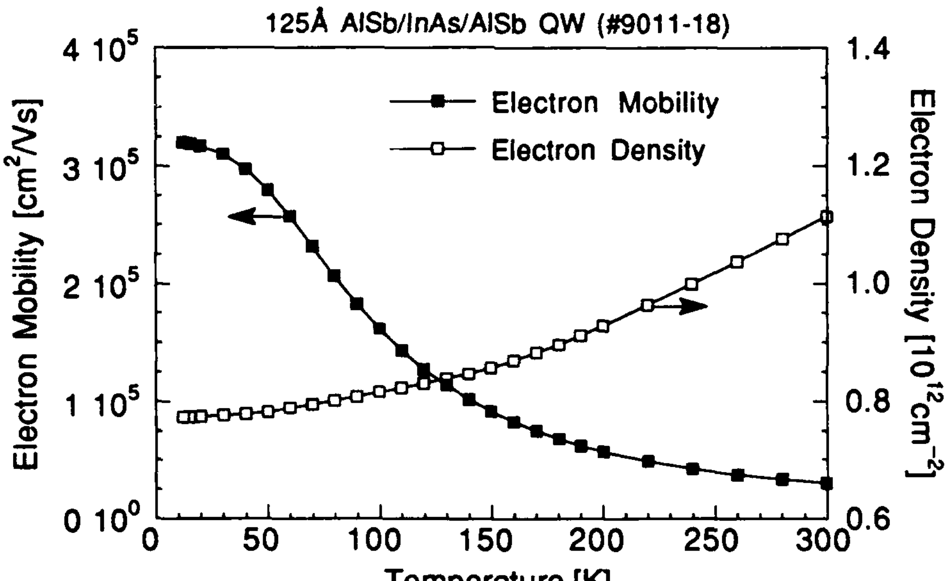

Fig.1. Transport properties of one of our better 12.5nm InAs/AlSb quantum wells.

These mobilities equal those of high-purity InAs bulk samples even though our samples have measured sheet electron density of approximately $10^{12}cm^{-2}$. The smoother surface presented to the AlSb nucleation is credited for the reduction of the defect density due to an enhanced two-dimensional layer-by-layer growth mode.

The data shown in Fig. 1, obtained by standard van der Pauw measurements, are typical *except* for the low-temperature mobilities, which still exhibit pronounced sample-to-sample variations. The value shown (320,000cm^2/Vs) is at the upper end of the *range* of values typically found; the lower end is around 200,000cm^2/Vs.

2.2) Donor and Defect Problems

2.2.1) Two-Donor Model for the Wells (C. Nguyen, B. Brar)

One of the most nagging problems since our very first work on InAs quantum wells has been the question as to the nature and spatial distribution of the donors that cause such a high electron concentration inside our not-intentionally doped wells, without interfering with the very high low-temperature mobilities in the structures. As we pointed out in the recent Final Report to the predecessor contract,

> "...the responsible donor cannot reside inside the InAs, but must be a deep donor of unknown origin inside the AlSb, most likely an antisite donor. But the peculiar slow increase of electron concentration with increasing temperature is the opposite of what one would obtain for a single *uniformly* distributed deep donor. We have been able to model the behavior by assuming that not-intentionally-doped AlSb contains a deep acceptor, and that the electrons are contributed by a high concentration of deep donors near the interface. But apart from being blatantly ad-hoc, such a model is hard to reconcile with the high low-temperature mobilities."

In order to shed more light on this question, a series of multi-quantum-well (MQW) structures with varying barrier widths was grown, along with a control sample with a single quantum well. The width of the quantum wells was kept fixed at 10nm in all cases. The measured *normalized* electron concentration N (i. e., the areal concentration *per well*) showed a strong and roughly linear dependence upon barrier width L_B, of the form

$$N(T) = N_{int}(T) + n_{bulk}(T) \cdot L_B \ . \tag{1}$$

Here, N_{int} is a width-independent contribution, presumably associated with the quantum well interfaces, and n_{bulk} a bulk contribution, presumably due to uniformly distributed donors in the barriers. By fitting the measured N against the barrier thickness, L_B, we were able to extract the temperature-dependent contributions from the barriers and the interface (**Fig. 2**).

