REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
25 February, 2003

3. REPORT TYPE AND DATES COVERED
Final report: 15 May 98 - 20 Dec 02

4. TITLE AND SUBTITLE
VCSEL and smart pixel research for VLSI photonics

5. FUNDING NUMBERS
DAAG55-98-1-0303

6. AUTHOR(S)
K. Y. Cheng, R. D. Dupuis, M. Feng, S. R. Forrest, N. Holonyak. Jr. and K. C. Hsieh

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Illinois, ECE Dept., 208 N. Wright St., Urbana, IL 61801
University of Texas, Microelectronics Research Center, PRC/MER 1.606D-R9900, Austin, TX 78712
Princeton University, EE Dept, Princeton, NJ

8. PERFORMING ORGANIZATION REPORT NUMBER
DA-02-1

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The goal of this research program is to develop smart pixels and related technology for VLSI photonic systems. The native oxide and tunneling contact technology developed at the University of Illinois is the enabling technology for high performance vertical cavity surface emitting lasers (VCSELs) which will be used in future photonic systems and specifically in the smart pixels that are the focus of this research program. The smart pixel 8 x 8 (2.5 Gb/s) and 2 x 2 (20 Gb/s) arrays that will be studied will operate at 670 nm or 1330 nm and will utilize the native oxide defined VCSELs with tunnel junction contacts and heterogeneous materials integration through direct-wafer fusion, epitaxial lift-off, and bump-bonding techniques for integration and packaging. The University of Illinois and the University of Texas (20 GHz) and the Vitesse GaAs E/D MESFET/MSM technology utilizing the MOSIS foundry (2.5 GHz).

14. SUBJECT TERMS
Vertical cavity surface emitting laser (VCSEL), MESFET, HBT, PIN photodetector, MSM photodetector, smart pixel array, flip-chip bonding, avalanche photodetector

15. NUMBER OF PAGES
11

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	**UNCLASSIFIED**	**UNCLASSIFIED**	**UL**

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

GENERAL INSTRUCTIONS FOR COMPLETING SF 298

The Report Documentation Page (RDP) is used for announcing and cataloging reports. It is important that this information be consistent with the rest of the report, particularly the cover and title page. Instructions for filling in each block of the form follow. It is important to ***stay within the lines*** to meet ***optical scanning requirements.***

Block 1. Agency Use Only (Leave blank)

Block 2. Report Date. Full publication date including day, month, and year, if available (e.g. 1 Jan 88). Must cite at least year.

Block 3. Type of Report and Dates Covered. State whether report is interim, final, etc. If applicable enter inclusive report dates (e.g. 10 Jun 87 - 30 Jun 88).

Block 4. Title and Subtitle. A title is taken from the part of the report that provides the most meaningful and complete information. When a report is prepared in more than one volume, repeat the primary title, and volume number, and include subtitle for the specific volume. On classified documents enter the title classification in parentheses.

Block 5. Funding Numbers. To include contract and grant numbers; may include program element number(s) project number(s), task number(s), and work unit number(s). Use the following labels:

C - Contract	**PR** - Project
G - Grant	**TA** - Task
PE - Program Element	**WU** - Work Unit Accession No.

Block 6. Author(s). Name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. If editor or compiler, this should follow the name(s).

Block 7. Performing Organization Name(s) and Address(es). Self-explanatory.

Block 8. Performing Organization Report Number. Enter the unique alphanumeric report number(s) assigned by the organization performing the report.

Block 9. Sponsoring/Monitoring Agency Name(s) and Address(es) Self-explanatory.

Block 10. Sponsoring/Monitoring Agency Report Number. (*if known)*

Block 11. Supplementary Notes. Enter information not included elsewhere such as; prepared in cooperation with....; Trans. of...; To be published in.... When a report is revised, include a statement whether the new report supersedes or supplements the older report.

Block 12a. Distribution/Availability Statement. Denotes public availability or limitations. Cite any availability to the public. Enter additional limitations or special markings in all capitals (e.g. NORFORN, REL, ITAR).

DOD - See DoDD 4230.25, "Distribution Statements on Technical Documents."
DOE - See authorities.
NASA - See Handbook NHB 2200.2.
NTIS - Leave blank.

Block 12b. Distribution Code.

DOD - Leave Blank
DOE - Enter DOE distribution categories from the Standard Distribution for unclassified Scientific and Technical Reports
NASA - Leave Blank.
NTIS - Leave Blank.

Block 13. Abstract. Include a brief (*Maximum 200 words)* factual summary of the most significant information contained in the report.

Block 14. Subject Terms. Keywords or phrases identifying major subject in the report.

Block 15. Number of Pages. Enter the total number of pages.

Block 16. Price Code. Enter appropriate price code (NTIS *only*).

Block 17. - 19. Security Classifications. Self-explanatory. Enter U.S. Security Regulations (i.e., UNCLASSIFIED). If form contains classified information, stamp classification on the top and bottom of the page.

Block 20. Limitation of Abstract. This block must be completed to assign a limitation to the abstract. Enter either UL (Unlimited) or SAR (same as report). An entry in this block is necessary if the abstract is to be limited. If blank, the abstract is assumed to be unlimited.

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

1 TABLE OF CONTENT

2 STATEMENT OF THE PROBLEMS STUDIED:

Task 1– VCSEL Development:

Design, growth, fabrication, and testing of M-V semiconductor VCSEL and RCPD optoelectronic devices. This work includes 670nm and 1330nm VCSELs employing the latest native oxide and tunnel injection techniques to achieve operation at low voltages and threshold currents.

Task 2–Smart Pixel Development

Design, fabrication, and testing of 8 x 8 smart pixels operating at 2.5 Gb/s using the Vitesse GaAs E/D MESFET/MSM MOSIS foundry. Design, fabrication, and testing of 2 x2 smart pixels operating at 20 Gb/s, using the University of Illinois 100 GHz InGaP/GaAs HBT process. A test plan has been developed to demonstrate board to board data conununication for the 8 x 8 MESFET/MSM/VCSELs and 2 x 2 HBT/PIN/VCSELs smart pixels operated at 10Gb/s per channel.

Task 3–Heterogeneous Material Integration:

Heterogeneous materials integration using direct-wafer fusion, epitaxial lift-off, and burripbonding techniques for packaging and assembly of components for board to board data communications.

Task 4–Avalanche Photodiode Array Development

Avalanche photodiode 2 x 2 arrays for 1330 nm detection will be designed and fabricated at Princeton University. They will be incorporated in smart pixels operating at 10 Gb/s per channel. High bandwidth, high sensitivity AlInAs/InGaAs mesa APIDs grown by gas source MIBE will be demonstrated. The bandwidth, excess noise figure and ionization rate as a function of gain will be characterized. In addition, primary and multiplied dark current will be characterized. A planar APD structure will be developed for bumb-bonding integration in smart pixels.

3 SUMMARY OF THE MOST IMPORTANT RESULTS:

3.1 Task 1-VCSEL Development

a) 670 nm VCSEL development:

We have worked on the development of red vertical cavity surface emitting lasers (VCSELs) using metalorganic chemical vapor deposition (MOCVD). We took three different approaches: (1) Native-oxide distributed Bragg reflector (DBR) VCSELs using InAlP/AlGaAs DBRs; (2) conventional InAlGaP VCSELs using semiconductor DBR structures; (3) InAlGaP lasers using InP quantum dot active regions. Our research work in these areas led to important new concepts for visible red lasers. The most important result in this area is the demonstration of the quantum-well-assisted quantum-dot laser (QD + QW laser).

During this program, we have been studying the quantum-dot (QD) laser modified into a quanturn-well-assisted quantum-dot laser (QD + QW laser). The auxiliary quantum well (QW) is coupled by tunneling to the QDs via a barrier. The purpose of the auxiliary QW layer, or layers, is to overcome the problem of carrier collection and rearrangement (QD to QD transport) in the QDs, problems that arise because of the disconnected form (from dot-to-dot) of the QD layers and the stochastic form of the QDs in size and geometry. A QW within tunneling distance of a QD layer collects carriers efficiently, allows rapid tunneling transfer of carriers to the QD layer (including rapid back-and-forth tunneling-assisted lateral charge re-adjustment) and, as a consequence, efficient recombination via the QDs. The expectation, the purpose of this work is to realize an improved form of QD laser.

The idea of a QW-assisted QD laser has been verified by experiments on visible-spectrum (λ ~ 650 nm) InP-QD/InGaP-QW/InAlP heterostructures and IR (λ ~ 980 nm) InAs-QD/GaAs-QW/AlGaAs heterostructures. Both photopumped and current-driven (diode) QD+QW lasers have been demonstrated in initial experiments. A patent application has been filed on the QD+QW laser, and on a number of variations of the basic device structure. There clearly are many opportunities afforded by coupling one-dimensional confined quantum systems to three-dimensional confined quantum systems (as demonstrated by the publications of the last two years). This work is merely in its infancy and obviously requires more attention.

