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This is the final tecnical report for ARO contract DAAL03-89-K-0038. In the report we describe our progress in the areas of III-V electronic device isolation and how they apply to the phenomena of sidegating and backgating in GaAs based devices. The program evolved into a highly collaborative effort between industry and university with several joint publications resulting. The sidegating/backgating problem in field effect transistors (FETs) has essentially been eliminated by the development of GaAs and other compounds grown at low temperatures by MBE.

Research included the developing techniques for synthesis of MBE material at low temperatures (LT), establishment of electrical and optical characterization techniques specifically designed for the study of such materials and the effect of electrical buffer layers made from the LT material on devices. We have made advances in several areas including first realizations of LT GaAs by GSMBE, first realization of LT InP, observation of variable range hopping conductivity in various LT III-V materials, determination of device degradation effects of LT buffer layers and thermal stability of these materials. Additionally we (with MOTOROLA) obtained an enhancement of mobility in two dimensional electron gas structures by separately confining electrons and phonons.

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Isolation Mechanisms in III-V Devices

Final Technical Report

George N. Maracas

August 12, 1993

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List of Appendices, Illustrations and Tables

Review of research under ARO program

This is the final technical report for ARO contract DAAL03-89-K-0038 in which we describe our progress in the areas of III-V electronic device isolation and how they apply to the phenomena of sidegating and backgating in GaAs based devices. The program evolved into a highly collaborative effort between industry and university with several joint publications resulting. The sidegating/backgating problem in field effect transistors (FETs) has essentially been eliminated by the development of GaAs and other compounds grown at low temperatures by MBE.

Research included the developing techniques for synthesis of MBE material at low temperatures (LT), establishment of electrical and optical characterization techniques specifically designed for the study of such materials and the effects of electrical buffer layers made from the LT material on devices. We have made advances in several areas including first realizations of LT GaAs by GSMBE, first realization of LT InP, observation of variable range hopping conductivity in various LT III-V materials, determination of device degradation effects of LT GaAs buffer layers and thermal stability of these materials. Additionally we (with MOTOROLA) obtained an enhancement of mobility in two dimensional electron gas structures by separately confining electrons and phonons.

We have initiated and developed several industrial interactions in the areas of low temperature MBE material growth and characterization. The collaborations are with MOTOROLA Phoenix Corporate Research Lab (PCRL), AT&T, MIT Lincoln Laboratory, U.C. Berkeley, Hughes Research Lab and Universität Ulm.

Statement of problem studied

In GaAs grown at low temperatures (LT) by molecular beam epitaxy (MBE), the presence of microscopic As precipitates and a high density of antisite defects dominate the conductivity, producing electronic transport mainly by variable range hopping conduction. The resulting high resistivity (~ 10^{10} Ωcm) and subpicosecond carrier lifetimes have enabled the use of LT GaAs in FET buffer layers as well as in ultra-fast optical switches. Electrical isolation between two field effect transistors (FETs) was increased to the point where crosstalk (called sidegating or backgating) was virtually eliminated. In addition to the technological impact of such a buffer layer was the question of what the specific conduction mechanisms were in the material. Insight into this could reveal properties of nonstoichiometric binary semiconductor compounds.

The application of MBE GaAs grown at temperatures below 300°C as an electrical buffer layer in field effect transistors [1] has spurred an investigation of other materials grown at low temperatures. Other material systems grown at low temperatures are AlGaAs [2], InAlAs [3], InP [4] and GaP [5]. Several applications of low temperature (LT) materials have subsequently been developed in electronic and photonic devices. A review of LT materials and their electrical properties can be found in reference [6].