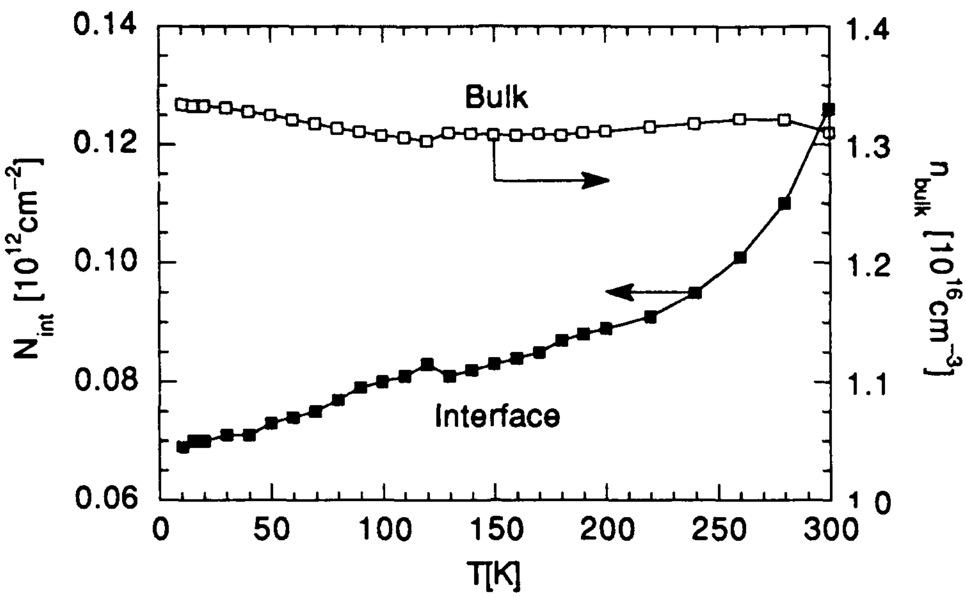

Fig. 2. Bulk and interface contributions to the electron concentrations.

Note that the two contributions have quite different temperature dependences, supporting the idea that there are two separate sources for the electrons in the wells. The bulk contribution is essentially temperature-independent, exactly as one would expect for a bulk donor that is significantly above the Fermi level throughout the width of the barrier, and hence fully ionized,[a] with a concentration $n_{bulk} \approx 1.3 \times 10^{16} \text{cm}^{-3}$.

The strong temperature dependence of the interface term suggests an interface donor *below* the Fermi level. A fit to a standard donor model with a spin degeneracy $g = 2$ leads to a donor level only 0.070 eV above the conduction band of InAs, which is actually about 56meV *below* the lowest free-electron quantum state E_1 in the 10nm well: The latter occurs about 126meV above the InAs conduction band, assuming a bottom-of-the-band effective mass of $0.023 m_e$, and including the $\mathbf{k} \cdot \mathbf{p}$ non-parabolicity corrections. The areal concentration if the interface donor is high, $N_{D,int} = 7.1 \times 10^{12} \text{cm}^{-2}$ per well, or half that value per interface.

Because of the temperature-independence of the bulk contribution, the energy level of the bulk donor cannot be obtained from the multi-quantum well data in Fig. 2. However, it is easily extracted from the data on the single-well control sample, where it controls the amount of band bending outside the well. Such a fit yields an energy

[a] A second — less plausible — interpretation is in terms of a donor right at the Fermi level, with a concentration about twice that of the electrons.

level about 0.58 eV below the conduction band of AlSb.[b] The overall model is shown in **Fig. 3.**

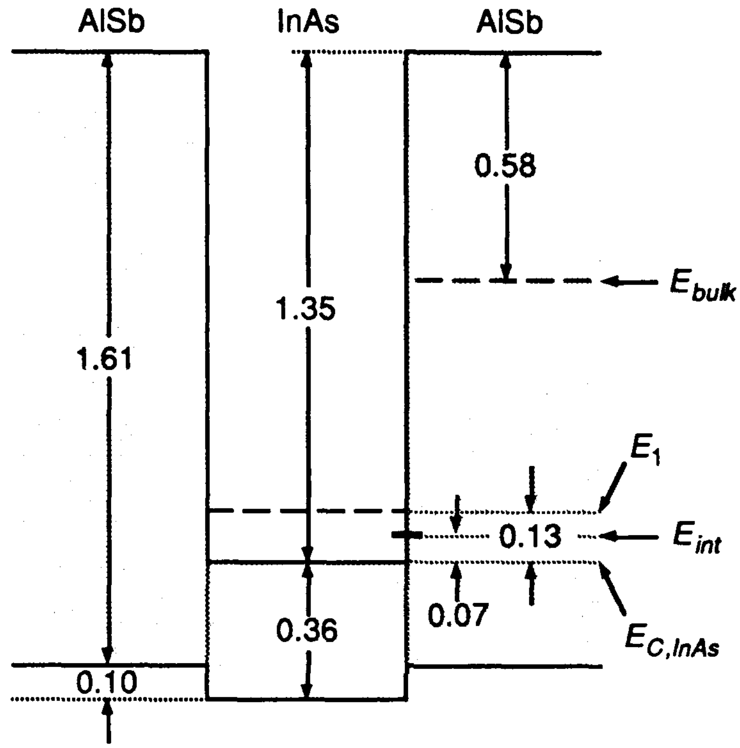

Fig. 3. Two-donor model for 10nm wide InAs/AlSb quantum well.

