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The Optoelectronic Materials Center is a collaborative program involving the University of New Mexico, Stanford University, and the California Institute of Technology. Sandia National Laboratories and MIT Lincoln Laboratory are also involved in this program under separate contract vehicles. This program emphasizes three main areas:

- diode-based visible sources,
- two-dimensional optical interconnects, and
- high-speed optoelectronics.

Progress on individual tasks is very briefly discussed below. Several of the tasks will impact more than one of the above areas For simplicity, the tasks are arranged by institution in an order roughly determined by the above areas.

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OPTOELECTRONIC MATERIAL CENTER
A Collaborative Program including:
Center for High Technology Materials,
of the University of New Mexico,
Stanford University, and
California Institute of Technology

ARPA Order No. 7526
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OPTOELECTRONIC MATERIALS CENTER

A Collaborative Program including:
Center for High Technology Materials, University of New Mexico,
Stanford University, and
California Institute of Technology

Quarterly Progress Report

for the period

October 1 1990 to December 31, 1990

University of New Mexico:
The Center for High Technology Materials has been awarded a contract, entitled "Advanced Materials for Optoelectronics", for $600 K from the State of New Mexico for establishing the new facility to house the new MOCVD reactor funded under this DARPA program. The DARPA funds under the current contract were used as matching and were instrumental in winning the contract.
(Principal Investigators: C. F. Schaus and S. R. J. Brueck)

A new type of diode laser array (denoted "leaky-mode" or "antiguided") has recently been reported. Despite their success, these devices are difficult to fabricate since they require a deep wet-chemical etch, which must be accurately controlled. We report a new strained GaInAs quantum well device structure which is produced by etching a thin (0.12 μm), transparent GaAs waveguide layer. These devices have demonstrated fundamental mode operation up to 2 A (172 mW/facet at 1 A) at 1% duty cycle pulsed condition and 700 mA (62.5 mW/facet) for cw operation.
(Principal Investigator: C. F. Schaus)

In September, 1990, we began the design of a new structure for an electrically-pumped, transverse-injection, multi-quantum well, vertical cavity surface-emitted laser. This structure consists entirely of undoped epilayers, thus simplifying the problems of device isolation and in-plane electrical interconnection, which are critical considerations for the monolithic integration of two-dimensional, individually-addressable VCSEL arrays. Wafers were grown by metalorganic chemical vapor deposition (MOCVD) and tested by optical pumping.

Transversely-injected VCSELs were fabricated with both diffused and ion-implanted contacts. The former uses the shallow, selective, lateral diffusion of dopants into etched wells to define the active volume and to delineate the contacts, while the latter uses self-aligned ion-implantation. The diffused VCSELs showed laser action under pulsed electrical injection, with a threshold current of 48 mA, a spectral width of less than 1A, and a series resistance of 200 ohms. The relatively high threshold (9 mA per quantum well) results from parasitic shunt currents through the upper mirror layers. New designs are being made to suppress these parasitic currents.

The implanted VCSELs used the self-aligned implantation of Be and Si to a depth of nearly 1 μm to define the p- and n-contacts, respectively. Conditions for the capless, rapid thermal annealing (RTA) of the implant damage were developed. Chemically-assisted ion-beam etching (CAIBE) of the upper mirror layers everywhere except at the active area leaves a largely planar, low-conductivity wafer surface. Light emission was observed, but the series resistance remains high due to the incomplete activation of the implant, and improvements in current confinement are also needed. A new mask design is in progress.

Efforts are also underway to develop an improved, vertically-injected, multi-quantum-well VCSEL by grading the upper mirror layers continuously in order to eliminate potential barriers at the heterointerfaces, thus improving injection efficiency and lowering the series resistance. Wafers were grown by MOCVD, and planar VCSELs with implant-isolated active regions are being processed.

