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13. ABSTRACT *(Maximum 200 words)*

We have successfully pursued the construction of high quality three-dimensional electron gases by the growth of wide parabolic GaAs quantum wells with modulation doping. The concept has worked -- by growth of wide, specially shaped wells with remote doping, we can allow high mobility electrons to spread out over regions thousands of Angstroms thick and have three-dimensional behavior without the impurity scattering and carrier freezeout of conventional semiconductors. Electron mobilities of several hundred thousand cm^2/Vs have been achieved. The wide parabolically shaped well system is fundamentally new, and the structures are showing a variety of new behavior. Electrical quantum conductivity phenomena due to occupancy of several subbands have been observed. Cyclotron resonance, plasma resonance, and coupled cyclotron/plasma resonances have been found and all have characteristics of a three-dimensional gas in a parabolic potential. The first evidence of strongly enhanced non-linear responses in the far-infrared submillimeter wavelength range were found. Capacitance oscillations as a function of voltage applied to surface gates on the structures were studied, and photoluminescence and photoluminescence excitation spectra of the electron excitations were observed.

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SUBJECT:	Final Technical Report, January 1, 1988 - December 31, 1990 Grant Nr. AFOSR-88-0099 (UCSB 08 148 88) "High Quality Three-Dimensional Electron Gases in Semiconductors"
TO:	Air Force Office of Scientific Research
ATTN:	Dr. Gerald L. Witt AFOSR Bolling AFB, DC 20332
FROM:	Professor Arthur C. Gossard Materials and ECE Departments University of California, Santa Barbara
DATE:	January 8, 1991

A. OBJECTIVES:

In this research, our objective has been to create and study the first semiconductor structures with electron gases having three degrees of motional freedom and having high electrical conductivity. While great progress had been made in the production and applications of two-dimensional electron gases in MOSFETs and in GaAs heterostructures, no comparable progress had been made in the development of a high quality three-dimensional electron gas before the start of the present research.

The general objectives of research under Grant Number AFOSR-88-0099 were to:

A. Produce high quality three-dimensional electron gas structures in semiconductors by growth of new modulation-doped heterostructures containing wide graded potential wells with carriers introduced by modulation doping,

B. Characterize the three dimensional electron gases structurally, electrically, and optically, and

C. Explore new phenomena and potential device applications associated with the materials.

In order to achieve these objectives, our specific goals were to:

1) grow wide modulation doped parabolic quantum wells with calibrated composition profiles and high electron mobility,

2) compare analog (graded) and digital (short period superlattice) alloy growth and find effects of alloy disorder and order,

3) determine carrier density profiles and carrier mobilities and correlate them with the structure of the wells and with growth conditions,

4) observe quantum electrical resistance phenomena,

5) measure electrical capacitance of quasi three dimensional electron gas structures

6) characterize the optical properties of full and empty potential wells by optical absorption, optical emission and light scattering,

7) observe infrared excitations of the three-dimensional electron gas, including cyclotron resonance, plasma resonance, and intersubband absorption in the submillimeter wavelength range,

8) study non-linear response in symmetric and asymmetric wells in this wavelength range,

9) search for ordering phenomena due to electron-electron interactions in three dimensions,

10) make tunable infrared device structures.

B. STATUS OF RESEARCH EFFORT:

- Executive summary --

We have successfully pursued the construction of a high quality three-dimensional electron gas by the growth of wide parabolic GaAs quantum wells with modulation doping. The concept has worked -- by growth of wide, specially shaped wells with remote doping, we can allow high mobility electrons to spread out over regions thousands of Angstroms thick and have three-dimensional behavior without the impurity scattering and carrier freezeout of conventional semiconductors. Electron mobilities of several hundred thousand cm^2/Vs have been achieved. We have grown approximately forty structures, have made measurements on them at the University of California, Santa Barbara, and have initiated collaboration on theory and measurement with several other research groups, both here in Santa Barbara and at Harvard University and at Hamburg and Munich in Germany. The wide parabolically shaped well system is fundamentally new, and the structures are showing a variety of new behavior. Electrical quantum conductivity phenomena due to occupancy of several subbands have been observed. Cyclotron resonance, plasma resonance, and coupled cyclotron/plasma resonances have been found and all have characteristics of a three-dimensional gas in a parabolic potential. The first evidence of strongly enhanced non-linear responses in the far-infrared submillimeter wavelength range were found in asymmetrically shaped wide wells studied by collaborators in the UCSB Quantum Institute. Capacitance oscillations as a function of voltage applied to surface gates on the structures have been found and modelled, and photoluminescence and photoluminescence excitation spectra of the electron excitations have been observed with new behaviors, as detailed below.

- Concept --

The concept of achieving a nearly three-dimensional electron gas while reducing electron-impurity interactions was introduced by Gossard and Halperin, who proposed the growth of remotely doped wide parabolic quantum well structures as a means of achieving the nearly ideal electron gas. In such wells, the conduction band edge potential $V(z) = Az^2$ of the undoped well mimics the potential of a uniform positive slab of material of positive charge density $n_0 = A\varepsilon/2\pi e^2$, where ε is the dielectric constant of the material and e is the electron charge. The band profile in the doped and undoped parabolic well are illustrated in Figure 1. In the AlGaAs system, the conduction band edge potential is nearly proportional to the aluminum content in the alloy. Electrons are introduced into the system by remotely doping the wide parabolic well structure with donor atoms in the barrier layer regions outside the well. The electrons from the donors fall into the well, where they screen the parabolic potential of the well and distribute themselves in a nearly uniform layer of density equal to the positive charge density that would produce the original unscreened parabolic potential.

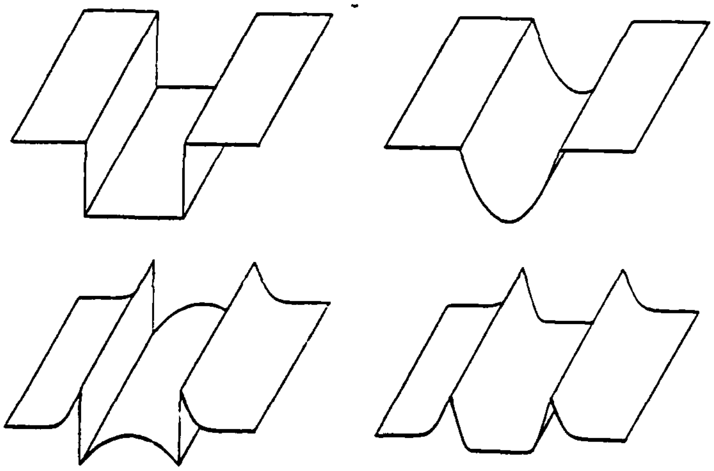

Figure 1. Band profile in undoped and doped square and parabolic wells where doping is added outside the well. Electrons accumulate at the potential minima at the interfaces for the square well, but distribute uniformly in the nearly flat potential within the parabolic well.

