Journal of Korean Institute of surface Engineering
Vol. 29, No. 6, Dec., 1996

# CHARACTERIZATIONS OF TILTED SUPERLATTICE QUANTUM WIRE GROWN BY MIGRATION ENHANCED EPITAXY METHOD

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## ABSTRACT

The artificial construction of well-defined low-dimensional (low-D) quantum structures, such as quantum wire (QWR) still attracts attention of many researchers due to their applications in room-temperature optoelectronic devices. In this work, the migration enhanced epitaxial growth (MEE) and the analysis of InAs/AlAs QWR are reported.

On the vicinal semi-insulating InP substrate of 3° tilted cut from (100) surface towards (010) direction, InAs/AlAs QWR superlattices have been successfully grown by MEE with the introduction of growth interruption at each shutter operation of MBE cell. The in-situ RHEED analyses show that MEE gives superior step-flow growth (SFG) and sharper interface formation over a conventional MBE growth. We have grown 4 samples in series varying the growth temperature. The QWR samples are analyzed by photoluminescence (PL) and atomic force microscopy (AFM). From the AFM images, we can get the definitely resolved 1-D structures. This structure is believed to be due to the MEE method and its separation is better than any other data from others. We are now studying the dependence of the structure on the growth temperature.

## INTRODUCTION

The structures of quantum wire (QWR) or quantum dot have attracted much attention owing to their extremely small size and the low dimensional properties. Specially, InAs quantum wire (QWR) structure is interesting because of the self-aligning effect to form strained layer superlattices.[1,2] Many resear-chers have tried to fabricate QWR structures by various kinds of techniques. One of them is the tilted superlattice (TSL) method.[3] In this method, the substrate is originally tilted from a standard faces of crystal with slight degrees and the growth of the epilayer is performed on the tilted surface. In that case, the preferred area of the growth front would be the staircase region of the surface and the resulting epilayer would be QWR structure. In spite of the suggested model and many experimental trial and error, the results were not so satisfactory. Another kind of method suggested for the epilayer growth using molecular beam epitaxy (MBE) is migration enhanced epitaxial method (MEE).[4] This technique offers the maximum opportunity for the precursors to migrate above the growth surface. We have adopted both TSL method and MEE technique for the fabrication of InAs/AlAs QWR structures. Since the staircase site on vicinal substrate has lower chemical potential, it is expected to become nucleation surface. In this step flow growth, it is important to enhance the migration of molecules to reach the staircase, and the MEE growth would maximize the migration to the staircase site. In Fig. 1. the diagram illustrating the TSL method and the resulting QWR structure is shown.

In this work, the results of InAs/AlAs QWR growth by TSL method is reported. The analyses of atomic force microscopy (AFM) and magnetoluminescence show that MEE indeed produces sharply defined QWR structure with clear 1-dimensional (1-D) crystalline formation and electronic confinement.

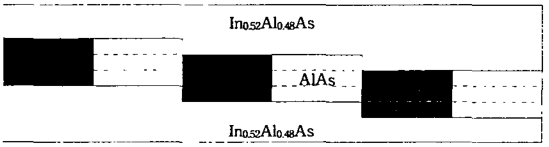


Fig. 1 A diagram representing "Tilted Superlattice method" (TSL) which we have adopted in this work. The width of InAs QWR is aimed to be 10 ML and the height is 20 ML.

## EXPERIMENTAL PROCEDURE

Four InAs/AlAs QWRs (28Å wide and 56 Å high) sandwiched by $In_{0.52}Al_{0.48}As$ barriers were grown with the TSL method using RIBER 2300P MBE system. InP substrates tilted $3^{\circ}$ from the (100) surface toward the (010) direction were used as substrates. Details of the growth procedure are as follows. On the 3,000 Å $In_{0.52}Al_{0.48}As$ cladding layer, the QWR structure was grown by either MEE or conventional MBE method. During the MEE growth, In shutter was opened for ~3 sec and then after closing In shutter, As shutter was opened for ~6 sec depending on the flux condition for the As deposition. And then opening of Al shutter was followed after closing As shutter. The opening time of Al shutter is ~3 sec also. During the whole procedure, the growth interruption of 3 s has been introduced after each step for the purpose of migration enhancement. The shutter operation of this MEE process is shown in Fig. 2. By repeating this processes, we have fabricated the QWR having 10ML width and 20ML height. On the top of QWR, another 1,000Å $In_{0.52}Al_{0.48}As$ cladding layer was grown, and finally additional QWR layer with the same structure was fabricated to obtain AFM image. Using MEE technique, we have grown three samples by varying growth temperature ($T_g$), $T_g$ = 460, 480 and 500℃, and using MBE technique, one sample was grown for the comparison and $T_g$ was set to be 480℃ in this case.

