MATERIALS

FINAL REPORT to ONR
Agency Award Number (#N00014-92-J-1694)

Dr. George Wright
Office of Naval Research
Code 1114/Room 607
800 North Quincy Street
Arlington, Virginia 22217

on

Novel Growth Technologies for In Situ Formation of Semiconductor Quantum Wire Structures

by

S. P. DenBaars
Materials Department
College of Engineering
University of California
Santa Barbara, CA 93106

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1. PROJECT SUMMARY

Novel growth technologies were developed for low dimensional quantum materials and devices. Non-hydride MOCVD and use of strain to produce InP quantum dots have been achieved. This ONR contract was key to our development of the less hazardous novel non-hydride sources, tertiarybutylarsine (TBA) and tertiarybutylphosphine (TBP) for the growth on InP based electronic devices. Indium Phosphide channel JFETs were fabricated by MOCVD using tertiarybutylphosphine (TBP) as the alternative source for phosphine for the first time.

We have developed the Stranski-Krastanow (SK) growth mode for the in-situ formation of InP quantum dots. It has been observed that many strained systems exhibit Stranski-Krastanow growth, where the epitaxy initiates in two dimensions but transforms to three dimensions with the formation of dislocations in response to the energetics and kinetics of the layer. We have observed that 3D growth can occur without the formation of dislocations where the islands are coherently strained to the substrate (coherent Stranski-Krastanow growth). Moreover, it is possible to use coherently strained islands to produce new structures. For example, $In_xGa_{1-x}As$ (x=0.5) grown by molecular beam epitaxy on GaAs(001), in the 4-6 ML range, has recently been used to produce quantum dots. We have used metalorganic chemical vapor deposition (MOCVD) to investigate the growth of InP on nominally flat GaAs(001). From structural characterization by atomic force microscopy (AFM) and transmission electron microscopy (TEM) of the surface as a function of thickness, we have observed that the growth proceeds in the coherent Stranski-Krastanow mode: initial 2D growth, coherent islanding, and incoherent islanding at some critical thickness. For example, at a substrate temperature of 650°C, 2D growth is observed until two monolayers, where coherently strained islands are observed with a density of 7×10^8 cm^{-2}. TEM observations show that the quantum dots are approximately 400-500Å in size, whereas These InP quantum dots are 1000 Å by 1400 Å and fall within a narrow size distribution. In addition, the size of these coherent islands remains essentially constant with increasing coverage's shown in Figure 1. In contrast, the density of dislocated islands increases with thickness. An appreciable density of dislocated islands (6×10^7 cm^{-2}) becomes evident at 4 monolayers.

By controlling the size of these small, direct bandgap semiconductor islands, we have an in-situ method for forming quantum structures that provide three dimensional carrier confinement. InP islands grown within a $Ga_xIn_{1-x}P$ (x=0.51) structure have strong photoluminescence peaks at both room temperature and low temperature. Samples with an estimated coverage of four monolayers emit a relatively narrow peak at 1.46 eV during low temperature measurement, which is 40 meV blue shifted with respect to bulk InP.

We have also used the novel non-hydride MOCVD technique to grow indium phosphide channel JFETs using tertiarybutylphosphine (TBP) as the alternative source for phosphine for the first time. At growth temperatures of 600°C specular surface morphology and mobilities as high as 61,000cm^2/V·s at 77K have been achieved using trimethylindium and TBP. To improve device isolation we employ a high resistivity (1x10^8 W-cm) semi-insulating InP buffer layer using ferrocene as the Fe-dopant. For the n-channel in our JFET structure disilane is used to obtain carrier concentrations of 2x10^{17}cm^{-3} with mobilities of 3000 cm2/V-s at room temperature. Devices with gate length of 1 μm showed very high extrinsic transconductance of 130 mS/mm, gate-drain breakdown voltage exceeding 20 V, maximum current density of > 450 mA/mm with record high f_T and f_{max} of 15 GHz and 35 GHz, respectively. These results indicates: that InP JFETs are promising electronic devices for both microwave power amplification and optoelectronic applications, and TBP is capable of device quality materials and offers several advantages over the more toxic phosphine counterpart

2. Theses/Publications Facilitated by ONR Award (#N00014-92-J-1694)

Theses

1. M.P. Mack, Master of Science Thesis, Growth and Characterization of III-V Semiconductors by Metalorganic Chemical Vapor Deposition Using Low Toxicity Tertiarybutylarsine and Tertiarybutylphosphine Precursors, University of California, Santa Barbara, CA (1992).