Considerable research has been carried out to determine the nature of the LTB's and the mechanism by which they provide device isolation which is superior to that of semi-insulating GaAs. As grown, these samples contain as much as 1% excess arsenic which forms As_{Ga} antisites, As interstitials and various complexes [7]. These "as grown" layers exhibit relatively large conductivities due to hopping between a broad array of defect sites with concentrations as high as 2×10^{19} cm^{-3}. An anneal of approximately 10 minutes at 600°C has the effect of converting these layers to very high resistivity (>10^8 Ω•cm). During the annealing process, the excess As in the LTB material "self-getters" forming arsenic precipitates. These precipitates have been observed in concentrations of about 1×10^{17} cm^{-3} and range in size from 20-100 Å [8]. However, the precipitate density is a strong function of growth temperature, anneal time, and anneal temperature [7]. Concurrent with the formation of As precipitates is a reduction in the defect density in the material.

There are two main theories on the origin of such a high resistivity and the observation of hopping conductivity below room temperature. The first states that the well-characterized, high density of As_{Ga}

and V_{Ga} related deep donors and acceptors is sufficient to compensate any carriers present in the material [7,10]. The second states that metallic As precipitates act as spherical Schottky barriers [9] whose overlapping space charge regions deplete the material of carriers and produce the observed high resistivities. It was calculated that semi-insulating behavior should occur in $n=5X10^{17}$ cm^{-3} doped material containing 30Å diameter precipitates for precipitate densities above $2X10^{16}$ cm^{-3}. This number varies as a function of precipitate size and shallow impurity concentration. In the VRH regime the conductivity follows the form [8]

$$\ln(\sigma) \propto T^{-v} \qquad (1)$$

with v=0.25. On the other hand Warren *et al.* [9] believe that the high resistivity of the material is due local depletion around the As precipitates (ϕ_{bAs}=0.8 eV). By this view, the high density of As precipitates results in a system of overlapping depletion regions. Conductivity then occurs by hopping between pockets of undepleted material. This view also predicts the v=0.25 variable range hopping (VRH) behavior which is commonly reported [11]. At this time there is evidence supporting both theories.

Summary of most important results

Scope of research and major research accomplishments:

a) First growth of LT GaAs by GSMBE

We have found that the electrical and optical properties of LTB's grown by conventional MBE and GSMBE are very similar showing that LTB growth is also feasible with GSMBE. We have also found that the exponent in the temperature dependence of ln(σ) is less than 0.25 for LTB's grown by both solid and gas source MBE which indicates that a modified form of the variable range hopping mechanism (see figure 1) proposed by Mott may be dominating conduction in these layers. Whether the hopping is occurring between deep levels or between normal conduction band electrons separated by depletion regions due to the arsenic precipitates cannot be conclusively determined from these results. However, the observations support the As precipitate model.

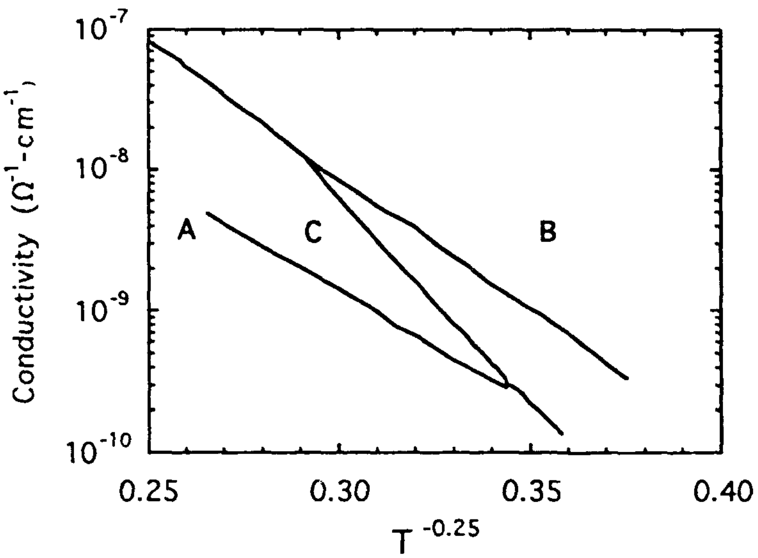

Figure 1. Conductivity of LT GaAs grown by MBE and GSMBE versus $T^{-0.25}$ showing hopping conductivity.