The quality of the overall fit is seen from **Fig. 4**, which shows the fit of the data for the single-well control sample to the two-donor model.

2.2.2) The Bulk Donor as an EL2-Like Antisite Defect.

The deep bulk donor is strikingly reminiscent of the deep EL2 donor in (Al,Ga)As, and we believe "our" donor to be simply the AlSb analog of EL2 in (Al,Ga)As. With the latter being presumably an As_{Ga} or As_{Al} antisite defect, its AlSb analog would be an Sb_{Al} antisite defect. The As_{Al} antisite donor we have invoked earlier as interface donor

[b] The fit is not unique. The overall data can be fitted just as well by assuming an even deeper (0.85eV) donor that is, however, no longer fully ionized, with the higher concentration $2.25\times10^{16}cm^{-3}$. The resolution of this ambiguity requires additional work, to be undertaken in early-1991.

at "arsenic-soaked" AlAs-like quantum well interfaces[2,3] would then simply be the arsenic analog of the bulk donor.

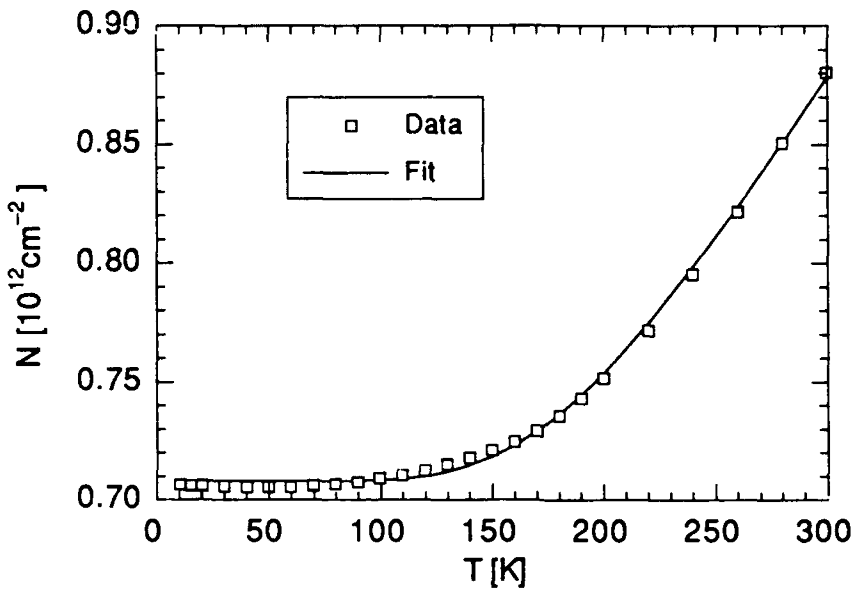

Fig. 4. Fit of single-well control sample to the two-donor model.

2.2.3) Is the Interface Donor Jellium-Like?

The big mystery is the nature of the new interface donor postulated by our analysis. It has two quite unprecedented properties: An essentially negligible effect on the electron mobilities in the well, and a bizarre energetic location. The latter immediately raises the question as to the dependence of this energy on quantum well width, and on the quantization energy in the well: Does it remain at a fixed distance relative to the InAs band edge or does it track the quantization energy? The answer to this question will be one of our highest-priority items for early-1991.

The properties of this new interface donor are totally different from those of the As-antisite interface donor referred to earlier, and the new donor cannot be identified with the As-antisite donor. Nor can it be a conventional impurity in InAs: In that case it would have to be present in a huge volume concentration ($\gg 10^{18}cm^{-3}$) which is over three orders of magnitude higher than the known background in our MBE machine. Also, the donor energy level, 56meV below the lowest quantum state, is totally wrong for an ionized impurity donor, even ignoring the presence of the huge screening charge. Most of all, such a high impurity concentration would cause massive impurity scattering and a drastic reduction in mobility, which is simply not what is observed. Note that the absence of massive impurity scattering can *not* be readily explained by the fact that most of the donors, being below the Fermi level, are not ionized: Neutral impurity scattering is not sufficiently weaker than ionized impurity scattering, because the neutralizing electron cloud is highly de-localized, leaving the very strong local scattering potential around each ion largely intact.

