PHOTONIC MATERIALS AND PROCESSING

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Not long ago photonics affected our lives only in the display interface between users and machines. Now photonics is spreading into areas that were the traditional domain of electronics: optical communications, optical memory, and optical interconnection. The trend is likely to continue, with photonics playing a major role in information switching and processing. This progress has been made possible by developing photonic materials with the required purity and physical and optical properties: glass fibers for transmission, semiconductors for lasers and detectors, and nonlinear optical materials for switching and processing. Future progress will continue to depend on improved materials and structures and, most of all, on high-yield, low-cost processing materials.

Introduction

Although the importance of optics for information transmission and processing was recognized as early as the 1960s, recent dramatic progress has been made possible because of advances in optical materials. The development of ultra-low-loss optical fibers, and high performance semiconductor lasers and detectors, revolutionized information transmission. During the 1990s we expect photonics to affect the field of information processing, a stronghold of electronics technology.

Because of the increasing density of electronic components on a chip, the ability to interconnect chips via electrical connections presently limits chip design. It is expected that optical interconnection of chips will become increasingly necessary, and will drive the integration of optics and electronics technologies. Hybrid systems will take advantage of the merits of both electronic and photonic technologies. Advances toward these future goals are linked to developing photonic materials and processes to build lower cost lasers, modulators, switches, and processors.

This article will emphasize the semiconductor materials that form the basis of current laser and detector technology. The epitaxial techniques now used to build the most advanced lasers lend them-

Panel 1. Terms and Acronyms in This Paper

AlAs	aluminum arsenide
$Al_xGa_{1-x}As$	aluminum gallium arsenide
atm	atmosphere
CBE	see GSMBE
cw	continuous wave
CVD	chemical vapor deposition
DBR	distributed Bragg reflector
d.c.	direct current
DH	double heterostructure
GaAs	gallium arsenide
GRIN-SCH	graded-index separate confinement quantum well
GSMBE	gas-source molecular beam epitaxy
$In_xGa_{1-x}As$	indium gallium arsenide
$In_xGa_{1-x}As_yP_{1-y}$	indium gallium arsenide phosphide
H_2	hydrogen
InP	indium phosphide
$LiNbO_3$	lithium niobate
LPE	liquid phase epitaxy
MBE	molecular beam epitaxy
MOCVD	metal-organic chemical vapor deposition
MOMBE	see GSMBE
MQW	multiple quantum well
NRZ	non-return to zero
PBX	private branch exchange
PIC	photonic integrated circuit
PMMA	polymethyl methacrylate
QCSE	Quantum Confined Stark Effect
QW	quantum well
RHEED	reflection-high-energy-electron-diffraction
SEED	Self Electro-Optic Effect Device
SEL	surface emitting laser

selves to constructing other photonic devices such as modulators and switches.

Thin Film Semiconductors for Opto-Electronics

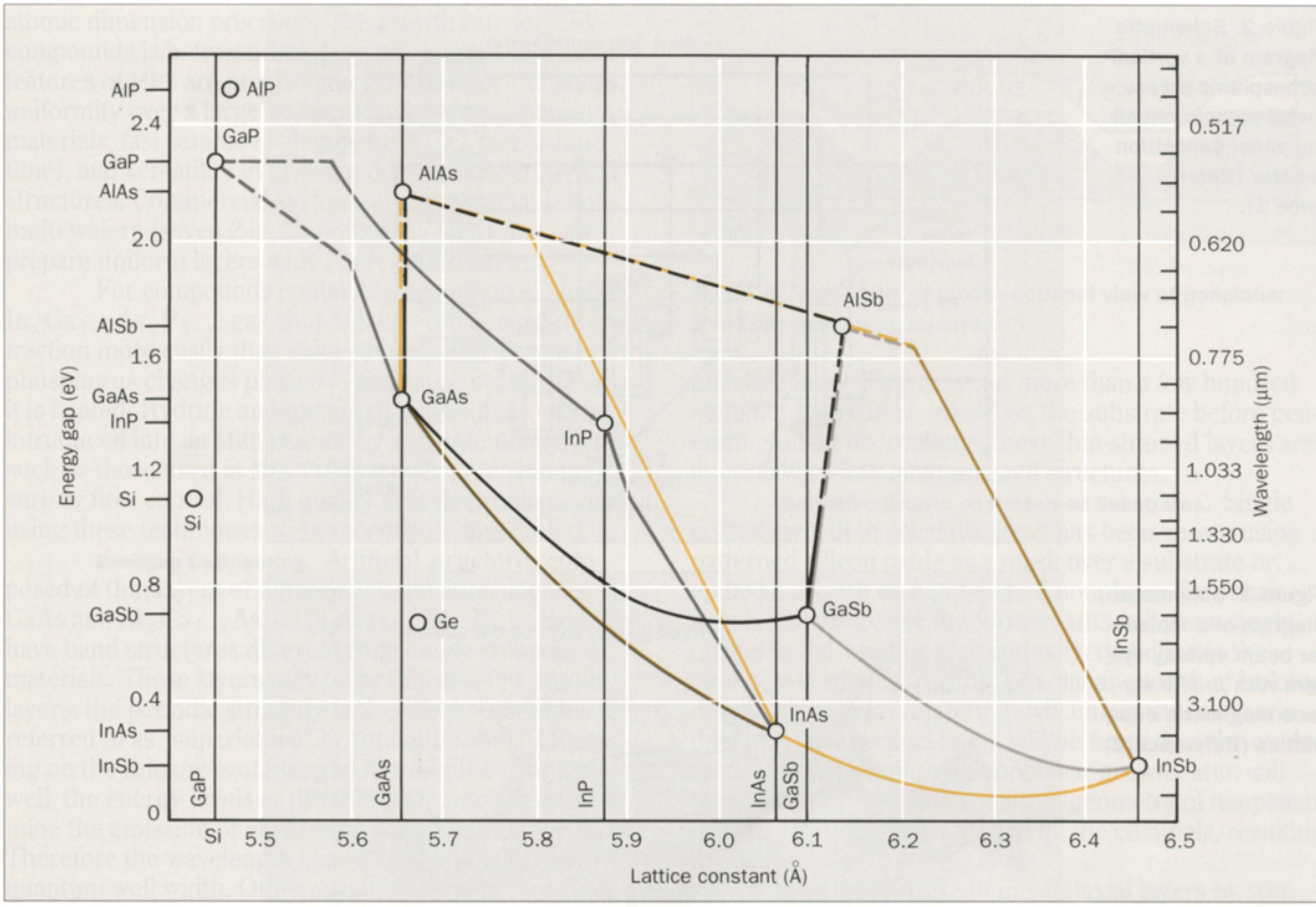
Most electronic devices use silicon as a base material. But because of its indirect bandgap, silicon cannot be used to make efficient light-emitting devices. The materials now commonly used for light-emitting sources are compounds such as gallium arsenide (GaAs), aluminum gallium arsenide ($Al_xGa_{1-x}As$), indium phosphide (InP), indium gallium arsenide ($In_xGa_{1-x}As$) and indium gallium arsenide phosphide ($In_xGa_{1-x}As_yP_{1-y}$) that have direct bandgaps. Most optoelectronic devices are made with single crystal (i.e., epitaxial) films of these materials on a crystalline substrate. Figure 1 shows the bandgap energies and their corresponding wavelengths of the III-V compounds as a function of their lattice constants.

