Direct nucleation and growth of $InAs_{1-x}Sb_x$ on InAs(111)B substrates

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Introduction

For optical application of semiconductor in mid-IR spectrum range (2-8 μm), $InAs_{1-x}Sb_x$ is one of an attractive material for such application like photodetectors and quantum computing. With its tunable bandgap according to the changing of composition, it can provide the narrowest band gap at room temperature, figure 1. However, there are not much understanding of the growth rate, radial and axial growth, with Au nucleation site in the recent researches. The common problem found when growing composition material with ternary structure on binary V-III substrate is the strain caused by lattice mismatch. With Au seed particles growing Sb based nanowire, it requires a stem material as the substrate. Thus, InAs substrate expecially InAs(111)B is a rigid platform for $InAs_{1-x}Sb_x$ nucleation to be occured. Even though this method can relax strain within the lattice, the stem can be decomposed when turning AsH_3 flow off for As-free material. As a result, nanowires are breakage during the growth. In this project, our main focus is on growing nanowire directly from substrate and investigate the growth rate of $InAs_{1-x}Sb_x$ nanowire as a result of various parameters in the key processes, Au aerosol nanoparticle and Metalorganic vapor phase epitaxy (MOVPE). For Au aerosol nanoparticle, there is a difference between diameter and density of Au seed particles for our sample. Furthermore, there are also variation parameters for MOVPE process as the flow of Sb to control the composition, x, and the growth time in reaction chamber.

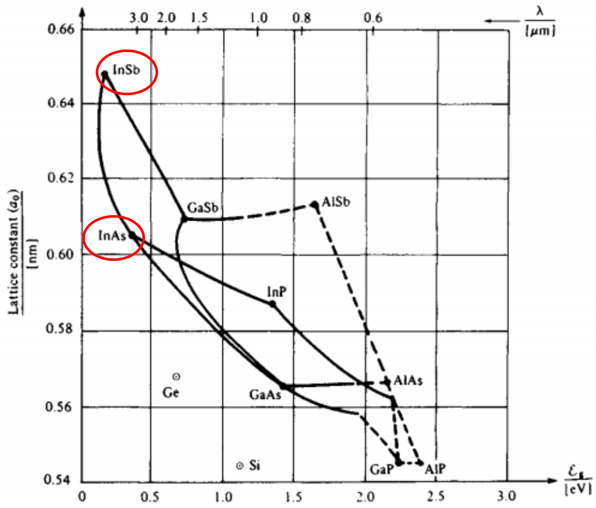


Figure 1 Plot of lattice constant and band gap for various semiconductor. Davies Et Al.

Theory

InAs(111)B

The (111) surface of InAs is composed of either In or As only with the higher density compare to (100). B here indicates that type of atom on the surface which is As atoms. The condition of this surface is more suitable for nanowire growth.

Au Aerosol nanoparticles

The very first step to construct this nanowire is to prepare InAs deposited by Au aerosol nanoparticles. With aerosol technology, vapourized Au was could be deposited on the substrate with a specific diameter and density. This Au seed nanoparticles have a diameter of 30nm and 50nm and they are deposited on the InAs substrate with the density of 1 particle/µm^2 and 0.1 particle/µm^2.

Metalorganic vapor phase epitaxy

During the MOVPE phase the following precursors: TmIn (trimethylindium), AsH_3 (arsine) and TMSb (trimethylantimony) as an In, As, and Sb precursors, respectively, were added to the substrate at an elevated temperature. All the precursors was introduced into the reaction chamber at the same time to grow InAsSb nanowire without the stem of InAs. With Au aerosol nanoparticles on top of InAs(111)B substrate, the density of the gold particles defines the density of the nanowire. The composition, x, depends on the amount of TMSb added to the process. The sample was heated up to 480°C. The V/III ratio between the precursors was high (above 100). It is the ratio between [As] + [Sb] and [In]. The amount of Sb is managed over the vapor composition value x which is defined as.

$$x_v = \frac{[TMSb]}{([TMSb] + [AsH_3])} \tag{1}$$

The composition, x, of our samples is x=0.08, x=0.1, x=0.12, and x=0.15 at the growth time of 5min, 5min, 15min, and 1hrs, respectively. The longer growth time is used for the higher composition because with the high composition the growth rate is quite low. Thus, with the higher growth time we can observed the growth easier.

