Chapter II

InGaAlAs/InGaAlAs MQW Growth by MOVPE

2.1 MOVPE Growth system

Metal Organic Vapor Phase Epitaxy (MOVPE) has become the most popular epitaxial growth technology for industrial production of III-V semiconductor devices. The configuration of an MOVPE system is schematically shown in Fig. 2.1. In the MOVPE of III-V semiconductors like InP, a carrier gas (usually H_2) brings a controlled amount of source materials into a high temperature reactor. The reactor is so designed that gas flow is not turbulent over the susceptor, on which the substrate with mirror-polished surface is placed. Usually the group III source gases are metal-organics, like Trimethyl-gallium (TMGa), Trimethyl-indium (TMIn) or Trimethyl-aluminum (TMAl). The group V sources can be Arsine (AsH_3) and Phosphine (PH_3), but due to their poisonous nature our reactor (AIXTRON 200/4), uses Tertial-butyl-arsine (TBAs) and Tertial-butyl-phosphine (TBP) under constant monitoring for H_2 leak and reduced ambient pressure. n-type dopant is introduced by Silane(SiH_4), H_2S or H_2Se, while the p-type dopant can be introduced by Di-methyl-zinc (DMZn). Table 2.1 shows the basic parameters of MOVPE sources.

At normal temperature and pressure, the metal-organic sources are liquid, and the temperature and pressure of their cylinders are well controlled. The carrier gas that is bubbled into the cylinder bring saturated vapor of chemical with it into the reactor. Due to high temperature in the reactor, the source molecules crack into smaller molecules and become highly activated. Reaction between group III and group V sources produce the solid shoot, with is deposited on top of the substrate. In reality, there are complicated processes like gas diffusion, adsorption, and evaporation. Since the group V atoms tend to easily evaporate from the surface, partial pressure of group V sources are kept much higher than the group III sources to prevent bad surface. The growth rate (GR) depends on temperature in the low temperature region, but at higher temperature growth rate is relatively temperature independent, depending more on the supply of group III sources. At even higher temperatures, GR tends to fall due to increase rate of evaporation. Usually the growth is done in the temperature independent region where GR can be well controlled by control and switching of the source gas flow by mass flow controllers.

Fig.2.1 shows a schematic of the reactor used in this research (AIXTRON AIX200/4). The reactor is a lateral chamber with a graphite susceptor. The gas flow can be switched instantaneously by a run and vent method, enabling relatively sharp interface for quantum wells. Typical growth conditions for growth of InGaAlAs/InP films are 680°C, 100mbar with total gas flow of 13slm including 7500sccm for III group and 5500 for V group. Lattice matched p+-InGaAs films for ohmic contact layers were grown at 550°C in order to raise the doping level.

Element	Source	Molecular weight	Fusing point	Boilingp oint	Vapor pressure $log_{10}P$ [Torr] T: temperature [K]	Thermostat temperature [degree]
In	Trimethylindium (TMG)	159.9	88.4	133.8	10.52 - 3014/T	17
Ga	Trimethylgallium (TMG)	114.8	-15.8	55.7	8.07 - 1703/T	0
As	Tertiarybuthylarsine (TBA)	134.1	-1	68	7.243 - 1509/T	17
P	Tertiarybuthylphosphine (TBP)	90.1	4	54	7.5857 - 1539/T	17
Zn (p-dopant)	Dimethylzinc (DMZn)	95.4	-42	46	7.802 - 1560/T	-10
S (n-dopant)	Hydrogen Sulfide (H_2S)	34.1	-82.9	-60.19	----	----

Table 2.1 Basic Parameters of MOVPE sources [1]