The most commonly used substrate materials are GaAs (lattice constant a = 5.65 angstrom [Å]) and InP (a = 5.87 Å). AT&T substrate technology was described in a recent issue of this publication.[1] Compounds with different bandgap energies—that can be translated to devices operating at different wavelengths—may be prepared with binary, ternary, and quaternary alloy systems. Most of the epitaxial films in the optoelectronic devices are lattice-matched to the substrate. Recently, epitaxial studies extended film growth to lattice-mismatched systems.

The epitaxial crystal growth technologies have greatly advanced in recent years. Liquid phase epitaxy (LPE) has been the major production technology, and is being replaced by metal-organic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE), and the combination of the two called gas-source MBE (GSMBE, MOMBE, or CBE) because of ever-demanding higher uniformity and yield.

The MOCVD process[2] involves pyrolysis of vapor-phase mixtures of metalo-organic compounds, e.g., trimethylgallium and trimethylaluminum, and hydride compounds such as arsine and phosphine. These mixed vapor phase compounds are usually pyrolyzed in a flowing hydrogen (H_2) atmosphere operating at atmospheric pressure or at a reduced pressure of about 70 torr (0.1 atm [atmospheres]). The substrate is placed on a graphite "susceptor" heated by a radio-frequency generator to 600 to 800°C (Figure 2). The growth rate used for a solid state laser structure is 3 to 4 micrometers (µm) per hour.

MBE[3] employs ultra-high vacuum systems in which elemental atomic or molecular beams are pro-



duced for each constituent of the desired compound semiconductor thin film. These molecular beams are formed by heating the corresponding elemental sources or compounds in precise temperature-controlled effusion cells (Figure 3). The substrate is mounted on a heated (500 to 700°C) rotating molybdenum block to achieve thickness uniformity. Molecular beam epitaxy relies on kinetic processes of adsorption, desorption, migration, and reaction of the thermal beams with the substrate.

Figure 1. Energy gap and lattice constant for several III-V compounds. The boundaries joining the binary compounds give the ternary or quaternary energy gap and lattice constant (after P. K. Tien).

Since MBE is conducted in a vacuum, various diagnostic instruments, such as reflection-high-energy-electron-diffraction (RHEED) and mass spectrometry may be used in the growth system to monitor the growth rate to

Figure 2. Schematic diagram of a vertical atmospheric-pressure metal-organic chemical vapor deposition reactor (Reference 1).

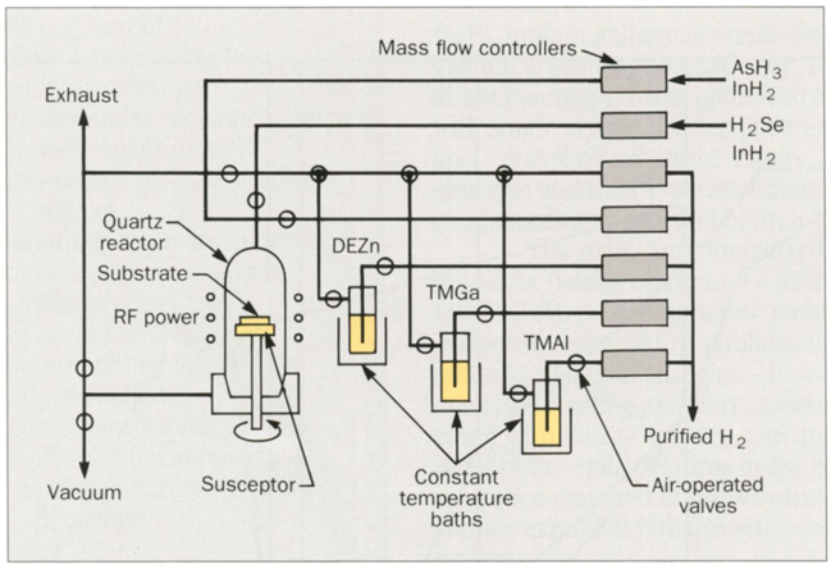
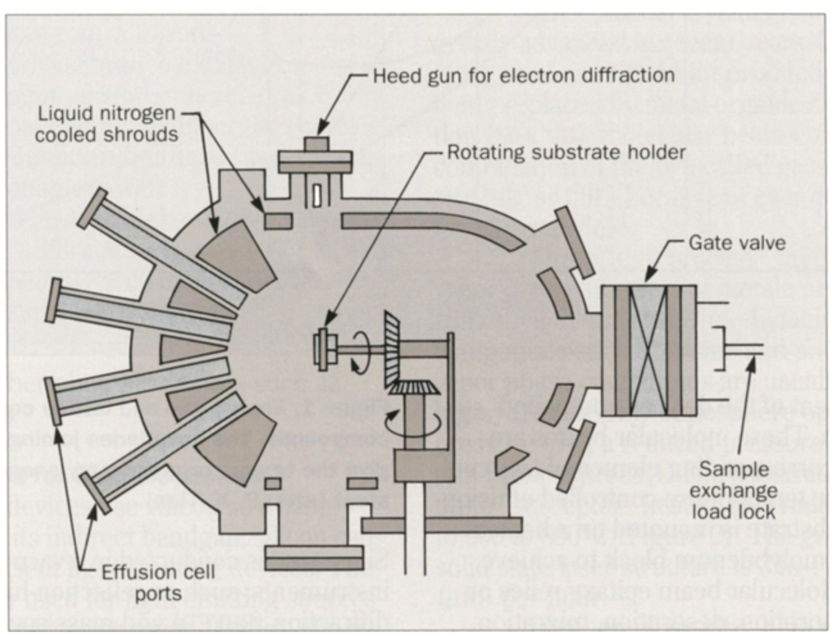


Figure 3. Schematic diagram of a molecular beam epitaxy system with *in situ* surface diagnostic capabilities (Reference 2).



atomic dimension precision. The growth rate for III-V compounds is between 1 to 2 μm per hour. The special features of MBE are precision in growth layer thickness, uniformity over a large wafer, efficient use of source materials, fast sample exchange time (i.e., turnaround time), and versatility in growing different materials and structures. Commercial systems are now available with multi-wafers (seven 2-inch and three 3-inch) that can prepare uniform layers with 1 percent variation.

For compounds containing phosphorus, such as $In_xGa_{1-x}As_yP_{1-y}$, gas source MBE[4] can control the mole fraction more easily than solid source MBE because solid phosphorus changes phases— and vapor pressure—as it is heated. Hydride and metal-organic sources can be introduced into an MBE reactor by a gas-handling system, such as those used in MOCVD, that uses precision pressure or flow control. High quality optoelectronic devices using these techniques were recently demonstrated.

Bandgap Engineering. Artificial structures composed of thin layers of different composition such as GaAs and $Al_xGa_{1-x}As$, or $In_xGa_{1-x}As_y\ P_{1-y}$ and InP, have band structures different from single compound materials. These layers may be as thin as a few atomic layers; the periodic structure is therefore sometimes referred to as "superlattice" or "quantum well." Depending on the thickness of material forming the quantum well, the energy levels of the sub-band in the well determine the emission or absorption wavelength of the device. Therefore the wavelength can be tuned by changing the quantum well width. Other structures under study consist of a single homogeneous compound semiconductor periodically doped with p- and n-type impurities.