Specifically, we have demonstrated CW 300 K photopumped InP QD laser operation (656-679nm) realized by modifying and coupling, via tunneling, an auxiliary InGaP QW to the QDs of the InP-In(AlGa)P-InAlP heterostructure. Carriers collected (efficiently) in the QW, and thus localized near the QDs, transfer by resonance tunneling to the QDs. The lattice-matched $In_{0.49}Ga_{0.51}P$ QW coupled to the InP QDs by a thin (L_B~ 20Å) $In_{0.5}Al_{0.3}Ga_{0.2}P$ barrier overcomes the limitations of carrier collection, lateral charge transport, and thermalization in the QDs, thus yielding a fundamentally different form of QD laser. These are the lowest threshold InP QD lasers and the first to operate CW at 300K. We have also established a record high characteristic temperature (T_0) for red-emitting injection lasers operating in the ~ 650 nm wavelength regime.

b) Fabrication of 1330 nmm VCSEL:

Long-wavelength (1.3 and 1.55 µm) InGaAsP/InP VCSEL is the key component for the realization of high-speed and high-density optical communication systems. Unfortunately, the InGaAsP/InP material system doesn't possess efficient lattice-matched epitaxial DBR because the refractive index difference of InGaAsP/InP is as small as 0.3 and their thermal conductivity is low. In order to overcome the existing problems in long-wavelength VCSELs, we have developed ex-cavity bonding methods which incorporates semiconductor/Al-oxide DBR, such as GaAs/Al-oxide and Si/Al-oxide, into the VCSEL fabrication process.

<u>Very-low temperature molecular beam epitaxy growth of substrate-independent DBRs:</u>

Using very-low temperature molecular beam epitaxy (VLT-MBE) growth techniques, substrate-independent DBRs were fabricated for use in the visible spectrum. The microstructure of the semiconductor material was found to be either polycrystalline or amorphous depending on the group-V overpressure used as seen in Fig. 1. Higher overpressures resulted in amorphous material. Because the material was not single-crystalline, it can be deposited on any host substrate without causing defects in the underlying material. In addition, the two materials used in the DBR do not need to be lattice matched to each other thereby allowing much freedom in the design of the DBRs. VLT-GaP and AlAs were used as the materials for the visible spectrum DBR. Figure 2 shows the reflectivity of a DBR with only 6 pairs of poly-GaP/Al-oxide layers grown on a GaAs substrate.

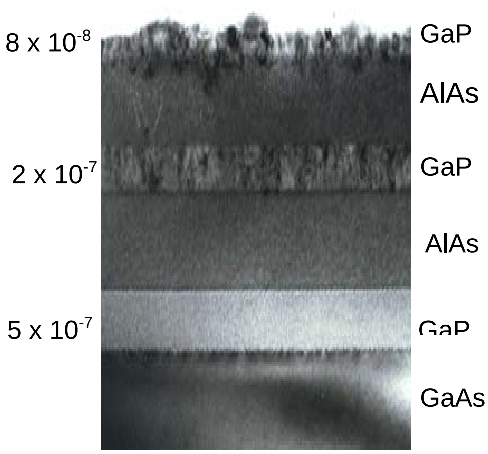


Figure 1 XTEM of a VLT-MBE grown (Ga,P)/(Al,As) heterostructure on GaAs substrate under different P overpressures.

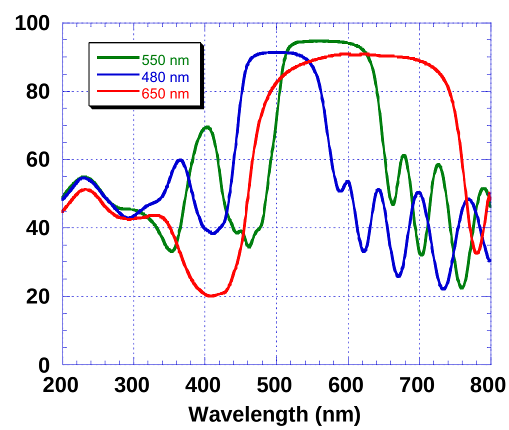


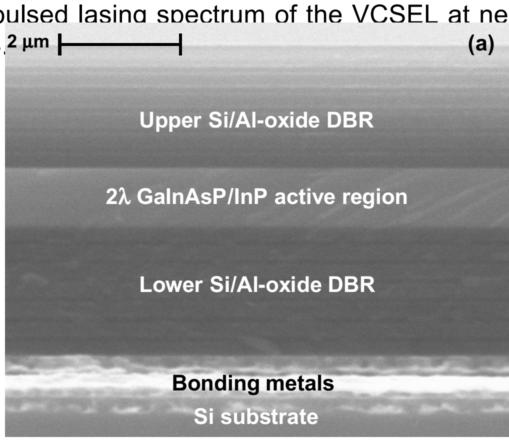
Figure 2. Reflectivity spectra for the six pair poly (Ga.P)/Al-oxide DBRs centered at 480, 550, and 650 nm.

<u>1.55µm VCSEL using metallic bonding:</u>

To overcome the problem associated with the small refractive index difference in the GaInAsP/InP material system, a novel wafer bonding method using AuGeNiCr multi-layered metals as the bonding medium has been developed to fabricate 1.55 µm VCSELs on Si substrates. The bonding was performed at a low temperature of 320 °C without any special treatment of the bonding surfaces, and the bonding interface was located outside the VCSEL cavity. This metallic bonding process is straightforward and generous in process latitude which makes this process attractive for manufacturing. In addition, the feasibility of this process to fabricate long-wavelength VCSELs on Si makes it useful for potential applications on module integration.

The fabrication process is briefly described here. The 2λ-thick GaInAsP/InP active region of the VCSEL was grown on a (100) InP substrate. After crystal growth, a 6.5-period Al-oxide/Si lower DBR was deposited on the as-grown wafer by e-beam evaporation. The DBR/GaInAsP/InP wafer and a Si substrate were then coated with the AuGeNiCr metallic bonding medium and bonded together at 320 °C under a uniaxial pressure. After bonding, the InP substrate was removed by HCl chemical etching and the GaInAsP/InP active region was exposed. Standard photolithography and selective chemical etching were used to define the VCSEL mesa. The p-type and n-type ohmic contacts were formed by Au/Zn/Au and AuGe/Ni/Au alloys, respectively. Finally, a 5-period Al-oxide/Si upper DBR was deposited on top of the device mesa to complete the VCSEL structure.

Figure 3 shows the cross-sectional scanning electron microscopy (SEM) micrograph of the fabricated long wavelength VCSEL. The room temperature current-voltage (I-V) and light-output versus injection current (L-I) curves of a 30 μm by 30 μm VCSEL are shown in Fig. 4. The VCSELs have a turn-on voltage around 0.8 volt and a threshold current of 12 mA. The pulsed lasing spectrum of the VCSEL at near room temperature was observed at 1.545 μm as shown in the inset of Fig. 4[illegible] μm.



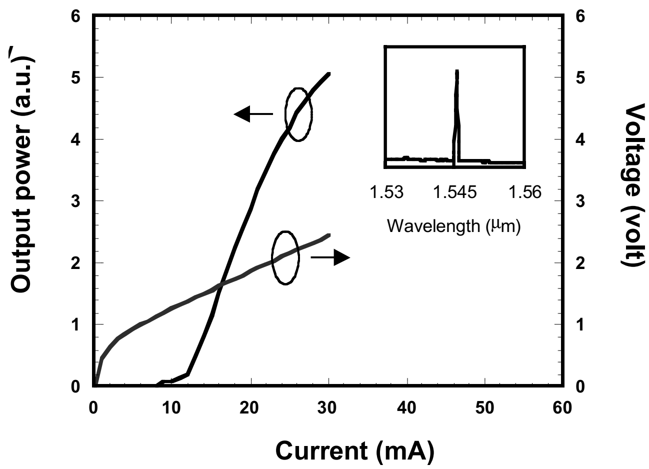


Figure 3. The cross-sectional SEM micrograph of the GaInAsP/InP VCSEL cavity.

Figure 4. The room temperature I-V, L-I and lasing spectrum of a 30 μm × 30 μm VCSEL.

3.2 Task 2-Smart Pixel Development

a). HBT/P-I-N Fabrication:

The InGaP/GaAs HBTs grown under the optimized growth condition at the UIUC have demonstrated the highest dc current gain to date. We have achieved a dc current gain of 217 at collector current density of 1kA/cm^2 with the base sheet resistance R_b =262 ohm/sq. The results (Table 1) surpassed that of Kopin (US), Ferdinand Braun Insitiute (Germany), and Hitachi (Japan). The current gain to base sheet resistance ratio of 0.827 is the highest ever reported. The high current gain was accomplished by optimizing the growth of the base and emitter layer as well as tailoring the collector-subcollector doping concentration.