Publications

1. C.M. Reaves, V. Bressler-Hill M. Krishnamurty, W. H. Weinberg, P.M. Petroff, and S.P. DenBaars, "InP Islands on GaAs Substrates: MOCVD Growth of Quantum-Sized Structures", *IEEE Proceedings of the 6th Intl. InP and Related Materials Conf* (1994).in press

2. M.M. Hashemi, J.B. Shealy, S.P. DenBaars, U.K. Mishra, High Performance heterojunction InGaAs/InP JFET grown by MOCVD using Tertiarybutylarsine and Tertiarybutylphosphine", P7, *IEDM Tech. Digest*, 311 (1992).

3. M.M. Hashemi, J.B. Shealy, S.P. DenBaars, U.K. Mishra, High Speed p+ GaInAs-n-InP Heterojunction JFETs (HJFETs) grown by MOCVD, *IEEE Electron. Device Lett.* 14, No. 2., 60 (1993).

4. M.M. Hashemi, J.B. Shealy, S.P. DenBaars, and U.K. Mishra, "Novel High Power Heterojunction JFETs (HJFETs) Grown by MOCVD" *IEEE Proceedings of the 5th Intl. InP and Related Materials Conf.*,Paris, France, ISBN 0-7803-0993-6, pp. 375-378, IEEE Society, Piscataway, New Jersey (1993).

5. M. E. Heimbuch A.L. Holmes, Jr., M.P. Mack, S.P. DenBaars, L.A. Coldren, and J.E. Bowers "High Quality Long Wavelength Lasers Grown by Atmospheric Pressure MOCVD with Liquid Group V Sources" *IEEE Proceedings of the 5th Intl. InP and Related Materials Conf.*,Paris, France, ISBN 0-7803-0993-6, pp. 239-242, IEEE Society, Piscataway, New Jersey (1993).

6. M.M. Hashemi, J.B. Shealy, S.P. DenBaars, U.K. Mishra, "High Performance InP JFET grown by Metalorganic Chemical Vapor Deposition using Tertiarybutylphosphine (TBP) as the Phosphorous Source", In Press, *Journal of Electronic Materials*, (1993).

Conference Presentations

1. M.M. Hashemi, J.B. Shealy, S.P. DenBaars, U.K. Mishra, *High Performance heterojunction InGaAs/InP JFET grown by MOCVD using Tertiarybutylarsine and*

Tertiarybutylphosphine", **P7**, presented at the International Electron Device Meeting, San Franciso, CA December, (1992).

2. S.P. DenBaars, M. E. Heimbuch A.L. Holmes, Jr., L.A. Coldren, and J.E. Bowers *"High Quality Long Wavelength Lasers Grown by Atmospheric Pressure MOCVD with Liquid Group V Sources"* 5th Intl. InP and Related Materials Conf., Paris, France(1993).

3. S.P. DenBaars, M.M. Hashemi, J.B. Shealy, U.K. Mishra, *"High Performance InP JFET grown by Metalorganic Chemical Vapor Deposition using Tertiarybutylphosphine (TBP) as the Phosphorous Source"*, Organometallic Vapor Phase Epitaxy Workshop, Palm Springs March (1993).

4. M.M. Hashemi, J.B. Shealy, S.P. DenBaars, and U.K. Mishra, *"Novel High Power Heterojunction JFETs (HJFETs) Grown by MOCVD"* Presented at the 5th Intl. InP and Related Materials Conf.,Paris, France, April (1993).

5. M.M. Hashemi, J.B. Shealy, S.P. DenBaars, and U.K. Mishra, *"High Speed Heterojunction JFETs grown by Non-Hydride MOCVD"*, Ultrafast electronics and Optoelectronics (1993).

Abstract

IEEE Proceedings of the 6th Intl. InP and Related Materials Conf (1994).