Growth of reproducible LT GaAs has enabled us to initiate collaborations with MOTOROLA PCRL, Mary Gray (AT&T), S. Lilienthal-Weber (U.C. Berkeley), R. Metzger (Hughes Research Lab) and E. Kohn (Univ. Ulm).

b) First growth of LT InP by GSMBE

We reported the first measurement of optical and electronic properties of InP grown at low temperatures in a gas source MBE using dimeric phosphorus produced from cracked phosphine. The conductivity is higher than the equivalent GaAs LT material and does not have the same temperature dependence. The conditions under which growth occurs ie, substrate temperatures, V/III ratios and annealing was explored. The structural properties, temperature dependence of the conductivity (figure 2), deep level structure and the photoluminescence properties of the material were also investigated. The major surprise in the InP system is that the resistivity of the LT InP is much lower ($\sim 10^{-2}$ Ωcm) than any other LT material system. This may be due to a donor level that comes out of the InP conduction band in the non-stoichiometric alloy.

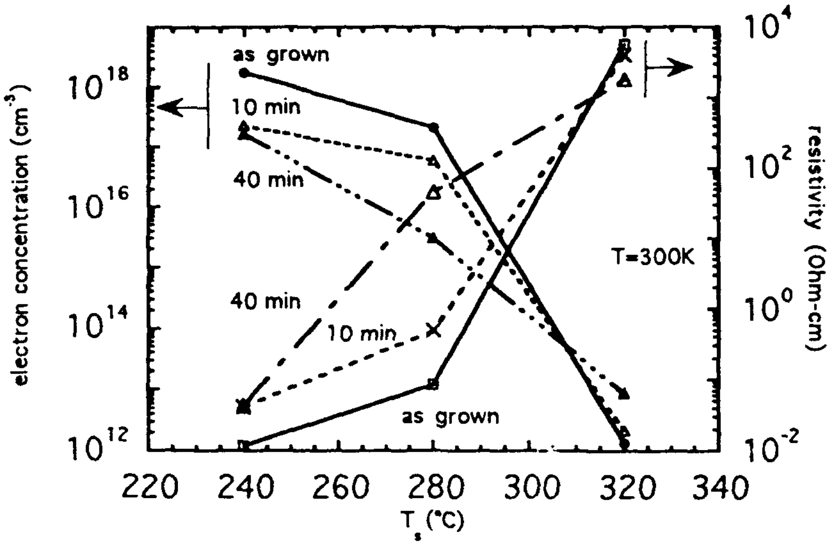

Figure 2. Electron concentration and resistivity of LT InP grown by GSMBE versus growth temperature.

c) Effects and thermal stability of LT GaAs buffers on electronic properties of FETs

Electrical isolation is only one requirement for a buffer layer to be successful in electronic devices. A high thermal stability which ensures that deep levels do not diffuse into the FET active region is necessary. To investigate this, we performed a series of thermal stability studies using Deep Level Transient Spectroscopy (DLTS) on FET structures with LT GaAs buffers.

Electron traps activation energies of 0.28eV, 0.45eV and 0.53eV were observed as well as hole traps with activation energies of 0.38eV and 0.52eV. The trap concentrations are below 10^{15} cm^{-3}. Control samples without LT buffers exhibited none of these electron or hole levels in detectable ($<2\times10^{14}$ cm^{-3}) quantities.

The stability of the same epitaxial layers was studied for various proximity anneal times. Samples were annealed for 1 and 24 hours at 400°C in a nitrogen ambient and referenced them to an unannealed sample. The distribution of trap levels is significantly altered by the annealing. The electrical DLTS (figure 3) shows an initial decrease in two of the levels and a slight increase in the highest temperature level after 1 hour. After 24 hours all of the electron traps increase in concentration and an entirely new level emerges at 240K. The optical DLTS shows a steady decrease in the 320K hole trap concentration and an initial decrease in the band of hole levels followed by an increase at 24 hours.

