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Two-Dimensional Systems: Physics and New Devices

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G. Bauer, F. Kuchar, and H. Heinrich

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Preface

In the series of International Winter Schools on New Developments in Solid State Physics, the fourth one was devoted to the subject: "Two-Dimensional Systems: Physics and Devices". For the second time the proceedings of one of these Winter Schools appear as a volume in the Springer Series in Solid-State Sciences (the earlier proceedings were published as Vol. 53). The school was held in the castle of Mauterndorf/Salzburg (Austria) February 24–28, 1986. These proceedings contain contributions based on the thirty invited lectures. The school was attended by 179 registered participants (40% students), who came from western European countries, the United States of America, Japan, the People's Republic of China and Poland.

As far as the subjects are concerned, several papers deal with the growth and characterization of heterostructures. Dynamical RHEED techniques are described as a tool for in situ studies of MBE growth mechanisms. Various growth techniques, including MBE, MOMBE, MOCVD and modifications of these, are discussed. The limiting factors for the carrier mobilities and the influence of the spacer thickness in single heterostructures of GaAs/GaAlAs seem to be understood and are no longer a matter of controversy. In addition, the growth of two fascinating systems, Si/SiGe and Hg_{1-x} Cd_x Te/CdTe, is discussed in detail.

A whole part is devoted to the subject of band edge discontinuities, which were not treated at all in the previous volume. Both experimental and theoretical contributions are presented. For GaAs/GaAlAs (for x = 0.3) a tendency towards a 60:40 ratio (ratio of the conduction to valence band discontinuity) is manifested.

Doping and compositional superlattices are treated, with regard to both their basic physics and their potential applications. These topics include nipi and the new sawtooth superlattices. The optical and electronic properties of Si/SiGe superlattices and possible optoelectronic applications of these structures are discussed.

The recent developments in bound states in quantum wells and two-dimensional impurity layers are reviewed. Of course, reviews on the present status of understanding of the integer and fractional quantum Hall

effects are also presented. Experimental papers deal with the observation of the integer quantum Hall effect at microwave frequencies and with the fractional quantum Hall effect. The significance of the observed fractions with even denominators is discussed. New determinations of the density of states of Landau levels in the quantum Hall effect regime from activated transport, capacitance, specific heat and magnetization measurements are presented.

Beside the device-related papers on growth and characterization, several papers deal with transport properties of two-dimensional electron gas devices, e.g. tunnelling devices, hot-carrier transport in submicron MOSFETs, microwave FETs (TEGFET, HEMT).

Whereas in the proceedings of the Winter School which was held two years ago the tutorial aspect was emphasized by many speakers, the new volume contains thorough reviews of the most recent developments in the topics mentioned above. We have also included papers on time-resolved spectroscopy of two-dimensional systems, a rapidly developing field of research, and the fascinating subject of electronic excitations in microstructured MIS and heterostructures. These two volumes now cover a broad spectrum of our present-day knowledge of the physics of two-dimensional systems.

The organizers are grateful to the authors, attendants and competitors in the final ski-race, who all helped to contribute to a successful meeting.

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March 1986

G. Bauer F. Kuchar
H. Heinrich

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Part I

Epitaxial Growth: Methods and Characterization

New Epitaxial Growth Methods and Their Application to Quantum Wells and 2DEG Structures

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New thin film epitaxial growth methods have been developed which provide the possibility of accurately controlling thicknesses and doping profiles. These methods can be applied to 2DEG structures having a modulation doped single heterojunction, and those having an asymmetric quantum well doped with an atomic layer profile.

1. Introduction

Both metal-organic chemical vapor desposition (MOCVD) and molecular beam epitaxy (MBE) have been shown to be useful methods of producing ultrathin semiconductor layers with reasonable quality for device applications. Even for these methods, however, it has seemed to be almost impossible to control the growing thickness to an accuracy of one atomic layer. Moreover, these methods still present difficulties in growing GaAs and AlGaAs. MOCVD requires relatively high substrate temperatures. Because of this restriction, it is difficult to obtain sharp heterojunction interfaces and steep impurity concentration profiles. It is rather difficult to grow GaAs and AlGaAs by MBE with precise control and rapid changes in arsenic beam intensity. These factors are very important to obtain high quality layers and heterojunctions.

