AIP | Journal of Applied Physics

Stimulated emission and laser oscillation from lighthole excitonic state in a ZnSeZn0.8Cd0.2Se superlattice

Z. P. Guan, Z. H. Zheng, and X. W. Fan

Citation: J. Appl. Phys. 78, 2478 (1995); doi: 10.1063/1.360101
View online: http://dx.doi.org/10.1063/1.360101
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v78/i4
Published by the American Institute of Physics.

Stimulated emission and laser oscillation from light-hole excitonic state in a $ZnSe-Zn_{0.8}Cd_{0.2}Se$ superlattice

Z. P. Guan, Z. H. Zheng, and X. W. Fan
Changchun Institute of Physics, Academia Sinica, Changchun 130021, China

(Received 4 October 1994; accepted for publication 10 January 1995)

At 77 K, stimulated emission from $n=1$ light-hole excitons in a $ZnSe-Zn_{0.8}Cd_{0.2}Se$ superlattice is observed and the oscillation mode properties of $n=1$ light-hole and heavy-hole excitons are analyzed. It is noticed that the $ZnSe-Zn_{0.8}Cd_{0.2}Se$ superlattice with the shorter Fabry–Pérot cavity length d has the larger threshold excitation. The threshold of each mode has been determined using its time delay curve. © *1995 American Institute of Physics.*

Major developments in the use of wide-gap II-VI semiconductor quantum well structures have recently led to the demonstration of blue-green diode laser action in ZnSe-based heterostructures.[1,2] In II-VI semiconductors, excitonic properties are expected to play a prominent role in optical transitions due to the large exciton binding energy in comparison to III-V compound semiconductors. For realizing stimulated emission, high excitation powers are necessary to achieve sufficient population inversion to have positive gain. Excitonic stimulated emission was discussed in a $ZnSe-Zn_{0.8}Cd_{0.2}Se$ quantum well (QW) structure by investigating a parallel shift of a stimulated emission peak relative to the excitonic absorption peak.[3] Earlier reports of both electron-beam and optically pumped ZnSe-based heterostructure lasers have demonstrated pulsed operation and its threshold at 77 K or near room temperature.[4–8] So far, however, the time delay curve of the laser oscillation mode and stimulated emission from light-hole excitons were not discussed. In this article, we report the observation of stimulated emission from $n=1$ light-hole exciton and analyze the corresponding laser oscillation mode properties.

The sample used for the photopumped lasing is a superlattice consisting of 120 periods of 8.0 nm ZnSe, 8.5 nm $Zn_{0.8}Cd_{0.2}Se$, with 0.5 μm ZnSe cladding and 1.5 μm ZnSe buffer layers grown on a GaAs (100) substrate. This constitutes an efficient waveguide structure for lasing emission. The superlattice was grown by atmospheric pressure metalorganic chemical vapor deposition (MOCVD) at 320 °C using dimethylzinc (DMZn), dimethylcadmium (DMCd), and H_2Se.

Figure 1 shows the photoluminescence (PL) spectra of ZnSe (8.0 nm)-$Zn_{0.8}Cd_{0.2}Se$ (8.5 nm) superlattice excited by the 365.0 nm line of a Hg lamp at 17 and by the 337.1 nm line of a N_2 laser at 77 K. At 17 K (solid curve) there are four peaks located at $E_{2lh}=2.701$ eV (458.7 nm), $E_{2hh}=2.651$ eV (467.3 nm), $E_{1lh}=2.524$ eV (490.9 nm), and $E_{1hh}=2.474$ eV (500.8 nm). In this article we focus on the properties of $n=1$ light hole (E_{1lh}) and heavy hole (E_{1hh}) excitons. The other lines will be discussed elsewhere. At 77 K (dashed curve) high excitation led to the E_{1hh} peak broadening, which covers the emission of light-hole excitons. Figure 2 shows the excitation dependence of the PL intensity, the peak shift, and the full width at half maximum (FWHM) of the E_{1hh} peak. Within the range $0.01<I_{in}<0.4$ MW/cm^2, the PL intensity of E_{1hh} peak increases with increasing excitation, and the PL peak shifts to higher energies and broadens, which corresponds to phase space filling. In the relation of incident I_{in} and PL intensity $J=I_{in}^{\alpha}$, α is about 0.94. For excitation above 0.7 MW/cm^2, the PL intensity increases rapidly, the peak position shifts toward lower energy side and the FWHM decreases, indicating the outset of stimulated emission. Figure 3 is the lasing emission from the cleaved edge of the SLS layer with the cavity length $d=4$ mm, where the insert shows the schematic structure. It is noticed that, except for E_{1hh}, all other peaks which were present in Fig. 1 disappear now.

