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# Lasing characteristics of low threshold ZnSe-based blue/green laser diodes grown on conductive ZnSe substrates

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Room temperature continuous wave operation of ZnSe-based blue/green laser diodes grown homoepitaxially on conductive ZnSe substrates with threshold current densities as low as 176 A/cm$^2$ has been demonstrated. This is the lowest reported threshold among all short wavelength lasers in the blue/green region. Lifetimes at room temperature of up to 2.1 h have been obtained for lasers with pre-existing defect densities lower than $3\times10^4$ cm$^{-2}$. © *1998 American Institute of Physics.* [S0003-6951(98)03227-6]

Advances in the development of II–VI compound materials in recent years have resulted in the demonstration of a blue/green laser operating in room temperature continuous wave (cw) mode for over 100 h.[1] A prototype of a high-density optical disk using the same type of laser has also been developed showing that improvement in device lifetime is practically the only criteria for materializing the commercialization of blue/green II–VI lasers.[2]

One of the major obstacles limiting the lifetime of these devices are pre-existing defects and the formation of dislocation networks in the active region due to recombination-enhanced defect motion (REDM). Since the majority of II–VI blue/green lasers reported to date have been grown on GaAs substrates, research efforts have concentrated on eliminating pre-existing defects such as stacking faults generated at the epilayer/substrate interface. However, due to both the heterovalency and the differences in the thermal expansion coefficients between the epilayer and the underlying GaAs substrate, reduction of the defect densities below $10^4$ cm$^{-2}$ is not always an easy task. An attractive alternative approach is to grow laser structures homoepitaxially on ZnSe substrates. This method not only circumvents the problems inherent in heteroepitaxy but may also have an effect on extending the lifetime of the devices because of the slow degradation rate.[3] In 1997, room temperature cw operation of a blue/green laser homoepitaxially grown on semi-insulating ZnSe substrate was demonstrated, but the threshold current density $J_{th}$ as well as the threshold voltage $V_{th}$ was extremely high resulting in lifetimes of only several seconds.[4] Recently, we succeeded in obtaining a similar type of laser grown homoepitaxially on conductive ZnSe substrates with $J_{th}$ and $V_{th}$ as low as 222 A/cm$^2$ and 5.4 V, respectively.[5] Room temperature cw lifetimes were, however, limited to 74 s since the defect density was in the order of $10^5$ cm$^{-2}$.

In this letter, we report the demonstration of homoepitaxially grown II–VI lasers with the lowest $J_{th}$ ever reported for short wavelength lasers in the blue/green region. These devices lased in cw mode at room temperature for over 2.1 h, which is the longer than any other homoepitaxially grown II–VI blue/green laser reported to date. The suppression of heat generation due to the low $J_{th}$ and $V_{th}$ along with the reduction of pre-existing defects are mainly responsible for the drastic improvement in lifetime of our lasers.

The laser structures were grown by molecular beam epitaxy (MBE) on low resistivity *n*-type (100) ZnSe substrates prepared in the following manner. ZnSe single crystals were grown in our laboratories by either the seeded chemical vapor transport (SCVT) method[6] or the modified recrystallization method.[7] Substrates from the SCVT crystals doped with iodine were mainly used unless stated otherwise. Typical values for the etch pit densities (EPD) and room temperature electron concentrations $n$ were $10^3-10^4$ cm$^{-2}$ and $3-10\times10^{17}$ cm$^{-3}$, respectively. The latter values were sufficient to obtain ohmic contacts on the substrate side of the laser. Slices with sizes of approximately 10 mm×10 mm×1 mm were cut out from the ingots and were then lapped and mechano-chemically polished to obtain smooth mirrorlike surfaces. The substrates were degreased using standard solvents, followed by a $K_2Cr_2O_7$:$H_2SO_4$:$H_2O$ chemical etching process to remove the surface damage introduced during polishing. The substrates were then dipped into a diluted HF solution to reduce the surface ZnO layer, followed by a rinse in deionized water and were blow dried with $N_2$. After loading the substrates in the MBE growth chamber, they were irradiated with active hydrogen from an rf plasma discharge source at the temperature of around 300 °C to remove the residual surface oxide. This resulted in the noticeable change of the reflection high energy electron diffraction (RHEED) pattern from a spotty 1×1 pattern to a streaky $C(2\times2)$ one. After succeeding in the 74-s-lived laser case,[5] we have improved our rf plasma cleaning conditions and are able to reproduce EPDs of $1-3\times10^4$ cm$^{-2}$ routinely.

