cw midinfrared (mid-IR) diode lasers with high operating temperature, high efficiency, and high output power are of exceptional interest for applications such as infrared remote sensing, infrared imaging systems, infrared countermeasures, atmospheric pollution measurement, and medical diagnostics, because the absorption lines of most chemical compounds fall in the midinfrared spectral region.\(^1,2\) Basically, mid-IR diode lasers are classified into three kinds, namely IV–VI lead–salt,\(^3,4\) quantum cascade (QC),\(^5\) and type-II quantum well (QW)\(^6–8\) lasers. Although much progress has been made in the development of mid-IR QC\(^9,10\) lasers so far, the reproducibility, the complexity of the fabrication, and large Joule heat within the active region challenge its further development. It is well known that the active region heating primarily caused by nonradiative recombination greatly affects the performance and the reliability of diode lasers. Among these mid-IR devices, IV–VI lead–salt diode lasers have the simplest laser structure and are easily tuned. Previously lead–salt lasers had held the record of maximum operating temperatures among all mid-IR diode lasers.\(^11,12\) Our simulation results showed that lead–salt materials are fully capable of higher power and higher operating temperatures.\(^13\) Recently, we obtained 4.9 W peak output power of photoluminescence (PL) at room temperature from a PbSe/PbSrSe multiple quantum-well (MQW) structure by combining molecular beam epitaxy (MBE).\(^14\) The room temperature Auger coefficient of bulk PbSe is one to two orders of magnitude lower than bulk narrow gap III–V and II–VI materials,\(^15\) and about four times lower than type II InAs/Al\(_{1-x}\)Ga\(_x\)InSb quantum wells.\(^16\) Its favorable material properties keep the PbSe based lead salts very promising for innovative mid-IR laser structures.

To reduce the laser threshold and to obtain single mode laser operation, we proposed IV–VI vertical-cavity surface-emitting lasers (VCSELs) grown on (111) BaF\(_2\) substrates.\(^17\) Such VCSELs have obtained above-room-temperature pulsed operation, 300 mW output power, and threshold density as low as 10.5 kW/cm\(^2\).\(^18–20\) Recently, we have observed cw laser emission up to 230 K.\(^21\)

In this work, as a part of a continuous effort to realize high temperature cw operation of mid-IR PbSe/PbSrSe VCSEL, we concentrated on the studies of cw PL of mid-IR PbSe/PbSrSe MQW structures with episide down and episide up mounting, respectively.

The growth of the PbSe/PbSrSe MQW structure was carried out in a MBE system by combining molecular beam fluxes from PbSe, Sr, BaF\(_2\) and Se effusion sources. The MQW structure was grown on freshly cleaved (111) BaF\(_2\) substrates, which lifts off the degeneracy of energy minima and allows dislocations to glide. Our theoretical simulation showed that the MQW structure grown on (111) oriented substrates has a stronger modal gain than that grown on (100) oriented substrates at the same pump level.\(^14\) The structure consists of a 65 nm PbSrSe buffer layer, seven 20 nm PbSe quantum wells separated by 20 nm PbSrSe barrier layers, a 65 nm PbSrSe confinement layer, and a 312 nm BaF\(_2\) capping layer to avoid strontium oxidation. The growth temperature is 385 °C. A 3% Sr-to-PbSe flux ratio remained under Se-rich conditions during the growth of the PbSrSe single layer and PbSrSe barrier layers. The growth rates of PbSe and BaF\(_2\) are 200 and 52 Å/min, respectively.

The MQW structure was characterized by a Bruker IFS 66/S Fourier-transform infrared (FTIR) spectrometer. The sample was directly mounted on the copper heat sink with silver paste and placed into a liquid nitrogen (LN\(_2\)) cooled cryostat. The sample temperature was monitored by a Si diode adjacent to the copper heat sink with 0.3 °C resolution. The sample was excited by a 1.064 μm cw Nd:yttrium–aluminum–garnet (YAG) laser with TEM\(_{00}\) mode at normal incidence. The focus spot size on the surface of the sample is 200 μm in diameter. The PL from the MQW structure was collected by the FTIR spectrometer and was recorded by a LN\(_2\) cooled InSb detector via a 3.3 μm long-pass filter to avoid collecting the scattered laser signal. The cutoff wavelength of the detector is around 5.5 μm. The spectra were collected with a 2 cm\(^{-1}\) (0.25 meV) resolution in single channel mode.
The background spectrum including the CO₂ absorption peak appearing around 4.2 μm were removed from the PL spectra by the subtraction technique of the Bruker instrument. The detailed setup of the measurements was described in Ref. 19.

The cw photoluminescence spectra of the MQW structure at various temperatures with epide side down and epide side up mounting are shown in Figs. 1(a) and 1(b), respectively. No Fabry–Pérot interference fringes that were normally superimposed on the PL spectra of IV–VI materials, 22,23 are observed. This is due to the thin thickness (~280 nm) of the QW s of which the optical path is so smaller that even the first order interference peak will not appear. The slow-changing interference is superimposed on the PL spectra has no significant impact. The PL intensity reaches its maximum when the temperature increases from 125 to 225 K for epide side down mounting and from 125 to 175 K for epide side up mounting. With further increasing temperatures, the PL intensities decrease. The excitation power remains at 2 W (6.4 kW/cm²) during the measurements. The blueshifts in PL spectra with temperature are observed clearly. The peak energies vary from 5.12 μm (242 meV) to 3.86 μm (321 meV) between 125 and 300 K for epide side down mounting and from 4.83 μm (256 meV) to 3.64 μm (341 meV) between 125 and 300 K for epide side up mounting. Near 5.5 and 3.3 μm, the sharp slopes are observed that are due to the InSb detector cutoff and the long-pass filter cutoff as mentioned earlier.