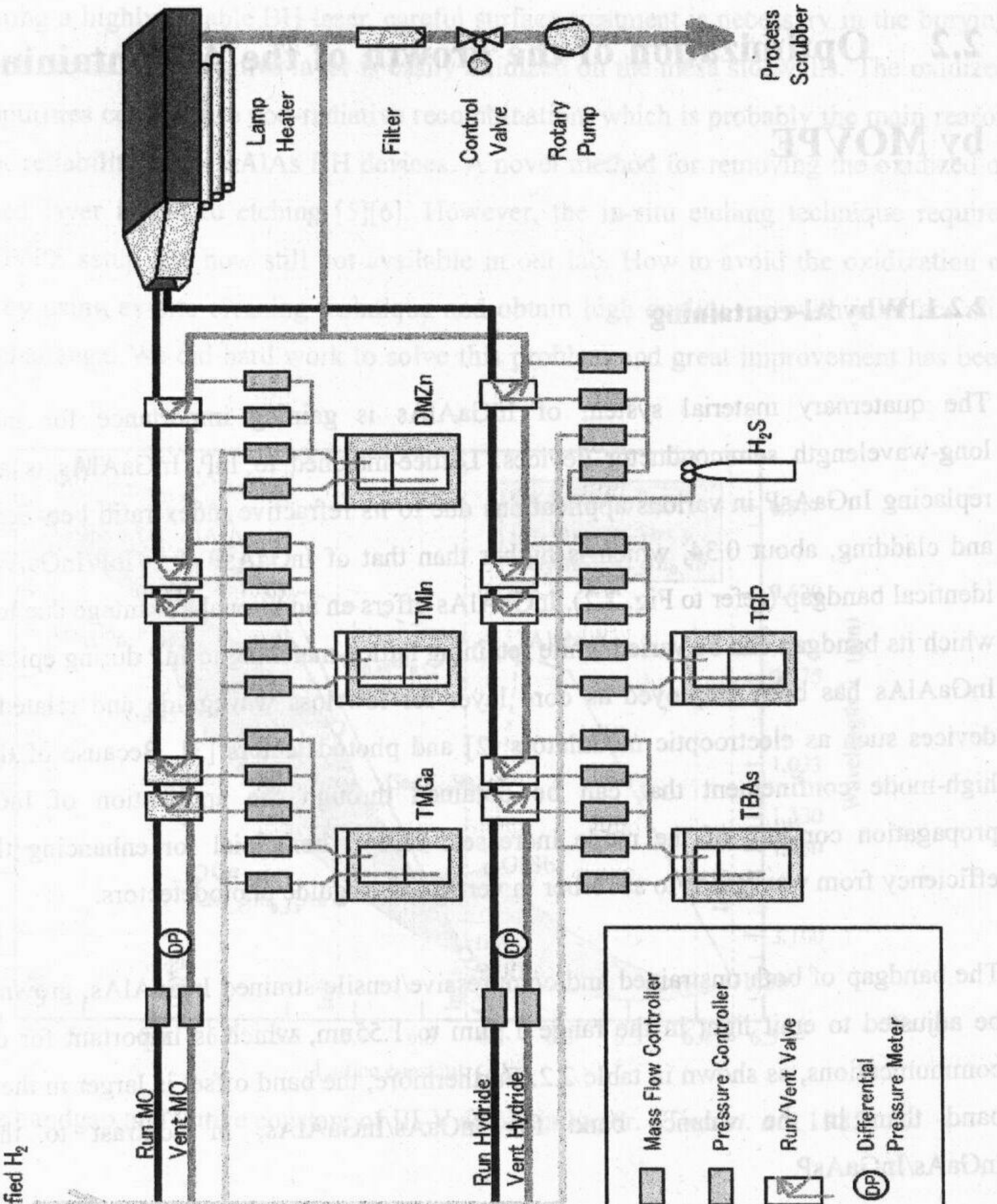

Figure 1 Schematic of MOVPE Reactor used in this research

2.2 Optimization of the growth of the Al-containing MQW by MOVPE

2.2.1. Why Al-containing

The quaternary material system of InGaAlAs is gaining importance for fabrication of long-wavelength semiconductor devices. Lattice-matched to InP, InGaAlAs is attractive for replacing InGaAsP in various applications due to its refractive index ratio between waveguide and cladding, about 0.34, which is higher than that of InGaAsP (0.27InP/InGaAsP)-InP with identical bandgap (refer to Fig. 2.2). InGaAlAs offers an additional advantage due to the ease by which its bandgap can be varied while retaining lattice-matching to InP during epitaxial growth. InGaAlAs has been employed as core layer for low-loss waveguide and related waveguide devices such as electrooptic modulators [2] and photodetectors [3]. Because of the relatively high-mode confinement that can be obtained through the application of InGaAlAs the propagation constant of the mode increases. This is beneficial for enhancing the coupling efficiency from waveguide to absorber in vertical waveguide photodetectors.

The bandgap of both unstrained and compressive/tensile-strained InGaAlAs, grown on InP can be adjusted to emit light in the range 1.3um to 1.55um, which is important for optical fiber communications, as shown in table 2.2. Furthermore, the band offset is larger in the conduction band than in the valance band for InGaAs/InGaAlAs, in contrast to the case of InGaAs/InGaAsP.

