# CHAPTER IV
# EXPERIMENTAL RESULT AND DISCUSSION

## 4.1 General

This chapter is composed of all the experimental results and discussions of research data. The samples are grown by Liquid Phase Epitaxy (LPE) and Molecular Beam Epitaxy (MBE). There are three kinds of AlGaAs/GaAs heterostructure solar cells. The first one is of Schottky barrier diode, the second one is of fixed Al content window layer and the third one has Al content of 0.3, 0.2, and 0.1 window layer. All of them were separately analyzed for spectral response, photoluminescence, and I-V curve measurements. Some of them are calculated for their fill factors and efficiencies. Basically, the analysis is divided into two categories in this study. First group of samples are grown by MBE and the second group of samples are grown by LPE. These two growth techniques are compared in terms of their solar cell structures and performances.

## 4.2 Heterostructure Solar cells realization

There are six samples fabricated by MBE and two samples by LPE. Their solar cell structures are shown in **figure 4.1~4.6**. The samples **A, B, C, D, E** and **F** are fabricated by MBE, and samples **G** and **H** are fabricated by LPE.

### 4.2.1 MBE samples

The sample **A** is Schottky type solar cell grown by MBE. This sample is used as a reference for spectral response and photoluminescence measurements. The spectral response gives basic information about the photon absorption in semiconductor materials used in the heterostructure.

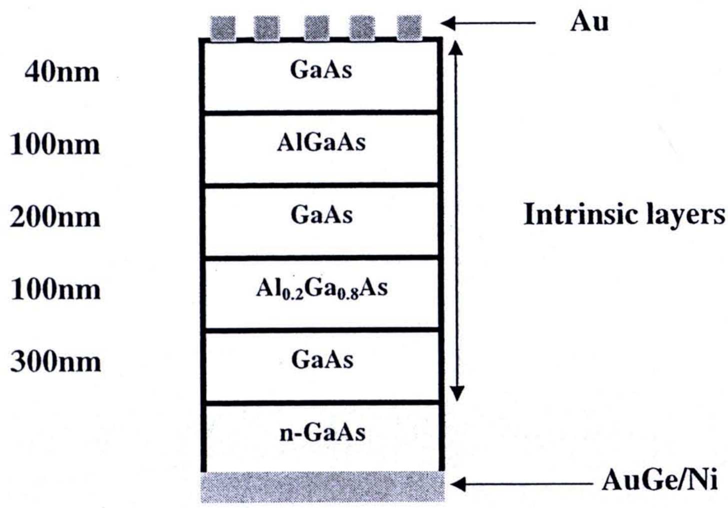



**Figure 4.1** Schematic diagrams of Schottky heterostructure solar cells (sample A).

The n-GaAs substrate is used as the starting material for solid-source MBE growth of different crystalline layers in Schottky heterostructure solar cells. After desorbing native oxide at 580°C, the temperature is increased up to 610°C for 15 minutes. The substrate temperature is then set back to 580°C. The epitaxial growth of 300nm-thick undoped GaAs buffer layer is conducted at 580°C with a growth rate 0.6 monolayer per second (ML/s). During the growth, the beam equivalent pressure of $As_4$ was $1x10^{-5}$mbar. The in-situ observation is done by employing the reflection high-energy electron diffraction (RHEED), which has been widely used for the study of the MBE kinetics and can be used to observe the crystal quality during the MBE growth. Then at the same temperature, a 100nm undoped $Al_{0.2}Ga_{0.8}As$, a 200nm undoped GaAs, 100nm undoped AlGaAs and 40nm undoped GaAs are grown respectively. The whole growth process is conducted at growth rate of 0.6 monolayer per second. The sample is taken out from MBE chamber for further metal evaporation. Au was evaporated to form Schottky metallic contact on the front side of solar cells by a finger-shape pattern metallic mask in the vacuum evaporation machine. On the other side of the sample, AuGe/Ni was deposited on over the whole back surface. To form the Ohmic contact, the sample is annealed in $N_2$ flowing gas at 375°C. Finally the sample is tested for its spectral response and PL.

In sample **B**, p-GaAs substrate is used as the starting material for solid-source MBE growth of different crystalline layers of heterojunction solar cell with fixed Al content of 0.3. After de-oxidation at 580°C, the temperature is increased up to 610°C for 15 minutes, and then the temperature is set back to 580°C for the whole growth process. The epitaxial growth starts with 500nm-thick undoped GaAs buffer layer. Then a 50nm n-GaAs with doping concentration of $1x10^{18}cm^{-3}$ and a 60nm of $Al_{0.3}Ga_{0.7}As$ layer are grown. Finally, $n^+$-GaAs with thickness of 50nm and doping concentration of $5x10^{18}cm^{-3}$ are grown. All process is controlled at the same growth rate of 0.7 monolayer per second (ML/s). After the MBE growth, AuGe/Ni is evaporated to form double metallic layers on the front side of the sample through a finger-shape pattern metallic mask in the vacuum evaporation machine. The sample was then annealed in $N_2$ ambient at 500°C about 2 minutes to obtain the Ohmic contact. Then on the back surface of sample, AuZn is deposited. To achieve the Ohmic contact, the sample is annealed again in $N_2$ flowing gas at 500°C about 2 minutes.

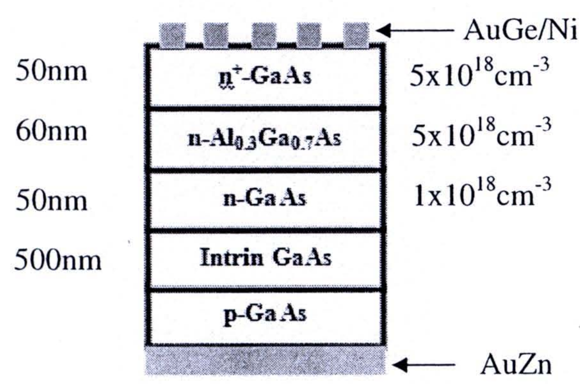



**Figure 4.2** Schematic diagram of heterojunction solar cells with fixed Al content of 0.3 (sample **B**).

The preparation of sample **C** is similar to sample **B**. The only change is to replace fixed Al content layer with stepped Al mole fractions in each of AlGaAs layers. The Al content in each layer is set up at 0.1, 0.2 and 0.3 respectively to increase the band gap of window layer.

