InAs film grown on Si(111) by Metalorganic Vapor Phase Epitaxy

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Abstract. We report the successful growth of high quality InAs films directly on Si(111) by Metal Organic Vapor Phase Epitaxy. A nearly mirror-like and uniform InAs film is obtained at 580 °C for a thickness of 2 µm. We measured a high value of the electron mobility of 5100 cm²/Vs at room temperature. The growth is performed using a standard two-step procedure. The influence of the nucleation layer, group V flow rate, and layer thickness on the electrical and morphological properties of the InAs film have been investigated. We present results of our studies by Atomic Force Microscopy, Scanning Electron Microscopy, electrical Hall/van der Pauw and structural X-Ray Diffraction characterization.

1. Introduction
For thirty years, considerable efforts have been devoted to grow III-V films on Silicon. The success would allow monolithic integration of high mobility and direct-bandgap III-V semiconductors with the well established, low-cost CMOS-compatible Si technology [1]. This would lead to advances in high frequency and low power electronic or optoelectronic hybrid devices. Recent studies have mainly focused on GaN/Si and to some extent GaAs and InP on Si, with some success [2]. Despite the advantages of InAs in a number of potential applications, very few studies have been reported on thick InAs layers grown on Si [3], and to the author’s best knowledge, no InAs films have been grown directly on Si(111) substrates.

We report the successful growth of high quality InAs films directly on Si(111) by Metal Organic Vapor Phase Epitaxy (MOVPE). The influence of the nucleation layer, group V flow rate, and layer thickness on the electrical and morphological properties of the InAs film have been investigated. We present results of our studies by Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM), electrical Hall/van der Pauw and structural X-Ray Diffraction (XRD) characterization.

2. Experimental details
Prior to InAs growth, highly resistive Si(111) substrates were carefully prepared. First the substrates were degreased in a tri-clean solution (Trichloroethylene, Acetone, Ethanol and rinsing in deionized water). Then the surface was prepared using the Shiraki cleaning procedure [4], resulting in a controlled thin oxide layer and very low carbon contamination of the surface. Prior to growth, samples were etched in HF solution (5 %) to form an H-terminated surface, safe from oxidation in air for the
time needed to transfer them into the growth reactor [5]. InAs layer growth was performed in an EpiQuip MOVPE reactor, using H<sub>2</sub> as the carrier gas at 100 hPa, and a total flow of 6000 Standard Cubic Centimeters per Minute (SCCM). Before starting to grow, samples were annealed for 5 min at 600 °C under AsH<sub>3</sub> flow to transform the surface from H-terminated to As-terminated. The growth was initiated at low temperature (350 °C) and ramped up to 600 °C for annealing of the nucleation layer before setting the temperature for the second step growth. The TMIn molar fraction was set at 6.0 \times 10^{-5} and kept constant for both the first and second growth step for all samples investigated here.

3. Results

In the 1<sup>st</sup> step a nucleation layer was grown at a low temperature (350 °C). This layer consists of densely packed Stranski-Krastanow or Volmer-Weber coalesced islands. It is assumed that the islands have plastically relaxed, creating a dense dislocation network (Fig. 1 (a)).

The nucleation layer was annealed at 600 °C for 5 min. Annealing lead to Ostwald ripening, and faceted pyramids with a truncated top surface (Fig. 1 (b)) oriented in the (111) direction. The measured root mean square (RMS) roughness, average height and peak-to-valley height values were measured to be respectively 6.4 nm / 27.8 nm / 20 nm before annealing and 5.5 nm / 43.7 nm / 15 nm after annealing. The roughness and peak-to-valley height (RMS) were slightly reduced during this annealing step.

As can be seen in the series presented in Fig. 2 ((a) to (c)), the 2<sup>nd</sup> growth step morphology evolves via triangular nuclei extension resulting in coalescence of the islands into a flat layer.

![Figure 2: AFM images of the second step evolution as a function of growth duration: (a) 1 min., (b) 10 min. (c) 45 min. (d) SEM topview of the final morphology after 180 min. of 2<sup>nd</sup> step growth and (e) associated XSEM images showing the InAs layer thickness. (f) shows a detailed view of (c) in derivative mode to enhance height contrast.](image-url)
The surface morphology is found to be flat in most regions, for layers thicker than 100 nm (Fig. 2 (c)) and the nuclei have nearly all merged with visible boundaries. However, there are still holes remaining in the layers (Fig. 2 (d)). On the other hand, for an InAs film grown for 180 min., areas as large as 10x10 µm² can be found that are completely flat. The sample grown for 180 min. has been cleaved and studied by SEM in cross-section geometry. The X-SEM image in Fig. 2 (e) confirms a homogenous layer thickness of around 2 µm, permitting determination of the growth rate. The InAs growth rate during the second step is evaluated at 11.2 nm/min.

