MOVPE growth and characterization of ZnSe–GaAs heterovalent heterostructures

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Abstract. ZnSe–GaAs heterovalent heterostructures were fabricated by metalorganic vapour phase epitaxy and characterized structurally and electrically. A study on growth behaviour of GaAs on ZnSe revealed that either the 2-dimensional or the 3-dimensional growth mode may occur depending on the growth conditions. This growth behaviour is applied to the construction of low-dimensional structures. Successful fabrication of quantum well structures and GaAs islands buried into ZnSe is demonstrated by means of X-ray diffraction and transmission electron microscopy. The electrical properties of the heterostructures are also described.

Keywords. ZnSe; GaAs; heterovalent heterostructure; X-ray diffraction; TEM; DLTS.

1. Introduction

The concept of integrating compound semiconductors seems attractive in the field of optoelectronic devices. For example, laser diodes and light emitting diodes cannot be realized without the integration of different materials such as GaAs and AlGaAs. So far, in order to avoid electron-excess or electron-deficient chemical bonds at the interfaces, devices have generally consisted of homovalent materials. On the other hand, recent considerable progress of growth techniques such as metalorganic vapour phase epitaxy (MOVPE) and molecular beam epitaxy (MBE) is making it possible to integrate heterovalent materials. This may allow a wider range of applicable thin-film materials and heterostructures. Compared with homovalent systems, heterovalent systems may have larger band-gap discontinuities and larger differences in the dielectric constant, which would enhance device performance. Furthermore, heterovalent systems may lead to new functions which cannot be predicted by the conventional idea of the compositional average (Greene 1983).

ZnSe–GaAs is one of the most promising heterovalent material combinations, because the lattice mismatch between ZnSe and GaAs is relatively small (0.27% at room temperature) and optoelectronic devices composed of this combination may cover the entire visible spectrum. Recently some theoretical analyses have shown interesting properties of ZnSe–GaAs quantum wells (QW) (Ihm and Cohen 1979; Khurgin 1988; Kumagai and Takagahara 1988; Shen *et al* 1988; Eppenga 1989). Kumagai and Takagahara (1988) proposed a dielectric QW in which the large difference in dielectric constants between well and barrier layers was positively utilized, and introduced a ZnSe–GaAs QW as a realistic example. Khurgin (1988) showed that the nonlinear and electrooptic coefficients of ZnSe–GaAs heterostructures are substantially larger than those of conventional materials, such as AlGaAs–GaAs heterostructures. However, there are few reports on the fabrication of ZnSe–GaAs QWs (Kobayashi and Horikoshi 1990; Funato *et al* 1992, 1993; Zhang and Kobayashi 1992), because growth of GaAs on ZnSe is considerably more difficult than the inverse, much-studied growth of ZnSe on GaAs. This is due to the widely different

optimum growth temperatures for the two materials: high-quality ZnSe on GaAs is grown at temperatures below 500°C, whereas GaAs with superior properties is grown at temperatures above 600°C by MOVPE.

Kobayashi and Horikoshi (1990) investigated GaAs MBE on ZnSe. To avoid the problem of the low As₄ sticking coefficient on the ZnSe surface, the combination of solid-phase epitaxy (SPE) and migration-enhanced epitaxy (MEE) was employed. The best quality of GaAs was obtained by initiating the growth on ZnSe with As₄ exposure and deposition of two monolayers (ML) of Ga at room temperature followed by SPE. Farrell *et al* (1991) examined the correlation between interface structures and the growth behaviour of GaAs MBE onto ZnSe. They pointed out that a ZnSe(100)*c*(2 × 2)-Zn surface, which is terminated with 1/2 ML of Zn, is optimized by a sequence of steps involving a predeposition of excess Se and a low-temperature deposition of 1/2 ML of Ga prior to GaAs epitaxy. This would provide equal numbers of Ga-Se and As-Zn bonds, resulting in charge neutrality at the interface.