Two new epitaxial growth methods reported here may solve the above-mentioned problems: One is based on MOCVD and using an alternate supply of source gases. We have termed this method "Flow-rate Modulation Epitaxy (FME)". This method effectively lowers substrate temperature, and improves thickness controllability. The other is based on MBE utilizing arsenic molecule transport by purified hydrogen gas. It is termed "Vapor Transport Epitaxy (VTE)". With this method, arsenic intensity can be precisely regulated. In addition, it was found that the hydrogen gas flow through the chamber is effective in purifying the grown layers. By applying the FME method, we fabricated single heterojunction modulation-doped 2DEG structures and a new 2DEG structure based on an asymmetric quantum well doped with an atomic layer profile. Reasonably high 2DEG mobilities were attained using this method.

2. Flow-rate Modulation Epitaxy

An epitaxial growth method based on an alternate supply of source gases has recently been reported and applied to the growth of II-VI compound semiconductors/1/. Much attention has been paid to this method because it provides the possibility of controlling thickness to an accuracy of one

atomic layer. This method was applied to GaAs growth by Nishizawa et al. /2/ and has been proved to be useful for obtaining well-thickness controlled layers. However, the GaAs layer showed heavy p-type conductivity, suggesting an incorporation of p-type impurities.

This phenomenon is probably caused by the use of trimethyl gallium (TMG) for the Ga source. This is because a large amount of carbon atoms are incorporated in the crystal when TMG is used for the Ga source in the conventional MOCVD growth. This problem almost disappears when triethyl gallium (TEG) is employed instead of TMG. For the MOCVD growth of AlGaAs, the combination of triethyl aluminium (TEA) and TEG yields layers with higher purity than that of trimethyl aluminium (TMA) and TMG. Another cause of the heavy p-type problem may be due to the formation of arsenic vacancies near the growing surface during the Ga adsorption period followed by a reaction with impurity atoms such as carbon.

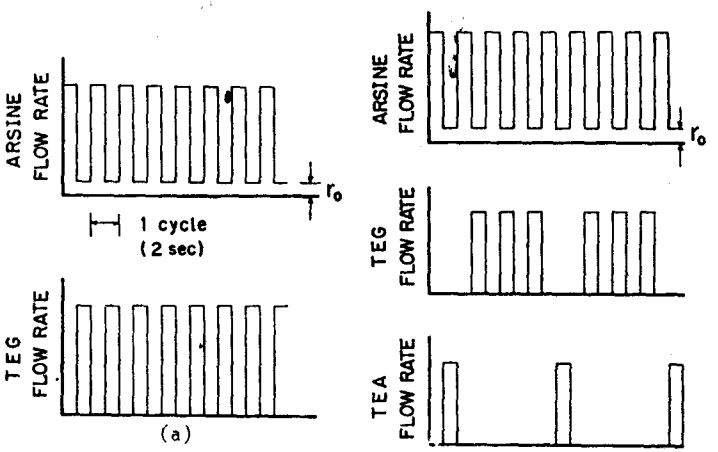

Fig. 1
Gas flow sequence for (a) GaAs, and (b) $Al_{0.25}Ga_{0.75}As$ growth by Flow-rate Modulation Epitaxy.

The FME method/3/ is based on the alternating gas flow of triethyl compounds (TEG and/or TEA) and arsine by using hydrogen gas, as shown in Fig. 1. The alternating gas flow of metallorganic compounds and arsine inherently has a very important advantage in addition to the possibility of improving thickness controllability. In the conventional MOCVD growth, additional compounds are formed between metallorganic compounds and arsine during growth. These compounds degrade the purity of layers when the growth temperature is lowered. In contrast, the formation of such compounds will be much reduced using the present method.

One of the practical advantages of this method is that both the layer thickness and alloy composition are determined by the number of gas flow pulses with fixed peak flow rates as shown in Fig. 1. Therefore, the growth process can be easily controlled by a computer. The growth appara-

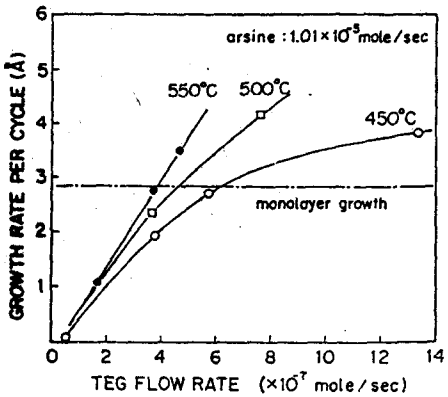

Fig. 2
Growth rate of GaAs layers per cycle as a function of TEG flow rate.

