Extended Abstracts of the 16th (1984 International) Conference on Solid State Devices and Materials, Kobe, 1984, pp. 671-674

Selectively Doped GaAs/n-AlGaAs Heterostructures Grown by MOCVD

Naoki Kobayashi and Takashi Fukui

Musashino Electrical Communication Laboratory,
Nippon Telegraph & Telephone Public Corporation.
Musashino-shi, Tokyo 180, Japan

Selectively doped GaAs/n-$Al_{0.3}Ga_{0.7}As$ heterostructures are grown by employing reduced pressure metal organic chemical vapor deposition. It is shown that the growth condition in an undoped $Al_{0.3}Ga_{0.7}As$ spacer layer has a remarkable effect on two dimensional electron gas (2DEG) mobility. A 2DEG mobility of 150000 $cm^2/V\cdot sec$ is obtained for a sheet electron concentration (N_s) of 6.9×10^{11} cm^{-2} at 4.2K. The 2DEG mobility increases with increasing N_s as a result of exposure to light and reaches a maximum value of 180000 $cm^2/V\cdot sec$ at $N_s=7.8\times10^{11}$ cm^{-2}.

(1) Introduction

Recently, selectively doped (SD) GaAs/n-AlGaAs heterostructures have become of major interest from the point of view of application to high-speed devices[1]. This is because the two dimensional electron gas (2DEG) accumulating at the heterointerface has extremely high mobility[2]. SD GaAs/n-AlGaAs heterostructures have conventionally been grown by Molecular Beam Epitaxy (MBE), and 2DEG mobility as high as 2120000 $cm^2/V\cdot sec$ (at 5K) has been reported[3]. These results show that MBE is a suitable growth method for obtaining abrupt heterointerfaces and doping profiles.

There have been several reports on SD GaAs/n-AlGaAs heterostructures grown by Metalorganic Chemical Vapor Deposition (MOCVD)[4-6]. However, MOCVD growth conditions for obtaining SD GaAs/n-AlGaAs heterostructures with high 2DEG mobility have not yet been clarified. In this paper, we describe the MOCVD growth apparatus and growth conditions for realizing SD GaAs/n-AlGaAs heterostructures having high electron mobility. From these results, it is clear that the growth conditions for the undoped $Al_{0.3}Ga_{0.7}As$ spacer layer, the ratio of arsine mole fraction to Ⅲ group organometallic compound mole fraction, has a considerable effect on 2DEG mobility.

(2) Experiment

O_2/H_2O contamination in the MOCVD growth of AlGaAs caused by an air-leak in the MOCVD gas manifold or reactor system or by O_2/H_2O included in materials such as arsine (AsH_3), results in oxygen incorporation in AlGaAs. Oxygen doped AlGaAs results

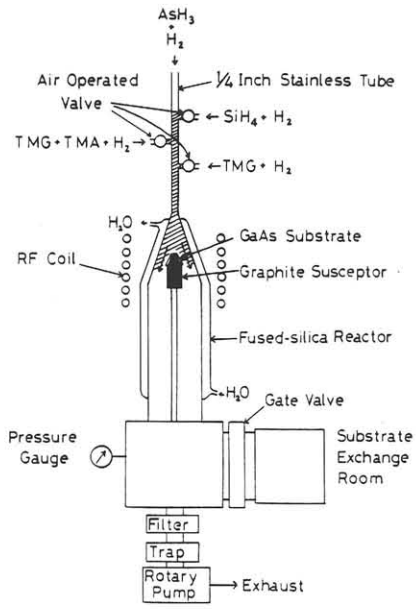

Fig.1 Schematic view of the reactor system in MOCVD apparatus used in this experiment.

in a semi-insulating layer due to the formation of deep impurity levels[7]. Therefore, in order to obtain stable n type doping in AlGaAs, a leak-proof gas manifold and reactor system are minimum requirements. Moreover, abrupt heterointerfaces and doping profiles are considered to be necessary to obtain SD GaAs/n-AlGaAs heterostructures with high 2DEG mobility. For this purpose, a rapid change in the gas composition over the substrate is required.

The MOCVD growth apparatus was helium leak-tested to a rate of less than 10^{-8} atm.cc/sec, and the oxygen concentration in the hydrogen carrier gas flowing through the gas manifold and the reactor from the paradium diffused hydrogen purifier was observed to

be less than 0.01 ppm. Figure 1 shows a schematic view of the reactor system in the MOCVD apparatus. Epitaxial layers were grown in the water-cooled vertical reactor system composed of a 100 mm inner-diameter fused silica tube and a graphite susceptor. Substrates were put on the graphite susceptor having inclined planes of about 25° to the gas flow direction. This is done to prevent gas flow pattern disturbance. The susceptor was heated by RF induction and its temperature was measured by an infrared radiation thermometer.

