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Se Atomic Planar Doping to GaAs by MOCVD and Its Application to Two-Dimensional Electronic Devices

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The Se atomic-planar doping to GaAs by an atmospheric MOCVD technique has been systematically investigated. By optimizing some preparation conditions, we have successfully obtained the steepest carrier concentration profile ever reported, the peak carrier concentration being 2×10^{19} cm^{-3} and the half-width below 10 Å. From the analysis of the relation between the peak carrier concentration and the half-width, it has been found that Se is doped in almost one atomic layer. The application of this atomic-planar doping technique to a new two-dimensional electronic device has been proposed and discussed.

1. Introduction

Recent advances in epitaxial growth techniques such as MBE and MOCVD allow us to fabricate very abrupt compositional and doping profiles in compound semiconductors, which results in the accomplishment of various novel fine structure devices. In selectively-doped AlGaAs/GaAs single heterostructures, high electron mobility transistor (HEMT)[1] is attracting a great deal of interest for high-frequency and high-speed applications. Moreover, we recently proposed a new far-infrared emitter with this structure, which utilizes the relaxation of grating-coupled two-dimensional (2D) plasmons excited by hot electrons, and observed an emission power in excess of 30 $\mu W/cm^2$ under an applied field of 760 V/cm.[2,3] The characteristics of these devices, however, suffer from instabilities caused by deep traps in n-AlGaAs[3,4] which are generally called DX centers[5].

Much attention has been paid to an atomic -planar doping technique[6] as an approach to overcome above-mentioned problems. The technique enables us to dope impurities heavily into an extremely narrow region normal to the surface and obtain a dirac-delta function like doping profile. Recently, some attempts to apply the δ-doped layer to a source of electrons in 2D electronic devices are successfully reported.[7-9] In the course of these studies, the establishment of the atomic-planar doping technique is strongly desired to improve their performance.

Si has been preferably used as a dopant in the technique regardless of the growth method. In this case, however, it is difficult to obtain a high doping efficiency due to self-compensation inherent in the group-IV elements. Therefore, we are motivated to use group-VI elements, S and Se, as a dopant. It is well known that Se exhibits a diffusion coefficient about three orders smaller than S in the growth temperature region[10] and a doping efficiency about two orders larger[11]. It is expected to obtain a steep carrier profile with a high peak carrier concentration by the use of Se as a dopant.

In this paper, we report the achievement of the steepest carrier profile ever reported and its application to a new 2D electronic device.

2. Experimental

The atmospheric pressure growth system with a horizontal reactor was utilized in this work. Trimethylgallium (TMG) and 10 % arsine in H_2 were used as source materials for GaAs growth. Se was introduced in the reactor in the form of H_2Se diluted with H_2 to 100 ppm. Typical GaAs growth temperature and all gas flow-rate were 670 ℃ and 4 SLM, respectively.

The sequence of the atomic-planar doping was as follows;

1)The TMG flow was stopped to suspend growth.
2)The doping gas was introduced at the growth temperature to form an atomic plane of dopant on the surface.
3)The GaAs growth was restarted to incorporate the dopant layer.

Between each step, a purging period was inserted to remove the residual gases. Carrier concentration profiles of atomic-planar doped GaAs samples were estimated from C-V measurements.

3. Results and Discussion

In order to obtain a steep carrier profile with a high peak carrier concentration, we have optimized some preparation conditions. Firstly, we have investigated effects of the substrate temperature during a H_2Se purging on a carrier profile. Figure 1 shows a carrier profile observed in sample #C018 where the substrate temperature drops to room temperature during a H_2Se purging, together with one in sample #C011 where the substrate temperature is kept at the growth temperature. In sample #C011, there is a tail in the carrier profile below the nominally planar-doped layer, which is shown

