# VISIBLE II-VI LASER DIODES

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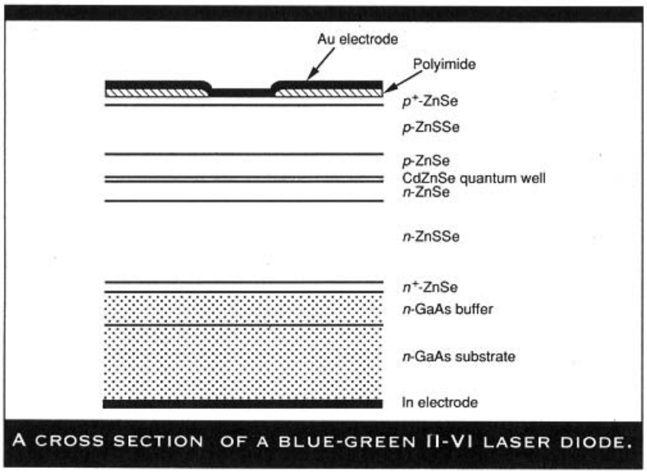
One current trend in laser diode research is to push toward shorter wavelengths. Due to limitations in their bandgaps, it is not likely that the III-V compound semiconductors will produce lasers with emission wavelengths significantly shorter than 600 nm. Therefore, the quest for green and blue injection lasers is forcing researchers to look elsewhere. Our recent demonstration of 490-535 nm laser diodes from ZnSe-based materials suggests that a new era of laser development using the wide bandgap II-VI semiconductors has begun.

The wide bandgap II-VI semiconductors have been described as promising materials for the development of visible light emitters for the past several decades. Problems with materials growth, doping, and ohmic contacts rendered these materials useless in early efforts to demonstrate practical devices. There were initial successes with the deposition of high quality undoped[1] and n-type ZnSe films by MBE,[2] but reliable p-type doping remained elusive. It wasn't until very recently that device-quality p-type films could be produced by doping with Li[3] or N[4].

Early LEDs were shown to emit 465 nm light at room temperature.[5] While this clearly represented a success for the II-VIs, the efficiency of the devices remained relatively low, often less than 0.002% external. The poor power efficiencies were consequences of the inability to make good ohmic contact to the p-side of the device and of excessive dislocations in the active layers.

Studies of optically excited ZnSe/$Cd_xZn_{1-x}Se$ single quantum wells demonstrated that the luminescence efficiency could be dramatically improved over that of bulk ZnSe. Efforts to produce SQW LEDs showed that internal quantum efficiencies greater than 10% could be achieved at 77K.[6] This result, along with the demonstration of waveguiding in $ZnS_xSe_{1-x}$/ZnSe double heterostructures,[7] provided the foundation for the fabrication of II-VI laser diodes.



A CROSS SECTION OF A BLUE-GREEN II-VI LASER DIODE.

The first II-VI visible laser diodes were developed in the Photonics Research Laboratory at 3M Company (see cover photo).[8] These separate confinement devices used a CdZnSe SQW centered in a ZnSe pn junction to generate the light. $ZnS_{0.07}Se_{0.93}$ layers were used as cladding to confine the optical mode to the ZnSe guiding layer away from the GaAs substrate and contact metal (see figure). The composition of the cladding was chosen to be lattice matched to the substrate. Gain guided devices were fabricated using Au stripes in a polyamide insulator layer. The mirrors were formed by cleaving facets while making 0.8 to 2mm long cavities.

Lasing was first observed at 77K under pulsed current injection. By varying the composition of the quantum well, lasers emitting at 490-535 nm have been demonstrated. The output from these devices is TE polarized and a "speckle pattern" is clearly visible. The emission spectra display many distinct, longitudinal modes with the mode separation determined by the length of the cavities. Output powers greater than 100 mW per facet have been obtained. The threshold current, has been as low as 95 A/$cm^2$ at 77K.

Room temperature lasing has also been recently demonstrated in devices that had high reflectivity coatings on both end facets. The quantum well in these devices was deeper and narrower than in the earlier lasers. At room temperature, these lasers operate at 535 nm with a threshold current density of 2800 A/$cm^2$.