In fact, this mobility argument seems to rule out *any* kind of charged *point* defect, including charged point-like *structural* defects. Thus, we are inexorably pushed towards the exotic hypothesis that the interface donor is not a point defect at all, but is an extended "jellium-like" charged object, highly de-localized at least *along* the interface plane.

This "Jelly Sandwich" model is not totally bizarre. One possibility we are considering is that the donor is a true Tamm state, that is, an interface state caused by the band structure discontinuity itself, rather than by any defect. Another possibility is that the donor is caused by many-body effects. Clearly, further research is necessary, and we expect this problem to be one of our main research topics during 1991.

2.2.4) Transport Properties vs. Well Width (C. Bolognesi)

With decreasing well width, the transport properties of quantum wells are expected to become strongly dependent on well width: Increasing quantization effects are expected to lead to some decrease in electron concentration, and increasing interface roughness scattering is expected to lead to a drastic decrease in the low-temperature electron mobilities,[4] roughly like w^{-6}. We have made an initial attempt to study these dependences; the 10K data are shown in **Fig. 5**.

Although these first data evidently still suffer from run-to-run variations, the expected steep falloff of mobility for narrow wells is clearly present, however, it is much weaker than the theoretical w^{-6} model, especially at the narrow-well limit.

There is also a weaker falloff for wide wells, which we believe to be real rather than a run-to-run variation. There are two quite different possible explanations for the wide-well falloff: (a) Scattering by misfit dislocations introduced into the wells for well widths above 12nm, or (b) inter-subband scattering, due to the reduced quantization in wider wells. We have not attempted to resolve this question; we consider such wider wells of lesser interest.

A very puzzling feature of the data, not visible in Fig. 5, is a very steep increase in the electron concentration in the narrowest (40Å) well with increasing temperature, to about $1.7 \times 10^{12} cm^{-2}$ at 300K. This a increase — by more than a factor of 5 — is much larger than anything we have ever observed. In fact, the 300K electron concentration in the 40Å well is higher than that in the wider wells. It may be possible to explain such a behavior in terms of the new two-donor model discussed above, by making enough ad-hoc assumptions about the dependence of the interface donor on the quantization energy inside the well. There was not enough time to attempt such a fit before this report had to be written, and such an attempt should in any event be backed up by additional data taken on additional samples, to see whether or not the observation is in fact reproducible. Such additional runs are planned for early-1991.

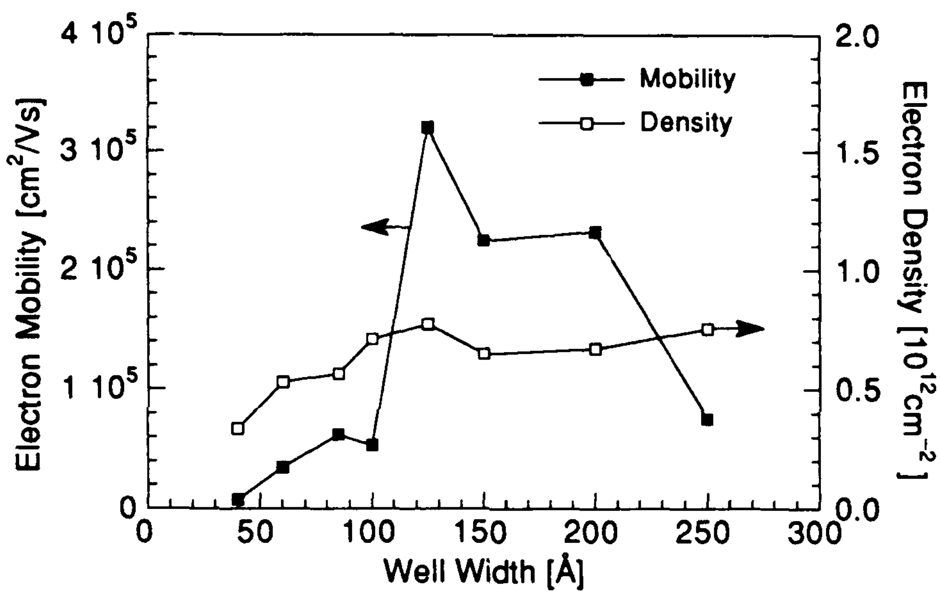

Fig. 5. Transport data at 10K as functions of well width.

2.2.5) Effects of Substrate Misorientation (S. Chalmers)

As a by-product of attempts to grow tilted superlattices (see item 2.6.2 below), we noticed that the low-temperature mobilities in "flat" (i.e. non-tilted) quantum wells grown on deliberately tilted ($\approx 2°$) substrates appear to by systematically higher than on nominally untilted (100) substrates. We expect to have detailed quantitative data by early-1991.