Uncooled high-speed operation with improved drivability is essential to meet the system requirements of cost efficiency and lower power consumption. These requirements can be met through a large relaxation oscillation frequency and low threshold current at high T. Laser diodes with InGaAlAs MQWs have been reported to provide larger frequency and higher T characteristics because of their large conduction band offset. These advantages of InGaAlAs MQW lasers enable uncooled high-speed operation [4]. Moreover, a buried-heterostructure (BH) InGaAlAs laser can effectively improve device performances because the injection currents are laterally confined in the active region.

For fabricating a highly reliable BH laser, careful surface treatment is necessary in the burying process since the InGaAlAs active layer is easily oxidized on the mesa sidewalls. The oxidized layer or impurities could cause non-radiative recombination, which is probably the main reason for the poor reliability of InGaAlAs BH devices. A novel method for removing the oxidized or contaminated layer is in-situ etching [5][6]. However, the in-situ etching technique requires special MOVPE setup and now still not available in our lab. How to avoid the oxidization of InGaAlAs by using ex-situ cleaning technique and obtain high quality regrowth interface still remains a challenge. We did hard work to solve this problem and great improvement has been achieved.

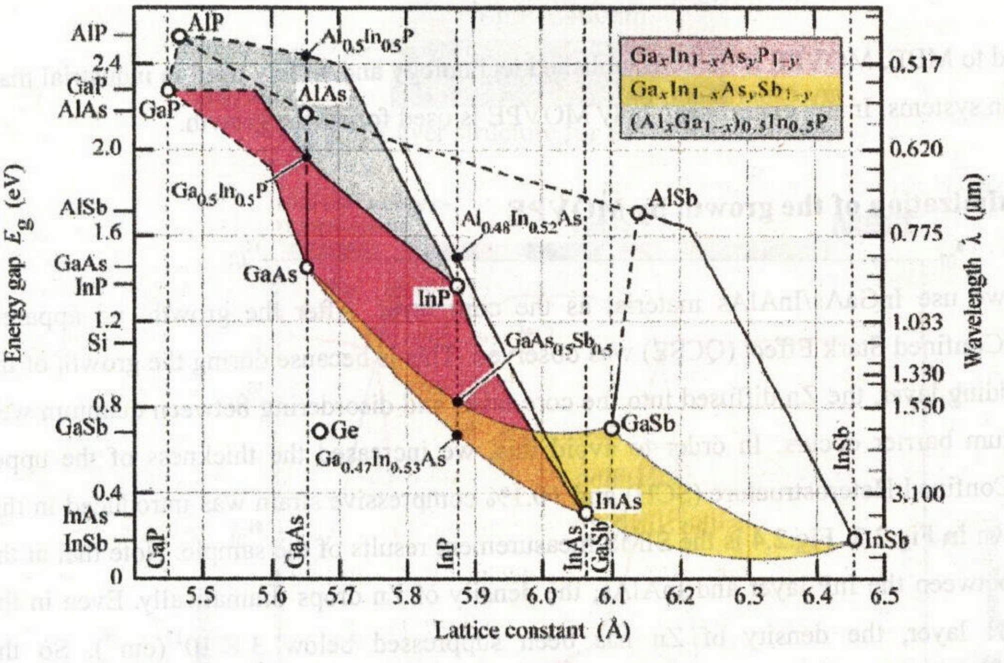

Fig.2.2 The bandgap and lattice constant of III-V semiconductor. (Tien *et. al.*, 1985)

System	Bandgap energy, E_g [eV]	Comments
$In_{0.53}Al_{0.47}As$	1.46	
$In_{0.53}Ga_{0.47}As$	0.86	Possible system for 1.5 μm telecom fibers
$In_xAl_{1-x}As_yP_{1-y}$	—	—
$In_xGa_{1-x}As_yP_{1-y}$	0.74–1.35	Extensively used, 1–1.5 μm
$In_{0.47}(Al_xGa_{1-x})_{0.53}As$		wavelengths of 0.8–1.5 μm

Table 2.2 Ternary and quaternary alloys matched to InP.

2.2.2 MOVPE versus MBE

Previously, we used MBE for the growth of InAlAs/InGaAs material system. Due to the beam-like nature of material transport from injector to substrate at low-pressure (10^{-7} torr) and low temperature (530 ^{0}C), fast switching between precursors is enabled. This allows for the epitaxial growth of very thin layers with automatically sharp interfaces. Furthermore, MBE-growth layers are in general uniform, since growth uniformity is not affected by complex gas flow patterns across the substrate. In principle, the thickness of the growth layer can be controlled with monolayer accuracy. The low growth pressure in MBE also enables in-situ growth monitoring, using for example Reflective High Energy Electron Diffraction (RHEED).

