Epitaxial Lateral Overgrowth of INP on Si Substrates

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Abstract-- Heteroepitaxy of indium phosphide(InP) on silicon(Si) substrate is of great interest, since it offers a promising opportunity for monolithic integration of InP based optoelectronic and high speed devices with Si integrated circuits. Epitaxial lateral overgrowth (ELOG) of InP has been carried out on different patterned substrates using HVPE technique. The growth experiments have been carried out in two steps on three different patterned substrates. All the patterns have been oriented at 30° along (110) direction on the substrate. . Optical properties have been studied by Photoluminescence, the ull width haf maximum(FWHM)has been calculated and compared on different substrates. Surface morphology of ELOG InP grown on different substrates have been observed by scanning electron microscopy. High resolution X-ray diffraction(HRXRD) rocking curve for (004) reflection plane has been carried out on ELOG InP. Hall measurement at room temperature has been carried out and confirmed that the layers are unintentionally doped n-type. Mobility and carrier concentrations have been calculated and compared with planar InP epilayer.

Keywords-- *Heteroepitaxy, Indium Phosphide, Silicon, Photoluminescence, Scanning electron Microscope, High resolution X-ray diffraction, Hall, Mobility, carrier concentration*

I. INTRODUCTION

III-V compound semiconductor InP with direct bandgap of 1.3 eV at room temperature plays a major role in high speed devices and also in fiber-optic communication systems[1]. On the otherhand, Silicon (Si) is an indirect band gap material and it is a dominating material in microelectronic industry because of high thermal conductivity, mechanical strength, large area and low cost but the disadvantage of this material is the poor light emission. In order to utilize the advantages, heteroepitaxy of InP on Si substrate is of great interest, since it offers a promising opportunity for monolithic integration of InP based optoelectronic and high speed devices with Si integrated circuits[2-4]. HVPE is a very suitable and efficient technique for depositions of Epitaxial lateral overgrowth(ELOG) InP layer on Si substrate because it is a near-equilibrium process and highly SAG[5-7]. During the growth of the ELOG, the dislocations propagate along certain directions. The dislocations are known to propagate parallel to the {111} plane and along <101> direction, which is at 45° from the normal to the substrate surface. If the openings are narrow enough, most of the defects and dislocations originating in the InP seed layer can be blocked during the ELOG[8-9]. Once the ELOG grown InP layer surpasses the thickness of silicon dioxide mask, lateral overgrowth accompanies vertical growth. Due to the blocking effect, only the defects located in the openings of SiO_2 mask can propagate upwards. Rest of the defects is “filtered away” due to the selective area growth(SAG). If the width and depth of these openings are optimized, the defects can be efficiently blocked by the side walls of the openings[10-12]. A successful ELOG requires a lateral growth rate higher than the vertical growth rate, leading to a coalescence of laterally grown layers from the consecutive openings. The lateral growth rate is strongly dependent on the orientation of the openings [13-14]. The maximum lateral growth rate achieved when the openings are oriented at 30° of [110] direction and the vertical growth rate is independent of the opening orientation [15].

II. EXPERIMENTAL PROCEDURE

ELOG of InP has been carried out on Fe-InP, InP(seed)/Si un-polished and polished patterned substrates using HVPE technique. The growth experiments have been carried out in two steps on three different patterned substrates. All the patterns have been oriented at 30° along (110) direction on the substrate in 1 µm subsequent openings with 3 µm spacing. In the first step, Fe doped InP growth has been conducted on two different patterned substrates, InP(seed)/Si un-polished and polished. The group III source was InCl, which was formed by flowing Hydrochloric Acid (HCl) over-heated Indium (In) metal. The group V source was phoshine (PH_3) and ferrocene ($Fe(C_5H_5)_2$) has been used for the source of dopant Fe. The V/III ratio,(i.e.,PH_3/InCl) was kept at 10 and the growth took place at 600° C in Nitrogern (N_2) ambient. The reactor pressure was 21 mbar and total flow inside the reactor was 900 sccm including N_2 carrier gas. The growth time was 15 min. In the second step, unintentionally doped InP growth experiments have been conducted on the same specimen as well as Fe-InP(100) patterned substrate. The growth has been found to take place at 610° C and the remaining parameters have been found to be the same as used in step one. The growth time was 20 min. An undoped InP on Fe-InP semi-insulating substrate, homoepitaxy has been noted to grow under the same conditions used as a reference.