- <u>Growth</u> --

Wide parabolic quantum wells were grown both by a high precision grading technique that involves computer-controlled chopping of the aluminum molecular beam in a short period (~20 Å) graded superlattice[1] and by a temperature-controlled aluminum oven deposition technique that varies the aluminum oven temperature during growth.

The digital alloy technique is shown schematically in Figure 2. A superlattice with a constant period of 20 Å is grown. The duty cycle of the Al in each period is varied in the desired fashion, say parabolic, by computer control of the Al oven shutter in the MBE machine. The carrier 'sees' an average Al mole fraction, in effect an analog alloy. Using the fact that the bandgap of $Al_xGa_{1-x}As$ is directly proportional to the Al mole fraction over a large range of x values (0 to 0.45), the result is a graded bandgap directly proportional to the graded alloy composition. To synthesize a wide graded potential that corresponds to a uniform positive charge density of ~ $2x10^{16}$ cm^{-3} would require a 2000 Å wide parabolic well in which the Al mole fraction went quadratically from zero at the center to 0.2 at the edges.

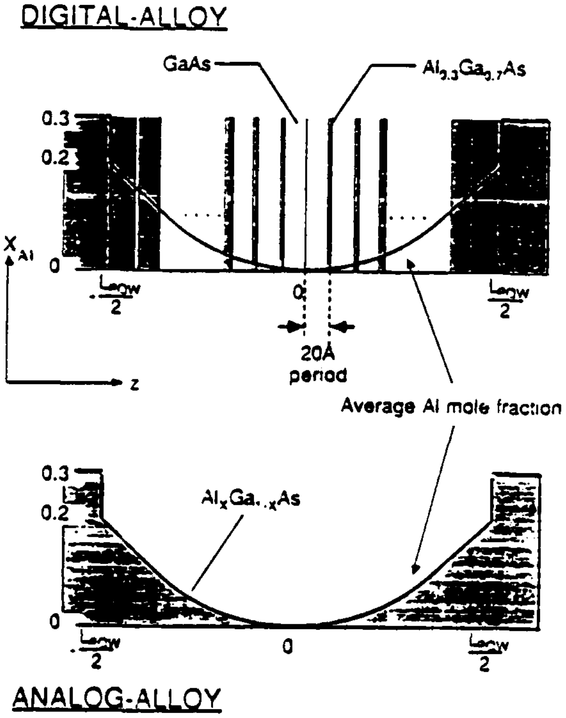

Figure 2. Digital alloy and analog alloy parabolic well compositional profiles.

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[1] M. Sundaram, A. C. Gossard, J. H. English, and R. Westervelt, Superlattices and Microstructures <u>4</u>, pp. 683-691 (1988).

- Well shapes --

The shape of the Al content profile in the graded alloy were measured by monitoring the variation with time of the collector current of an ion gauge flux monitor at the position of the substrate. Comparisons between the measured flux profiles for digital and analog alloys are shown in Fig. 3. The measured Al mole fraction (m.f.) vs. depth profiles for a 2000Å wide parabolic well with Al m.f. going from 1% at the center to 30% at the edges, grown with both the pulsed Al beam (digital alloy), and the variable Al oven temperature (analog alloy) methods are shown. The design profile is also shown for comparison. A constant background GaAs growth rate of 0.75 µm/hour is assumed. The bottom half of the figure shows deviations of both measured alloy-grades from the design alloy.

To verify experimentally that the digital alloy technique does indeed work like an analog alloy, parabolic quantum wells grown using this technique were optically tested through photoluminescence excitation spectroscopy. Harmonic oscillator like exciton transitions were seen in the spectra as shown in Fig. 4. Shown is an excitation spectrum for a sample comprising ten undoped 520 Å - wide parabolic quantum wells with Al content going from zero at the center to 0.3 at the edges as pictured in Fig. 4a.[2] The peaks in the excitation spectrum reflect the harmonic oscillator like transitions between electron and hole states and confirm the electron and hole energy level spacings for parabolic wells.

More recently, excitation spectra have been measured on our doped and undoped wide parabolic well samples by John Burnett and Prof. William Paul at Harvard.[3] The undoped parabolic well shows the simple harmonic oscillator spacings of electron and hole energy levels for parabolic potentials, whereas the doped parabolic wells show a different spacing of optical absorption lines. The doped well spectra are not yet completely understood. Professor Lu Sham of the University of California at San Diego is currently spending a sabbatical leave with us at Santa Barbara and is currently working on this problem, for which he is developing a possible single particle explanation.

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[2] M. Sundaram, A. C. Gossard, and J. H. English, "Modulation Doped Graded Structures: Growth and Characterization", Journal of Applied Physics, to appear.

[3] J. H. Burnett, H. M. Cheong, W. Paul, P. F. Hopkins, E. G. Gwinn, A. J. Rimberg, R. M. Westervelt, M. Sundaram, and A. C. Gossard, "Photoluminescence Excitation Spectroscopy of Remotely Doped Wide Parabolic GaAs/$Al_x Ga_{1-x}As$ Wells", Physical Review B, to appear.

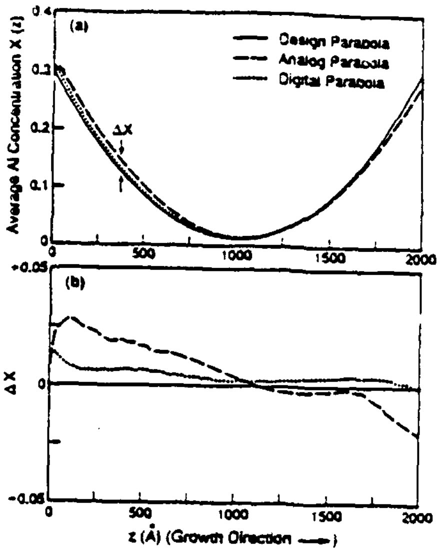

Figure 3. Average aluminum concentration, X(z), profile for design parabola and measured for analog parabola and digital parabola with in situ ion gauge flux monitor. Deviations from the design profile are shown in the bottom half.

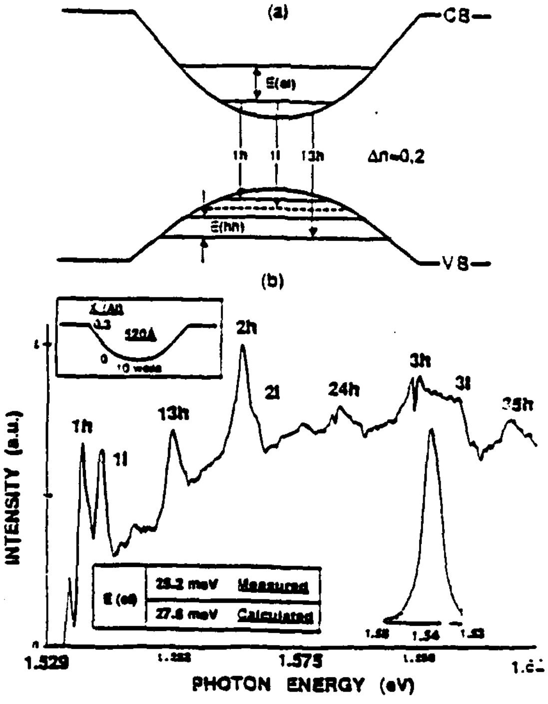

Figure 4. Energy levels and optical interband transitions in an undoped 520 Å parabolic quantum well are shown at top. Observed photoluminescence excitation spectrum and emission peak are shown at bottom.

