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Frontiers of Monolithic Integration of Semiconductor III-V Optoelectronic Devices with Silicon Technology

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In this paper, we review the advances made in the area of monolithic integration of III-V technology with Si technology. The major issue of heteroepitaxy of III-V films on Si substrates has advanced considerably, that many III-V devices have been fabricated on Si substrates and comparable performance was obtained on these devices. Though, many minority carrier devices on Si have been demonstrated but still, their performance is limited by dislocations. Recent demonstration of a monolithic GaAs based OEIC offers great promise for further research in this area.

INTRODUCTION

There has been considerable interest in the integration of III-V semiconductors with Si technology using the best aspects of both technologies to produce cheaper and faster devices. Si technology is mature, and electronic devices based on Si have comparable speed with III-V devices. Also, Si has higher thermal conductivity and mechanical strength compared to III-V materials, and large area substrates are available. However, the major disadvantage of Si is indirect gap and its application to optoelectronic devices. In this regard, III-V materials such as GaAs and InP are the best candidates for optoelectronic applications. Hence, a better approach is to combine the best properties of both III-V and Si devices.

A lot of research has been done on both GaAs based materials and devices on Si substrates.[1-4] Compared to GaAs based materials, not much research has been performed on InP based materials on Si, since the lattice mismatch between InP and Si (8%) is higher than the lattice mismatch between GaAs and Si (4%). In this paper, we review some of the recent advances in III-V on Si, materials and device performances, and also the present problems in this area.

III-V HETEROSTRUCTURES ON Si

There has been a lot of research in growing different types of III-V heterostructures on Si Substrates. Two recent review articles have covered the progress made in the area of GaAs based materials.[2,3] Hence, we concentrate on the progress made in the area of InP based materials.

High mobility, good quality InP films have been grown by MOCVD on Si substrates using GaAs buffer layer. It was observed that the quality of InP layer strongly depended on the thickness of GaAs intermediate layer. With optimum GaAs thickness, electron mobilities as high as 4000 and 25000 $cm^2/V.s$ at 300 and 77K, respectively were achieved, which are the highest values for InP films grown on Si substrate.[5]

GaAs-GaInP system is another important system for many applications such as lasers, FETs and HBTs. This system is also considered as a good material to replace AlGaAs. Hence, growth of this system on different substrates is of considerable interest. Recently, low pressure MOCVD was used to grow multiquantum well structure of GaAs/GaInP on GaAs, InP and Si substrates.[6] It was found from x-ray diffraction and photoluminescence measurements that the films grown on Si substrate is of comparable quality to the films grown on GaAs substrate. Also, it was observed that the films grown on InP substrate is of inferior quality to the films grown in Si substrates suggesting a great promise for monolithic integration.

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Table 1 shows a list of first GaAs based devices fabricated on Si substrates. FETs were the first devices to be realized in GaAs on Si with properties comparable to similar devices on GaAs. With simple GaAs buffer layer, GaAs MESFET grown on Si substrate showed similar performance in terms of device parameters such as electron mobilities, transconductance, and current gain cutoff frequencies with similar devices on GaAs substrates.[7] It is known that MODFETs are more sensitive than MESFETs to the material quality since, auto doping and defects at the interface affect the quality of the channel and carrier confinement in the layer. Yet comparable performance was obtained on AlGaAs/GaAs MODFET.[8] In the above structure, in order to grow high quality layers, tilted substrate, slow growth of initial layer and a superlattice buffer layer were adopted to improve the quality of AlGaAs/GaAs layers. Of all the electronic devices, bipolar transistors are the minority carrier devices and hence they are sensitive to crystalline defects. However, bipolar transistors fabricated on Si substrates did show comparable performance to the similar devices fabricated on GaAs substrates.[9]

Light emitting diodes at wavelengths of 700 and 870 nm have been achieved on AlGaAs[10] and GaAs[11] epitaxial films grown on Si substrates by both MBE and MOCVD techniques. GaAs/AlGaAs laser diode lasers were achieved first on Ge-coated Si substrates.[12] Later, GaAs/AlGaAs lasers emitting at room temperature were demonstrated on films grown on Si Substrates.[13,14] Typically, threshold current density of 214 A/cm^2 was obtained on 120 μm x 1900 μm broad area lasers.[14] But, due to large defects present in the films, the life time of the device is very short (17hrs). Recently, strained InGaAs/AlGaAs quantum well diode lasers fabricated on Si substrates were reported.[15] In these lasers, room temperature pulsed threshold current densities as low as 174 and 195 A/cm^2 were obtained for active layer compositions of $In_{0.02}Ga_{0.98}As$ and $In_{0.05}Ga_{0.95}As$, respectively.