Compared to MBE, MOVPE is better-established technology and widely used in industrial mass production systems. In my experiment, only MOVPE is used for all the growth.

2.2.3 Optimization of the growth by MOVPE

At first, we use InGaAs/InAlAs material as the core layer. After the growth, no apparent Quantum Confined Stark Effect (QCSE) was observed. This is because during the growth of the p-InP cladding layer, the Zn diffused into the core layer and disordering between quantum well and quantum barrier occurs. In order to avoid this, we increased the thickness of the upper Separate Confined Heterostructure (SCH) and +0.1% compressive strain was introduced in this layer, shown in Fig.2.3. Fig.2.4 is the SIMS measurement results of the sample. Note that at the interface between the InP layer and InAlAs, the density of Zn drops dramatically. Even in the upper SCH layer, the density of Zn has been suppressed below $3 \times 10^{15}(cm^{-3})$. So the compressive strain can effectively avoid the diffusion of the Zn and thickness of the upper SCH layer can be much smaller. In the next growth, both the upper SCH and lower SCH are 100nm.

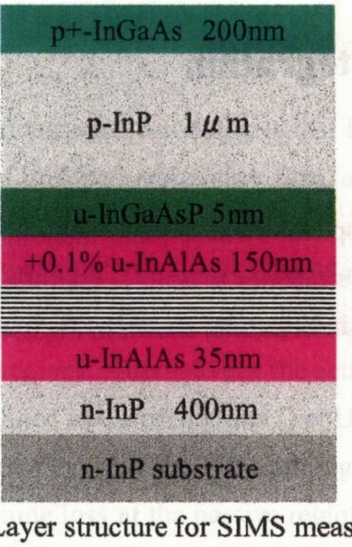

Fig 2.3. Layer structure for SIMS measurement

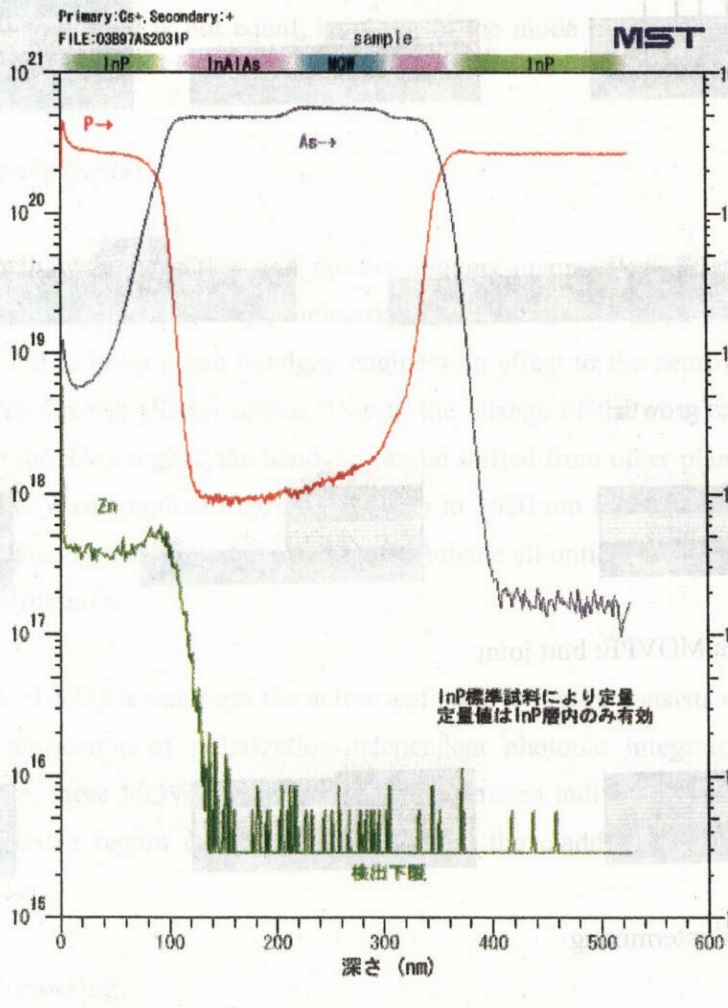

Fig 2.4. Result of SIMS measurement for the device shown in Fig.2.3

2.3 Monolithic integration

In order to fabricate the all optical switch, some monolithic integration technology must be applied. Till now, a number of strategies to achieve the integration of active devices and passive waveguide have been reported in literature, shown in Fig.2.4, and one of these is selected for the work carried out in this thesis.