- Mobility measurements

Electrical measurements of Hall mobility of electrons in modulation-doped wide parabolic wells have shown mobilities greatly enhanced over values obtained for uniformly doped materials and have also revealed the occurrence of significantly reduced carrier freezeout.[1] Typical Hall mobility (parallel to the superlattice layers) and concentration vs temperature for the 3DEG in a 2000 Å wide parabolic well with a curvature ~2.2×10^{16} cm^{-3} is shown in Fig. 5. Spacer layers of width 200 Å were inserted between the well and the barrier charge, on either side. Low temperature Hall mobilities as high as 3×10^{5} cm^{2}/Vs have been obtained in such samples. The superior mobility of the quasi-three-dimensional electron gas as opposed to the uniformly doped three-dimensional gas is clear, especially at low temperatures where the reduced ionized-impurity scattering of the electrons in the modulation-doped parabolic well results in an improvement in mobility by two orders of magnitude.

Another source of scattering has recently been proposed and calculated by Wladislaw Walukiewicz at Lawrence Berkeley Laboratories[4], in response to experimental data from our wide parabolic wells. This new source of scattering is size effect scattering of high-mobility electrons at the edges of the electron gas. It occurs when the potentials at the edges of the gas are not uniform, allowing the edge of the electron gas to expand in regions of potential fluctuations. With this mechanism, Walukiewicz has been able to explain, for the first time, the magnitude and temperature dependence of the electron mobility in the three-dimensional electron gas in wide parabolic wells. A similar effect had been proposed for thin semiconductor films[5] and for silicon inversion layers[6], but had not been identified experimentally because of the relatively hard edges and steeply sloping potentials for the two-dimensional electron gas in MOSFET's. The effect could be important in graded heterostructures, though, where the edges of the electron gas are softer. It had not been observed in uniformly-doped semiconductors because of the short mean free paths of carriers. In the uniformly doped case, the path lengths are generally much shorter than sample dimensions.

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[4] Wladek Walukiewicz, "Size Effect in Wide Parabolic Wells", Physical Review Letters, to appear.

[5] F. S. Ham and D. C. Mattis, IBM J. Res. Dev. 4, 143 (1960).

[6] J. R. Schrieffer, Phys. Rev. 97, 641 (1955).

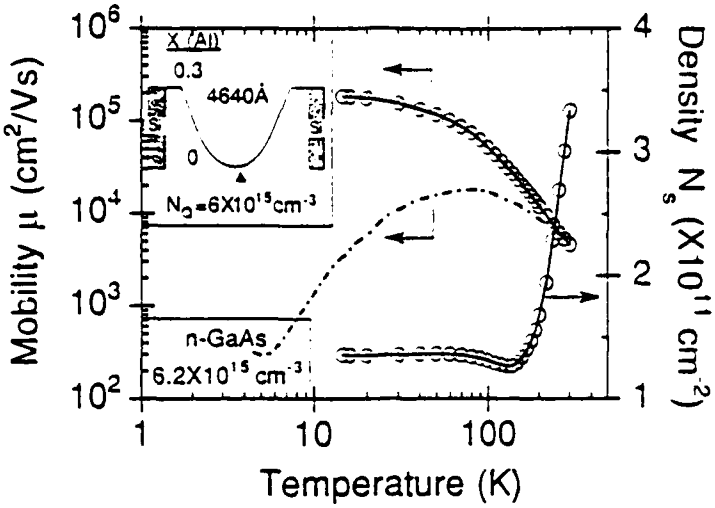

Figure 5. Electron mobility and charge density per unit area versus temperature within a 4640 Å parabolic well (solid curves) and in uniformly doped GaAs of equivalent charge density of 6.2 x 10^{15} cm^{-3} (dashed curve).

- Charge distribution and modeling

Both semiclassical and quantum-mechanical calculations of the electron distribution anticipated in modulation-doped parabolic wells have been made.[7] [8] In the semiclassical calculations, exactly filled as well as underfilled and overfilled well distributions were calculated. A computer simulation of the 0K electron distribution in one half of a symmetric 2000 Å-wide parabolic well that has a curvature of ~ 1×10^{16} cm^{-3}, is shown in Fig. 6 for a range of electron occupations of the well. At a particular value of the occupation, n_d, the electron distribution in the graded well is exactly uniform at the value of the quasi-doping. The well fills with electrons by forming a slab of electron gas of increasing width at nearly constant three dimensional density. At larger barrier dopings, excess electrons are inserted in accumulation layers at the well edges, and at smaller barrier dopings they are extracted from the edges. Over most of the well, though, the electron profile tends to mimic the quasi-doping profile, for a wide range of barrier dopings. This behavior is observed at all temperatures from 0K to 300K although the tendency toward ideality is more pronounced at lower temperatures.

Quantum-mechanical calculations of the wave functions and charge distribution in wide parabolic wells have been performed by several groups.[9] [10] [11] With increasing carrier density, Ns, the potential wells become wider and flatter and approach the ideal case of a wide square well. Fig. 7 shows the calculated self-consistent potential (solid lines) and probability amplitudes (broken lines) for a quasi-three-dimensional electron system in a parabolic well of width 4640 Å. The potential and probability amplitudes for the individual subbands, and the net charge density distribution, N(z), are shown for three different total carrier densities per unit area, N_s, within the well. Typical subband energies are of the order of 1 meV. Inflections in the electrical capacitance versus voltage characteristic have been observed experimentally in a corresponding gated wide parabolic well and occur at the voltages for successive subband occupations, although the observed capacitance steps are greater in amplitude than predicted by theory.

Capacitance profiling is a powerful method to measure carrier distributions experimentally in semiconductors. We have successfully extended this technique to the study of quasi-doped semiconductors.[2] We measured capacitance vs voltage between a Schottky-barrier gate and heavily-doped substrate of a parabolic well structure, using the depletion region of the Schottky-barrier gate to sweep through the carriers in the parabolic well. Measured and simulated apparent profiles were then compared. The data demonstrated that uniform quasi-doping profiles could be achieved in wide parabolic wells.

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[7] A. Wixforth, M. Sundaram, K. Ensslin, J. H. English, and A. C. Gossard. Applied Physics Letters 56, pp. 454-456 (1990).

[8] A. J. Rimberg and R. M. Westervelt, Phys. Rev B 40, 3970 (1989).

[9] M. Shayegan, T. Sajoto, J. Jo, and M. Santos, Surf. Sci. 229, 83 (1990).