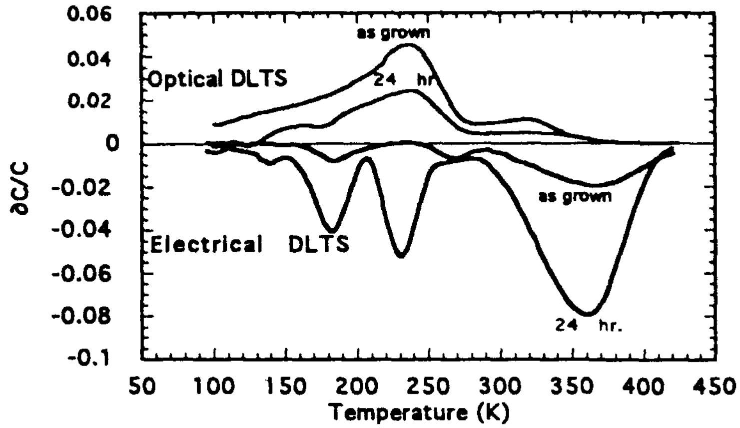

Figure 3. Electrical and optical DLTS of MESFET active layer grown on top of an LT GaAs buffer layer after low temperature anneal cycles.

This shows that even during moderate temperature annealing the material properties of the epitaxial layers are changing. The trend is that the hole trap concentration decreases while the electron trap concentration increases with anneal time. The use of AlAs barrier layers has been successful in eliminating some of the As outdiffusion problems.

d) Effects and thermal stability of LT GaAs buffers on optical properties of quantum wells

Another probe that we used to observe deep level outdiffusion was photoluminescence on quantum wells. We found that the optical properties of the QWs were very sensitive to the growth condition of the LTBs, showing a gradual shift in peak energy, a reduction of the PL intensity and a broadening of the QW linewidth as the V/III ratio of the LTB was increased. The excess arsenic present causes strain in the LTBs and hence in the QWs, appearing as a shift in the transition energy position. The degraded linewidth and luminescence efficiency are a result of an out-diffusion of arsenic related traps which introduces non-radiative recombination centers into the epitaxial layers during QW growth. The linewidth and intensity degradation are most evident in the 100Å wells which are closest to the LTBs. LTBs grown using larger V/III flux ratios containing larger quantities of arsenic show a more pronounced change.

e) TEM of LT InP

A study of the structural properties of LT InP was performed in which the P-rich precipitates were analyzed using high resolution electron microscopy (HREM), analytical electron microscopy (AEM) and convergent beam electron diffraction (CBED) techniques.

Cross sectional transmission electron microscopy (TEM) was performed (near 110 zone axis conditions) on several samples which were prepared by mechanical grinding and low angle argon ion milling. The microscope used was an Akashi 002B operating at 200keV. The epitaxial layers having a thickness of 1.5μm exhibited a moderate to low dislocation density and thin twin planes on {111} extending approximately 0.5 μm from the LT layer surface. Throughout the layer, a density of approximately $1X10^{10}$ precipitates per square centimeter ranging in size from 100Å to 500Å was observed. These were analyzed by electron probe energy dispersive x-ray nanospectroscopy and found to be phosphorus-rich. Moire fringes on the precipitates and microdiffraction showed them to be crystalline. The precipitate density was a factor of ten less than that observed for As precipitates in LT GaAs. The average small precipitate size is 250Å which is more than twice the average size found for As precipitates grown by As_2 [12].

Maps of stoichiometry in the epitaxial layer growth direction showed gradients in the P content of approximately 3%. The strain induced by the excess P is responsible for the observed critical thickness for dislocation formation effect that is also observed in LT GaAs.

f) Mobility enhancement in 2D structures by phonon confinement

We were successful in increasing the room temperature mobility of two dimensional carriers in ultrathin quantum wells by constructing novel GaAs/AlGaAs epitaxial structures. While there is still some debate about the mechanism of the increased mobility, it can be explained by a model in which the electron and longitudinal-optical (LO) phonon modes are separately confined. LO phonon nodes were placed inside the well by insertion of thin (2 monolayer) AlAs barriers. The electron wavefunction was essentially undisturbed by these barriers. Thus by separately confining the electrons and phonons, a reduction of the electron-LO phonon scattering was achieved which increases the mobility. An example of this effect is shown in figure 4 where the multiple quantum well structure has a higher mobility than the control sample at temperatures above 60K. The increase in mobility at room temperature is 44%.

