PbS/PbSSe/PbSnSe heterostructure lasers with a quantum-well active region

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A quantum size effect has been observed in an ultrathin active region of PbS/PbSSe/PbSnSe semiconductor lasers. The selection rule $\Delta n = 0$ holds in lasing on optical transitions between bound states.

The effort to lower the threshold current density has led to the development of semiconductor lasers with active-layer thicknesses comparable to the de Broglie wavelength of an electron.[1,2] The quantum size effect which results gives rise to a set of lines in the emission spectrum which stem from transitions of electrons between bound states in quantum-mechanical potential wells formed by band discontinuities. A topic of special research interest is the quantum size effect in IV–VI semiconductors, because of the particular band structure of these semiconductors: The dispersion laws for electrons and holes are nearly mirror-symmetric.

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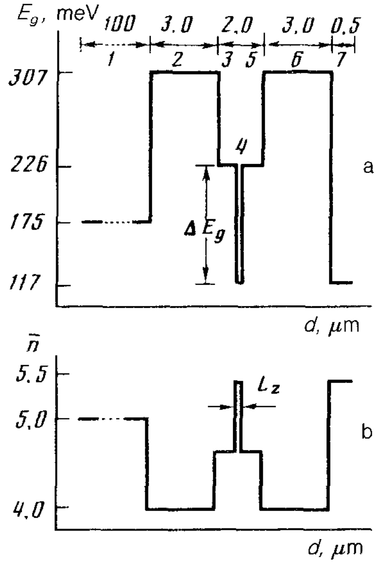

FIG. 1. Schematic diagram of the PbS/PbSSe/PbSnSe laser structure. a: Profile of the band gap E_g. 1—Epitaxial n-PbSe substrate; 2—n-PbS; 3,5—waveguiding layers, n- and p-type $PbS_{0.4}Se_{0.6}$; 4—active region, n-$Pb_{0.95}Sn_{0.05}Se$; 6—p-PbS; 7—contact layer, p-$Pb_{0.95}Sn_{0.005}Se$. b: Profile of the refractive index n at the wavelength 10.6 μm. Here L_z is the thickness of the active layer.

In this letter we report the first fabrication of PbS/PbSSe/PbSnSe injection heterostructure lasers with a quantum size effect in the active region. The laser structures are grown by the method of hot-wall molecular epitaxy.[3] The laser is a double heterostructure with separate electronic and optical confinement (Fig. 1). The active region and the waveguiding layers of the heterostructure laser are grown from $Pb_{0.95}Sb_{0.05}Se$ and $PbS_{0.4}Se_{0.6}$, respectively, with the result that there is a jump $\Delta E_g = 109$ meV in the band gap at 77 K. The layers are doped with Bi and Se to produce n-type and p-type conductivities, respectively. The central active region is not doped. The test samples are lasers with a broad contact, fabricated by the technique of Ref. 4.

The thicknesses (L_z) of the active region of the samples are 400, 500, 1000, and 2000 Å. Lasers with $L_z \geqslant 1000$ Å emit at the frequency corresponding to the band gap E_g^{ac} in $Pb_{0.95}Sn_{0.05}Se$ over the entire range of working temperatures. For lasers with $L_z = 400$ and 500 Å, we observe two output lines with energies greater than E_g^{ac} over the temperature range from ~ 60 to ~ 130 K.

The solid lines in Fig. 2 show the increase in the output energy observed experimentally for a laser with $L_z = 400$ Å. This increase amounts to 9.7 meV for the line $\lambda_1 = 9.8$ μm or 38 meV for the line $\lambda_2 = 8$ μm. These shifts are found from the difference between the output energy of the quantum-well laser and that of a heterostructure laser with a thick active region[4] ($L_z > 1$ μm) in pulsed operation (to eliminate heating effects). The energy levels in the quantum wells ($L_z = 400$ Å) are calculated for a parabolic dispersion law from the model of a square potential well of finite depth.[5]

The very fact that lasing is observed indicates a contravariant type of heterostructure. Since we do not know the details of the energy-band diagram of PbS/PbSSe/PbSnSe heterojunction, we use the discontinuity in the valence band, ΔE_v

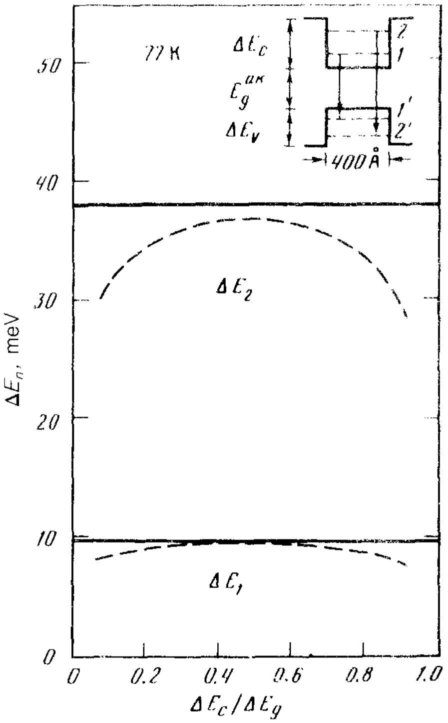

FIG. 2. Calculated energy shift of the output as a function of $\Delta E_c/\Delta E_g$; experimental increase in the energy for the laser with $L_z = 400$ Å. Here $\Delta E_n = E_{n,c} + E_{n,v}$ ($n = 1,2,...$), where $E_{n,c}$ and $E_{n,v}$ are the energies of the quantum-mechanical levels for electrons and holes, reckoned from the bottom of the well.