Recent advances in materials processing have extended the growth of epitaxial layers to non-lattice-matched systems. For instance, the growth of $In_xGa_{1-x}As$ on GaAs allowed us to extend the emission wavelength of lasers from 0.8 μm to 1.1 μm, a region that would not be accessible with lattice-matched materials. Because only a limited thickness of the non-lattice-matched layer—typically not more than a few hundred nanometers—can be grown on the substrate before generating misfit dislocations, these thin-strained layers are generally used in quantum well structures.

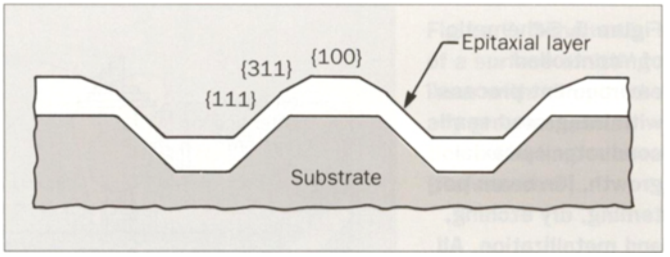


Figure 4. Schematic of cross-sectional view of nonplanar substrate and epitaxial layer.

Selective Growth on Patterned Substrates. Single crystal growth in selective areas has been shown using patterned silicon oxide as a mask over a substrate or epitaxial growth on a pre-etched nonplanar (i.e., channeled) substrate. For the former, MBE will grow single crystal in the window area and polycrystalline in the oxide-covered area, resulting in planar growth of isolated devices. However, LPE or CVD will only grow in the window area, and no nucleation will be formed on the oxide-covered area, resulting in nonplanar growth. MBE will preserve the channeled substrate geometry of nonplanar growth, while LPE and CVD will fill the channels, resulting in a planar structure.

The growth rate of the epitaxial layers by MBE depends on the orientation of the surface where these layers grow. For instance, on a substrate with ridges oriented in the crystallographic {100} direction, and grooves formed with {111} oriented side walls, the gallium (Ga) atoms tend to migrate from the side walls to {100} plane resulting in a 50 percent thicker layer on the ridge and groove than on the side walls (see Figure 4).[5] If we grow GaAs and AlGaAs superlattice over the whole channeled substrate, the resulting structure has a higher

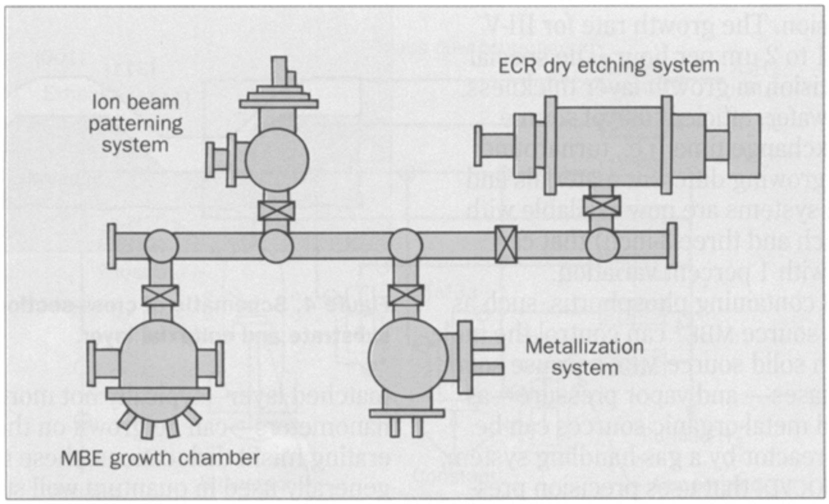


Figure 5. Schematic of "controlled environment process" with integrated semiconductor epitaxial growth, ion-beam patterning, dry etching, and metallization. All the modules are interconnected under vacuum.

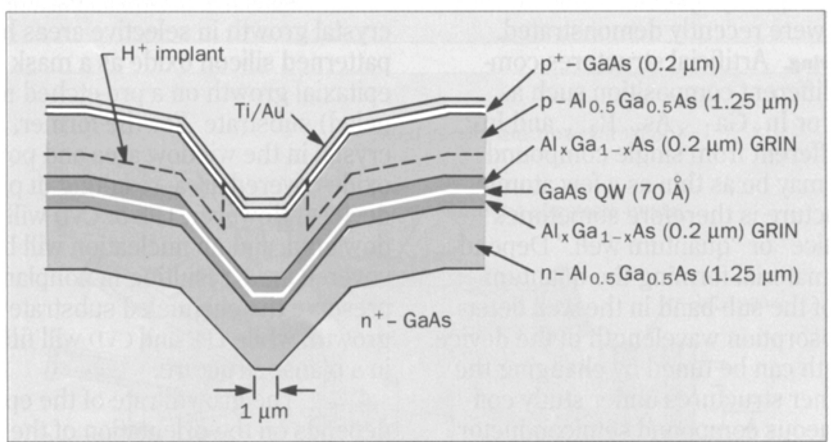


Figure 6. Cross section of patterned graded-index separate confinement (GRIN-SCH) quantum well laser. This laser has a threshold current as low as 0.35 mA (Reference 6).

aluminum arsenide (AlAs) mole fraction on the side walls than on the {100} plane; a natural formation of index-guided injection laser structure with single-step growth is produced. Similar structures can be obtained by epitaxial growth of strained InGaAs/GaAs quantum well structure on nonplanar substrates. Dislocations of lattice-mismatched materials may be reduced by growing on patterned substrates because the isolated mesas can prevent the propagation of threading dislocations.[6]

Controlled Environment Processing. For more reliable and higher yield manufacturing, we will need a cleaner environment with particle reduction and controlled, chemically clean interfaces of semiconductor, metal, and dielectric depositions. An integrated process system is the key for advanced semiconductor assembly.

Figure 5 shows a controlled environment

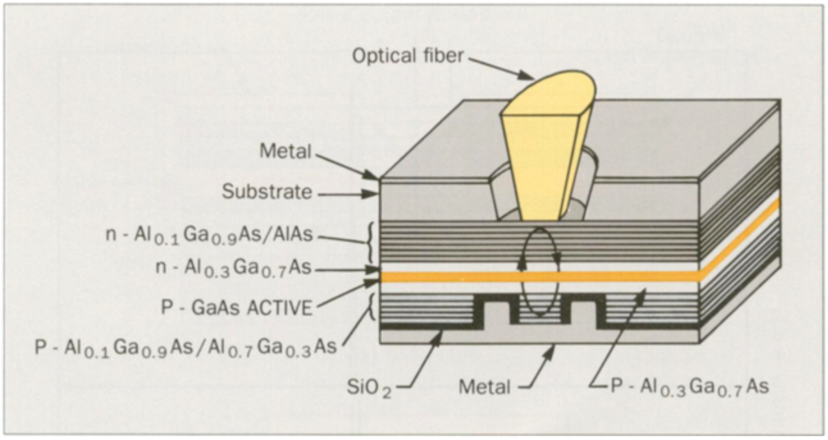


Figure 7. Schematic of a surface emitting laser with all epitaxially grown superlattice reflecting mirrors (Reference 9).

process for surface-emitting lasers. It consists of an MBE chamber for the semiconductor deposition, an ion beam system for patterning, an electron cyclotron resonance apparatus for dry etching, and an *in situ* metallization system for metallic mirror and contacts. The high vacuum chamber contains the transport mechanism to move wafers from module to module. A major advantage of integrated systems is that they allow regrowth, clean interfaces, and reduced overall turnaround time.