2.2.6) The Arsenic Antisite Interface Donor (C. Bolognesi)

A casual observation made near the end of the predecessor contract suggested that the As-antisite donor discovered earlier[2,3] would drain electrons only into InAs, but not into GaSb. This matter was pursued further, by actually growing a GaSb quantum well with AlSb barriers, and incorporating an As-antisite doping sheet into the AlSb barrier, about 10nm away from the well. We found that the GaSb well was strongly p-type. This observation places the donor level below the GaSb conduction band at a GaSb/AlSb interface, at least 420 meV below the AlSb conduction band, and probably much more. This is consistent with the behavior of the related EL2-like antisite *bulk* donor discussed above. An exact determination of the energy of the As_{Al} level remains to be made.

2.3) Optical Properties of InAs/AlSb Wells

2.3.1) Photo-Luminescence – or Lack Thereof (B. Brar)

Numerous attempts were undertaken to characterize our wells by PL, all without success. It appears that non-radiative recombination totally dominates the recombination. Possibly, this is a result of the staggered lineup of the bands at the well interfaces and/or of the deep interface donor. Be that as it may, we have temporarily abandoned further attempts to characterize our wells by photoluminescence, and are currently setting up for *absorption* measurements in multi-quantum well structures.

2.3.2) Negative Persistent Photoconductivity (G. Tuttle, P. Hopkins, C. Nguyen, A. Wixforth)

Although no systematic studies of the negative PPC effect were undertaken during the reporting period, numerous "everyday" observations of the effect were made by almost everybody participating in the study of these wells, including individuals outside UCSB. Some of these observations revealed a great deal of new detail.[c]

The strength of the negative persistent photoconductivity (PPC) effect decreases strongly with decreasing photon energy. This is not surprising. What *is* surprising is that the *saturation level* of the reduction in carrier concentration under continuous illumination, $-\Delta N_0$, decreases both with decreasing photon energy and with decreasing illumination intensity. Furthermore, the PPC effect occurs even for photon energies significantly below the energy gap of AlSb, for example, under illumination with a GaAs laser. The long-wavelength response appears to be strongly sample-

[c] Some of the observations reported below were already made under the predecessor contract, but were never specifically reported before now.

dependent. In fact, in two samples, Dr. Wixforth of the University of Munich, with whom we have started to cooperate (see item 2.4 below), has observed a *positive* PPC under IR illumination, even though illumination by a red or green LED shows a negative PPC.

Several of these observations do not fit our earlier simple model of the negative PPC effect,[1] in which we assumed that electron-hole pairs are generated across the gap inside the AlSb barriers, the holes being collected by the quantum wells, where they reduce the electron concentration by recombination, and the electrons being trapped by deep donors. The new observations seem to call for a *two-stage* excitation process, presumably via a deep level in the AlSb gap. For example, an electron might be ejected from an occupied deep donor in the AlSb barrier (outside the depletion layer adjacent to the barrier), a process possible with sub-gap photons. At weak illumination intensities, this donor is likely to recombine with an excited electron. But at sufficiently high illumination intensities, that deep donor might be re-occupied by exciting an electron from the valence band, leaving a hole, which then acts as in the original model. All this is clearly speculative, requiring additional work.

2.3.3) Recovery from Negative Persistent Photoconductivity (G. Tuttle)

Whatever the mechanism by which negative PPC is created, the recovery of the equilibrium carrier concentration upon warm-up appears to be thermally activated, with an activation energy of about 0.26 eV. This energy was obtained from an Arrhenius plot of the recovery rate as a function of temperature, in the course of work done already under the predecessor contract, but not previously reported.

2.4) Cyclotron Resonance (A. Wixforth)

During 1990, we initiated what promises to be a very productive cooperation with Professor Kotthaus and Dr. Wixforth at the University of Munich. Prof. Kotthaus is a frequent visitor to the UCSB Physics Department, and Dr. Wixforth spent a year at UCSB as a postdoc. Together, they have developed at Munich a superb far-infrared magneto-transport capability.

The previous research interest of Dr. Wixforth has been the use of this capability to study the electron transport in surface layers, and especially the miniband formation that takes place at slightly mis-oriented surfaces, due to periodic surface steps. The method appears ideally suited to a study of our quantum wells, even more so than to the study of GaAs surface layers. When we pointed this out to Dr. Wixforth, he eagerly proposed a collaboration on this topic, and we provided him with an initial batch of samples for practicing

We have just received the first results from this cooperation, in the form of excellent cyclotron resonance data on some of these wells. The data show a strong dependence of the cyclotron resonance effective mass on carrier concentration, as a result of the strong non-parabolicity of the conduction band structure of InAs. For example, a 12nm wide well with a sheet concentration of $1 \times 10^{12} \mathrm{cm}^{-2}$, yields an effective mass of $0.040 m_e$, as opposed to the literature value of $0.023 m_e$ at the bottom of the conduction band of bulk InAs. We were able to fit Wixforth's data nearly perfectly to a Kane-type model; Wixforth himself has confirmed our analysis.