Table 1. HBT performance comparison.

Research group	Current gain	R_b (Ω/sq)	Gain/R_b (sq/Ω)
UIUC	**217 @ 1kA/cm^2**	**262.3**	**0.827**
Kopin	150 @ 1kA/cm^2	250	0.6
Hitachi	130 @ 40 kA/cm^2	250	0.52
Ferdinand-Braun-Institute	113 @ 10 kA/cm^2	200	0.56

In this work, photoreceivers using PIN/HBT are investigated for 20 Gb/s and 40 Gb/s OEIC applications. A 20-Gb/s and a 40 Gb/s short wavelength PIN/HBT photoreceivers are. Implemented using f_T = 60 GHz InGaP/GaAs HBT technology, PIN-TZ-1L4 has simulated 3-dB bandwidth of 17.4 GHz with 43.3 dB gain using a 25-μm diameter PIN photodetector. PIN-TZ-1L1-L using inductor peaking technique has simulated -3 dB bandwidth of 33.5 GHz with 49.3 dB gain using a 10-μm diameter PIN photodetector.

b). 20 Gb/s Photoreceiver Designs, Fabrication, and Testing:

PIN-TZ-1L4 transimpedance gain is given in Fig 5. The transimpedance gain is 43.3 dB-ohm which is equivalent to 146 ohm. The receiver -3 dB bandwidth is 17.4 GHz. PIN-TZ-1L4 is DC coupled with single-ended input and single-ended output. The output return loss is simulated with the input open and output attached to 50-ohm load. The data is at 20-Gb/s data rate. The input data has extinction ratio of 10 dB and signal swings from 10 µA to 100 µA.

Figure 6 shows the layout of PIN-TZ-1L4. PIN with diameter of 25 µm is used. The photodetectors are intentionally placed far away from the circuit to avoid the influence of the illumination on the transistors. The photodetectors are connected to the transimpedance amplifiers through coplanar transmission lines that have characteristic impedance matched to the equivalent input impedance of the transimpedance amplifiers. Figure 7 shows the layout of a 2 x 2 two-dimensional photoreceiver array for a real space interconnect. The distance between two adjacent horizontal and vertical photodetectors is 250 µm. The total data rate is estimated to be 80 Gb/s.

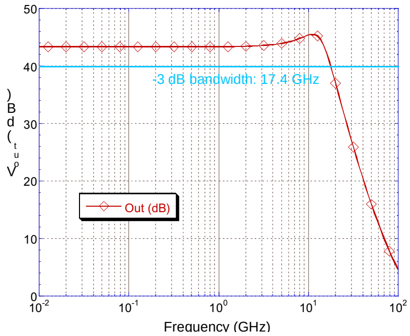


Figure 5. Simulated gain of PIN-TZ-1L4 transimpedance amplifier.

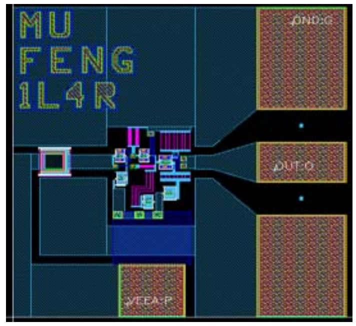


Figure 6. Layout of PIN-TZ-1L4 transimpedance amplifier.

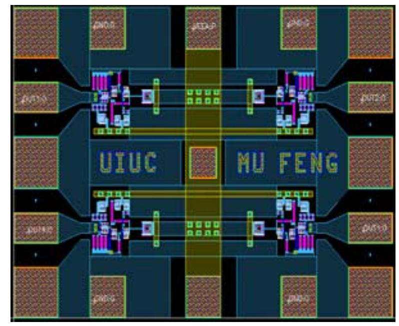


Figure 7. Layout of a 2x2 photoreceiver array.

The InGaP/GaAs chips, including the 10 to 40 Gb/s transimpedance amplifiers and photoreceivers arrays were fabricated by Network Device Inc.(NDI). Figure 8 shows the measured I-V curve for the InGaP/GaAs HBT H2. Figure 9 shows the measured Gummel plot for H2.

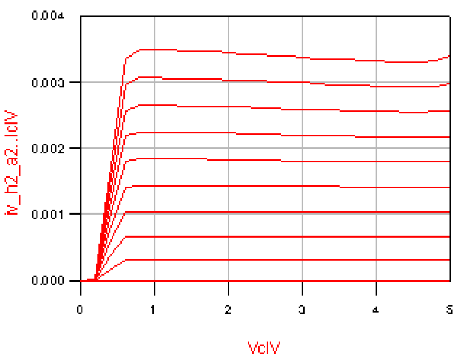


Figure 8. Measured I-V curve for InGaP/GaAs HBT H2.

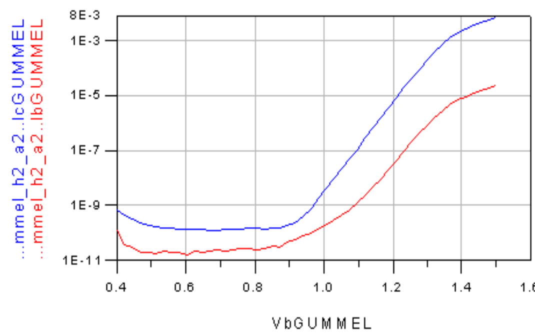


Figure 9. Measured Gummel Plot for InGaP/GaAs HBT H2.

Figures 10–12 show the tested s-parameters result of the transimpedance amplifier TZ-1A. The red line is the simulation result, and the blue line is the testing result by using a regular DC probe, while the black line shows the results with an improved DC probes with various capacitances on the probe needle. From the experimental results shown below, we can see the bandwidth of TZ-1A is around 8GHz and S21 is 8dB, which is close to design specification. The corresponding transimpedance gain is 44 dBΩ. S22 is less than –20dB, which makes the output impedance fairly close to 50Ω.

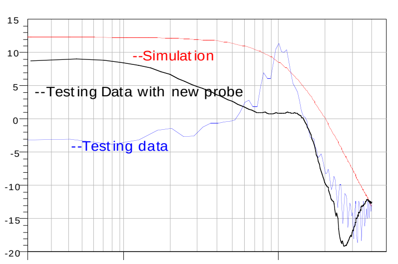


Figure 10. Measured S21 of TZ-1A.

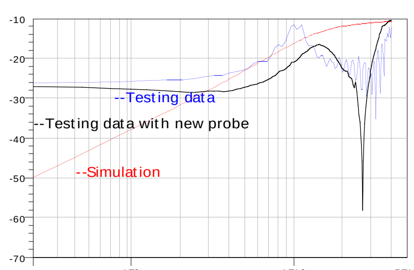


Figure 11. Measured S22 of TZ-1A.

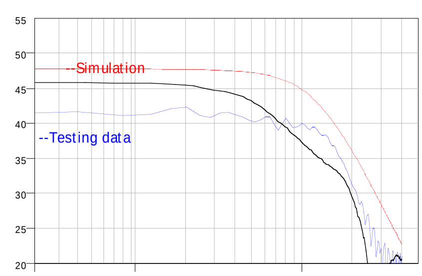


Figure 12. Measured gain of TZ-1A.

We also did the eye-diagram testing. The testing setup is shown on Figure 13. In this projectment, we did the electrical input and electrical output (E/E) eye-diagram. The test set has a measurement upper limit of 3GHz. Figure 14 shows an eye of TZ-1L with PBRS of 2^15-1 pattern. The input data has amplitude of 500mV with high level at –3V. The eye is widely open with low jitter. The bit-error-rate calculated from this eye-diagram is lower than 10^{-15}. It suggests our circuit should be able to work on speed higher than 3Ghz.

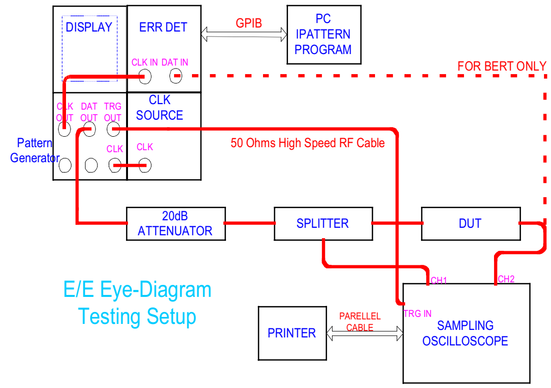


Figure 13. E/E Eye-diagram test setup.

