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Special Issue Paper

Heavily p-Type Doped ZnSe Using Te and N Co Doping

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We have studied photoluminescence (PL) of ZnSe samples codoped with Te and N in δ-layers. We have concluded that Te clusters are involved in the PL. We also compared the PL data of samples with lower Te concentrations to those with higher Te concentrations; the results corroborate the Te-cluster conclusion.

Key words: ZnSe, Te clusters, photoluminescence, p-type

INTRODUCTION

A lot of progress has been made on the fabrication of solid-state light emitters; however, there is a spectral gap in the green-yellow region (530–590 nm) with all commercially available devices.[1] This spectral region is important for many emerging applications, such as the use of plastic-optical fibers, that require green lasers to achieve the lowest attenuation coefficient.[2] Thus, ZnSe-based devices are still of high interest because, in principle, they can cover the whole spectral region between 490–590 nm. However, successful production of bright, "long-lived" laser diodes and light-emitting diodes is tempered by the lack of good p-type ZnSe, among other problems.[3] The use of the ZnSe-Te system for improving the p-type doping has been suggested because ZnTe is an easily doped p-type. The best results so far within such an approach have been obtained by Jung et al.,[4] who have reported hole concentrations up to 7×10^{18} cm^{-3} by using a δ-doped ZnSe/ZnTe:N superlattice. However, because of a large lattice mismatch between the ZnSe and ZnTe (~7.4%), such a structure tends to form defects, for instance, dislocations,[5] that are detrimental to device operation.

Recently,[6] the use of a planar (δ-) doping technique has been suggested to reduce the average Te content in the material. In such an approach, ZnSe is codoped with Te and N in delta layers (which do not form full ZnTe monolayers), separated by undoped-ZnSe spacers.[6] The highest achieved net-acceptor concentration ($N_A - N_D$) is $\sim 6 \times 10^{18}$ cm^{-3} with an average Te concentration of <1.8% (Table I).[7] In this paper, we report results of photoluminescence (PL) studies of δ-doped ZnSe with very low Te content but otherwise similar to previously reported samples. We studied two types of samples: the so-called single δ-doped (δ-doping) and triple δ-doped (δ^3-doping), both of which have Te concentrations as low as about 0.5%.

GROWTH AND DOPING

Growth was performed in a Riber 2300 molecular beam epitaxy system. Atomic N was produced by a radio-frequency discharge N source. All samples were grown on (001) p-type GaAs substrates. The present samples, prior to the growth of the delta region, have buffer layers of uniformly N-doped ZnSe. The growth rate was about 0.8 μm/h. The shutter control sequence used during the growth is described elsewhere.[6] Two types of samples were studied. One was single δ-doped (sample A), where only a small enhancement in the net-acceptor concentration was obtained; the other was δ^3-doped (sample B), and a significant increase of the net-acceptor concentration was obtained.

PHOTOLUMINESCENCE RESULTS

In Figs. 1 and 2, we show the PL from samples A and B (both have Te content of ~0.5%). The PL from both samples shifts to red with decreasing excita-

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Table I.

Samples and Doping	Spacer (ML)	$N_A - N_D$ (cm^{-3})	Te Concentration (%)
Uniform ZnSe:N	N/A	3.0×10^{17}	N/A
δ-ZnSe:(N)	N/A	5.6×10^{17}	N/A
δ-ZnSe:(Te, N)	10	1.5×10^{17}	~0.5
δ^3-ZnSe:(Te, N)	12	4.0×10^{17}	<3
δ^3-ZnSe:(Te, N)	7	6.0×10^{17}	<1.8

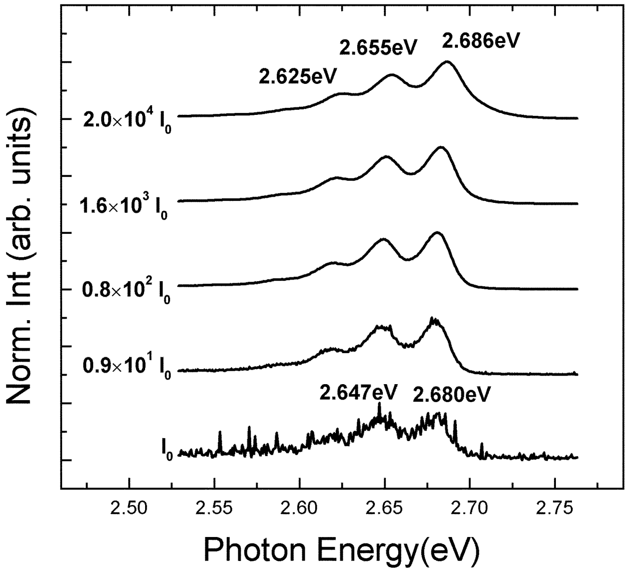

Fig. 1. The PL spectra of sample A at different excitation intensities.