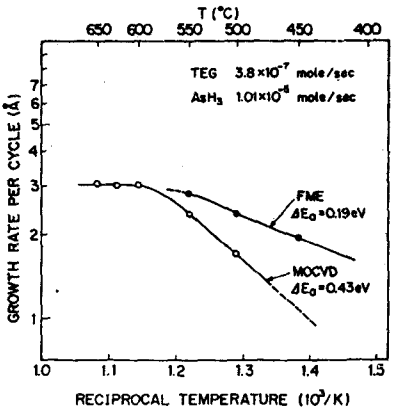

Fig. 3
Temperature dependence of the growth rate of GaAs by FME and MOCVD method.

tus used in this experiment was designed so as to obtain rapid exchange of gas composition (<0.1 sec) on the substrate. The total flow-rate and the pressure inside the reactor were 10 sl/min and 90 Torr, respectively. The period for the introduction of each source gas was fixed at 1 second. For GaAs growth, one cycle comprises a 1 second TEG flow period and a succeeding 1 second arsine flow period.

Another characteristic point of this method is that a very small amount of arsine is added during the TEG flow period (see Fig. 1). This small amount of arsine was introduced to reduce the formation of arsenic vacancies in the growing surface during the Ga adsorption period. Figure 2 shows the dependence of GaAs layer thickness per cycle on the TEG flow-rate. At 450 °C, the layer thickness per cycle increases in proportion to the TEG flow-rate in the low flow rate region, but tends to saturate in the higher flow rate region. This phenomenon may indicate the onset of "atomic layer growth". Although no such evidence is found at the higher growth temperatures shown in Fig. 2, it is interesting to note that if the growth rate per unit cycle is chosen to be equal or less than one atomic layer thickness (0.28 nm) high-quality layers with improved lateral uniformity were obtained. Therefore, the flow-rate of TEG was chosen to yield a growth of one monolayer per cycle. A typical growth duration was 7200 cycles (4 h) which produces layers totaling about 2 microns in thickness.

The FME method produces uniform GaAs and AlGaAs layers with high crystal quality even when the substrate temperature is as low as 450°C. In the conventional MOCVD method, however, good quality AlGaAs layers can be grown when the substrate temperature is higher than about 700°C. This remarkable reduction in the growth temperature implies that a different growth mechanism is operative in FME. To see this effect more clearly, we measured the temperature dependence of the growth rate as shown in Fig. 3. The activation energy of FME estimated at lower growth temperatures is much less than that of MOCVD. This difference can be accounted for by the adsorption-decomposition mechanism with the FME method/3/.

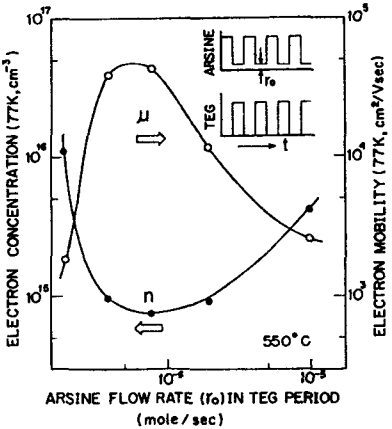

Fig. 4
Electron mobility and carrier concentration of FME grown GaAs as a function of r_o.

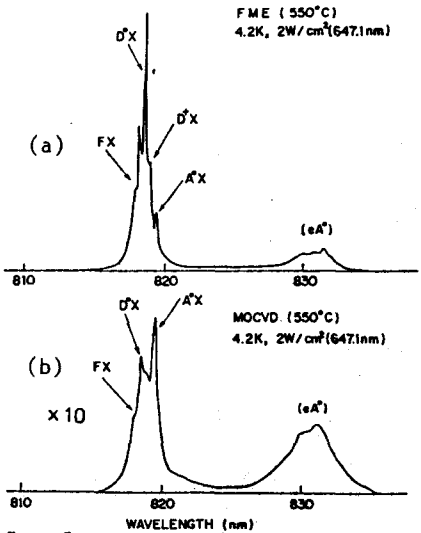

Fig. 5
Photoluminescence from GaAs grown by: (a) FME and (b) MOCVD at 550°C.