On the other hand, MOVPE has an advantage over MBE that GaAs can be grown on ZnSe at constant growth temperature (Funato *et al* 1992, 1993). In the work described in this paper, the effect of growth conditions, especially growth temperature and V/III ratio, on the growth behaviour in GaAs MOVPE onto ZnSe (001) was studied by means of transmission electron microscopy (TEM). The growth was carried out without changing the growth temperature, unlike GaAs MBE on ZnSe mentioned above. We show that either the 2-dimensional or 3-dimensional growth mode occurs depending on the growth conditions. This growth behaviour is applied to the fabrication of low-dimensional structures and then structural properties characterized in detail by means of double-crystal X-ray diffraction (XRD) and TEM. Finally we refer to electrical properties of Zn(S)Se-GaAs heterostructures.

2. Experimental

Samples were grown on [001]-oriented GaAs substrates by an atmospheric-pressure MOVPE system with a cold-wall vertical reactor. Both ZnSe and GaAs layers were grown in the same reactor. Prior to the growth, GaAs substrates were cleaned by degreasing in solvents followed by chemical etching in acidic solution. Etched substrates were loaded into the reactor and were heated to thermally desorb the surface oxide layer at a temperature of 580°C for 10 min in an As ambient. The growth temperature (T_g) was varied between 450°C and 550°C. Source materials used were diethylzinc (DEZn) and dimethylselenium (DMSe) for ZnSe, and triethylgallium (TEGa) and tertiary butylarsine (TBAs) for GaAs. Typical flow rates of DEZn, DMSe and TEGa were 6, 48 and 10 $\mu\text{mol/min}$, respectively, and the TBAs flow rate ([TBAs]) ranged from 20 to 100 $\mu\text{mol/min}$. It should be pointed out that in the case of homoepitaxy, the growth rates of GaAs did not depend on the growth conditions employed here.

Double-crystal XRD patterns were obtained in the vicinity of the symmetric 004 GaAs Bragg angle, utilizing a $\text{CuK}\alpha_1$ line ($\lambda = 1.5405 \text{ \AA}$). Theoretical calculation of the X-ray rocking curve is based on the step model (Segmüller and Blakeslee 1973). In the calculation, it was assumed that only ZnSe layers were distorted tetragonally (coherent growth) and that GaAs layers were not distorted. Validity of this assumption was confirmed structurally by comparison of the experimental diffraction pattern with the theoretical calculation and optically by the reflection measurement.

TEM is a powerful technique which provides direct visualization of the interfaces in cross-sectional images, and allows accurate thickness measurements. A $[110]$ cross-section was prepared by ion milling (3 keV Ar^+). The image was obtained in the bright field.

3. Growth of GaAs on ZnSe

An effort was made to grow the double-layered structure designed as in figure 1, wherein we investigated the growth behaviour of GaAs heteroepitaxy on ZnSe, ZnSe heteroepitaxy on GaAs, and GaAs homoepitaxy through observation of cross-sectional views of layers A, B and C, respectively. A series of samples were grown at the same gas flow rates of $\text{VI/II} = 8$ and $\text{V/III} = 5$ at the different growth temperatures of $T_g = 450\text{--}550^\circ\text{C}$. The surface morphology observed by a Nomarski microscope revealed that the double layers grown at high temperature (550°C) have rough surfaces, while those grown at low temperatures ($\leq 550^\circ\text{C}$) have mirror-like surfaces, consistent with the previous report on thicker double layers (Funato *et al* 1992). Figure 2 shows cross-sectional $[110]$ TEM bright-field images of the samples. These images clearly indicate that the growth mode of GaAs buffer layers on GaAs substrates (homoepitaxy) is 2-dimensional at any growth temperature examined here. ZnSe layers grown on GaAs are also uniform in thickness at all temperatures. In contrast, although GaAs growth on ZnSe below 500°C is 2-dimensional, as easily predicted by the Nomarski microscope observation, GaAs grown at 550°C is highly 3-dimensional. These findings indicate that the growth behaviour of GaAs on ZnSe is quite different from that of the reverse sequence of ZnSe on GaAs and that of GaAs homoepitaxy.