Novel Laser Structures

This section discusses various types of novel laser structures, including quantum well, patterned quantum well injection, and surface emitting lasers in terms of their basic features, advantages, and disadvantages.

Quantum Well Lasers. Quantum well lasers are advantageous for high frequency modulation, because they exhibit less chirping. They have a smaller change of refractive index with injected carrier density than bulk material. Their performance is further enhanced because of reduction in the asymmetry of the conduction, and valence band effective mass in the strained layers. Strained multiple quantum well (MQW) lasers built with $In_{0.2}Ga_{0.8}As$ on GaAs substrates have an order of magnitude narrower continuous wave (cw) laser linewidth and a factor of ~5 lower chirp than regular double heterostructure (DH) lasers.[7] These features are desirable when these lasers are used as light sources in optical communication systems.

These InGaAs/GaAs strained MBE quantum well lasers can be used as high power lasers. Ridge waveguide lasers emitting 100 milliwatts (mW) from each facet (i.e., at each end of the laser chip) in the phase-locked laser arrays with powers up to 4 watts have been shown. The laser arrays had 10 stripes, each 3 μm wide separated by 3 μm.

Patterned Quantum Well Injection Lasers. Buried heterostructure quantum well lasers can be grown in a single step by MBE by growing directly on patterned substrates. Figure 6 shows the cross section of the patterned graded-index separate confinement (GRIN-SCH) quantum well laser. It consists of a GaAs active region 70 angstroms (Å) thick and 1 μm wide, embedded in a 0.4 μm thick and 1.5 μm wide GRIN optical waveguide. With high-reflection coated mirrors, these lasers exhibited threshold currents as low as 0.35 milliamps (mA) pulsed and 0.5 mA continuous operation for a cavity length of 125 μm.[8]. The light output as a function of current characteristics showed no kinks up to more than 15 times the threshold current (200 μW). It is believed that a still

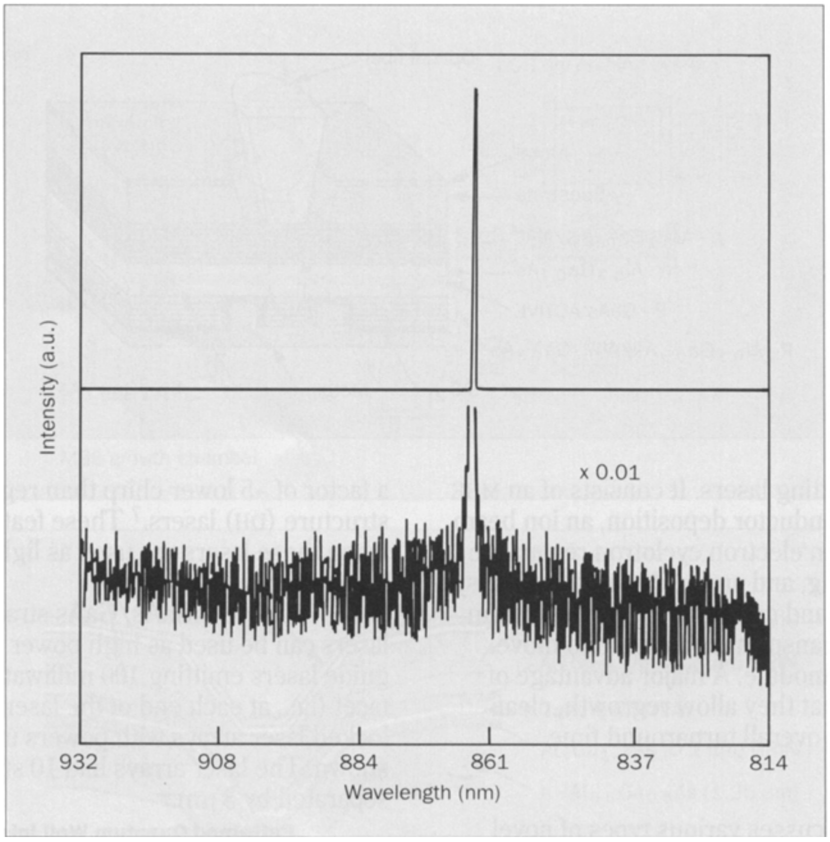


Figure 8. Room temperature cw emission of the surface emitting laser. The side mode suppression is ratio better than 35 dB (Reference 9).

lower threshold current (~0.1 mA) can be reached by reducing the QW active region's width to 0.2~0.4μm.

Surface Emitting Lasers. Surface emitting lasers[9-11] emit the output beam normal to the substrate surface, and are emerging as a promising solution for building low-cost lasers because:

- They can be evaluated at the wafer level before separation into chips.
- They may be used as a high optical power source because it can readily be built into a two-dimensional array.
- They can be used as a high performance single-frequency laser because of the inherent dynamic single-longitudinal mode operation that results from their large-mode spacing of the short cavity (0.5-2 μm).

The most recently studied surface emitting laser (SEL) consists of two superlattice stacks of layers that act as reflecting mirrors for the active region (Figure 7). MBE, as well as MOCVD, can prepare the precisely controlled layer thickness that makes SEL technology possible. With AlGaAs/AlAs multilayer mirrors, more than 20 superlattice layer pairs are needed to form a mirror with reflectivity above 98 percent. To reduce the series resis-

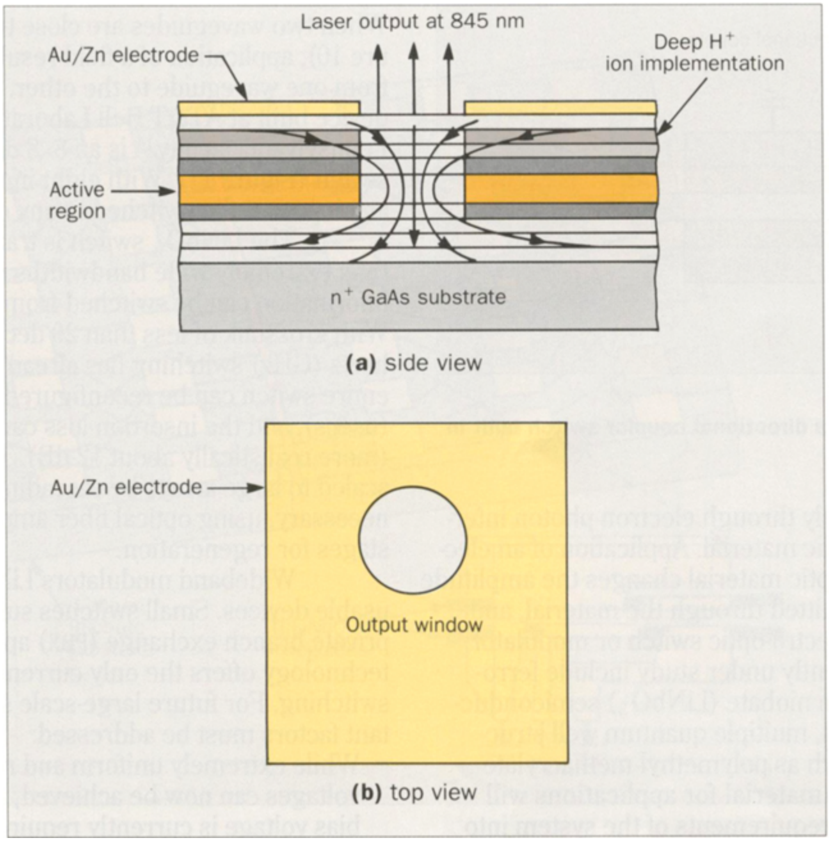


Figure 9. Schematic of a deep ion-implantation to isolate individual surface emitting lasers (Reference 10).