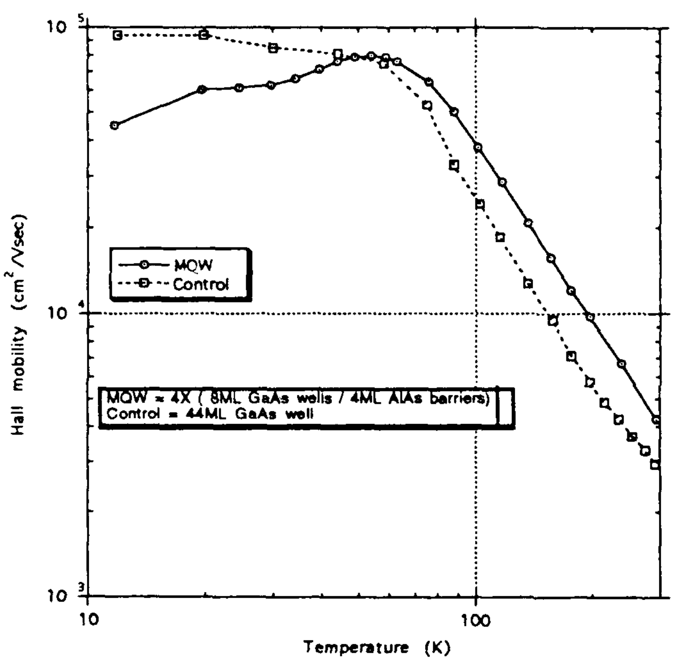

Figure 4. Mobility versus temperature for a control sample and the MQW in which electron-phonon scattering is reduced. The MQW sample has a higher mobility than the control at temperatures above 60K.

These results have started work by other groups in theoretically and experimentally studying the effect. Theoretical work on this portion of the project was in close collaboration with Mike Stroscio of ARO. This work could potentially be significant in high speed device applications.

Industrial collaborations:
MOTOROLA PCRL
Mike Stroscio, ARO
Mary Gray, AT&T
Zuzanna Lilienthal-Weber, U.C Berkeley
Bob Metzger, Hughes Research Lab
Erhard Kohn, Univeraität Ulm

List of all publications and technical reports

Papers

G. N. Maracas, K. Shiralagi, R. Ramamurti and R.W. Carpenter, "A Comparison of As and P Based Semiconductors Grown at Low Temperatures by MBE and GSMBE," to appear in J. Electr. Mater.

R. Droopad, K. T. Shiralagi, R. A. Puechner, K. Y. Choi and G. N. Maracas, "Low Temperature GaAs grown by Gas Source Molecular Beam Epitaxy," J. Crystal Growth, 120 p. 200-205 (1992)

X. T. Zhu, H. Goronkin, G. Maracas, R. Droopad, M. Stroscio, G. lafrate, K. Kim, A. Bhatt, "Electron Mobility Enhancement by Confining Optical-Phonons in Ultrathin GaAs/AlAs Multiple Quantum Wells", Appl. Phys. Lett., 60 (17) p. 2141-2143, April 1992

K. T. Shiralagi, R. A. Puechner, K. Y. Choi, R. Droopad and G. N. Maracas, "Optical Properties of Quantum Wells Grown Upon Gas Source MBE Low Temperature Buffers," J. Appl. Phys. 69 (11), pp 7942-7944 (1991)

R. A. Puechner, D. A. Johnson, K. Shiralagi, R. Droopad and G. N. Maracas, "Electrical and Optical Characterization of Gas Source and Solid Source MBE Low Temperature Buffers," J. Crystal Growth III, p. 43 - 49 (1991)

