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C-V Profiling Studies on MBE-Grown GaAs/AlGaAs Heterojunction Interface

Miyoko O. Watanabe, Jiro Yoshida, Masao Mashita, Takatosi Nakanisi and Akimichi Hojo

Toshiba Research and Development Center

1, Komukai Toshiba-cho, Saiwai-ku, Kawasaki 210, Japan

A C-V profiling technique is employed to investigate the GaAs/AlGaAs heterojunction interface grown by MBE. Systematic studies are carried out to determine the conduction band discontinuity ΔE_c by examining the dependence of ΔE_c on the composition of AlGaAs layer. The valence band discontinuity ΔE_v is also investigated. All the results consistently show that ΔE_c and ΔE_v are 0.62 and 0.38 of the band gap discontinuity ΔE_g respectively for the abrupt heterojunction.

§1. Introduction

Recent rapid progress in epitaxial growth techniques enables one to control the heterojunction structure in atomic scale, making it possible to design the band structure to realize the required device performance. There has been a growing interest in the use of GaAs/AlGaAs heterojunction for new optoelectronic and high-speed devices, such as the multiquantum-well laser, the modulation doped field effect transistor and the heterojunction bipolar transistor. Although many works have been reported concerning the heterojunction device performances, there still are subjects to be explored regarding the basic properties of the heterointerface.

The most fundamental problem is the band discontinuity at the heterointerface. The first attempt to determine the band discontinuity of GaAs/AlGaAs heterojunction was reported by Dingle et al. based on the infrared absorption spectra of multiquantum-well structures.[1,2] Kroemer et al. reported a C-V analysis for the heterojunction using the LPE-grown single heterostructure.[3] However, a systematic study on the band discontinuity has not been sufficiently made.

This paper describes the first detailed experimental determination of the band discontinuity of GaAs/AlGaAs heterojunction by means of the C-V profiling technique.

§2. Experimental

Three types of samples, shown in Fig.1, were prepared for the measurements of the conduction band discontinuity ΔE_c and the valence band discontinuity ΔE_v. The sample specifications are listed in Table I. The samples of type A have n-AlGaAs on n-GaAs structure (designated as normal structure), whereas the samples of type B have the reverse structure, that is n-GaAs on n-AlGaAs (inverted structure). The measurements of ΔE_c were performed using the samples of type A and B. Samples with various composition x of $Al_xGa_{1-x}As$ layers ranged from 0.15 to 0.3, were prepared. Futhermore, compositional graded AlGaAs layers with the width L_G of 100A and 500A were introduced in some of samples of type A. The samples of type C have p-AlGaAs on p-GaAs sturcture (normal structure), which were used for the measurement of ΔE_v.

The substrates used in this experiment were (100) Si-doped n^+ GaAs for type A and B, and Zn-doped p^+ GaAs for type C. The epitaxial layers were grown by MBE with typical growth conditions of a substrate temperature of 700°C, a flux ratio of As_4 to Ga of 2, and a growth rate of 1μm/hr. All layers were uniformly doped to a level of $4\times10^{16} \sim 8\times10^{16}$ cm^{-3} with Si and Be for n-type and p-type layers, respectively. Uniform doping is required for the accurate quantitative measurements. Compositional graded AlGaAs layers

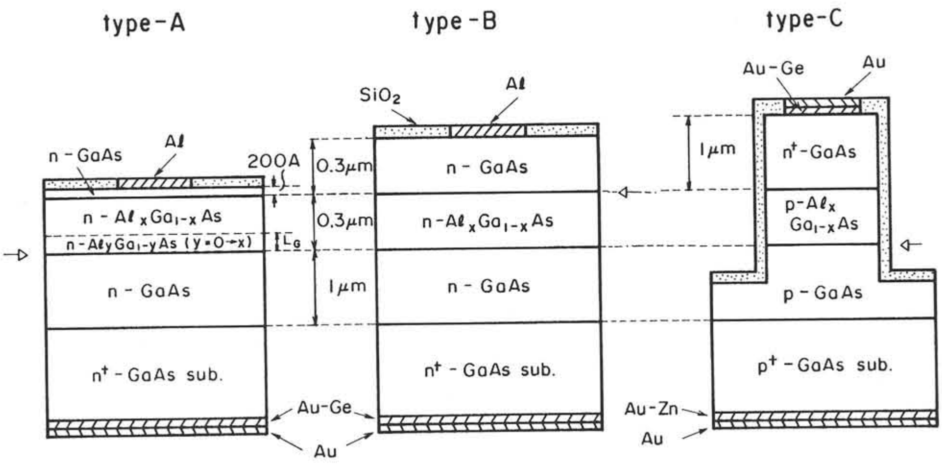

Fig.1. Cross sectional view of the three types of samples. The arrows indicate the measured heterointerfaces.

with 100 and 500A width were grown by heating the Al cell in 3 and 5 steps, respectively.

The Al Schottky diodes with 400 μm in diameter were fabricated for the n-type heterojunction, whereas the n^+p diodes with 500μm in diameter were fabricated for the p-type one.