GaAs solar cells fabricated on Si substrates showed cell efficiency of 18% compared to 23% on GaAs substrate. Recombination loss at dislocations is the limiting factor in the performance of GaAs/Si solar cells.[16] High speed GaAs detectors grown on Si showed a 3-dB corner frequency near 6 GHz and also slightly softer turn on characteristics compared to similar device on GaAs substrate.[17] GaAs/AlGaAs optical reflector modulators,[18] GaAs optical waveguides and optical phase modulators[19] have also been achieved on Si substrates. The performance of these devices is comparable to similar devices on GaAs substrate.

Table 2 shows a list of first InP based devices fabricated on Si substrate.

The only electronic device that has been fabricated is, a double heterojunction bipolar transistor (DHBT) using InP/InGaAs.[20] Epitaxial layers for this DHBT were grown on the Si substrate with a thin GaAs buffer layer, followed by a two-step growth process for InP epitaxial layer. For comparison, the same epitaxial layers were grown on InP and GaAs substrates. The emitter -base forward I-V characteristics indicated ideality factor of 1.1, 1.55, and 1.4 for InP, Si, and GaAs substrates, respectively. This suggests that, the dislocations degrade the I-V characteristics on Si and GaAs substrates. Still the DHBT on Si exhibited high current gains of more than 250 and an ideality factor of 1.3, which are comparable to similar devices on InP.

The first high-speed InP/InGaAs heterojunction phototransistor was achieved recently on Si substrate.[21] In this case, 1 μm GaAs was grown as a buffer layer. A two-stage growth process was used for InP growth followed by a post-growth anneal to improve the quality of the layers. In this device, optical gain as high as 125 A/W at 1300 nm, dark current as low as 300 pA and high bandwidth of 4.4 GHz were achieved.

The first room temperature GaInAsP-InP double heterostructure broad area laser emitting at 1.27 μm, grown by low pressure MOCVD on Si substrate was demonstrated.[22] InP/GaInAsP superlattice, with the InP thickness of 50 Å, was grown on Si to reduce the dislocation density. A pulsed threshold current density of 10 KA/cm^2 at room temperature with an external quantum efficiency of 10% per facet and an output power of 20 mW (for an oxide-defined stripe geometry with 12 μm stripe width and 250 μm cavity length) were measured. Preliminary aging tests showed that an increase in threshold current of 7% for a cumulative time of 80 seconds at room temperature. Such a rapid increase of threshold current may be due to the mismatch dislocation between the GaInAsP active layer and InP confinement layer.

Recently, first successful room temperature cw operation of GaInAsP/InP buried ridge laser structure grown by low pressure MOCVD on Si substrate was reported.[23] For this structure, 1 μm thick GaAs buffer layer, followed by a GaInAs/InP superlattice were grown to reduce the dislocations. Also, a two step growth process was used to grow InP layers. Threshold current of 45 mA with a differential quantum efficiency of 16% per facet, and an output power of 10 mW under CW operation at room temperature have been measured for a cavity length of 200 μm and a stripe width of 2 μm. The best threshold current obtained on this structure is 45 mA, corresponding to a threshold current density less than 4 KA/cm^2. Aging test on these devices showed an increase in the injected current less than 10% after one hour testing without any decrease of differential quantum efficiency.

The first InGaAsP double heterostructure (DH) laser emitting at 1.55 μm on a Si substrate was achieved recently.[24)] In this work, a combination of MOCVD and vapor mixing epitaxy (VME) was used to grow InP films. A pulsed threshold current as low as 46 mA with a differential quantum efficiency of 0.03 mW/mA per facet was measured for a ridge waveguide laser with a 4 μm strip width and a 200 μm cavity length.

Room temperature cw operation of an InGaAs/InGaAsP multiple quantum well (MQW) laser on Si substrate emitting at a wavelength of 1.5 μm was demonstrated.[25)] The threshold current was as low as 55 mA and differential quantum efficiency was 0.1 W/A per facet in cw operation at room temperature. They also found that this laser did not exhibit degradation after over 1000 hours of operation.