Our separate confinement heterostructure (SCH) laser has been described previously in Ref. 5 and consists of a 0.8-$\mu$m-thick *n*-ZnSe buffer layer; a 1.0-$\mu$m-thick *n*-ZnMgSSe cladding layer; a 0.15-$\mu$m-thick *n*-ZnSe optical guiding layer; a 4-nm-thick ZnCdSe active layer; a 0.15-$\mu$m-thick *p*-ZnSe optical guiding layer; a 1.0-$\mu$m-thick *p*-ZnMgSSe cladding; a 0.2-$\mu$m-thick *p*-ZnSe layer; a 40-nm-thick pseudograded ZnSe/ZnTe multiple quantum well

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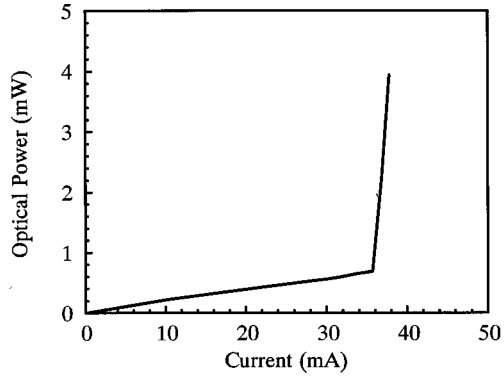


FIG. 1. Light output vs current ($L-I$) characteristic of a gain-guided laser under cw operation at room temperature.

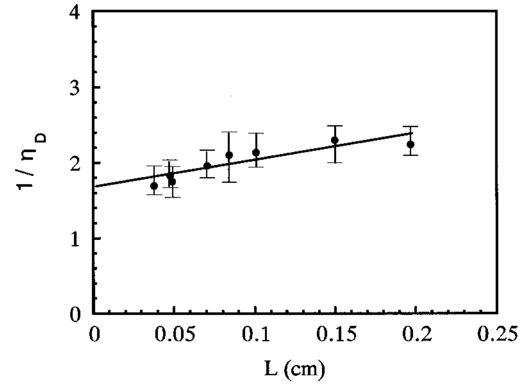


FIG. 2. Reciprocal of differential quantum efficiency as a function of cavity length at room temperature.

(MQW) layer and a 60-nm-thick $p$-ZnTe top contact layer. The material was processed into gain-guided lasers with 20-$\mu$m-wide stripes. An insulating layer of polycrystalline ZnS was deposited in the region outside of the stripe to restrict the path of the electric current. An ohmic contact to the top $p$-ZnTe layer was formed by depositing Pd/Au. The substrate side of the epitaxial wafer was lapped down to approximately 250 $\mu$m and chemically etched to remove the damaged layer. The wafers were cleaved into resonators of about 1 mm long, and high reflectivity coatings (70%–95%) were made on the end facets unless stated otherwise. The laser diodes were mounted with $p$-side up configuration on a copper heatsink using an indium solder that also acted as the $n$-contact electrode. The mounted chip was thermally annealed at 250 °C in $N_2$ ambient for several minutes, which was high enough to assure the ohmic properties of both $p$ and $n$ electrodes.

The light output vs current ($L-I$) and voltage vs current ($V-I$) characteristics measured in cw mode from a device lasing at the wavelength of 538 nm is shown in Fig. 1. The threshold current $I_{\mathrm{th}}$ was 37 mA, which corresponds to $J_{\mathrm{th}}$ of 176 A/cm$^2$. The differential quantum efficiency $\eta_D$ was 66%/facet, and $V_{\mathrm{th}}$ was as low as 3.9 V. The lowest values for the $J_{\mathrm{th}}$ reported up to now for II–VI blue/green lasers and nitride-based III–V blue lasers are 250 A/cm$^2$ and 3.0 kA/cm$^2$, respectively.[8,9] The $J_{\mathrm{th}}$ of our laser in Fig. 1 is, thus, by far the lowest among all blue–green lasers reported to date. The majority of the devices that we have fabricated over the last 10 growth runs have shown $J_{\mathrm{th}}$ of less than 300 A/cm$^2$, and over 75% of them less than 250 A/cm$^2$. These results suggest that blue/green lasers grown homoepitaxially on ZnSe substrates may essentially have lower $J_{\mathrm{th}}$ than those grown on GaAs substrates.