The structural, optical and electrical properties of ELOG InP grown on patterned substrates have been characterized by high resolution X-ray diffraction (HRXRD), Photoluminescence (PL), scanning electron microscopy (SEM), and Hall measurement.

III. RESULTS AND DISCUSSIONS

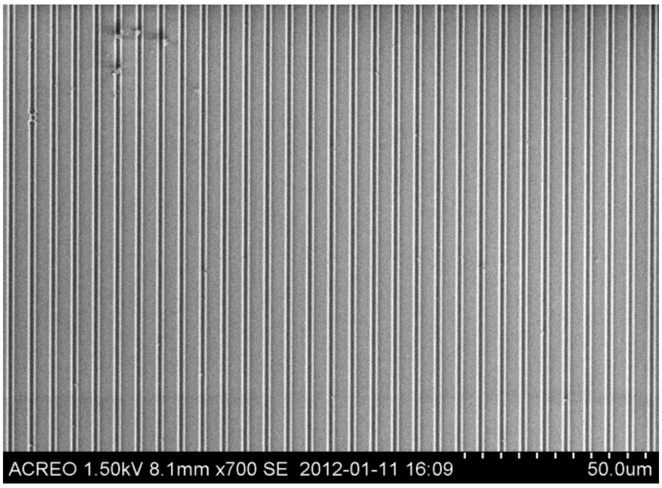

Figure 1: Surface morphology of SEM pattern on the Fe-InP substrate

Figure 1 shows the surface morphology of the patterns on Fe-InP substrate. It can be seen clearly that some surface damage occurred on the surface of the patterns and as well as on the openings. This might be due to some resists which remained on the surface and also on the openings while developing the resist after exposure. These unremoved resist present on the openings were not allowed to etch the SiO_2 mask while etching, which creates the uneven surface on the openings. Also some resists were not removed on the surface of the patterns after developing. These uneven surfaces on the openings has caused the growth to starts at different heights and lead the multiple points of coalescence on the top of the mask which makes the uneven growth and creates voids on the epitaxial layer.

The room temperature of PL spectra for ELOG InP layers on different substrates and planar InP was used as reference have been shown in Figure 2. The 514.5 nm line of Ar-ion laser has been used to optically pump the InP layers. It is observed that the PL - intensity of ELOG InP/InP is less compared to the InP planar. The reduction in intensity is due to the mask material, SiO_2 having different co-efficient of thermal expansion compared to InP. This difference in co-efficient has created dislocations at the interface between ELOG InP and SiO_2 mask and also due to some edge and sidewall damage on the patterns while etching the mask, SiO_2. The ELOG of InP on polished InP seed has been found very much comparable to the ELOG of InP than unpolished InP seed on Si substrate. The reduction in intensity on ELOG InP is due to the uneven surface of unpolished InP seed on Si substrate and also due to uneven patterned mask, SiO_2.

The FWHM of ELOG InP on polished InP seed spectrum has been found to be as narrow as 22 nm, which is wider than planar InP spectrum by only 2 nm. The ELOG InP/InP is around 21 nm and the ELOG InP on unpolished seed which is wider, 24 nm. The wavelength is slightly red-shifted to 2 nm for ELOG InP grown on Si substrate from ELOG InP/InP. This shift indicated that there is a mismatch residual strain created in the ELOG InP grown on Si substrate. This strain is caused mainly because of the difference in thermal expansion co-efficient between InP and Si.

