



ELSEVIER

Journal of Crystal Growth 156 (1995) 177–185

JOURNAL OF **CRYSTAL
GROWTH**

Influence of the temperature of the reactor top wall on growth processes in horizontal MOVPE reactors

Yuan Li ^{*}, L.J. Giling

Department of Solid State Physics III, RIM, University of Nijmegen Toernooiveld, 6525 ED Nijmegen, The Netherlands

Received 27 March 1995; manuscript received in final form 26 June 1995

Abstract

The influence of the temperature of the top wall of horizontal reactor cells on the growth rate, the doping of GaAs with disilane and diethylzinc, and on the Al composition in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ has been studied. It is found that the uniformity of the growth rate of the GaAs layer, the carrier concentration in GaAs and the Al composition in $\text{Al}_x\text{Ga}_{1-x}\text{As}$, all are significantly improved by keeping the top wall temperature at around 370°C. These effects are found to be more pronounced at one atmosphere than at 200 mbar. The experimental results are explained by the influence of thermal diffusion on the growth and doping of GaAs or AlGaAs, which depends on the temperature gradient above the susceptor, and by the depletion of the growth and dopant species because of the deposition of the compound or of the individual dopant species on the top wall of the reactor. Controlled top cooling in this way provides an effective and simple method to improve the performance of the horizontal MOVPE reactors, especially atmospheric pressure reactors, with almost no extra cost for the operation of the system.

1. Introduction

Metalorganic vapor phase epitaxy (MOVPE) has found widespread use in the field of micro- and opto-electronics because it has shown to be the most versatile technique to produce virtually all III/V and II/VI semiconductor compounds and alloys. For the epitaxial growth of these compounds an abrupt interface, uniform layer thickness, uniform composition and doping profile are quite important for both material studies

and device fabrication, therefore, much attention has been paid to the flow dynamics, reactor design and depletion effects during the last decade.

Among the different types of reactors which are known, the horizontal reactor, because of its simplicity, is widely used in many laboratories. If this reactor is provided with a rectangular cross-section, the growth results lend themselves to analytical studies of the growth process, which will give more and direct insight into the physics and chemistry of the MOVPE process [1,2]. The influence of the temperature gradient above the susceptor on the growth rate in the horizontal MOVPE reactor theoretically has been intensively investigated [3], however, no corresponding

^{*} Corresponding author.

experimental studies have been done so far to demonstrate that influence. To our knowledge also no systematic attention has ever been paid to the effect of the temperature gradient on the doping phenomena and on the composition of ternary materials.

A further improvement of the horizontal reactor cell at a first glance is very difficult because the simple geometry of horizontal reactors leaves almost no space for designers to improve their performances by changing the configuration. Depletion of the growth species along the flow direction will always occur which reduces the thickness uniformity of the grown layer over a whole wafer. By increasing the free height of the reactor above the susceptor, h , the thickness uniformity could be improved, because when the growth is gas-phase diffusion-controlled the depletion is quadratically dependent on h in the exponent as follows from the formula of growth rate, r_g , as a function of the axial position on the susceptor, z

$$r_g = \frac{2.68DC_0}{h} \exp\left(-\frac{2.84D}{h^2V_0}z\right), \quad (1)$$

where D is the diffusion coefficient, C_0 the input concentration of group III components, V_0 the mean gas velocity at the reactor inlet at room temperature [1–3]. However, the height is limited by the onset to destabilization of the laminar flow to convective flow which occurs when the Rayleigh number exceeds a critical value [4,5]. An improvement can also be achieved by increasing the total gas flow through the reactor, although this is less effective because the depletion effect only linearly depends on the gas flow velocity in the exponent (see Eq. (1)), while much more source material will be wasted which raises the operational cost of the system. Another way to counteract the effect of depletion is to tilt the susceptor a few degrees [1], while an optimum condition can only be achieved for a certain tilt angle of the susceptor at a fixed gas velocity which is dependent on the growth temperature.