Measurement

With all the recipes mentioned previously, the total number of samples is 15 samples. The summarized of all recipes are in table 1.

Number	Compositions x	Time (min)	Diameter of Au particles (nm)	Density of Au particles (µm^{-2})
1	0.08	5	30	1
2	0.08	5	50	1
3	0.08	5	50	0.1
4	0.1	5	30	1
5	0.1	5	30	0.1
6	0.1	5	50	1
7	0.1	5	50	0.1
8	0.12	15	30	1
9	0.12	15	30	0.1
10	0.12	15	50	1
11	0.12	15	50	0.1
12	0.15	60	30	1
13	0.15	60	30	0.1
14	0.15	60	50	1
15	0.15	60	50	0.1

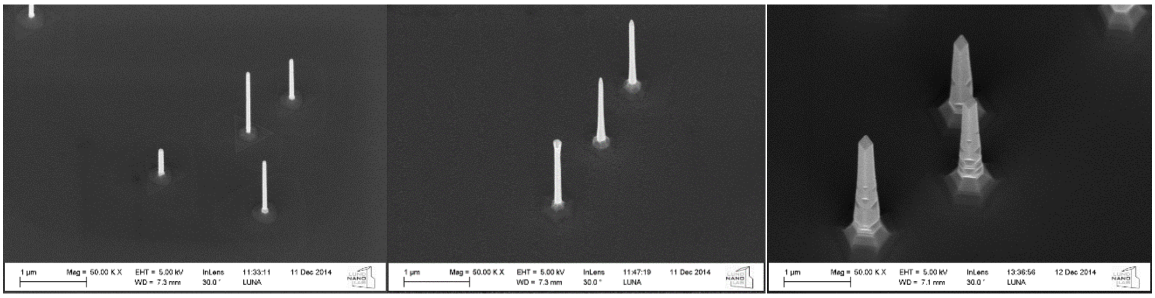
Table 1 Recipes of all samples

Those samples were observed under scanning electron microscope (SEM). In addition, sample holder in SEM was tilted 30degree to observed nanowire on top of the surface. Then, the dimension of nanowires were measured with software ImageJ.

Results and discussions

With SEM image, we observe the two major difference type of growth among the samples. There is a group which the growth is more prefer on an axial direction. This kind of growth generates nanowire structure. On the other hand, there is another growth which is only an accumulation of precursors at the nucleation site. This process is called *surface growth.* Figure 2 displays these two main difference type of growth from some of the samples. The first group of samples, the axial growth, could obviously be seen with there verticle InAsSb nanowire structure. However, diameter of those nanowires is still difference depending on the recipes used in each samples. Therefore, we could observe different nanowire between those samples (1, 3, 5, 7, and 9). Besides, there is also a sample, sample 2, that have neither nanowire growth nor surface growth.

(a)



(b)

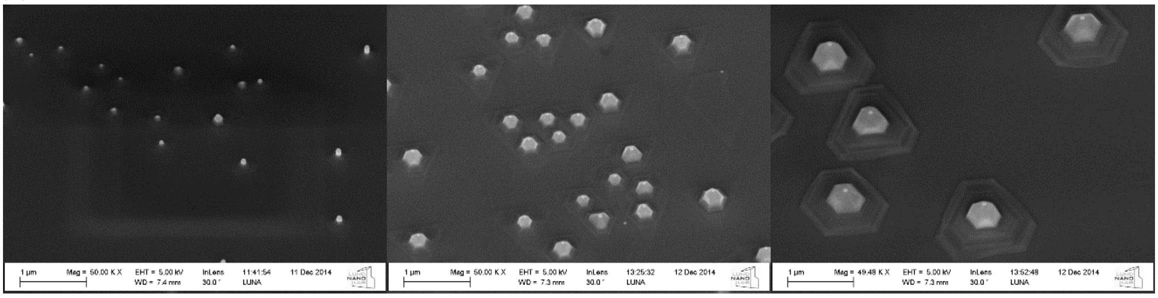


Figure 2 SEM image displays the difference growth as (a) nanowire and (b) the acummulation of precursor. (a) is a picture of sample 3, 5, and 9 from left to right and (b) is a picture of 4, 8, and 11 from left to right.