[10] A. J. Rimberg and R. M. Westervelt, Phys. Rev B 40, 3970 (1989).

[11] A. Wixforth, M. Sundaram, K. Ensslin, J. H. English, and A. C. Gossard, Appl. Phys. Lett. 56, 454 (1990).

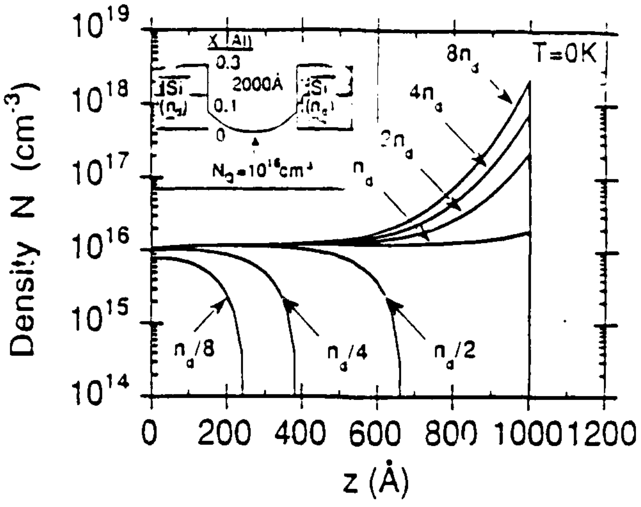

Figure 6. Density profile calculated semiclassically for the right half of a parabolic well containing from one-eighth to eight times the number of electrons needed to fill the well at a volume density of 10^{16} cm^{-3}.

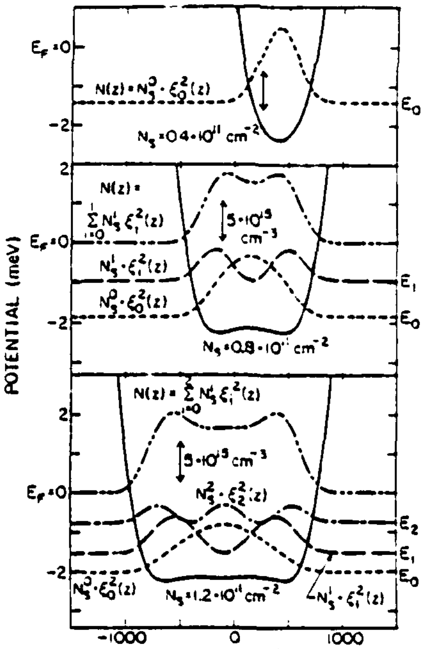

Figure 7. Quantum mechanically calculated self-consistent potential and probability amplitudes for a quasi-three-dimensional electron system in a parabolic well of width 4640 Å for three different values of well occupation. The solid lines show the self-consistent potential while the dashed lines show the shape of the charge density for the individual and summed occupied wavefunctions.

- Ordered electron states --

Theoretical calculations for jellium and for the wide parabolic well constructs predict a number of ordered electron states as a result of interactions between conduction electrons.[12][13][14] The ordered states were not observable in uniformly doped materials because of the presence of dopant atoms that led to charge localization and strong electron scattering by impurity ions.

Magneto-transport measurements on the wide parabolic wells have revealed a thick, high-mobility slab of electrons.[15] Figure 8 shows low temperature transverse magnetoresistance (magnetic field perpendicular to the electron layer) and Hall resistance for a single parabolic well. Oscillations are visible starting at fields as low as B ~ 0.05 T and show a beating structure due to the interference of oscillations with different periods. A fast Fourier transform of the data shows oscillations periodic in 1/B with frequencies 1.19 T, 1.05 T, and 0.60 T and possibly a fourth peak near zero frequency. The periods are due to occupation of closely spaced subbands. They are within ~10% agreement with calculations for an ideal parabolic well and yield a total sheet density in close agreement with the Hall value. This agreement is comparable to uncertainties in well parameters and effective masses. They confirm our interpretation of the structures as nearly ideal parabolic wells.

Preliminary measurements have been made at Harvard and the National Magnet Laboratory in higher fields at which spin density waves or Wigner crystals might be expected to occur. DC conductivity measurements with magnetic fields applied in the plane of the electron layer show potentially interesting anomalies. The resistance shows anisotropic oscillations for in-plane magnetic fields H which change sign as the sample (and current direction) is rotated from parallel to perpendicular to H. These are apparently caused by single particle effects, although a similar anisotropy at comparable fields is predicted by spin-ensity wave models[14] . Further work is needed to elucidate the anomalies.

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[12] A. H. MacDonald and G. W. Bryant, Phys. Rev. Letters 58, 515 (1987).

[13] B. I. Halperin, Japanese Journal of Applied Physics 26, Suppl. 26-3 1913 (1987).

[14] L. Brey and B. I. Halperin, Physical Review B 40, 11634 (1989).

[15] E. G. Gwinn, P. F. Hopkins, A. J. Rimberg, R. M. Westervelt, M. Sundaram, and A. C. Gossard, Phys. Rev B 41, 10700 (1990).

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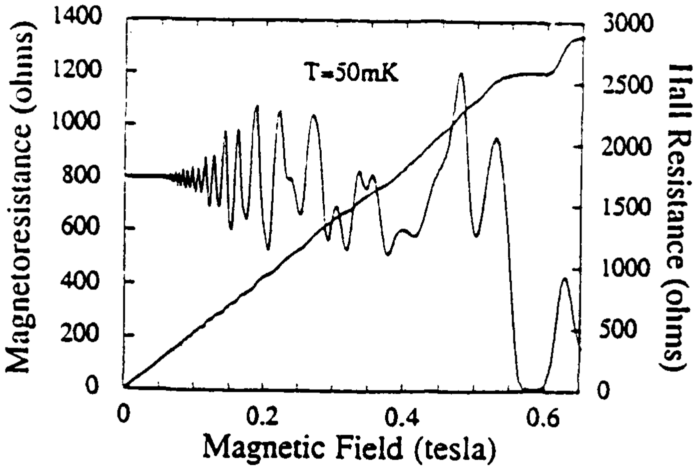

Figure 8. Low temperature transverse magnetoresistance (magnetic field perpendicular to the electron layer) and Hall resistance for a single 4600 Å parabolic well with electron sheet density 1.4 x 10^{11} cm^{-2} and a low field mobility of 2.3 x 10^5 cm /Vs.

- <u>Quantum Hall effect</u> --

At high magnetic fields, the integral quantum Hall effect was observed in parabolic wells (Fig 9).[16] The data show how the integral quantum Hall effect makes a transition from two-dimensional toward three-dimensional behavior as electrons are added to the well via the persistent photoconductivity effect. As the thickness of the electron layer increases on filling of the well, the magnetic field position of the $\nu = 1$ filling factor Hall step remains fixed, indicating a nearly constant Fermi energy; positions of Hall steps at higher filling factors change due to the decreasing subband energy spacings as the electron layer gets wider. For a sufficiently thick layer of electrons, the quantum Hall effect is predicted to disappear as cores of extended states from corresponding Landau levels overlap.