Figure 2 shows the measured PL spectra at 225 K for cw and pulsed excitation. The peak quantum energy dependence on temperature is shown in the inset. The peak energies vary at the rates of 0.45 and 0.50 meV/K for cw excitation with epide side down and epide side up mounting, respectively. Assuming the temperature to remain unchanged between the active region and the heat sink during pulsed excitation (pulse width = 23 ns; period = 100 ms; λ = 1.064 μm), we estimated the temperature differences between the active region and the heat sink for epide side down and epide side up mounting to be 32 and 75 °C, respectively. The somewhat high temperature differences between the active region and the heat sink is due to a thick BaF₂ capping layer (312 nm) and an existing CuO film on the surface of the heat sink.

The measured cw spectra at 225 K from various excitation powers are shown in Fig. 3. The cw PL intensities increase with pump power up to 5.0 W (15.9 kW/cm²) for epide side down mounting, as shown in Fig. 3(a). However, for epide side up mounting, intensity saturation occurs due to poor heat dissipation when the excitation power is beyond 1.5 W (4.8 kW/cm²). The BaF₂ substrate thickness is fairly large with 780 μm. Although the thermal conductivity of BaF₂ is much higher than that of PbSe material, it is still lower than that of many other semiconductor materials, such as GaAs, Si, etc. As a result, for epide side up mounting, the heat generated within the active region leads to a considerable temperature increase.

Figure 4 shows the dependence of the position of the spectral emission peak on pump power. For the epide side down mounting, there is a blueshift with a nearly constant rate of 1.03 meV/(kW/cm²), which is mainly attributed to the band filling effect. For epide side up mounting, initially the peak energy increases quickly at the rate of 4.04 meV/(kW/cm²) caused by the combinations of active region temperature rise and band filling effect, and at the excitation intensity of 5 kW/cm², the rate of the peak energy changes becomes 1.55 meV/(kW/cm²), which might be an indication that a new thermal balance is reached or a change in the electronic states involved in the transitions.

Figure 5 shows cw PL output power as a function of heat

![FIG. 1. Temperature-dependent cw PL spectra under a constant excitation power of 2 W with epide side down (a) and epide side up (b) mounting, respectively. The excitation power is generated with a 1.064 μm cw YAG laser with TEM₀₀ mode.](image1)

![FIG. 2. PL spectra measured at 225 K at cw and pulsed excitation. The dependence of the quantum energy position of the spectral peak on temperatures is shown in the inset.](image2)

![FIG. 3. 225 K cw PL spectra at various excitation powers for epide side down (a) and epide side up (b) mounting, respectively.](image3)
compared with episide up mounting. The cw output power down mounting significantly improved the heat dissipation, the used excitation intensity region, which shows that episide power saturation is observed for episide down mounting at clearly observed for episide up mounting. However, no cw PL output power is 18 and 5.4 mW for episide down and excitation intensity at 225 K is inserted in Fig. 5. The maximum and 0.6 mW for episide down and episide up mounting, respectively. The maximum cw PL output power increases monotonically from 100 K and reaches the maximum at 225 K for episide down and episide up mounting, respectively. The maximum cw PL output power with episide down mounting is 18 mW at 225 K and 2.5 mW at room temperature within our excitation intensity region. From temperature tuning rates, the temperature differences between the active region and the substrate were determined to be 32 and 75 °C for episide down and episide up mounting. The temperature of the active layer must and can be decreased by appropriate design and mounting. Our results indicate that with improved heat dissipation, cw optically and electrically pumped lasers are feasible with this active layer design.

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sink temperature. The cw PL output power increases monotonically from 100 K and reaches the maximum at 225 K for episide down mounting and at 175 K for episide up mounting. This abnormal behavior compared with PL from bulk PbSe material might be attributed to the following possible temperature-dependent factors: (1) carrier injection from the QW barrier layers due to the temperature-dependent dielectric constant; (2) temperature-dependent interface states; and (3) temperature-dependent band alignment. With further increasing heat sink temperature, the cw PL output power decreases, which is associated with nonradiative recombination caused by phonon scattering and temperature-dependent gain coefficient. Under a constant excitation intensity of 6.4 kW/cm², the cw PL output power at room temperature is 2.9 and 0.6 mW for episide down and episide up mounting, respectively. The cw PL output power as a function of excitation intensity at 225 K is inserted in Fig. 5. The maximum cw PL output power is 18 and 5.4 mW for episide down and episide up mounting, respectively. The power saturation is clearly observed for episide up mounting. However, no power saturation is observed for episide down mounting at the used excitation intensity region, which shows that episide down mounting significantly improved the heat dissipation, compared with episide up mounting. The cw PL output power was calibrated by using a standard blackbody source and the angle-dependent PL measurement of the sample (Ref. 14).

In summary, we have systematically investigated the mid-IR PbSe/PbSrSe MQW cw PL spectra for episide down and episide up mounting at various temperatures and excitation intensities. The expected blueshift was observed, the shift rates were 0.45 and 0.50 meV/K for episide down and episide up mounting, respectively. The maximum cw PL output power with episide down mounting is 18 mW at 225 K and 2.5 mW at room temperature within our excitation intensity region. From temperature tuning rates, the temperature differences between the active region and the substrate were determined to be 32 and 75 °C for episide down and episide up mounting. The temperature of the active layer must and can be decreased by appropriate design and mounting. Our results indicate that with improved heat dissipation, cw optically and electrically pumped lasers are feasible with this active layer design.