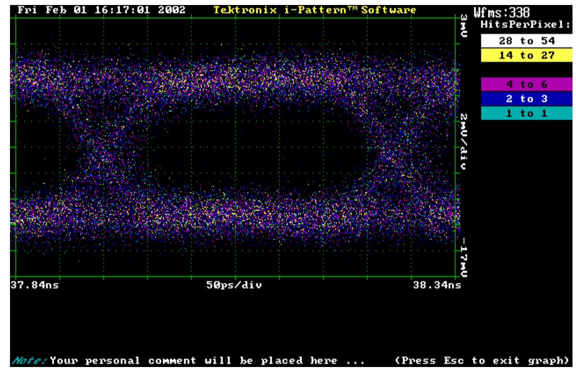


Figure 14. Measured eye diagram of TZ-1L.

3.3. Task 3-Heterogeneous Materials Integration

The goal of this research was to develop a bonding technique for the integration of an array of VCSELs to a photodetector array. The bonding would need to be performed at reasonably low temperatures (<450 °C) so that the process would not affect the performance of the sensitive devices. The bonding would also need to be electrically conductive and take up as little area as possible. For these purposes, a flip-chip bonding technique was investigated. In the flip-chip bonding process, a metallic solder is selectively deposited in certain areas referred to as bond pads. Bond pads of two separate samples are then brought together and the samples are heated to a point in which the solder on both samples melts together forming a conductive bond. The metal combinations that were used as the solders in this experiment are Sn/In, Sn/Zn, and Sn/Au. Lead was avoided as a solder material for environmental reasons. The process parameters that were investigated in these experiments were ease of processing, resistance of bonds, and temperature of bonding process.

Metals were deposited in thickness to target eutectic points in which the melting point would be at a minimum. Sn/In had a eutectic temperature of approximately 117 °C at a composition of 48 at. % Sn. This was the lowest melting point for any of the three solders. For Sn/Au combinations a composition of 72 at. % Sn was used and a composition of 60 at. % Sn was used for Sn/Zn. All metals were deposited by thermal evaporation and final thickness of the solder combinations were varied between about 1 and 2 µm. Thus the final bonded unit would have a gap distance up to 4 µm. These extremely thick metal depositions were necessary so that the gap between bonded samples would exceed the height of any device arrays being bonded. The VCSELs that would be bonded for this project were estimated to be as much as 2-µm tall. Initially there was some difficulty with the sticking of Sn/Zn and Sn/Au solders, however these problems were solved by that deposition of a thin Ti layer prior to solder deposition.

A simple mask was designed to simulate a 4x8 bonding array. Two different patterns were developed on the mask to process the top and bottom samples in the bonded pair. These patterns can be seen in Fig. 15.

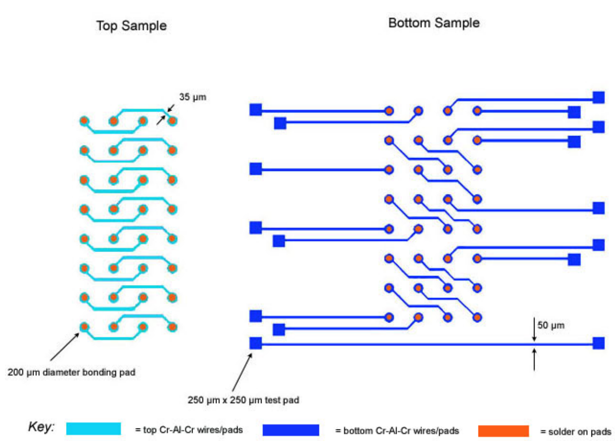


Figure 15. Masks of the 4x8 solder-array testing pad.

In Fig. 16, the results of the mask pattern are seen after bonding. A Nomarski optical micrograph of two glasses intentionally mis-aligned is shown in Fig. 17 to show the metal bonds. With this simple design it is possible to measure conduction through 2, 4, 6, and 8 bonds. At the very bottom of the mask patterns is a conduction path that does not pass through any bonds. The purpose of this pattern is to measure and calculate the resistance of the metal wire paths so that these results may be subtracted and the actual resistance of the bonds calculated. With the use of Sn/In as a solder, samples could be repeatedly bonded. Si was bonded to Si, glass was bonded to glass, and glass was bonded to Si. Using the simple mask design described above, the resistance of the bonds could be calculated. All bonds in the 4x8 array had bonded successfully with an average bond resistance of 0.75 Ω/bond as shown in Fig. 18.

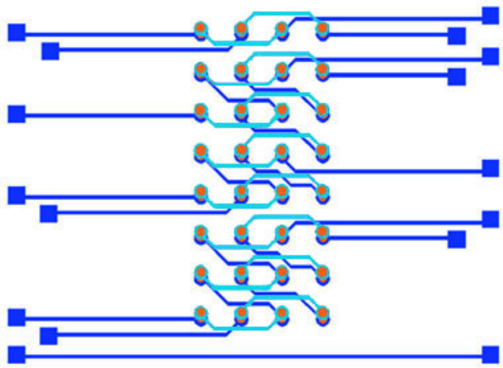


Figure 16. Overlay of top and bottom 4x8 solder pad.

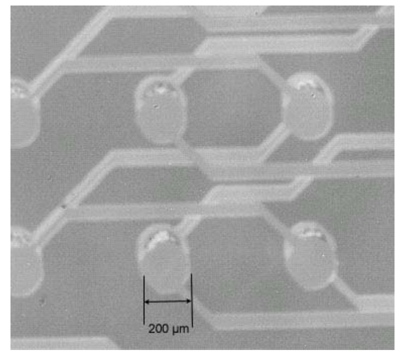


Figure 17. Normarski photograph of two pieces of glass bonded together. The sample is intentionally misaligned to show the bottom solder.

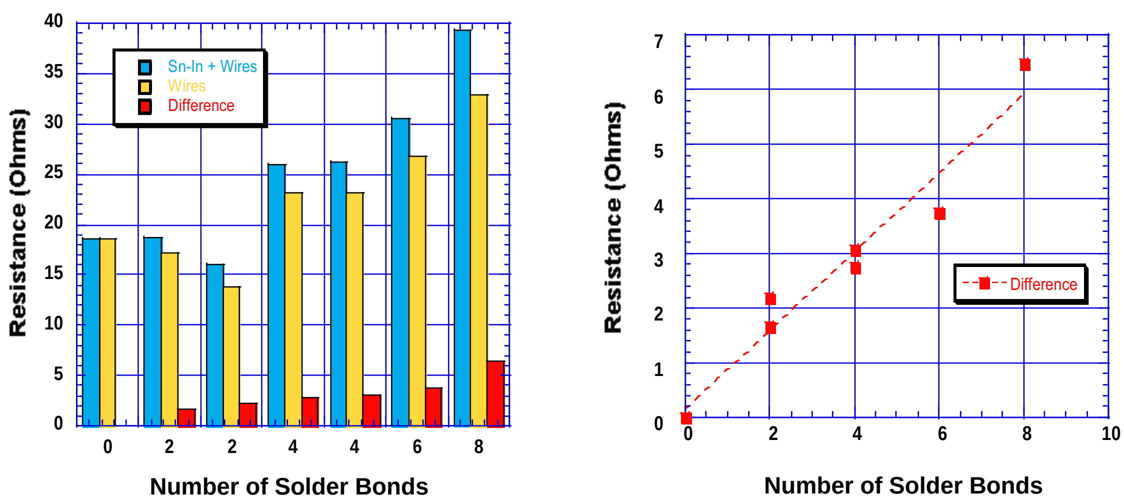


Figure 18. Measurement of solder ball resistance

3.4. Task 4-Avalanche Photodiode Array Development

During this program, the most significant advance was to model, and then demonstrate extremely low cost, high performance integratable avalanche photodiodes for use at long wavelengths based on our proprietary floating guard ring (FGR) planar structure. These InP/InGaAs separate absorption, grading and multiplication (SAGM) APDs operate at 10Gb/s. The advance comes from the finding that by appropriate design, the APDs can be made, for the first time, at extremely high yields and low cost, literally dropping the bottom out of the cost of APDs used at long-wavelengths from a few hundred dollars to <$10 each! This technology was then successfully transferred to the industrial sector (Sensors Unlimited) who have been able to produce the APDs in very large quantities (tens of thousands). More importantly for the future of VLSI-photonics, Sensors Unlimited then went on to demonstrate large 2D arrays of APDs with no pixel drop outs, and extremely uniform breakdown voltages across the array. To my knowledge, this is the first time that APD arrays have been demonstrated, and is simply a result of the careful modeling and design of the FGR SAGM APD afforded by this program. It is difficult to over estimate the importance of this result on future, high density optical systems since APDs provide significant sensitivity advantages over alternative detection schemes, yet APDs, first successfully demonstrated by the PI in 1981 for application to long wavelength systems, have always been prohibitively expensive and hence have not penetrated deeply into the optical fabric.

In other advances, we demonstrated the highest efficiency 40GHz detectors using our asymmetric twin waveguide technology, resulting in ~1A/W sensitivity at a wavelength of 1.55 microns. This too is a significant improvement over previous attempts at demonstrating very high bandwidth and sensitive detectors. This technology was transferred successfully to ASIP, Inc.