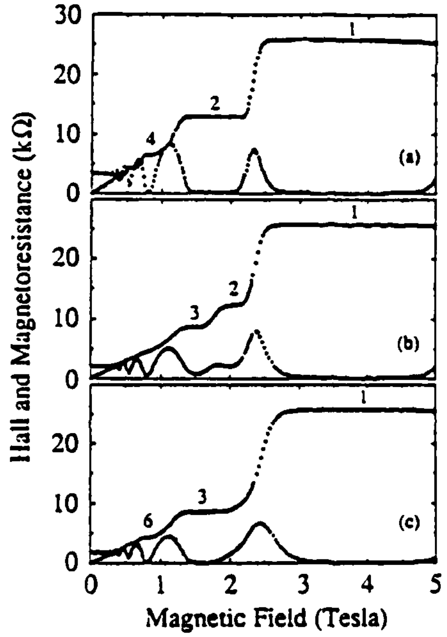

Figure 9. Quantum Hall effect and magnetoresistance versus magnetic field in a 4000 Å wide parabolic well: (a) before illumination, (b) and (c) after increasing periods of illumination, which raise the number of electrons from $0.78\text{x}10^{11}$ cm-2 to $1.12\text{x}10^{11}$ cm^{-2}.

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[16] E. G. Gwinn, R. M. Westervelt, P. F. Hopkins, A. J. Rimberg, M. Sundaram, and A. C. Gossard, Phys. Rev. B <u>39</u>, 6260 (1989).

- Far-infrared and submillimeter wave excitations --

The spectrum of far-infrared excitations has been observed in a number of parabolic wells.[17] [18] Coupling of infrared energy to the electron modes for motion perpendicular to the epitaxial layers can be accomplished with surface normal radiation either by the use of a surface grating or by coupling via the cyclotron resonance motion of the electrons in an inclined magnetic field. By application of a magnetic field at various angles with respect to the sample surface, infrared cyclotron resonance and infrared plasma resonance have been observed by Drew and coworkers at Maryland and by Wixforth at Santa Barbara (Fig. 10). In the pure cyclotron resonance with magnetic field normal to the surface, the second occupied subband contributes to cyclotron resonance response with a higher mass, leading to a shoulder on the resonance curve. The higher effective mass for the upper subband arises from the spatially varying aluminum content in the parabolic well.

By use of the surface grating, the pure plasma oscillations of the electrons were observed directly. Preliminary spectra were obtained as a function of carrier density as the carrier density was changed by either persistent photoconductivity or by application of a gate voltage to a semi-transparent electrode. Measurements were carried out in conjunction with the infrared facilities of the Quantum Institute at Santa Barbara and the University of Hamburg.

Most recently, the first evidence of strongly enhanced non-linear responses in the far-infrared submillimeter wavelength range has been found in asymmetrically shaped wide wells studied by Professor Mark Sherwin and his students in the UCSB Quantum Institute. The wells that were studied were half parabolas in which one side of the wide potential wells is an abruptly stepped heterojunction, while the other side of the wells is quadratically graded. The intensity of harmonic generation in response to fixed frequency laser excitation at wavelengths of approximately 0.2 mm is several orders of magnitude higher than from either GaAs or $LiNbO_3$, each of which is already a strongly nonlinear materaial (Figure 11). In addition to generating harmonics, the submillimeter wave pulses are being found to cause recombination of photo-excited electrons and partial quenching of persistent photoconductivity. More details on these results and the first manuscript will be available within the next few weeks.

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[17] K. Karrai, H. D. Drew, M. W. Lee, and M. Shayegan, Phys. Rev. B 39, 1426 (1989).

[18] A. Wixforth, M. Sundaram, D. Donnelly, J. H. English and A. C. Gossard, Surf. Sci. 228, 489 (1990).

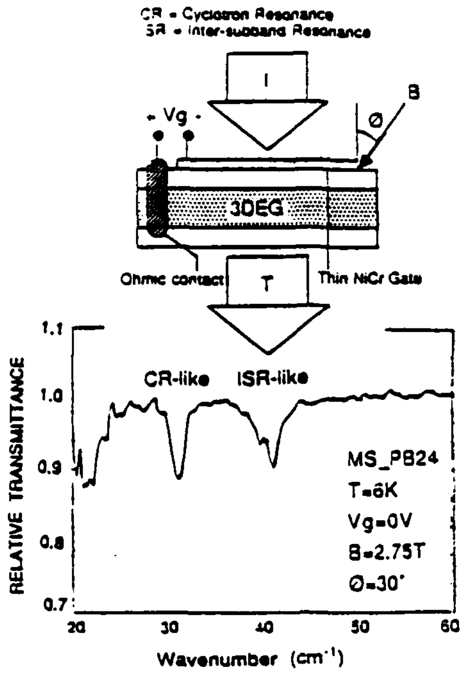

Figure 10. Coupled cyclotron resonance-like and intersubband-like far-infrared resonance spectra in parabolic well.

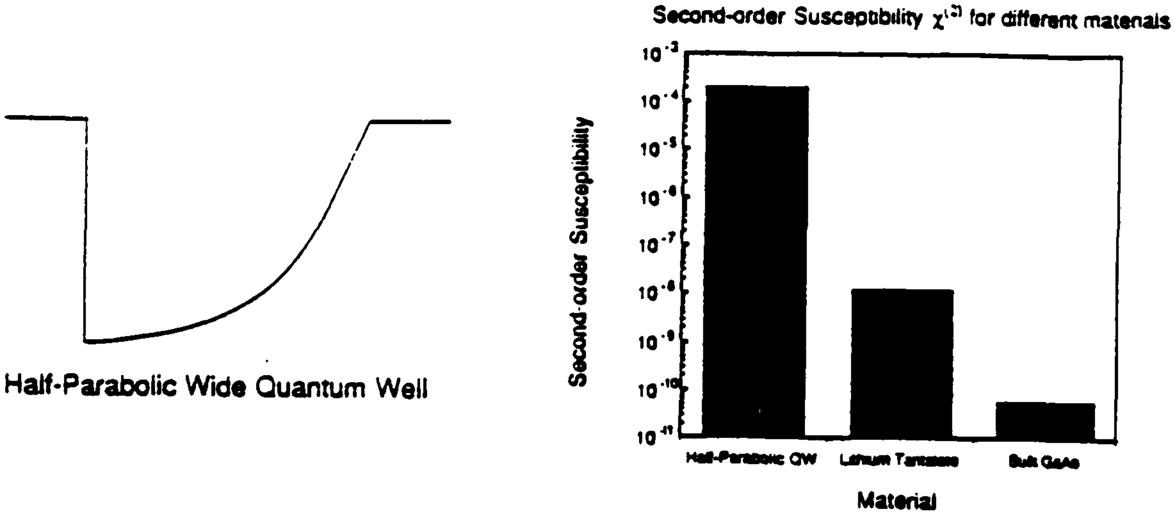

Figure 11. Potential profile of half parabolic wide well is shown at left. Second oreder susceptibility is shown at the right in comparison with bulk GaAs and lithium tantalate.

