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Invited

Blue/Green Light Emitters Based on II-VI Heterostructures on ZnSe Substrates

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High-brightness blue and green light-emitting diodes (LEDs) operating at peak wavelengths in the range 489 -514 nm have been successfully synthesized, processed, and tested. The high-brightness LEDs are II-VI heterostructures grown by molecular beam epitaxy (MBE) at NCSU using (100) ZnSe substrates produced at Eagle-Picher Laboratory by the Seeded Physical Vapor Transport (SPVT ^{TM}) process. The double-heterostructure (DH) LED devices consist of a ~1.8 μm thick layer of n-type ZnSe:Cl, a ~0.1 μm thick active region consisting either of a ZnCdSe MQW (blue) or a ZnTeSe layer (green), and a ~1.8 μm thick p-type ZnSe:N layer deposited using a nitrogen plasma source. Thin (~100 Å) epitaxial surface layers of HgSe/ZnTeSe were deposited by MBE to obtain excellent ohmic contact to the top p-type ZnSe layer. Standard photolithographic techniques were used to fabricate 250 μm x 250 μm mesa diode structures. Gold was used as a metal contact to the top HgSe layer of each device; indium was used to contact the n-type ZnSe layer. Direct contact to the n-type ZnSe epilayer was necessitated because of the insulating nature of current ZnSe substrates. The devices were packaged in a standard T-13/4 clear-epoxy lamp configuration for testing. The blue LEDs produce 327 μW @ 10 mA with external quantum efficiency of 1.3%. If one compares the ZnCdSe LED with the Nichia Chemical InGaN blue LED characteristics one finds that the Nichia device is about three times brighter but displays a much broader spectral output. In contrast, the ZnCdSe DH blue LED output is sharply peaked at 489 nm with a spectral purity of 96%. In terms of photometric units, the luminous performance of the ZnCdSe LED is 1.6 lumens/watt at 10 mA. The brightest ZnTeSe green LEDs tested to date produce 1.3 mW at 10 mA peaked at 512 nm with an external quantum efficiency of 5.3%. These are the brightest pure green LEDs ever produced in the history of semiconductors. The luminous performance of the green LED is 18 lumens/watt at 10 mA. This exceeds the luminous performance of super-bright red LEDs (650 nm) based on AlGaAs DHs and greenish-yellow (570 nm) AlGaInP DH devices; it also exceeds the luminous performance of the super-bright Nichia blue LEDs based on GaN/InGaN DHs (3.6 lumens/watt). Eagle-Picher has developed conducting n-type ZnSe wafers using an Al-based dopant. Using these n-type conducting ZnSe substrates, green LEDs having external quantum efficiencies of 2.7% have also been demonstrated. At NCSU, our best green LEDs presently have useful lifetimes (40% degraded) of more than 750 hr when operated at 15 A/cm^2. Several LEDs have been operational for more than 10,000 hrs. The degradation process involves the generation of dark line defects. For a given initial dislocation density, the degradation process appears to depend on the total charge/unit area flowing through the device. Detailed studies of degraded devices, based on optical microscopy and TEM/SEM experiments, will be reported.

All of the II-VI blue/green laser diodes reported to date have been prepared using GaAs substrates. At DRC in 1994, however, we reported and demonstrated high brightness green LEDs based on ZnSe/ZnTeSe double-heterostructures grown on <u>insulating</u> ZnSe substrates. In this paper, we report the first blue/green laser diodes grown on <u>conducting</u> ZnSe substrates. Within the past twelve months, a series of bulk crystal growth experiments was completed at Eagle-Picher Laboratory using several potential dopants in an effort to prepare n-type conducting crystals of ZnSe by the Seeded Physical Vapor Transport (SPVT^{TM}) process for use as substrates in the development of blue/green light emitting diodes and laser diodes. Prior to these experiments, conducting bulk crystals of ZnSe had never been prepared by any technique. It was found, however, that by employing an aluminum-based dopant during the SPVT^{TM} process, controlled substitution doping of ZnSe is possible. ZnSe crystals doped to 1×10^{17} carriers/cm^3 were obtained which display electron mobilities up to 460 cm^2/V-s at 300 K. More recently, ZnSe crystals have been grown with doping levels up to 7×10^{17} carriers/cm^3 and electron mobilities of 250 cm^2/V-s using the SPVT^{TM} crystal growth process. Laser diode structures were grown by MBE at NCSU using the conducting ZnSe substrates described above. The laser diode structure employed is a p-on-n separate confinement heterostructure (SCH) consisting of 0.8 μm thick ZnMgSSe cladding layers (E_g ~ 3.0 eV) lattice-matched to ZnSe , 0.1 μm thick ZnSe light guiding layers, and a single 60-200 Å thick pseudomorphically- strained ZnCdSe quantum well. The laser structures were grown at 280 °C using $ZnCl_2$ and plasma-nitrogen for n-type and p-type dopants, respectively. Thin epitaxial layers of p-type ZnSe/ZnTeSe followed by undoped HgSe were deposited onto the top p-type ZnMgSSe layer of the laser structure to improve the p-type contact. Gain-guided laser devices were fabricated by preparing 500-1000 μm long cleaved-cavity resonator structures with a 10 μm wide Au stripe electrode as the top p-type electrical contact. The device facets were uncoated. Green laser emission (507-517 nm; 2.443-2.394 eV) was observed at temperatures ranging from 77-220 K using cw excitation at 77K and pulsed excitation (50 ns; 10^{-1} - 10^{-4} duty cycle) at higher temperatures. Threshold currents ranged from 8.7 mA (77 K) to 30.9 mA (220 K) for green laser diodes having cavity lengths of 545 μm. Blue laser diodes with outputs at 485 nm (2.553 eV) at 77K have also been fabricated using the same basic SCH structure but with less Cd in the ZnCdSe quantum well. The threshold current for initial devices of this type was found to increase to 230 mA at 77K due in part, we believe, to the decrease in carrier confinement associated with the active blue-light-emitting ZnCdSe quantum well.