C-V profile measurements were carried out to determine the band discontinuity ΔE_c, ΔE_v and the interface charge density σ.[3] The value of σ is directly derived from the total number of carriers calculated from the C-V profile curve, whereas some calculations are required for the evaluation of ΔE_c and ΔE_v, as described in Ref.3. In order to attain a high accuracy in the determined ΔE_c and ΔE_v values, following procedure was carried out. (1) Samples were carefully prepared to obtain the flat profile in C-V curve in both sides of the heterojunction in order to assign doping levels without ambiguity, in contrast to early works.[3,4] (2) The distance between the peak position of the C-V carrier profile and the heterointerface was determined by numerically solving the Poisson's equation and then reconstructing the C-V profile curve. (3) The values of ΔE_c and ΔE_v were corrected by taking the presence of σ into account.

§3. Results and Discussion

Figure 2 shows the apparent electron concentration profiles obtained by the C-V measurements at room temperature for $GaAs/Al_{0.3}Ga_{0.7}As$ samples, A-2 and B-2. It is noted that the flat profiles in both GaAs layers

Table I. Heterostructure samples.

sample (type)	structure	n or p	x	grading width(A)
A-1	normal	n	0.2	0
A-2	normal	n	0.3	0
A-3	normal	n	0.3	0
A-4	normal	n	0.3	100
A-5	normal	n	0.3	500
B-1	inverted	n	0.15	0
B-2	inverted	n	0.3	0
C-1	normal	p	0.3	0

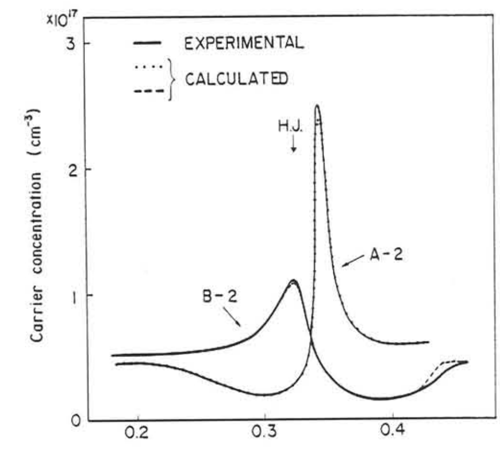

Fig.2. Apparent carrier profiles obtained by C-V method for $GaAs/Al_{0.3}Ga_{0.7}As$ heterojunctions, A-2 and B-2. The dotted curve shows the calculated result assuming ΔE_c=0.22eV and σ=7.3×10^{10} cm^{-2}, while the broken curve shows the calculated result assuming ΔE_c=0.25eV and σ=-1.3×10^{10} cm^{-2}.

and $Al_{0.3}Ga_{0.7}As$ layers are realized. From the measured profile and the procedure described above, we obtained ΔE_c=0.22eV and $\sigma=7.3\times10^{10}cm^{-2}$ for A-2, and ΔE_c=0.25eV and $\sigma=-1.3\times10^{10}cm^{-2}$ for B-2. Dotted curve in Fig.2 is calculated assuming ΔE_c=0.22eV and $\sigma=7.3\times10^{10}cm^{-2}$ for type A, while broken curve shows the result of calculation assuming ΔE_c=0.25eV and $\sigma=-1.3\times10^{10}cm^{-2}$ for type B. The agreements between the measured curves and the calculated ones are quite well for both normal and inverted structures. The agreements confirm the reliability of the derived ΔE_c and ΔE_v. On the contrary, the curve calculated based on Dingle's rule (ΔE_c=0.33eV) showed substantial deviation from the measured curve.

We also observed the C-V profile for the samples with x=0.15 and 0.2. Figure 3 shows the apparent electron concentraiton profiles at room temperature (RT) and 77K for a sample B-1 ($GaAs/Al_{0.15}Ga_{0.85}As$). The value of ΔE_c is obtained as 0.11eV at both temperatures of RT and 77K. Measurements at 77K are performed only for the sample with $x\leq0.2$. In the region of $x>0.2$, ΔE_c cannot be evaluated, because the DX centers, which are the dominant donors in this region, become filled with electrons and no longer emit electrons.[5] In case of a sample A-1 ($GaAs/Al_{0.2}Ga_{0.8}As$), ΔE_c was obtained as 0.15eV at both RT and 77K.

Figure 4 (a) shows the conduction band discontinuity ΔE_c as a function of composition x for abrupt $GaAs/Al_xGa_{1-x}As$ heterointerfaces. The valence band discontinuity ΔE_v was also measured using the samples of type C, and the result is shown in Fig.4 (b). From these plots, it was found that the values of ΔE_c followed $0.62\Delta E_g$ rather than $0.85\Delta E_g$ expected from Dingle's rule.[2] Similar disagreement with Dingle's rule was found in the value of ΔE_v, which followed $0.38\Delta E_g$ rather than $0.15\Delta E_g$. Moreover, it is seen that ΔE_c of normal structure interfaces agrees with that of inverted structure interfaces. This is clear evidence that the band discontinuity is independent on growth sequence in the GaAs/AlGaAs heterojunction system.