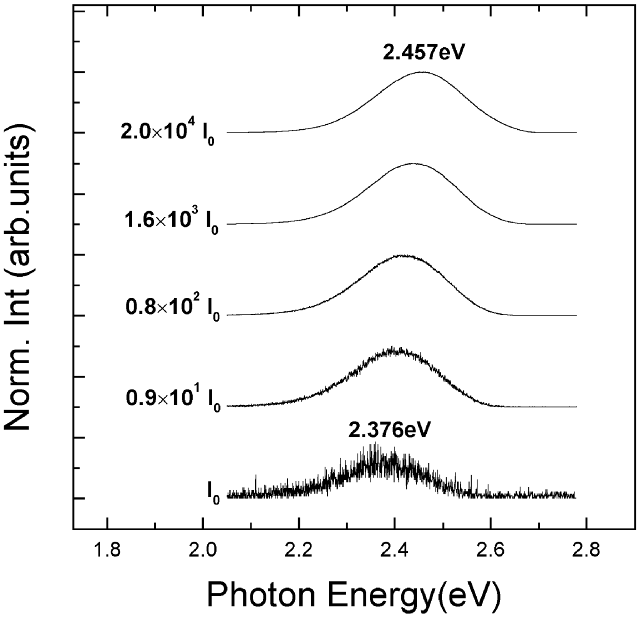

Fig. 2. The PL spectra of sample B at different excitation intensities.

tion intensity, with such a shift being considered a hallmark of a donor-acceptor pair (DAP) PL.[8] The PL of sample A shows a series of peaks at 2.686 eV, 2.655 eV, 2.625 eV, and 2.594 eV. These peaks are separated by 30–31 meV, which is about the ZnSe longitudinal-optical phonon energy.[9] However, it is clear from Fig. 1 that the intensity of the peak at 2.655 eV does not scale with the intensity of the 2.686-eV peak, which indicates that these two peaks are associated, at least partly, with different centers. Also, we note that the peak at 2.655 eV is in the 2.63–2.68-eV energy range, where we have previously observed PL caused by excitons bound to Te pairs and/or clusters.[10] Therefore, we suggest that this 2.655-eV peak has some contributions from recombination of excitons bound to such Te complexes. As to the 2.686-eV peak, it is very close to the peak position of the "deep" DAP emission in ZnSe:N.[11] The current value is slightly high, but the present system is expected to have a relatively strong Coulomb shift because of preferential DAP[11] emission, which could account for this. Furthermore, it can be seen that, at low-excitation intensity, this sample shows a small broad shoulder at around 2.42 eV (Fig. 3), which is in the range of the peak position (2.487 eV) of excitons bound to $Te_{n\geq 3}$ clusters.[10] Therefore, even though the Te concentration is as low as 0.5% in this sample, it still shows quite efficient Te-cluster-related PL. This can be understood by considering the geometry of our sample, which could result in relatively high Te concentration in the δ-doped layer.

As to sample B, it shows only one broad peak at around 2.457 eV. As mentioned, this peak shifts to red with decreasing excitation intensity. However, 2.457 eV is too deep for the "ordinary" DAP peaks in ZnSe. Furthermore, as mentioned previously, this peak is close to the one assigned to excitons bound to $Te_{n\geq 3}$ clusters. Therefore, we believe that, in addition to N, Te clusters are also involved in this transition.

Previously, we reported PL spectra of another set of δ- and δ^3-doped ZnSe:(N + Te) samples[12] with

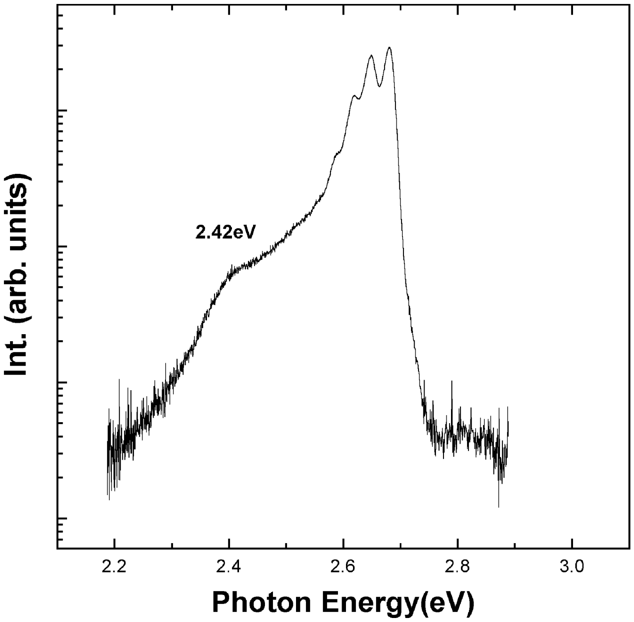

Fig. 3. The PL spectra of sample A at low-excitation intensity.

