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Recent progress on HVPE-grown III-V solar cells with extremely high growth rates

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Abstract

Hydride vapor-phase epitaxy (HVPE) has several features to lower manufacturing costs of III-V solar cells, such as a high-speed growth, a high utilization efficiency of input materials, and a use of less expensive group III sources. Under traditional HVPE growth of GaAs that involve the growth from As_x species, the growth rate exhibits a strong temperature dependence due to slow kinetics at the surface, and the growth rate was limited to 10 μm/h at a low deposition temperature of 660°C. Despite this limitation, the kinetic barrier can be reduced in non-standard growth condition, when the AsH_3 reaches the surface before decomposing. Using this growth mechanism, we demonstrate GaAs solar cells grown at an extremely high growth rate of 120 μm/h with a conversion efficiency of 20.01%.

1. Introduction

III-V photovoltaic devices hold record conversion efficiencies for both single and multijunction cells, as well as modules [1]. Despite their superior performance compared to prevalent materials such as Si solar cells, these high-efficiency III-V devices are currently limited to high-value applications such as space systems, owing to their high growth cost that arises from the use of incumbent metal–organic vapor phase epitaxy (MOVPE). The growth costs are generally related to the input material costs and throughput performance. The growth costs should be lowered to enable their large-scale applications, such as in street vehicles, unmanned aerial vehicles, while simultaneously maintaining their high conversion efficiency.

Hydride vapor phase epitaxy (HVPE) is considered as a promising low-cost alternative to MOVPE. HVPE has several features to lower the growth costs of III-V solar cells, such as a high-speed growth, a high utilization efficiency of input materials, and a use of less expensive group III sources. Using HVPE, we have successfully produced GaAs solar cells with conversion efficiency of 22.1% at growth rates of 8 μm/h [2], which was comparable with MOVPE-grown devices. However, this rate was not enough to improve the throughput performance. Here, we study the growth kinetics of GaAs in HVPE to develop GaAs solar cells grown at extremely high growth rates.

2. HVPE design

Recently, we developed a custom-built, laminar flow-type, hot-wall HVPE reactor (Taiyo Nippon Sanso, H260) operated under atmospheric pressure as shown in Fig. 1 [3]. This unique quartz reactor tube possesses three chambers: two growth chambers (GaAs and InGaP) and one preparation chamber. Multiple layers with abrupt heterointerface that are vital to high performance III-V devices can be grown by transferring the substrate from one to another growth chamber through a mechanical transfer arm.

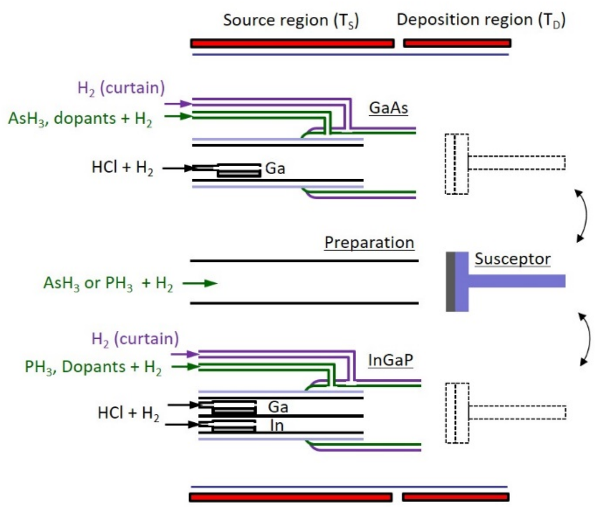

Fig. 1 The schematic of growth chambers of the custom-built quartz HVPE reactor utilized.

Gaseous hydrogen chloride (HCl), Ga, and In metals were used to form cost-effective metal-chlorides as group-III precursors instead of metalorganics. AsH_3 and PH_3 were used as group-V precursors. DMZn and H_2S were used as the p- and n-type dopants, respectively. The temperatures of source (T_S) and deposition (T_D) regions were independently controlled using a six-zone clamshell resistance furnace. The total flow rate of the H_2-carrier gas excluded H_2 curtain gas was 8 slm, while 10 slm of H_2 curtain gas was used to prevent contaminations of the reactants present in the two growth chambers.