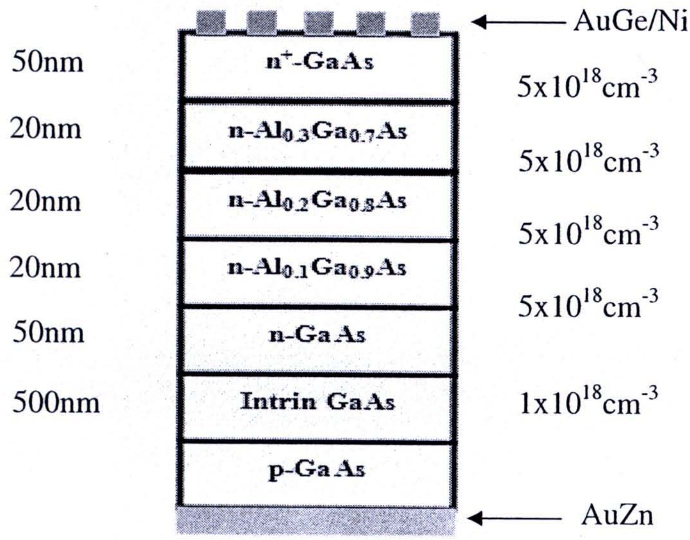



**Figure 4.3** Schematic diagram of heterojunction solar cell having $Al_xGa_{1-x}As$ window with stepped Al mole fractions (sample **C**).

The sample **D** has, carrier concentration and layer thickness of $n^+$-GaAs, $Al_{0.1}Ga_{0.9}As$, $Al_{0.2}Ga_{0.8}As$ and $Al_{0.3}Ga_{0.7}As$ the same as those of sample **C**, but the undoped GaAs buffer layer is 200nm thick.

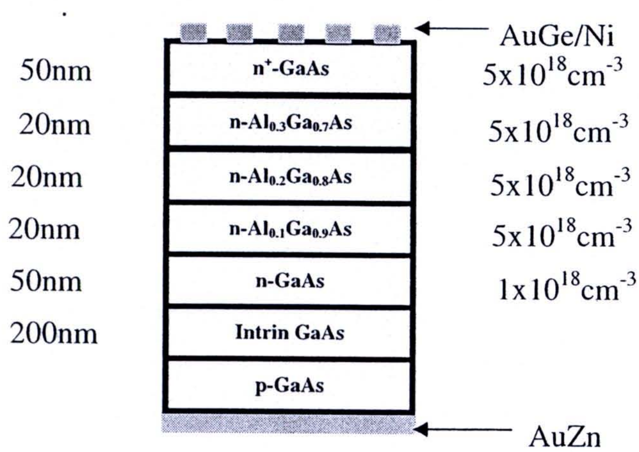



**Figure 4.4** Schematic diagram of heterojunction solar cell, the $Al_xGa_{1-x}As$ window with a stepped Al mole fraction having thin 200nm GaAs buffer layer (sample **D**).

The structure of sample **E** is exactly the same as sample **D,** but the carrier concentrations of n-GaAs, $Al_{0.1}Ga_{0.9}As$, $Al_{0.2}Ga_{0.8}As$ and $Al_{0.3}Ga_{0.7}As$ are $1x10^{18}m^{-3}$ as shown in **figure 4.5**.

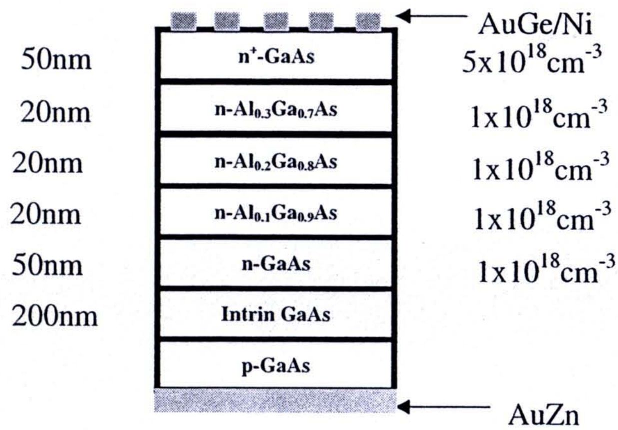



**Figure 4.5** Schematic diagram of heterojunction solar cell, the $Al_xGa_{1-x}As$ window with a stepped Al mole fraction (sample **E**).

The last MBE sample **F** has intrinsic layer GaAs and n-GaAs similar to sample **E,** but one more window layer of n-$Al_{0.37}Ga_{0.63}As$ is added to the structure as shown in the **figure 4.6**.

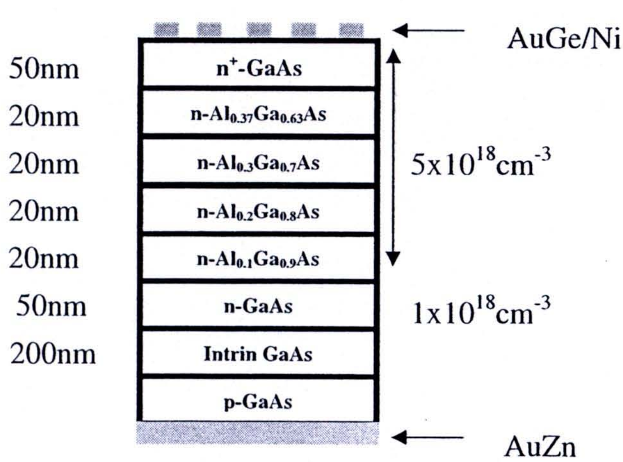
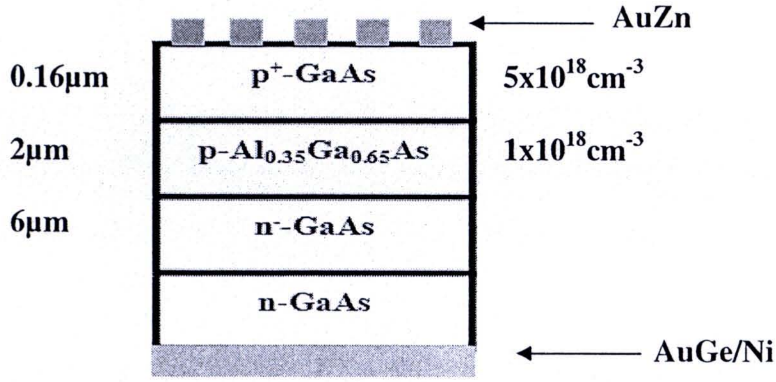