To elucidate the reason for this growth behaviour, we attempted to grow the same structures as shown in figure 1 at 550°C , varying the V/III ratio from 2 to 10. Since the flow rate of TEGa is unchanged, a variation of the V/III ratio means flow rate variation of TBAs. Cross-sectional $[110]$ TEM bright-field images are shown in figure 3. They reveal that as the V/III ratio increases i.e. as $[\text{TBAs}]$ increases, GaAs

Figure 1. Schematic diagram of the designed GaAs on ZnSe double-layered structure. The expected dimensions are GaAs (200 Å), ZnSe (200 Å) and GaAs buffer layer (200 Å).

$T_g=450^{\circ}\text{C}$ $T_g=500^{\circ}\text{C}$ $T_g=550^{\circ}\text{C}$

Figure 2. Cross-sectional [110] TEM bright-field images of GaAs (200 Å)/ZnSe (200 Å) double-layered structures grown at various temperatures. V/III ratio is fixed at 5.0.

$V/III=2$

GaAs

ZnSe

GaAs buffer

GaAs sub.

 $V/III=5$

GaAs

ZnSe

GaAs buffer

GaAs sub.

 $V/III=10$

GaAs

ZnSe

GaAs buffer

GaAs sub.

500Å

Figure 3. Cross-sectional [110] TEM bright-field images of GaAs (200 Å)/ZnSe (200 Å) double-layered structures grown under various V/III ratios. The growth temperature is kept constant at 550°C.

becomes flat, whereas as the V/III ratio decreases, GaAs exhibits island-type 3-dimensional growth in which the islands tend to separate from each other.

Figure 4 shows the variation of GaAs island height as a function of the V/III ratio. Island height was measured from cross-sectional TEM images at several different positions on the samples, and is equivalent to layer thickness for the flat layers grown at 450°C or 500°C. For GaAs grown at 550°C, as the V/III ratio increases GaAs shows a stronger tendency for 2-dimensional growth, as seen in figure 3, and the island height decreases. At high V/III ratios, the island height approaches the thickness of the flat layers. This figure suggests that the mechanism behind the formation of GaAs islands on ZnSe is mainly related not to desorption but to migration, because if desorption were the main cause of island formation, the island height would decrease with decrease of the V/III ratio.

For confirmation of this hypothesis, ZnSe–GaAs multilayered structures were grown at 500°C and 550°C without changing the duration of supply of source precursors; hence, unless desorption occurs, the nominal mean thickness of 3-dimensional GaAs growth at 550°C must be equal to the thickness of 2-dimensional GaAs grown at 500°C. This is because GaAs growth rate is constant through the growth conditions employed here, as mentioned in § 2. XRD analysis of multilayered structures was applied for the evaluation of the mean thickness. The XRD pattern has satellite peaks and a fundamental peak. The satellite peaks reflect the periodicity and the fundamental peak is located at the angular position determined by the thickness ratio of a set of alternating layers, from which the mean thickness can be estimated. Figure 5 shows double-crystal XRD patterns of the multilayered structures grown at 500°C and 550°C. The structure intended is two cycles of GaAs (200 Å)/ZnSe (250 Å). The XRD profile of the multilayer grown at 500°C has satellite peaks (denoted by open arrows in the figure), indicating good periodicity. On the other hand, satellite peaks are absent in the profile of the multilayer grown at 550°C. This is due to degradation of the periodicity by 3-dimensional growth of GaAs at 550°C.

Figure 4. Dependence of GaAs island height on V/III ratio.

Figure 5. Double-crystal XRD patterns of GaAs (200 Å)/ZnSe (250 Å) $\times$ 2 multilayered structures grown at 500°C and 550°C. The open arrow designates the fundamental peak and the closed arrows the satellite peaks.

However, since the fundamental peaks of both multilayers are at the same angle, we can conclude that the mean thickness of GaAs grown 3-dimensionally is equal to the layer thickness of GaAs grown 2-dimensionally. This finding provides the evidence for the above hypothesis that migration, not desorption, causes the 3-dimensional GaAs island formation.

