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Advantages of Using CdS as Cd-Source for Growth of CdSe Quantum Islands and Wells

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In this study we report on the fabrication and investigation of high quality CdSe-based quantum structures embedded in ZnSe. The structures were grown by molecular beam epitaxy using a novel growth technique in which the commonly used Cd-elemental source is substituted by a CdS compound source. An exchange reaction between the sulfur and elemental Se leads to the growth of CdSe with a minor sulfur contamination of the order of 1% depending on the growth conditions. Quantum structures grown with the compound show a better homogeneity and narrower photoluminescence linewidth than conventionally grown structures even though high resolution transmission electron microscopy indicates that intermixing of CdSe and ZnSe still occurs. The properties and implications of the structures grown by the new method will be discussed.

1. Introduction In recent years the fabrication of high quality self-organized quantum islands has become a major topic in semiconductor research. Possible applications include diode lasers and single electron tunneling devices, which currently gain importance. III–V-based self-organized systems like InAs/GaAs are well established by now and first laser devices have been demonstrated [1].

It is desired to extend the possible range of applications to opto-electronic devices for the visible range. One suitable system which is similar to the commonly investigated InAs/GaAs with respect to band gap energy difference ($\approx$1 eV) and lattice mismatch ($\approx$7%) is CdSe/ZnSe. Formation of self-organized quantum islands in this system has already been demonstrated by various groups [2–5]. However, the system suffers from the fact that Cd/Zn segregation is a predominant process. Interfaces of quantum wells and islands are usually strongly smeared out and the CdSe is intermixed with the ZnSe. The Cd concentration profile corresponds to a typical segregation profile that can be roughly approximated by a Gaussian distribution. One finds that the average layer thickness remains roughly constant for CdSe deposition in the range of 1–4 monolayers (ML) while the maximum Cd concentration changes with the amount of CdSe deposition [6]. Another difficulty is the low reproducibility and control of the island formation, which becomes very important when designing CdSe-based opto-electronic devices in the future.

In this report we will demonstrate the advantages of a new growth method that allows the growth of CdSe-based quantum structures with well defined interfaces and an improvement of the overall homogeneity of both island and quantum well structures.

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2. Experiment and Results In order to fabricate these structures we have considered introducing sulfur in the CdSe-system by employing a CdS-compound source for Cd supply in molecular beam epitaxy (MBE) [7]. At growth temperatures of 280–300 °C an exchange reaction between elemental Se and the CdS leads to an almost complete substitution of the sulfur by selenium. Optical and structural measurements suggest a contamination of the order of only 1% sulfur. An additional advantage of the CdS-compound source employed, is its operation temperature of 650 °C. The molecules emitted by the source have a higher kinetic energy than Cd-ions from a standard elemental source with an operation temperature of typically 250 °C which leads to an enhancement of the adatom mobility on the growing surface and a general improvement of the structural quality of such CdSe based quantum structures.

The samples have been studied by high resolution transmission electron microscopy (HR-TEM) and chemically evaluable lattice fringe analysis (CELFA) [8]. We observe that structures grown by a standard MBE growth mode, i.e. simultaneous exposure of the growing surface to CdS and Se, behave in general similar to structures grown with