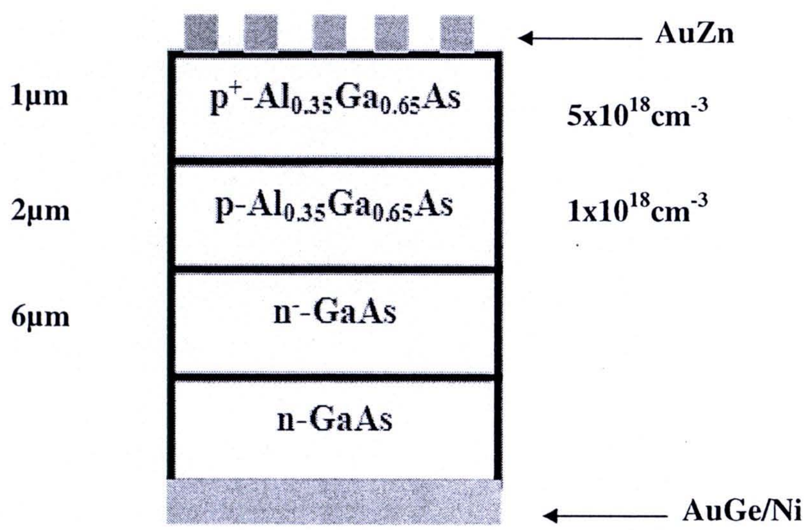

**Figure 4.6** Schematic diagram of heterojunction solar cell, the $Al_xGa_{1-x}As$ window with a stepped Al mole fraction (sample **F**).

### 4.2.2 LPE samples

Two heterostructure solar cells are also fabricated by liquid phase epitaxy (LPE) technique. These LPE samples are compared to pervious MBE samples. It is noticeable that n-GaAs substrate is used as starting material in this LPE technique. The structures of these two LPE samples are shown in **figure 4.7 (a)** and **(b)** respectively.




**(a)**




**(b)**

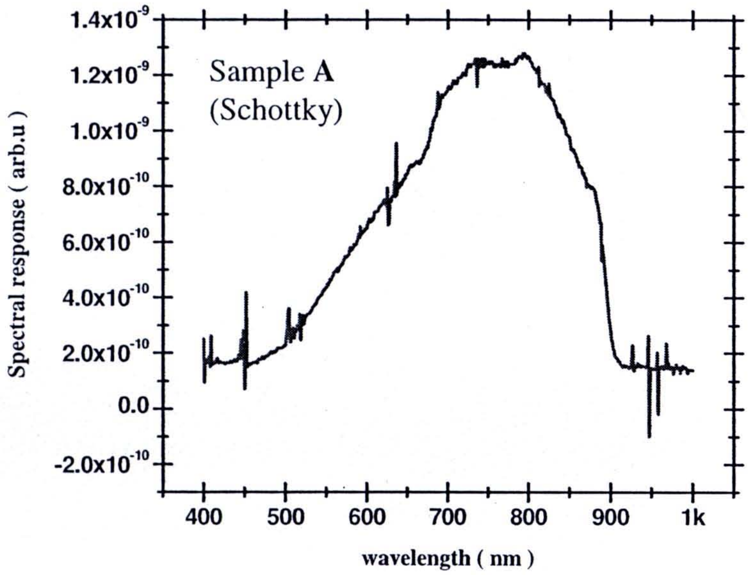
**Figure 4.7 (a), (b)** Schematic diagram of the heterostructure solar cells, (sample **G** and **H**) grown by LPE technique.

After preparing the materials on the **table 3.1,** graphite boat containing difference materials in multiple slots is loaded into the quartz tube. The boat initially remains outside the heating coil of LPE furnace. First, it is flushed with flowing $N_2$ in order to evaluate and to check for leaks (approximately 1 hour). Then it is safe to flow with Pd-purified $H_2$. $H_2$ atmosphere prevents oxidation of the solution and the substrate. The heating furnace is then slided to the position of the graphite boat. In the first processing step, the temperature is kept constant at 800°C for 4 hours in order to saturate material solutions and then the temperature is increased to 804°C for in-situ etching. When the temperature reaches the peak of 804°C, LPE process starts. For the sample **G,** 6μm thick n-GaAs layer is grown by moving the substrate under the solution consisting of Ga 3g, GaAs 140mg for 6 minutes. Then $Al_{0.35}Ga_{0.65}As$ (p) 2μm thick is grown by moving the substrate under the solution consist of Ga 3g, GaAs 62.1mg, Al 2.89mg and Ge 12.4mg for 2 minutes. Finally, the substrate is moved to the solution consisting of Ga 3g, GaAs 142.2mg and Ge 64.9mg for another 10 second to grow 0.16μm GaAs ($p^+$) thick. When the sample is moved from solution, the LPE growth is finished. The growth process of sample **H** is the same as that of sample **G**, but GaAs ($p^+$) layer is replaced by $Al_{0.35}Ga_{0.65}As$ ($p^+$) as shown in the **figure 4.7 (b)**. LPE samples are metalized with AuZn on the front side through finger-shape pattern metallic mask in the vacuum. The samples are annealed in $N_2$ ambient at 500°C to obtain the Ohmic contact. On the rear side of the samples, AuGe and Ni are deposited on the whole surface for Ohmic contact. The samples are annealed again in $N_2$ flowing gas at 500°C. The LPE samples are ready for testing such as their spectral responses and I-V curves.