By controlling the temperature of the reactor top wall the temperature gradient above the susceptor can be varied independently. In this paper, experimental results are given of a systematic

study of the effect of the top wall temperature of the reactor cell on the growth rate and doping with disilane (Si_2H_6) and diethylzinc (DEZn) of GaAs, and on the Al composition in $\text{Al}_x\text{Ga}_{1-x}\text{As}$. This study provides new insight into the MOVPE processes, which leads to an effective and simple improvement of the performance of the horizontal MOVPE reactor, especially atmospheric pressure reactors, with almost no extra costs for the operation of the system.

2. Experiments

The experiments were performed in two growth systems. The first is an atmospheric pressure system (indicated as reactor I) containing a quartz reactor cell with a rectangular cross-section which could be water or air cooled on its top. The free height above the susceptor, h , is about 1.6 cm. The results of growth and doping experiments in this system when the water cooler was used have been reported elsewhere [1,6,7]. When the water cooler was used, the temperature of the top wall, T_{top} , was so low that elemental arsenic was deposited on the top wall. With the use of the air cooler, T_{top} could be varied by changing the air flow to the top of the reactor. In this way a temperature could be established at which the deposition of arsenic did not occur. Calculations and measurements indicated that this temperature was in the range from 350 to 385°C, depending on the partial pressure of arsine in the reactor. At these temperatures almost no deposition of GaAs on the top wall of the reactor will occur too, so that the top wall could be kept transparent during the growth run. When no top cooler was used, the top wall temperature was so high that strong deposition of GaAs on the top wall of the reactor was observed.

The second system involved in this study is a system which can be used at 1 atm and at lower pressure (herewith referred to as reactor II). This system has a single wall reactor cell so that the air cooler could be used. The reactor cell is made of quartz material with a cross section between a rectangle and ellipse; therefore, it can withstand

the over pressure when operated at low pressure. The free height above the susceptor is 2.0 cm in the middle of the susceptor and 1.8 cm at both sides of the susceptor.

Trimethylgallium (TMG), trimethylaluminium (TMAI) and arsine (AsH_3) were used as source materials with H_2 as the carrier gas. Si_2H_6 and DEZn were used as n-type and p-type doping precursors, respectively. Semi-insulating GaAs wafers misoriented 2° off (100) towards (110) were used as substrates. All growth runs were performed at 700°C , at which the growth of (Al)GaAs is gas phase diffusion limited. When the total pressure was decreased from 1 atm to 200 mbar the mole fractions of TMG, TMAI, and Si_2H_6 were kept unchanged while the V/III ratios were increased in order to ensure that the crystalline quality of the grown materials remained good. Flow conditions in reactor I and reactor II are quite similar so that the results from both system could be compared. The exact conditions are shown in the figures.

The thickness of the grown layer was measured by cleaving and staining. The electrical characterization was performed at room temperature by Hall–Van der Pauw measurements. The aluminum solid phase composition x_s of the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layers was determined by photoluminescence (PL) measurements performed at 4.3 K [8].

3. Results and discussions

The effect of the temperature of the reactor top wall on the growth rate of GaAs and the Zn-doping of GaAs has been studied with reactor I, while its effect on the growth rate, Al incorporation in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ and Si-doping of GaAs has been investigated with reactor II. For a proper understanding of the experimental results, first a general discussion is given of the three mechanisms which play an important role in these experiments: In the first place, an increase of T_{top} will decrease the temperature gradient in the vertical direction which actually reduces the thermal diffusion effect of the growth species. In general, the effect of thermal diffusion is to de-

crease the concentration of the growth species at the hot susceptor [3,9,10], so a reduction of this effect will increase the concentration of growth species at the susceptor. At the same time, the mean temperature in the reactor will increase, so also the diffusion coefficient will become larger [3]. Both these effects will enhance the growth rate. In practical situations for growth of GaAs the thermal diffusion effect is predominant, therefore, only this effect will be taken into account hereafter. The consequence of a higher growth rate, while keeping the input concentration constant, is an increase in the depletion of growth species. In the second place, when T_{top} is high the possibility of decomposition of the growth species at the top wall of the reactor will become larger so that deposition of the concerned compound at the top wall may occur, which is certainly the case when no top cooler is used. It is important to know the absolute value of the temperature of the inside top wall of the reactor, in order to decide whether the deposition is reaction rate or diffusion rate limited. The temperature, as measured by the thermocouple, was lower than 550°C for all the experiments in this work. This means that the deposition of GaAs on the top wall is reaction rate limited. For such a case, the growth rate, r_{top} , is given by the following expression [11]:

$$r_{\text{top}} = k_0 C_0 \exp\left(\frac{-E_a}{RT_{\text{top}}}\right), \quad (2)$$

where k_0 is a pre-exponential factor, E_a is the activation energy, C_0 is the input concentration of the group III component, R is the gas constant. In the third place when T_{top} is too low the deposition of the individual elements, e.g. elemental arsenic, on the top wall will occur, which is the case when the water cooler is used.

3.1. Layer thickness uniformity of GaAs

The effect of the top wall temperature on the layer thickness uniformity was studied with both reactor I and reactor II. The growth rate as a function of the axial position of the samples on the susceptor, z , for reactor II is shown in Fig. 1

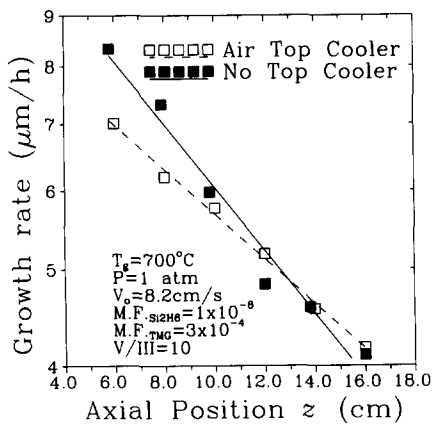


Fig. 1. Semilog plot of growth rate of GaAs as a function of axial position on the susceptor, for experiments with and without air top cooler performed with reactor II at 1 atm. The solid line and the dashed line represent the best fits to an exponential function.

and in Fig. 2 for experiments performed at 1 atm and 200 mbar, respectively. From Fig. 1 it can be seen clearly that at 1 atm the depletion gets less pronounced when the air top cooler was used compared to when no top cooler was employed. At 200 mbar the layer thickness uniformity only slightly improved when the air top cooler was used (Fig. 2).

The improvement of layer thickness uniformity at 1 atm by using the air top cooler can be explained by the enhancement of the thermal diffusion effect of the growth species and the suppression of the deposition of GaAs on the top wall, due to the decrease of the top wall temperature. Both of these effects lower the depletion, which accounts for the smaller slope for growth with the use of the air top cooler in Fig. 1. The effect will be stronger for reactor cells with a smaller height because T_{top} without cooling will be higher in that case, which results in a larger cooperative effect in increasing the T -gradient and suppressing parasitic deposition on the top wall when the top cooler is used. This was confirmed in reactor I where h was 20% smaller.

At lower pressures, the deposition of GaAs on the top wall – even without cooling – does not

occur because the concentration of TMG is decreased simultaneously with the decrease of the total pressure (mole fraction of TMG constant). A lower input concentration at 200 mbar does not lead to a lower growth rate at the susceptor (compare Fig. 1 and Fig. 2), because the smaller value of C_0 is compensated by the larger diffusion coefficient, as follows from Eq. (1). However, at the top wall, the deposition is limited by the reaction rate and for that case the deposition is given by Eq. (2). Both the smaller input concentration and the low temperature lead to a very small (negligible) deposition rate on the top wall. In this case, the effect of the air top cooler on the growth rate is only found back in an enhancement of the thermal diffusion effect of the growth species, leading to a smaller overall growth rate. Therefore, top cooling in this case is less effective in improving the layer thickness uniformity as compared with its use at 1 atm.