Milestones for next quarter: 1) Design new mask set for the fabrication of VCSELs, 2) Fabricate and evaluate VCSELs with both vertical and transverse-injection, 3) Acquire and set up tunable, pulsed and cw, optical sources for the evaluation of MQW spatial light modulators (SEESs).
(Principal Investigator: J. Cheng)

An all-expitaxial, transverse-junction surface-emitting GaAs/AlGaAs vertical-cavity laser (TJ-VCSEL) incorporating wavelength-resonant periodic gain has been fabricated and tested. Metalorganic chemical vapor deposition is used for epitaxial growth of a structure containing 5 GaAs quantum wells. The simple p+-pn+ transverse junction is fabricated using reactive ion etching and diffusion techniques. Contacts are situated on the wafer surface resulting in a nearly planar structure. The device exhibits a room-temperature threshold of 48 mA (pulsed) and a resolution-limited spectral width of 0.11 nm at a 855.8 nm lasing wavelength.
(Principal Investigators: C. F. Schaus and J. Cheng)

Electrically pumped Surface Emitting Laser Diode: Three novel strategies for future low threshold current cw operation have been designed and specified. One design is an improvement of the mushroom-structure SELD (Electron. Lett. Vol 26, No. 5, pp307-308, 1990). The other two designs utilize a diffused current blocking layer or selective epitaxial growth to provide current confinement and a planarized device at the same time. These planarized structures can facilitate heat removal so that devices can operate at high power cw conditions.

The masks layout for these devices were done. Two iron-oxide masks, each containing four different layers, have been done. Lithographic and process conditions have been tested on dummy wafers for these novel device fabrication techniques. Both An diffusion and the selective silicon-nitride film for current blocking have been performed without problem. Wafers with this patterned substrate have been sent out to MBE (through a cooperative effort with AT&T Bell Lab) and MOCVD here at CHTM crystal growth facility for the vertical structure growth.

If the MBE and MOCVD grown structures arrive in time, the devices can be fabricated within two weeks. However, testing will take more time. The initial goal is to demonstrate a low threshold current (less than 5 mA) and high power (larger than 1 mW) single mode cw operation of these devices. However, whether this goal can be achieved during the next report period or not depends on the crystal growth capability of either MBE or MOCVD.

Two iron-oxide masks and a batch of n-type GaAs substrate wafers have been purchased. One hydrogen purifier Palladium diffusion cell has been purchased for the LPE system in the cleanroom. One small pump has been ordered for building a circulating etching jet for back-side etching process purposes.

At the present time the biggest problem is the epitaxial layer growth both by MBE and by MOCVD.
(Principal Investigator: W. Hsin)

High-power optical pumping of vertical-cavity surface-emitting lasers (VCSELs) for doubling and for parallel optical data processing.

Progress - GaAlAs/GaAs and InGaAs/GaAs RPG-VCSEL wafers have been optically pumped above threshold using pulsed dye lasers with pulse widths of 7 ns and 500 ns, at wavelengths of 740 nm and 760 nm, with lasing spot diameters ranging from 10 μm to 10 mm. Pulsed diode laser array pumping at 740 and 770 nm has also been accomplished, but at much lower power levels (smaller spot sizes).

Peak powers obtained in the dye laser pumping experiments ranged from 100 W from the smaller spots to 50 kW from spots a few mm in diameter. The best results were pulse energies of 25 mJ from InGaAs VCSEL samples (pumped area ~1 mm^2) and approximate area scaling of threshold and maximum available output power (limited by the optical pumping damage threshold) was observed.

Summary of best results - 1) Largest peak power: 1 mm2 InGaAs at 918 nm, 50kW, Typical result 40 kW; 2) Largest optical pumping efficiency: 1 mm^2 InGaAs at 918 nm, 28% (34% quantum efficiency), Typical result 18-20% (22-24% quantum efficiency) (same experiment as #1); 3) Largest lasing area: 1 cm^2 GaAs at 850 nm, 20 kW peak power, 5-10% optical pumping efficiency

Planned activities and milestones - Optimize high-power pulsed operation by reducing lasing threshold and raising pump damage threshold in RPG-VCSEL samples (see Problems section below). Obtain lasing over larger areas, possibly over most of a 2 in. or 3 in. diameter wafer, to produce several joules of energy per pulse at 850-950 nm using 500 ns pump pulses. Use rack-and-stack incoherent diode laser arrays as pump sources instead of the cavity-dumped dye laser. Design and construct an intracavity frequency-doubling arrangement to produce efficient conversion of the high-power surface-emitting laser into the blue and blue-green spectral regions. Investigate optical pumping in 2-D array formats for parallel optical processing.