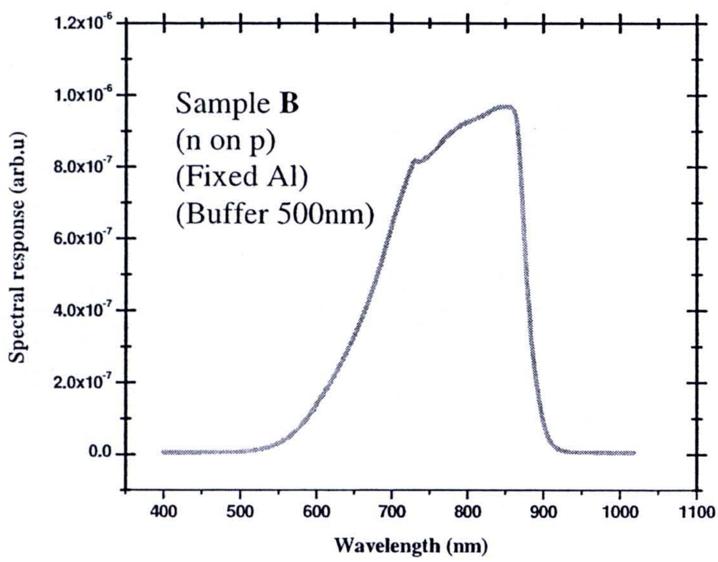
## 4.3 Results and discussion

The photoluminescence (PL), the spectral responses and I-V curves characteristics of the samples grown by MBE and LPE are investigated and compared. The experiment results are as follows.

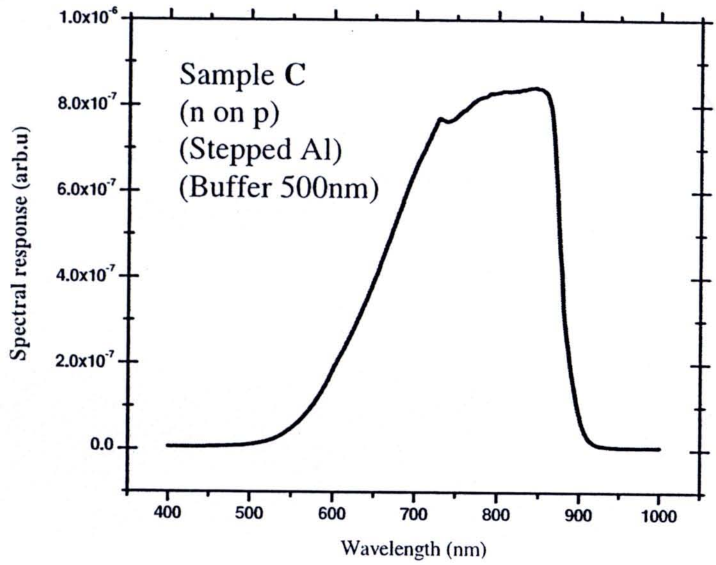
- **Spectral responses**


Sample A
(Schottky)
1.4x10^-9
1.2x10^-9
1.0x10^-9
8.0x10^-10
6.0x10^-10
4.0x10^-10
2.0x10^-10
0.0
-2.0x10^-10
Spectral response ( arb.u )
400
500
600
700
800
900
1k
wavelength ( nm )

**(a)**


Sample B
(n on p)
(Fixed Al)
(Buffer 500nm)
1.2x10^-6
1.0x10^-6
8.0x10^-7
6.0x10^-7
4.0x10^-7
2.0x10^-7
0.0
Spectral response (arb.u)
400
500
600
700
800
900
1000
1100
Wavelength (nm)

**(b)**




(c)



**Figure 4.8 (a), (b)** and **(c)** Spectral responses of samples **A, B** and **C**

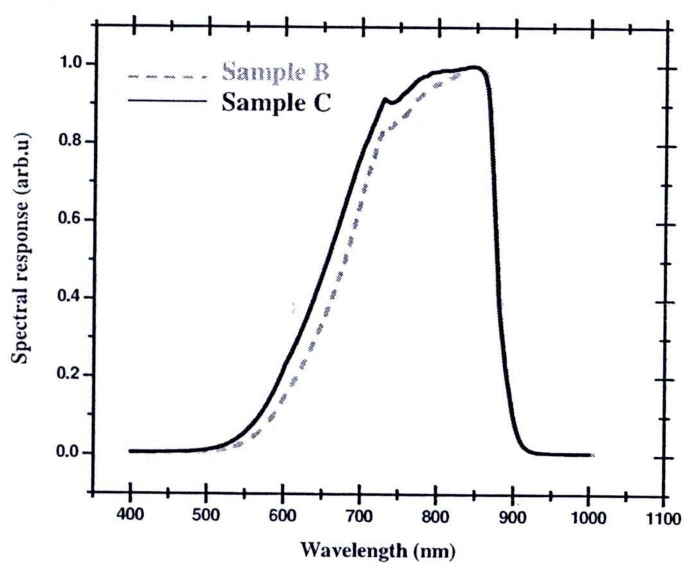
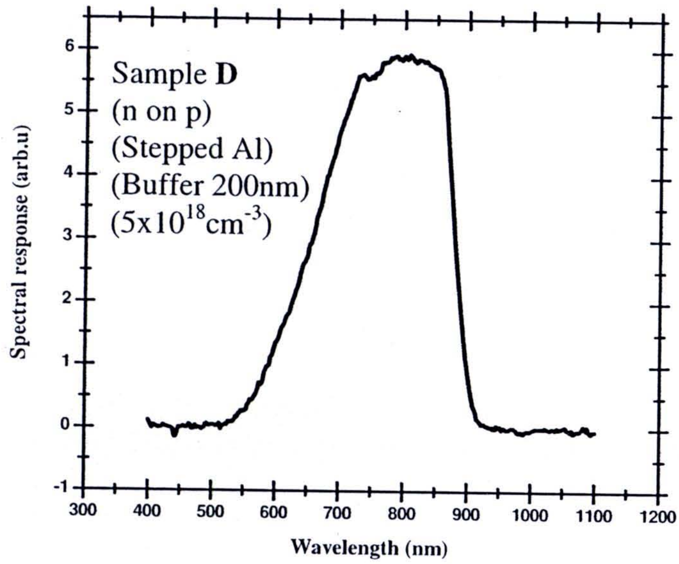
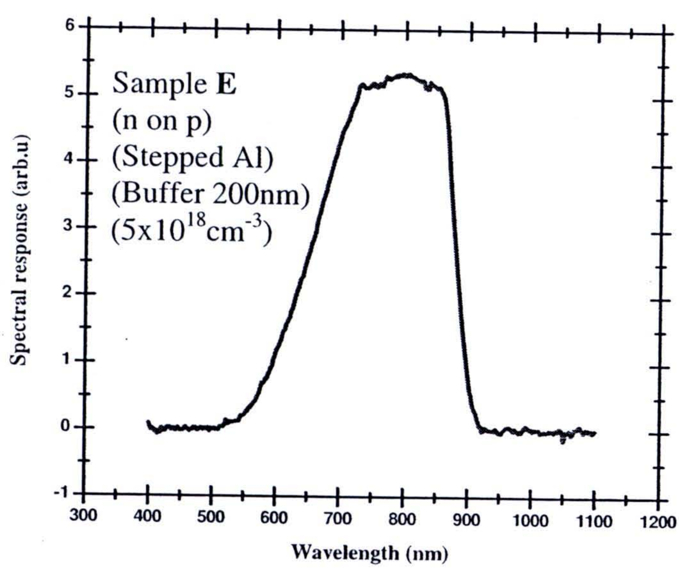