Remnants of some of the earliest problems in II-VI semiconductors remain with us today. The two most serious are difficulty in making good ohmic contacts to p-type material and difficulty with controlling dislocations. Both have strong implications in the performance. In these devices, the operating voltages are large ($\approx$20V) and nearly 75% of the input power is lost at the contacts. This problem may be the greatest obstacle to room temperature, CW operation.

Adequate optical confinement is needed to keep threshold current densities small. Unfortunately, the II-VIs don't provide an analog of AlAs/GaAs where optical confinement can be achieved in a lattice matched system. In our devices, the lattice parameter changes from the cladding to the guiding layers, generating misfit dislocations. Some of these propagate into the active layer, leading to a reduction of internal quantum efficiency.

Although several challenges remain, our recent demonstration of visible laser diodes from II-VI compound semiconductors opens a new era of laser research. Devices emitting at 490-535 nm under pulsed current injection have been operated up to room temperature. In light of these results, future research on visible laser diodes will likely involve II-VI compound semiconductors.

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# DRESSED-STATE TWO-PHOTON LASER

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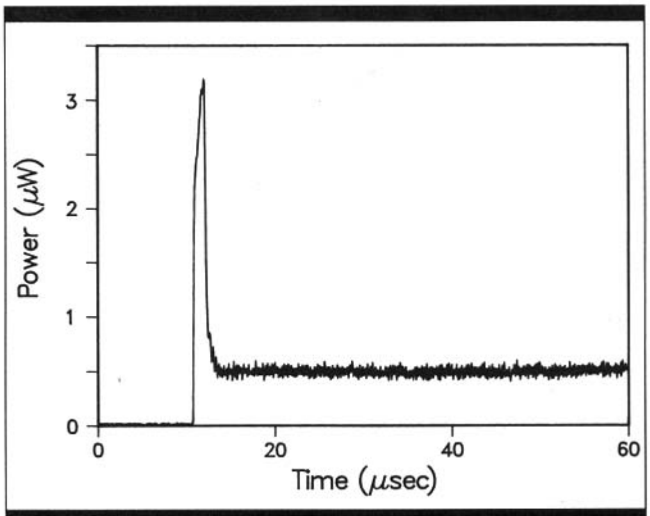
Though the possibility of two-photon laser action[1] was first discussed over 25 years ago, it has been realized only under a very limited set of circumstances[2,3] and never, in the optical regime, under continuous-wave conditions. This is unfortunate, since the two-photon laser has been predicted to display a number of interesting properties[4] such as bistable operation, unique threshold behavior, and, in some cases, squeezing.

The introduction of a novel gain medium, ideally suited for the maximization of two-photon gain relative to competing one-photon processes, has allowed us during the past year to finally achieve continuous-wave optical two-photon laser action. The gain medium that made this success possible consists of an atomic beam of two-level-like barium atoms that passes through the center of high finesse optical cavity. On passing the cavity center, the barium atoms are exposed to a strong nearly resonant laser driving field. In the driven two-level-atom system, the two-photon gain arises in the absence of inversion between the atomic levels involved, but can be viewed as arising from inverted two-photon transitions in the dressed-atom picture.[5]

The two-photon gain occurs at a frequency displaced from the driving-field frequency by one-half the driving-field's generalized Rabi frequency. This frequency can be adjusted so that it is well isolated from the one-photon gain features known to arise in the same system,[6] and can therefore be selectively enhanced through use of the high finesse optical cavity. Wave-mixing type processes that could arise in the same medium are suppressed by using an experimental geometry that does not allow for phase-matching of such processes.



TIME RESOLVED OUTPUT INTENSITY OF THE DRESSED-ATOM TWO-PHOTON LASER FOLLOWING INJECTION OF A TRIGGER PULSE (LARGE SPIKE AT THE LEFT).

We have observed that the dressed-state two-photon laser will not turn on unless a trigger pulse (derived from the output of a tunable dye-laser) is injected into the cavity. This is because the two-photon gain is intensity-dependent and there is little spontaneous emission at the two-photon lasing frequency. The figure shows the time resolved output intensity of the two-photon laser as it is triggered on. The intensity spike at the left represents a portion of the trigger pulse transmitted through the laser cavity. It is seen that the output power remains at a constant value after the intense trigger-pulse drives the two-photon laser above threshold. This behavior is indicative of a first-order phase transition and is strong evidence that we have indeed observed two-photon lasing.

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