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# Heterogeneous integration of InAs on W/GaAs by MOVPE

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**Abstract.** InAs has been grown on W-GaAs patterned substrates using MOVPE. The selectivity of the growth and the nucleation process has been studied as a function of the temperature and the V/III-ratio in the MOVPE reactor. It is shown that the W guides the nucleation of the InAs on the GaAs and that the islands formed may be used to embed metal features in a hybrid InAs/GaAs structure in agreement with previous overgrowth studies of W-InAs and W-GaAs. The electrical properties have also been evaluated demonstrating a reduction of resistance by a factor 5 for a hybrid structure with an embedded grating as compared to an InAs/GaAs reference sample.

## 1. Introduction

Materials with narrow band gap are attractive for high-speed devices and long wavelength optical devices. For instance, high electron mobility transistors [1] and lasers operating above 2  $\mu\text{m}$  [2] have been fabricated in materials lattice-matched to InAs or GaSb. A major limitation is the lack of semi-insulating substrates which requires the growth on GaAs or InP substrates using thick and complex buffer layers. In this paper, we present an alternative approach, in which we grow InAs on semi-insulating GaAs substrates patterned by W-features. It is demonstrated that the W affects the nucleation of InAs on GaAs and guides the material towards the edges of the pattern. These nucleation sites form the basis for the subsequent lateral overgrowth over the W pattern.

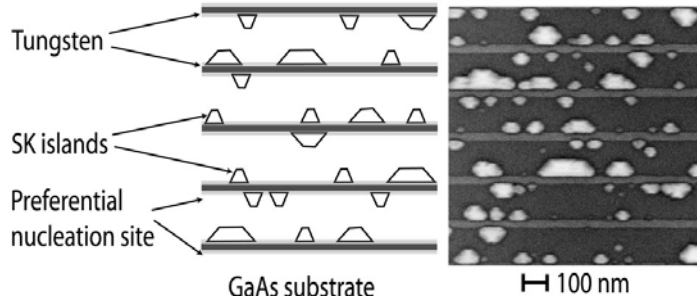
## 2. Fabrication of samples

The fabrication of the W-GaAs patterns is based on a liftoff process using evaporated metal [3]. The patterns formed consist of lines (width 120 nm and periods of 300 to 700 nm) and concentric rings (width 100 nm and periods of 400 nm). Epitaxial growth of InAs on GaAs were performed on patterned substrates at 3 different growth temperatures (500°C, 550°C, 600°C) and V/III ratios of either 14 or 56. The lower temperature was set as the InAs deposits polycrystalline on the W patterns at lower temperatures [4]. Trimethylindium (TMI) and Arsine ( $\text{AsH}_3$ ) were used as sources for the InAs growth. The reactor pressure was kept at 100 mbar during the growth runs. After the growth, the samples were inspected using scanning electron microscopy (SEM), followed by atomic force microscopy (AFM) measurements, and electrical evaluation.