C. PUBLICATIONS IN TECHNICAL JOURNALS:

1. "REMOTELY DOPED GRADED POTENTIAL WELLS", by Mani Sundaram, A. C. Gossard, J. H. English, and R. Westervelt. Superlattices and Microstructures 4, pp. 683-691 (1988).

2. "QUANTUM HALL EFFECT IN WIDE PARABOLIC GALLIUM ARSENIDE/ALUMINUM GALLIUM ARSENIDE WELLS", by E. G. Gwinn, R. M. Westervelt, P. F. Hopkins, A. J. Rimberg, M. Sundaram, and A. C. Gossard. Superlattices and Microstructures 6, pp. 95-97 (1989).

3. "QUANTUM HALL EFFECT IN WIDE PARABOLIC GALLIUM ARSENIDE/ALUMINUM GALLIUM ARSENIDE WELLS", by E. G. Gwinn, R. M. Westervelt, P. F. Hopkins, A. J. Rimberg, M. Sundaram, and A. C. Gossard. Physical Review B 39, pp. 6260-6263 (1989).

4. "MODULATION-DOPED GRADED STRUCTURES: GROWTH AND CHARACTERIZATION", by M. Sundaram, A. C. Gossard, and J. H. English. Journal of Applied Physics (accepted 12/90).

5. "GRADED POTENTIAL WELLS WITH QUASI-UNIFORM CHARGE DISTRIBUTION", by A. Wixforth, M. Sundaram, D. Donnelly, J. H. English, and A. C. Gossard. Surface Science 228, pp. 489-492 (1990).

6. "GATE CONTROLLED SUBBAND STRUCTURE OF THE ELECTRON SYSTEM IN A WIDE PARABOLIC QUANTUM WELL", A. Wixforth, M. Sundaram, K. Ensslin, J. H. English, and A. C. Gossard. Applied Physics Letters 56, pp. 454-456 (1990).

7. "CHARACTERIZATION OF THE ELECTRON GAS IN WIDE PARABOLIC GaAs/$Al_xGa_{1-x}As$ QUANTUM WELLS", E. G. Gwinn, P. F. Hopkins, A. J. Rimberg, R. M. Westervelt, M. Sundaram, and A. C. Gossard. Physical Review B 41, pp. 10700-10705 (1990).

8. "A DIRECT METHOD TO PRODUCE AND MEASURE COMPOSITIONAL GRADING IN $Al_xGa_{1-x}As$ ALLOYS", M. Sundaram, A. Wixforth, R. S. Geels, A. C. Gossard, and J. H. English. (unpublished)

9. "WIDE GRADED POTENTIAL WELLS: GROWTH, ELECTRICAL PROPERTIES AND THEORETICAL RESULTS", by K. Ensslin, A. Wixforth, M. Sundaram, J. H. English, and A. C. Gossard. Proceedings, SPIE Conference, San Diego, March 1990.

10. "PHOTOLUMINESCENCE EXCITATION SPECTROSCOPY OF REMOTELY DOPED WIDE PARABOLIC GaAs/$Al_xGa_{1-x}As$ QUANTUM WELLS", by J. H. Burnett, H. M. Cheong, W. Paul, P. F. Hopkins, E. G. Gwinn, A. J. Rimberg, R. M. Westervelt, M. Sundaram, and A. C. Gossard. Physical Review B (submitted 3/90).

11. "PHOTOLUMINESCENCE EXCITATION SPECTROSCOPY OF WIDE PARABOLIC GaAs/AlGaAs QUANTUM WELLS", by J. H. Burnett, H. M. Cheong, W. Paul, P. F. Hopkins, A. J. Rimberg, R. M. Westervelt, M. Sundaram, and A. C. Gossard. Superlattices and Microstructures (submitted

8/90).

12. "MAGNETO-CAPACITANCE-VOLTAGE MEASUREMENTS OF ELECTRONS IN WIDE PARABOLIC QUANTUM WELLS", by M. Sundaram, K. Ensslin, A. Wixforth, and A. C. Gossard. Superlattices and Microstructures (submitted 8/90).

13. "MOBILITY AND UNIFORMITY OF ELECTRON GASES IN WIDE PARABOLIC POTENTIAL WELLS", P. F. Hopkins, A. J. Rimberg, E. G. Gwinn, R. M. Westervelt, M. Sundaram and A. C. Gossard. Superlattices and Microstructures (submitted 8/90).

14. "LOW-DENSITY HIGH-MOBILITY ELECTRON GAS IN WIDE PARABOLIC GaAs/$Al_xGa_{1-x}As$ WELLS", by P. F. Hopkins, A. J. Rimberg, E. G. Gwinn, R. M. Westervelt, M. Sundaram, and A. C. Gossard. Applied Physics Letters 57, pp. 2823-2825 (1990).

15. "FAR INFRARED EXCITATIONS OF AN ELECTRON SYSTEM IN A PARABOLIC QUANTUM WELL", by A. Wixforth, M. Sundaram, J. H. English, and A. C. Gossard. Proceedings, International Conference on Physics of Semiconductors, Thessaloniki, Greece, August, 1990.

16. "OPTICAL STUDY OF WIDE PARABOLIC GaAs/AlGaAs QUANTUM WELLS", by J. H. Burnett, H. M. Cheong, W. Paul, P. F. Hopkins, A. J. Rimberg, R. M. Westervelt, M. Sundaram, and A. C. Gossard. Proceedings, International Conference on Physics of Semiconductors, Thessaloniki, Greece, August, 1990.

17. "SIZE EFFECT IN PARABOLIC GaAs/AlxGa1-xAs QUANTUM WELLS", by W. Walukiewicz, P. F. Hopkins, M. Sundaram, A. C. Gossard, and R. M. Westervelt. Physical Review Letters (submitted 11/90).

18. "ELECTRON RESONANCES IN WIDE PARABOLIC QUANTUM WELLS", by A. Wixforth, M. Sundaram, K. Ensslin, J. H. English, and A. C. Gossard. Physical Review B, Rapid Communications (submitted 1/91).

19. "SUPPRESSION AND RECOVERY OF QUANTUM HALL PLATEAUS IN A PARABOLIC QUANTUM WELL", by K. Ensslin, M. Sundaram, A. Wixforth, J. H. English, and A. C. Gossard. Physical Review B, Rapid Communications (submitted 1/91).

D. PERSONNEL

1. Professor Arthur C. Gossard (Principal Investigator)

Dr. Gossard received his PhD degree in Physics from University of California, Berkeley in 1960. His PhD thesis title was "Nuclear Magnetic Resonance in Ferromagnetic Materials". He was at AT&T Bell Laboratories from 1960 to 1987, with the exception of a year of research at the Centre d'Etudes Nucleaires, Saclay France from 1962 to 1963. He has been Professor of Materials and of Electrical and Computer Engineering in the University of California, Santa Barbara from July, 1987 to the present. His special interests are in the field of growth and properties of new artificially structured materials. He has 12 patents in this area and over 420 publications.