Before trying to obtain AFM image, the top layer of QWR was selectively etched with

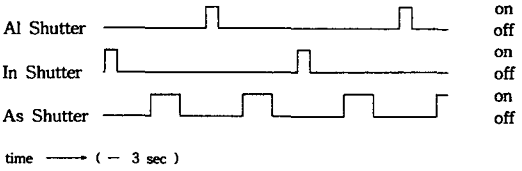
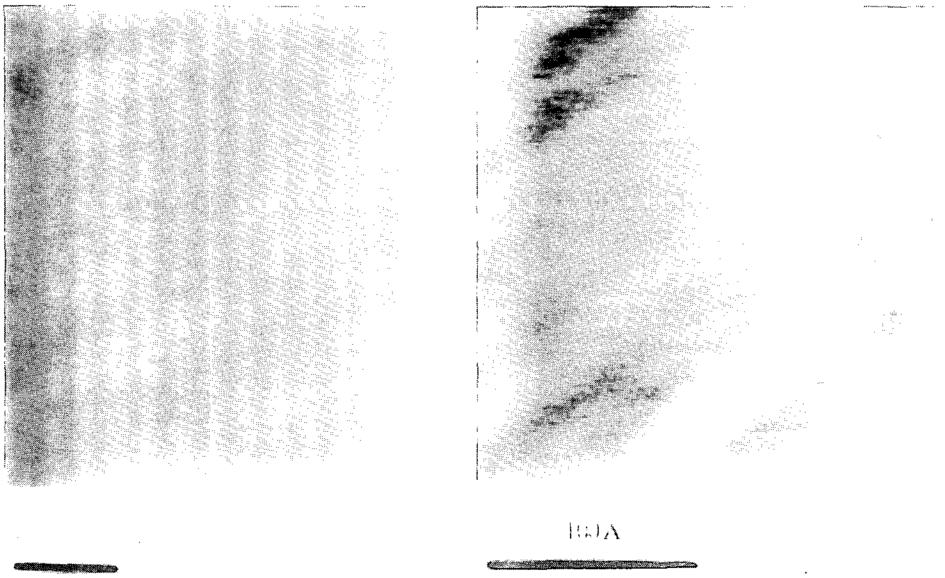


Fig. 2 Schematic illustration of Migration Enhanced Epitaxy (MEE). The shutter opening time was set to be ~3 sec for Al and In, and ~6 sec for As.



(a) (b)

Fig. 3 The AFM images of the InAs/AlAs QWRs, in these images dark regions represent AlAs region and the bright regions represent InAs. (a) The AFM image of the QWR grown by MEE method at $T_S = 460$℃. (b) The AFM image of the QWR grown by conventional MBE method at $T_S = 480$℃. There is no critical difference among the AFM images of the three MEE grown QWRs, but that of conventional MBE grown QWR does not show the clear 1-dimensional structure.

HF, which etch out the oxidized Al. Resulting surface is expected to be the form of 1-dimensional wave, whose top is InAs and the bottom is AlAs. The magnetoluminescence was performed with 20T resistive magnet and $Ar^+$ laser at 4.2K, varying the magnetic field by the step of 1 T.

## RESULT AND DISCUSSION

### Result of AFM analysis

The AFM images obtained from MEE grown InAs/AlAs QWRs show that the well defined QWRs of extended length have been fabricated for all the growth conditions tried in this work. There appears little difference in the AFM images between the samples grown at different substrate temperature when MEE method was adopted. However, in the sample grown by conventional MBE, we could not observe the clear image with wavelike structure. AFM image of MEE grown QWR with the substrate temperature 460℃ is compared with that of MBE grown QWR in Fig. 3(a) and (b), respectively. As we have etched out the oxidized Al just before taking the images, the bright and dark regions represent InAs and AlAs, respectively.

From the AFM analysis, we are able to manifest that the clear 1-D structure is formed within the detection range without any imperfection. Also, the periodicity of the wavelike picture is neatly uniform and the transverse length of QWR period is measured to be 58.7Å, which agrees well with the designed value from the tilting degree 3° and the lattice constant of InP substrate. However, the measured height of the wire have some large error, that is, the value of height of the wave is distributed from 40 to 90Å, with the average value of 60Å. Thus, the dimension of our QWR is 29.4Å × 60Å, which is fairly good result considering the aimed structure. From these results, we can say that MEE method is superior to the conventional MBE technique for the fabrication of the 1-D or 0-D structures.