tance of such a superlattice heterostructure, a graded compositional interface or hybrid metal mirror is used.

Figure 8 shows the typical lasing characteristics under cw at room temperature. Recent results showed that a 15 μm diameter device has a cw threshold current of 2.5 mA giving an output power of 0.2 mW, with a temperature coefficient for lasing $T_0 = 115K$.

Ion implantation may be used to isolate the surface emitting lasers and preserve a planar geometry. Most recently, deep H^+-ion implantation [300 kilo electron volts (KeV)] was used to form an embedded insulating layer at the depth of the active region to isolate individual SEL devices (Figure 9). The active region consists of four 100 Å thick GaAs quantum wells separated by three 70 Å thick $Al_{0.3}Ga_{0.7}As$ barriers. The threshold current is 2.2 mA for a 10 μm diameter laser operating cw at room temperature with differential quantum efficiency as high as 20 percent[12].

Photonic Switching and Modulation

The strong Coulomb interaction between electrons permits switching functions to be performed merely by electron-electron interactions. Photons, on the other hand, do not interact with other photons, so photonic

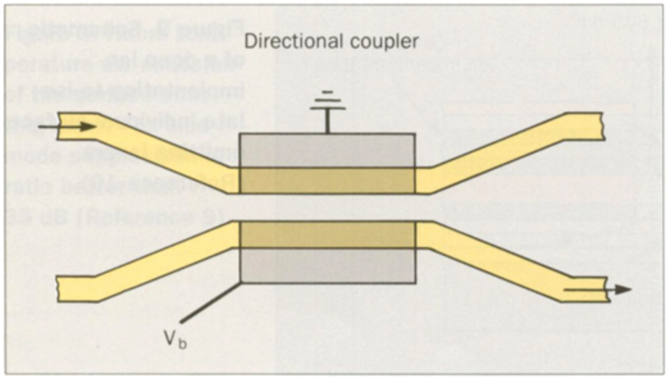


Figure 10. Schematic of a directional coupler switch built in $LiNbO_3$.

switching is possible only through electron-photon interactions in an electro-optic material. Application of an electric field to an electro-optic material changes the amplitude or phase of light transmitted through the material, and forms the basis of an electro-optic switch or modulator.

Materials currently under study include ferroelectrics such as lithium niobate ($LiNbO_3$) semiconductors such as GaAs/AlAs, multiple quantum well structures, and polymers such as polymethyl methacrylate (PMMA). The choice of material for applications will depend on the specific requirements of the system into which the device will be incorporated.

Lithium Niobate. $LiNbO_3$ is the only mature electro-optic switching technology. Single crystals of $LiNbO_3$, four inches in diameter with uniform properties, are grown in AT&T Bell Laboratories' Murray Hill facility. Optical waveguides are built in the $LiNbO_3$ by depositing a titanium metal pattern on the surface of the $LiNbO_3$ wafer, and diffusing the titanium into the crystal at elevated temperatures. This results in an increase of the refractive index that traps light in specific channels by internal reflection. By depositing electrodes on the wafer surface near the waveguide, the phase of the light in the guide can be modulated by an electric field.[13] When two waveguides are close to each other (Figure 10), application of a field results in light switching from one waveguide to the other. The most complex device built at AT&T Bell Laboratories' Allentown, Pennsylvania facility[14] is an 8×8 directional coupler switch (Figure 11). With eight input and output fibers, any input can be switched to any output.

The $LiNbO_3$ switch is transparent to the data rate: extremely wide bandwidths terahertz (THz) of information can be switched from one fiber to another. With crosstalk of less than 20 decibels (dB), 72 gigahertz (GHz) switching has already been shown. The entire switch can be reconfigured in 1 to 2 nanoseconds (nsecs), and the insertion loss can be as low as 7 dB (more realistically about 12 dB). The switch can be scaled to large arrays by cascading 8×8 chips and, if necessary, using optical fiber amplifiers between stages for regeneration.

Wideband modulators $LiNbO_3$ are now mature, usable devices. Small switches suffice for wideband private branch exchange (PBX) applications, and $LiNbO_3$ technology offers the only current option for photonic switching. For future large-scale switching, two important factors must be addressed:

- While extremely uniform and repeatable switching voltages can now be achieved, a direct current (d.c.) bias voltage is currently required at each switch to set the operating point. The voltage required varies somewhat from one switch to another and each switch has to be individually set. This is a materials processing issue believed to be due to defects introduced during waveguide fabrication or crystal growth.
- The $LiNbO_3$ switch cannot read a header on the carrier for packet switching. To set the switch, another means for reading the header must be incorporated into the switch.

Electro-Optic Polymers. The electro-optic coefficients of some crystalline organic polymers such as metanitroaniline can considerably exceed that of $LiNbO_3$. Because of the low dielectric constant of these

