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Growth of InAs on Si substrates at low temperatures using metalorganic vapor phase epitaxy

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ABSTRACT

The growth behavior of InAs on Si using metalorganic vapor phase epitaxy (MOVPE) was studied. The large lattice mismatch of InAs to Si, ~12%, results in island formation under typical MOVPE growth conditions, which prevents the development of the thin coherent films of InAs needed for high-speed device applications. The growth of InAs at low temperature is expected to lead to rapid nucleation and low surface mobility, resulting in the formation of a coherent film at low thicknesses. This study explored the growth behavior of InAs on Si at low temperatures, i.e. <350 °C and varying V/III ratio. InAs films were grown on {1 0 0}-, {1 1 1}- and {2 1 1}-oriented Si substrates using trimethyl indium, tertiary butyl arsine and AsH_3. Small islands ranging from 15 to 30 nm form on the samples at growth temperatures <325 °C. Subsequent annealing of this thin layer at 600 °C for 5 min leads to island coarsening. High-resolution X-ray diffraction, atomic force microscopy and scanning electron microscopy were used to characterize InAs layer grown on Si.

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1. Introduction

The integration of direct band gap III–V semiconductors on Si has potential applications in Si-based opto- and high-speed electronics. InAs is attractive for many of these applications in high-speed electronics [1], thermophotovoltaics [2] and optical emitters/detectors [3] due to its high electron mobility and narrow band gap. The integration of InAs and Si by direct epitaxial growth using the metalorganic vapor phase epitaxy (MOVPE) technique would be an attractive approach to fabrication, but has not been investigated systematically. In this study, low-temperature growths of InAs on different Si surfaces have been performed using MOVPE. A major challenge involved in the growth of InAs on Si is the 11.6% lattice mismatch. Due to this high lattice mismatch, the growth of InAs on Si takes place via the Stranski–Krastanov (SK) mode in which a very thin wetting layer forms [4,5], followed by 3D islands. The large lattice mismatch and the polar/nonpolar interface generally lead to high defect densities in the film and deterioration of device performance. Low-growth temperatures have been employed in this study to suppress the formation of large islands. Rapid nucleation and low-surface mobility at these low temperatures are expected to result in the formation of a coherent film at a low thickness. The resulting films were characterized to determine the temperature dependence of the growth rate at these very low growth temperatures, and their structural properties were assessed.

2. Experimental details

InAs films were grown on {1 0 0}-, {1 1 1}- and {2 1 1}-oriented Si substrates in a horizontal MOVPE reactor operated at 10^4 Pa. Trimethyl indium (TMIn) was used as group III precursor and tertiarybutyl arsine (TBAs) as well as arsine (AsH_3) were used as group V precursors. Pd-diffused hydrogen was used as the carrier gas. Prior to growth, the substrates were etched in HF solution to remove any native oxides and form a hydrogen-terminated surface [6]. After loading into the reactor, the substrates were annealed under AsH_3/H_2 ($P_{AsH_3} = 93$ Pa) at 800 °C for 5 min to transform the surface from H-termination to As-termination [7]. The growth temperature was varied from 260 to 650 °C. After the annealing step, the substrate temperature was lowered to the specific growth temperature. TBAs was used as group V precursor during the low-temperature growths (<350 °C) due to its higher decomposition rate at low substrate temperatures than AsH_3 [8]. The films were grown at a constant TMIn mole fraction of

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1.05×10^{-4}. The V/III ratio was varied for each growth temperature below 350 °C in order to produce single-phase material, i.e. no excess In on the surface. For the samples discussed here, the V/III ratio was 25 at 325 °C and 90 for growths below 300 °C.

High-resolution X-ray diffraction (HRXRD) was used to characterize the structure and orientation of the films. The surface morphology of the InAs film was characterized by atomic force microscopy (AFM) and scanning electron microscopy (SEM). The growth rate was determined by profilometry on samples where the InAs was preferentially etched from a portion of the Si substrate with HCl.

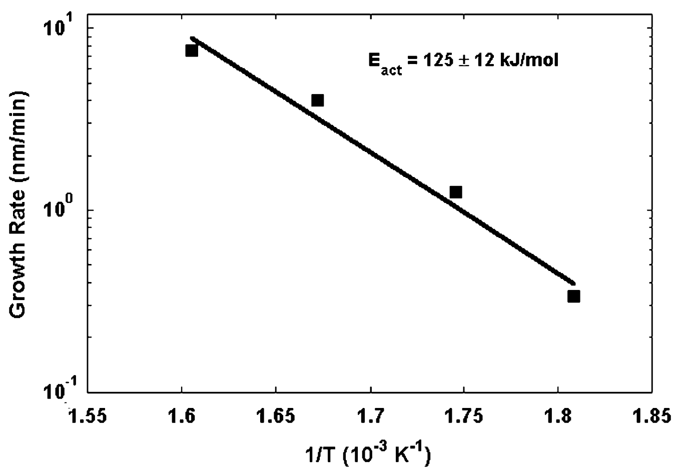

Fig. 1. The growth rate behavior at low growth temperature (280–350 °C) exhibits an Arrhenius type behavior with characteristic activation energy of 125±12 kJ/mol.