## Result of magnetoluminescence analysis

Though we have examined the topological configuration of our QWRs, we cannot tell the low dimensional confinement effects in the real QWR layer sandwiched by $In_{0.52}Al_{0.48}$ As barriers. To see the 1-D confinement effects of the electrons, we have performed the magnetoluminescence spectroscopy up to 20 T, as shown in Fig. 4.

Generally, when the high magnetic field is applied to the pure thin films, the nearly quadratic diamagnetic shift occurs in the luminescence peak energy. The value of this shift varies depending on the degree of confinement because of the quantized Landau

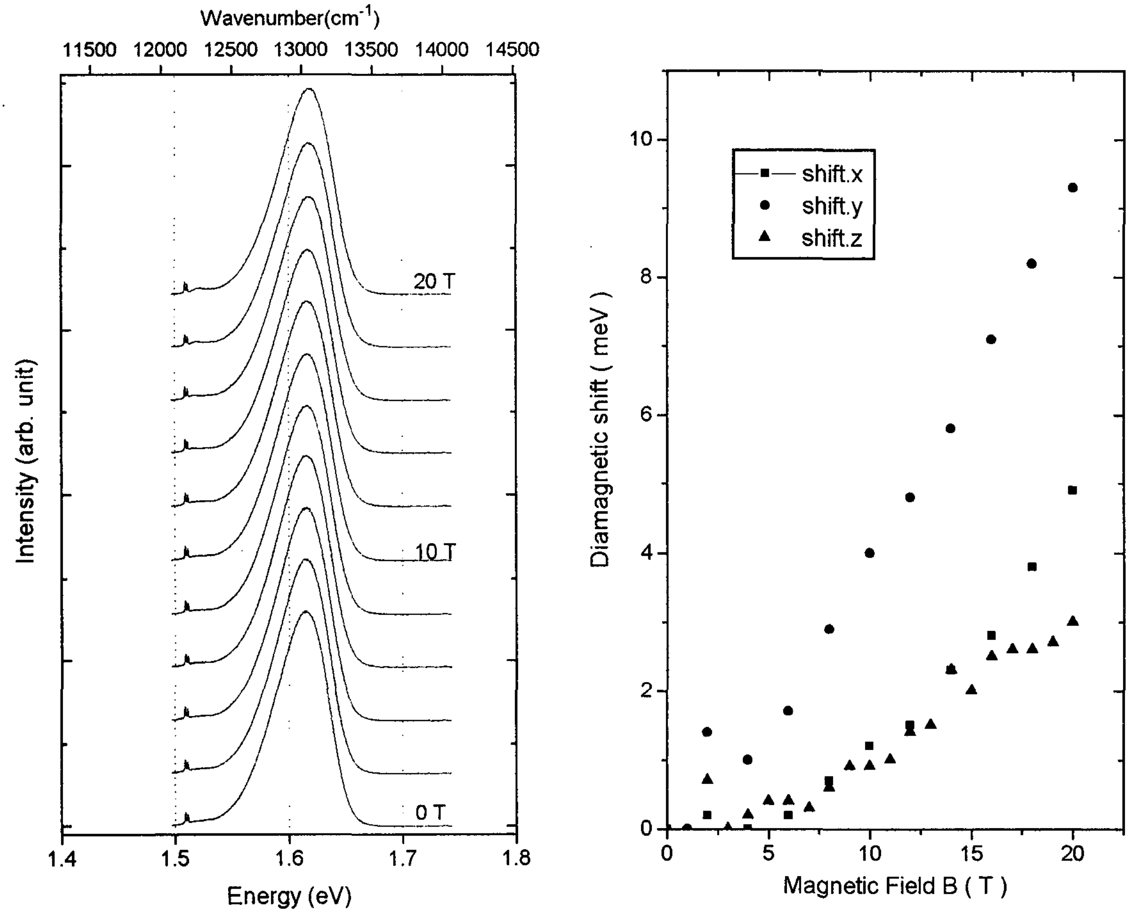


Fig. 4 (a) Magnetoluminescence spectra of InAs/AlAs QWR obtained at 4.2 K. Each of the spectra was obtained in the magnetic field from 0 to 20T. (b) The diamagnetic shift of the magnetoluminescence peak energy when the magnetic field is parallel to the growth direction. Notice that diamagnetic shift is small.

state. Typically, in case of bulk GaAs, the diamagnetic shift is over 15meV at 20T. This shift gets smaller as the dimensionality decreases. For example, in case of quantum well (QW), this shift decreases down to around 8meV as the well layer thickness gets narrower to 60Å,[5] and 4meV when the QW width is 30Å,[6] Similarly, in case of QWR, the effect of magnetic field is also decreasing with decreasing wire width.