Finally, considerable effort was devoted to demonstrating APD receivers based on integrating InAlAs/InGaAs SAM APDs with InP/InGaAs HEMTs. The receiver bandwidth was 5GHz. This integration work was only moderately successful, and it was our conclusion that flip-chip bonding of the detector and receiver is ultimately the most high yield, and simplest process. Indeed, our industrial partner, Sensors Unlimited, has made a large business out of high yield flip chip bonding of detector arrays to multiplexer circuits, and work during this program with them on this particular program is extremely promising. Undoubtedly, this is the solution in both the near and long term for VLSI photonic applications. In addition to the integration work, we explored the performance of InAlAs/InGaAs SAM APDs as a lower noise alternative to conventional InP/InGaAs SAGM-APDs. Indeed, we found that such was the case, with ionization coefficient ratios of k~0.2 as opposed to 0.4-0.5 for InP. This suggests that an optimum gain of the InAlAs, and bandwidth of these same devices is improved by a factor of two, while the excess noise is halved compared to InP.

4 LIST OF PUBLICATIONS:

(a) <u>Journal articals</u>:

1. D. Mathes, R. Hull, R. D. Dupuis, and R. Heller, and B. P, Tinkham, “Nanoscale structure and Chemistry of Al0.49In0.51P Thermal Oxide,” Appl. Phys. Letters, **75**, 2572 (1999).
1. B. P. Tinkham and R. D. Dupuis, “Photoluminescence Properties of Zn-doped Heterostructures Having Native-oxide Layers,” J. Appl. Phys **87**, 203 (2000).
2. Q. Yang, D. Scott, J. Miller, P. Meyer, H.C. Kuo, J.E. Baker, G.E. Stillman, "Precipitate Formation in carbon-doped base of InGaP/GaAs heterojunction bipolar transistors grown by metel-organic chemical vapor deposition." Appl. Phys. Lett. **74**, 2993 (1999).
3. Q. Yang, D. Scott, T. Chung, G.E. Stillman, "Optimization of Emitter Growth Condictions for InGaP/GaAs HBTs with High Current Gain by LP-MOCVD." J. Eletron. Mater. **29**, 75 (2000).
4. Q. Yang, D. Scott, T. Chung, G.E. Stillman, "Minority carrier lifetime degradation in carbon-doped base of InGaP/GaAs heterojunction bipolar transistors." Appl. Phys. Lett., **77**, 271-273 (2000).
5. T. Chung, S. Bank and K.C. Hsieh, “High DC current gain InGaP/GaAs HBTs grown by LP-MOCVD,” *Electronics Lett*. Vol. **36**, pp. 1885-1886, Oct. 2000.
6. C. Reddy, V. Narayanamurti, J. H. Ryou, U. Chowdhury, and R. D. Dupuis, “Imaging and Local Current Transport Measurements of AlInP Quantum Dots Grown on GaP,” Appl. Phys. Lett., Vol. **76**, No. 11, pp. 1437-1439 (2000).
7. D. A. Kellogg, N. Holonyak, Jr., and R. D. Dupuis, “Reliability of Photopumped $Al_xGa_{1-x}As$-GaAs Quantum-Well Heterostructure Lasers with Top and Bottom Distributed Native-Oxide Reflectors,” Appl. Phys. Lett., Vol. **77**, No. 11, pp. 1608-1610 (2000).
8. D. A. Kellogg, N. Holonyak, Jr., and R. D. Dupuis, “Mode Behavior of Photopumped AlGaAs-GaAs Lasers Confined by Oxide Semiconductor Distributed Bragg Reflectors,” Appl. Phys. Lett., Vol. **77**, No. 20, pp. 3152-3154 (2000).
9. D. A. Kellogg and N. Holonyak, Jr., “Scattering (Stochastic) Recoupling of a Coupled Ten-Stripe AlGaAs-GaAs-InGaAs Quantum Well Heterostructure Laser,” Appl. Phys. Lett. **78**, 2202-2204 (2001).
10. T. Chung, S. Bank, J. Epple, and K.C. Hsieh, “Current Gain Dependence on Subcollector and Etch-stop Doping in InGaP/GaAs HBTs,” *IEEE Transaction on Electron Devices*, **48**, 835-839, 2001.
11. D.E. Wohlert, K.Y. Cheng, and S.T.Chou, “Temperature invariant lasing and gain spectra in self-assembled GaInAs quantum wire Fabry-perot lasers,” Appl. Phys. Lett., **78**, 1047-1049, 2001
12. N. Holonyak, Jr., "The Silicon p-n-p-n Switch and Controlled Rectifier (Thyristor)," IEEE Trans. Power Electronics **16**, 8-16 (2001).
13. N. Holonyak, Jr., “Gregory Eugene Stillman, 1936-1999," Memorial Tributes, Vol. **9**, (National Academy of Engineering, Washington, D.C., 2001), pp. 260-265.
14. M. G. Craford, N. Holonyak, Jr., and F. A. Kish, Jr., "In Pursuit of the Ultimate Lamp,” Sci. Am. **284** (No. 2), 62-67 (2001).
15. N. Holonyak, Jr., “ZHORES I. ALFËROV (2000 Nobel Prize)”, IEEE Electron Devices Soc. Newsletter **8** (No.2), 9 (2001).
16. J. H. Ryou, R. D. Dupuis, C. V. Reddy, V. Narayanamurti, D. T. Mathes, R. Hull, A Mintairov, and J. L. Merz, “Growth and Characterization of InP Self-Assembled Quantum Dots Embedded in InAlP on GaAs Substrates,” J. Electron. Mat., Vol. **30**, No. 5, pp. 471-476 (2001).
17. J. H. Ryou, R. D. Dupuis, G. Walter, D. A. Kellogg, N. Holonyak, Jr., D. T. Mathes, R. Hull, C. V. Reddy, and V. Narayanamurti, “Photopumped Red-Emitting $InP/In_{0.5}Al_{0.3}Ga_{0.2}P$ Self-Assembled Quantum Dot Heterostructure Lasers Grown by Metalorganic Chemical Vapor Deposition,” Appl. Phys. Lett., Vol. **78**, pp. 4091-4093 (2001).

