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High electron mobility of modulation doped GaAs after growing InP by solid source molecular beam epitaxy①

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Abstract: Modulation-doped AlGaAs/GaAs structures were grown on GaAs(100) substrate by solid source molecular beam epitaxy(SSMBE) system. The factors which influence the electron mobility were investigated. After growing InP based materials, growth conditions were deteriorated, but by an appropriate method and using reasonable process high electron mobility(77 K) of more than 1.50×10^5 $cm^2/(V\cdot s)$ can still be obtained. The structures and growth conditions have been studied and optimized via Hall measurements. For a typical sample, 2.0 K electron mobility as high as 1.78×10^6 $cm^2/(V\cdot s)$ is achieved, and the quantum Hall oscillation phenomena can be observed.

Key words: modulation doped GaAs; high electron mobility; quantum Hall oscillation
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1 INTRODUCTION

Modulation doping produced high-mobility two dimensional electron gas(2DEG) in the AlGaAs/GaAs heterointerface by the physical separation of free electrons from positively ionized mother donors[1, 2]. Modulation doped heterostructure have attracted much interest for high-speed devices[3-5], low-noise microwave amplifiers[6] and for millimeter-wave integrated circuits(MMICs)[7] because of the extremely high mobility of two dimensional electron gas accumulating at the heterojunction interface. The high quality heterostructure materials have been achieved by molecular beam epitaxy(MBE). MBE makes abrupt doping profile and abrupt heterojunction interface in the materials possible, resulting in the surprising high mobility of 2DEG at low temperatures because of the nearly ideal spatial separation between electron and their parent ionized donors. The novel lasers and photo detectors can be integrated monolithically with GaAs integrated circuit to form opto-electronic integrated circuits(OEICs) which are very important in application[8].

The factors to limit electron mobility in a modulation doped GaAs are as follows[9, 10]: 1) remote impurity scattering by the ionized donors in the doped AlGaAs layer; 2) background impurity scattering from centers in the undoped GaAs and in the undoped AlGaAs spacer; 3) acoustic phonon scattering; 4) scattering at the GaAs-AlGaAs interface caused by surface roughness, alloy composition change or interface changes. The effect of scattering mechanism on electron mobility of modulation doped GaAs under different conditions is quite different.

The growth of phosphorus-contained materials by molecular beam epitaxy using solid-state phosphorus source is a good choice not only for environmental consideration but also device application. Reproducible growth of quantum well lasers with excellent performance[11, 12] and InGaP/GaAs heterostructure bipolar transistor(HBT) with a high yield[13, 14] are demonstrated by SSMBE.

In the molecular beam epitaxy system, the effect after growing phosphor-contained materials on the growth and electron mobility of modulation doped GaAs are very attractive. After growing phosphor-contained(P-contained) materials, the residual P may substrate As during epitaxial growth as equivalent electron doping. Even though the electron amounts in atomic outer space of As and P are equal, coulomb forces between ions and electrons in As and P are quite different. GaAsP/GaAs formed by equivalent electron doping may produce a tensile strain[15] which is beneficial to in-

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creasing the roughness of interface AlGaAs/GaAs in MD-GaAs. Both effects above may cause a decrease of electron mobility of MD-GaAs at 77 K. In this paper, an investigation on high electron mobility of modulation doped GaAs grown by SSMBE system is investigated. The factors which influence the electron mobility have been studied. After growing P-contained materials, growth conditions were deteriorated seriously; but high electron mobility at 77 K more than 1.50×10^5 $cm^2/(V \cdot s)$ can still be obtained by using an appropriate method. The structures and growth conditions have been studied and optimized via Hall measurements. For a typical sample, 2 K electron mobility as high as 1.78×10^6 $cm^2/(V \cdot s)$ can be achieved, and the quantum Hall oscillation phenomena can be observed.

2 EXPERIMENTAL

In this experiment, the growth of modulation doped GaAs structure materials was carried out in a Riber Compact 21 MBE system equipped with Riber VAC 500 arsenic(As) valve cracker cell and a Riber KPC250 phosphorus(P) cracker cell. The purities of As and P charge used were 7N5 and 7N (Nine), respectively, supplied by Rasa Industries of Japan. The purities of gallium and aluminum charge used are 7N and 6N5 respectively supplied by GEO and Pechiney of France. Silicon charge used for dopant is 4 500 Ω · cm made in China.

The semi-insulating GaAs substrates oriented (100) were made in China. In order to reduce the background impurities of the epitaxial layers, before and after loading source materials, the MBE system has to be baked (at 200 ℃ for 300 h), and source cells and materials have to be degassed thoroughly.