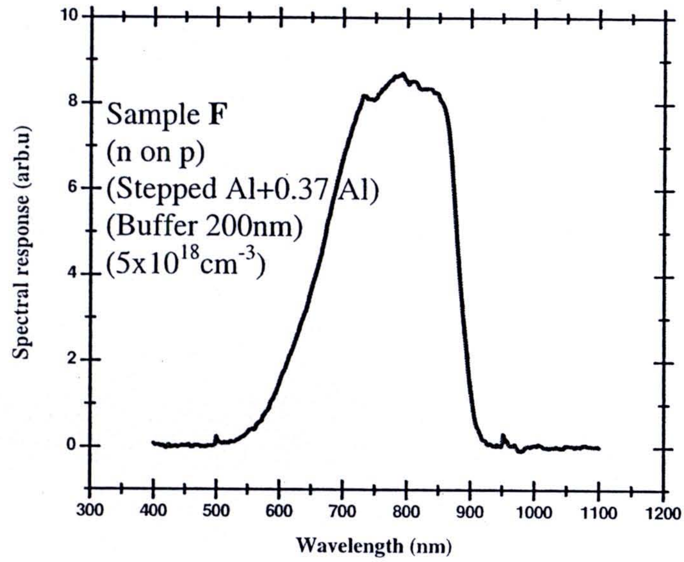

**Figure 4.9** Normalized spectral responses of samples **B** and **C**


Sample **D**
(n on p)
(Stepped Al)
(Buffer 200nm)
(5x10^18cm^-3)
Spectral response (arb.u)
Wavelength (nm)
-1
0
1
2
3
4
5
6
300
400
500
600
700
800
900
1000
1100
1200

**(a)**


Sample **E**
(n on p)
(Stepped Al)
(Buffer 200nm)
(5x10^18cm^-3)
Spectral response (arb.u)
Wavelength (nm)
-1
0
1
2
3
4
5
6
300
400
500
600
700
800
900
1000
1100
1200

**(b)**




(c)

**Figure 4.10 (a), (b)** and **(c)** Spectral responses of samples **D, E** and **F**

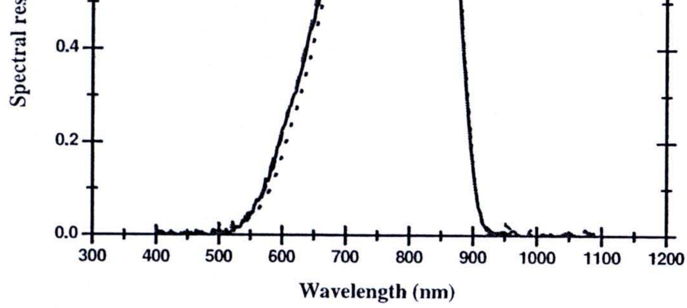



**Figure 4.11** Normalized spectral responses of samples **D, E** and **F**

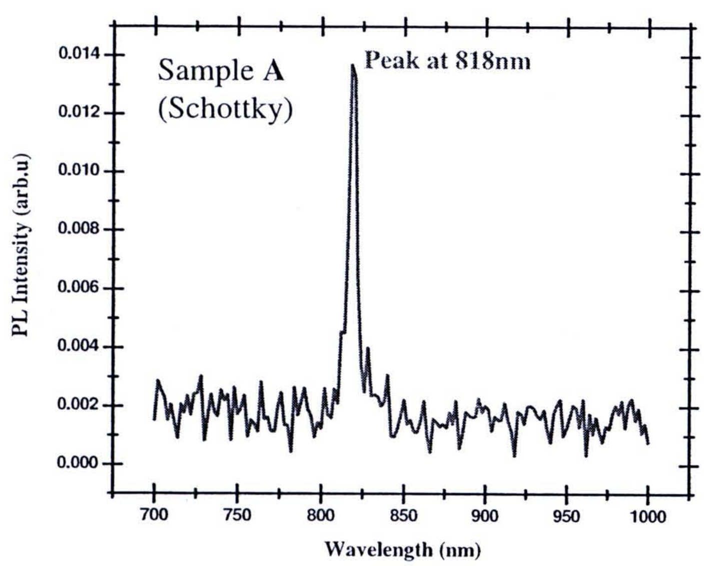
The spectral responses of AlGaAs/GaAs heterostructure solar cells, sample **A**, **B** and **C**, are measured. The board spectrum of photocurrent ranging from 700 to 900 nm could be explained by the window effect of AlGaAs having a wide direct band gap especially at the short wavelength region. The spectral responses of samples **B**, **C** are also measured for comparison as shown in the **Figure 4.9**. It is found that the spectral response of sample **C** is better than those of samples **B.**

The spectral responses of the sample **D, E** and **F** are similar to each other as shown in the **Figure 4.11**