While analyzing the data, we discovered a theoretical relationship between the cyclotron resonance effective mass and the 2-D density of states, in the form

$$m^*_{CR} = \pi\hbar^2 \cdot D_2(E_F)\ . \qquad (1)$$

This relation has been known for some time to hold for isotropic parabolic bands; we were able to show that it holds even in the presence of arbitrary non-parabolicity and anisotropy of the bands. We believe this generalization to be new.

2.5) FETs (C. Bolognesi, J. Werking)

Numerous attempts to make better FETs than the mediocre devices reported earlier[5, 6] led essentially nowhere. Our best transconductances, under 200mS/mm, are at least an order of magnitude below what *should* be possible with conducting channels having carrier concentrations and mobilities as our wells. More embarrassingly, our results are a factor of 3 below what others *have* achieved[7] using structures that have *inferior* non-FET transport properties compared to ours. Somehow, we are not able to modulate the electron concentration in our channels efficiently, but we do not know why.

In order to test whether the poor transconductances were due to channel pinning by interface states, a gated Hall effect structure was built, to measure the actual modulation of the carrier concentration by the gate electrode. The result, obtained at low temperature, showed that the modulation was, within the accuracy of the measurement, equal to the value expected theoretically for the known gate-to-channel distance, which was corroborated by a gate capacitance measurement. At room temperature, excessive gate leakage made it impossible to obtain any data permitting the extraction of the modulation efficiency.

The FET goal is not one we are going to give up easily, and we have a number of ideas concerning device design modifications, which we will try out in early-1991.

2.6) Tilted Superlattices

2.6.1) Tilted GaSb/AlSb Superlattices and their Luminescence Properties (S. Chalmers, B. Brar, H. Weman)

As we had reported in the Final Report to the predecessor contract, we had failed in a first attempt to grow tilted InAs/GaSb superlattices, and had therefore decided to go back to the GaSb-AlSb pair extensively studied earlier. Attempts to grow tilted superlattices with that pair were very successful almost immediately. Two papers on the first of these structures have already appeared in print;[8, 9] we report here on progress made since then, especially photoluminescence data.

All structures investigated showed PL peaks that could be interpreted as superlattice peaks, but might also be ordinary alloy peaks. In order to discriminate between the two possibilities, polarization-sensitive PL measurements were performed. Theory predicts that the PL intensity for an anisotropic electron gas such as it should be present in a tilted superlattice, the luminescence intensity for an electric vector parallel to the wafer step edges should be twice as strong as for perpendicular polarization,[10] whereas luminescence from a disordered alloy should be unpolarized.

Data exhibiting that behavior are shown in **Fig. 6**, from a recent sample that contained a 12nm thick TSL layer, on top of an equally thick *random* alloy layer with the same overall Al:Ga ratio (35:65). The two layers were separated by an 18nm AlSb barrier, and confined on top and bottom by similar barriers. Two distinct PL peaks were observed, separated by approximately 30meV. The higher-energy peak exhibited the polarization predicted for a TSL, the lower-energy peak did not. Subsequent samples omitting either the alloy or the TSL confirmed the identification of the higher-energy peak with the TSL and the lower-energy peak with the alloy.

Lifetime measurements were also performed, indicating a recombination lifetime of 750 ps for the TSL peak.

The energetic ordering of the two peaks is surprising. Normally, one would expect the SL peak to occur at lower energy, unless the random alloy exhibits extraordinarily strong bowing in its energy gap vs. composition relation. The energy band structure of LPE-grown (Al,Ga)Sb alloys as a function of composition has been determined with excellent precision by Alibert et al.,[11] indicating a degree of bowing insufficient to explain the energy reversal. However, bowing is often due to near-range ordering in the alloy, which may depend on the growth technology employed. For example, Kondow and Minagawa[12] have reported a drastic reduction in energy gap of (Al,In)P and (Ga,In)P alloys grown by OMVPE relative to that in LPE-grown alloys, presumably due to greater ordering in the OMVPE alloys. We are tentatively speculating that a similar enhanced bowing may exist in MBE-grown (Al,Ga)Sb alloys, relative to LPE-grown alloys.