Next, we will describe the effect of a very small amount of arsine during the TEG flow period. Even without this small amount of arsine, the resulting layers grown at 550°C exhibit n-type conductivity. However, the mobilities at 77 K are less than 3000 cm^2/Vsec. An important effect of this small amount of arsine is to enhance the electron mobility in the GaAs layers. Figure 4 demonstrates the electron mobility and residual carrier concentration of GaAs layers grown at 550°C as a function of the arsine flow rate (r_o) during the TEG period. Electron mobility at 77 K drastically increases from 2000 to 50000 cm^2/Vsec, and electron concentration decreases from 10^{16} to less than 10^{15} /cm^3 when r_o is increased from 0 to 5×10^{-6} mole/sec. This r_o value corresponds to an arsine flow of only 4 % during the arsine flow period.

Photoluminescence measurements also suggest that the quality of GaAs layers grown by the FME method is superior to that of layers grown by the MOCVD method. Figure 5 compares 4.2 K photoluminescence spectra of the GaAs layers grown by the FME and MOCVD method at 550°C. The sample was excited by a Kr-ion laser (647.1 nm) with an intensity of about 2 W/cm^2. The GaAs layers grown by the FME method exhibit a lower carrier concentration than those grown by the conventional MOCVD method. Nevertheless, photoluminescence intensity was about 10 times that for the MOCVD-grown sample. In addition, relative intensities of acceptor related emissions (band-to-acceptor and excitons bound to acceptors) are much reduced in the FME-grown sample.

3. Vapor Transport Epitaxy

Quick, precise regulation of arsenic beam intensity is difficult during MBE growth of GaAs and AlGaAs. One fixed arsenic beam intensity has been

used during the growth of GaAs/AlGaAs heterojunctions because of this difficulty. This is in spite of the fact that optimum values for arsenic beam intensity for GaAs and AlGaAs at a given substrate temperature differ slightly. The quality of the heterojunctions would be greatly improved if the prospective optimum arsenic beam intensities were used during growth. In addition, precise and quick regulation of the arsenic beam intensity will make it possible to supply alternately constituent source materials, which seems to be useful to control the thickness of the layers to an accuracy on the order of one atomic layer. The application of arsine instead of arsenic is one possible means of regulating arsenic beam intensity more precisely and quickly/4/. Although it is expected that residual impurities in arsine will increase the background carrier concentration, high quality GaAs has been reported/5/. Hydrogen gas at up to 5 x 10^{-4} Torr was injected into the growth chamber in an attempt to purify the grown GaAs/6/ and AlGaAs/7/ layers. This was done because hydrogen gas is expected to deoxidize and decarbonize the materials. Although discernible improvements were reported in mobility and photoluminescence measurement, this method still results in an incorporation of a large amount of impurities. This limitation may be ascribed to the fact that evaporated arsenic molecules have no practical chance to collide with hydrogen molecules on their trip to the substrate surface. Therefore, purification by hydrogen gas is not so effective.

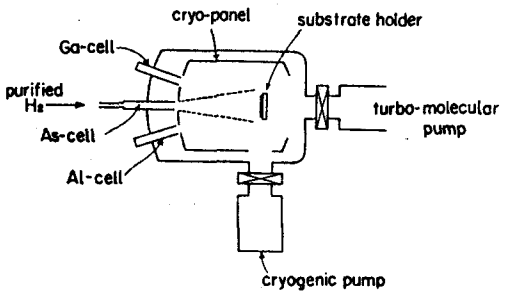

Fig. 6
High-vacuum growth chamber for the VTE growth. Purified hydrogen gas is introduced through the arsenic effusion cell.

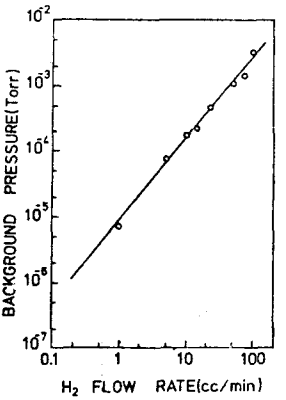

Fig. 7
Plotting of background hydrogen gas pressure as a function of hydrogen gas flow rate through the arsenic cell.

In the present experiment, GaAs layers were grown in a high-vacuum MBE chamber using arsenic molecules transported by purified hydrogen carrier gas. This was done to demonstrate the possibility of quick, precise arsenic beam intensity regulation as well as the purification effect due to hydrogen gas. Figure 6 shows the apparatus used in this study. A conventional MBE system was modified by adding a turbo-molecular pump with a capacity of 1800 l/sec to evacuate a large amount of hydrogen gas. The minimum background pressure of the system (2 x 10^{-10} Torr) was attained

using a cryogenic pump (1500 l/sec). The hydrogen gas flow rate through the heated arsenic cell varied over a range of 0.3 to 100 cc/min. This corresponds to a background hydrogen gas pressure range of 1×10^{-6} to 1×10^{-3} Torr, as demonstrated in Fig. 7.