As cracker zone temperature was fixed at 600 ℃ and bulk evaporator temperature was fixed at 330 ℃, the beam equivalent pressure of As (BEPAs) was precisely adjusted by controlling the valve opening of As cracker cell using an automatic position controller. The growth rates of GaAs and AlGaAs were 0.72 and 1.0 μm/h, respectively, As_4/Ga BEP ratio was between 10 and 15. The growth chamber without cooling by liquid nitrogen reached a pressure of 1.1×10^{-10} Pa, as the source cells were at idle temperatures. The growth chamber is cooled by liquid nitrogen and reached a pressure of 2.6×10^{-8} Pa before growth run.

The sketch diagram of modulation doped GaAs structure is shown in Fig. 1. It consists of a 55 nm-thick Si-doped $Al_xGa_{1-x}As$ layer($x = 0.28$) with doping concentration of 1.0×10^{18} cm^{-3}, an undoped $Al_xGa_{1-x}As$ spacer-layer with thickness of 16 ~ 25 nm, and a 1.20 μm-thick undoped GaAs layer. 2DEG is formed at the GaAs side of hetero-junction interface. AlAs mole fraction(x) of 0.28 was chosen for considering the persistent photo conduction(PPC) effect in the sample due to higher value of x with Si doping to form DX center. As is well known, AlAs mole fraction(x) as high as 0.37 was reported[16, 17], but a delta-doping with Si has been used at the structures[18, 19]. The experimental results of the structure with Si delta-doping will be reported in another paper.

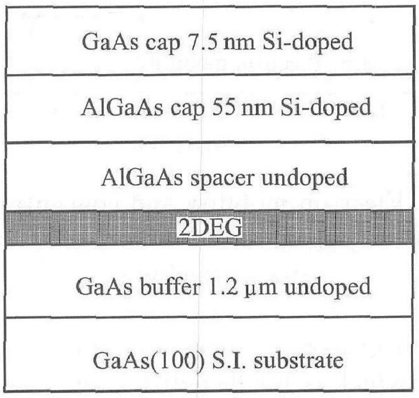

Fig. 1 Structure modulation doped GaAs

3 RESULTS AND DISCUSSION

Fig. 2 shows the plot of electron mobility and concentration of modulation doped GaAs at 77 K as a function of spacer thickness. As it can be seen from Fig. 2 that, when the spacer thickness increases, the electron concentration reduces gradually, but the mobility appears to be in different variation. When the spacer increases from 16 nm to 22 nm, the mobility increases from 1.6×10^5 to 1.86×10^5 $cm^2/(V \cdot s)$. The mobility reaches a peak value at the thickness of 22 nm. The mobility reduces significantly as the spacer thickness is higher than 22 nm. In order to analyze these data above, the different possible scattering mechanisms have been taken into account. As the thickness is less than 22 nm, the remote ionization impurities in the doped AlGaAs dominate the scattering and an increase in spacer thickness produce increase mobility. However, for larger spacers(⩾ 22 nm), the background impurities in the undoped GaAs, undoped AlGaAs spacer dominate the scattering, and since mobility can be shown to vary as $n^{3/2}$[17]. The fall in carrier concentration(n) will produce a reduction in 77 K mobility[19]. It is clear that the more carrier concentration can be beneficial to shield carrier transport from ionized background impurities.

Fig. 3 shows the dependence of growth temperature on 77 K electron mobility of modulation doped GaAs. As seen in Fig. 3, the highest electron mobility at 77 K of modulation doped GaAs was grown at the growth temperature of 710 ℃. The higher growth temperature may cause. As ad-

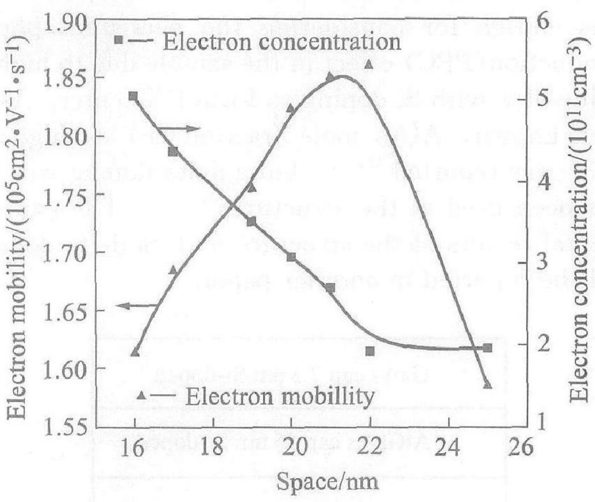

Fig. 2 Electron mobility and concentration of modulation doped GaAs at 77 K as function of spacer thickness

sorptions which is not beneficial for stoichiometric growth. The lower growth temperature may lead to increasing Ga(Al) vacancies or the roughness of AlGaAs/GaAs interface that would cause a decrease of electron mobility.