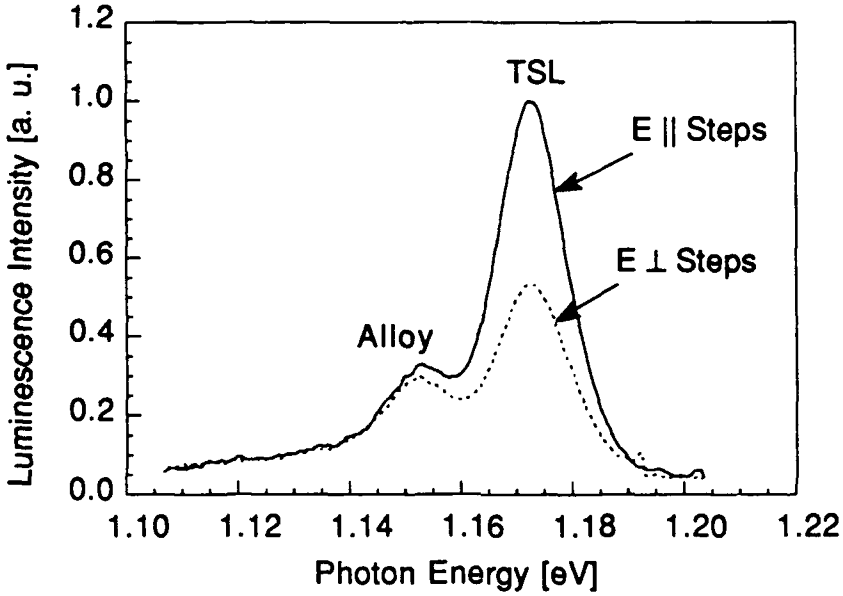

Fig. 6. Luminescence spectrum of a GaSb/AlSb TSL structure

In fact, inasmuch as ordering may be viewed as a precursor to spinodal decomposition of the alloy, which would aid the phase separation during TSL growth, the reversed PL peak ordering may be related to our observation that (Al,Ga)Sb TSLs are significantly easier to grow than (Al,Ga)As TSLs.

2.6.2) Corrugated Quantum Wells (S. Chalmers)

Following our success with tilted GaSb/AlSb superlattices, we returned to our goal of incorporating broken-gap InAs/GaSb interfaces into a tilted superlattice, but with a new twist, which combines this goal with the other goal of achieving corrugated quantum wells, for assorted transport effects. Two structures were grown and analyzed, both combining a smooth InAs quantum well with one or two GaSb/AlSb TSLs. (**Fig. 7**)

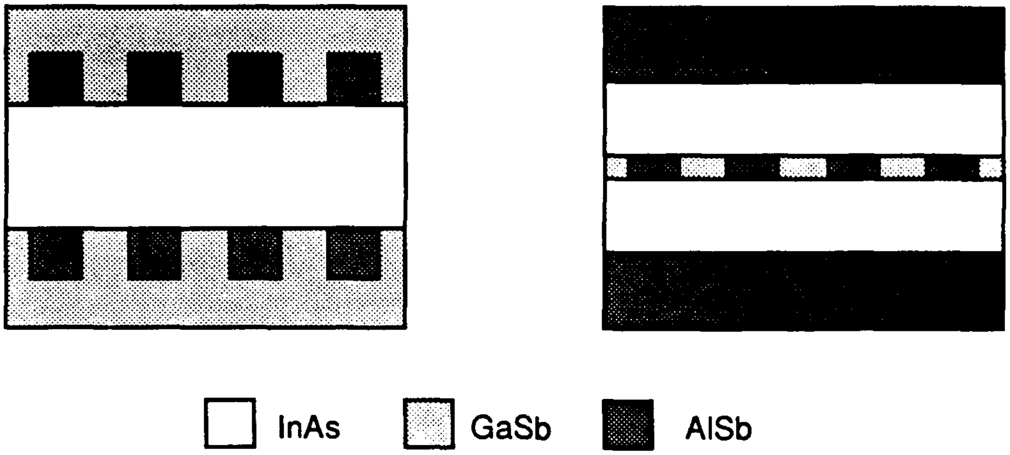

Fig. 7. InAs quantum wells with corrugated GaSb/AlSb barriers and with periodic center loading

In the first structure, a smooth InAs quantum well was given corrugated barriers on both sides, by using tilted GaSb/AlSb superlattices as barriers.[13] To our great surprise (and disappointment), this structure exhibited no transport anisotropy, but it rewarded us with the highest low-temperature mobility ever seen in InAs, 613,000cm^2/V·s.

In the second structure, an otherwise ordinary InAs/AlSb quantum well was periodically "center-loaded" by inserting a thin GaSb/AlSb TSL sheet into the center plane of the well. This structure showed a 2:1 mobility anisotropy.

Both kinds of structures are currently under intensive further investigation, and we expect to have more detailed quantitative data by early-1991.