2. Dr. Achim Wixforth (Postdoctoral research scientist)

Dr. Wixforth received his "Diplom" degree in Physics from Universitat Hamburg, Hamburg, Germany in 1984 with a thesis entitled "Untersuchung der quasistatischen Leitfahigkeit in Raumladungsschichten von MOS Strukturen durch eine kapazitive Messmethode" ("Investigation of the quasi-static conductivity in space charge accumulation layers on Si MOS structures by a capacitive measurement technique") . He received the PhD degree in Physics from Universitat Hamburg, Hamburg, Germany in 1987 with a thesis entitled "Wechselwirking von akustischen Oberflachenwellen mit einem zweidimensionalen Elektronensystem" ("Interaction of surface acoustic waves with a two-dimensional electron system"), supervised by Professor Jorg P. Kotthaus. He began his research at UCSB on January 1, 1989, completed it on December 31, 1989, and has now returned to Germany as a faculty member at the University of Hamburg and the University of Munich.

3. Mr. Mani Sundaram: Research Assistant

Mr. Sundaram received his Bachelors Degree in Electrical Engineering from the Indian Institute of Technology, Madras, in 1985. He came to UCSB in 1985 and did research with Professor Steve Long on high speed GaAs field effect transistor devices before his present research on the fabrication and properties of high quality three dimensional electron gases. He is a PhD candidate and has extensive experience in growth, in fabrication and processing, and in electrical and optical measurements of semiconductors.

4. Dr. Peter F. Hopkins, Postdoctoral Research Engineer.

A new postdoctoral researcher, Dr. Peter F. Hopkins, joined the UCSB research effort in June, 1990 immediately after receiving his Ph.D. degree in Physics from Harvard University, where he worked under Professor Robert Westervelt on electrical and optical measurements of wide parabolic well materials generated at UCSB under this program. In his work at Harvard, he observed the quantum Hall effect and associated magnetotransport phenomena in the parabolic well structures and participated in the discovery of the new features in the optical spectra of the doped wells. He previously received his B.S. degree in Engineering Physics from University of California, Berkeley with highest honors.

E. INTERACTIONS (COUPLING ACTIVITIES):

i. PAPERS PRESENTED:

1. "ELECTRON TRANSPORT IN WIDE PARABOLIC GaAs/$Ga_{1-x}Al_xAs$ WELLS", P. F. Hopkins, E. G. Gwinn, A. J. Rimberg, R. M. Westervelt, M. Sundaram, and A. C. Gossard. 1989 March Meeting, American Physical Society, St. Louis, Missouri, March 21, 1989.

2. "QUANTUM HALL EFFECT IN WIDE PARABOLIC GaAs/$Ga_{1-x}Al_xAs$ WELLS", E. G. Gwinn, P. F. Hopkins, A. J. Rimberg, R. M. Westervelt, M. Sundaram, and A. C. Gossard. 1989 March Meeting, American Physical Society, St. Louis, Missouri, March 21, 1989.

3. "MODULATION-DOPED GRADED STRUCTURES: GROWTH AND CHARACTERIZATION", M. Sundaram, A. C. Gossard, and J. H. English. 1989 Spring Meeting, Materials Research Society, San Diego, CA, April 24, 1989.

4. "GRADED POTENTIAL WELLS WITH QUASI-UNIFORM CHARGE DISTRIBUTION", A. Wixforth, M. Sundaram, D. Donnelly, J. H. English, and A. C. Gossard. Fourth International Conference on Modulated Semiconductor Structures, Ann Arbor Michigan, July 20, 1989.

5. "GROWTH OF ARTIFICIAL QUANTUM MICROSTRUCTURES", Arthur C. Gossard. 1989 Vacuum Mechatronics Conference, Santa Barbara, CA, February 2, 1989.

6. "ARTIFICIALLY LAYERED STRUCTURES", Arthur C. Gossard, Materials Department Seminar, University of California, Berkeley, CA, April 13, 1989.

7. "WIDE PARABOLIC POTENTIAL WELLS", Arthur C. Gossard. AT&T Bell Laboratories General Physics Seminar, Murray Hill, NJ, October 31, 1989.

8. "WIDE GRADED POTENTIAL WELLS: GROWTH, ELECTRICAL PROPERTIES AND THEORETICAL RESULTS", by K. Ensslin, A. Wixforth, M. Sundaram, J. H. English, and A. C. Gossard. SPIE Conference, San Diego, March 1990.

9. "PHOTOLUMINESCENCE EXCITATION SPECTROSCOPY OF WIDE PARABOLIC GaAs/AlGaAs QUANTUM WELLS", by J. H. Burnett, H. M. Cheong, W. Paul, P. F. Hopkins, A. J. Rimberg, R. M. Westervelt, M. Sundaram, and A. C. Gossard. Conference on Superlattices and Microstructures, Berlin, August, 1990.

10. "MAGNETO-CAPACITANCE-VOLTAGE MEASUREMENTS OF ELECTRONS IN WIDE PARABOLIC QUANTUM WELLS", by M. Sundaram, K. Ensslin, A. Wixforth, and A. C. Gossard. Conference on Superlattices and Microstructures, Berlin, 1990.

11. "MOBILITY AND UNIFORMITY OF ELECTRON GASES IN WIDE PARABOLIC POTENTIAL WELLS", P. F. Hopkins, A. J. Rimberg, E. G. Gwinn, R. M. Westervelt, M. Sundaram and A. C. Gossard. Conference on Superlattices and Microstructures Berlin, 1990.

12. "FAR INFRARED EXCITATIONS OF AN ELECTRON SYSTEM IN A

PARABOLIC QUANTUM WELL", by A. Wixforth, M. Sundaram, J. H. English, and A. C. Gossard. International Conference on Physics of Semiconductors, Thessaloniki, Greece, August, 1990.

13. "OPTICAL STUDY OF WIDE PARABOLIC GaAs/AlGaAs QUANTUM WELLS", by J. H. Burnett, H. M. Cheong, W. Paul, P. F. Hopkins, A. J. Rimberg, R. M. Westervelt, M. Sundaram, and A. C. Gossard. International Conference on Physics of Semiconductors, Thessaloniki, Greece, August, 1990.

14. "ELECTRONIC TRANSPORT IN REMOTELY-DOPED WIDE PARABOLIC GaAs WELLS", by R. M. Westervelt, P. F. Hopkins, A. J. Rimberg, E. G. Gwinn, M. Sundaram, and A. C. Gossard. International Conference on Physics of Semiconductors, Thessaloniki, Greece, August, 1990.

15. 'ULTRAFINE SUPERLATTICES FOR NEW DIMENSIONS OF ELECTRON CONFINEMENT", by Arthur C. Gossard, Pierre M. Petroff, Mani Sundaram, Scott A. Chalmers, and Mark S. Miller. 1990 Fall Meeting, Joint plenary invited session, Materials Research Society, Boston, Massachusetts, November, 1990.