InP Islands on GaAs Substrates: MOCVD Growth of Quantum-Sized Structures

C. M. Reaves, V.Bressler-Hill, M. Krishnamurthy,
W. H. Weinberg, P. M. Petroff, and S. P. DenBaars

NSF Center for Quantized Electronic Structures (QUEST)
University of California, Santa Barbara CA 93106

As the use of strained semiconductor structures becomes more common, there is a greater need to understand the growth of such systems. It has been observed that many strained systems exhibit Stranski-Krastanow growth, where the epitaxy initiates in two dimensions but transforms to three dimensions with the formation of dislocations in response to the energetics and kinetics of the layer. Recently, it has been observed that 3D growth can occur without the formation of dislocations where the islands are coherently strained to the substrate (coherent Stranski-Krastanow growth)[1]. Moreover, it is possible to use coherently strained islands to produce new structures. For example, $In_xGa_{1-x}As$ (x=0.5) grown by molecular beam epitaxy on GaAs(001), in the 4-6 ML range, has recently been used to produce quantum dots[2].

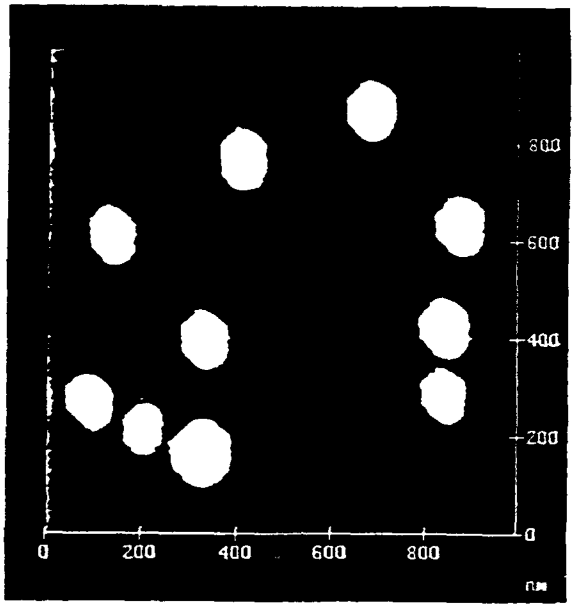
We have used metalorganic chemical vapor deposition (MOCVD) to investigate the growth of InP on nominally flat GaAs(001). From structural characterization by atomic force microscopy (AFM) and transmission electron microscopy (TEM) of the surface as a function of thickness, we have observed that the growth proceeds in the coherent Stranski-Krastanow mode: initial 2D growth, coherent islanding, and incoherent islanding at some critical thickness. For example, at a substrate temperature of 650°C, 2D growth is observed until two monolayers, where coherently strained islands are observed with a density of $7x10^8$ cm^{-2}. These islands are 1600 Å by 1400 Å and fall within a narrow size distribution. In addition, the size of these coherent islands remains essentially constant with increasing coverage's shown in Figure 1. In contrast, the density of dislocated islands increases with thickness. An appreciable density of dislocated islands ($6x10^7$ cm^{-2}) becomes evident at 4 monolayers. We will present how growth parameters, affect the size and distribution of the coherent islands and the growth of the relaxed islands.

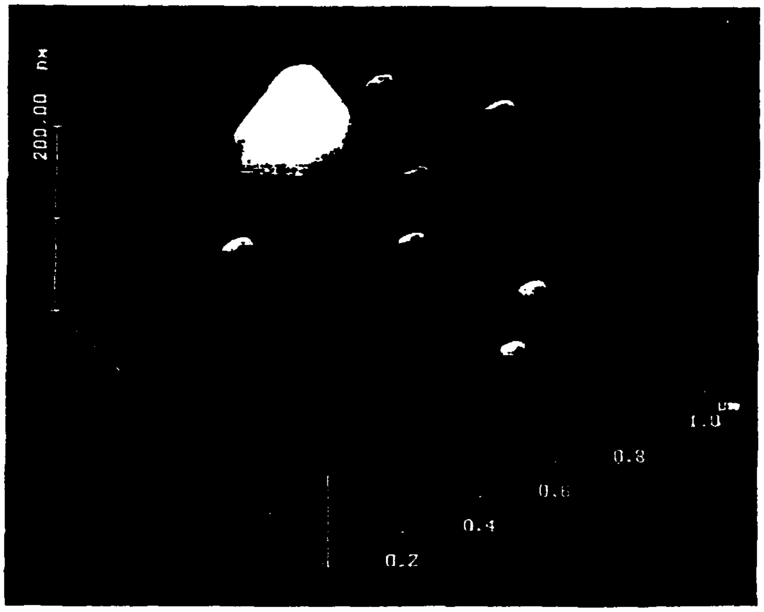
By controlling the size of these small, direct bandgap semiconductor islands, we have an in-situ method for forming quantum structures that provide three dimensional carrier confinement. InP islands grown within a $Ga_xIn_{1-x}P$ (x=0.51) structure have strong photoluminescence peaks at both room temperature and low temperature. Samples with an estimated coverage of four monolayers emit a relatively narrow peak at 1.45 eV during low temperature measurement. We will present the evolution of the photoluminescence with variations in the size and the density of the islands.