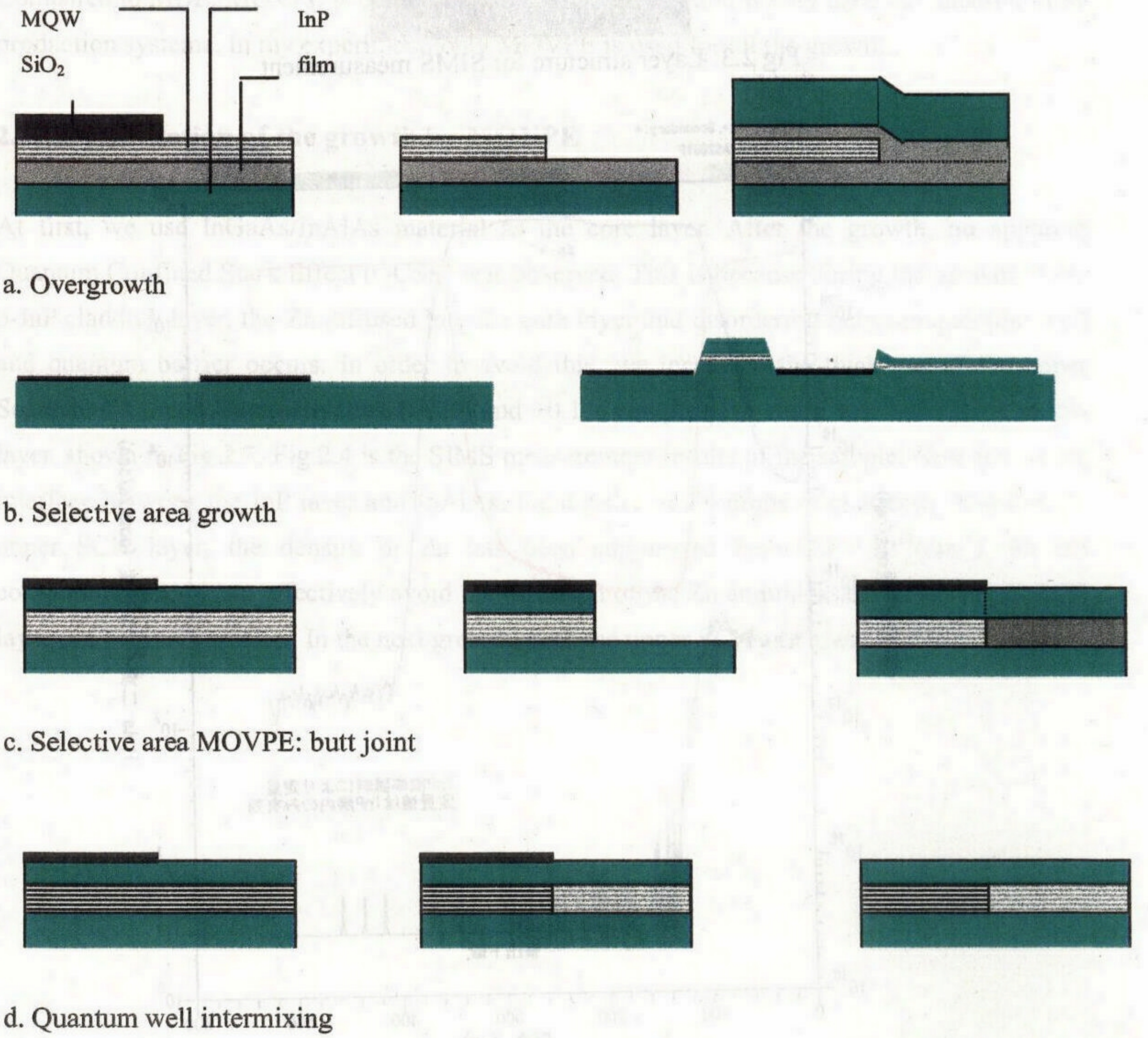

Fig.2.4. Strategies to achieve the definition of active and passive regions on a single chip.