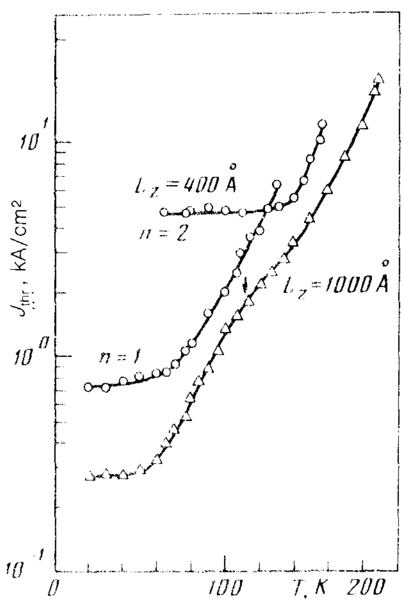

FIG. 3. Temperature dependence of the threshold current density J_{thr} for two lasers, with $L_z = 400$ Å and 1000 Å.

$= \Delta E_g - \Delta E_c$, as an adjustable parameter. Working from the longitudinal (m_l) and transverse (m_t) components of the effective masses in[6] $Pb_{0.95}Sn_{0.05}Se$, we determined effective conduction masses for electrons and holes. At 77 K, the results are 0.035 and 0.031, respectively, of the mass of the free electron. The dashed lines in Fig. 2 show the calculated increase in the output energy due to the quantum size effect for the 1–1′ transition (ΔE_1) and the 2–2′ transition (ΔE_2). The energy shifts calculated for the 2–1′ and 1–2′ transitions are in the interval 16–24 meV. It can be seen from Fig. 2 that the calculations agree with experiment under the condition that the transitions conserve the principal quantum number n, as shown in the inset. The slight extent (~ 3 meV) to which the observed shift ΔE_2 exceeds the calculated shift may be a consequence of a change in the parameters of the potential wells (the $n = 2$ level is more sensitive than the $n = 1$ level to such changes) for electrons and holes because of the diffusion of sulfur (S) into the active layer. For transitions between harmonics with $n = 3$, the calculations yield $\Delta E_3 \approx 76$ meV ($\lambda_3 = 6.4\ \mu$m), but this line was not observed. The fact that the effective masses of the electrons and holes are very nearly equal leads to a comparatively weak dependence of the shifts ΔE_1 and ΔE_2 on $\Delta \epsilon_c / \Delta E_g$ and permits an essentially unambiguous identification of the electronic transitions between bound states in the quantum-mechanical potential wells.

A comparison of the calculations with the experimental results for the laser with $L_z = 500$ Å again provides evidence for the selection rule $\Delta n = 0$. The energies of the photons for the observed transitions between the $n = 2$ states in the structures with $L_z = 400$ and 500 Å differ by ~ 12 meV at 77 K. The calculated energy difference for these lines, 10 ± 3 meV, agrees with the experimental value.

Figure 3 shows the temperature dependence of the threshold current density J_{thr} during pulsed pumping (1 μs, 600 Hz) of the lasers with $L_z = 400$ Å and 1000 Å. At low temperatures ($T \leqslant 125$ K) the laser with $L_z = 400$ Å works at the lasing threshold on transitions between states with $n = 1$ in the conduction band and the valence band. Transitions between states with $n = 2$ require a higher pump current. This current remains essentially the same as the temperature is raised, until the currents required for observing the lines with $n = 1$ and $n = 2$ become equal ($T = 125$ K). Above this point, J_{thr} increases exponentially, and the laser emits on transitions with $n = 2$ up to 160 K ($\lambda_2 = 6.5\ \mu m$). Above 130 K, the $n = 1$ line is not observed. A similar behavior is found for the laser with $L_z = 500$ Å. For the laser with $L_z = 1000$ Å, the $J_{thr}(T)$ curve has a structural feature, which indicates a switching of the laser from the $n = 1$ line to the $n = 2$ line. The shift of the output energy is small in this case, however, and the photon energy is quite close to E_g^{ac}. The temperature dependence $J_{thr}(T)$ for the sample of $L_z = 2000$ Å is of the standard form for lead chalcogenide lasers[4,6]; i.e., the quantum size effect occurs in the active region at thicknesses $L_z \leqslant 1000$ Å. The laser with $L_z = 2000$ Å operates in pulses up to 218 K ($\lambda = 6.5\ \mu$m); this is the highest working temperature that has been achieved for PnSnSe lasers.

In summary, we have detected a quantum size effect in the active region of PbS/PbSSe/PbSnSe heterostructure lasers. The results of this study show that the observed output lines stem from transitions of electrons between localized states in potential wells. The selection rule $\Delta n = 0$ holds for these transitions. The effect is observed at thicknesses $L_z \leqslant 1000$ Å.

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