## 3. Results

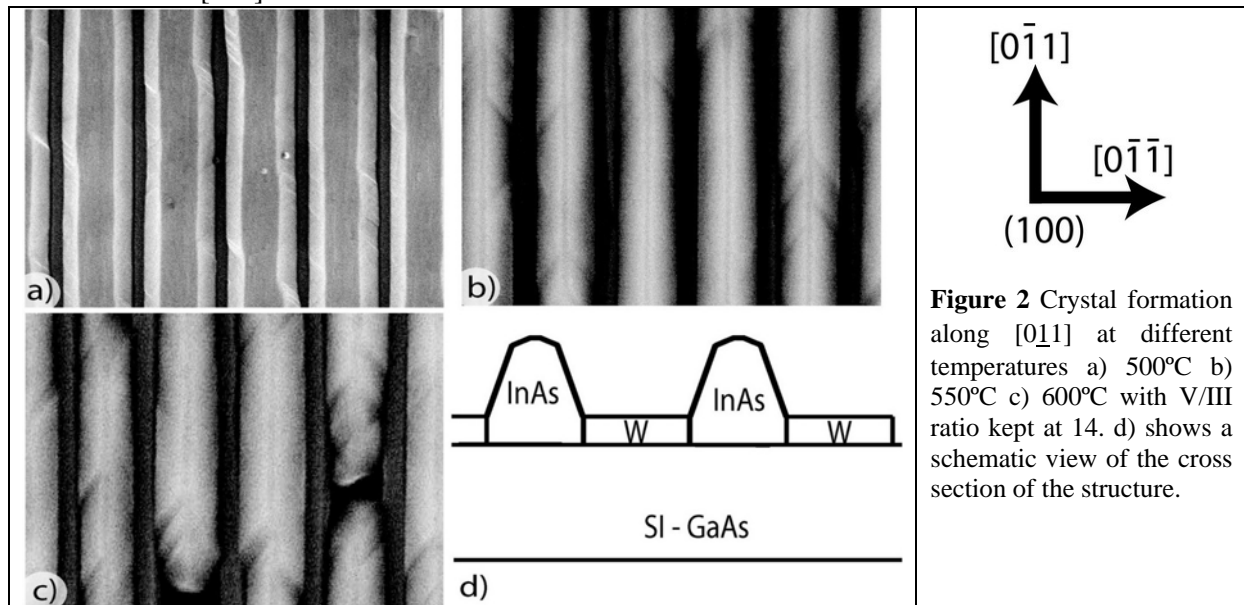
We started the investigation by analyzing the InAs nucleation on patterned GaAs sample with tungsten gratings. For this purpose, a sample with short growth time was grown and 10 nm of equivalent InAs layer thickness was deposited at 600°C. Due to large lattice mismatch, Stranski Krastanow (SK) islands formed on the substrate [5] with nonuniform island sizes, ranging in diameter from less than 2 nm up to 20 nm. The islands show no preferential nucleation sites outside the grating, while the situation

is different inside the grating, Fig. 1. In the grating area, most islands nucleate along the tungsten lines with only very few SK islands forming in between the tungsten lines. Besides, the islands along the tungsten lines are also substantially larger in size, than the ones in the middle. This indicates that these islands also have a high growth rate as more material is deposited.



**Figure 1** Preferential nucleation of Stranski-Krastanow islands along tungsten lines at 600 °C and V/III = 14

100 nm nominal thickness of InAs was grown on patterned W-GaAs wafers at 600, 550 and 500°C. Figure 2 shows the crystal shapes obtained during the growth of InAs on a pattern with W grating oriented in the  $[0\bar{1}1]$ -direction.

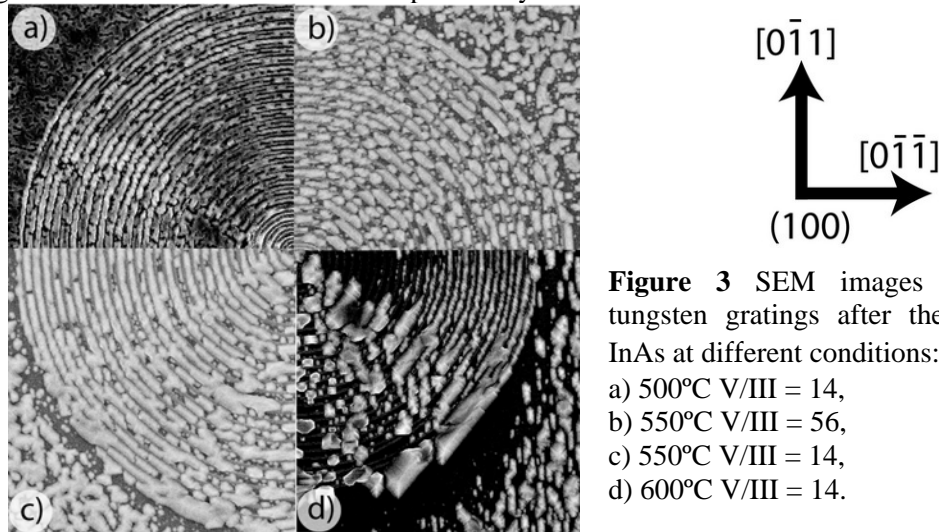


**Figure 2** Crystal formation along  $[0\bar{1}1]$  at different temperatures a) 500°C b) 550°C c) 600°C with V/III ratio kept at 14. d) shows a schematic view of the cross section of the structure.