In order to understand the mechanism responsible for the low $J_{\mathrm{th}}$ of our lasers, the four main parameters that define $J_{\mathrm{th}}$, namely the internal loss $\alpha_i$, the internal differential quantum efficiency $\eta_i$, the gain constant $\beta$, and the nominal transparency current density $J_0$ were determined experimentally. The lasers under investigation were the same type as those described in the previous section except that a substrate grown by the modified recrystallization method and doped with Al was used. The $J_{\mathrm{th}}$ for a device having a linear gain relationship can be expressed using these parameters as

$$J_{\mathrm{th}} = J_0 d/\eta_i + d\alpha_i/\beta\Gamma\eta_i + (d/B\Gamma\eta_i)[\ln(1/R)/L], \tag{1}$$

where $d$, $L$, $R$, and $\Gamma$ are the thickness of the active layer, the cavity length, the power reflectivity of a cleaved mirror, and the optical confinement factor, respectively.[10] The first two parameters, $\alpha_i$ and $\eta_i$, were determined utilizing the following relationship between $\eta_D$ and $L$:

$$1/\eta_D = (1/\eta_i)[1 + \alpha_i L/\ln(1/R)]. \tag{2}$$

Figure 2 shows the plot of $1/\eta_D$ as a function of L obtained from $L-I$ measurements performed under pulsed operation (5 $\mu$s pulse, 1% duty) at room temperature. Facet coatings were not applied to the cleaved mirrors of the lasers for the measurements. The solid circles represent the average $1/\eta_D$ of five devices measured for each $L$, and the error bars show the range in which these values varied. A linear fit to these points are also shown in Fig. 2. From the slope and intercept of the $1/\eta_D$ axis and assuming $R=0.24$, $\alpha_i$ and $\eta_i$ were estimated to be 3.1 cm$^{-1}$ and 60%, respectively. The $\eta_i$ value obtained here is considered to reflect the ratio of the leakage current to the total injection current in addition to the $\eta_i$ since the leakage current is included in the injection current in Eq. (1). Although the value for the $\eta_i$ without the contribution of the leakage current is unknown, the low $\eta_i$ in our lasers suggests the possibility that the leakage current levels in our lasers are not much different from, if not higher than, those of the heteroepitaxially grown lasers. The differences in the band gaps of the active and the cladding layers of our lasers determined from room temperature photoluminescence measurements as being 0.440–0.488 eV and the $N_a-N_d$ of the $p$-ZnMgSSe cladding layer determined from $C-V$ measurements as being $1\times10^{17}$ cm$^{-3}$, both of which are typical for this material system, also support this point. On the other hand, $\alpha_i$ is significantly lower than that of a ZnCdSe/ZnSe/ZnMgSSe SCH laser grown on GaAs substrate, which was reported to be 21 cm$^{-1}$ at room temperature.[11] A large portion of the loss in their laser, estimated as 16.53 cm$^{-1}$ in the literature, was attributed to optical field spreading due to absorption in the GaAs substrate. Since absorption in the ZnSe substrate is almost negligible in the blue/green region, this has little or no effect on increasing the $\alpha_i$ of homoepitaxially grown lasers. $\beta$ and $J_0$ were determined next by using these values for $\alpha_i$ and $\eta_i$, and utilizing Eq. (1). Figure 3 shows the plot of $J_{\mathrm{th}}$ as a function of $1/L$. The solid circles again represent the average $J_{\mathrm{th}}$ of five devices measured for each $L$, and the error bars show the range in which these values varied. A clear linear depen-

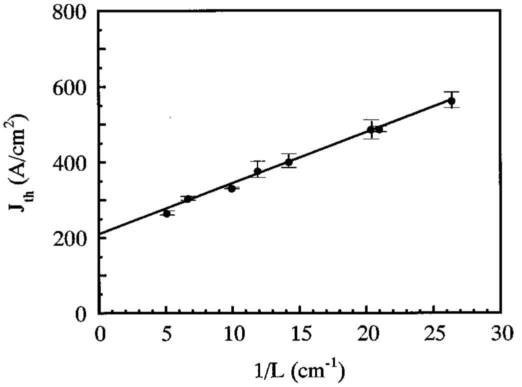


FIG. 3. Threshold current density as a function of reciprocal of cavity length at room temperature.