Figure 5 shows apparent ΔE_c versus compositional graded width L_G. As is expected, ΔE_c decreases with increasing L_G. The solid line in Fig.5 shows apparent ΔE_c calculated based on

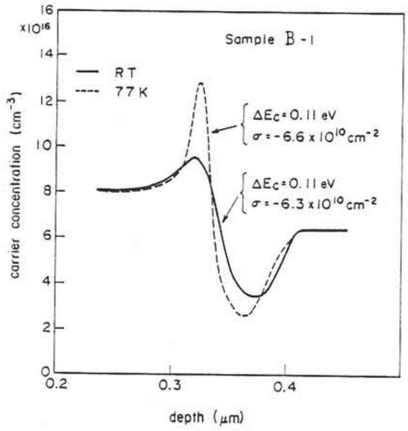

Fig.3. Apparent carrier profiles at RT and 77K for the $GaAs/Al_{0.15}Ga_{0.85}As$ heterojunction.

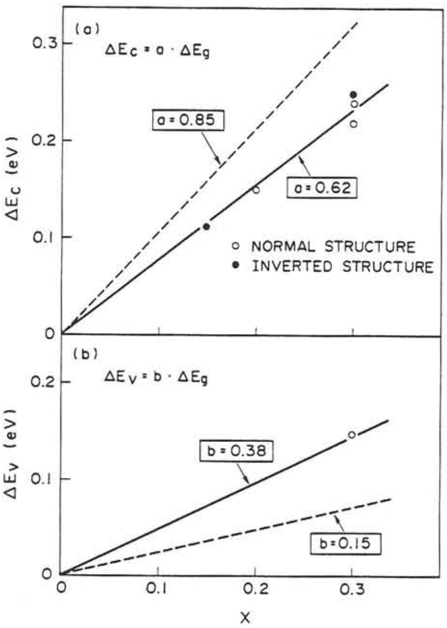

Fig.4. (a) Conduction band discontinuity ΔE_c and (b) valence band discontinuity ΔE_v at $GaAs/Al_xGa_{1-x}As$ heterointerface as a function of composition x.

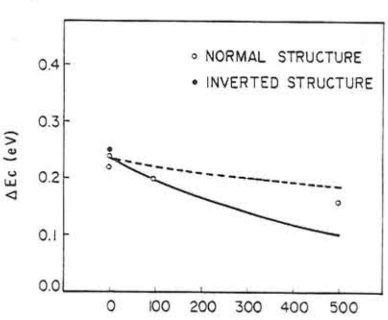

Fig.5. Apparent conduction band discontinuity ΔE_c versus grading width L_G. The solid curve is calculated assuming $\Delta E_c=0.62\Delta E_g(L_G=0)$ and linear compositional grading over L_G. The broken curve shows the calculated results assuming $\Delta E_c=0.62\Delta E_g(L_G=0)$ and stepping grading layer.

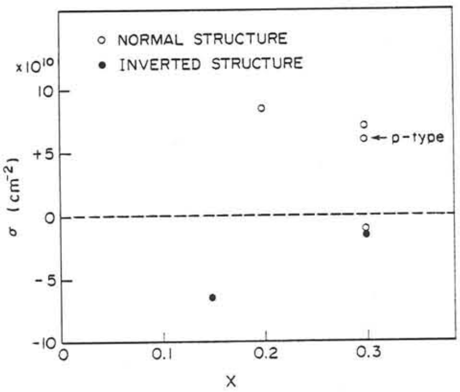

Fig.6. Dependence of interface charge density σ on composition x.

the assumption that the abrupt junction has $\Delta E_C=0.62\Delta E_g$ and the compositional grading is made linearly over L_G. The broken curve indicates calculated values of ΔE_C, assuming that the compositional grading is made with 3 and 5 steps without smearing. The measured ΔE_C lies between the two calculated curves, suggesting that the compositional change in the graded layer lies between the steplike- and linear shapes. These results presented in Fig.5 support the rule of $\Delta E_C=0.62\Delta E_g$.

Figure 6 shows the interface charge density σ versus composition x for abrupt heterojunctions. Many of normal structures have positive σ , whereas the inverted structure has negative σ . However, the clear tendency is not observed. It is considered that σ is dependent on the run to run growth condition.

§ 4.Conclusion

The conduction band discontinuity ΔE_C , the valence band discontinuity ΔE_V and the interface charge density σ have been investigated for a GaAs/AlGaAs single heterojunction grown by MBE. The C-V profiling technique was employed for the measurements, that is the best of the purely electrical measurements. In order to attain a high accuracy in ΔE_C and ΔE_V, considerable attention was paied to sample preparation and analysis of the C-V profile curve. The effect of the composition of AlGaAs layer as well as of the compositional graded width on ΔE_C was examined. All experimental results consistently showed that ΔE_C and ΔE_V were 0.62 and 0.38 of the band gap discontinuity ΔE_g for the abrupt heterojunction.

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