3. Results and discussion

The growth rate of InAs was measured for films grown on the Si substrates below 350 °C. At these low temperatures (280–350 °C) the islands are small (~20 nm) and they coalesce into a film. For growths above 350 °C large islands are formed on the substrate and there is no coalescence for the growth times employed. Although the InAs growth rate on GaAs substrates are orientation dependent [9], the thickness variation for the InAs growths on differently oriented Si substrates is almost negligible, within the range of experimental measurement errors. While the growth of InAs and In-based semiconductor alloys are typically grown under mass transport limited conditions [10], over the low-temperature range 350–280 °C InAs growth on Si is kinetically limited when using TMIn and TBAs. The incomplete pyrolysis of TMIn [11] and TBAs [8] at 280 °C leads to the low growth rate of 0.34 nm/min. The activation energy determined over this growth temperature range is 125±12 kJ/mol as shown in Fig. 1. Individually these growth sources can exhibit strong temperature dependence over this temperature range, particularly at short residence times. The TMIn and TBAs activation energies for decomposition were determined in previous studies to be ~167 and ~146 kJ/mol, respectively [8,11]. The TMIn and TBAs activation energies were determined, however, over a temperature range higher than that employed here. The measured activation energy for the temperature range (280–350 °C) is lower than the activation energies of decomposition for both TMIn and TBAs,

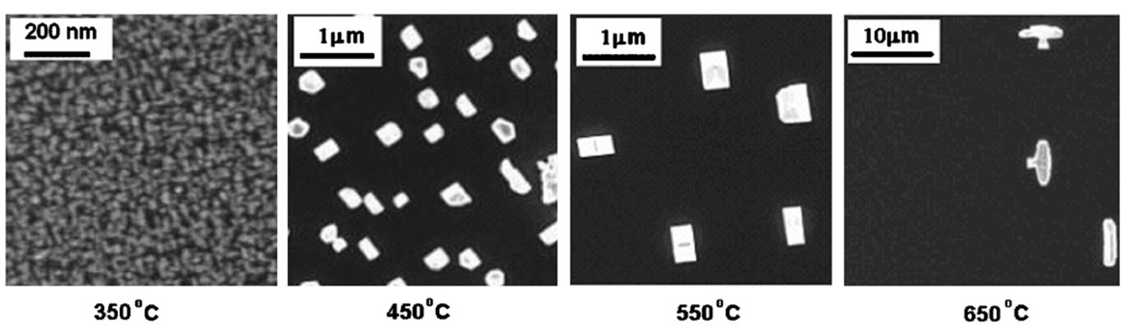

Fig. 2. The SEM micrographs of the InAs grown on {1 0 0} Si substrates indicate a decrease in island size and an increase in the island density with decrease in growth temperature.

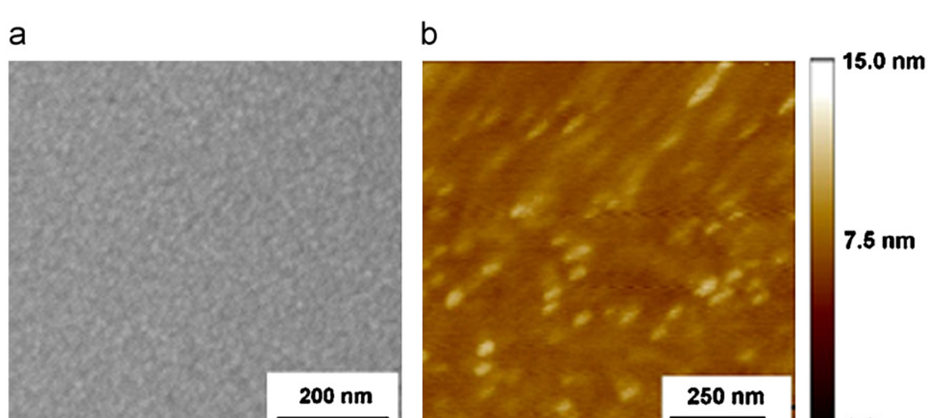

Fig. 3. SEM (a) and AFM (b) micrographs obtained from InAs grown on {2 1 1} Si at 280 °C.