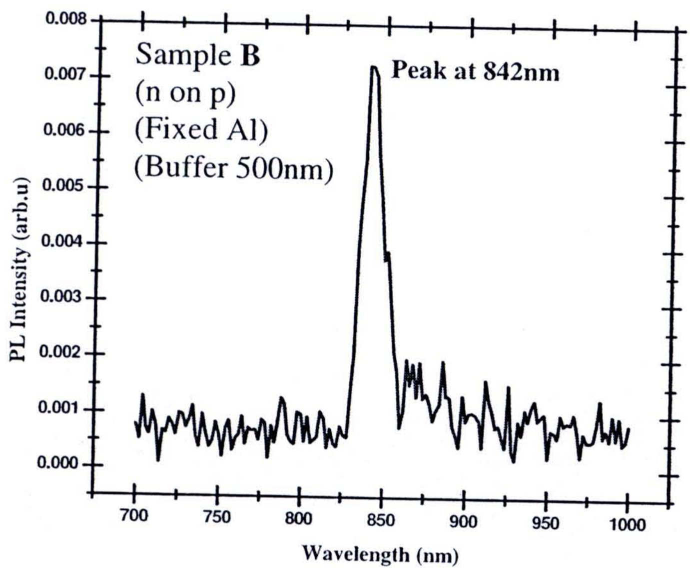
In general, wide band gap AlGaAs layers are preferable in the solar cell structure.

- **Photoluminescence (PL)**

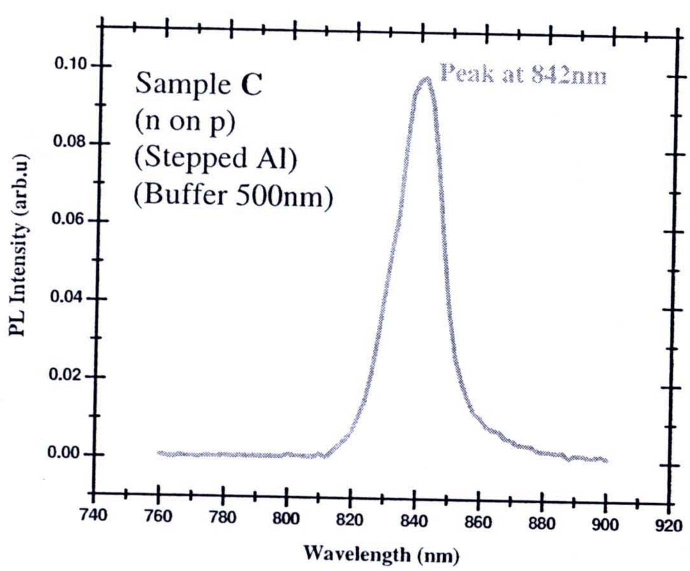
The photoluminescence measurement of samples **A, B** and **C** were conducted at temperature 20°K by using $Ar^+$ laser with excitation power of 20mW. Sharp PL peaks of sample **A, B** and **C** are at 812, 842 and 842nm respectively. These PL peaks are evident that epitaxial layers have good crystalline quality for device fabrication.




(a)




(b)

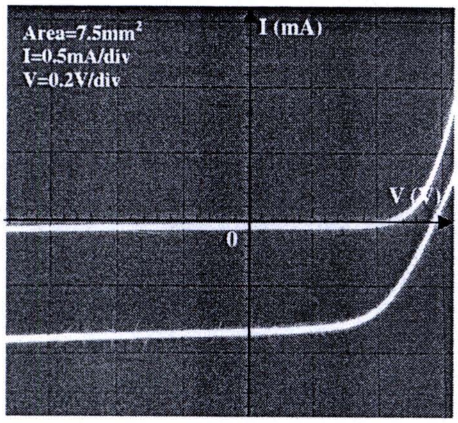



(c)

**Figure 4.12 (a), (b)** and **(c)** Photoluminescence of samples **A, B** and **C,** respectively

- **The I-V curve characteristics**

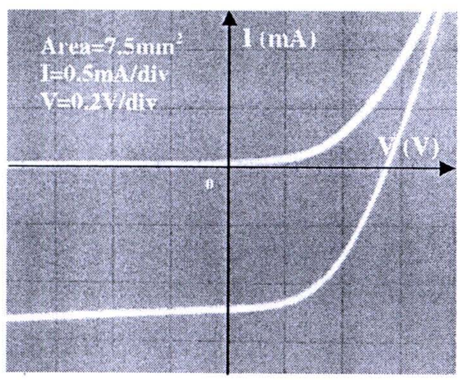
All MBE samples having AlGaAs/GaAs heterostructures are tested for their respective I-V curves both under dark and illuminated condition of one sun ($100 mW/cm^2$ and AM1). The I-V curves are displayed in the following figures.




Sample **B**
(n on p)
(Fixed Al)
(Buffer 500nm)

$I_{SC}$=0.85mA
$V_{OC}$=0.59V
$I_{max}$=0.7mA
$V_{max}$=0.42V

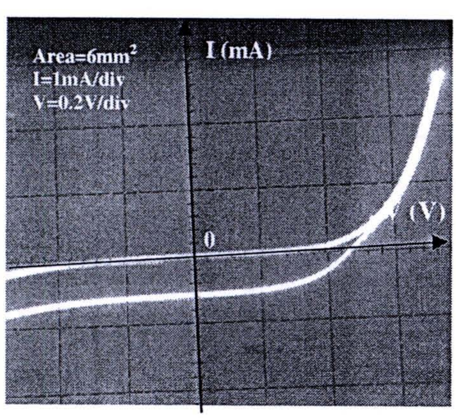
**(a)**




Sample **C**
(n on p)
(Stepped Al)
(Buffer 500nm)

$I_{SC}$=1.25mA
$V_{OC}$=0.58V
$I_{max}$=0.7mA
$V_{max}$=0.4V

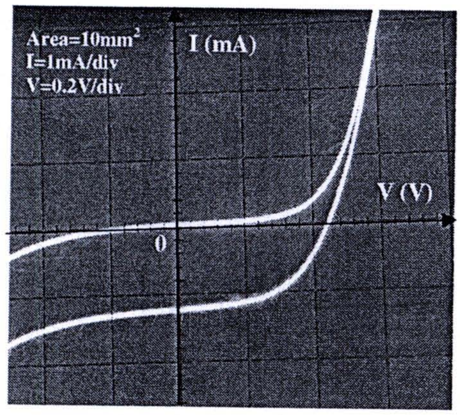
**(b)**




Sample **D**
(n on p)
(Stepped Al)
(Buffer 200nm)
($5x10^{18}cm^{-3}$)