From the last image of figure 2 a which took from sample 9, there is a very high growth occured on both directions, thus we get a thick and tall wire. There must be a local defects on nanowire which has a lower surface energy, so those parts have a lower radial growth rate compared to the rest of nanowire. Hence, we see the dimp on the side facet.

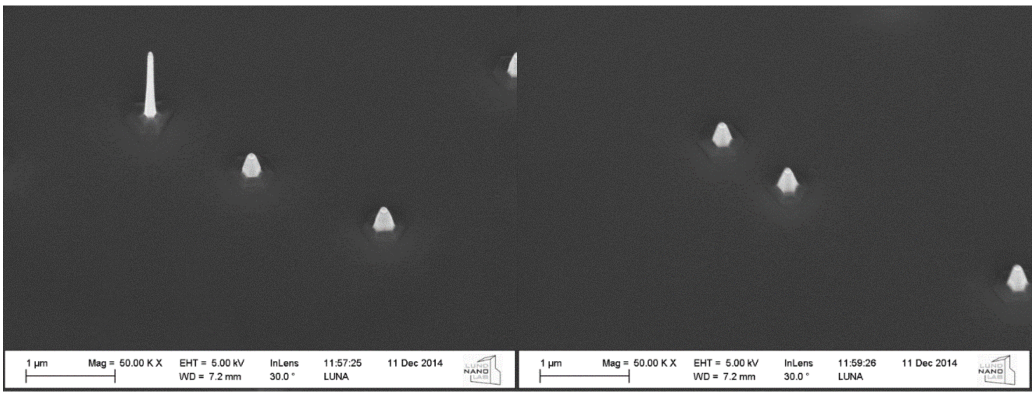


Figure 3 The variation of growth within the same sample according on the variation of Au nanoparticle.

In addition, the growth could distinctively vary, even they grown in the same MOVPE condition, if the diameter of Au nanoparticles is difference. As we can see in the sample 7, there is a variation of Au diameter which can be observed from the top of the growth section, thus the growth on that particular nucleation site has a difference result, figure 3. This is a good evidence to show that the growth is strongly depend on diameter of nucleation site. Furthermore, we can get another parameter for the InAsSb nanowire growth condition. Apparently, the difference between these two groups of sample is their Au nanoparticles density on the substrate. The less density provide more suitable condition for InAsSb nanowire growth on InAs substrate. This is because the higher density of Au particles leads to the lower local supply of the growth species.

There is also an interesting observation from all of the samples. The growth could not be much observed around the sample edge, figure 4. This is due to the excessive material that have been deposited and have built up on the susceptor of the machine from the previous runs. They could interrupt the growth process at the nucleation site, thus nanowire cannot grow there. The result of this error is called an *Edge effect*.