3.2. Si-doping of GaAs

The effect of the top wall temperature of the reactor on the uniformity of the carrier concentration, $n(N_D^+ - N_A^-)$, of GaAs doped with Si_2H_6

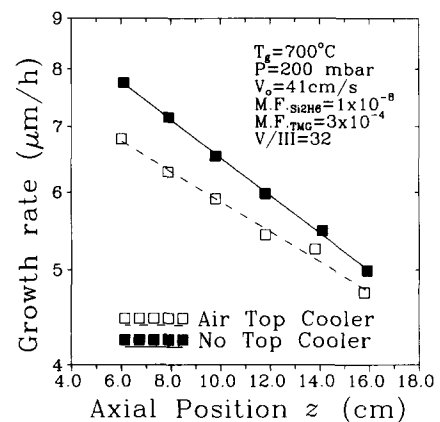


Fig. 2. Semilog plot of growth rate of GaAs as a function of axial position on the susceptor, for experiments with and without air top cooler performed with reactor II at 200 mbar. The solid line and the dashed line represent the best fits to an exponential function.

was investigated with reactor II. The results are shown in Figs. 3 and 4 for growths performed at 1 atm and 200 mbar, respectively. An evident improvement of the carrier concentration uniformity in the Si-doped GaAs is found at 1 atm when the air top cooler was used compared to when no top cooler was used. At 200 mbar, the carrier concentration level of the Si-doped GaAs is quite uniform in both cases with and without use of the air top cooler.

Doping of GaAs with disilane in MOVPE or the deposition of Si from disilane have been investigated extensively [7,12–15], although the uniformity of the carrier concentration of Si-doped GaAs was scarcely studied. It was found that the temperature dependence followed a complicated behavior, but there is a general agreement about the inverse dependence of the doping level on the growth rate.

At 1 atm all Si₂H₆ is effectively converted at the susceptor to SiH₄ and the doping takes place via the small amount of SiH₂ which is determined by the equilibrium SiH₄ ⇌ SiH₂ + H₂, so that the concentration of the input dopant in the MOVPE reactor is almost constant showing no apparent depletion of the “disilane” at all [7]. The deposition of Si on the top wall, where the temperature

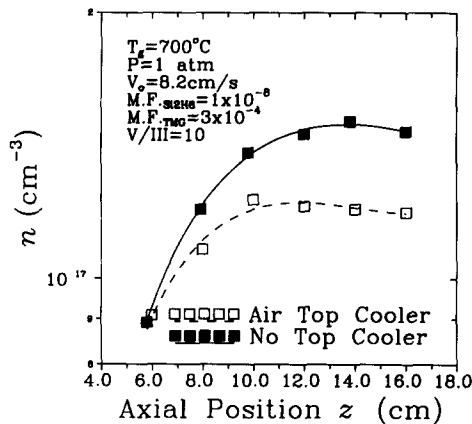


Fig. 3. Semilog plot of carrier concentration of Si-doped GaAs as a function of axial position on the susceptor, for experiments with and without air top cooler performed with reactor II at 1 atm. The solid line and the dashed line are drawn as a guidance to the eye.

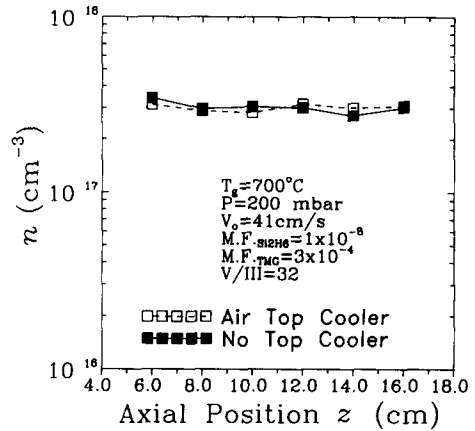


Fig. 4. Semilog plot of carrier concentration of Si-doped GaAs as a function of axial position on the susceptor, for experiments with and without air top cooler performed with reactor II at 200 mbar. The experimental points are connected with a solid line and a dashed line for the above two cases, respectively.

is lower, is negligible because of the high overall activation energy of the process [7]. In contrast, a strong depletion of TMG is always present in the horizontal reactor along the flow direction, as has been demonstrated in Fig. 1, therefore, an increase of the doping level as a function of z is normally expected because the flux ratio SiH₂/TMG increases, as shown in Fig. 3. Similar behavior of Si-doping of GaAs was also observed in reactor I. The improvement of the carrier concentration uniformity with the use of the air top cooler in this case can be explained by the improvement of the layer thickness uniformity as mentioned in the preceding section. The grown layers show very low compensation ratios, $\Theta = N_A^-/N_D^+$, of around 0.1, determined with the measured values of the free carrier concentrations and the mobilities, using the data given by Walukiewicz et al. [16]. The Si incorporation rate, R_{Si} , can be calculated from the carrier concentration, n , the compensation ratio, Θ , and the growth rate of GaAs, r_g , with the relation:

$$R_{Si} = r_g N_{Si} = r_g \frac{1 + \Theta}{1 - \Theta} n, \quad (3)$$

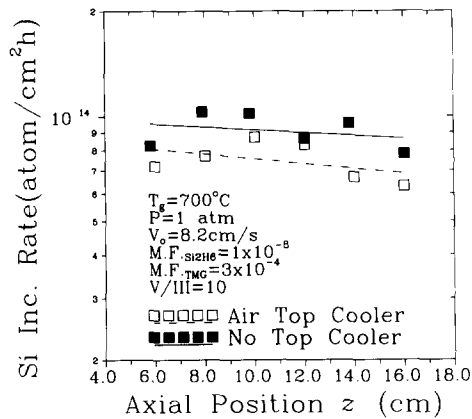


Fig. 5. Semilog plot of Si incorporation rate as a function of axial position on the susceptor for growth performed with reactor II at 1 atm. The solid line and the dashed line represent the best fits to an exponential function.

where N_{Si} is the incorporated Si concentration [16]. The results are shown in Fig. 5. It can be seen that the incorporation of Si is relatively uniform along the susceptor, decreasing only by 12% from a value z of 6 cm to a value z of 16 cm. An enhancement of the incorporation of Si when no top cooler was used can be seen clearly, which can be explained by the decrease of the thermal diffusion effect of Si_2H_6 .

At 200 mbar, the mechanism of doping of GaAs with Si_2H_6 is different. Following the chemical boundary layer model of the system [12,17] it is known that under these conditions the incorporation of Si is limited by the bulk gas phase diffusion of Si_2H_6 , similar behavior as TMG for the growth of GaAs itself. Consequently, similar depletion behavior of Si_2H_6 as TMG is expected, resulting in a homogeneous flux of $[\text{Si}]/[\text{Ga}]$ and therefore a uniform doping concentration. The compensation ratios of the grown materials are around 0.2 in this case. From Eq. (3) the Si incorporation rate is calculated and the results are shown in Fig. 6. The higher magnitude of the incorporation rate is due to the higher concentration of SiH_2 which is directly produced from the decomposition of Si_2H_6 : $\text{Si}_2\text{H}_6 \rightarrow \text{SiH}_4 + \text{SiH}_2$. The much longer effective free path of SiH_2 at lower pressures – before it reacts back

with H_2 to SiH_4 – is the reason for a higher surface concentration of SiH_2 in this case. Because the supply of SiH_2 is limited by the diffusion of Si_2H_6 to the susceptor, strong depletion effects are expected and therefore the incorporation rate decreases gradually with z (Fig. 6). The effect of the top wall temperature on the depletion of Si in this case can be explained in a similar way as for TMG. The similarity can be seen directly by comparing Fig. 6 with Fig. 2.

3.3. The Al composition in AlGaAs

The effect of the top wall temperature of the reactor on the Al incorporation in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ was investigated at 1 atm and 200 mbar with reactor II. In Fig. 7 the Al composition in the solid phase of the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is shown as a function of z , for growth at 1 atm with and without use of the air top cooler. The gas phase composition of Al, x_g , was 0.25 in this study. It can be seen clearly that at 1 atm the Al composition uniformity along the susceptor is significantly improved by the use of the air top cooler as compared with when no top cooler was used, indicated by a reduction of the deviation of the Al composition in the solid phase ($x_{\text{s,max}} - x_{\text{s,min}}$)

