# Photoelectronic Integrated Circuits [and Discussion]

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# Photoelectronic integrated circuits

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The encounter of optoelectronics and microelectronics leads to photoelectronic integrated circuits (ICS). The concept is not new, but it has become more feasible in the last couple of years because of advances in the compound semiconductor technologies used to produce laser diodes and photodetectors and GaAs MES ICS. In particular, molecular beam epitaxy and vapour phase epitaxy have shown big improvements so that it is now possible to fabricate well-controlled thin layers of semiconductor, which is difficult using conventional liquid phase epitaxy. In this paper, I discuss the motives for pursuing photoelectronic integration in semiconductor materials and also the relevant essential technologies. I then give examples of monolithic integration at the photonic device level which gives higher performance and higher functionality, and describe prototype photoelectronic integrated circuits highlighting the new process technologies used.

## 1. INTRODUCTION

The idea of the optical integrated circuit was suggested by analogy with the electronic integrated circuit, but with optical devices connected by optical wiring on the same substrate or chip. However, the idea still remains in laboratories and is far from development. One reason is that the first leading industry driven by quantum electronics grew in the telecommunications field, and led to breakthroughs in optical transmission technology exclusively in common carrier networks. Optical fibre cable transmission technology required only three new components: optical fibres, lasers and detectors, and these have been good enough to realize systems deployed so far. Recently, however, the telecommunications network is drastically changing towards digitalization driven by digitalized customer equipment as well as by the new digital environment in trunk level links. For example, 1.6 Gb (NTT) and 1.7 Gb (AT&T) systems which were believed to be too high capacity for most systems a few years ago are going to be bestsellers. The digital environment will require much higher performance and function in transmission repeaters and terminal equipment and such equipment will also have to be inexpensive and easy to maintain. The photoelectronic IC could meet these requirements.

The photoelectronic IC, often referred to as the OEIC, is similar to the microwave monolithic IC (MMIC) operating at present in the microwave range up to 30 GHz. High performance can be realized by using monolithic integration technology, because there are many common bases in the material system and the process technology and, moreover, MMICS will be a part of many photoelectronic ICS.

## 2. Motivation for photoelectronic integrated circuits

Information engineering is supported by microelectronics technology and electronic signals play the main role in information processing even in telecommunications. In that environment, optical signal to electrical signal (OE) or the reverse (EO) conversion is an essential function if optical fibre networking among terminal equipments exists. Even at present, lightwave communication is becoming very common, both at short and long ranges and user-friendly OE and/or EO blocks are welcomed by system manufacturers.

The merits of photoelectronic ICs are as follows.

1. High performance: in particular, it is hardly possible to make high-bit-rate circuits by wiring discrete devices because of the high level of parasitic C, L and R.
2. High functionality: including two-dimensional functions.
3. Compactness, stability and robustness: customers require modules or building blocks having clear interfaces to make subsystems or systems and to maintain them easily.
4. Good reproducibility and potential for mass-production: e.g. manual adjustment of optical connections or drive/post amplifier circuits could be eliminated.

The generic steps toward photoelectronic ICs are considered as shown in figure 1. Presently, there are many issues at the photonic device level where only lasers and detectors are relatively matured. However, other analogue devices, for example, a relational device for switching or routing or a logic device in which bistability may be incorporated, are still in basic research. Photonic devices can add 'wavelength' and 'space/beam' as novel parameters (or degrees of freedom or axes) to that of 'time/frequency' used in electronic devices. A two-dimensional or three-dimensional photonic device will make the best use of the additional new parameters.

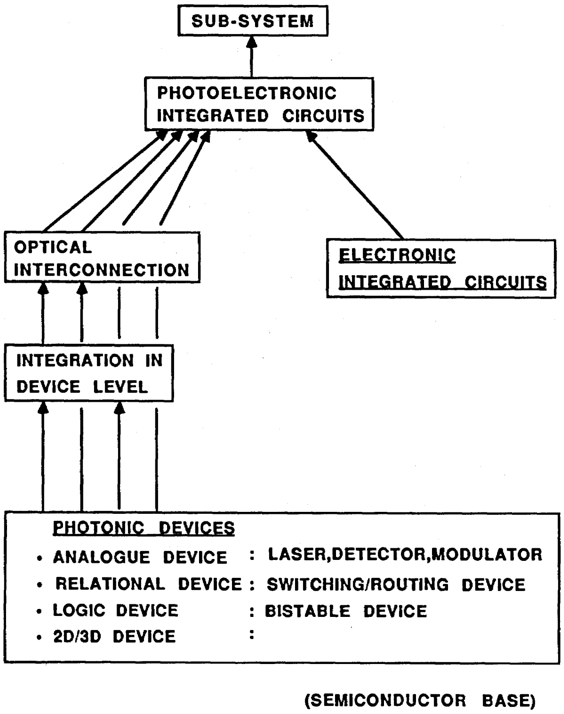


Figure 1. Generic steps towards the photoelectric integrated circuit.