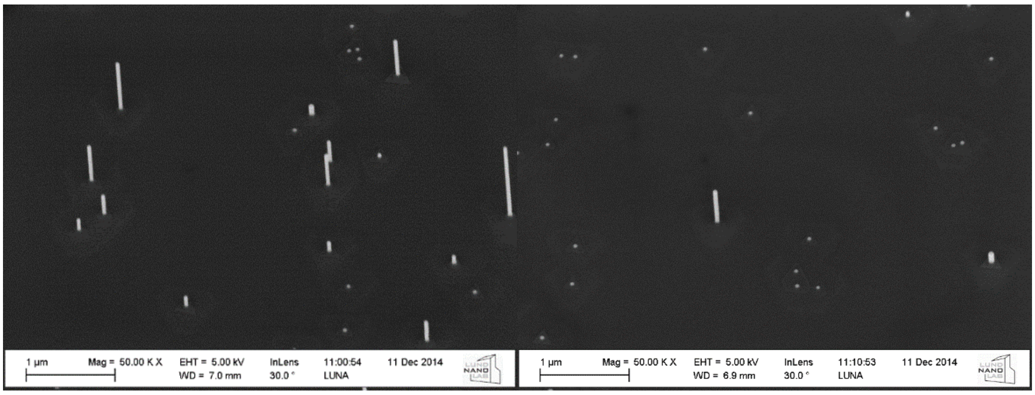


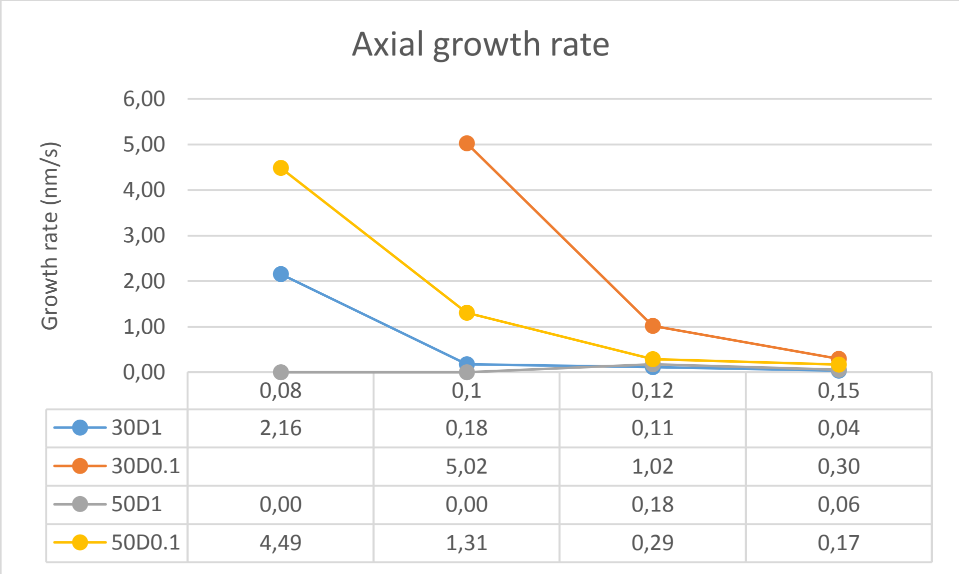
Figure 4 SEM image comparing the growth of nanowire at (left) center area of the sample and (right) edge of the sample

The axial length and diameter of samples are measured by program named ImageJ. All the measurements is in table 2. Since the samples were tilted 30degree in SEM sample holder, the measurement results of axial length in table 2 are the actual length. That means it is a measured length divided by sine 30degree.

Number	Recipes	Average length (nm)	Average diameter (nm)	Number	Recipes	Average length (nm)	Average diameter (nm)
1	0.08_30D1	647.33	41.00	9	0.12_30D0.1	914.67	273.00
2	0.08_50D1	-	-	10	0.12_50D1	158.00	451.00
3	0.08_50D0.1	1346.00	61.00	11	0.12_50D0.1	260.67	569.00
4	0.10_30D1	52.67	83.00	12	0.15_30D1	131.33	825.00
5	0.10_30D0.1	1507.33	89.33	13	0.15_30D0.1	1062.67	624.00
6	0.10_50D1	-	169.50	14	0.15_50D1	57.33	187.00
7	0.10_50D0.1	392.67	136.25	15	0.15_50D0.1	164.67	138.00