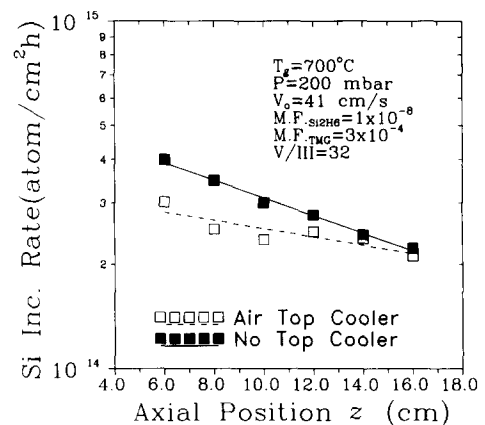


Fig. 6. Semilog plot of Si incorporation rate as a function of axial position on the susceptor for growth performed with reactor II at 200 mbar. The solid line and the dashed line represent the best fits to an exponential function.

from 0.086 to 0.013. At 200 mbar, the Al composition homogeneity is also improved when the air top cooler is used. The corresponding difference in Al composition for samples at different positions as compared to that of the first sample on the susceptor, Δx_s , is shown in Fig. 8. The improvement of the Al composition uniformity, although less significant, is characterized by a decrease of the deviation of x_s from 0.006 when no top cooler was used to a deviation of 0.001 when the air top cooler was used. The x_s values in this case are quite close to the values of the layers grown at 1 atm with the use of the air top cooler.

It is known that the incorporation of Al in AlGaAs can be considered as a simultaneous deposition of AlAs and GaAs on the substrate, both follow a similar process [11]. Since the thermal diffusion factor of TMG and TMAI are very close to each other [10], and their diffusion coefficients are quite similar too [18], the influences of the top cooler on the Al incorporation through a change of the temperature gradient and the mean temperature in the reactor is expected to be small. Therefore, the effect of top wall temperature on the Al composition in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ can only be ascribed to a difference in deposition of GaAs and AlAs on the top wall due to an unequal chemical behavior of TMG and TMAI:

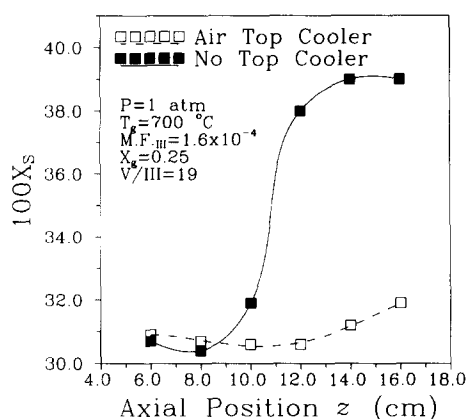


Fig. 7. Al composition in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ as a function of axial position on the susceptor, for experiments with and without air top cooler performed with reactor II at 1 atm. The solid line and the dashed line are drawn as a guide to the eye.

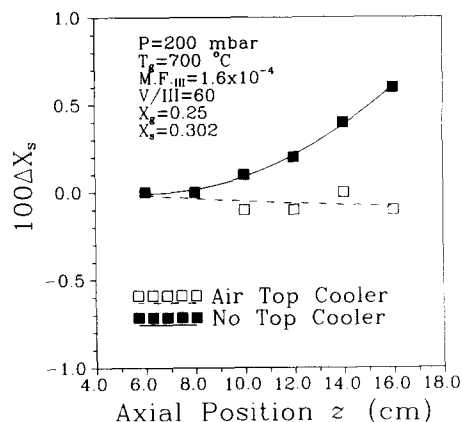


Fig. 8. Difference in Al composition of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ with reference to the first sample, $x_s = 0.302$, as a function of axial position on the susceptor, for experiments with and without air top cooler performed with reactor II at 200 mbar. The solid line and the dashed line are drawn as a guide to the eye.

TMG can decompose more easily than TMAI at the temperature of the top wall [18] so that the deposition of GaAs on the top wall is predominant. At 1 atm, GaAs could be easily deposited on the top wall of the reactor if no top cooler was used, leading to a fast depletion of Ga species, as could be seen in Fig. 1, which resulted in an increase of the Al composition in the grown $\text{Al}_x\text{Ga}_{1-x}\text{As}$ from a z value of 8 cm. When the air top cooler was used, the deposition of GaAs at the top wall of the reactor was suppressed, consequently, a quite uniform Al composition in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ along the axis of the susceptor can be obtained.