Hall/van der Pauw measurements on the InAs films were performed at room temperature. The measurements indicate that all samples are n-type doped. The donors are most probably coming from carbon incorporation during growth as commonly found in MOVPE growth. The electron concentrations and mobilities are highly dependent on the growth parameters, such as growth temperature, layer thickness, and AsH₃ flow. We found that the mobility increases with increasing growth temperature, with an optimum at around 580 °C. The mobility also increases with increasing layer thickness (Fig. 3 (a)). For a 1 µm InAs film the mobility is high, and does not increase substantially with the thickness. A low AsH₃ flow is important to obtain a high mobility (Fig. 3 (b)). The carrier concentrations are roughly two orders of magnitude above the intrinsic values for high quality homoepitaxial InAs films, as obtained using liquid phase epitaxy [6] and follow an inverse evolution compared with the mobilities (Fig. 3). These carriers are thought to mainly originate from ionized defects from growth, as for example interface states at grain boundaries. Unintentional doping by carbon impurities from the metalorganic precursors could also be significant.

Figure 3: Electron mobility and carrier concentration evolution for the series considered. (a) Evolution as a function of the 2nd step layer thickness growth duration, at 580 °C (c) Evolution as a function of the 2nd step AsH₃ flow for a thickness of 500 nm. The experimental accuracy is indicated by error bars and is limited by the uncertainty of the determination of the magnetic field strength inside the experimental set-up.

The lowest flow possible in our system (2 SCCM) resulted in the highest mobility value, while higher AsH₃ flows gave a much lower mobility value. The electron mobility of a 2 µm InAs film grown at 600 °C and AsH₃ flow of 2 SCCM, was measured to be 5100 cm²/Vs at room temperature. The mobility of this film was also measured at liquid nitrogen temperature (77 K), giving 8700 cm²/Vs, which is an improvement by 70 %. However, these values are still far from the best values obtained for very thick InAs films grown on GaAs(001) (1.73 x 10⁴ cm²/Vs in [6]) homoepitaxial InAs(001) (3.2 x 10⁴ cm²/Vs in [7]).

Following electrical characterization, the structural properties of the samples were studied by X-ray diffraction (XRD). A typical XRD spectrum for these InAs films is shown in Fig. 4 (a). The InAs{111} peaks have high intensity compared with other peaks, demonstrating that the InAs is grown epitaxially in the (111) direction on Si(111). The peak corresponding to InAs(111) has a full width at half maximum of 144 arcsecs.
Moreover, Fig. 4 (b) illustrates the reproducibility of the InAs(111) peak position and shape for different growth durations. As evidenced in the figure, the sample grown for 45 min., corresponding to 500 nm only, already has a good crystal quality with a full width at half maximum of 216 arcsecs.

4. Conclusions
We have demonstrated high quality InAs layers grown on Si(111) substrates by MOVPE using a two step growth procedure. Annealing of the nucleation layer (1\textsuperscript{st} step) improves the surface morphology and enables a nearly flat layer to be grown in the 2\textsuperscript{nd} step. The surface roughness decreases for thicker layers up to 1 µm, but some holes are still present after growth optimizations. It was found by Hall/van der Pauw measurements that the InAs layers were n-type with an electron mobility which is highly dependent on the 2\textsuperscript{nd} step growth temperature and AsH\textsubscript{3} flow. A best room temperature mobility of 5100 cm\textsuperscript{2}/Vs was found for growth at 600 °C using as low AsH\textsubscript{3} flow as possible. At 77 K the mobility has risen by 70 %, to 8700 cm\textsuperscript{2}/Vs, which implies a high quality of the InAs layer. Analysis by XRD proves the epitaxial nature of the InAs films, and that the crystal quality is best for a growth temperature in the range of 580 °C. In summary, InAs layer growth on Si(111) is achievable with a reasonably small film thickness of 1 µm or below with resulting mobilities as high as 5100 cm\textsuperscript{2}/Vs at room temperature. Growth quality is strongly improved by enhancement of the surface diffusion of the constituents, achieved at high temperature and low V/III ratio.

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