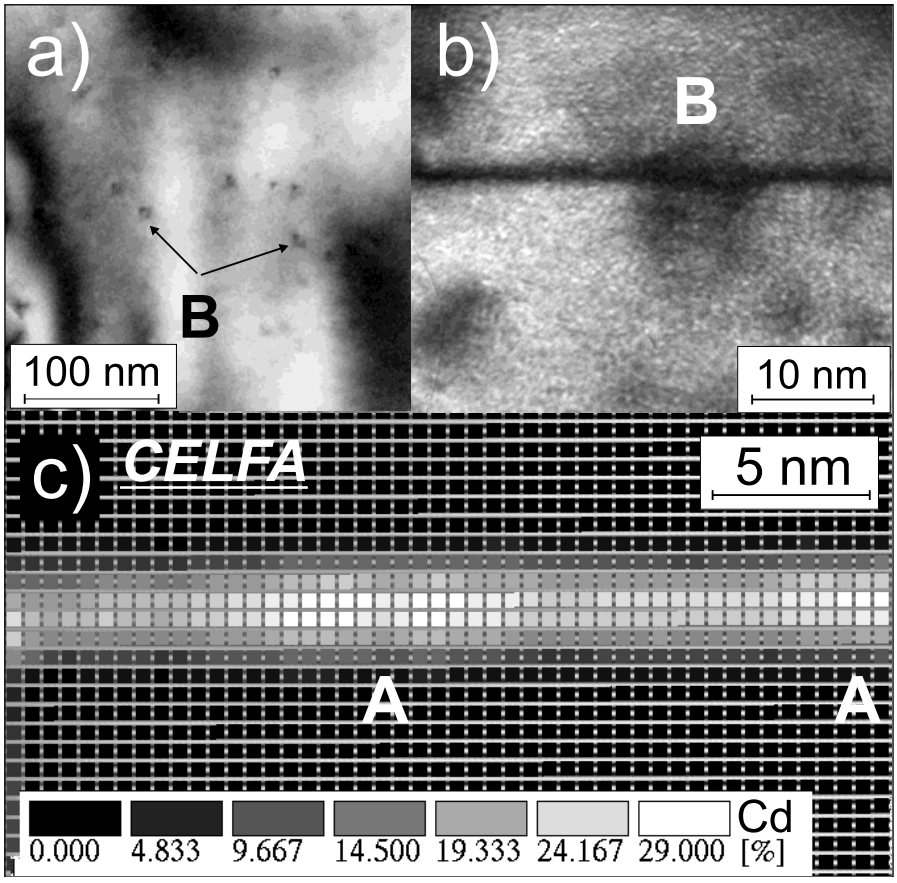

Fig. 1. a) (220) bright field plan view TEM, b) (200) dark field cross-sectional TEM and c) CELFA for sample 1 containing CdSe:S islands grown with CdS-compound and Se elemental source. Random natural fluctuations are referred to as islands type A while organized islands are denoted as B

conventional Cd and Se elemental sources, meaning, that Cd enriched islands form within a quantum well like wetting layer. Depending on the exact growth conditions the island size can be influenced by a growth interruption or annealing step.

Figure 1 shows the TEM and CELFA results for a layer (sample 1 (ek9)) grown with the new method and containing natural fluctuations, referred to as island type A, and larger, self-organized quantum dot like islands with a diameter of about 5 nm, referred to as type B. The islands appear within an intermixed quantum well. Photoluminescence (PL) of the layer as shown in Fig. 2a exhibits a rather narrow emission (half-width ≈ 30 meV) which points to a quite homogeneous distribution of islands while micro-PL of an area of $< 1\ \mu m^2$ reveals single island emission lines.

In order to prevent the formation of type A islands and to obtain an improved homogeneity of our samples, a migration enhanced growth mode was introduced. While the Se shutter was kept open continuously the CdS shutter was opened and shut periodically (typically 2.5 s open, 20 s shut). The cycles were set to nominally deposit a little less than one half monolayer, which corresponds to atomic layer epitaxy with conventional elemental sources.

The result of this new technique is quite outstanding. While intermixing between the CdSe and ZnSe still occurs, the interfaces are well defined as compared to our other samples and to conventionally grown samples (compare [4]), which is very well demonstrated in Fig. 3. Two samples with a nominal deposition of roughly 1.6 ML (sample 2 (ek33)) and 3 ML (sample 3 (ek44)) are shown. The Cd-concentration profile has almost a rectangular shape with a width of about 13 ML for both samples and an average height of 18±2% and 34±3% for the nominally thinner and the thicker sample, respectively. This is quite different from the findings for conventional samples where the Cd distribution generally follows a typical segregation profile, which may be approximated by a Gaussian distribution. Remarkable is the fact that an increased

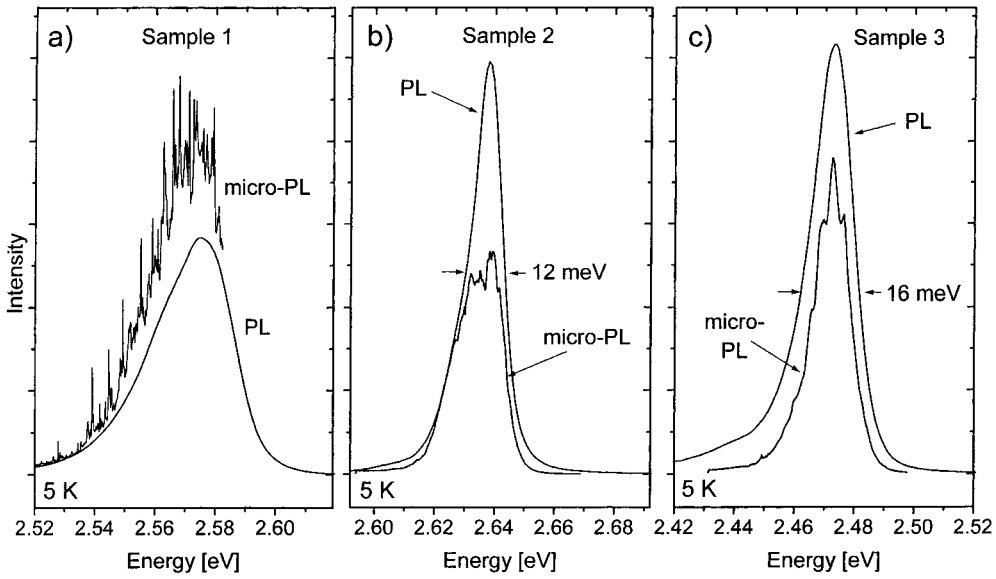

Fig. 2. Photoluminescence and micro-PL for the three samples discussed in the text