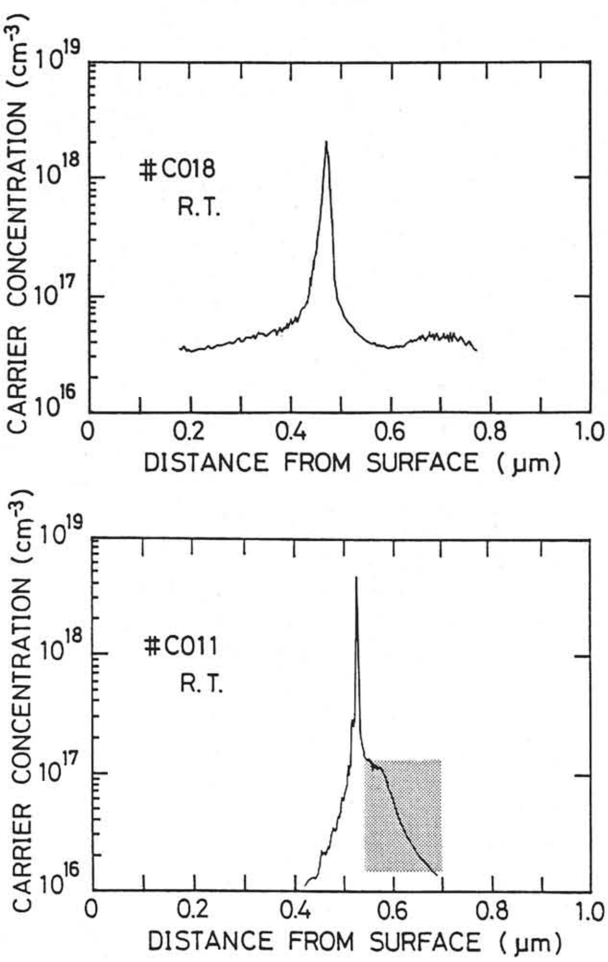

Fig. 1 Effects of the substrate temperature during a H_2Se purging on the carrier profile.

by shade. Since this tail can be never observed in sample #C018, it is thought to be due to a interdiffusion of Se or any defects introduced during the purging period (for example, donor-like arsenic vacancy[12]). Therefore, a purging of H_2Se is performed at room temperature hereafter.

Secondly, we have investigated the H_2Se flow-rate dependence of the carrier profile. We have observed a decrease in peak carrier concentration with the increase in H_2Se flow-rate. It might be caused by any radicals produced from a dissociation of H_2Se or by any impurities involved in H_2Se gas. On this point, further study should be required. Anyway, it is necessary to decrease the H_2Se flow-rate to obtain a steep carrier profile.

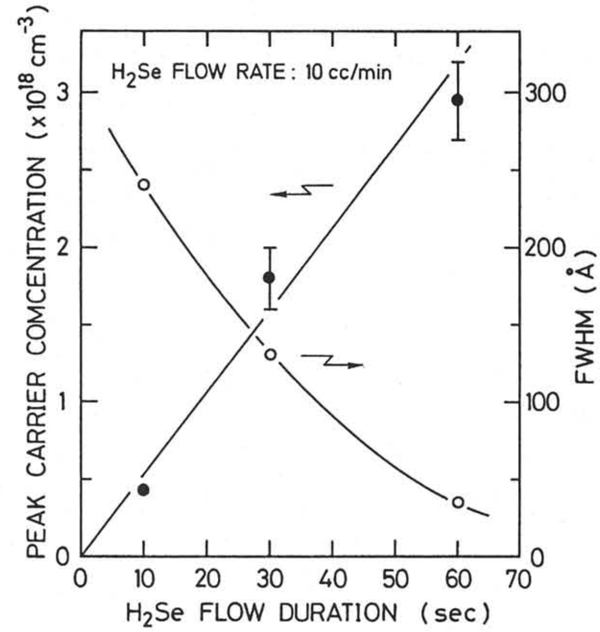

Fig. 2 H_2Se flow-duration dependence of the peak carrier concentration and the half-width in the carrier profile.

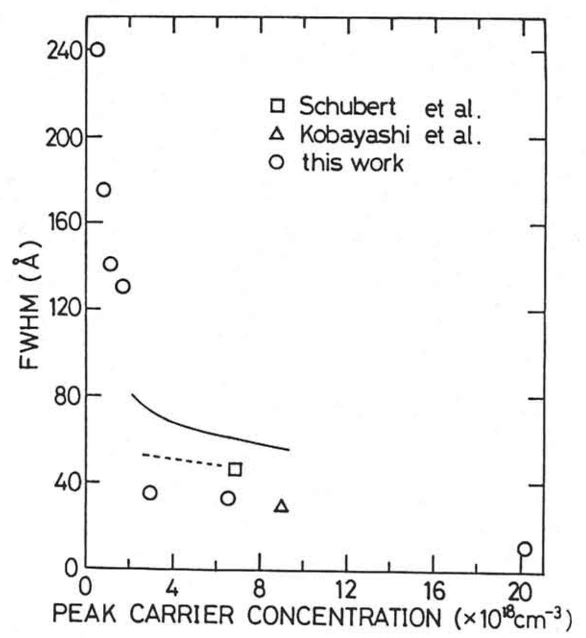

Fig. 4 Peak carrier concentration dependence of the half-width in the carrier profile.