For growth performed at 200 mbar, the deposition of GaAs on the top wall was eliminated anyway, as has been discussed in Section 3.1, resulting in a good Al composition uniformity along the susceptor for both cases with and without use of the air top cooler. The slight improvement of the Al composition profile when the air top cooler was used could still be explained as a further decrease of the deposition of GaAs on the top wall when the air top cooler was used. The fact that the aluminum fractions are quite similar for $\text{Al}_x\text{Ga}_{1-x}\text{As}$ grown at 200 mbar with and without use of the air top cooler, grown at 1

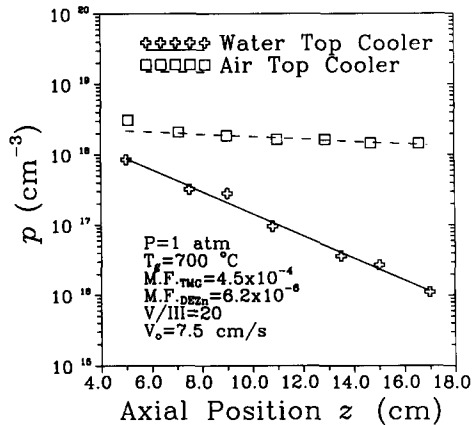


Fig. 9. Semilog plot of carrier concentrations of Zn-doped GaAs, p , as a function of the axial position on susceptor, for growths at 1 atm using a water top cooler or an air top cooler in reactor 1. The solid line and the dashed line represent the best fits to an exponential function.

atm with use of the air top cooler and grown at 1 atm on the first half of the susceptor without use of the air top cooler, supports the above interpretation.

3.4. Zn-doping of GaAs

The effect of the top wall temperature on the Zn-doping of GaAs by DEZn was studied with reactor I. When the water cooler was used, Zn-doping of GaAs by DEZn showed a strong depletion effect. Instead, when the air cooler was used, the depletion effect was significantly suppressed, leading to a quite uniform Zn-doping profile along the flow direction, as well as an enhancement of the doping level. The results are compared in Fig. 9.

The strong depletion of Zn during Zn-doping of GaAs when the water top cooler was used has been reported in a previous paper and it was explained by the deposition of Zn at the cold top wall of the reactor [19]. It is known that doping of GaAs with DEZn is controlled by an adsorption/desorption equilibrium at the surface steps and no depletion of Zn should be expected [19]. The results presented here demonstrate clearly that the depletion of Zn in the reactor indeed could be almost completely suppressed by

increasing the top wall temperature with the use of the air top cooler instead of the water cooler, preventing in this way the deposition of Zn on the top wall. The higher doping level obtained when the air top cooler was used is a direct consequence of the elimination of the deposition of Zn on the top wall, which leads to a higher partial pressure of Zn in the reactor.

4. Conclusions

The effects of the temperature of the top wall on the uniformity of the growth rate of GaAs, Al composition in $\text{Al}_x\text{Ga}_{1-x}\text{As}$, carrier concentration of Si-doped GaAs with disilane and Zn-doped GaAs with DEZn, have been studied in horizontal MOVPE reactors with a rectangular cross-section. The temperature of the top wall of the reactor was varied by using a water top cooler, an air top cooler or no cooler at all. It is found that at atmospheric pressure, the thickness uniformity of the grown layer, Al composition uniformity in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ and carrier concentration profiles of Si-doped GaAs, all are significantly improved by keeping the top wall temperature at about 370°C with the use of an air top cooler, as compared with those when no cooler is used. By using the air top cooler instead of the water top cooler, the strong depletion of Zn is suppressed in the doping of GaAs with DEZn, while also the deposition of arsenic on the top wall of the reactor is avoided. At 200 mbar the effect of the top wall temperature on the MOVPE process is less pronounced as compared with that at 1 atm; however, clear improvements on the growth rate uniformity, Al composition uniformity can still be obtained by the use of the air top cooler. The carrier concentration level of GaAs doped with disilane is only slightly influenced by the top wall temperature at 200 mbar, while a strong effect of the top wall temperature on the Si incorporation rate is found. The similar depletion effect of Si_2H_6 and TMG, and a similar dependence of the incorporation rate of Si and the growth rate of GaAs itself on the top wall temperature, lead to a carrier concentration level in Si-doped GaAs almost independent of the position on the sus-

ceptor and the temperature of the reactor top wall at 200 mbar. The experimental results are explained in terms of the influences of top wall temperature on the deposition of the involved elements or compounds on the top wall and its effect on the thermal diffusion process. This work demonstrates that the temperature gradient above the susceptor in the horizontal reactor influences the MOVPE process significantly. From the practical points of view this work offers an effective, simple and easy technique to improve the function of the horizontal MOVPE reactor, especially the atmospheric pressure system, with almost no extra cost for the operation of the system.