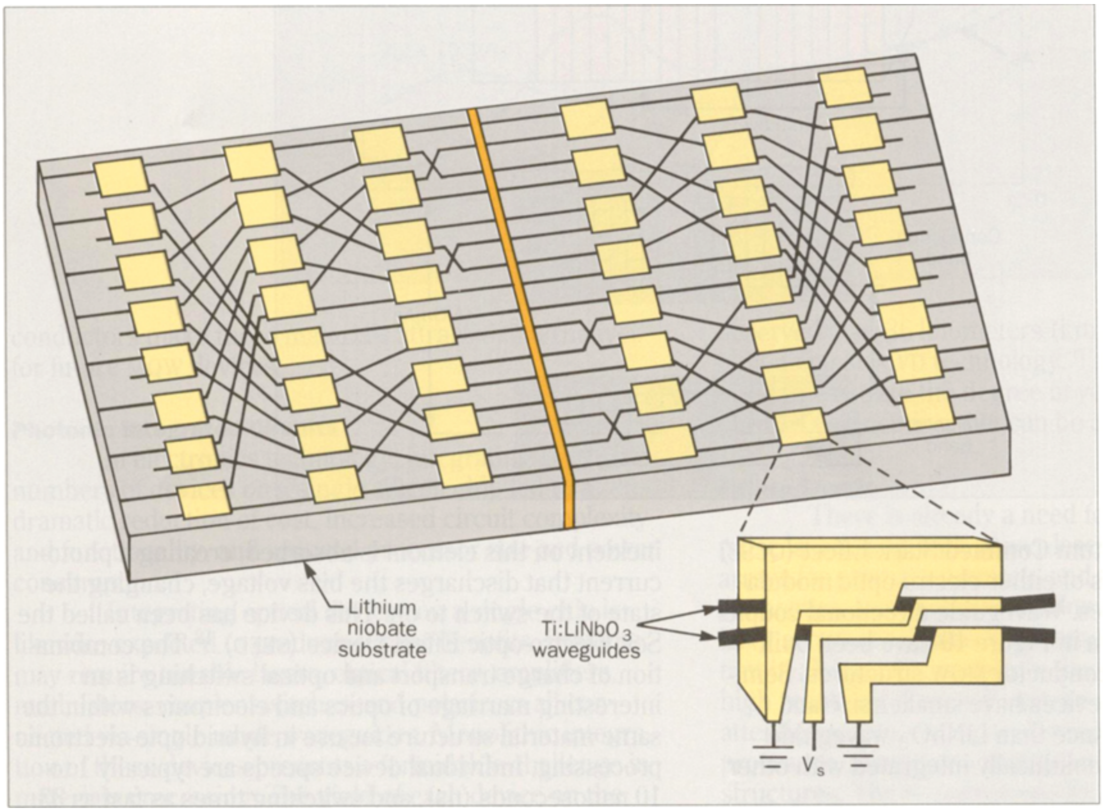


Figure 11. Schematic of an 8×8 directional coupler switch built in $LiNbO_3$.

materials, they are potentially useful for high speed modulation. To avoid difficulties associated with the growth of single crystal films, highly nonlinear organic molecules are dissolved in an amorphous polymeric host such as polymethyl methacrylate, followed by orientation of the solute molecules in an electric field. Thin electro-optic waveguides may be simply built by spinning the polymer onto a silicon surface, thereby permitting integration of photonic technology with silicon.[15] This research is primarily driven by the simplicity and low cost of device fabrication, but polymeric waveguide development is still immature, and much progress is required before a practical switching technology is feasible.

Semiconductor Quantum Wells. During the 1980's it was discovered that strong electro-optic effects can be observed in semiconductor MQW structures near the electronic band edge.[16] Electro-optic devices based on these effects are now the subject of intense research.

The basic material design is shown in Figure 12. The structure consists of a series of about 60 alternating lattice matched layers of GaAs and $Ga_{1-x}Al_xAs$ (typically $x \sim 0.3$). The layer thicknesses are typically in the range between 35 and 90 Å. The optical transmission spectrum of such a wafer consists of a series of sharp excitonic absorption peaks near the band edge. These absorption peaks are sensitive to an applied electric field

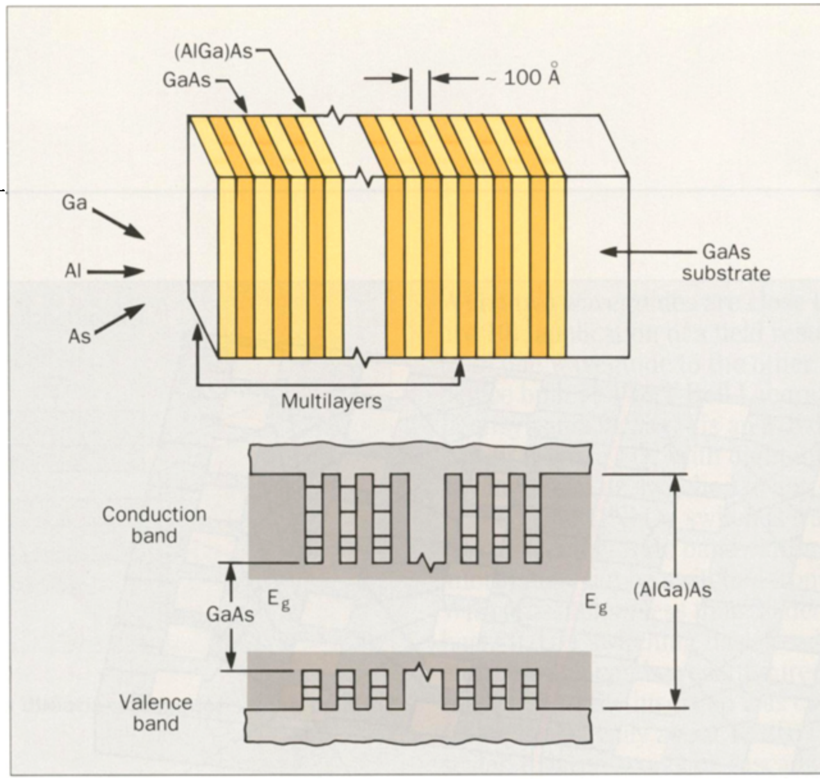


Figure 12. Schematic of a GaAs/GaAlAs multiple quantum well structure, and the resulting electronic band structure. Electrons and holes in the narrower gap GaAs regions are confined by the wider gap AlGaAs layers. This results in the quantum confined electron states shown in the lower figure.

(Figure 13). This Quantum Confined Stark Effect (QCSE) can be used as the basis of either electro-optic modulators or photonic switches. Waveguide directional coupler switches like that shown in Figure 10 have been built[17] with several III-V semiconductor MQW structures. Semiconductor waveguide devices have smaller size and lower electrical capacitance than $LiNbO_3$ waveguide devices, and can be monolithically integrated with other semiconductor devices.

Free Space Optical Switching. One characteristic of the QCSE is that switching can be done with light propagating that is normal to the semiconductor wafer, with total MQW layer thickness of only one micron. A change of 3:1 in transmission of the MQW structure can be done with low voltages. Unlike waveguide directional couplers where the input signal is routed to one of two outputs, the electro-absorption switch is an on-off gate switch. The individual switching elements can be small (typically $< 10\mu m^2$ cross-sectional area) so many switches can be built on a single wafer. The switches can be either electrically or optically addressed. A dc bias applied to the MQW structure makes the element absorbing because of the band edge shift, and it turns the switch off. Light incident on this element is absorbed, creating a photocurrent that discharges the bias voltage, changing the state of the switch to on. This device has been called the Self Electro-optic Effect Device (SEED).[18] The combination of charge transport and optical switching is an interesting marriage of optics and electronics within the same material structure for use in hybrid opto-electronic processing. Individual device speeds are typically 1 to 10 nanoseconds (ns), and switching times as fast as 33 picoseconds (ps) have been observed by careful design of the MQW structure. In arrays, these speeds are reduced. Typical optical energies required to alter the state of a switch is about 1 picojoules (pJ). SEED devices can be operated as bistable logic switches. Arrays of switches can be cascaded by imaging the output of one array on the input of a later array. Because of absorption loss the signal must be regenerated at each stage. An array of logic switches[19] on a 3-inch GaAs wafer is shown in Figure 14. Each has 32×64 switch elements. AT&T recently announced the commercial availability of such MBE wafers. While most of the research has used GaAs/GaAlAs materials and other III-V semiconductors, recent progress[20] with the growth of II-VI semi-

