Strain Estimation in III-V Materials by Analysis of the Degree of Polarization of Luminescence

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Strain Estimation in III-V Materials by Analysis of the Degree of Polarization of Luminescence

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Abstract *The degree of polarization (DOP) of luminescence of III-V materials is a sensitive function of the strain in the material. The DOP can be measured with a spatial resolution of roughly 1 μm and an rms noise equivalent to a strain difference of 2×10^{-5}. The DOP can be measured on cleaved facets, surfaces free of metals, or luminescent layers buried by transparent materials or thin films. Thus maps of the strain near surfaces for devices and materials can be deduced from analysis of the DOP from the facets or surfaces. Since the reliability and operation of devices depends on strain, DOP measurements have utility in studies of reliability, of enhancement of reliability, and of device operation.*

I. INTRODUCTION

Mechanical strain affects the reliability of III-V emitters. Oudart *et al*. reported that strain from die attached, *i.e.*, bonding strain, reduced the lifetime of cm-bar high-power lasers by a factor of three [1]. Lisak *et al*. found that the life expectancies of high-power GaAs-based lasers were dependant on the magnitude of the bonding strain and that devices with larger bonding strain owing to different adhesives and sub mounts showed shorter life times [2]. Lisak found through DOP mapping of the facets that even small voids created distinctive strain patterns and concluded that the effects of the bonding adhesive on reliability should be considered in packaging.

Some emitters seem more susceptible to strain than others. This may arise because of a threshold mechanism in the creation of defects or because stress acts as a motive force that moves pre-existing defects around and these defects interact when current is applied to the device. Chuang *et al*. [3] developed a kinetic model for the degradation of blue-green LEDs and later applied this model to blue-green lasers. One feature of this model is that the current versus time characteristic depends on the pre-existing density of defects. Lam developed an analytic multicomponent model (MCM) that fits well the long term aging characteristics of InP lasers [4]. Lam concluded, with > 97.5 % confidence, that the life test performance is limited by the pre-existing defects or resources that feed larger defects. These larger defects grow and ultimately impair the operation of the device. Lam's MCM assumes that the resource density is fixed at growth and the resource is depleted in time. The MCM model accurately fits the saturation of the aging characteristic and provides for estimates of the lifetimes and activation energies.

Clearly, techniques to measure defects and strain are of interest. Measurements of pre-existing defects (resources in the MCM approach) are difficult to perform and it appears difficult to control the density of pre-existing defects. However, it is possible to estimate strain and hence take steps to control strain and thus impact reliability. This paper is concerned with the estimation of strain in III-V devices through analysis of the degree of polarization of luminescence and the effect of strain on the operation of III-V emitters.

II. MEASUREMENT OF STRAIN

For luminescent III-V materials, the degree of polarization (DOP) of the luminescence is related to the strain in the material that creates the luminescence. We defined the degree of polarization of the luminescence DOP_y to be

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$$DOP_y = \frac{L_x - L_z}{L_x + L_z} = -C_\varepsilon(\varepsilon_{xx} - \varepsilon_{zz}) \quad (1)$$

where y is the normal to the surface that the luminescence is collected from; L_i is the luminescence that is polarized in the i direction; C_ε is an experimentally determined, positive, calibration constant; and, ε_{ii} is the normal component of strain in the i direction [5].

With the equipment that is shown schematically in Fig. 1(a), maps of the DOP of photoluminescence (PL) DOP_y can be made with a spatial resolution of the order of 1 µm and an rms noise of 0.1%. This rms noise level corresponds to a strain difference of 2×10^{-5}. The spatial and strain resolutions are such that the type, direction, and Burgers vector of single dislocations in III-V materials can be determined from maps of the DOP of luminescence [6, 7]. The maps are made by raster scanning the sample under the stationary measurement system.

Figure 1(b) shows schematically and not to scale a v-groove bar and mounting system that was used in the determination of the calibration constant.