Problems - 1) Power, threshold and efficiency scaling measurements have been hampered by non-uniformities across the areas of the first VCSEL wafers. These have been estimated to cause ~0.5-1% wavelength variations across a 1 mm pumped spot, and variations of ~50% in threshold power density in 1 mm spots over an entire 2 in. wafer. 2) anomalous dynamical effects in pulsed optical pumping - the pumping efficiency decreases as the pump pulses become shorter. This requires careful study. 3) The optical pumping damage thresholds of the first RPG-VCSEL wafers were relatively low, approximately 1 MW cm-2, with considerable (50%) variation across complete 2 inch wafers. We shall develop specific strategies - antireflection coatings, nonabsorbing cap layers and surface passivation by inorganic sulfides or similar reagents - to increase the damage thresholds of subsequent wafers and hence increase the maximum available VCSEL output power per unit of pumped area. 4) We observed considerable (30-40%) reflection of the pump power from the VCSEL wafer surface. We will tackle this by developing an end mirror which is highly reflecting at the lasing wavelength but highly transmitting (ideally antireflecting) at the pump wavelength.
(Principal Investigators: J. G. McInerney and C. F. Schaus)

Deposition and Characterization of PLZT thin films for optical switching and harmonic generation.

Several PLZT thin films have been deposited on Si (100) and Si (110) substrates for the purpose of waveguide modulation experiments. However, there is little progress in characterization of these films because of equipment difficulties with the X-ray diffractometer and EDS/SEM systems. A new student has joined the group to continue work on the materials and device characterization.

Surface Normal Second Harmonic Generation in Nonlinear Waveguides.

Progress: We have succeeded in coupling light into a structure consisting of 2000Å of PLZT on an SiO2 buffer on a Si substrate. While two dimensional waveguiding was observed, scattering losses at the facets and other losses in the film prevented waveguiding in a rib structure. we have attempted to validate our experimental setup by studying SHG in a GaAs waveguide. We were able to successfully couple 1.064 μm light into a rib waveguide consisting of a 3000 Å GaAs layer grown on an $Al_{0.3}Ga_{0.7}As$ layer, but the second harmonic signal has yet to be observed.

Plans: We have designed a multilayer GaAs/AlGaAs structure with the intent of achieving quasiphase matching normal to the surface, and higher SHG efficiencies. We will also move our experiment from a CW to a mode-locked Nd:YAG laser so that much higher peak energies can be present in the waveguides before the facets are damaged. Recent PLZT samples have given hints of much lower losses, and considerable progress has been made in other programs poling these films, so we plan to return to PLZT in the future.
(Principal Investigator: K. J. Malloy)

High-Speed Quadrant Detectors.

We have previously demonstrated very high speed operation of Si MSM single-element detectors to 24 GHz (the fastest detectors have a calculated 90-GHz response but have not yet been measured). Design of a new mask set for quadrant array operation is underway. We are also investigating techniques for extending the high-quantum efficiency wavelength range towards longer wavelengths.
(Principal Investigator: S. R. J. Brueck)

Ultrafast visualization of high-speed circuits.

The first quarter has been devoted to the development of a fs oscillator-amplifier source. We achieved a pulse duration of 70 fs, for a pulse energy of 10 lJ, before the copper vapor laser failed. Much time and effort has been expanded in the repair of the copper vapor laser (new plasma tube, new thyratron, ne quartz envelope of te plasma tube). We expect the system to be back in operation in February. The steps of the program for the following quarter are:

ordering of a high resolution image intensifier
depth resolved imaging of test patterns
magnified imaging (time and depth resolved)
Determination of temporal response of field induced second harmonic generation in PLZT, using ps pulses

(Principal Investigator: J.-C. Diels)

California Institute of Technology

Objectives: Investigation of strain and lattice parameter modification, as well as dislocation *control in strain layers grown by ion-assisted molecular beam epitaxy,* This research will be applied to improve growth of GaAs on Si and SiGe alloy substrates.