As the temperature is decreased at constant V/III-ratio (14), less microfacets appear on the side walls along the  $[110]$ -direction. This indicates that lower energy surfaces become favorable during the epitaxial growth. This effect is explained by the Wulff theorem [6]. Especially interesting is the growth at 500°C, where a flat top surface (001) develops on the mesa ridge during the growth. AFM inspections revealed that the side planes, which were extending down to the tungsten grating, have angles of either 45° or 54.6° towards the (001) surface. This corresponds to the  $\{110\}$  and  $\{111A\}$  planes. It was reported [3], that similar ridges were observed during epitaxial overgrowth of InAs on W-InAs substrates at 600°C, with the gratings oriented along the  $[0\bar{1}1]$ -direction. The identification of the same shape and directional dependence of the limiting growth planes as in homoepitaxial overgrowth indicates that the strain does not considerably influence the growth of InAs on W-patterned GaAs. At higher temperatures, the ridge formation is further influenced by a lower nucleation density and the increased diffusion length of the mobile In species.

Next we study how the InAs grow under different grating orientations. Fig. 3 shows SEM images with a comparison of different growth conditions on the circular tungsten gratings. We observe that a high temperature leads to the formation of larger InAs crystals within the pattern. This is in agreement with the observation of the grating at 600°C in Fig. 1. We also note that there is a small area without

InAs nucleation at the edges of the pattern with large ridges forming just at the interface between the tungsten and the GaAs. This is well explained by diffusion to the nearest nucleation site.