higher Te concentrations (1.8% and 3%, respectively). It is instructive to compare those results with those of our new samples with less Te concentrations (0.5%). In Fig. 4, we plot the integrated intensity versus the excitation intensity for each of our new samples, which show one slope for sample A (δ-doped) and two slopes for sample B (δ^3-doped). We note that with our previous samples, there are two distinct slopes for each of them. Because the only difference between the new δ-doped sample and the previous one is the Te concentration, the difference in slopes corroborates our conclusion that Te is involved in the PL. Regarding the two-slope case, as discussed in Refs. 12 and 13, the plots show two slopes if two recombination paths are present. We, thus, note that despite the low Te content of the new sample, the δ^3 geometry still gives a large number of Te complexes around the δ^3-layer region, enough to give two paths. We also note that the PL-peak position of the new δ^3-doped sample is higher than that of the previous one. This could be due to the fact that the previous δ^3-doped sample has more $Te_{n\geq3}$ clusters, or alternatively, a sufficiently high Te concentration to change the bandgap for this effect to take place.

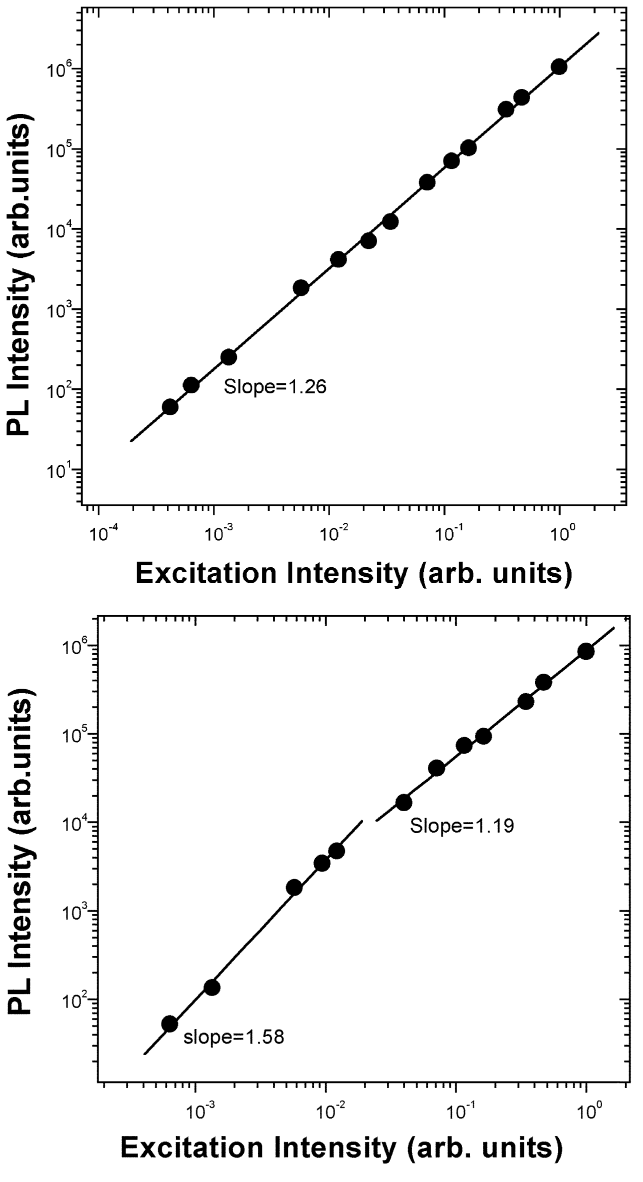

Fig. 4. The integrated PL intensity as a function of laser-excitation intensity: (a) δ-doped ZnSe:Te, N) and (b) δ^3-doped ZnSe:(Te, N).

SUMMARY

In summary, we employed a modulation-doping technique that allowed us to achieve a net-acceptor concentration as high as 6×10^{18} cm^{-3} with Te less than 1.8%. The low-temperature PL spectra of these samples showed dominant Te-related peaks but also involved N. We also compared the PL spectra of our present samples (with lower Te concentrations) to that of previous samples (with higher Te concentrations). The results are consistent with our conclusion that Te clusters are involved in the PL.

ACKNOWLEDGEMENT

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Annotations from 620-S26.pdf

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