18. G. Walter, N. Holonyak, Jr., J. H. Ryou and R. D. Dupuis, “Room Temperature Continuous Photopumped Laser Operation of Coupled InP Quantum Dot and InGaP Quantum Well InP-InGaP-InAlP Heterostructures,” Appl. Phys. Lett. Vol. **79**, pp. 1956-1958 (2001).
19. G. Walter, N. Holonyak, Jr., J. H. Ryou and R. D. Dupuis, "Coupled InP Quantum Dot InGaP Quantum Well InP-InGaP-In(AlGa)P-InAlP Heterostructure Diode Laser Operation," Appl. Phys. Lett. **79**, 3215-3217 (12 Nov 2001).
20. T. Chung, G. Walter, and N. Holonyak, Jr., "Coupled Strained Layer InGaAs Quantum Well Improvement of an InAs Quantum Dot AlGaAs-GaAs-InGaAsInAs Heterostructure Laser," Appl. Phys. Lett. **79**, 4500-4502 (31 Dec 2001).
21. G. Walter, T. Chung, and N. Holonyak, Jr., "High-Gain Coupled InGaAs Quantum Well InAs Quantum Dot AlGaAs-GaAs-InGaAs-InAs Heterostructure Diode Laser Operation," Appl. Phys. Lett. **80**, 1126-1128 (18 Feb 2002).
22. S. L. Chuang and N. Holonyak, Jr., "Efficient Quantum Well to Quantum Dot Tunneling: Analytical Solutions," Appl. Phys. Lett. **80**, 1270-1272 (18 Feb 2002).
23. J. H. Ryou, R. D. Dupuis, G. Walter, N. Holonyak, Jr., D. T. Mathes, R. Hull, V. Reddy, and V. Narayanamurti, "Properties of InP Self-Assembled Quantum Dots Embedded in In0.49(AlxGa1-x)0.5IP for Visible Light Emitting Laser Applications Grown by Metalorganic Chemical Vapor Deposition," J. Appl. Phys. **91**, 5313-5320 (15 April 2002).
24. G. Walter, T. Chung, and N. Holonyak, Jr., "Coupled-Stripe Quanturn-Well Assisted AlGaAs-GaAs-InGaAs-InAs Quantum-Dot Laser," Appl. Phys. Lett. **80**, 3045-3047 (29 April 2002).
25. G. Walter, N. Holonyak, Jr., R. D. Heller, and R. D. Dupuis, "Visible spectrum (654 nrn) Room Temperature Continuous Wave (cw) InP Quantum Dot Coupled to InGaP Quantum Well InP- InGaP-ln(AlGa)P-InAlP Heterostructure Laser," Appl. Phys. Lett. **81**, 4604-4606 (9 Dec 2002).
26. J. J. Huang, T. Chung, M. Lerttamrab, S. L. Chuang, and M. Feng, “1.55 µm asymmetric Fabry-Perot modulator for high-speed applications,” IEEE Photon. Tech. Lett., **14**, 1689-1691, 2002.
27. D.E. Wohlert, H.C. Lin, K.L. Chang, G.W. Pickrell, Jr., J.H. Epple, K.C. Hsieh, and K.Y. Cheng, “Fabrication of a Substrate-Independent Aluminum Oxide-GaAs Distributed Bragg Reflector,” Appl. Phys. Lett. **75**, 1371-73, (1999).
28. K.L. Chang, L.J. Chou, K.C. Hsieh, D.E. Wohlert, G.W. Pickrell, and K.Y. Cheng, “ Formation of Amorphous Native Oxides by Very-Low-Temperature Molecular Beam Epitaxy and Water Vapor Oxidation,” J. Crystal Growth, **201/202**, 633-637, (1999).
29. D.E. Wohlert, K.L. Chang, H.C. Lin, K.C. Hsieh and K.Y. Cheng, “Improvement of AlAs-GaAs Interface Roughness Grown with High As overpressures,” J. Vac. Sci Technol. **B18**, 1590-1593, (2000).
30. G. W. Pickrell, K. L. Chang, J. H. Epple, K. Y. Cheng and K. C. Hsieh,, "The Growth of Low Defect Density In0.25Ga0.75As on GaAs by Molecular Beam Epitaxy", J. Vacuum Sci. and Technol., **B18**, 2611-2614, 2000.
31. G.W. Pickrell, J.H.Epple, K.L. Chang, K.C. Hsieh and K.Y. Cheng, “Improvement of Wet-Oxidized AlxGa1-xAs (x~1) through the Use of AlAs/GaAs Digital Alloys,” Appl. Phys. Lett. **76**, 2544-2546, (2000).
32. J.H. Epple, K.L. Chang, G.W. Pickrell, K.Y. Cheng, and K.C. Hsieh, “Thermal Wet Oxidation of GaP and Al0.4Ga0.6P,” Appl. Phys. Lett. **77**, 1161-1163, (2000).
33. K. L. Chang, J. H. Epple, G. W. Pickrell, H. C. Lin, K. Y. Cheng, and K. C. Hsieh, "Strain Relaxation and Defect Reduction in InxGa1-xAs/GaAs by Lateral Oxidation of An Underlying AlGaA Layer," J. Appl. Phys., **88**, 6922-2924, (2000).
34. K. L. Chang, G. W. Pickrell, D. E. Wohlert, J. H. Epple, H. C. Lin, K. Y. Cheng, and K. C. Hsieh, "Microstructure and Wet Oxidation of Low-Temperature-Grown Amorphous (Al/Ga.As)," J. Appl. Phys., **89**, 747-752, 2001.
35. G.W. Pickrell, H.C. Lin, K.L. Chang, and K.Y. Chang, "Fabrication of GaP/Al-oxide Distributed Bragg Reflectors for the Visible Spectrum," Appl. Phys. Lett. **78**, 1044-1046, (2001).
36. D.E. Wohlert, G.W. Pickrell, K.L. Chang, K.C. Hsieh, and K.Y. Cheng, "Self-Assembled GaInAs Quantum Wire Heterostructure Design for Temperature Stablized Emission Wavelength", J. Crystal Growth, **227/228**, pp. 985-989 (2001).
37. G.W. Pickrell, K.L. Chang, H.C. Lin, K.C.Hsieh and K.Y. Cheng, "Very-Low-Temperature Molecular Beam Epitaxial Growth of GaP/AlAs Heterostructures for Distributed Bragg Reflector Applications", J. Vac. Sci. Technol. **B19**, 1536-1540 (2001).
38. D.E. Wohlert, K.L. Chang, G.W. Pickrell, K.C. Hishe and K.Y. Cheng, "Strain-Dependence on Barrier Material and Its Effect on the Temperature Stability of Photoluminescence Wavelength in Self-Assembled GaInAs Quantum Wires", J. Appl. Phys. **90**, 5623-5626 (2001).
39. H.C. Lin, K.L. Chang, G.W. Pickrell, K.C. Hsieh, and K.Y. Cheng, “Low Temperature Wafer Bonding by Spin on Glass”, J. Vac. Sci. Technol. **B20**, 752-754 (2002).
40. H.C. Lin, W.H. Wang, K.C. Hsieh and K.Y. Cheng, “Fabrication of 1.55 µm VCSEL on Si using Metallic Bonding”, Electronic Lett. **38**, 516-517, (2002).
41. H.C. Lin, K.L. Chang, K.C. Hsieh, K.Y. Cheng, and W.H. Wang,”Metallic Wafer Bonding for the Fabrication of Long-Wavelength Vertical-Cavity Surface-Emitting Lasers”, J. Appl. Phys. **92**, 4132-4134 (2002).
42. G.W. Pickrell, K.L. Chang, J.H. Epple, K.Y. Cheng and K.C. Hsieh, “Protection of In0.25Ga0.75As/GaAs Structures during Lateral Oxidation using an Amorphous InGaP Layer”, J. Vac. Sci. Technol. **B20**, 876-879 (2002).
43. J.H. Epple, C. Sanchez, T. Chung, K.Y. Cheng and K.C. Hsieh, “Dry Etching of GaP with Emphasis on Selective Etching over AlGaP”, J. Vac. Sci. Technol. **B20**, 2252-2254 (2002).
44. F. Xia, J. K. Thomson, M. R. Gokhale, P. V. Studenkov, J. Wei, W. Lin and S. R. Forrest, “An asymmetric twin-waveguide high-bandwidth photodiode using a lateral taper coupler”, IEEE Photon. Technol. Lett., **13**, 845 (2001).

45. J. Wei, J. C. Dries, H. Wang, G. H. Olsen and S. R. Forrest, “Optimization of 10Gb/s Long Wavelength Floating Guard Ring InGaAs/InP Avalanche Photodiodes”, IEEE Photon. Technol. Lett., **14**, 977 (2002)
46. J. Wei, F. Xia, S. R. Forrest, “A high responsivity, high bandwidth, asymmetric twin-waveguide coupled InGaAs/InP/InAlAs avalanche photodiode”, IEEE Photon. Technol. Lett., **14**, 1590 (2002).

(b). Conference proceedings:

1. D. Mathes, R. Hull, K. D. Choquette, K. M. Geib, R. D. Dupuis, and R. Heller, “Nanoscale Structural and Chemical Characterization of III-V Thermal Oxides,” Proc. Spring MRS Meeting, San Francisco CA (5-9 April 1999), to be published.
2. J. H. Mu and M. Feng, “100 GHz Low-noise MESFET, HFET and MSM Technology for 10 Gb/s OEIC Applications,” *SPIE Optoelectronic Interconnects and Packaging,* vol. 3795, pp. 528-541, July, 1999
3. D. A. Ahmari, Q. J. Hartmann, M. Feng, G. E. Stillman, “GaAs- and InP-based HBT technology for 100-GHz applications,” *SPIE Optoelectronic Interconnects and Packaging,* vol. 3795, pp. 542-550, July, 1999
4. J. H. Ryou, U. Chowdhury, R. D. Dupuis, C. Reddy, V. Narayanamurti, D. T. Mathes, and R. Hull, “Self-Assembled InAlP/GaP Quantum Dots Grown by MOCVD,” Mat. Res. Soc. Symp. Proc. 583, 39-44 (2000).
5. J. H. Ryou, R. D. Dupuis, C. V. Reddy, V Narayanamurti, D. T. Mathes, and R. Hull, “InP and InAlP Self-Assembled Quantum Dots Grown by Metalorganic Chemical Vapor Deposition,” in Proceedings of the Twelfth Indium Phosphide and Related Materials Conference, Williamsburg VA, May 2000 (IEEE Press)
6. J. Mu, Z. Tang, D. Becher, S. Shen, M. Feng, “Low Cost GaAs MESFET and InP HFET technology for 40 Gb/s OEICs,” Proceeding of SPIE Vol. 4111-30, August 1, 2000 in San Diego, CA.
7. J. Mu, D. A. Ahmari, Q.J. Hartmann, M. Feng, “ InGaP/GaAs and InGaAs/InP HBT/PIN technologies for 20Gb/s and 40 Gb/s,” Proceeding of SPIE Vol. 4111-31, August 1, 2000 in San Diego, CA.
8. K. Y. Cheng and D. E. Wohlert, "Strain-Induced Lateral Ordering and Quantum Effects in Self-Assembled GaInAs Quantum Wires", *Proceedings of the Thirteenth Int. Conf. on InP and Related Materials*, May 14-18, 2001, Nara, Japan, p.43-46.
9. R. D. Dupuis, J. H. Ryou, R. D. Heller, G. Walter, D. A. Kellogg, N. Holonyak, Jr., C. V. Reddy, V. Narayanamurti, D. T. Mathes, and R. Hull, "InP Self Assembled Quantum Dot Lasers Grown on GaAs Substrates by Metalorganic Chemical Vapor Deposition," Mat. Res. Soc. Symp. Proc. 692, pp. 643-648 (2002).