Overgrowth:

Overgrowth is the simplest of the integration technologies that involve a regrowth step. First, an n-InP buffer, the lower part of an undoped quaternary film, and an undoped active layer are grown on this substrate. The active layer is then locally removed using lithography and etching, after which the etching mask is removed. The upper part of the film, a p-InP cladding and a highly p-doped InGaAs contact layer are subsequently grown, and active and passive devices are fabricated in their appropriate regions. Alternatively, the active layer may be on top or below the film. This technique is well applied in Coldren group [] at UCSB.
The main disadvantage of overgrowth is that the InP cladding is grown over the entire wafer. This will cause substantial waveguide loss at the passive regions. Another drawback is that the active and passive regions share the same films, which limits the design flexibility. Moreover, the thickness of the core layer is not equal, resulting in the mode mismatching and coupling loss.

Selective Area Growth (SAG)

SAG can also growth both the active and passive regions in one step. First, an mask was patterned on the substrate. The role of the dielectric mask pattern is to mask epitaxy growth of the region beneath and to bring about bandgap engineering effect to the nearby growth region called Selective Area Growth (SAG) region. Due to the change of the alloy composition and epitaxy thickness in the SAG region, the bandgap can be shifted from other planar region. After removal of the mask. Wavelength shift from 1400 nm to 1620 nm has been demonstrated for 40nm SiO2 mask gap[song thesis], and is applied to fabricate all optical switches by integrating the SOA and MMI structures.

The main drawback of SAG is that both the active and passive region consists of MQW layers, which makes the fabrication of polarization-independent photonic integrated circuits very difficult. Furthermore, these MQW layers can not be optimized individually and will result in large loss in the passive region due to the p-doping in the cladding layer, as well as the overgrowth technology.

Quantum Well Intermixing

In Quantum well intermixing, the active and passive regions are defined by altering the profile of the quantum well in the passive region. The atomic interdiffusion between the barrier and well in the passive region results in a blue shift of the MQW absorption edge. This interdiffusion can be realized by sputter annealing [7] or ion implantation [8].

The active region and passive region share the same core layer stacks, so the modal matches quite well in these two regions. The main disadvantage of QWI is that it is only applicable to MQW structures. The wavelength shift is limited and the waveguide losses are high.

Butt-joint

Butt-joint technology offers the most flexible method to optimize different regions individually because every region is grown in one step. In the first growth step, the active layer stack with optional separate confinement layers is grown, then removed at the passive regions. After that, mask like SiN or SiO2 remains in the active region. Then the core layer with another material will be grown as the passive core layer whose modal field matches well with that of the active core layer. The growth of the cladding layer depends on the design and cost concerns. The cladding layers can be grown together with its beneath layer or grown after all of the core layers of active and passive regions are formed in one additional growth.

Table 2.3 shows the comparison of different active-passive integration schemes mentioned above. In this work, due to the inherent large insertion loss of the EAM, the total loss of the integrated device is the main concern. Among the other integration methods above, butt-joint technology offers the most flexible way to reduce the loss in the passive waveguide, so will be used in this work.

Method	Total Size	Performance	Fabrication Cost	Merits/Demerits
Hybrid Integration	Large	Good	High	+ Individual optimization + Easy design - Alignment problem - Large scale integration difficult
Etching and regrowth	Small	Normal	Normal	+ Individual optimization - Large scattering loss at junction - Complicated fabrication process - Large scale integration difficult
Quantum well intermixing	Small	Normal	Low	+ Device layout easy + Easy alignment - Difficult to achieve more than 3type of materials
Selective area MOVPE	Small	Normal	Low	+ Design of different material easy + Easy alignment + Suitable for large scale integration - Need to find optimum condition

Table 2.3 Comparison of different active-passive integration schemes

2.4 Butt-joint technology experiment

Conventionally, the InGaAsP is used for butt joint. And the butt-joint regrowth of InGaAlAs remains a challenge. The difficulty arises from the formation of stable Al-Oxides due to the often inevitable air-exposure of the InGaAlAs core layer during device processing. This may be the cause why little has been published about buried InGaAlAs waveguide structures thus far. In order to avoid the exposure during the process, in-situ cleaning has been well investigated,. In situ cleaning effectively removes the oxides and the related contaminations at the mesa sidewall of InGaAlAs MQW and improves the quality of the hetero-interface between InGaAlAs and the InP buried layer [9] or InGaAsP core layer [10]. Selective area growth is another option, which has initially investigated by the Central Research Laboratory of Hitachi [11] .