That is, in wider QWRs, the wave function is softer and more squeezable, which causes the larger magnetic field effects. So, the small diamagnetic shift is the clear evidence of the reduced dimensionality of the QWR structure.[7] And this theoretical expectation was already examined with GaAs/$Al_xGa_{1-x}$As QW and QWR samples which have the same width of 19 ML.[8] In that experiment, the diamagnetic shift of the QWR is significantly smaller than that of QW, which is typical manifest of 1-D confinement.[9]

The magnetoluminescence spectra of the InAs/AlAs QWR obtained at 4.2K in the magnetic of 0 to 20T and the corresponding values of diamagnetic shift are shown in Fig. 4(a) and (b), respectively. In Fig. 4(a) the small and sharp peak appearing at 1.51eV is not from the sample but a reference line. In this figure, the data is obtained with the geometrical configuration of B//z (denoted as shift.z by solid triangles). Though spectra are not shown here, you can find the diamagnetic shifts obtained in different geometrical configurations, that is in B//x (denoted as shift. x by solid squares) and B//y configuration (denoted as shift.y by solid circles) in Fig. 4 (b). Here, x is the direction of QWR and z is that parallel to the growth direction and y is normal both to QWR and the growth direction.

As you can see in Fig. 4(b), the magnitude of diamagnetic shift is small when the magnetic field is parallel to the growth direction (B//z or shift.z), the maximum is 3meV at 20 T. This value is very small compared with that of QW having the nearly same width. From this experimental results and the above discussions, we are able to have the confidence that this sandwiched layer have reasonable 1-D confinement characteristics. In the other configurations, slightly different results were obtained. When B is parallel to x, the diamagnetic shift is small also with nearly same magnitude at 20 T. But, the shift is relatively large in B//y configuration. The maximum value of the shift is nearly 10meV at 20T, which is comparable to the ones observed in QW structure. To the best knowledge of the authors, this kind of result was not reported yet. Though further detailed study is necessary for the satisfactory explanation, we can speculate that this unexpected large shift is originated from the height of the QWR, measured value of which is nearly 60Å (twice of the lateral width of QWR). If this measured value is applied to the layer sandwiched by $In_{0.52}Al_{0.48}As$ barriers, the wave function in B//y configuration is much broader than those in the other configurations, which means that wave function is much softer or squeezable. Thus, the effect of the external magnetic will appear drastically contrary to the other configurations, which is due to the cyclotron radius of the electron. In this structure, the barrier is composed of binary AlAs layer whose thickness is nearly the same as that of InAs wire. Considering the fact that the layer thickness of AlAs barrier is thin, at first, the bandgap of the AlAs barrier is so large compared with that of InAs that it is not easy for the wave function to penetrate into the adjacent wire. And, in second the cyclotron orbit is normal to the line connecting InAs and AlAs layer that shrinkage of the confined wave function arise in the plane of InAs and very thick (order of 1,000Å) $In_{0.52}Al_{0.48}As$ barriers. As describe above, the situation of B//y is very similar with the configuration of B//x, the only remaining difference is the effect of the wire dimension according to the configuration.

Additionally, though not shown here, the full width half maximum of the luminescence peak was plotted and appeared to increase as the applied magnetic field intensity increases, which agrees well with the statistical fluctuation model.[10]

## CONCLUSIONS

In this work, it has been demonstrated that the migration enhanced epitaxy is an excellent method of growing InAs/AlAs quantum wire superlattice structures on InP vicinal substrate.

Atomic force microscope analysis has shown the sharply-defined periodic images and it says that one of the most ideal 1-dimensional structure was formed on a vicinal substrate by migration enhanced epitaxy in a relatively wide range of substrate temperature, from 460 to 500℃. The diamagnetic shift of quantum wire is observed very small through the magnetoluminescence study and this result provides a clear indication of transverse periodicity of quantum wire superlattice. The new experimental fact showing the variation of the diamagnetic shift depending on the configuration is illustrated qualitatively and further study is needed. In comparison, the quantum wire fabricated by conventional molecular beam epitaxy technique did not show any clear evidence of the clear wire formation. Conclusively, the migration enhanced epitaxy technique provides one of the reliable methods of growing quantum wire. The superbly structured quantum wires have been presented with a unique 1-dimensional confinement effect in a magnetic field.

## ACKNOWLEDGMENTS

This work was supported in part by the MOE, Korea and Korea Telecom. Special appreciation is delivered to the devoted service of NHMFL staffs and Dr. S. J. Park in KJIST.

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