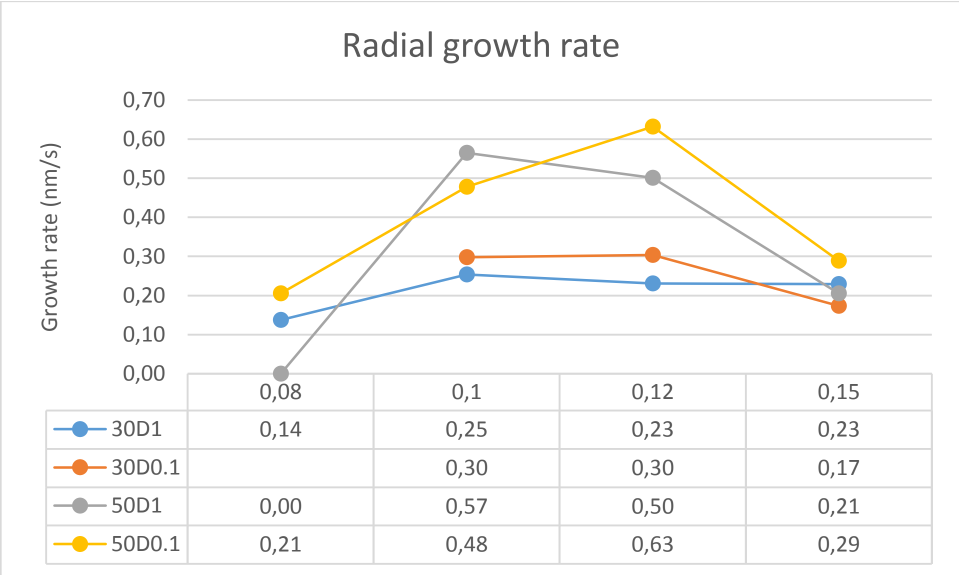
Table 2 Average axial length and diameter of samples.

With these measurement result, we divide those length with growth time used for each sample to get the growth rate which plot in figure 5 for both axial and radial growth. From these plot we can see the trend of growth for each of the samples.



	0,08	0,1	0,12	0,15
30D1	2,16	0,18	0,11	0,04
30D0.1		5,02	1,02	0,30
50D1	0,00	0,00	0,18	0,06
50D0.1	4,49	1,31	0,29	0,17

(a)



	0,08	0,1	0,12	0,15
30D1	0,14	0,25	0,23	0,23
30D0.1		0,30	0,30	0,17
50D1	0,00	0,57	0,50	0,21
50D0.1	0,21	0,48	0,63	0,29

(b)

Figure 5 Plot of (a) axail and (b) radial growth rate from all of the sample

Figure 5 a, the axail growth of nanowire inversly proportion to the composition of Sb. As the composition increase, the growth of nanowire decrease gradually except samples with high density (1 particle/µm^2). With the previous observation, there is not much growth in verticle direction for those high Au nanoparticles density. On the other hand, the radial growth, figure 5 b, has the same trend in all of the sample either nanowire growth or surface growth at nucleation site. This rate is proportion to the composition but, when the composition is above 0.12, the growth decreases. Hence the radial growth rate is drop at x=0.15 in all of the samples.

Conclusion

The growth within the sample could be effect by the other parameter like an excessive material in the machine as edge effect. Besides, the difference between the density of nucleation site like Au nanoparticles could effect the growth of nanowire directly. As we seen that there is only surface growth for those high density Au nanoparticles. In addition, It could be clearly seen that diameter of Au nanoparticles also affect the growth of nanowire. As we can observe the different growth in the same growth condition but with variation of Au nanoparticles diameter, the less particle diameter has the higher growth.

With data acquired from the experiment, it showes that nanowires with a higher density, diameter, and the composition have got lower axial growth rate. However, the growth in radial direction is directly proportional to the composition and we can oberve this kind of growth in all of the samples, either axial growth as nanowire or surface growth at nucleation site.

Reference

1. Enhanced Sb incorporation in InAsSb nanowires grown by metalorganic vapor phase epitax, B. Mattias Borg, Kimberly A. Dick, Joël Eymery, and Lars-Erik Wernersson, 2011
2. John H. Davies, The physics of low-dimensional semiconductors: An introduction, Cambridge University press, 1998.