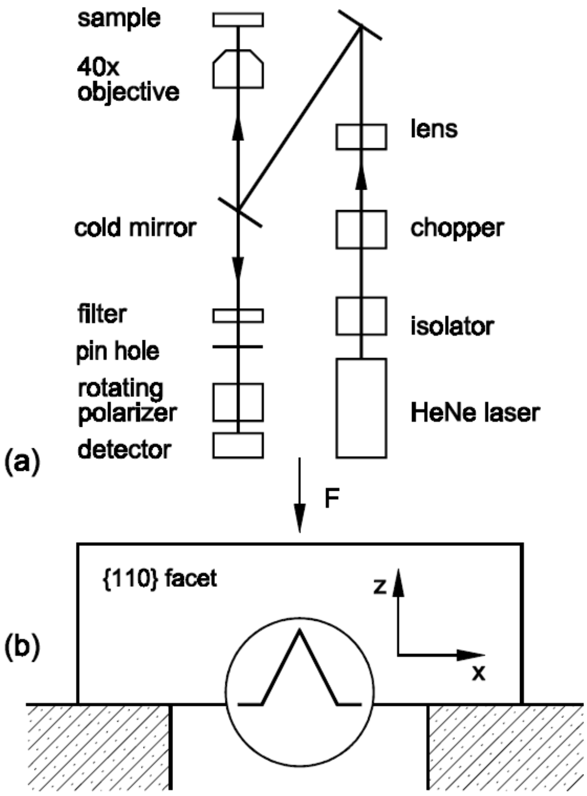


Fig. 1: Schematic diagram of the measurement apparatus and of the calibration bar.

Another quantity, the rotated DOP or ROP, is obtained from the measurement system. We defined ROP_y as

$$ROP_y = \frac{L_{x'} - L_{z'}}{L_{x'} + L_{z'}} = -2C_\varepsilon \varepsilon_{xz} \quad (2)$$

where x' and z' are obtained by a 45 deg rotation of the xyz coordinate system about the y axis [5]. The ROP is proportional to the shear strain. The ROP is of interest as lasers appear stable against homogeneous biaxial strain – quantum well lasers are designed with large, homogeneous biaxial strains and are highly reliable. The shear strain, and hence the ROP, is a measure of the rotation of the coordinate systems and hence related to the inhomogeneous nature of the strain and to, quite possibly, the reliability of the device.

Figure 2 shows false colour maps of the DOP and ROP when a non-zero force F is applied to the semiconductor bar of Fig 1(b). The groove acts to concentrate the strain owing to the applied bending moment and creates distinctive patterns of DOP and ROP. An area of 60 µm wide by 50 µm high around an 11 µm wide $\{111\}_B$ groove is displayed. The colour bar at the side gives the mapping of colour to DOP. The data were offset to show the detail in the maps. The green colour at the mid-point of the bar corresponds to a DOP_y of −6.1% and an ROP_y of −0.3 %. Moving up the colour bar indicates a more positive DOP while moving down the colour bar indicates a more negative DOP. The grey colours at the top and bottom of the bar are used to display signals that are off-scale. The purple colour is used to display areas, such as the groove, where the PL yield, which equals $L_x + L_z$, is zero or too small to make a reliable estimation of the DOP. For the 10× gain used to display Fig 2., the just offscale signals correspond to ±2.90 percentage points relative to the midpoint of the colour bar.

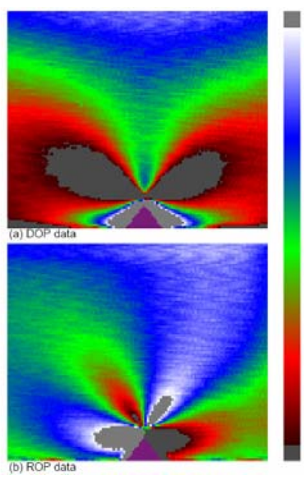


Fig. 2: Maps of the DOP and ROP near a v-groove of the calibration bar of Fig. 1(b) for a non-zero F.

The calibration constant for InP was [5] determined by performing least squares fits of FEM simulations to the data. For the calibration, the force F was measured with a strain gauge. The dimensions, physical constants, and measured force are inputs to the FEM simulation. For a {110} facet of InP, C_{ε} = 65±10. For GaAs, the calibration constant was determined by fitting analytic solutions of bending of a bar to the data [8]. The {110} calibration constant for GaAs was reported to be 50±10 [9].

The technique of least squares fitting of FEM simulations to the measured data can be also be used to obtain the tractions that are acting on the surfaces to create the observed patterns of DOP and ROP [10]. With an FEM model calibrated to the data, the changes in refractive index owing to the strain can be estimated and used in other analyses to estimate the effect on operation of a device [11].