The next step is integration at the photonic device level to boost the performance and the function of the devices. For example, monolithic integration of external cavity laser diode is one of the proposals for a light source in coherent systems.

Optical connection is also important because amplification of light signals is not a reliable technology so that low-loss waveguiding and high coupling efficiency is important. The losses in semiconductor waveguides have been improved to be less than 1 dB $cm^{-1}$ for straight guides; however, curve guides still require care.

There have been recent interesting advances in electronic MMICs handling signals at more than 10 GHz. MMICs use almost the same materials, GaAs and InP, as photonic devices. Thereby, the integration of both kinds of devices becomes more and more realistic (see tables 1 and 2).

TABLE 1. COMPOUND SEMICONDUCTOR IC

1. GaAs–MES–IC

| | |
|---|---|
| material | bulk crystal |
| device | MES (Schottky gate) FET |
| process | lithography (EB), ion-implantation, annealing, diffusion, etching (dry) |
| guide line | fine as possible<br>high speed and high density |
| complexity | 16k SRAM |
| application | analogue microwave monolithic IC (MMIC)<br>digital |

note: CAD used.

2. InP junction FET–IC

3. Hetero-junction TR IC (at present)

| | | |
|---|---|---|
| material | GaAlAs/GaAs, InGaAs/GaAs, InGaAs/InAlAs/InP | |
| device | MOD–FET or HEMT (2D electron gas) | |
| process | epitaxial growth | |
| guide line | under study | |
| complexity | one device | one device and MMIC |
| application | analogue MMIC, low noise digital | |

note: $f_T > 100$ GHz, $f_T = 100$ GHz, $f_T > 100$ GHz

4. Hetero-junction bipolar TR IC

TABLE 2. PHOTONIC DEVICES

| | |
|---|---|
| material | Si, GaAs system, InP system |
| device | laser, detector, sw, bistable |
| process | lithography, etching, regrowth cleaving,<br>diffusion, ion-implantation |
| guide line | good design, good process! |
| complexity | one device, integration (device level) |
| application | lightwave communication terminals |

The features of this integration will be as shown in figure 2. It is worth pointing out that 'perfect monolithic integration' could be limited by the material needed to fabricate optical isolating segments (YIG is used). The laser requires very high isolation to keep its stable operation and the issue is how to replace magneto-optic crystal by semiconductor material or how to grow that kind of heteroepitaxial layer.

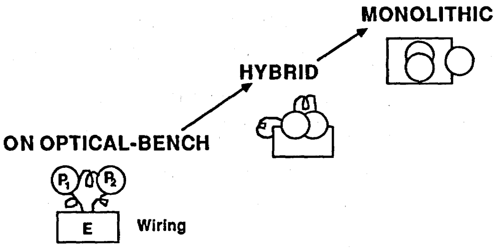
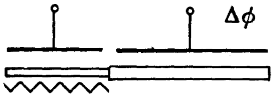
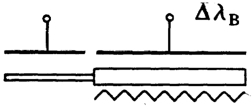
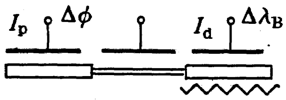
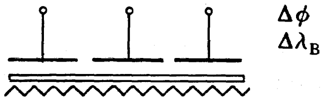


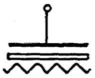
FIGURE 2. Steps towards integration

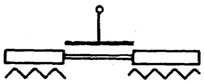
## 3. RECENT ADVANCES OF DEVICE LEVEL INTEGRATION IN LASERS

A laser diode has already integrated the functions of light generator, modulator, power amplifier and launcher. In the subgigabit-per-second range, conventional Fabry–Perot type laser diodes can be used, however, in the 1 Gb s$^{-1}$ range, a distributed feedback (DFB) laser should be used to overcome mode-partition noise. This device incorporates gratings or corrugations in the vicinity of the lasing layer. In intensity modulation schemes at higher data rates, higher performance, e.g. chirp control, will be required. Also, the coherent detection system, which draws our attention to its high potential including high sensitivity, terminal selectivity and technological matching to the conventional microwave technologies, requires laser diodes having narrow linewidth and the capability for direct-current modulation. To meet these requirements, multiterminal monolithic integrated laser diodes are proposed as shown in table 3.