Figure 4 is the light output from three different cavity lengths with the same $ZnSe-Zn_{0.8}Cd_{0.2}Se$ superlattice structure. Three regions can be seen: a region at low excitation, in which the dependence on excitation intensity is linear; a region of superlinear dependence; and, at the highest excitation densities, a region in which the gain is saturating. In general, the threshold depends on the particular structure investigated, as well as on the temperature and on the wavelength excited. For cavity lengths $d=4$, $d=2$, and $d=0.8$ mm, the value of the thresholds and α are 160 kW/cm^2 (α=2.2), 230 kW/cm^2 (α=12), and 300 kW/cm^2 (α=7.2), respectively. It is noticed that the shorter Fabry–Pérot (F-P) cavity length d has the larger threshold. Figure 4 also shows the excitation dependence of the FWHM for the sample with the $d=4$ mm cavity length.

The gain spectra were measured using the following relationship:[9]

$$I=I_s[\exp(gl)-1]/g, \tag{1}$$

where I_s is the spontaneous luminescence intensity and g is the net optical gain (i.e., total gain-loss). Hence, a superlinear (exponential if $gl>1$) dependence of I on l is a direct indication of gain and the presence of stimulated emission. That is, $I(l)$ is proportional to $\exp(gl)$. Figure 5 shows the dependence of the stimulated emission intensity I from the cleaved edge on the excitation length l in the above superlattice sample with the 4 mm cavity length. The magnitude of the optical gain is found to be about 44 cm^{-1} when the excitation density is about 1 MW/cm^2 at 77 K. In our experiments, the 337.1 nm line of a N_2 laser was used as the pumping source. In this case, the pumping laser photon energy is much larger than the band gap of the $ZnSe-Zn_{0.8}Cd_{0.2}Se$ superlattice. Moreover, the penetration depth is about an order of magnitude shorter than that for resonant pumping. In the

 0021-8979/95/78(4)/2478/4/$6.00

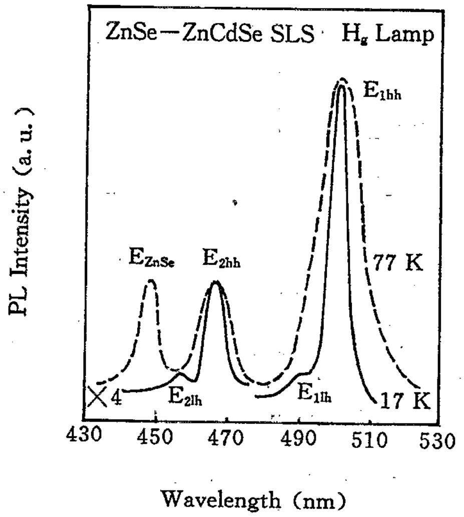

FIG. 1. PL spectra of ZnSe (8.0 nm)-$Zn_{0.8}Cd_{0.2}Se$ (8.5 nm) SLS under lower excitation at 17 K (solid curve) and high excitation at 77 K (dashed curve).

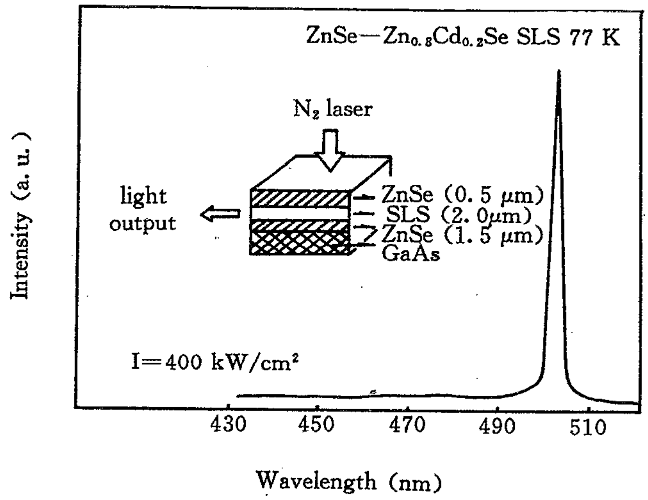

FIG. 3. Lasing emission spectra of ZnSe (8.0 nm)-$Zn_{0.8}Cd_{0.2}Se$ (8.5 nm) SLS. Inset shows the structure.