The apparatus described in this section can be used to map small areas to estimate the strain from features such as grooves and ridges and the interactions with bonding and overlayers. The apparatus can also be used to map large areas, such as facets and the top surface (with the metal removed) of devices to observe strain owing to bonding, surface features, and bottom side layers.

Maps of the PL yield are a useful byproduct of measurement of the DOP of photoluminescence. Figure 3 is a map of the PL yield of a telecom laser that had been subjected to accelerated life testing. Maps of the reflectance at the pump wavelength can be obtained simultaneously with the maps of the DOP, ROP, and PL yield. For the device shown in Fig.3, the reflectance did not change across the device, indicating that the facet passivation was changing with aging [12].

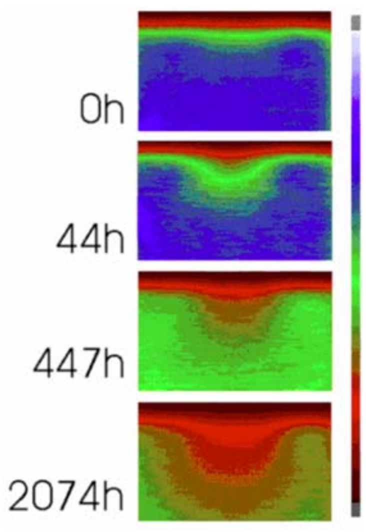


Fig. 3: Maps of the PL yield as a function of time on accelerated aging. The active region is at the top.

In the next section, we present some DOP related results for reliability estimation of optoelectronic devices.

III. Some Results

Bonding strain is not necessarily constant in time [13, 14]. Tomm *et al*. reported that there is a tendency for a small increase in packaging induced strain during burn-in and a tendency for strain relaxation during operation [13]. Colbourne measured the relaxation of bonding strain through measurement of the DOP of electroluminescence [14]. Figure 3a of Ref. [15] shows a ‘transient’ in the current required to maintain a constant power after the device was removed from the 60 C aging environment, tested at room temperature, and then returned to the 60 C aging environment. The time constant of the transient is similar to that measured by Colbourne and suggests that the transient of Ref. [15] owes to relaxation of bonding strain. Since the threshold current and the operating current of lasers can be functions of the strain, changes of bonding strain with time can mask the true rate of degradation and impair the ability to estimate device lifetime.

Fritz and Cassidy [16] found using DOP, SEM, AES, AFM, and measurements of wavelength shifts with current that the strain, thermal impedance, and bond microstructure depend on the cooling rate of the solder bond during die attach. Although not measured, it is expected that dependence of thermal impedance, strain, and solder microstructure on the bonding process will impact the reliability of devices.

Strain might act a motive force to move resources to regions where the resources interact to form defects that degrade the operation of emitters. Strain does shift the band edges of III-V semiconductors. This shift of the band edges leads to a DOP of the luminescence and hence a means to estimate the strain in the semiconductor [9, Sec. 3.3]. Since the refractive index and the absorption spectra are coupled (the coupling is described by the Kramers-Kronig relations) strain induced shifts in the band edges produces strain induced changes in the refractive index.

Figure 4 shows the changes in refractive index as a function of wavelength for different applied strains. Note that the refractive index changes are greatest near the band edge, where the device operates.

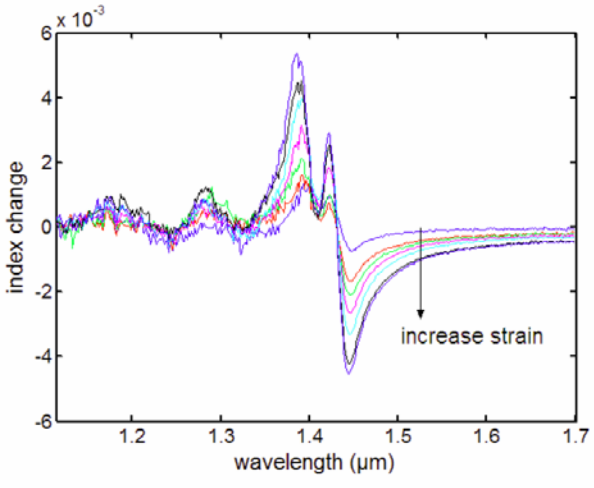


Fig. 4: Refractive index as a function of wavelength and for increasing strain.