TABLE 3. DEMONSTRATION OF TUNABLE LASERS

| | parameter | total tuning range | sweep range | linewidth |
|---|---|---|---|---|
| 1. phase-control<br>DFB-LD<br><br> | $\Delta\phi$ | 1.2 nm | ← | 20 MHz |
| 2. MQW DBR-LD<br><br> | $\Delta\lambda_{\mathrm{Bragg}}$ | 9.4<br>(9 hops) | — | > 5.75 |
| 3. phase-control<br>DH or MQW DBR-LD<br><br> | $\Delta\phi$<br>$\Delta\lambda_{\mathrm{Bragg}}$ | —<br>8<br>(13 hops) | 3.4 ($I_p$, $I_d$)<br>1.4 | ~ 17 (DH)<br>5–25 (MQW) |
| 4. multi-electrode<br>DFB-LD<br><br> | $\Delta\phi$<br>$\Delta\lambda_{\mathrm{Bragg}}$ | —<br>— | —<br>0.5 | —<br>~ 7 |


distributed feedback LD (DFB-LD)


distributed Bragg reflector (DBR-LD)

Recently, an InGaAs avalanche photodiode (APD) has been successfully produced in a planar structure. This is a necessary condition for its integration as well as for the improvement in its reliability.

## 4. Demonstration of photoelectronic integrated circuits

Preliminary reports on photoelectronic ICs have been presented from many laboratories, and I review the recent 'masterpieces' that have been developed in Japan.

1. GaAs based OE-IC, EO-IC and 4 × 4 OE-E-SW-EO SW by Fujitsu (1987).
2. InP based OE-IC and EO-IC with a single voltage source by Matsushita (1986).
3. InP based EO-IC made with MO-CVD by NTT (1988).
4. InP based 4 × 4 0 SW by Hitachi (1988).
5. GaAs on InP based OE-IC and EO-IC with gigabit performance by NEC (1988).

## 5. Technical issues for monolithic integration of electronic circuits and photonic devices

### 5.1. *Material technologies*

Epitaxial growth and regrowth methods are the basic technology to control compound semiconductors. The rapid advances in molecular beam epitaxy (MBE) and vapour phase epitaxy (VPE), in particular, metal–organic (MO) VPE, can produce epitaxial layers of semiconductors in the InP material family as well as in the GaAs material family. They are capable of making well-controlled thin layers at nearly atomic levels and also offer wider freedom in piling up a variety of hetero-materials. However, liquid phase epitaxy (LPE) is still reliable for the manufacture of simple and discrete photodevices. Thin-layer growth techniques are said to be almost matured, however the problems of regrowth are not fully overcome by MBE or VPE and LPE is often used to make buried-heterostructure (BH) lasers, that is under hybrid growth technology. (See figure 3.)

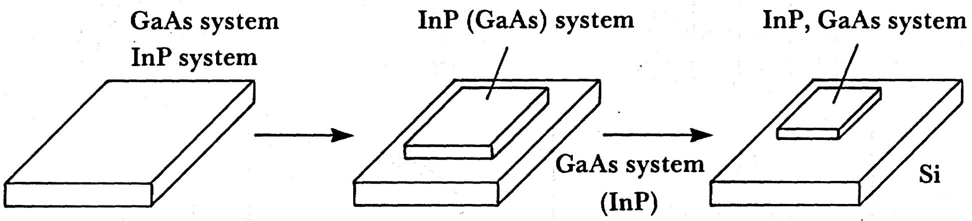


FIGURE 3. Technical issues for monolithic integration of electronic circuits and photonic devices: material technology, thin layered structures, processes, device design and CAD.

It is also claimed that good epitaxial layers for electronic devices are not necessarily good epitaxial layers for photonic devices. It is likely that the interband transition is more delicate than the intraband phenomena. (See table 4.)

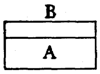
Selective-area epitaxy is expected to be a new and powerful technology for the future. Heteroepitaxy between lattice mismatched semiconductors is also a new and powerful technology for the future, and is one of the biggest topics at present. By introducing an 'interface layer', which can interface two materials at the sacrifice of its own crystal perfection,

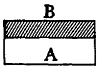
TABLE 4. MATERIAL TECHNOLOGY

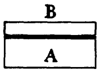
expitaxial growth and regrowth
– MBE, VPE, LPE, still powerful
– layer growth: almost matured
– regrowth: pre-matured
– selected area epitaxy: being studied
good epitaxial layer for electronic device is not necessarily good for photonic device (interband transition)

*hetero-epitaxial*

lattice matching at hetero-boundary
(AlGaAs/GaAs, InGaAsP/InP, etc.)
lattice mismatching at hetero-boundary
(GaAs/Si, GaAs/InP, InP/Si, etc.)
– very poor quality of epitaxial layer
introduction of 'interface layer' between mismatched materials
(GaAs/Si, GaAs/InP, etc.)
– two-step growth method
– superlattice layers: GaAs//GaP/GaAsP//Si
issues: stress, dislocation, bending







a GaAs layer can be formed on a Si substrate or on an InP substrate. Two-step growth methods and superlattice interface methods are already proposed; however, at present, stress, bending and dislocations are still issues and the lowest etch-pit density of an InP layer on Si records $2 \times 10^6\ \mathrm{cm}^{-2}$, the value of which should be less than $10^5\ \mathrm{cm}^{-2}$ for the practical applications.