$I_{SC}$=0.6mA
$V_{OC}$=0.5V
$I_{max}$=0.4mA
$V_{max}$=0.38V

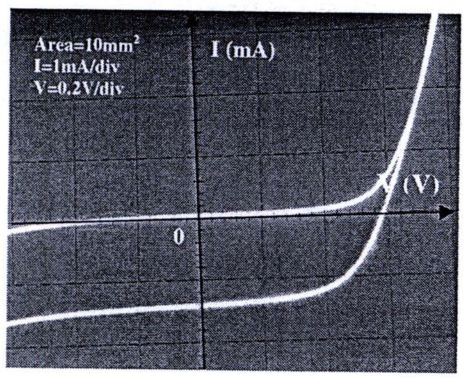
**(c)**




Sample **E**
(n on p)
(Stepped Al)
(Buffer 200nm)
($5x10^{18}cm^{-3}$)

$I_{SC}$=1.3mA
$V_{OC}$=0.43V
$I_{max}$=0.9mA
$V_{max}$=0.38V

**(d)**




Sample **F**
(n on p)
(Stepped Al+0.37 Al)
(Buffer 200nm)
($5x10^{18}cm^{-3}$)

$I_{SC}$=1.5mA
$V_{OC}$=0.6V
$I_{max}$=1mA
$V_{max}$=0.5V

**(e)**

**Figure 4.13 (a), (b), (c), (d)** and **(e)** I-V curves in dark and one sun of AlGaAs/GaAs heterostructure solar cells, samples **B**, **C, D, E** and **F** respectively.

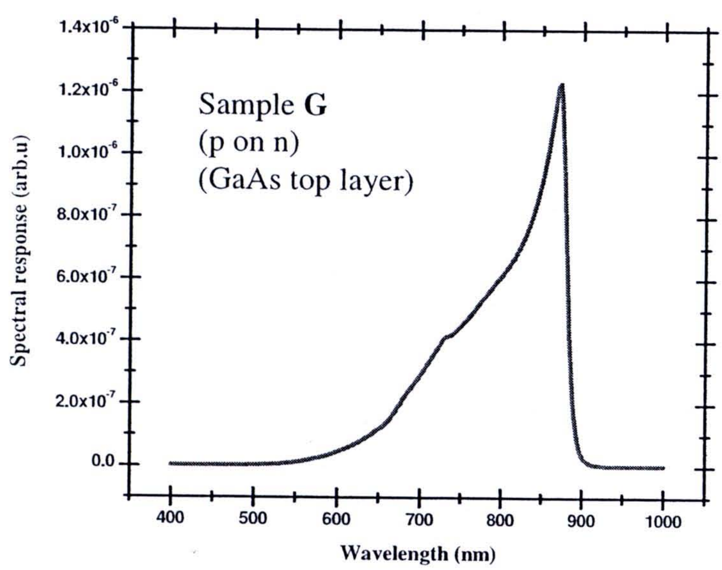
From these I-V curves, all solar cell parameters are summarized in **table 4.1.** It is found that most of MBE samples give rather low open circuit voltages not greater than 0.6V. The breakdown voltage is quite low as observed in the third quadrant of I-V curves. This implies that junction quality is not good. There are some leakage current in the junction. The best efficiency from this group of MBE samples is only 5%. This solar performance could be improved by high doping of $p^+$ at the back surface of p-GaAs substrate.

**Table 4.1** Solar cell parameters of samples **B, C, D, E** and **F**

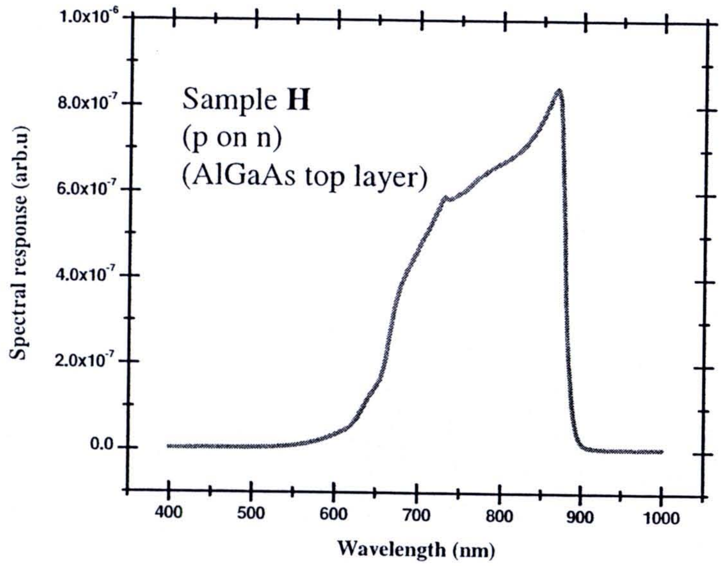
| Sample | Area($mm^2$) | $I_{Sc}$(mA) | $V_{Oc}$(V) | $I_{max}$(mA) | $V_{max}$(V) | FF | η (%) |
|---|---|---|---|---|---|---|---|
| B | 7.5 | 0.85 | 0.59 | 0.7 | 0.42 | 0.58 | 3.86 |
| C | 5.5 | 1.25 | 0.58 | 0.7 | 0.4 | 0.38 | 5 |
| D | 6 | 0.6 | 0.5 | 0.4 | 0.38 | 0.47 | 2.3 |
| E | 10 | 1.3 | 0.43 | 0.9 | 0.38 | 0.61 | 3.4 |
| F | 10 | 1.5 | 0.6 | 1 | 0.5 | 0.55 | 4.9 |