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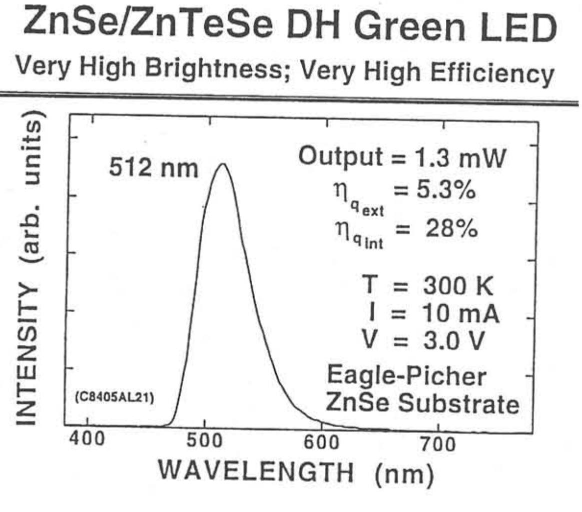

Figure 1. High-brightness green LED output.

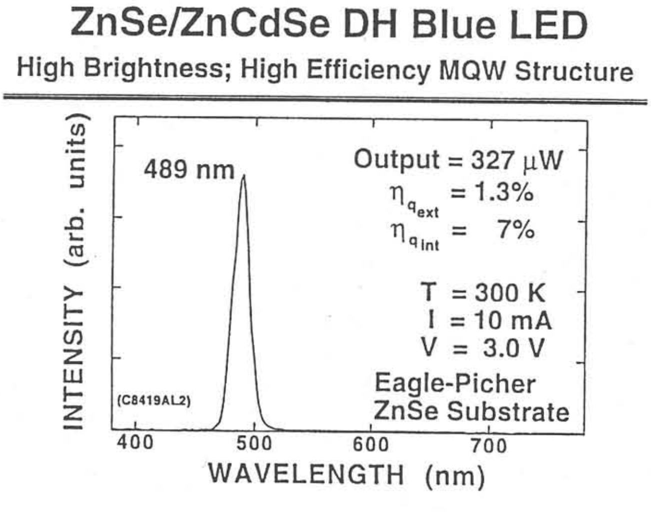

Figure 2. High-brightness blue LED output.

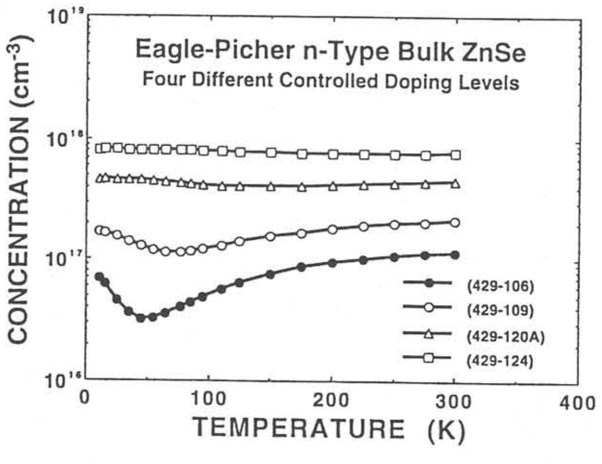

Figure 3. Hall data for conducting ZnSe.

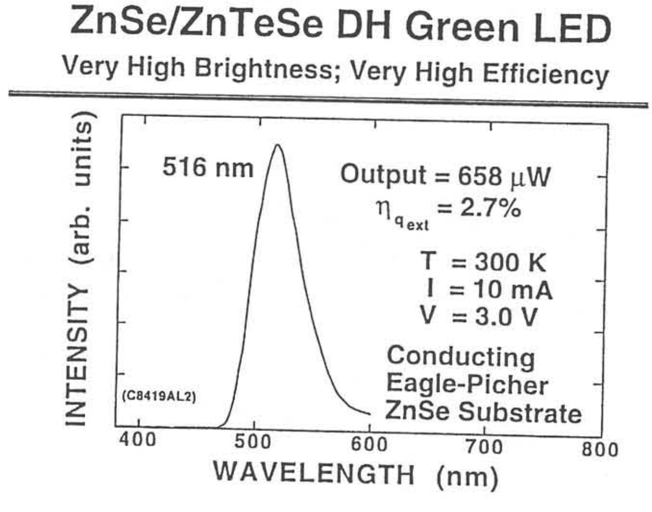

Figure 4. Green LED on conducting ZnSe.