This work is supported by the NSF Science and Technology Center for Quantized Electronic Structures (DMR#91-20007), NSF Materials Synthesis and Processing (DMR#92-02290), and Office of Naval Research (#N00014-92-J-1694).

1. D. J. Eaglesham and M. Cerullo, *Physical Review Letters*, **64**, 1943-1946 (1990).
2. D. Leonard *et al., Applied Physics Letters*, to be published.

InP/InGaP/GaAs (001)





Growth Temp: 650°C
InP thickness: 4 mono layers

Figure 1.
AFM micrograph of InP quantum-size islands grown on a GaInP layer exhibit a bi-modal size distribution. TEM measurements indicate that the smaller size InP quantum islands are coherently strained, while the larger islands are incoherently strained.

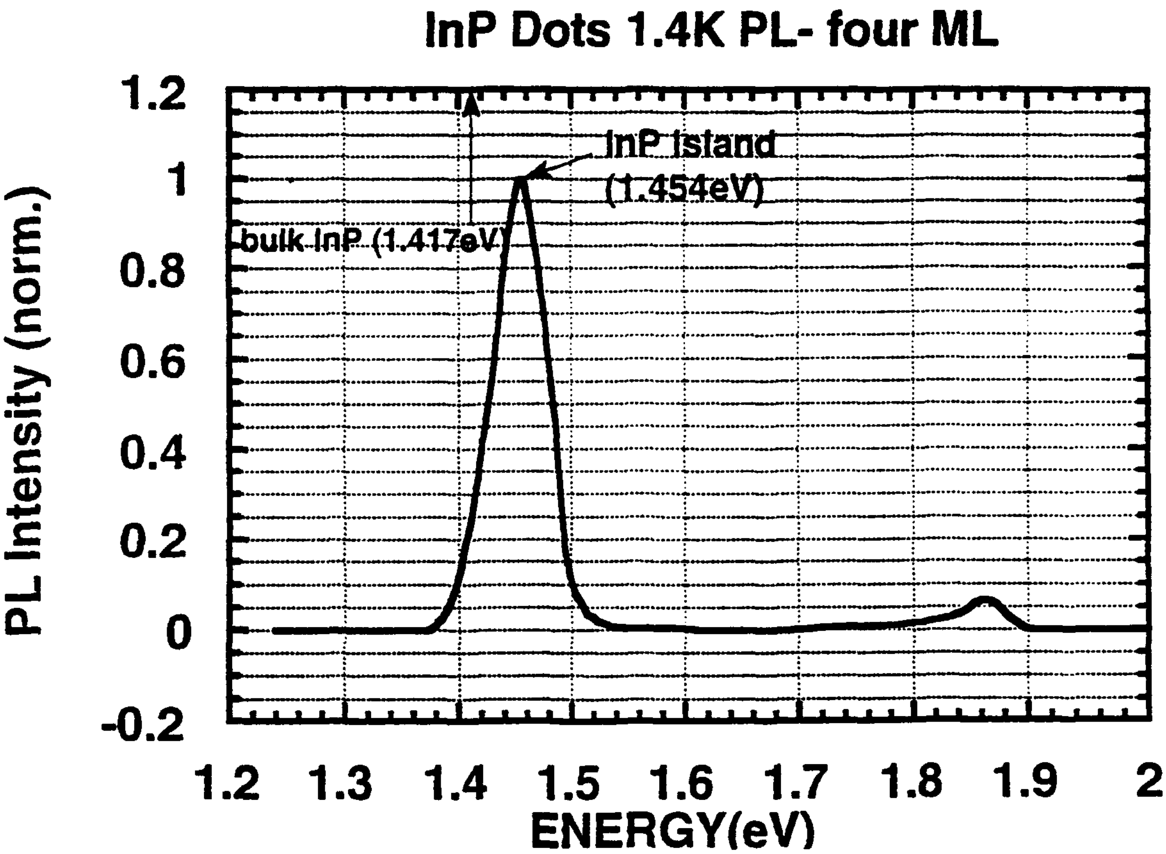


Figure 2.
Low temperature PL of InP islands embedded in high bandgap InGaP epilayer exhibit blue shifted luminescence.

University of California
Santa Barbara

Growth and Characterization of III-V Semiconductors by Metalorganic Chemical Vapor Deposition Using Low Toxicity Tertiarybutylarsine and Tertiarybutylphosphine Precursors

A thesis submitted in partial satisfaction of the requirements for the degree of

Masters of Science

in

Electrical Engineering

by

Michael Patrick Mack

Committee in charge:

Professor Steven P. DenBaars

Professor John E. Bowers

Professor James L. Merz

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Abstract

Growth and Characterization of III-V Semiconductors by Metal Organic Chemical Vapor Deposition Using Low Toxicity Tertiarybutylarsine and Tertiarybutylphosphine Precursors

by

Michael Patrick Mack

An MOCVD laboratory designed exclusively for use with low toxicity group V precursors tertiarybutylarsine (TBA) and tertiarybutylphosphine (TBP) was facilitized on the UC Santa Barbara Campus.

A systematic review of the literature concerning the growth of III-V semiconductors with TBA and TBP was conducted. Important milestones and trends are identified and discussed. Conclusions are drawn and presented with respect to the future of these sources in the electronic industry.