F-P cavity, the intervals between the oscillation modes in the wavelength varies as the inverse ratio of the cavity length, as follows:[10]

$$\Delta\lambda = \frac{\lambda^2}{2d(n - \lambda dn/d\lambda)}. \tag{2}$$

Here $\Delta\lambda$, d, n, and λ are the mode spacing, cavity length, index of refraction, and wavelength, respectively. Thus decreasing the cavity length can increase the mode spacing $\Delta\lambda$.

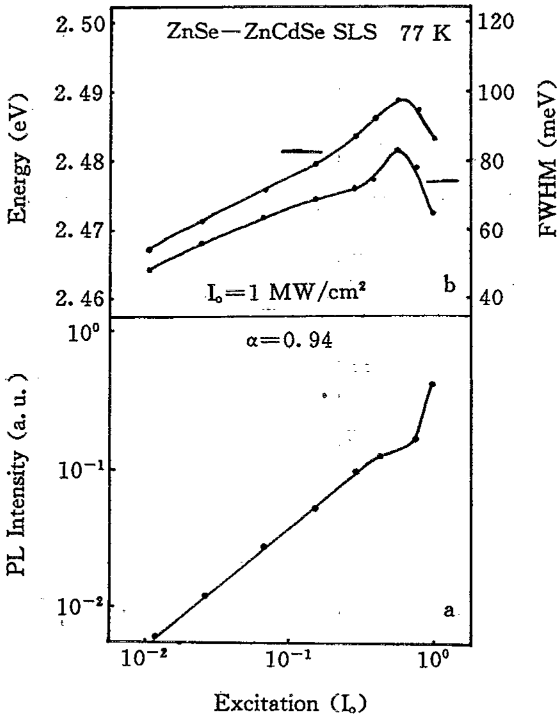

FIG. 2. Excitation dependence of PL intensity, peak shift, and FWHM of ZnSe (8.0 nm)-$Zn_{0.8}Cd_{0.2}Se$ (8.5 nm) SLS at 77 K.

The laser emission spectrum of the above ZnSe-$Zn_{0.8}Cd_{0.2}Se$ superlattice with a cavity length d=2 mm is shown in Fig. 6 for 77 K, displaying longitudinal modes. It is noticed that the FWHM and mode interval for each mode is not the same. The FWHM of the narrowest mode (503.9 nm) is less than 0.1 nm, and for the other mode (502.0 nm) is about 0.9 nm.

In order to understand the polarization of stimulated emission, the lasing intensity was determined for different angles between the TE direction of a polaroid and the sample surface, as listed in Table I. If the magnitude of the electric field vector is E, then its projection in the TE direction is

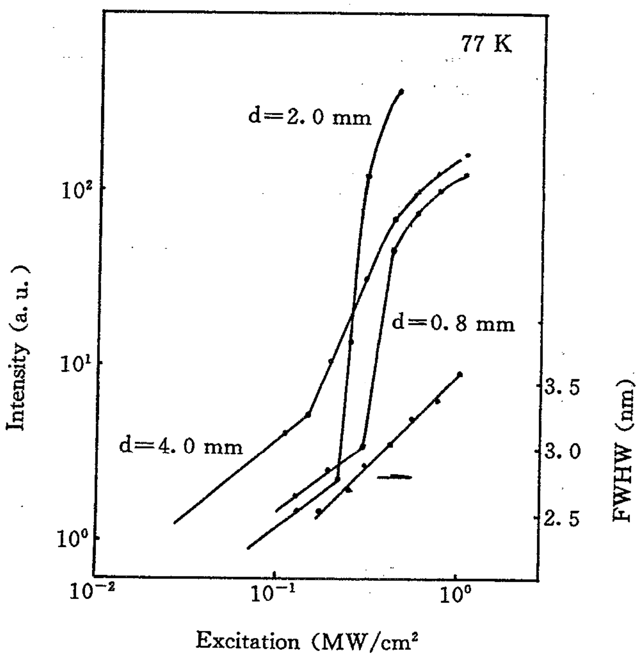

FIG. 4. Excitation dependence of the light output for different widths (d) of the samples, and the FWHM of the sample with d=4 mm.