3. Results and discussion

In order to improve the throughput performance of the HVPE growth, it is important to know how the growth condition change the growth kinetics of GaAs. Fig. 2(a) shows the growth rate of GaAs as a function of the T_D. The T_S was set to 850°C. The flow rate of gaseous HCl over Ga metal and AsH_3 were 10 and 40 sccm. GaAs films were grown on 2-inch diameter p-GaAs (001) substrates miscut 4° toward the

(111)B direction. The growth rate exhibits a strong temperature dependence and the highest growth rate of 24 μm/h was obtained at T_D = 710°C. In addition, we calculated a kinetic barrier to be ~198 kJ/mol from Arrhenius plot in this study. This value fairly agrees with the previously reported value of ~200 kJ/mol for the traditional HVPE growth using As_x species [4]. Therefore, in this growth condition, a large fraction of AsH_3 was decomposed to As_x species until it reached the surface. However, GaAs solar cells commonly include InGaP layers, which require a low T_D of 660°C to suppress the decomposition during the growth [5]. Hence, in order to grow GaAs solar cells in a single growth temperature with improved throughput performance, the development of high growth rates at lower T_D is prerequisite. On the other hand, it is known that the kinetic barrier can be drastically reduced to less than ~10 kJ/mol in non-standard growth condition, when the AsH_3 reaches the surface before decomposing [6]. Because the cracking ratio of AsH_3 in a hot wall reactor seems to be related to the ambient temperature and gas velocity [7], we study the effect of T_S on the growth rate as shown in Fig. 2(b). The T_D was set to 660°C. When the Ts was decreased from 850 to 700°C, the growth rate was significantly increased from 10.5 to 120.0 μm/h. This suggests that lower Ts left a significant fraction of uncracked AsH_3 until it reached the surface, leading to a change in the growth regime from kinetically limitation using As_x species to mass transport limitation using uncracked AsH_3.

Then, we compared characteristics of GaAs solar cells [3] grown at varying growth rates as shown in Fig. 3. The growth rate of the p-GaAs base layer was varied from 8 μm/h to 120 μm/h, while growth rates for other layers were not changed for all cells. Here, note that T_S = 850°C was used for cells grown at 8 and 12 μm/h, while T_S = 700°C was used for cells grown at 56, 82, and 120 μm/h. In solar cell measurements in Fig. 3(b), we successfully obtained the conversion efficiency of 20.01% for the cell grown at 120 μm/h. However, we can clearly see that both the open-circuit voltage (V_{OC}) and short-circuit current density (J_{SC}) for cells grown at T_S = 700°C (56, 82, and 120 μm/h) was slightly lower than those for cells grown at T_S = 850°C (8 and 12 μm/h). The independent measurements using secondary ion mass spectrometry revealed that poor abruptness of heterointerface between the p-GaAs base and the p-InGaP BSF layer was observed for the cell grown at 120 μm/h (not shown). This suggests that abruptness of heterointerfaces becomes more sensitive to the growth sequence for mass transport limitation due to faster kinetics at the surface. Further discussion on structural and optical characteristics will be presented at the conference.

4. Conclusions

We demonstrated GaAs solar cells grown at an extremely high growth rate of 120 μm/h with a conversion efficiency of 20.01% using HVPE. The growth rate of 120 μm/h enables the growth of the GaAs cell structure in less than 4 minutes instead of hours in typical growth technique. Though there is a window to improve the cell performance, this study is a major step toward the development of low-cost, highly-efficient III–V solar cells using HVPE.

Acknowledgements

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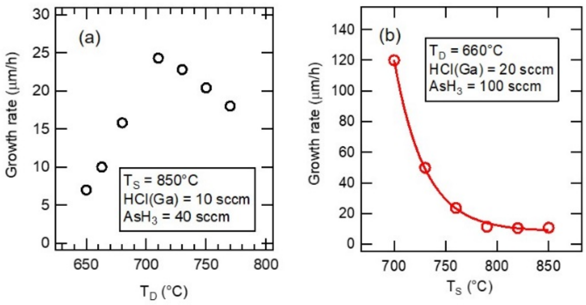

Fig. 2 The growth rate of GaAs as a function of (a) T_D and (b)T_S.

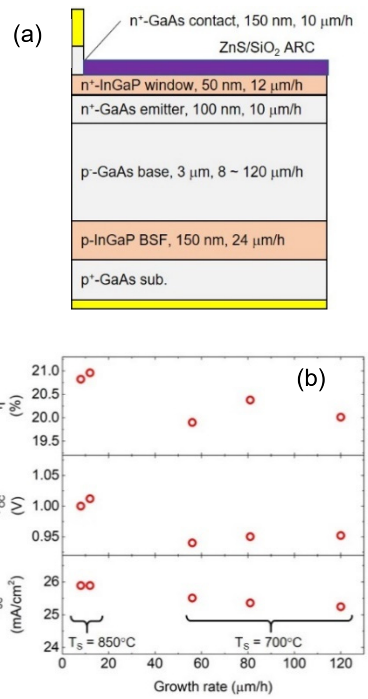

Fig. 3 (a) Schematic structure of GaAs solar cells used and (b) cell performance of GaAs solar cells as a function of the growth rate.