16. "ELECTRON MOBILITIES IN WIDE PARABOLIC GaAs/AlxGa1-xAs WELLS: SIZE EFFECT SCATTERING", by Wladyslaw Walukiewicz, Mani Sundaram, Peter F. Hopkins, and Arthur C. Gossard, and Robert M. Westervelt. 1990 Fall Meeting, invited paper, Materials Research Society, Boston, Massachusetts, November, 1990.

17. "FAR-INFRARED PHOTOVOLTAIC RESPONSE OF OHMIC AND SCHOTTKY CONTACTS TO n+ GaAs", by J. J. Plombon, M. S. Sherwin, M. Sundaram, and A. C. Gossard, , Paper M19-9, March 1990 Meeting of the American Physical Society, Anaheim, California, March 12-16, 1990.

18. "MAGNETOTRANSPORT CHARACTERIZATION OF WIDE PARABOLIC GaAs/GaAlAs WELLS", BY A. J. Rimberg, P. F. Hopkins, E. G. Gwinn, R. M. Westervelt, M. Sundaram, and A. C. Gossard, , Paper N19-1, March 1990 Meeting of the American Physical Society, Anaheim, California, March 12-16, 1990.

19. "IN-PLANE MAGNETOTRANSPORT IN WIDE PARABOLIC GaAs/GaAlAs wells", by P. F. Hopkins, A. J. Rimberg, E. G. Gwinn, R. M. Westervelt, M. Sundaram, and A. C. Gossard, , Paper 19-2, March 1990 Meeting of the American Physical Society, Anaheim, California, March 12-16, 1990.

20. "DIRECT OBSERVATION OF SUBBANDS BY CAPACITANCE-VOLTAGE PROFILING"M. Sundaram, K. Ensslin, A. Wixforth, A. C. Gossard, and J. H. English, , Paper N19-5, March 1990 Meeting of the American Physical Society, Anaheim, California, March 12-16, 1990.

21. "PHOTOLUMINESCENCE EXCITATION AND RAMAN SPECTROSCOPY OF WIDE PARABOLIC GaAs/GaAlAs WELLS", by J. H. Burnett, H. M. Cheong, W. Paul, P. F. Hopkins, A. J. Rimberg, R. M. Westervelt, E. G. Gwinn, M. Sundaram, and A. C. Gossard, Paper N19-7, March 1990 Meeting of the American Physical Society, Anaheim, California, March 12-16, 1990.

ii. CONSULTATIVE AND ADVISORY FUNCTIONS WITH OTHER LABORATORIES:

Harvard University:

We interacted closely with researchers at Harvard University in the course of this year's work.

A number of specially grown semiconductor structures were grown for Professor Robert Westervelt's group at Harvard for electrical measurements at high magnetic fields and at low temperatures. Structures were also produced for Professor William Paul's laboratory for optical measurements by photoluminescence, photoluminescence excitation spectroscopy, and Raman light scattering. We also consulted on theoretical expectations for the new materials and theoretical interpretation of the observed behavior with Professor Bert Halperin. Professors Westervelt and Halperin both visited Santa Barbara for discussions with us this year and Professor Gossard and research assistant Mani Sundaram visited Harvard for consultations this year. Former Westervelt graduate student Elizabeth Gwinn who worked on this research, has come to Santa Barbara as a faculty member in the Physics Department and devotes a major portion of her research to the subject of this contract. Harvard University Robert Westervelt graduate student, Pete Hopkins, received his PhD degree for work on the electrical and optical properties of these materials and came to our UCSB group as a postdoctoral research scientist under this contract in June 1990.

UCSB Physics Department:

In addition to extensive interactions with the other members of the UCSB Materials and ECE departments and use of the processing and characterization facilities of these departments, we are also collaborating with several groups in the UCSB Physics Department. We are working with Professor Mark Sherwin in studies of non-linear and chaotic infrared properties of our materials by use of the free electron laser and other high power submillimeter wave lasers in the UCSB Quantum Institute and Center for Free Electron Laser Studies. We are also working with Professor Beth Gwinn in studies of the infrared plasmon properties of the new materials. We also interact with the theoretical group of Walter Kohn and the Institute for Theoretical Physics, where we have given three internal seminars this year, and where a great deal of interest has been expressed in the plasma wave excitations and the electron interactions in the quasi three dimensional electron gases that we are making.

Lawrence Berkeley Radiation Laboratory, University of California, Berkeley:

We collaborated with Dr. Wladek Walukiewicz of the Lawrence Berkeley laboratory in the calculation of the new electron transport phenomena in the three dimensional electron gas. This work provided the first evidence of the role of size effect scattering in semiconductor heterostructures.

Universities of Hamburg and Munich, Germany:

We collaborated with Dr. Achim Wixforth upon his return to Professor Jorg Kotthaus' laboratory in Germany after his postdoctoral research at Santa Barbara under this grant. Wixforth and Kotthaus have developed an excellent far-infrared capability which is now at the University of Munich, and which Dr. Wixforth used to observe directly the electron plasma resonances in wide parabolic wells without the mediating help of a magnetic field.

Other Interactions:

We also cooperated with the group of Professor Dennis Drew at the University of Maryland, who made infrared measurements on several wide parabolic quantum well structures grown at UCSB for the purpose of examining the difference in cyclotron resonance and plasma properties of structures made with analog grading and digital grading of composition profiles.

In other advisory and organizational contributions not directly involved with the work of this contract, but benefiting it indirectly, Professor Gossard was active in national and international professional activities. He was named to the editorial board of the Journal of Applied Physics and Applied Physics Letters in 1989 and is co-chair of the 1990 MBE-VI International Molecular Beam Epitaxy Conference.

F. DISCOVERIES AND INVENTIONS:

The concept of the tunable submillimeter wave generator was proposed theoretically and disclosed by Joseph Maserjian of Jet Propulsion Laboratory and Arthur Gossard under support of the present AFOSR contract. It was pursued experimentally by growth of the first exponentially graded compositional profile structures. The submillimeter wave response of these modulation doped quasi three dimensional electron gas structures was tested by Fourier transform infrared spectrometry measurement. Plasma wave excitations in the anticipated submillimeter wave region were observed in the structures.

G. OTHER STATEMENTS:

The use of wide parabolically graded potential wells originated under this contract to realize a high quality three dimensional electron gas has attracted wide attention and is being perceived to offer experimental challenge in fabrication and measurement and theoretical challenge in the understanding of the material and the application to new physics and to new devices. The publications that resulted from this work are attached to this report as as appendix.

Among the major challenges that remain to be solved are 1) obtaining evidence of electron ordering in three dimensions, 2) study of the electron plasma response in non-parabolic and superlattice configurations, 3) observation of the three dimensional hole gas, 4) study of submillimeter wave harmonic generation in asymmetrical structures, experimental realization of tuneable infrared components, and 5) the study of interface and surface plasma waves.