Finally, we have also investigated effects of a H_2Se flow-duration. In Fig. 2, the H_2Se flow-duration dependence of the peak carrier concentration and the half-width in the observed carrier profile is shown. As can be seen in the figure, it has been found that the peak carrier concentration is proportional to the H_2Se flow-duration and the half-width inversely, which suggests that an adsorption of Se to the surface is rather

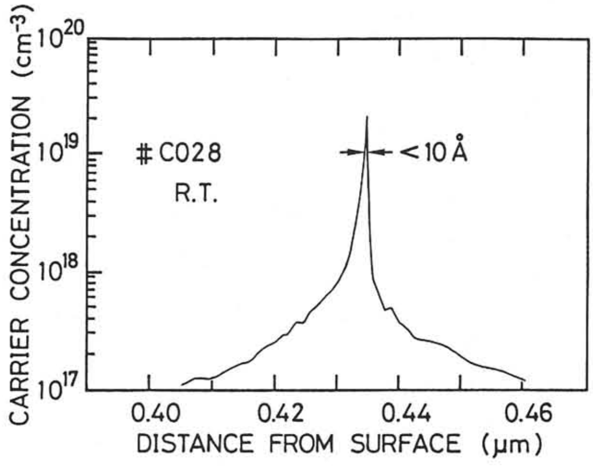

Fig. 3 Best carrier profile obtained in this work.

moderate. Since the H_2Se flow-rate dependence of the peak carrier concentration never exhibits a saturation in the experimental range, it is expected to obtain a steeper carrier profile with a higher peak carrier concentration by the increase in H_2Se flow-duration. Therefore, we have prepared a sample blown by H_2Se for five minutes. The obtained carrier profile is shown in Fig. 3. The peak carrier concentration is 2×10^{19} cm^{-3} and the half-width below 10 Å, which exceed ever reported values[13] (peak carrier concentration: 8×10^{18} cm^{-3}, half-width: 30 Å). Figure 4 shows the peak carrier concentration dependence of the half-width obtained in this work, together with those of others. In this figure, the results calculated by Schubert et al and Zrenner et al with an assumption of the doping to one atomic layer[14] are shown by solid and broken lines, respectively. It has been found that the half-width decreases with the increase in peak carrier concentration and that the behavior corresponds qualitatively to the calculated results, suggesting that Se is doped in almost one atomic layer by our procedure.

We have proposed a new 2D electronic device to apply this Se atomic-planar doping technique. The structure is a normal AlGaAs /GaAs/AlGaAs single quantum well structure with a δ-doped layer inside the GaAs quantum well. The schematic real-space energy band diagram is shown in Fig. 5. This structure has the following two characteristics. Firstly, the Se atomic-planar doped layer is asymmetrically placed against the quantum well. In this case, as can be seen in the figure, it is expected that the peak position of a wave function of electron in the well can be intentionally misaligned with the position of the δ-doped layer, which is shown by arrows. This spatial gap acts as an effective spacer layer and suppresses a scattering by parent donors, which suggests that we can obtain a high electron mobility in this device. Secondly, the AlGaAs layer used as a barrier layer is undoped. Therefore, it involves no DX center, which enables us to overcome some problems induced by them. At present, in order to improve device performances, work continues to optimize the thickness of the quantum well and the position of the δ-doped layer.

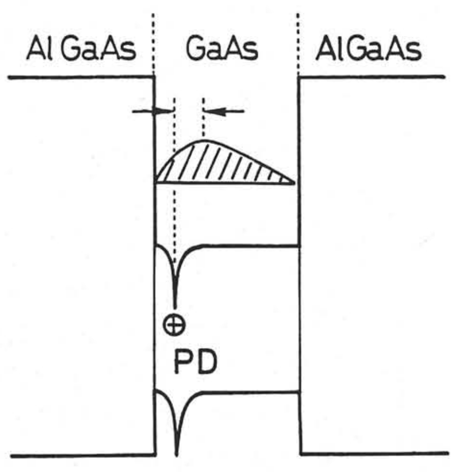

Fig. 5 Schematic real-space energy band diagram of our new 2D device.

4. Conclusions

We have systematically investigated the Se atomic-planar doping to GaAs by an atmospheric MOCVD technique. It has been found that the H_2Se flow-duration plays an important role in obtaining a steep carrier profile with a high peak carrier concentration, suggesting that the adsorption of Se to the substrate surface is rather moderate. The optimization of some preparation conditions has enabled us to obtain the steepest carrier profile ever reported, the peak carrier concentration being 2×10^{19} cm^{-3} and the half-width below 10 Å. By analyzing the relation between the peak carrier concentration and the half-width, it has been found that the Se impurity atoms are doped inside almost one atomic layer. A new 2D electronic device employing this atomic-planar doping technique has been proposed and discussed.

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