(c). Conference presentations:

1. J. H. Mu, Z. Tang, D. Becher, S. C. Shen and M. Feng, “Low Cost GaAs MESFET and InP HFET Technologies for 40 Gb/s OEICs,” submitted to *SPIE Optoelectronic Interconnects and Packaging,* July, 2000
2. J. H. Mu, D. Ahmari, Q. Hartmann and M. Feng, “InGaP/GaAs and InGaAs/InP HBT/PIN Technologies for 20 Gb/s and 40 Gb/s OEICs,” submitted to *SPIE Optoelectronic Interconnects and Packaging,* July, 2000
3. T. Chung et al., “Current Gain Dependence on Subcollector and Etch-stop Doping in InGaP/GaAs HBTs,” presented at *Electronic Material Conference* (EMC), Denver, Colorado, June 2000.
4. R. Heller and R. D. Dupuis, ”Growth and Characterization of InAlGaP Lasers with Native-Oxide Optical and Carrier Confinement” Presented at the 2000 *Electronic Materials Conference*, Denver CO June 2000.
5. (INVITED) R. D. Dupuis. R. D. Heller, Jr., J. H. Ryou, U. Chowdhury, A. P. Curtis, G. E. Stillman, D. T. Mathes, and R. Hull, “Formation and Characterization of III-V Native Oxides for Optoelectronic Applications,” IEEE/LEOS Annual Meeting, Orlando, Florida (1-4 December 1998).
6. (INVITED) R. D. Dupuis. R. D. Heller, Jr., J. H. Ryou, U. Chowdhury, A. P. Curtis, G. E. Stillman, D. T. Mathes, and R. Hull, “Formation and Characterization of III-V Native Oxides for Optoelectronic Applications,” IEEE/LEOS Annual Meeting, Orlando, Florida, Vol. 2, pp. 238-239 (1999).
7. R. D. Dupuis, J. Park, R. D. Heller, Jr., J. H. Ryou, and U. Chowdhury, “Formation and Characterization of III-V Native Oxides for Electronic and Optoelectronic Applications,” WOCSEMMAD, New Orleans, Louisiana (21-24 February 1999).
8. D. Mathes, R. Hull, K. D. Choquette, K. M. Geib, R. D. Dupuis, and R. D. Heller, Jr.,“Nanoscale Structural and Chemical Characterization of III-V Thermal Oxides,” 1999 Materials Research Society Spring Meeting, San Francisco, California (5-9 April 1999).
9. R. D. Dupuis, Y. Sasahima, R. D. Heller, Jr., D. A. Kellogg, J. J. Wierer, N. Holonyak, Jr., D. T. Mathes, and R. Hull, “Room-Temperature Lasers with InAlGaP/InGaP Superlattice,” Ninth Biennial Workshop on Organometallic Vapor Phase Epitaxy, Ponte Vedra Beach, Florida (23-27 May 1999)
10. J. H. Ryou, U. Chowdhury, R. D. Dupuis, C. Reddy, V. Narayanamurti, D. T. Mathes, and R. Hull, “Self-Assembled InAlP/GaP Quantum Dots Grown by MOCVD,” 1999 Materials Research Society Fall Meeting, Boston, Massachusetts (28 November-3 December 1999).
11. B. P. Tinkham and R. D. Dupuis, “Photoluminescence Properties of Zn-doped Heterostructures Having Native-oxide Layers,” J. Appl. Phys. Vol. 87, No. 1, pp. 203-206 (2000).
12. R. D. Heller, Jr., M. S. Noh, Y. Sasajima, R. D. Dupuis, D. A. Kellogg, and N. Holonyak, Jr., D. T. Mathes, and R. Hull, “Growth and Characterization of InAlGaP Lasers with Native-Oxide Optical and Carrier Confinement,” WOCSEMMAD, San Diego, California (12-16 February 2000).

13. J. H. Ryou, R. D. Dupuis, C. V. Reddy, V. Narayanamurti, D. T. Mathes, and R. Hull, “InP Self-Assembled Quantum Dots Embedded in InAlP Grown by MOCVD,” WOCSEMMAD, San Diego, California (12-16 February 2000).
14. J. H. Ryou and R. D. Dupuis, “Growth and Properties of InP Quantum Dots,” WOCSEMMAD, San Diego, California (12-16 February 2000).
15. R. Heller and R. D. Dupuis, “Growth and Characterization of InAlGaP Lasers with Native-Oxide Optical and Carrier Confinement,” Microelectronics Research Center Graduate Student Research Seminar, Austin, Texas (20 April 2000).
16. J. H. Ryou, U. Chowdhury, R. D. Dupuis, C. V. Reddy, V. Narayanamurti, D. T. Mathes, and R. Hull, “InP and InAlP Self-assembled Quantum Dots Grown by Metalorganic Chemical Vapor Deposition,” Twelfth International Conference on Indium Phosphide and Related Materials IPRM ’00, Williamsburg, Virginia (14-18 May 2000).
17. J. H. Ryou, U. Chowdhury, R. D. Dupuis, C. V. Reddy, V. Narayanamurti, D. T. Mathes, and R. Hull, “InP and InAlP Self-assembled Quantum Dots Grown by Metalorganic Chemical Vapor Deposition,” Conference Proceedings, Twelfth International Conference on Indium Phosphide and Related Materials IPRM ’00, Williamsburg, Virginia, pp. 223-226 (14-18 May 2000).
18. P. J. Barrios, S. K. Cheong, D. C. Hall, N. C. Crain, G. L. Snider, C. B. DeMelo, T. Shibata, B. A. Bunker, U. Chowdhury, R. D. Dupuis, G. Kramer, and N. El-Zein, “Residual As and the Electrical Characteristics of AlGaAs Native Oxides for MOS Applications,” 42nd Electronic Materials Conference, Denver, Colorado (21-23 June 2000).
19. J. H. Ryou, R. D. Dupuis, C. V. Reddy, V. Narayanamurti, D. T. Mathes, R. Hull, A. Mintairov, and J. L. Merz, “Growth and Characterization of InP Self-Assembled Quantum Dots on GaAs Substrates,” 42nd Electronic Materials Conference, Denver, Colorado (21-23 June 2000).
20. R. D. Heller, Jr., M. S. Noh, Y. Sasajima, D. A. Kellogg, N. Holonyak, Jr., and R. D. Dupuis, “Growth and Characterization of InAlGaP Lasers with Native-Oxide Optical and Carrier Confinement,” 42nd Electronic Materials Conference, Denver, Colorado (21-23 June 2000).
21. C. V. Reddy, V. Narayanamurti, J. H. Ryou, U. Chowdhury, and R. D. Dupuis, “Observation of Resonant Tunneling through InP Quantum Dots Using Ballistic Electron Emission Microscopy,” Fall 2000 Materials Research Society Meeting, Boston, Massachusetts (27 November-01 December 2000).
22. J. H. Ryou, R. D. Dupuis, D. T. Mathes, R. Hull, C. V. Reddy, V. Narayanamurti, D. A. Kellogg, G. Walter, N. Holonyak, Jr., “InP Self-assembled Quantum Dots Embedded in In0.5Al0.3Ga0.2P Grown on GaAs Substrates by Metalorganic Chemical Vapor Deposition,” Indium Phosphide and Related Materials IPRM-01, Nara, Japan (14-18 May 2001).
23. INVITED R. D. Dupuis, J. H. Ryou, G. Walter, N. Holonyak, Jr., D. T. Mathes, R. Hull, C. V. Reddy, and V. Narayanamurti, “Properties of InP Self-Assemble Quantum Dots Embedded in In0.49(AlxGa1-x)0.1P Grown by Metalorganic Chemical Vapor Deposition,” Ninth International Symposium of Nanostructures: Physics and Technology, Saint Petersburg, Russia, June 2001
24. J. H. Ryou, R. D. Dupuis, C. V. Reddy, V. Narayanamurti, D. T. Mathes, R. Hull, D. A. Kellogg, G. Walter, and N. Holonyak, Jr., “InP Self-Assembled Quantum Dots Embedded in In0.49(AlxGa1-x)0.51P Grown by Metalorganic Chemical Vapor Deposition,” 43rd Electronic Materials Conference, Notre Dame, Indiana (27-29 June 2001).
25. R. D. Heller, Jr., X. B. Zhang, J. H. Ryou, R. D. Dupuis, C. V. Reddy, V. Narayanamurti, D. T. Mathes, R. Hull, G. Walter, and J. Holonyak, Jr., “The Growth of InP Quantum Dot Lasers,” NanoNight, The University of Texas at Austin, 25 April 2002.
26. R. D. Dupuis, R. D. Heller, Jr., J. H. Ryou, C. V. Reddy, V. Narayanamurti, D. T. Mathes, R. Hull, G. Walter, N. Holonyak, Jr. “Lasers Based Upon InP Self-Assembled Quantum Dots Embedded in InAlGaP Grown by Metalorganic Chemical Vapor Deposition,” Fourteenth Indium Phosphide and Related Materials Conference (IPRM’02), Stockholm, Sweden (12-16 May 2002).
27. R. D. Heller, Jr., J. H. Ryou, R. D. Dupuis, G. Walter, N. Holonyak, Jr., C. Reddy, X. Zhang, V. Narayanamurti, D. Mathes, and R. Hull, “Low-threshold InP Self-assembled Quantum Dot Lasers Grown by Metalorganic Chemical Vapor Deposition,” ICMOVPE XI, Berlin, Germany, 03 – 07 June 2002.
28. R. D. Heller, Jr., J. H. Ryou, R. D. Dupuis, G. Walter, N. Holonyak, Jr., C. C. Reddy, N. Narayanamurti, D. T. Mathes, and R. Hull, “Low-threshold InP Quantum-Dot Lasers Coupled to Strained InGaP Quantum Wells Grown by Metalorganic Chemical Vapor Deposition,” 44th Electronic Materials Conference, Santa Barbara, California, 26-28 June 2002.
29. X. B. Zhang, J. H. Ryou, R. D. Dupuis, C. V. Reddy, V. Narayanamurti, D. T. Mathes, R. Hull, G. Walter, and N. H. Holonyak, Jr., “The Influence of the Nominal Thickness of InP Quantum Dots on the Surface Morphology and Structural Properties of InAlP Capping Layers,” 44th Electronic Materials Conference, Santa Barbara, California, 26-28 June 2002.
30. J. Wei, J. C. Dries, G. H. Olsen and S. R. Forrest, “Optimization of Double Diffused Floating Guard Ring InGaAs/InP Avalanche Photodiodes”, LEOS 2001 Ann. Mtg., Paper ThF3, San Diego (Nov. 15, 2001).
31. (INVITED) S. R. Forrest, J. Wei, M. Gokhale, P. Studenkov and J. Thomson, “Photonic integration made easy using asymmetric twin waveguide technology”, OSA Annual Meet., Orlando (Sept., 2002).