The first cw GaInAsP/InP LED, emitting at 1.15 μm grown by LP-MOCVD on a Si substrate was reported recently.[26)] This structure was grown on a (100) Si n^+ substrate misoriented 4° towards (110) with 100 Å GaAs-GaInP superlattice as a buffer layer. The LED structure consisted of a 2 μm InP doped with sulfur as a n-type confinement layer, 2000 Å GaInAsP undoped active layer, and a 500 Å zinc doped InP layer as p-type confinement layer. These LEDs did not show any degradation when they were operated for 24 hours, with an injection current of 200 mA.

The first InP solar cells fabricated on Si substrates showed solar cell efficiency of 12%,[27)] which are lower than cells fabricated on InP substrates (20%). It was observed that, high recombination current caused by the dislocations in the films reduced the cell efficiency.

MONOLITHIC DEVICES

Recently, the first fabrication of a monolithic integrated resonant photoreceiver fabricated on Si was reported.[28)] It consisted of a long wavelength (1.3 - 1.55 μm) metal-semiconductor-metal (MSM) photodetector, a GaAs metal-semiconductor field effect transistor (MESFET) and in inductor as shown in ref. 28. The epitaxial layers were grown by low pressure MOCVD. First, GaAs epilayers suitable for MESFET were grown. Then for MSM photodetector, selective epitaxy was used. For photodetector, $Ga_{0.6}In_{0.4}As$/GaAs layers were grown.

The MESFET exhibited transconductance of ~110 ms/mm and a transition frequency of ~14 GHz. The dark current of the GaAs/GaInAs MSM was lower than 20 μA for 2V. Microwave measurements indicated that the integrated device exhibited a gain of approximately 10 dB higher than the calculated value for a PIN photodiode at 7.25 GHz. This clearly demonstrated the feasibility of achieving monolithic integrated devices using III-V devices on Si substrate.

CONCLUSIONS

At present, the demonstration of monolithic OEICs is encouraging, however, a lot of issues have to be solved. In the areas of heteroepitaxy, though APD can be reduced to an extent that they don't affect the device performance, but still misfit dislocations have to be reduced below $10^6/cm^2$ in order to improve the performance of optical devices. In comparison to GaAs based devices, the performance of InP based devices are found to be less sensitive to the defects. InP based lasers show longer lifetime than AlGaAs/GaAs lasers suggesting that GaInP is the best alternative to GaAlAs.

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Device	Structure	Growth Method	Reference
LED	GaAs/Ge/Si	MBE	Shinoda et al., 1983 (13)
DH Laser	GaAs/GaAlAs /Si	MBE	Windhorn et. al., 1984 (15)
SLS Laser	InGaAs/AlGa As	MOCVD	Choi et. al., 1991 (18)
P-i-n Photodiode	GaAs/Si	MBE	Paslaski et. al., 1988 (20)
MESFETs	GaAs/Ge/Si	MBE	Choi et. al., 1984 (10)
MODFETs	GaAs/GaAlAs /Si	MBE	Fischer et. al., 1986 (12)
Bipolar Transistor	GaAs/Si	MBE	Fischer et. al., 1985 (11)
Solar Cell	GaAs/Ge/Si	MOCVD	Gale et. al., 1987 (19)
Modulator	GaAlAs/GaAs \Si	MBE	Dobbelaere et. al., 1988 (21)
Waveguide	GaAs/AlGaAs /Si	MBE	Kim et. al., 1990 (22)

Table 1. First experimental device results of GaAs on Si

Device	Structure	Reference
LED at RT	GaInAs/InP/Si = 1.15 µm	Razeghi et. al., 1987 (29)
DH Laser	GaInAsP/InP/Si = 1.3 µm	Razeghi et. al., 1988 (25)
BRS cw Laser	GaInAsP/InP/Si = 1.3 µm	Razeghi et. al., 1988 (26)
P-i-n Photo-diode	GaInAs/InP/Si	Razeghi et. al.,1989 (1)
Waveguide	MQW GaInAs/InP/Si = 1.5 µm	Razeghi et. al., 1989 (1)
Solar Cell	InP/Si	Yamaguchi et. al., 1987 (30)
Bipolar Transistor	InGaAs/InP/Si	Makimoto et. al., 1991 (23)
Heterojunction Phototransistor	InGaAs/InP/Si	Aina et. al., 1991 (24)
MQW Laser at RT	InGaAs/InGasP/Si	Sugo et. al., 1991 (28)

Table 2. First experimental device results of InP on Si.