2.7) Serpentine Superlattices

The P.I. participated actively in the new serpentine superlattice effort described in the Final Report to the predecessor contract.

Several such structures were grown by Mark Miller, a graduate student supervised jointly by the P. I. and Professor Petroff. The most recent and most successful of these structures exhibited a polarized photoluminescence peak readily identifiable as the desired SSL peak. The success of the SSL scheme was demonstrated by the fact that the peak was not much broader than a homogeneous random alloy peak with the same overall Al:Ga ratio, and — most importantly — that the photon energy was essentially the same over the entire wafer area, something never seen in "ordinary" (non-serpentine) TSLs.

2.8) References to Secs. 2

1 G. Tuttle, H. Kroemer, and J. H. English, J. Appl. Phys. **65**, 5239 (1989).

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3) PUBLICATIONS AND PRESENTATIONS RESULTING FROM THIS RESEARCH

3.1) Papers Published

All papers either published or submitted during the reporting period still draw on work already initiated under the predecessor contract, and hence a complete list of these papers was already included in the recent (delayed) Final Report to that contract; this list is not repeated here.

3.2) Invited Presentations at Topical or Scientific/Technical Society Conferences[d]

Innovative Long-Wavelength Infrared Detector Workshop, Pasadena, CA, April 1990:
"AlSb/InAs/AlSb Quantum Wells."

3.3) Contributed Presentations at Topical or Scientific/Technical Society Conferences

Electronic Materials Conference, Santa Barbara, CA, June 1990:
"A RHEED study of InAs(100) and GaSb(100) singular and vicinal surfaces,"
(by S. A. Chalmers, H. Kroemer, A. C. Gossard, and J. H. English)

International Conference on Molecular Beam Epitaxy, San Diego, Aug. 1990:
"Tilted Superlattice Growth in the (Al,Ga)Sb System,"
(by S. A. Chalmers, H. Kroemer, and A. C. Gossard)
"Serpentine Superlattice: "Concept and First Results,"
(by M. S. Miller, C. E. Pryor, H. Weman, L. A. Samoska, H. Kroemer, and P. M. Petroff)

4) SCIENTIFIC PERSONNEL SUPPORTED UNDER THIS CONTRACT, AND DEGREES EARNED

4.1) Principal Investigator

Professor Herbert Kroemer: Support throughout entire contract period.

4.2) Post-Doctoral Research Associates

none.

4.3) Research Assistants working towards a Ph.D. Degree

Mr. Colombo Bolognesi: Full support.

[d] Items 3.2 and 3.3 list only presentations given by the P. I. himself or by a student supervised or co-supervised by the P. I. Presentations by others, listing the P. I. as a co-author, are omitted.

Mr. David Braun (supervised jointly with Prof. Heeger): Partial support (33%) until summer 1990, at which time support for Mr. Braun under this grant was terminated, and Prof. Heeger assumed the full responsibility for Mr. Braun.

4.4) Research Assistants working towards an MS Degree

Mr. Bobby Brar: Full support. — Note: In the Final Report to the predecessor contract, Mr. Brar had been erroneously reported as working towards a Ph. D. degree.

4.5) Individuals Contributing to this Research, but not receiving Financial Support from the Grant

Professor Arthur C. Gossard: Participant in all MBE and tilted-superlattice work.

Professor Evelyn Hu: Participant in all FET work, especially all device processing aspects.

Professor James L. Merz: Advisor and contributor to photoluminescence work.

Professor Pierre M. Petroff: Participant in all tilted superlattice work.

Dr. Helge Weman: Postdoc under Professor Merz, is in charge of Prof. Merz' photoluminescence laboratory and as such co-supervised all photoluminescence work conducted under this grant, and contributed to it.

Dr. Peter Hopkins: Performed quantum Hall effect measurements while a graduate research assistant under Prof. Westervelt at Harvard; also contributed valuable observations on the persistent photoconductivity effect. He is now a postdoc under Prof. Gossard at USCB, supported by NSF through the "QUEST" Science and Technology Center.

Mr. Scott Chalmers (co-supervised by Profs. Gossard and Petroff):. During the reporting period, Mr. Chalmers was supported by NSF through the "QUEST" Science and Technology Center.

Mr. Mark Miller (co-supervised by Prof. Petroff): During the reporting period, Mr. Miller was supported by an AFOSR contract with Prof. Petroff as P. I.

Mr. Chanh Nguyen: Graduate research assistant under the P.I., working principally on InAs/AlSb superconducting weak links, supported by a DARPA contract with Prof. Hu as P.I.

Mr. Jim Werking: Graduate research assistant under Professor Hu, working on device processing research, supported by a DARPA contract with Prof. Hu as P.I.