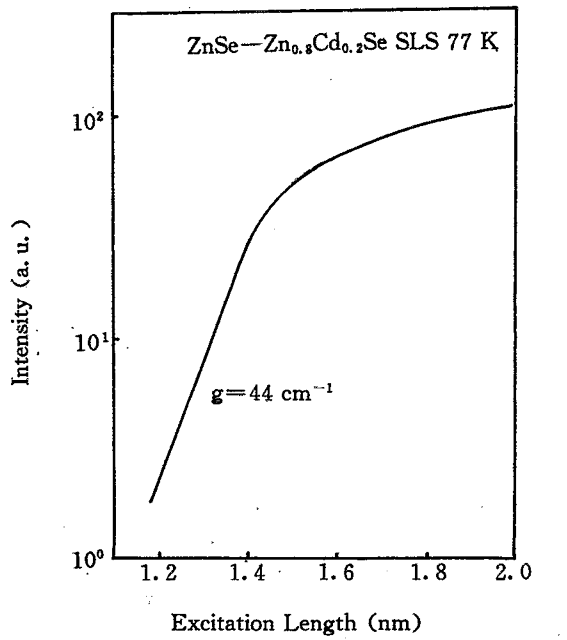

FIG. 5. Lasing output as a function of excitation length for ZnSe (8.0 nm)-$Zn_{0.8}Cd_{0.2}Se$ (8.5 nm) SLS at 77 K.

TABLE I. Polarization properties of the stimulated emission in ZnSe-$Zn_{0.8}Cd_{0.2}Se$ SLS. The angle of polarization is between the TE mode and epilayer direction.

θ	0°	30°	60°	90°	120°	150°	180°
I^{exp}	805	580	170	30	175	590	800
I^{cal}	805	603	201	0	201	603	805

$E\cos\theta$ and the luminescence intensity in this direction is $E^2\cos^2\theta$. The deviation from this may stem from (1) the error of experimental angle, and (2) the poor quality of the polaroid. As seen from the results, the stimulated emission is the light of polarization along the layer direction.

In the sample with the shortest cavity length (d=0.8 mm), the longitudinal modes are more interesting as shown in Fig. 7. The evolution of the mode structure with increasing pump power is clearly demonstrated. The threshold for lasing action is 300 kW/cm^2, with narrow mode structure first appearing at ~501.3 nm. As pump power is increased to 0.4 MW/cm^2, more modes appear, at both the lower and the higher energy side of 501.3 nm. With further increasing excitation, the modes at the lower energies increase, and the ones at the higher energies decrease. Above 0.32 MW/cm^2, a group of new modes, near the energies corresponding to the n=1 light-hole exciton in Fig. 1, appear, while the modes with higher energies continue to increase with increasing pump power.

It is found that different modes have different thresholds. In order to understand this feature, the time delay curve of some modes are measured as shown in Fig. 8. It is obvious that for different modes the halfwidths of the time delay are different. The halfwidth for curve (a), corresponding to the n=1 light-hole exciton mode at the energy position E=2.522 eV, is narrowest (only 5 ns), the others, corresponding to the n=1 heavy-hole exciton, are (b) 7.1 ns (2.474 eV), (c) 8.1 ns (2.468 eV), and 5.9 ns (2.462 eV), respectively. In Fig. 8, we also list the time delay curve (10.5 ns) for the 337.1 nm line