M. A. Stroscio, G. J. lafrate, K. W. Kim, M. A. Littlejohn, H. Goronkin, G. N. Maracas, "Transition from Longitudinal-Optical Phonon Scattering to Surface-Optical Phonon Scattering in Polar Semiconductor Superlattices," Appl. Phys. Lett. 59 (9), p.1093-1095, March 1991

R. Droopad, R. A. Puechner, K. T. Shiralagi, K. Y. Choi and G. N. Maracas, "Low Temperature GaAs Grown by Gas Source MBE," 3rd International Conference on Chemical Beam Epitaxy, Oxford, UK, September 1991

Conferences Proceedings

G. N. Maracas, K. T. Shiralagi, R. A. Puechner, F. Yu, K. T. Choi, J.S. Bow, R. Ramamurti, M.J. Kim and R.W. Carpenter, "Growth and Characterization of Low Temperature InP by GSMBE," Materials Research Society Symp. Proc. Vol. 241, p.271 (1992)

R. Rajesh, M. J. Kim, J. S. Bow, R. W. Carpenter, G. N. Maracas, "HREM of Low Temperature InP Growth by Gas Source MBE," 51st Annual Meeting of the Microscopy Society of America, Boston, MA (1992)

H. Goronkin, X. T. Zhu, G. N. Maracas, R. Droopad, M. A. Stroscio, "Mobility, Enhancement by Modulated Electron-Phonon Interaction," Int. Conf. on Quantum Functional Devices, Japan (1992)

K. T. Shiralagi, R. A. Puechner, K. Y. Choi, R. Droopad, and G. N. Maracas, "Gas Source MBE Growth of Low Temperature Buffers", 9th Annual Symposium of AVS, February 1991

G. N. Maracas, K. T. Shiralagi, R. A. Puechner, F. Yu, K. T. Choi, J.S. Bow, R. Ramamurti, M.J. Kim and R.W. Carpenter, "Growth and Characterization of Low Temperature InP by GSMBE," Materials Research Society Meeting - Low Temperature GaAs and Related Materials Symposium, Boston, MA, December 1991

R. Droopad, R. A. Puechner, K. T. Shiralagi, K. Y. Choi and G. N. Maracas, "Low Temperature GaAs Grown by Gas Source MBE," 3rd International Conference on Chemical Beam Epitaxy, Oxford, UK, September 1991

R. A. Puechner, D. A. Johnson, K. Shiralagi, R. Droopad and G. N. Maracas, "Electrical and Optical Characterization of Gas Source and Solid Source MBE Low Temperature Buffers," Sixth International Conference on MBE, San Diego, CA, August1990

R. A. Puechner, D. A. Johnson, K. Shiralagi, R. Droopad and G. N. Maracas, "Deep Levels in GaAs FETs grown on LTBs," Proceedings of the Sixth International Conference on MBE, San Diego, CA , August1990

Other presentations

H. Goronkin, X. T. Zhu and G. N. Maracas, "Enhanced Electron Mobility by Separate Confinement of Phonons," WOCSEMMAD, San Antonio, TX, February 1992

G. N. Maracas and K. T. Shiralagi, "Growth and Properties of Low Temperature InP by GSMBE," WOCSEMMAD, San Antonio, TX, February 1992

H. Goronkin, J. Shen, S. Tehrani, R. Droopad, G. N. Maracas, R. N. Legge, and X. T. Xhu, "Enhancement of Mobility in Pseudomorphic FET's with Up and Down Monolayers," International Conference on Solid State Devices and Materials, Japan, October 1991

H. Goronkin, S. Tehrani, J. Shen, R. N. Legge, X. T. Zhu, R. Droopad, and G. N. Maracas, "Enhancement of Mobility in Pseudomorphic FETs with Up and Down Monolayers," Device Research Conference, June 1991

G. N. Maracas, "Properties of Low Temperature GaAs Buffer Layers grown by MBE and GSMBE," Advanced Heterostructure Transistor Workshop, Hawaii, December 1990

G. N. Maracas, "GaAs grown at Low Temperatures by Gas Source MBE," First Workshop on Low Temperature Semiconductor Growth, San Francisco, CA, April 1990

G. N. Maracas, "Conduction in Low Temperature MBE GaAs buffers," First Workshop on Low Temperature Semiconductor Growth, San Francisco, CA, April 1990

G. N. Maracas, "Conduction in Low Temperature MBE GaAs buffers," Workshop on Compound Semiconductor Microwave Materials and Devices, San Francisco, CA, February 1990

Other technical reports

Six interim technical reports to ARO.