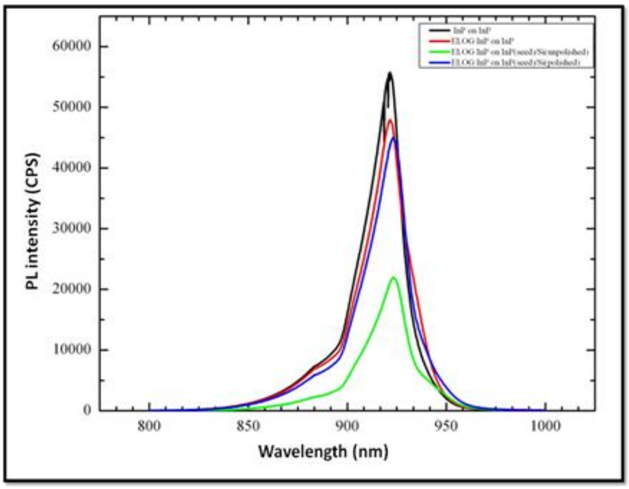

Figure 2: Room temperature Photoluminescence spectrums of ELOG InP and InP/InP planar substrates

HRXRD rocking curves have been recorded using a Panalytical Xpert MRD system for the samples. Figures 3 (a) to 3 (c) show the X-ray rocking curve of (004) reflection plane for ELOG InP grown on different substrates in omega-2 theta scan. Figure 3 (a) shows the rocking curve of ELOG InP on InP substrate and the FWHM as 0.54º which is higher than the planar growth. The higher FWHM obtained was due to dislocations created at the interface between the mask SiO_2 and the ELOG InP since the mask material has a different co-efficient of thermal expansion compared to InP. Figures 3 (b) and (c) show the rocking curve for ELOG InP on InP(seed)/Si both unpolished and polished and the FWHM as 0.063º and 0.062º ,which are comparable with ELOG InP on Si substrate reported in the literature.

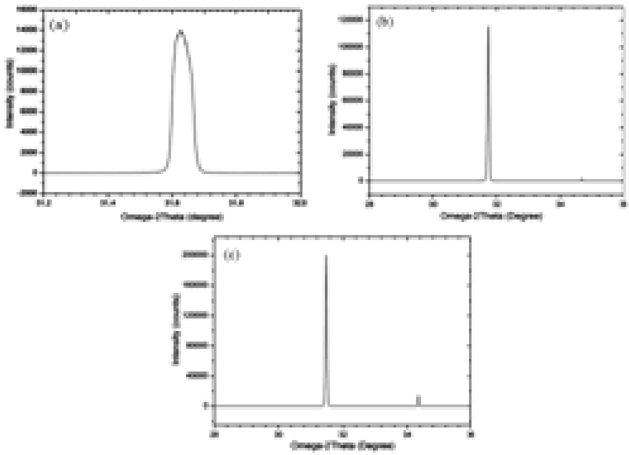

Figure 3: (004) XRD rocking curve of ELOG InP on (a) InP (b) InP(seed)/Si unpolished and (c) InP(seed)/Si polished substrates

Table 1: HRXRD data for ELOG InP of (004) reflection

Samples	ω -2θ	FWHM (004)	$a_{\perp}$(Å)	Strain (10^{-3})
ELOG InP on InP	31.6°	0.054°	5.877	1.5
ELOG InP on InP(seed)/Si unpolished	31.7°	0.063°	5.888	3.4
ELOG InP on InP(seed)/Si polished	31.4°	0.062°	5.878	1.7

Figures 4(a) and (b) shows the SEM micrographs of ELOG InP on InP patterned substrate. The smooth and mirror finishing InP layer has obtained which is clearly shown in Figure 4(a). From the Figure 4(b), it is observed that some voids on the surface which has been obtained due to some residue remains on the openings. These residues are caused from the mask, SiO_2 or from photoresist while processing. Figure 4(c) show the surface morphology of ELOG InP on InP/Si unpolished substrate. The surface looks very uneven compared to the ELOG of InP on InP/Si polished which shows in Figure 4(e).