Trimethyl gallium (TMG), trimethyl aluminum (TMA), arsine (AsH_3) and silane (SiH_4) were used as the Ga, Al, As and Si sources, respectively. A rapid change in gas composition over the substrate is required to obtain abrupt heterointerfaces and doping profiles. For this purpose, it is necessary to minimize the inside volume V_0 (the crosshatched region shown in Fig.1) and increase the total gas flow velocity over the substrate. (60 cm/sec for a total flow of 10 standard liters per minute under a reactor pressure of 80 Torr, which were the typical condition used here) This reactor construction enabled the rapid change (within 0.1sec) of gas composition over the substrate. Cr-O doped semi-insulating substrates were used in the experiment. The substrate orientation was (100) tilted 2° toward (110). The growth temperature was 650°C and the growth rate was 4.0~12.0 Å/sec.

(3) Result and Discussion

3.1 Estimation of the abruptness in MOCVD growth GaAs/AlGaAs heterointerfaces

The abruptness of GaAs/$Al_{0.3}Ga_{0.7}As$ heterointerfaces grown by MOCVD was estimated by using Auger Electron Spectroscopy (AES) and Ar^+ ion sputtering. Figure 2 shows the composition depth profile of an epitaxial wafer with $Al_{0.3}Ga_{0.7}As$(500Å)/GaAs(5000Å)/GaAs substrate structure, having almost the same structure as SD heterostructures which will be described later. To obtain the exact abruptness of the GaAs/$Al_{0.3}Ga_{0.7}As$ heterointerface, the thickness of the $Al_{0.3}Ga_{0.7}As$ surface layer was measured with a field emission scanning electron microscope (x70000) and a low energy Auger sygnal (Al LVV line) was used because of the low escape depth (~5Å) of Auger electrons[8]. The abruptness measured by using the Al LVV and Ga LMM lines are observed to be 10.5Å and 20.5Å, respectively. This difference in abrupt-

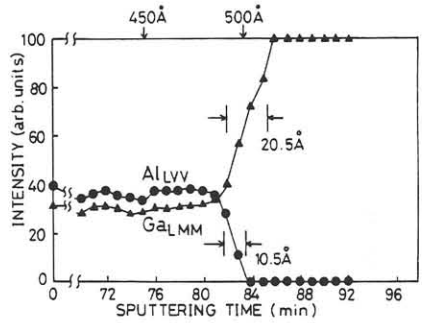

Fig.2 Composition depth profile of GaAs/AlGaAs heterostructure by using AES measurement.

ness is considered to arise from the escape depth difference in Al LVV and Ga LMM Auger electrons. The real abruptness in a MOCVD growth GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructure was assumed to be less than 6Å considering the Auger electron escape depth into the measured value. The very abrupt heterointerface was realized by the MOCVD growth apparatus used here.

3.2 Selectively doped GaAs/n-$Al_{0.3}Ga_{0.7}As$ heterostructures

It has been reported that both the impurity concentration and the conduction type for MOCVD growth GaAs[9-11] and AlGaAs[12] layers depend on the ratio, γ, of the AsH_3 mole fraction to the III group organometallic compound mole fraction, $[AsH_3]/[TMG]$ or $[AsH_3]/\{[TMG]+[TMA]\}$. In order to obtain SD GaAs/n-AlGaAs heterostructures with high 2DEG mobility by MOCVD, it is necessary to minimize the total impurity concentration in both the undoped GaAs and $Al_{0.3}Ga_{0.7}As$ spacer layers, as it has a direct effect on 2DEG mobility due to ionized impurity scattering.

In this paper, the most suitable MOCVD growth condition for obtaining SD GaAs/n-$Al_{0.3}Ga_{0.7}As$ heterostructures with high 2DEG mobility was determined by examining the effect of γ in both undoped GaAs and $Al_{0.3}Ga_{0.7}As$ spacer layer growth on 2DEG mobility. SD heterostructures fabricated here have

Table 1. Conduction type, carrier concentration and mobility for undoped GaAs layers.