In heteroepitaxy of dissimilar materials, migration length of adspecies is crucial to determine the growth mode. Lower growth temperatures will mean lower, or perhaps even negligible, migration lengths, and will therefore promote 2-dimensional growth (Bean *et al* 1984). A high density of adspecies may also bring about the 2-dimensional growth mode, because it inhibits migration and reduces epilayer surface roughness. These tendencies agree well with our results shown in figures 2 and 3. The problem is what the migrating species are. We investigated the effects of TEGa and TBAs on the ZnSe surface (Funato *et al* 1995). When ZnSe was annealed at 550°C in a TBAs ambient, ZnSe was drastically etched at the rate of 150 Å/min under [TBAs] = 20 μ mol/min, whereas it was not appreciably etched thermally. Therefore As-containing molecules, which are generated through decomposition of TBAs, are not the cause of island formation, because an As-related process includes a desorption process. On the other hand, when ZnSe was exposed to TEGa at 550°C, the ZnSe surface became rough due to the nucleation of adsorbed Ga, indicating that metallic Ga may easily migrate on ZnSe. These results indicate that Ga-related clusters are the migrating species and cause GaAs island formation on ZnSe.

4. Fabrication of ZnSe–GaAs low dimensional structures

The growth behaviour discussed above suggests that QWs or quantum dots (QD), where GaAs dots are buried in ZnSe, can be fabricated by controlling the TBAs flow rate and the growth temperature so that GaAs may be grown 2-dimensionally or 3-dimensionally, respectively. We describe the fabrication and structural properties of those low-dimensional structures.

4.1 Multiple quantum well structures

A multiple QW (MQW) whose structure is 10 cycles of ZnSe (200 Å)/GaAs (100 Å), inset of figure 6b, was fabricated under the growth conditions of $T_g = 500^\circ\text{C}$ and $V/\text{III} = 5$, which bring about 2-dimensional GaAs growth on ZnSe.

Figure 6 shows (a) the [110] cross-sectional TEM bright-field image and (b) the XRD pattern. TEM reveals the successful alternating deposition of 2-dimensional ZnSe and GaAs. The thicknesses of ZnSe and GaAs layers extracted from the photograph turned out to be about 200 Å and 100 Å, respectively, and these values are consistent with the expected dimensions. Fluctuation of the layer thicknesses from period to period seems quite small; we give detailed discussion on this on the basis of XRD. Neither threading dislocations nor stacking faults were observed over the whole area, implying that the lattice mismatch strain is accommodated elastically. Despite some possible intermixing of the layers, the evidence of abrupt compositional modulation is given by the marked contrast between dark ZnSe and bright GaAs.

The XRD pattern shown in figure 6b exhibits intense and well-defined satellite peaks. For comparison, the result of theoretical calculation is also indicated. Supposing

Figure 6a.

Figure 6. a. Cross-sectional [110] TEM bright-field image and b. double-crystal XRD patterns of GaAs (200 Å)/ZnSe (100 Å) $\times 10$ MQW. The growth conditions are $T_g = 500^\circ\text{C}$ and $V/\text{III} = 5$.

that the thicknesses of ZnSe and GaAs are 206 and 88 Å, respectively, the calculated peak positions agree well with those of the measured one, indicating the achievement of the designed structure. The full width at half maximum (FWHM) of 53 arcsec and relative intensity of satellite peaks against the fundamental peak are almost equal to the theoretical values; hence the sample may have a high crystalline quality, a high degree of lateral uniformity, and well-defined interfaces. These findings validate the conclusions derived from TEM.

Interference fringes which appear between Bragg peaks are quite sensitive to the small thickness fluctuation (Funato *et al* 1993). The thickness fluctuation in the same

MQW was investigated by examining the profile of interference fringe. The layer thickness with small fluctuation of Δ was assumed as $L(1 + \Delta)$ in the theoretical calculation, where L is the designed layer thickness. Δ will probably follow a Gaussian distribution. We can therefore define the thickness fluctuation using only one parameter, i.e. dispersion (δ) of the Gaussian distribution. Since the fluctuation is considered to be proportional to the thickness, the same dispersion can be used for both GaAs and ZnSe layers.