Progress:

We have achieved perpendicular strain changes of 1.8% in Ge epitaxial films and of 0.7% in Si films by ion-assisted molecular beam epitaxy. We have also observed a reduction in misfit dislocation density by ion-assisted epitaxy for pure Ge on Si (001) substrates. Sources for GaAs heteroepitaxy on these layers have been identified.
(Principal Investigator: H. Atwater)

Visible laser materials
Objectives; The feasibility of fabricating an AlSb/ZnTe light emitter for emission in the green will be determined.

Progress: We have studied the growth of AlSb/ZnTe heterojunctions and have measured the band offset by X-ray photoemission spectroscopy. The band offset indicates a green light emitter is feasible with this heterojunction; we are currently comparing this material system with others to determine which is the most promising.
(Principal Investigator: T. McGill)

Development of a novel lock-in based cathodoluminescence imaging system for analysis of nanometer scale structures (July 1, 1991). *In-situ* formation of nanometer scale wire and dot structures by orientation dependent confinement (December 30, 1992).

Progress: Design of lock-in based cathodoluminescence system complete and necessary parts ordered.
(Principal Investigator: K. Vahala)

Development of ultra-low threshold quantum well lasers using pseudomorphic InGaAs active layers.

Progress: We have studied the operation of ultra low threshold current lasers at cryogenic temperatures. We find that the threshold currents can be reduced to the microampere regime when operating at 5°K. For InGaAs the corresponding threshold currents were 1.6 mA and 165 lA. Both lasers show a linear decrease in threshold with decreasing temperature, however with different slopes. This behavior can be explained by a simple effective mass model of the transparency carrier density
(Principal Investigator: A. Yariv)

Integration of a bipolar heterojunction phototransistor, MESFETS and light emitting diodes on a single substrate. Fabrication of a large array for (100X100 units) optoelectronic switches with optical gain.

Progress: A monolithically integrated optoelectronic neuron, consisting of a bipolar transistor, 2 MESFET's and a LED has been demonstrated in a single GaAs substrate. An optical gain of 6 and an optical switching energy of 10pJ have been measured.
(Principal Investigator: D. Psaltis)

Stanford University

Our efforts in the past few months have concentrated on optical modulators for applications in the area of optical computing, optical processing, and interconnects. The vertical devices show the greatest promise in these areas and have been the subject of intensive investigation. We have developed a model to optimize the reflectivity changes in these devices, and used the theory to fabricate high performance modulators. We have demonstrated the first strained InGaAs/GaAs modulator with a reflectivity change (66%) and lowest insertion loss (1.2dB) reported, operating with a bias voltage of 5 Volts.

For optical computing and switching purposes, one generally desires a normally-off device that exhibits negative differential photoconductivity and therefore optical bistability. To achieve this, a decrease in optical absorption with voltage is required. Though the Quantum Confined Stark Effect (QCSE) can be used to obtain this decrease with voltage, a large residual absorption remains that limits device performance. The Wannier-Stark effect on the other hand, though weaker, gives the required increase in absorption with no such residual absorption. We have investigated this effect in the strained InGaAs/GaAs system and achieved optical bistability by using an increase in absorption with voltage using a novel cavity design. In this case, an increase in absorption breaks the Fabry-Perot resonance in the cavity and increases the reflectivity. Since the OCSE is very strong when used in this mode, we have obtained the largest reflectivity modulation reported in such a bistable device.

We have demonstrated MOCVD growth of CdTe on <100> GaAs wafers patterned with 100A-thick silicon dioxide stripes. The CdTe grew as alternating single crystal (<111>) and polycrystalline regions. Second harmonic generation (from 1.06 microns to 0.5 microns) is observed in the single crystal CdTe regions. Further analysis to determine the suitability of this structure for quasi-phase matching is in progress. In the next quarter, we also plan to investigate CdTe orientation patterning using alternating GaAs/AlGaAs stripes.
(Principal Investigator: J. Harris)

Material design work in the Ultrafast Electronics Laboratory began for two projects: a GaAs monolithic Schottky photodiode/sampler and an external-cavity surface-emitting laser (a "topless" laser). The photodiode/sampler was fabricated and preliminary testing showed that the response time was less than 10 ps.
(Principal Investigator: D. Bloom)