dence of $J_{th}$ on $1/L$ was observed indicating that a linear gain relationship is a good approximation for this system. The effects of pseudoindex guiding due to a lateral refractive index step caused by heating, which would otherwise show nonlinear gain behavior,[12] are apparently minimal in our system. From the slope and intercept of the $J_{th}$ axis of the fitted line, $\beta$ and $J_0$ were estimated to be 0.036 cm $\mu$m/A and 26.1 kA/cm$^2$ $\mu$m, respectively. A numerically obtained value of $\Gamma = 1.9\%$ was used in the calculation. Comparing these values to those of the heteroepitaxially grown laser mentioned above,[11] $J_0$ was of the same order while $\beta$ was nearly 10 times larger in our devices. The reason for the high $\beta$ is not clear, but Suemune *et al.* reported $J_0$ and $\beta$ calculated for a 10 nm ZnSe quantum well with infinite barrier height to be 50 kA/cm$^2$ $\mu$m and 0.026 cm $\mu$m/A, respectively.[13] Both $J_0$ and $\beta$ in our devices are close to these calculated values. From the above discussion and Eq. (1), we believe the low $J_{th}$ in our lasers is not due to the improvement of the carrier confinement but stems directly from the use of ZnSe substrates leading to the low $\alpha_i$ and the high $\beta$.

The results of an aging experiment carried out at 20 °C under automatic power control with the laser power output set at 2 mW for some of our longest-lived lasers are shown in Fig. 4. A lifetime of 24 min was obtained for the laser with $L-I$ characteristics shown in Fig. 1, while a lifetime of 2.1 h was obtained for a different device lasing at the wavelength of 522 nm with $J_{th}$ of 222 A/cm$^2$ and $V_{th}$ of 4.8 V. The EPD's of the devices measured on parts of the wafer adjacent to the areas used for device fabrication were $\sim 7\times 10^4$ and $\sim 2\times 10^4$ cm$^{-2}$, respectively. These are the longest lifetime values ever reported for homoepitaxially grown II–VI lasers. The low threshold current densities and voltages demonstrated with our lasers are some of the key ingredients responsible for the drastic improvement in lifetime characteristics since the enhancement of REDM due to local heating of the device is minimized. Complete elimination of the preexisting defects from the current injected area in our lasers is, thus, needed to assess whether or not homoepitaxially grown lasers will have longer lifetime than those grown on GaAs substrates. We are still making efforts to improve the substrate preparation and pregrowth treatment methods towards this goal.

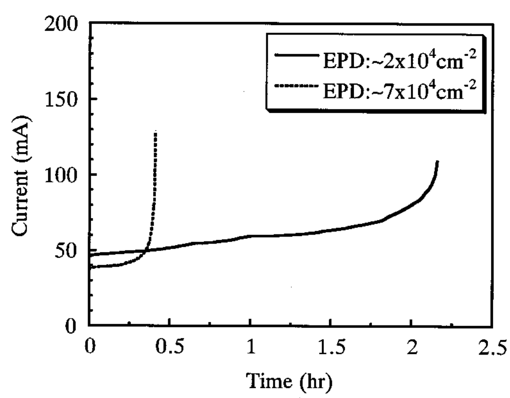


FIG. 4. Aging characteristics under 2 mW constant light output at room temperature.

In conclusion, room temperature cw operation of ZnCdSe/ZnSe/ZnMgSSe SCH laser diodes grown homoepitaxially on conductive ZnSe substrates with $J_{th}$ as low as 176 A/cm$^2$ and lifetimes of up to 2.1 h has been demonstrated. The value for the $J_{th}$ is the lowest ever reported for short wavelength lasers in the blue/green region. The extremely low $J_{th}$ obtained in our devices indicate that lasers homoepitaxially grown on conductive ZnSe substrates may have an advantage over those grown on GaAs substrates in terms of degradation due to thermal effects. A more thorough discussion on the lifetime characteristics will be possible upon realization of pre-existing defect densities comparable to those of lasers grown heteroepitaxially on GaAs substrates.

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