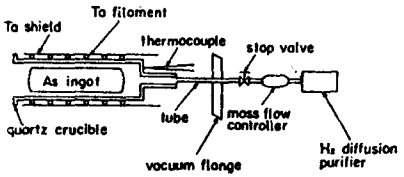

Fig. 8
Structure of the arsenic cell designed for the VTE study.

As shown in Fig. 8, the arsenic effusion cell has a quartz crucible with a thin quartz tube at its bottom. The other end of this tube was connected with a stainless steel tube to introduce palladium-diffused hydrogen gas. Since a large amount of hydrogen molecules are introduced through the heated arsenic cell, the arsenic molecules over the arsenic ingot will frequently collide with hydrogen molecules. This is because the mixture of hydrogen and arsenic molecules in the arsenic crucible has characteristics of a viscous fluid. Thus, we expect an effective purification of arsenic by hydrogen gas. The transport of arsenic vapor from the heated arsenic ingot to the substrate surface by hydrogen gas flow was directly observed by measuring the thickness of the adsorbed arsenic on the cooled (< 0°C) substrate surface. Figure 9 represents the observed arsenic deposition rate as a function of the hydrogen gas flow rate. In this experiment, the arsenic beam was impinged for 3 hours, and the arsenic cell temperature was maintained at a value to attain an arsenic beam-equivalent-pressure of 7×10^{-6} Torr (without hydrogen gas flow). A distinct increase in the amount of adsorbed arsenic was observed as the flow rate increased. This result clearly indicates that the arsenic beam intensity can be regulated by the flow rate of hydrogen gas.

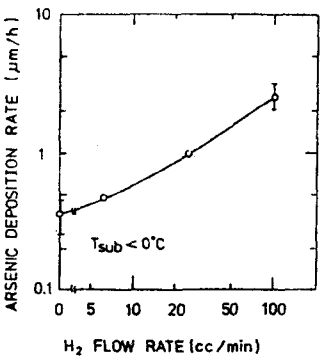

Fig. 9
Arsenic deposition rate on cooled GaAs substrate as a function of the hydrogen gas flow rate.

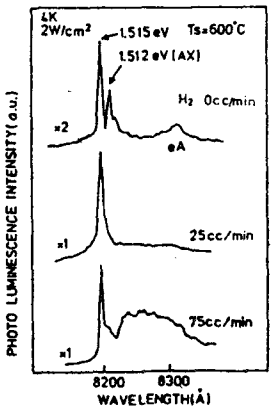

Fig. 10
Photoluminescence spectra of GaAs layers grown by the VTE method.

The surface morphology of grown GaAs layers was examined to see the effect of the arsenic transported by hydrogen gas. In our apparatus, the arsenic stabilized surface condition cannot be established with an arsenic beam-equivalent-pressure of 5×10^{-7} Torr when the substrate temperature is 600°C. Under this condition, the GaAs layers exhibit rough surfaces. By introducing a flow of hydrogen gas through the arsenic cell at a rate of 50 cc/min, an arsenic stabilized condition is established by the transported arsenic, and a specular grown surface is obtained.

Undoped GaAs layers grown without flowing hydrogen gas showed p-type conductivity with carrier concentrations of about 2×10^{14}/cm. The hole concentrations were reduced to about 5×10^{13}/cm when the hydrogen gas flow was applied. This result is consistent with low-temperature photoluminescence measurements shown in Fig. 10. The spectra for the GaAs layers grown at 600°C with hydrogen gas flow rates of 25 and 75 cc/min are compared with the results for a zero-flow-rate sample. It is interesting to note that the intensities of acceptor related luminescence (AX and eA) are much reduced by introducing a flow of hydrogen gas. However, a broad emission band appears at an increased flow rate(75 cc /min). This is probably caused by the defect-induced-bound excitons. This phenomenon may be explained as follows: At a higher hydrogen gas flow rate, arsenic molecules over the arsenic ingot will be supercooled by the collision with hydrogen molecules. Thus, the arsenic vapor tends to form clusters composed of a larger number of arsenic atoms. This may enhance emission due to the defect induced excitons.