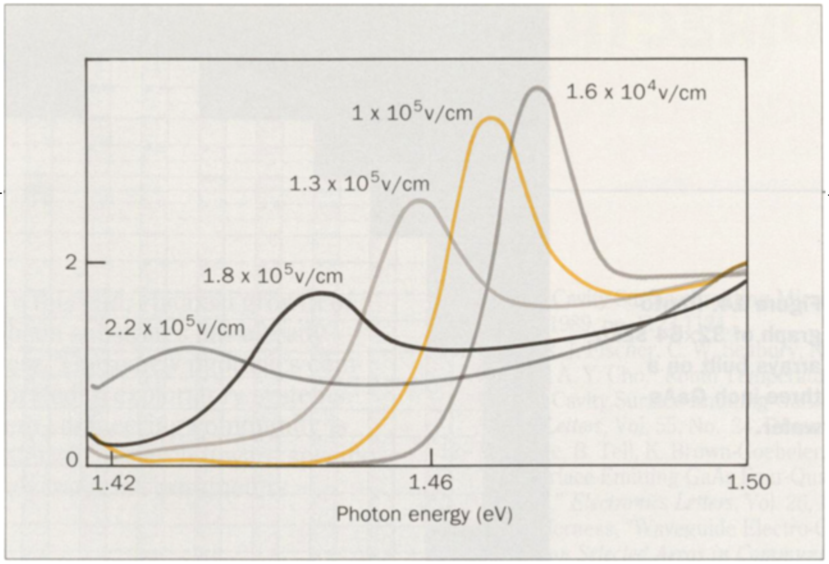


Figure 13. Change of optical absorption near a MQW exciton absorption peak as a function of applied electric field: the Quantum Confined Stark Effect.

conductors make these materials attractive alternatives for future MQW devices.

Photonic Integrated Circuits

In electronics technology, integrating large numbers of devices on a single silicon chip led to a dramatic reduction of cost, increased circuit complexity and functionality, and reduced processor size and power consumption.

Integrating optical devices on a single chip is likewise expected to produce similar benefits. Systems may require tunable lasers, optical filters, amplifiers, modulators, coupler switches, and polarizers all connected via single mode waveguides. Monolithic integration of these devices presents a formidable challenge in materials processing. The yield of each device on the chip must be high to assure reasonable chip yields. Precise control of this crystal growth parameters and the etching, lithography, metallization, and dielectric layers is essential.

There have been recent demonstrations of photonic integrated circuits (PICs) containing several devices integrated on a single chip that perform complex functions. One example shown in Figure 15 is a wavelength division multiplexer in which four tunable MQW-distributed Bragg reflector (DBR) lasers feed a common amplifier for coupling into a single mode fiber.[21] With a 25Å channel spacing between the lasers, error-free transmission at 2Gb/s for each channel with pseudo-random non-return to zero (NRZ) format intensity modulation was observed over 36 kilometers (km) of fiber. This PIC was built using MOCVD technology. These research demonstrations illustrate the degree of versatility in device and process engineering that can be achieved.

Future Trends

There is already a need for tunable lasers, short pulse lasers, and high power lasers. Monolithic laser arrays for printers, memory, and two-dimensional interconnection and high power kilowatts (kw) phase-locked laser arrays are driven by commercial need. Most important in all laser technology is the need for low cost and high reliability. This will only be achieved by special attention to process control: minimizing the number of processes, minimizing testing and simplifying packaging structures. The requirements for photonic switches are not as well developed as the requirements for lasers. For modulators or space division switching of wide bandwidth channels, $LiNbO_3$ technology is at an advanced stage of development. Future advances in modulators and directional couplers will be made with MQW waveguide devices where the advantages of monolithic integration with lasers and other optical devices is evident.

For free-space photonic switching and image processing, the focus will be on developing uniform materials with larger nonlinearities that require lower optical and electronic energies for switching, and faster response.

Realizing the potential of photonics will only come with monolithic integration of electronic and

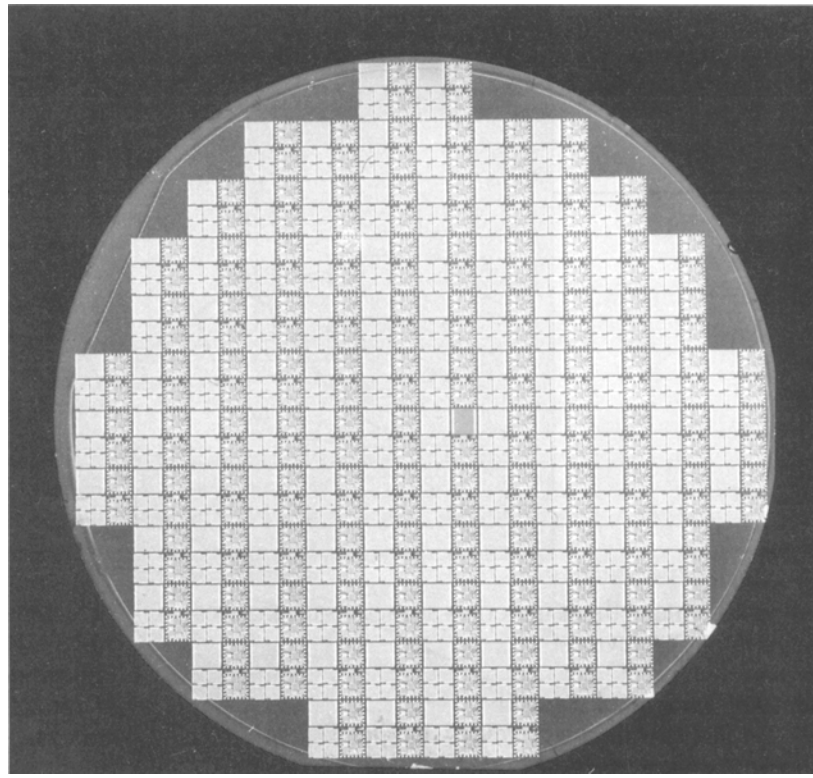


Figure 14. Photograph of 32×64 SEED arrays built on a three-inch GaAs wafer.