$\gamma = \frac{[AsH_3]}{[TMG]}$	Conduction Type	Carrier Concentration at 77K (cm^{-3})	Mobility at 77K ($cm^2/V\cdot sec$)
10	P Type	1.22×10^{15}	6730
28	Semi-insulating	——	——
56	Semi-insulating	——	——
80	N Type	9.88×10^{13}	106400

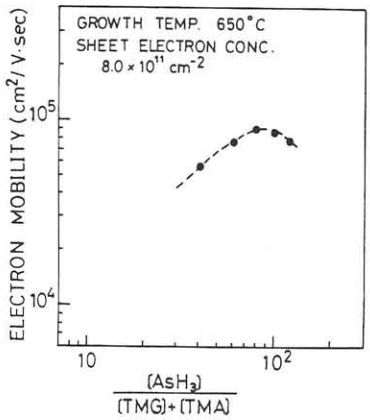

Fig.3 Relation between 2DEG mobility at 77K and value for undoped $Al_{0.3}Ga_{0.7}As$ spacer layer growth, when N_s at 77K was fixed to $8.0\times10^{11}cm^{-2}$.

the layer structure of Si doped n-$Al_{0.3}Ga_{0.7}As$(500Å) /undoped $Al_{0.3}Ga_{0.7}As$(100Å)/undoped GaAs(0.7~3μm)/ semi-insulating GaAs substrate.

The conduction type, carrier concentration, and mobility of undoped GaAs layers grown at four γ values (10, 28, 56 and 80) are shown in Table 1. The total impurity concentration in the undoped GaAs layer is considered to be minimum around the γ value at which the conduction type changes from semi-insulating to n type. Therefore, the most suitable growth condition for undoped GaAs in SD heterostructures is expected to be around γ =56.

An undoped $Al_{0.3}Ga_{0.7}As$ spacer layer is inserted between the Si doped n-$Al_{0.3}Ga_{0.7}As$ and undoped GaAs layer to increase 2DEG mobility. This layer weakens the scattering of 2DEG due to ionized impurities in the Si doped $Al_{0.3}Ga_{0.7}As$ layer. Therefore, the growth condition for minimizing the total impurity concentration including the carbon acceptor, which becomes a serious problem in AlGaAs layer[12], is required to obtain high 2DEG mobility. Figure 3 shows the relation between 2DEG mobility at 77K and the γ value for the growth of the undoped $Al_{0.3}Ga_{0.7}As$ spacer layer, when N_s at 77K was fixed at $8.0\times10^{11}cm^{-2}$. 2DEG mobility as high as 83000 cm^2/V·sec was obtained, and a remarkable increase in 2DEG mobility was observed when γ was increased from 40 to 80 for the growth of the undoped AlGaAs spacer layer. The increase in 2DEG mobility is considered to be due to the decrease in the carbon acceptor in the $Al_{0.3}Ga_{0.7}As$ spacer layer. On the other hand, the decrease in 2DEG mobility observed at $\gamma > 80$ is considered to be due to the increase in the donor

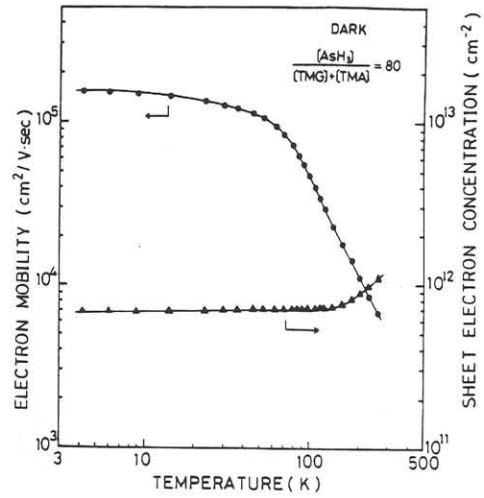

Fig.4 Temperature dependence of both sheet electron concentration and mobility for SD GaAs/n-$Al_{0.3}Ga_{0.7}As$ heterostructure.

concentration. As a result of this observation, the total impurity concentration in the undoped $Al_{0.3}Ga_{0.7}As$ layer is assumed to be minimum at γ =80.

Figure 4 shows the temperature dependence of both the sheet electron concentration and mobility for the SD GaAs/n-$Al_{0.3}Ga_{0.7}As$ heterostructure with the highest mobility. Electron mobility at room temperature, 77K and 4.2K was 6800, 83000, and 150000 cm^2/V sec, respectively.

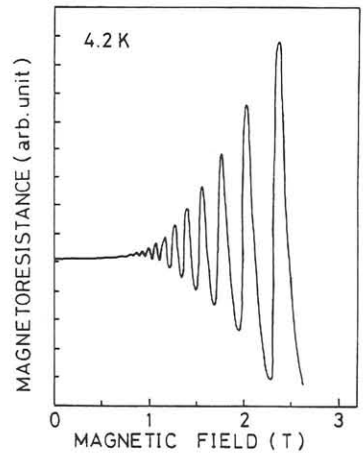

Fig.5 Magnetoresistance measured at 4.2K as a function of the magnetic field applied perpendicular to the heterointerface for SD GaAs/n-$Al_{0.3}Ga_{0.7}As$ heterostructure.