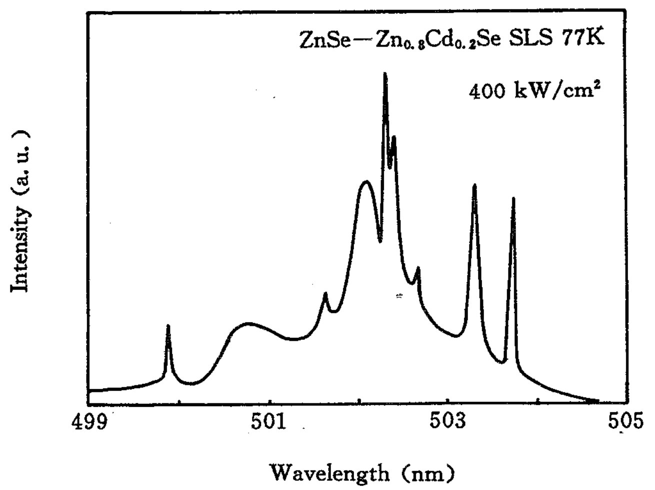

FIG. 6. Lasing spectra of ZnSe (8.0 nm)-$Zn_{0.8}Cd_{0.2}Se$ (8.5 nm) SLS at 77 K for d=2.0 mm.

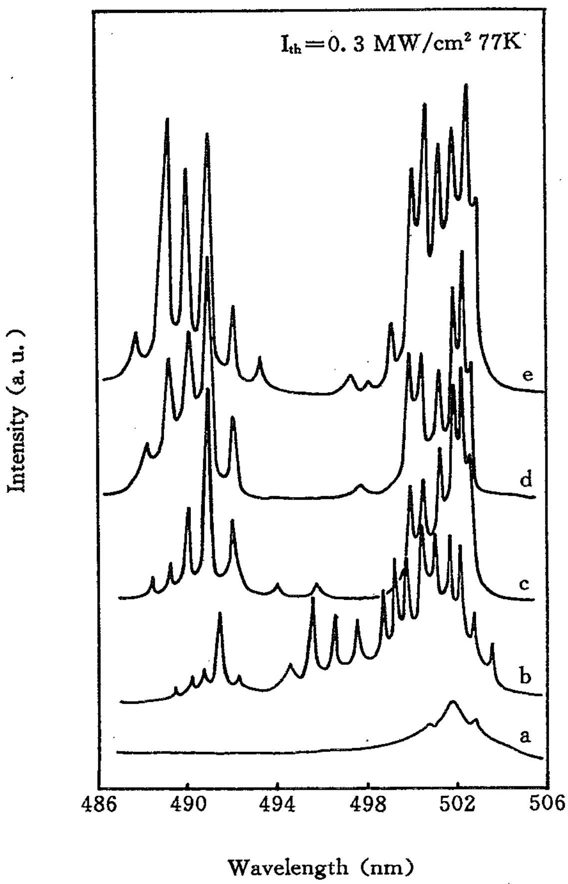

FIG. 7. Lasing spectra of ZnSe (8.0 nm)-$Zn_{0.8}Cd_{0.2}Se$ (8.5 nm) SLS at different excitation of (a) I=0.32 MW/cm^2, (b) 0.4 MW/cm^2, (c) 0.54 MW/cm^2, (d) 0.77 MW/cm^2, and (e) 1 MW/cm^2 at 77 K.