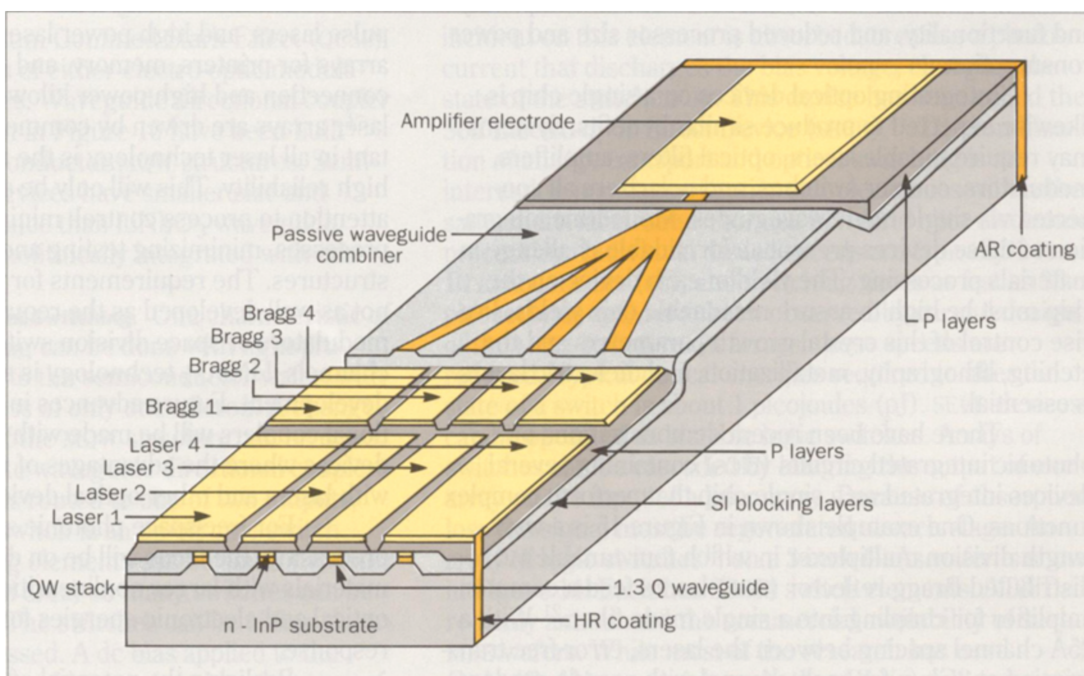


Figure 15. Configuration of a wavelength division multiplexer PIC built on InP.

photonic components. To this end, epitaxial growth of photonic materials on silicon substrates has already shown significant progress. These new photonics components must be incorporated in exploratory systems. Feedback from the system engineering community is essential to focus the materials research toward specific targets, and to identify key materials parameters.

References

1. Jim E. Clemans, Theophilus I. Ejim, William A. Gault, and Eric M. Monberg, "Bulk III-V Compound Semiconductor Crystal Growth," *AT&T Technical Journal*, Vol. 68, No. 1, January/February 1989, pp. 29-42.
2. R. D. Dupuis, "Metaloorganic Chemical Vapor Deposition (MOCVD) of III-V Semiconductors," *Science*, Vol. 226, No. 4675, November 9, 1984, pp. 623-629.
3. E. H. C. Parker, Ed., *The Technology and Physics of Molecular Beam Epitaxy*, Plenum Press, New York, 1985, pp. 1-13.
4. M. B. Panish, "Molecular Beam Epitaxy," *AT&T Technical Journal*, Vol. 68, No. 1, January/February, 1989, pp. 43-52.
5. S. Nilsson, E. Van Giesson, D. J. Arent, H. P. Meier, W. Walter, and T. Forster, "Ga Adatom Migration Over a Nonplanar Substrate During Molecular Beam Epitaxy Growth of GaAs/AlGaAs Heterostructure," *Applied Physics Letters*, Vol. 55, No. 10, September 1989, pp. 972-974.
6. E. A. Fitzgerald, G. P. Watson, R. E. Proano, D. G. Ast, P. D. Kirchner, G. D. Pettit, and J. M. Woodall, "Nucleation Mechanism and the Elimination of Misfit Dislocations at Mismatched Interfaces By Reduction In Growth Area," *Journal of Applied Physics*, Vol. 65, No. 6, 1989, p. 2220.
7. N. K. Dutta, J. Wynn, D. L. Sivco and A. Y. Cho, "Linewidth Enhancement Factor in Strained Quantum Well Lasers," *Applied Physics Letters*, Vol. 56, No. 23, June 1990, pp. 2293-2294.
8. E. Kapon, S. Simhony, J. P. Harbison, and L. T. Florez, "Threshold Current Reduction in Patterned Quantum Well Semiconductor Lasers Grown by Molecular Beam Epitaxy," *Applied Physics Letters*, Vol. 56, No. 19, May 1990, pp. 1825-1827; Vol 56, No. 23, June 1990, pp. 2304-2306.
9. K. Iga, F. Koyama, and S. Kinoshita, "Surface Emitting Semiconductor Lasers," *IEEE Journal of Quantum Electronics*, Vol. QE-24, 1988, pp. 1845-1855.
10. J. L. Jewell, A. Scherer, S. L. McCall, Y. H. Lee, S. Walker, J. P. Harbison, and L. T. Florez, "Low Threshold Electrically Pumped Vertical Cavity Surface-Emitting Micro-Lasers," *Electronics Letters*, Vol. 25, 1989, pp. 1123-1124.
11. K. Tai, R. J. Fischer, C. W. Seabury, N. A. Olsson, T-C. D. Huo, Y. Ota, and A. Y. Cho, "Room Temperature Continuous-Wave Vertical-Cavity Surface-Emitting GaAs Injection Lasers," *Applied Physics Letters*, Vol. 55, No. 24, December 1989, pp. 2473-2475.
12. Y. H. Lee, B. Tell, K. Brown-Goebeler, J. L. Jewell, and J. V. Hove, "Top-Surface-Emitting GaAs Four-Quantum-Well Lasers Emitting at 0.85 μm," *Electronics Letters*, Vol. 26, 1990, p. 710.
13. R. C. Alferness, "Waveguide Electro-Optic Switch Arrays," *IEEE Journal on Selected Areas in Communication*, Vol. 6, 1988, p. 1117.
14. J. E. Watson, M. A. Milbrodt, K. Bahadori, M. F. Dautartas, C. T. Kemmerer, D. T. Moser, A. Schelling, T. O. Murphy, J. J. Veselka and D. A. Herr, "A Low Voltage 8×8 Ti:$LiNbO_3$ Switch with a Dilated Benes Architecture," *IEEE Journal of Lightwave Technology*, Vol. 8, 1990, p. 794.
15. K. D. Singer, W. R. Holland, M. G. Kuzyk, G. L. Wolk, H. E. Katz, M. L. Schilling and P. A. Cahill, "Second Order Nonlinear Optical Devices in Poled Polymers," *Proceedings SPIE*, Vol. 1147, 1989, p. 233.
16. D. A. B. Miller, D. S. Chemla and S. Schmitt-Rink, "Electric Field Dependence of the Optical Properties of Semiconductor Quantum Wells," *Optical Nonlinearities and Instabilities in Semiconductors*, H. Hang, Ed., Academic Press, San Diego, California, 1988, pg. 235.
17. J. E. Zucker, "Electrorefraction in Semiconductor Quantum Wells," *Proceedings SPIE*, Vol. 994, No. 142, 1988.
18. D. A. B. Miller, "Quantum Well Self-electro-optic Effect Devices," *Journal of Optical and Quantum Electronics*, Vol. 22, 1990, p. S61.
19. L. F. Chirovsky, L. A. D'Asaro, C. W. Tu, A. L. Lentine, G. D. Boyd and D. A. B. Miller, *Optical Society of America Proceedings on Photonic Switching*, J. E. Midwinter and S. H. Winton, Eds., Optical Society of America, Washington, D. C., 1989, p. 32.
20. D. Lee, J. E. Zucker, A. M. Johnson, R. D. Feldman and R. F. Austin, "Room Temperature Excitonic Saturation in CdZnTe/ZnTe Quantum Wells," *Applied Physics Letters*, Vol. 57, 1990, p. 1132.
21. T. L. Koch and V. Koren, "Photonic Integrated Circuits," *Proceedings of the Materials Processing Society*, Vol. 167, 1990, p. 71.

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