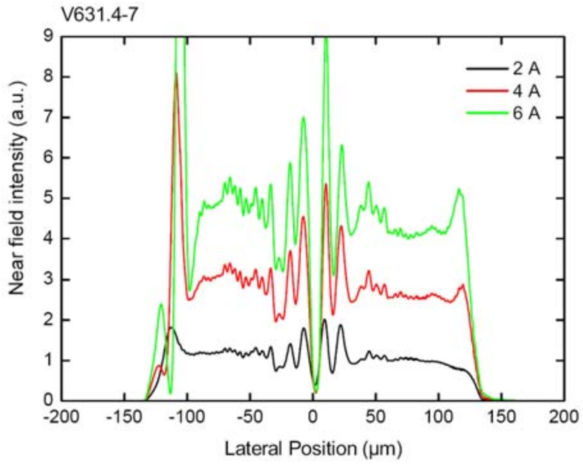
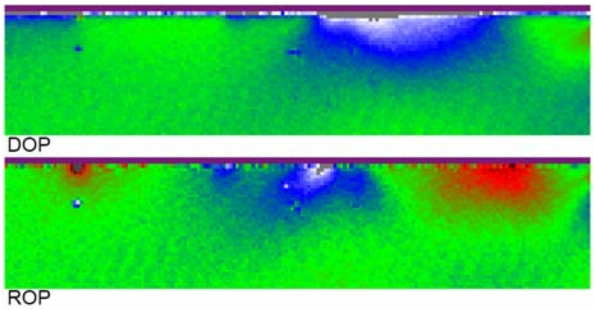


Fig. 5: Predicted near field of a broad area laser. The simulation included index variations that were estimated from DOP measurements.

Mark Fritz, a Ph.D. student at McMaster University at the time, and Senta Kellenback, a Dipl.-Phys. candidate at Fraunhofer Institut Angewandte Festkörperphysik at the time, collaborated on some measurements and modelling on high-power broad area lasers. Mark made DOP of the bonding strain and used FEM fits [10] to estimate the refractive index profile owing to the bonding strain. Senta made near field measurements on the lasers and incorporated the estimated refractive index perturbations into a BPM of the devices. Senta noted that the near fields of the devices were not smooth as expected and that the addition of the refractive index perturbations caused the predicted near fields to be similar to the measured near fields.

Figure 5 shows near fields for the high power devices. If the bonding strain is responsible for the break-up of the near field, then changes with bonding strain with time will lead to changes in the operating characteristics of the device. This has implications for the ability of the device to perform and hence for the reliability of the device.

DOP measurements can be used to determine where strain is introduced in the fabrication process. This knowledge should help to minimize strain and maximize the reliability of devices. Measurements on cleaves through the process control monitor (pcm) regions on wafers have been made. Figure 6 shows DOP maps on a facet through a section of a pcm area on an InP wafer. The dielectric, area #12, was designed for low strain and the DOP measurements confirm this. The next fabrication step, metallization, area #13, adds considerable strain to the device.



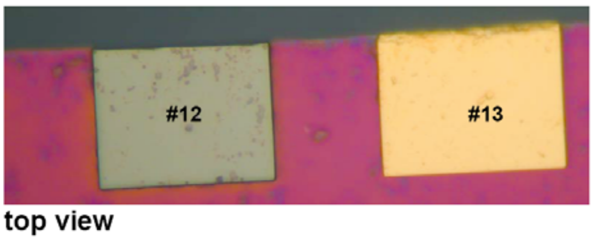


Fig. 6: Maps of the DOP and ROP over an area of 180 μm × 40 μm on the facet for a cleave through a pcm area. An image of the top of the pcm area is shown.

Over the recent years high power laser diodes bars have shown a strong increase of available power per bar. The increased power and the reliability of the devices were constantly improved at the same time. Today the reliability is often still limited by the distribution of the stress induced by the packaging process. In order to improve the reliability, as required especially for space applications, a better understanding of the failure mechanisms is needed.