(d). **<u>Submitted manuscript but not published</u>:**

1. J. H. Ryou, R. D. Dupuis, G. Walter, N. Holonyak, Jr., D. T. Mathes, R. Hull, C. V. Reddy, and V. Narayanamurti, "Properties of InP Self-Assembled Quantum Dots Embedded in $In_{0.49}(Al_xGa_{1-x})_{0.51}P$ for Visible Light Emitting Laser Applications Grown by Metalorganic Chemical Vapor Deposition," J. Appl. Phys. (to be published).
2. J. H. Ryou and R. D. Dupuis, "Growth and Characterization of Ternary InAlP and InGaP Self-Assembled Quantum Dots Grown by Metalorganic Chemical Vapor Deposition: Effect of Strain and Composition on Self-Assembling Compared to InP Quantum Dots," J. Elect. Mat. (accepted for publication).
3. C. V. Reddy, V. Narayanamurti, J. H. Ryou, and R. D. Dupuis, "Current Transport in $InP/In_{0.5}(Al_{0.6}Ga_{0.4})_{0.5}P$ Self-Assembled Quantum Dot Heterostructures Using Ballistic Electron Emission Microscopy/Spectroscopy," Appl. Phys. Lett. (to be published).
4. R. D. Dupuis, J. H. Ryou, R. D. Heller, C. V. Reddy, V. Narayanamurti, D. T. Mathes, R. Hull, G. Walter, and N. Holonyak, Jr., "InP Self-Assembled Quantum Dots Embedded in InAlGaP Grown by Metalorganic Chemical Vapor Deposition," Proceedings of Symposium H, 2001 Fall MRS Meeting, Boston MA (to be published).

5 SCIENTIFIC PERSONNEL:

5.1 PI's:
K. Y. Cheng, R. D. Dupuis, M. Feng. S. R. Forrest, N. Holonyak, Jr., and K. C. Hsieh

5.2 Graduate students:
K. L. Chang, T. Chung, J. Epple, J. Feng, Q. He, R. Heller, H. C. Lin, G. W. Pickrell, J. H. Ryou, J. Thomson, G. Walter, J. Wei

5.3 Honors and Awards:
a. Professor Milton Feng received Outstanding Research Award in High Speed Microelectronics, Dr. Pan Wen Yuan Foundation, Taiwan, September 2000.
b. Professor Milton Feng was named Nick Holonyak, Jr. Professor in Electrical and Computer Engineering at the University of Illinois.
c. Professor K. Y. Cheng was elected to a Fellow of the IEEE.
d. Professor N. Holonyak, Jr. received Frederic Ives Medal of OSA (2001).
e. Professor Stephen Forrest received 2001 IEEE/LEOS Wm. Streifer Award.

5.4. Degrees Awarded:
a. T. Chung, "High-gain InGaP/GaAs heterojunction bipolar transistors by low-pressure metalorganic chemical vapor deposition." MSEE, UIUC, 2000.
b. G. W. Pickrell, "Growth and optimization of GaInAs-InP heterostructures by solid-source MBE," MSEE, UIUC, 2000.
c. J. H. Ryou, "III-phosphide semiconductor self-assembled quantum dots grown by metalorganic chemical vapor deposition." Ph.D., U-Texas at Austin, 2001.
d. J. Mu, "Monolithic High-Speed Optoelectronic Integrated Receivers for Greater than 10 Gigabits per Second Optical Communications", Ph.D., University of Illinois at Urbana-Champaign, 2000
e. K.L. Chang, "Lateral Oxidation of Aluminum Gallium Arsenide Compound for Defects Reduction and Optical Applications", MSEE, UIUC, 2000
f. J. Epple, "Low temperature wafer bonding using amorphous gallium arsenide", M.S., University of Illinois at Urbana-Champaign, 2001.
g. John Thomson, "Integratable Long Wavelength Detectors and Electronics for Communications and Sensing", Ph.D., Princeton University, 2001
h. Jian Wei, "Photodetectors Based on Novel Materials and Structures for Fiber Optical Communications and Long Wavelength Sensing", Ph.D., Princeton University, 2001
i. Jae Hyun Ryou, "III-Phosphide Semiconductor Self-Assembled Quantum Dots Grown by Metalorganic Chemical Vapor Deposition", Ph.D., U-Texas at Austin, 2000.
j. David E. Wohlert, "Temperature invariant photoluminescence and gain spectra of strained Gallium-Indium-Arsenide quantum wires," Ph.D., UIUC, June 2000.
k. Gregory William Pickrell, "Compliant epitaxy of III-V compound semiconductors for optoelectronic device applications," Ph.D., UIUC, May 2002.
l. Hung-Cheng Lin, "Design and fabrication of long-wavelength vertical-cavity surface-emitting lasers using wafer bonding technologies," Ph.D., UIUC, December 2002.

6 REPORT OF INVENTION:

a. N. Holonyak and R. D. Dupuis: Provisional patent filed on quantum-well-assisted quantum-dot photonic devices (lasers, LEDs, etc.)

MASTER COPY: PLEASE KEEP THIS "MEMORANDUM OF TRANSMITTAL" BLANK FOR REPRODUCTION PURPOSES. WHEN REPORTS ARE GENERATED UNDER THE ARO SPONSORSHIP, FORWARD A COMPLETED COPY OF THIS FORM WITH EACH REPORT SHIPMENT TO THE ARO. THIS WILL ASSURE PROPER IDENTIFICATION. NOT TO BE USED FOR INTERIM PROGRESS REPORTS; SEE PAGE 2 FOR INTERIM PROGRESS REPORT INSTRUCTIONS.

MEMORANDUM OF TRANSMITTAL

U.S. Army Research Office
ATTN: AMSRL-RO-BI (TR)
P.O. Box 12211
Research Triangle Park, NC 27709-2211

☐ Reprint (Orig + 2 copies)

☐ Technical Report (Orig + 2 copies)

☐ Manuscript (1 copy)

X☐ Final Progress Report (Orig + 2 copies)

☐ Related Materials, Abstracts, Theses (1 copy)

CONTRACT/GRANT NUMBER: **DAAG55-98-1-0303**

REPORT TITLE: ***VCSEL and smart pixel research for VLSI photonics***

is forwarded for your information.

SUBMITTED FOR PUBLICATION TO (applicable only if report is manuscript):

Sincerely,