Magnetoresistance for the same sample as in Fig.4 was measured at 4.2K as a function of the magnetic field applied perpendicular to the heterointerface. As shown in Fig.5, Shubnikov De Haas

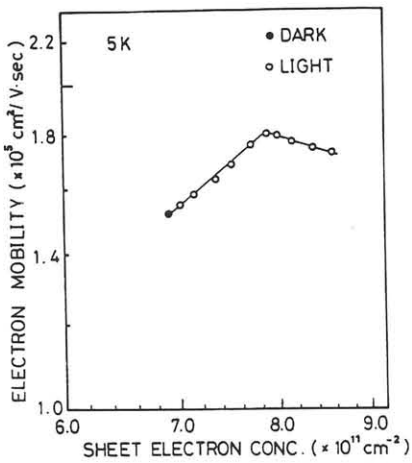

Fig.6 Relation between 2DEG mobility and sheet electron concentration at 5K, when sheet electron concentration was increased with exposure to light.

(SdH) oscillation was observed and the sheet electron concentration calculated from the period of the SdH oscillation agreed closely with the value (=6.9 $\times 10^{11}$ cm^{-2}) obtained by Hall measurement.

Persistent photoconductivity was observed for all SD heterostructures fabricated here. Fig.6 shows the relation between 2DEG mobility and sheet electron concentration, when sheet electron concentration was increased as a result of exposure to light at 5K. 2DEG mobility increased with increasing N_s and reached a maximum value of 180000 cm^2/V sec at $N_s = 7.8 \times 10^{11}$ cm^{-2}. Beyond this point, 2DEG mobility decreased.

(4) Conclusion

A leak-proof MOCVD growth apparatus capable of producing rapid changes in gas composition over the wafer has been constructed and suitable growth conditions for SD GaAs/n-$Al_{0.3}Ga_{0.7}As$ heterostructures having high 2DEG mobility have been obtained. It is shown that the total impurity concentration in the undoped $Al_{0.3}Ga_{0.7}As$ spacer layer has a remarkable effect on 2DEG mobility. A 2DEG mobility of 150000 cm^2/V sec at 4.2K was obtained. In order to obtain further increase in 2DEG mobility, the use of organometallic compounds such as triethyl gallium and triethyl aluminum in place of TMG and TMA is considered. This is because it has been reported that the use of triethyl gallium results in less carbon incorporation into GaAs than the use of TMG[13].

Acknowledgement

The authors would like to thank K. Tsubaki and K. Kumabe for helpful discussion and encouragement throughout this work. The authors also thank H. Okamoto for AES measurement.

References

1) T. Mimura, S. Hiyamizu, T. Fujii and K. Nanbu : Jpn. J. Appl. Phys. 19 (1980) L225.
2) R. Dingle, H. L. Störmer, A. C. Gossard and W. Wiegmann : Appl. Phys. Lett. 33 (1978) 665.
3) S. Hiyamizu, J. Saito, K. Nanbu and T. Ishikawa : Jpn. J. Appl. Phys. 22 (1983) L609.
4) J. J. Coleman, P. D. Dapkus and J. J. J. Yang : Electron. Lett. 17 (1981) 606.
5) S. D. Hersee, J. P. Hirtz, M. Baldy and J. P. Duchemin : Electron. Lett. 18 (1982) 1076.
6) J. Maluenda and P. M. Frijilink : Jpn. J. Appl. Phys. 22 (1983) L127.
7) G. B. Stringfellow and G. Hom : Appl. Phys. Lett. 34 (1979) 794.
8) R. D. Dupuis, P. D. Dapkus, C. M. Garner, C. Y. Su and W. E. Spicer : Appl. Phys. Lett. 34 (1979) 335.
9) S. Ito, T. Shinohara and Y. Seki : J. Electrochem. Soc. 120 (1973) 1419.
10) T. Nakanishi, T. Udagawa, A. Tanaka and K. Kamei : J. Cryst. Growth 55 (1981) 255.
11) N. Kobayashi, T. Fukui and Y. Horikoshi : Jpn. J. Appl. Phys. 21 (1982) L705.
12) Y. Mori, O. Matsuda, M. Ikeda, K. Kaneko and N. Watanabe : Int. Symp. GaAs & Related Compounds 1981, Inst. Phys. Conf. Ser. 95 (1982) 95.
13) R. Bhat, P. O'Connor, H. Temkin, R. Dingle and V. G. Keramidas : Int. Symp. GaAs & Related Compounds 1981, Inst. Phys. Conf. Ser. 63 (1982) 101.