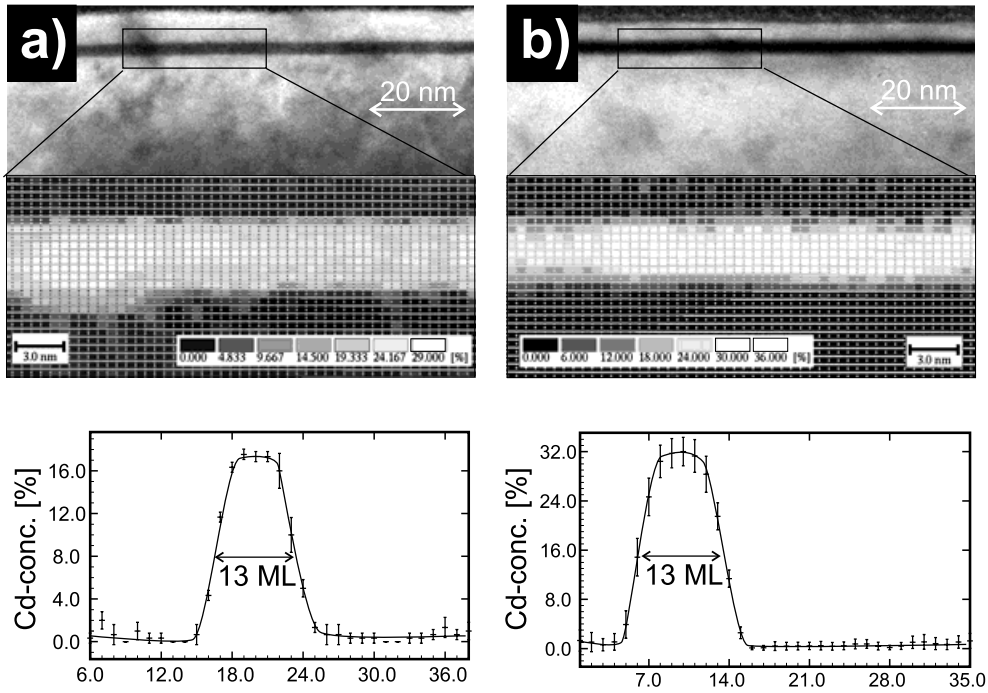

Fig. 3. From top to bottom: (002)-dark field cross-sectional TEM, CELFA (colour code corresponds to Cd-concentration in %) and Cd concentration profile (note: units of the *x*-axis correspond to $\approx$2 ML) for a) sample 2, b) sample 3. For discussion see text

nominal deposition thickness does not lead to an increase in quantum well width but rather to an enrichment of Cd within the QW-layer. This is clearly seen in the contrast of the cross-sectional TEM but even more clearly in the CELFA of the two samples shown. The extremely high quality of the samples mirrors also in their PL spectra, Fig. 2b. The halfwidth corresponds to 12 and 16 meV, respectively. Considering the intermixing and the larger halfwidth of the Cd-concentration profile of about 13 ML, a theoretical calculation of the transition energies using an extended Kronig-Penney model including strain [9], agrees quite well with the PL spectra. We find a value of 2.66 $\pm$ 0.01 eV for sample 2 and 2.49 $\pm$ 0.01 eV for sample 3. The result further corroborates the assumption that almost no sulfur is included in the CdSe-based layer.

At a first glance the island formation appears to be completely suppressed in the samples obtained be the migration enhanced growth method. However, we find areas where few peculiarly shaped islands appear, see Fig. 3. These islands bulge towards the GaAs-substrate/ZnSe interface which indicates a correlation with a special type of dislocation. In particular 60° dislocations or stacking faults that start off at the GaAs/ZnSe interface and penetrate the CdSe layer may be responsible for the Cd accumulation and the Cd diffusion into the underlying ZnSe buffer layer. Currently there is no indication, that these particular structures are optically active. On the contrary, micro-PL of samples 2 and 3 show no or very few distinct single dot lines furthermore indicating the absence of distinct confining lateral localization sites.

3. Conclusion and Outlook In conclusion, we have demonstrated that the structural quality of CdSe-based quantum structures can be improved by employing a CdS-compound source and elemental Se instead of the conventionally used elemental sources for Cd and Se during MBE growth. Island formation can be suppressed by using a special migration enhanced growth sequence which leads to samples with strongly improved homogeneity. The application of the exchange growth technique to ZnSe/ZnS quantum structures is currently under investigation.

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