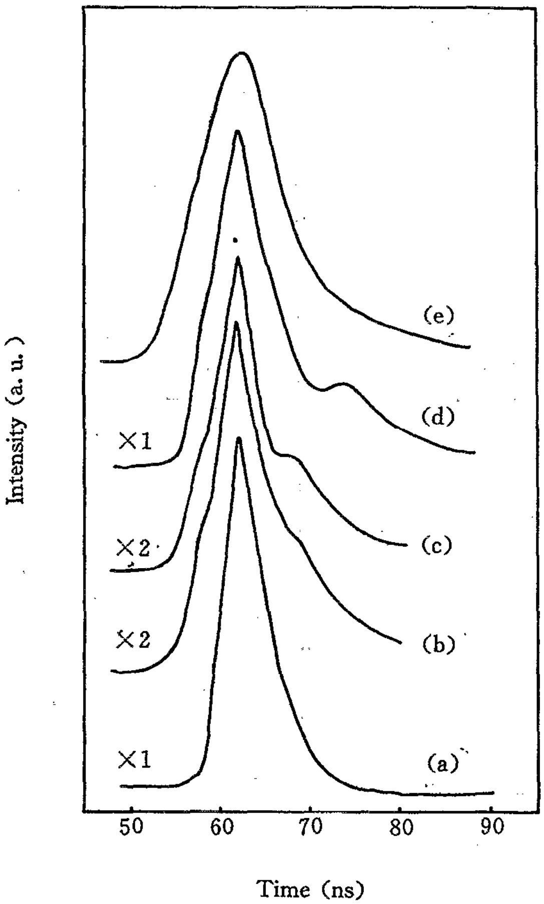

FIG. 8. Time behavior of different lasing modes in ZnSe (8.0 nm)-$Zn_{0.8}Cd_{0.2}Se$ (8.5 nm) SLS: (a) 2.522 eV line of E_{1lh} lasing, (b) 2.474 eV line of E_{1hh} lasing, (c) 2.468 eV line of E_{1hh} lasing, (d) 2.462 eV line of E_{1hh} lasing, and (e) 3371 nm line of N_2 laser.

of the N_2 laser. It is well known that the stimulated emission operates only for the excitation above its threshold. The time delay curve for the 337.1 nm line of N_2 laser is a Gaussian-type function as seen in the curve (e) of Fig. 8. In the rising part of this time delay curve, the intensity of the N_2 laser increases gradually from zero to the maximum intensity. When the intensity is strong enough in the above region, the stimulated emission can operate. The beginning of the time delay curve for stimulated emission is later than that of the N_2 laser. In the same way, the end of the time delay curve for stimulated emission is earlier than that of the N_2 laser. So the halfwidth of the time delay for stimulated emission is less than that of N_2 laser. Apart from the maximum intensity of the N_2 laser, in the time delay spectra the lower intensities did not result in stimulated emission. This depends on the threshold of each mode. Thus different halfwidths of the time delay for different modes indicate that they have different thresholds. The narrower the halfwidth of the time delay, the higher the threshold of the mode.

In conclusion, we have reported the observation of stimulated emission and laser oscillation from the light-hole excitonic state in a ZnSe-$Zn_{0.8}Cd_{0.2}Se$ superlattice. The sample with the shorter cavity length has the higher threshold. We also determined the time delay curve for several of the lasing modes. It is found that the different modes have different halfwidths of the time delay, which is due to the different threshold for each mode.

This work was supported by Laboratory of Excited State Process, Changchun Institute of Physics, Chinese Academy of Science.

[1] M. Haase, J. Qui. DePuydt, and H. Cheng, Appl. Phys. Lett. **59**, 1272 (1991).
[2] H. Jeon, J. Ding, W. Patterson, A. V. Nurmikko, W. Xie, D. Grillo, M. Kobayashi, and R. L. Gunshor, Appl. Phys. Lett. **59**, 3619 (1991).
[3] H. Jeon, J. Ding, A. V. Nurmikko, H. Luo, N. Samarth, and J. Furdyna, Appl. Phys. Lett. **59**, 1293 (1991).
[4] I. Suemune, K. Yamada, H. Masato, Y. Kan, and M. Yamanishi, Appl. Phys. Lett. **54**, 981 (1989).
[5] J. Khurgin, B. J. Fitzpatrick, and W. Secmungai, J. Appl. Phys. **61**, 1606 (1987).
[6] H. Jeon, J. Ding, A. V. Nurmikko, H. Luo, N. Samarth, J. K. Furdyna, W. A. Bonner, and R. E. Nahory, Appl. Phys. Lett. **57**, 2413 (1990).
[7] C. A. Zmudzinski, Y. Guan, and P. S. Zory, IEEE Photon. Tech. Lett. **2**, 94 (1990).
[8] D. A. Cammack, R. J. Dalby, H. J. Cornelissen, and J. Khurgin, J. Appl. Phys. **62**, 3071 (1987).
[9] K. L. Shakee, R. F. Leheng, and R. E. Nahory, Phys. Rev. Lett. **26**, 888 (1971).
[10] D. Lee, A. M. Johnson, J. E. Zucker, C. A. Burrus, R. D. Feldman, and R. E. Austin, Appl. Phys. Lett. **60**, 739 (1992).