The profile of interference fringes between 0th and 1st satellite peaks is shown in figure 7, with results calculated by changing the degree of fluctuation from $\delta = 0\%$ to 7% . With increasing dispersion, i.e. increasing fluctuation, the profile becomes more irregular. Even when $\delta = 3\%$, a distinct deviation from the ideal diffraction pattern is already observed, whereas such deviation is not detectable in the theoretically calculated intensity and FWHM of the fundamental and ± 1 st satellite peaks. Of course, higher-order satellite peaks will be more sensitive probe to degradation of structural properties, but we believe that interference fringes provide another sensitive approach to evaluating a very small fluctuation. Comparing the experimental result with the calculations (a)–(d) in figure 7, it is found that the experimental profile shows relatively

Figure 7. Profile of interference fringe between 0th and -1 st satellite peaks of the MQW described in figure 6. The results calculated by assuming various degrees of thickness fluctuation of each individual layer are shown together with the experimental result.

regular oscillation and the structure has fairly complete periodicity, such that the dispersion of fluctuation is within a few per cent.

To investigate the fluctuation in the fabricated structure in detail, the difference between the profile with fluctuation and that without fluctuation ($\delta = 0$) was evaluated in terms of the R factor defined by (1) below. The profiles of interference fringes between 0th and -1st satellite peaks were used again.

$$R = \frac{\Sigma(|I_f| - |I_i|)}{\Sigma|I_f|}, \quad (1)$$

where I_f is observed scattering intensity or calculated one under the assumption of some fluctuation, and I_i the calculated ideal scattering intensity ($\delta = 0$). Scattering amplitude would be used in the conventional R factor. However, since what is observable is intensity, we use scattering intensity directly instead of scattering amplitude modulus. The result is shown in figure 8. The dashed line indicates the experimental R factor and the solid line is the R factor theoretically calculated under the assumption of some fluctuation. In the calculation, random numbers were used in order to express fluctuation, therefore the calculated R factor would change with every series of random numbers. Hence the calculation was done with 15 different series of random numbers and the theoretical curve in figure 8 represents its average. The calculation shows the best agreement with the experiment under around $\delta = 3\%$, which corresponds to the fluctuations of one ($2.8 \text{ \AA}$) and two ($5.6 \text{ \AA}$) monomolecular layers for GaAs and ZnSe, respectively. Therefore the fluctuation, if it exists, seems to be very small in the fabricated structure.

It is important to investigate to what extent constituent layers can be made thinner, especially in the case of multilayered structures constructed from heterovalent

Figure 8. Evaluation of fluctuation in terms of the R factor, using $\delta = 0\%$ as a standard. The dashed line indicates the experimental value and the solid line represents result of theoretical calculation.

semiconductors such as ZnSe–GaAs QWs. Another MQW, 100 cycles of ZnSe (33 Å)/GaAs (25 Å), which has much smaller layer thicknesses and larger number of cycles compared with the MQW mentioned above, was fabricated. To our knowledge, this is the first reported fabrication of MQW that consists of heterovalent materials with such thin constituent layers. Successful construction was confirmed by comparing the X-ray rocking curve with that calculated theoretically, as shown in figure 9. FWHM of the fundamental peak is 31 arcsec, which provides the evidence of its good crystalline quality. However, FWHM of two satellite peaks are broad and intensities are weak, compared with the theoretical calculation. The satellite peaks have the feature of tailing toward the fundamental peak. The thickness fluctuation is considered to be the origin of this tailing. However, if an accidental thickness fluctuation were the origin, the broadening would occur symmetrically. Therefore, either increase or decrease of period in the growth direction may be the origin of the tailing. Additionally, since the FWHM of the fundamental peak itself is very narrow, the average lattice spacing is unchanged even if there is the change in period; in other words, thickness ratio of constituent materials is constant. This also supports the assumption that the origin is not an accidental fluctuation but an increase or a decrease of period. The mechanism of this phenomenon is unknown yet and further investigation is required.