- **Spectral responses**

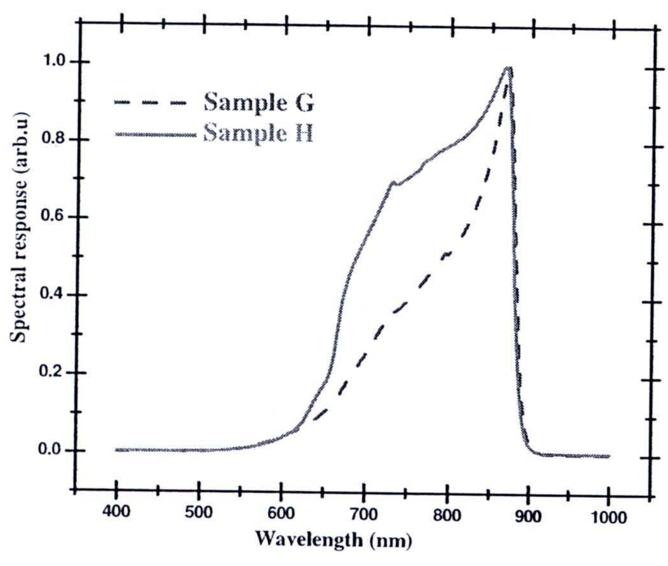
The spectral responses of both samples **G** and **H** are also measured and exhibit a strong absorption edge by n-GaAs substrate 900nm as shown in **figure 4.14.**




**(a)**




(b)

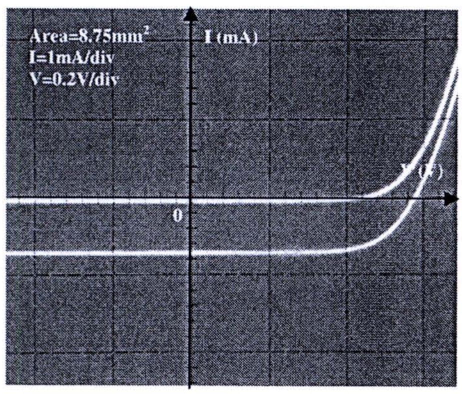



(c)

**Figure 4.14** **(a)** Spectral responses of sample **G**, **(b)** Spectral responses of sample **H** and **(c)** normalized spectral responses of sample **G** and **H**

- **The I-V curve characteristics**

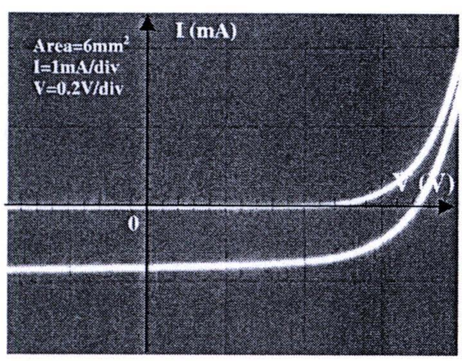
The LPE samples are tested for their I-V curves at dark and one sun illumination (100mW/cm$^2$ and AM1). The experimental results are displayed in **figure 4.15 (a)** and **(b)** respectively. All solar cell parameters are summarized in **table 4.2.** It is observed that the breakdown voltage is improved. $V_{OC}$ of sample **I** is 0.7V which is higher than those of MBE samples. However, over all I-V curves characteristics are not improved. The efficiency of LPE samples is comparable with those of MBE samples.




Sample **G**
(p on n)
(GaAs top layer)

$I_{Sc}$=0.8mA
$V_{Oc}$=0.59V
$I_{max}$=0.6mA
$V_{max}$=0.58V

**(a)**




Sample **H**
(p on n)
(AlGaAs top layer)

$I_{Sc}$=0.9mA
$V_{Oc}$=0.7V
$I_{max}$=0.6mA
$V_{max}$=0.48V

**(b)**

**Figure 4.15 (a)** and **(b)** I-V curves in the dark and one sun of AlGaAs/GaAs heterostructure solar cells, sample **G** and **H** respectively.

**Table 4.2** The calculated solar cell's output parameters of sample **G** and **H**

| Sample | Area($mm^2$) | $I_{Sc}$(mA) | $V_{Oc}$(V) | $I_{max}$(mA | $V_{max}$(V) | FF | η (%) |
|---|---|---|---|---|---|---|---|
| G | 8.75 | 0.8 | 0.59 | 0.6 | 0.48 | 0.61 | 3.2 |
| H | 6 | 0.9 | 0.7 | 0.6 | 0.48 | 0.45 | 4.7 |

All MBE samples are grown on p-type GaAs substrate. The epitaxial layers are undoped GaAs, n-GaAs, and $Al_xGa_{1-x}As$ window layer. Finally, very thin layer of $n^+$-GaAs for Ohmic contact is grown on the top-most surface. All MBE sample structures are illustrated in **figure 4.2, 4.3, 4.4, 4.5** and **4.6** respectively. All MBE samples are tested for their spectral responses, I-V curve characteristics. Solar cell parameters such as voltage, current, fill factor and efficiency are calculated from I-V curves. It is observable from **table 4.1** that both $V_{OC}$ and $I_{SC}$ are too low. These can be explained that the heterojunction is not in good quality. There are some junction leakages leading to low $V_{OC}$. The high series resistance due to too low doping density and contact resistance give small $I_{SC}$. Therefore, the efficiencies of those MBE grown solar cells are low. One technical problem is that we do not have p-type dopant source in our MBE system. Hence, $p^+$ doping for back surface field is not possible in our experiment.

LPE samples (samples **G** and **H**) are grown on n-type GaAs substrate. The epitaxial growth is conducted from undoped GaAs, p-GaAs, to p-$Al_{0.35}Ga_{0.65}As$ window layer, respectively. Very thin layer of $p^+$-GaAs is used for Ohmic contact. All LPE samples are tested for their spectral responses and I-V curve characteristics. It is found from our experiment data that LPE samples have some improvement in their $V_{OC}$ due to better junction quality. However, too thick epitaxial layers grown by LPE lead to large junction depth. The absorbed photons are not effectively in producing high $I_{SC}$. Therefore, our LPE samples are not good solar cells due to the uncontrollability of epitaxial layer thickness below 1μm.

The comparison between MBE and LPE growth techniques for heterostructure solar cells can give some technical information as follows. MBE can provide very thin epitaxial layers which are ideal for shallow junction devices like solar cells. However, junction properties and doping profiles should be carefully designed to provide both high value of $V_{OC}$ and $I_{SC}$ as well as the fill factor. LPE growth technique is appropriate for thick epitaxial layers having good crystal quality for most of electronic devices, but LPE can not provide shallow junction depth for solar cell application.