### 5.2. *Thin layer structures*

The above-mentioned technology can create new structures composed by piling up many thin hetero-layers, for example GaAs/AlGaAs/GaAs/AlGaAs.... Quantum well structures are particularly likely to be used because of their high gain and nonlinear capabilities (figure 4). A threshold current of less than a few milliamps has been demonstrated in a laser using quantum wells.

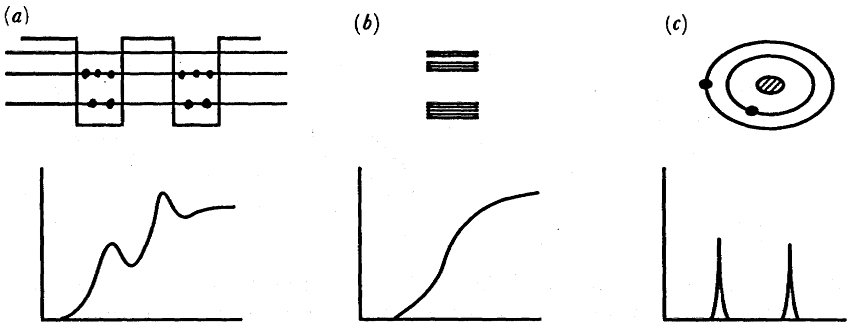


FIGURE 4. Thin layered structures (5–20 nm) in which novel properties emerge. Energy band tailoring, Si/SiGe/Ge; superlattice and quantum well, AlGaAs/GaAs, InGaAs/InP, InGaAs/InAlAs. (*a*) Quantum well, (*b*) semiconductor, (*c*) atom.

### 5.3. *Processes*

Electrons can be controlled through their mobility and by electric fields or potentials and photon can be controlled through the gain/loss and refractive index of materials. Thus the processes are basically very different. However, advances in the processes for MMICs and photonic devices will produce smarter technologies.

### 5.4. *Device design and computer aided design*

Device design is a common issue between photonic devices and GaAs or InGaAs high-speed devices, in connection with processes realizing the design concept. For example, the following issues need to be clarified for photonic devices very soon.

1. Discontinuities due to 'cleaving facets' in laser diodes.
2. The isolation problem.
3. Planar-structure, i.e. horizontal integration rather than vertical integration.
4. Low-loss waveguiding and spot-size matching at interfaces.

Computer aided design (CAD) will be considered so as to generate patterns for masks, even though the complexity of the integration is not great. (See figure 5.)

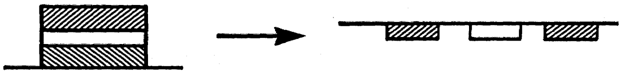


FIGURE 5. The planar structure: vertical integration going to horizontal integration.

## 6. CONCLUSIONS

I have reviewed recent advances in photoelectronic integrated circuit technologies that can provide powerful building-blocks for the next generation of lightwave communication systems. The benefits of using photoelectronic ICs are high performance and high-functionality with inexpensive and easy fabrication and easy maintenance. At present, photonic integration is behind electronic integration and is still at the device level; however, advanced lasers for coherent lightwave systems are proposed even at this level. On the other hand, microwave monolithic ICs show steady progress and they and their technologies will be very helpful in the new challenge. Current demonstrations are limited to the peripheral circuits of lasers and photodetectors, however, if photoelectronic ICs could be made available with user-friendly features, the impact would be great. The photoelectronic IC for coherent systems in subscriber networks or LAN will be the most important target in this research area.

### *Discussion*

G. GUEKOS (*ETH, Zurich, Switzerland*). The 4 × 4 optical switch mentioned by Dr Ikegami needs a rather high current to switch, about 120 mA per cell. Is it possible to reduce the current?

T. IKEGAMI. Power consumption is one of the key issues for integration on a single chip. The waveguide-structure optical switching is performed with the refractive index changed by the injection current. If a very narrow waveguide can be made, i.e. a well-controlled monomode waveguide, then the total current could be reduced by one order of magnitude, keeping the current density high.

A. J. LOWERY (*University of Nottingham, U.K.*). Dr Ikegami has talked of the need for an optical CAD system; does he think that this should include a simulation facility?

T. IKEGAMI. Exactly. How to control the waveguide structure, coupling of optical field and material, current flow, etc., could be made clear by using the simulation.