List of all participating scientific personnel showing any advanced degrees earned by them while employed on the project

Fan Yu, PhD candidate (Electrical characterization of thin quantum well structures)

Rajesh Ramamurti, MS July 1993, "Microscopy and Electrical Properties of InP Grown at Low Temperature MBE"

Tze-Yiu Yong, MS August 1991, "A Study Of GaAs/AlGaAs Phase Modulators Fabricated By the Process of Epitaxial Lift-Off"
Assisted in realizing free-standing LT GaAs layers that were removed from the substrate to facilitate electrical characterization and double crystal x-ray rocking curve measurements.

Suchitra Krishnan, MS June 1991, (Computer simulation of p-i-n structure carrier injection)

Johanes Suryananta, MS June 1991, "Development of a Fabrication Process for $In_xGa_{1-x}As/GaAs$ Vertical Cavity Lasers" Part of the thesis investigates LT GaAs as a surface passivation for photonic devices.

Ron Puechner, MS candidate, (Electrical and optical characterization of LT GaAs and InAlAs)

Report of inventions

No inventions during this period of performance.

Bibliography

[1] F.W. Smith, A.R. Calawa, C.-L. Chen, M.J. Mantra and L.J. Mahoney, IEEE El. Dev. Lett., vol. EDL-9, no. 77, (1988).

[2] J.N. Miller and T.S. Low, J. Crystal Growth 111, pp30-37, (1991)

[3] R. Metzger & A. Brown, WOCSEMMAD 1991

[4] G. N. Maracas, K. T. Shiralagi, R. A. Puechner, F. Yu, K. T. Choi, J.S. Bow, R. Ramamurti, M.J. Kim and R.W. Carpenter, "Growth and Characterization of Low Temperature InP by GSMBE," Materials Research Society Symp. Proc. Vol. 241, p.271 (1992)

[5] J. Ramdani, Y. He, M. Leonard, N. El-Masry and S.M. Bedair, Appl. Phys. Lett. 61, 1646 (1992)

[6] G. N. Maracas, K. Shiralagi, R. Ramamurti and R.W. Carpenter, "A Comparison of As and P Based Semiconductors Grown at Low Temperatures by MBE and GSMBE," to appear in J. Electr. Mater.

[7] F. W. Smith, A. R. Calawa, C. L. Chen, M. J. Manfra, and L. J. Mahoney, IEEE Trans. on Elec. Dev. **9**, 77 (1988).

[8] B. J. Lin, C. P. Kocot, D. E. Mars, and R. Jaeger, IEEE Trans. on Elec. Dev. **37**, 46 (1990).

[9] A.C. Warren, J.M. Woodall, J.L. Freeouf, D. Grischowsky, D.T. McInturff, M.R. Melloch and N. Otsuka, Appl. Phys. Lett. 57, 1331 (1990)

[10] D.C. Look, D.C. Walters, M.O. Manazreh, J.R. Sizelove, C.E. Stutz and K.R. Evans, Phys. Rev. B 42, 3578 (1990)

[11] R. A. Puechner, D. A. Johnson, K. Shiralagi, R. Droopad and G. N. Maracas, "Electrical and Optical Characterization of Gas Source and Solid Source MBE Low Temperature Buffers," Sixth International Conference on MBE, San Diego, CA, August1990

[12] M.R. Melloch, K. Mahalingham, N. Otsuka, J.M. Woodall and A.C. Warren, "GaAs buffer layers grown at low substrate temperatures using As_2 and the formation of arsenic precipitates," J. Crystal Growth 111, pp39-42, (1991)