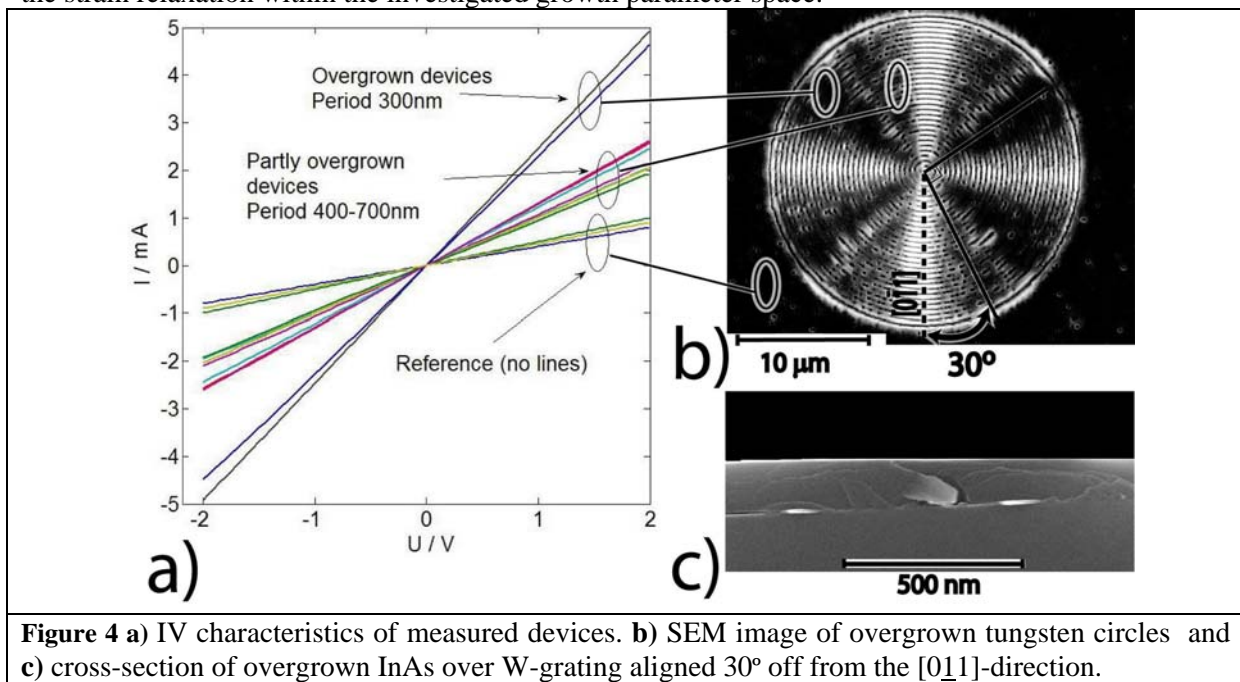


**Figure 3** SEM images of circular tungsten gratings after the growth of InAs at different conditions:

- a) 500°C V/III = 14,
- b) 550°C V/III = 56,
- c) 550°C V/III = 14,
- d) 600°C V/III = 14.

The sample overgrown at 550°C and with a V/III-ratio of 14 shows a clear orientation dependence in the lateral growth rate. The part of the pattern along the  $[0\bar{1}1]$ -direction shows a uniform InAs growth, while the part of the pattern oriented towards the  $[011]$ -direction shows nonuniform growth.

We note that the distribution of ridges is most uniform at the lowest growth temperature. According to Yuan et al.[2 not consistent order of references], InAs nucleation density is the highest at this temperature and a high island density support the rapid coverage of the GaAs surface, and support the planarization process. By analyzing the filling of the lines, we can identify that high temperature growth does not relax strain efficiently, therefore large crystalites are formed. As the filling is more uniform at lower temperatures, this indicates that reduction of surface tension has occurred and Frank - Van der Merve growth mode started to take place. The relaxation mechanism is attributed to an increase of density of InAs islands with lower growth temperature[9]. V/III ratio has minor effect for the strain relaxation within the investigated growth parameter space.



**Figure 4** a) IV characteristics of measured devices. b) SEM image of overgrown tungsten circles and c) cross-section of overgrown InAs over W-grating aligned 30° off from the  $[0\bar{1}1]$ -direction.

Finally, a thicker layer of InAs was grown on a sample with ring structures to evaluate the overgrowth of the W and the planarization above the grating. The thickness of the grown InAs layer was in this case 220 nm. The circular patterns of tungsten reveal a strong directional dependence of the InAs growth, as shown in Fig. 4. Three clearly distinguishable growth modes at different directions can be identified in the developed patterns above the circles: successful overgrowth, mesa type ridge formation along [011], and mixed region of mesa-ridges and partial overgrowth along the [0 $\bar{1}$ 1]. It is observed that complete overgrowth of the tungsten features occurs without the formation of voids over the lines, when the grating is aligned 30° off from the [0 $\bar{1}$ 1]-direction.

Electrical measurements were done to evaluate the resistance of the material. 70 $\mu$ m $\times$ 10 $\mu$ m devices (Hall bars) including embedded gratings oriented 30° off the [011]-direction (Overgrown devices), gratings 60° off from the [011]-direction (Partly overgrown) and without any lines (Reference). As shown in Fig. 5, the overgrown devices have the smallest resistivity. In total, the resistance decreases 5 times for the overgrown samples as compared to reference samples without tungsten lines. The partly overgrown devices show higher resistivity as compared to the overgrown ones. This can be attributed to a reduced quality for the overgrowth in this direction. However, the resistance is still smaller than that of the reference, due to the conductive tungsten lines [anneli reference].

### Summary

We have in summary studied the conditions for epitaxial overgrowth of InAs on W-GaAs patterned substrates. It is demonstrated that the InAs preferentially nucleates along the metal patterns and that these nucleation sites form the basis for the subsequent lateral overgrowth over the metal. A deposition temperature of 500 °C is preferred as it is sufficiently high to prevent polycrystalline deposition on the metal, while it still provides a high density of nucleation sites and a reduced diffusion of In-species on the growing surface. A complete void-free overgrowth with a planarized top surface can be achieved after 200 nm of deposition for a metal grating oriented in 30° off from the [1 $\bar{1}$ 0]-direction. Electrical evaluation of the material shows that the resistivity is reduced a factor 5 via the introduction of a metal grating.

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