4.2 GaAs island in ZnSe

In figure 5, FWHM of both profiles are comparable, indicating that crystalline quality of the multilayered structure with 3-dimensional GaAs ($T_g = 550^\circ\text{C}$) is equivalent to that with 2-dimensional GaAs ($T_g = 500^\circ\text{C}$). This high-quality 3-dimensional GaAs

Figure 9. Double-crystal XRD pattern of GaAs (25 Å)/ZnSe (33 Å) $\times 100$ short-period MQW.

Figure 10. Cross-sectional [110] TEM bright-field image of GaAs islands buried into ZnSe. The growth conditions are $T_g = 550^\circ\text{C}$ and $V/\text{III} = 2$.

suggests the way to bury high-quality GaAs QDs into ZnSe. The TEM bright-field image of a [110] cross-section of GaAs islands surrounded by ZnSe is shown in figure 10. The growth conditions are $T_g = 550^\circ\text{C}$ and $V/\text{III} = 2$. GaAs shows the Vollmer–Weber growth mode and is isolated completely by ZnSe layers. This preliminary experiment strongly suggests successful fabrication of GaAs QDs buried into ZnSe by reducing island size.

5. Electrical properties of Zn(S)Se–GaAs heterostructures

Heterojunction diodes (HD) which consist of n-Zn(S)Se and p-GaAs were used to characterize the electrical properties of the heterostructures. The impurity density of p-GaAs is $1.0\text{--}2.0 \times 10^{19} \text{ cm}^{-3}$. The electrodes used were AuZn for p-GaAs, Au/AuGeNi for n-GaAs and In for n-ZnSe through n^+ -ZnSe ($2 \times 10^{19} \text{ cm}^{-3}$) contact layer. Following evaporation of electrodes, mesa structure was fabricated by chemical etching procedure.

5.1 ZnSSe/GaAs HD

Since the dimension of ZnSe in HDs is usually much larger than its critical thickness (1500 Å), lattice-matched ZnSSe is adopted instead of ZnSe to keep full coherence. The impurity density of n-ZnSe is $1.0\text{--}2.0 \times 10^{17} \text{ cm}^{-3}$.

Figure 11 shows I – V characteristics at various temperatures. In order to clarify carrier transport mechanism, dependence of I on temperature was investigated as a function of bias voltage. Consequently, I is proportional to $\exp(1/T)$ below 0.7 V, and to $\exp(T)$ above 0.7 V. This indicates that I is limited by injection and recombination below 0.7 V, and by tunnelling above 0.7 V (Ribben and Feucht 1966). The diode factor in the region of injection and recombination is 1.8.

Dependence of C – V characteristics of the same sample on measurement frequency is shown in figure 12. The straight line obtained in the $1/C^2$ versus V plot indicates

Figure 11. I - V characteristics of ZnSSe/GaAs HD.

Figure 12. C - V characteristics of ZnSSe/GaAs HD.

abrupt junction without serious interdiffusion, and the slope gives the effective impurity concentration of $2.5 \times 10^{17} \text{ cm}^{-3}$, which is very close to the expected value. If a heterojunction has a large interface state density, the C - V curve shows frequency dispersion (Choi *et al* 1990). Since the frequency dispersion of the ZnSSe/GaAs HD is within the measurement error, the state density at the interface is below $10^{10} \text{ cm}^{-2}/\text{eV}$, which is the lowest detectable limit derived from the measurement error.

Deep levels in heterostructures often act as recombination and/or nonradiative centres and degrade their carrier transport and/or optical properties. We study the nature of deep traps in the HD by means of deep-level transient spectroscopy (DLTS), which provides a very sensitive method for identifying deep levels and for determining their parameters. A typical DLTS spectrum is shown in figure 13, where a majority-carrier pulse (V_p) of 0.4 V is applied to the HD for 3 ms under a quiescent measurement bias (V_m) of -3.6 V. Although two deep electron trap levels peaking around 120 K (labelled A) and 150 K (labelled B) are observed, comparing with reported DLTS spectra of ZnSe/GaAs HDs (Shirakawa and Kukimoto 1981; Venkatesan *et al* 1989) it is easily found that the ZnSSe/GaAs HD fabricated in this study has fewer traps. Since the difference between the ZnSe/GaAs HDs and the ZnSSe/GaAs HD is lattice relaxation, reduction of traps in the ZnSSe/GaAs HD is due to lattice-matching effect. The Arrhenius plot of thermal emission rate times square of temperature gives the thermal activation energy of 220 meV for both traps. Although detailed discussion of the origins of these peaks will be shown elsewhere, trap A is attributed to the lattice mismatch-induced trap and we believe that the trap may be suppressed by further optimization of growth conditions. There are many reports on trap B (Shirakawa and Kukimoto 1981; Venkatesan *et al* 1989) and it is considered to arise from dopantsite (Ga_{Zn} , V_{Zn}) complexes. Relatively large capture cross-section of trap B ($9 \times 10^{-15} \text{ cm}^2$), which is estimated from the Arrhenius plot, seems to cause recombination current and to make the diode factor large, to the value of 1.8.