4. Application to 2DEG Structures

By applying the Flow-rate Modulation Epitaxy method, we have grown single heterojunction modulation-doped structures at 550°C /8/. An undoped GaAs layer was grown on a [001] oriented semi-insulating GaAs substrate using the gas flow rate program shown in Fig. 1(a). The succeeding $Al_{0.25}Ga_{0.75}As$ layer was grown using the program shown in Fig. 1(b). Thus, the $Al_{0.25}Ga_{0.75}As$ layer is formed by repeating the growth of three GaAs monolayers followed by the growth of one AlAs monolayer. Therefore, the Al $Ga_{0.75}As$ layer is no longer a "random alloy", but has an "ordered" structure. Si impurity was added by allowing silane gas pulses to flow during the TEG gas flow period for the middle GaAs monolayer growth.

Figure 11 shows the measured electron mobility and carrier concentration for this structure. Also shown for comparison is the result for a modulation doped single heterostructure prepared by the conventional MOCVD method using the same apparatus at a higher substrate temperature. The structure prepared using the FME method with the above-mentioned gas-flow program at a substrate temperature of 550°C showed 2DEG mobility as high as 8×10^4 cm^2/ Vsec at 5 K. This value is, however, still lower than that obtained in a sample prepared by the conventional method at a higher growth temperature. This relatively low mobility in FME grown structure may be caused by impurities in the AlGaAs "ordered" alloy layer probably incorporated during the Al-atomic layer growth. Since the Al-stabilized surface is chemically very active, impurity atoms in the gas phase are anticipated to be incorporated into the surface. The sample prepared using the MOCVD method at 680°C showed much higher electron mobility as indicated by a dashed curve in this figure (as high as 4.5×10^5 cm^2/Vsec at 5 K). When the growth temperature is decreased, however, the observed 2DEG mobility drops very rapidly. At 550°C, there is no evidence for 2DEG formation. These experimental results indicate that the crystal

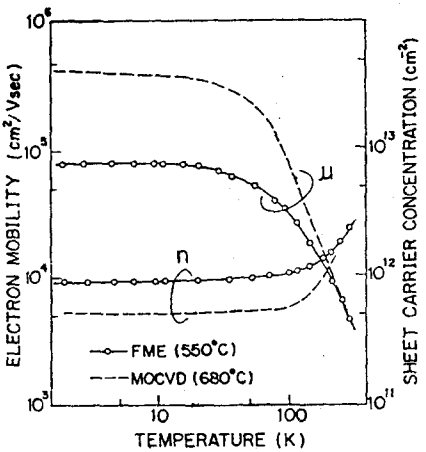

Fig. 11
Electron mobility and carrier concentration in a FME grown modulation-doped single heterostructure grown at 550°C. The dashed curve represents the results for a MOCVD grown wafer at a higher temperature(680°C).

quality of GaAs and AlGaAs is much deteriorated by decreasing the substrate temperature in the conventional MOCVD growth, and that the FME method is useful to reduce the substrate temperature maintaining a reasonable quality of the grown crystals.

In the following, we propose a new 2DEG (or 2DHG) structure which utilizes characteristics of an asymmetric quantum well. An asymmetric quantum well need not have any quantized states in the well if the well width Lz is smaller than some critical value (see Fig. 12). If donor (or acceptor) impurities are doped in such a quantum well, no electrons (or holes) from these donors (or acceptors) will be confined in the well. Instead, they form 2DEG (or 2DHG) at the neighboring heterojunction, as shown in Fig. 12 (b). The AlGaAs barrier layers are undoped in this structure. Therefore, 2DEG characteristics are expected to be free from the undesirable effects of DX centers.

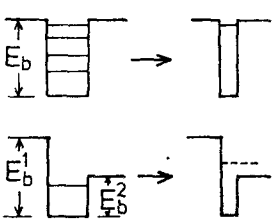

Fig. 12 (a)
Comparison between symmetric and asymmetric quantum wells when the well thickness is decreased.

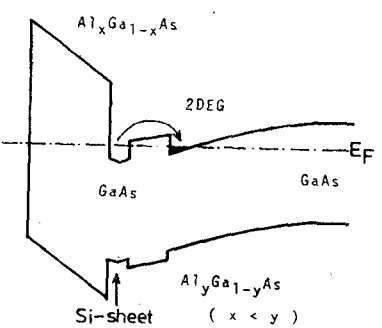

Fig. 12 (b)
Schematic 2DEG structure having an asymmetric quantum well. The well width is so narrow that we applied an atomic layer doping.