TBA and TBP were used to grow common III-V semiconducting materials. The materials grown include GaAs, InP, InGaAs and InGaAsP. Bulk materials were grown under various conditions in an attempt to determine the attainable growth regimes. Important parameters for optimizing the growth of InP and InGaAs bulk materials are identified as they relate to the growth conditions, such as V/III ratio, temperature and growth rate. Dopant incorporation studies were also performed as necessary to facilitate the growth of device structures.

InP was grow with 77K mobilities as high as 61,000 cm^2/Vs. Low temperature luminescence measurements show intense well resolved free and bound excitonic emissions indicative of exceptionally pure material. Si doping of InP showed linear p-type doping from $2.7x10^{17}$ to $3.4x10^{19}$ cm^{-3}.. Zn doping was linear from $2x10^{17}$ to $2x10^{18}$ cm^{-3} with saturation occurring around $3x10^{18}$ cm^{-3}.

InGaAs was grown lattice matched to InP. Double crystal X-ray rocking curves displayed lattice mismatch as low as 100 ppm and FWHM as narrow as 23 arc sec, indicating the exceptional structural quality the InGaAs. Low temperature luminescence measurements showed very strong luminescence and line widths as narrow as 1.6 meV, which also indicates the high optical quality of the InGaAs. Doping studies of InGaAs achieved p-type (Zn) doping as high as $2\text{-}3x10^{19}$ cm^{-3} using diethylzinc as the source. After

implementing a 1000Å doping set-back layer InGaAs/InP double heterostructure laser diode was grown and tested. The diode exhibited a low and "soft" reverse breakdown indicative of poor junction quality. This is though to be due to excessive Zn diffusion into and through the active region

A 1.3 and 1.5μm DH laser diodes were also grown and fabricated. The threshold current densities were 1.27 kA/cm2 and 2.0 kA/cm^2 respectively. Both devices are quite comparable to state-of-the-art arsine and phosphine grown devices. The threshold current densities are thought to be the best result to date for devices grown with both TBA and TBP.

InGaAs/InP multi-quantum wells were grown for the first time by MOCVD with both TBA and TBP. Low temperature photoluminescence showed narrow line widths comparable with similar arsine and phosphine grown quantum wells. The quantum wells were studied and optimized with respect to the growth temperature and growth interruption sequence.