5.2 GaAs/ZnSe HD

We refer to first investigation of electrical properties of GaAs on ZnSe HD, briefly. The thickness of underlying ZnSe is $1.8 \mu\text{m}$. Therefore, crystalline quality at ZnSe surface, i.e. at the interface of p-GaAs/n-ZnSe junction, recovers well from the damage caused by lattice relaxation. The GaAs layer thickness is as thin as $1000 \text{ \AA}$ to keep

Figure 13. DLTS spectrum of ZnSSe/GaAs HD taken at a rate window of $1.2 \times 10^3 \text{ s}^{-1}$.

coherency of GaAs against ZnSe. Coherent growth of GaAs on ZnSe is confirmed by XRD. The impurity density of n-ZnSe is $1.0 \times 10^{16} \text{ cm}^{-3}$.

I - V measurement at various temperatures revealed that the current transport was limited by tunnelling and implied the existence of high density of interface state at a level near conduction band edge. C - V curves showed frequency dispersion and the interface state density is estimated to be $\sim 6 \times 10^{10} \text{ cm}^{-2}/\text{eV}$ by the similar procedure with Choi *et al* (1990). DLTS spectrum of the HD showed no peak, but the junction capacitance depended on temperature strongly. The analysis of the temperature dependence provided the deep-level parameters; thermal activation energy is 180 meV and trap density $7.3 \times 10^{15} \text{ cm}^{-3}$. It is worth noting that the trap density is comparable to the impurity density, which is consistent with the result derived from I - V measurement.

Although further optimization should be directed to improve electrical properties, this preliminary experiment may open the way to the applications of ZnSe-GaAs multilayered structures for electronic devices.

6. Conclusions

We studied MOVPE growth and characterization of ZnSe-GaAs heterostructures.

Growth behaviour of GaAs grown on ZnSe by MOVPE was studied as a function of growth conditions. TEM observations revealed that GaAs growth at 550°C and low V/III ratio (≤ 5) was highly 3-dimensional, whereas the growth at low temperatures ($\leq 500^\circ\text{C}$) or high V/III ratios (≥ 10) was 2-dimensional. The cause of 3-dimensional growth is considered to be migration of Ga-related clusters.

This variation of the growth mode was applied for the fabrication of ZnSe-GaAs low-dimensional structures; QW was fabricated and the possibility of burying GaAs QDs into ZnSe was indicated. The structural properties of QW were characterized mainly by XRD. Good correspondence of the experiments with the simulations indicates high crystalline quality, a high degree of lateral uniformity, and well-defined interfaces. Additionally, it was found by analysis of interference fringe that the dispersion of thickness fluctuation, if it existed, was about 3%, that is, one or two monomolecular layers in the fabricated structure. Further optimization in order to grow thinner layers successfully allowed fabrication of the MQW with $\sim 30 \text{ \AA}$ layers.

Zn(S)Se-GaAs heterostructure was characterized electrically. The diode factor of ZnSSe/GaAs heterostructure obtained from I - V curve is 1.8, which is attributed to the deep level related to Ga dopant. The transport mechanism in GaAs/ZnSe heterostructure is limited by tunnelling and the existence of high density of interface state at a level near conduction band edge was implied by both I - V and DLTS measurements.

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