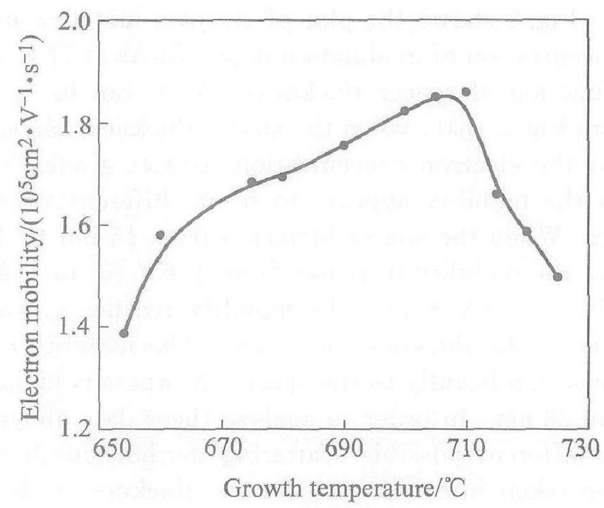

Fig. 3 Dependence of growth temperature on electron mobility of modulation doped GaAs at 77 K

Table 1 shows the 77 K electron concentration and mobility of modulation doped GaAs grown before and after growing P-contained materials. It can be seen from Table 1 that before growing P-contained materials, the 77 K electron mobility reaches 1.62×10^5 cm^2/(V·s) easily, and after growing a series of P-contained materials, growth conditions were deteriorated seriously, an appropriate method was used for suppressing the influence caused by using phosphorus solid source. The modulation doped GaAs was grown once again, the 77 K electron mobility reached 1.58×10^5 cm^2/(V·s) at the beginning. Then the material structure and growth conditions have been optimized via the results of Hall measurements. The 77 K electron mobility increases to 1.85×10^5 cm^2/(V·s). For a typical sample, after illuminated the 77 K electron mobility reaches as high as 2.35×10^5 cm^2/(V·s), and the 2.0 K electron mobility as high as 1.78×10^6 cm^2/(V·s) has been achieved, and the quantum hall oscillation phenomena can be observed(Fig. 4). Fig. 4 shows the illuminated results for R_{xx} (Shubnikovde Haas effect) and R_{xy} (Integral Hall effect) of the 2DEG as a function of magnetic field at a temperature of 2.0 K. In the vicinity of 2.8 T and 4.1 T, R_{xx} approaches the zero-resistance state. At these same field positions, R_{xy} develops plateaus characteristic of the integral quantum Hall effect (IQHE). All features reflected the high quality of the 2DEG very clearly. The results above demonstrate that the high quality MD-GaAs materials can still be obtained after

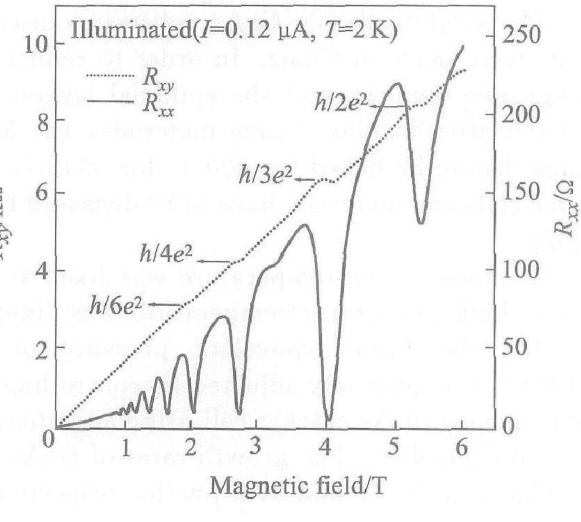

Fig. 4 Shubnikovde Haas effect and integral Hall effect of illuminated sample L037 at temperature of 2.0 K

Table 1 Electron concentration and mobility before and after growing P-contained materials at 77 K

Sample	Electron concentration/ (10^{11} cm^{-2})	Electron mobility/ (10^5 cm^2·V^{-1}·s^{-1})	Note
L005	5.56	1.62	1) Before P-contained materials growing
L030	4.54	1.58	2) After P-contained materials growing, $BEP_{ph} < 6.5 \times 10^{-4}$ Pa
L035	4.36	1.85	

growing P-contained materials.

In order to characterize modulation doped two-dimensional electron gas (2DEG) structure, the quantum Hall measurements have been carried out at low temperature in high intensity magnet field[7]. Fig. 4 shows the dependence of magneto-resistance of modulation doped 2DEG structure on the intensity of magnet field at temperature of 2.0 K, with electrical current 0.12 μA. As seen in Fig. 4, the amplitude and shape of quantum Hall oscillation curve does not depend on electrical current, but on the irradiation, especially when the intensity is higher than 5 T.

4 CONCLUSIONS

After growing P-contained materials, growth conditions were deteriorated, but using appropriate method to suppress the influence after growing P-contained materials, high electron mobility (77 K) more than 1.50×10^5 $cm^2/(V\cdot s)$ can still be obtained. The structures and growth conditions have been studied and optimized via Hall measurements. For a typical sample, 2.0 K electron mobility as high as 1.78×10^6 $cm^2/(V\cdot s)$ has been achieved, and the quantum Hall oscillation phenomena can be observed.

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