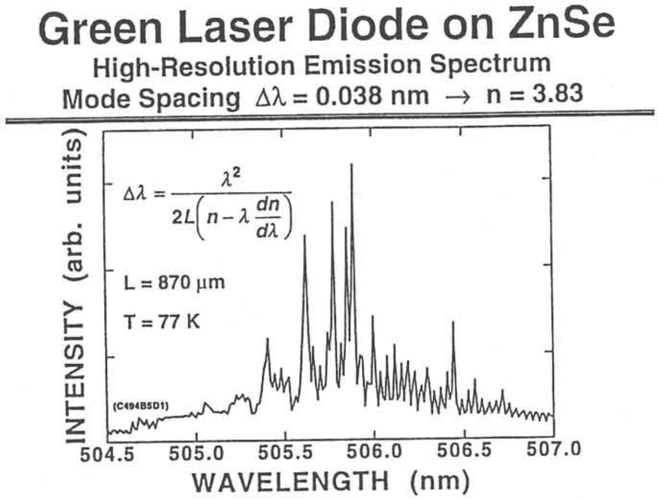

Figure 5. Green laser diode on ZnSe.

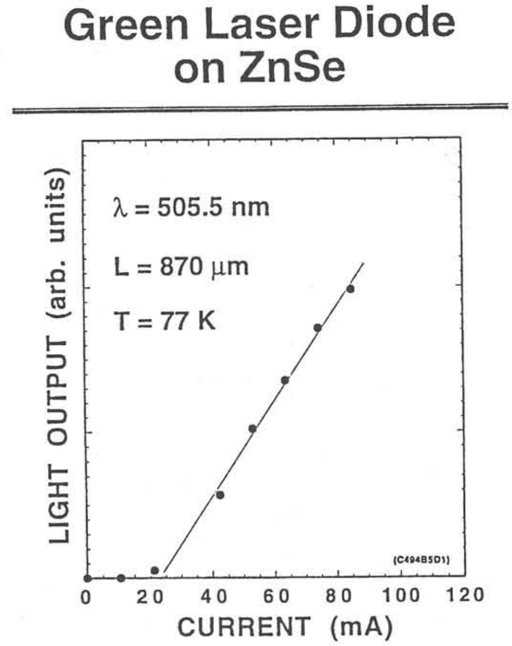

Figure 6. L vs. I characteristics for green laser diode.

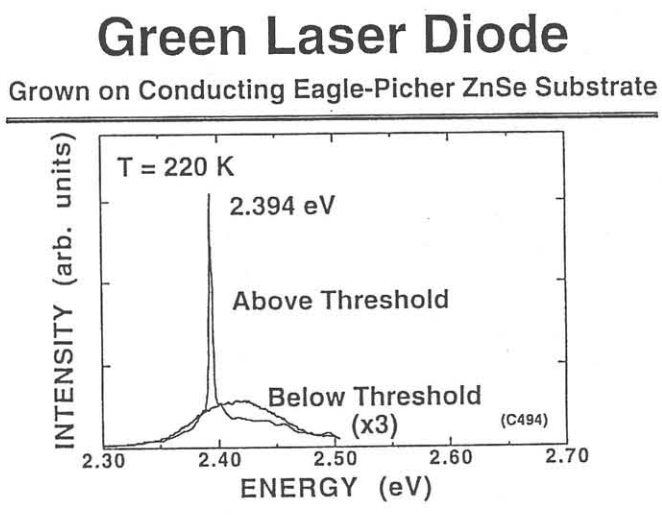

Figure 7. Green laser diode at 220K.

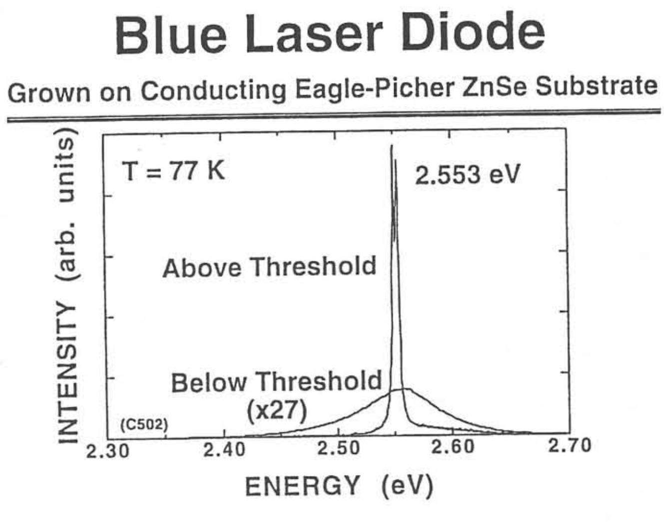

Figure 8. Blue laser diode at 77K.