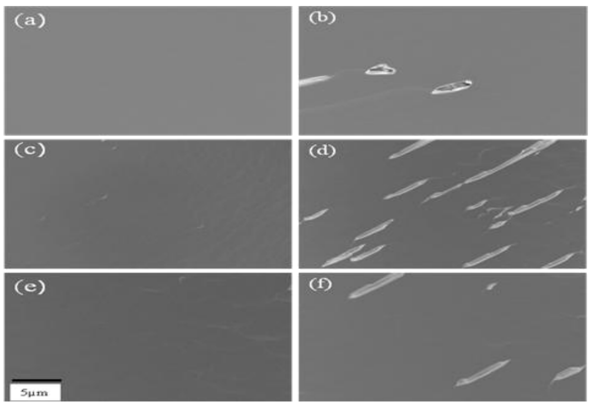

Figure 4: (a) and (b) SEM micrographs of ELOG InP on InP patterned substrate,

(c) and (d) SEM micrographs of ELOG InP on InP/Si substrate unpolished and (e) and (f) SEM micrograph of ELOG InP on InP/Si substrate polished**.**

This uneven surface was due to uneven surface of InP seed on Si substrate. This uneven surface makes the growth to start at different heights from the subsequent openings on the seed which makes to coalesce on the top of the mask at different heights. This height difference makes multiple points of coalescence which leads the uneven surface on the ELOG InP. Figure 4(e) shows the surface is even and very much comparable to the ELOG InP/InP. This is due to the effect of polishing on InP seed by CMP technique which makes the ELOG InP surface very even. From Figure 4(f), it is observed that voids are very minimum for ELOG InP on InP/Si polished compared to unpolished InP seed shown in Figure 4(d). The reduction in voids was due to even surface of InP seed on Si substrate by polishing which leads to minimize the residues and damages on the openings.

Van der Pauw Hall measurements have performed to analyze the electrical properties of ELOG InP grown on different patterned substrates. Indium was evaporated at the four corners of the samples and was annealed at 175° C for 10 min under H_2 ambient to form ohmic contacts. Room temperature Hall measurements showed that all the grown epilayers were unintentionally doped n-type.

Table 2: Room temperature Hall measurement data of InP

Samples	Carrier concentration (cm^{-3})	Carrier mobility (cm^2/Vs)
InP on InP (Planar)	1.92E+14	2853
ELOG InP on InP	1.83E+15	1948
ELOG InP on InP(seed)/Si (Unpolished)	1.98E+17	645
ELOG InP on InP(seed)/Si (polished)	1.79E+17	815

Table 1 shows the carrier concentration and carrier mobility of planar and ELOG InP grown on different substrates. The carrier concentration of ELOG InP on Si substrate was found to be slightly higher than the ELOG InP on InP substrate. This effect has been due to Si diffusion in to the InP layer which makes the increase of carrier concentration on ELOG InP grown on Si substrates. Carrier mobility of ELOG InP grown on Si substrate polished seed has been observed to be slightly higher than the unpolished seed.

CONCLUSION

ELOG InP on Si patterned substrates was successfully grown by HVPE technique. The growth experiments have been carried out in two steps on three different patterned substrates. Structural, surface, optical and electrical properties have been studied on ELOG InP grown on Si patterned substrates. The full width half maximum have been calculated and compared with the planar InP. Surface morphology has been studied on three different substrates and the better morphology has been obtained for polished InP/Si substrate than unpolished one. Optical properties have been studied by Photoluminescence (PL) at room temperature. The 514.5 nm line of Ar-ion laser has been used to optically pump the InP layers. PL measurements revealed that the red shift obtained on ELOG InP was due to mismatch residual strain created in the ELOG InP grown on Si substrate. Hall measurements at room temperature have been carried out and confirmed that the layers are unintentionally doped n-type. Mobility and carrier concentrations have been calculated and compared with planar InP epilayer.

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