Acknowledgements

The authors would like to thank Dr. X. Tang for fruitful discussions and Mr. H. van der Linden and Mr. P. van Rijsingen for their technical support. Ir. J. Schermer is acknowledged for his contribution of installing the computer program for the new system. The authors are grateful to Dr. F. Driessen and Mr. S. Olsthoorn for the PL measurements and Ir. G. Bauhuis for the Hall measurements.

References

- [1] J. van de Ven, G.M.J. Rutten, M.J. Raaijmakers and L.J. Giling, *J. Crystal Growth* 76 (1986) 352.
- [2] W.G.J.H.M. van Sark, G. Janssen, M.H.J.M. de Croon and L.J. Giling, *Semicond. Sci. Technol.* 5 (1990) 16.
- [3] W.G.J.H.M. van Sark, M.H.J.M. de Croon, G. Janssen and L.J. Giling, *Semicond. Sci. Technol.* 5 (1990) 36.
- [4] L.J. Giling, in: *Crystal Growth of Electronic Materials*, Ed. E. Kaldis (Elsevier, Amsterdam, 1985).
- [5] E.P. Visser, C.R. Kleijn, C.A.M. Govers, C.J. Hoogenboom and L.J. Giling, *J. Crystal Growth* 94 (1989) 929.
- [6] X. Tang, J. te Nijenhuis, Yuan Li and L.J. Giling, *J. Crystal Growth* 107 (1991) 263.
- [7] P.R. Hageman, X. Tang, M.H.J.M. de Croon and L.J. Giling, *J. Crystal Growth* 98 (1989) 249.
- [8] H.G.M. Lochs, S.M. Olsthoorn, T.P. Huijgen, F.L.M. Spijkers, F.A.J.M. Driessen and L.J. Giling, *J. Phys.: Condens. Matter* 3 (1991) 7179.
- [9] K.E. Grew and T.L. Ibbs, *Thermal Diffusion in Gases* (Cambridge University Press, London, 1952).
- [10] W.L. Holstein, *J. Electrochem. Soc.: Solid-State Sci. Technol.* 135 (1988) 1788.
- [11] W.G.J.H.M. van Sark, G.J.H.M. Janssen, M.H.J.M. de Croon, X. Tang, L.J. Giling, W.M. Arnold Bik, C.P.M. Dunselman, F.H.P.M. Habraken and W.F. van der Weg, *J. Appl. Phys.* 64 (1988) 195.
- [12] P.R. Hageman, M.H.J.M. de Croon, J.N.H. Reek and L.J. Giling, *J. Crystal Growth* 116 (1992) 169.
- [13] M. Shimazu, K. Kamon, K. Kimura, M. Mashita, M. Mihara and M. Ishii, *J. Crystal Growth* 83 (1987) 327.
- [14] H.K. Moffat and K.F. Jensen, *J. Electrochem. Soc.* 135 (1988) 459.
- [15] K.F. Roenigk, K.F. Jensen and R.W. Carr, *J. Phys. Chem.* 91 (1987) 5732.
- [16] W. Walukiewicz, L. Lagowski, L. Jastrzebski, M. Lichtensteiger and H.C. Gatos, *J. Appl. Phys.* 50 (1979) 899.
- [17] M.H.J.M. de Croon and L.J. Giling, *Prog. Crystal Growth Charact.* 19 (1989) 125.
- [18] M. Suzuki and M. Sato, *J. Electrochem. Soc.: Solid-State Sci. Technol.* 132 (1995) 1684.
- [19] P.R. Hageman, M.H.J.M. de Croon, X. Tang and L.J. Giling, *J. Crystal Growth* 129 (1993) 281.