The performances of laser diode bars are now limited by the degradation at the individual emitter level and a wide range of experimental techniques can be used for individual emitter degradation analysis

(Micro-Photoluminescence Spectroscopy, Photo-Current Spectroscopy, Laser beam Induced Current, Photo-Current Microscopy). Aging tests have shown the presence of different degradation signatures for a number of emitters. We have demonstrated that the degradation of each individual emitter can be both correlated to their initial value of DOP and the centre emission wavelength. Especially emitters presenting dislocation defects after aging, the so-called "V-defect", as seen on output facets could be in relation with a weak DOP and a red-shift of the optical spectrum before occurrence of the V-shaped defects [17].

These results are also correlated with DOP-PL measurements from the McMaster set-up by recording the polarization characteristics of luminescence emitted by the device. Some complementary understanding elements are reported below on a single emitter from a 1 cm wide bar.

Figure 7 shows maps over areas of 400 µm by 115 µm of the DOP and ROP obtained from the facets of cm-bar lasers that were bonded to heat sinks. The predominant features in the maps owe to the interaction of the bonding and fabrication strain with the grooves that isolate the emitters. An offset caused by the bonding strain has been removed. Figure 8 shows the results of fitting FEM simulations to the data shown in Fig. 7. The boundary conditions that were used to match the data of Fig. 7 are consistent with strain owing to the metal in the emitter regions.

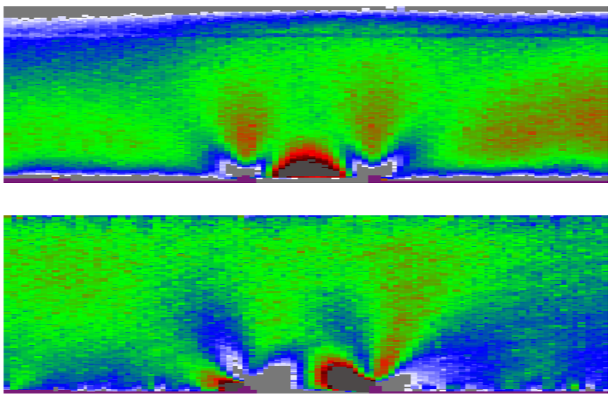


Fig. 7: Measured DOP (top) and ROP (bottom) from the facet of a bonded cm-bar laser.

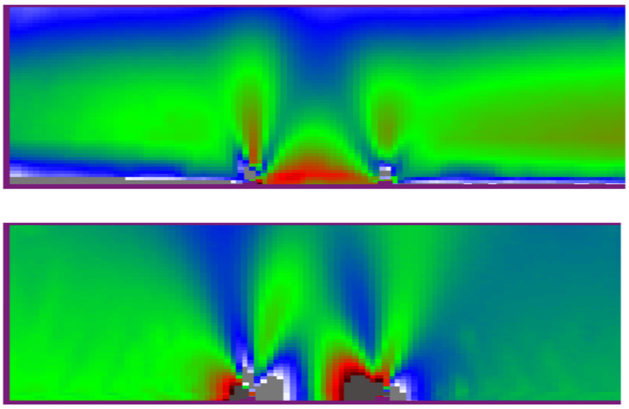


Fig. 8: FEM fits to the data of Fig. 7

Bonding tool planarity can have an effect [18]. It was noted in DOP measurements that the DOP of the top surface was asymmetric. The asymmetry followed the bonding tool. When the tool was rotated 180 deg, the asymmetry in the DOP rotated 180 deg. This effect is expected to become more prominent as the lengths of chips become longer. The explanation, which is consistent with SEM measurements and FEM simulations, is that the tool is not perfectly parallel to the bonding surface. As a result, one end of the chip has a thicker solder layer than the other end and there is a bend in the mid section of the chip. By a careful optimization of the packaging process an improved homogeneity of the strain field should be achieved, with perhaps an improvement in device reliability and operation.

IV. Conclusion

The degree of polarization (DOP) of luminescence is a function of the mechanical strain in III-V materials and devices. Estimates of the strain in III-V materials and devices can be obtained by analysis of the measured degree of polarization over a surface of the material or device. The analysis can take the form of symmetry arguments, of comparison to results obtained from simple calculations using elasticity theory, or from least squares fits of FEM simulations to the data.

Since the reliability of III-V lasers depends on strain, and the operation of III-V devices can be altered via the photoelastic effect with strain, DOP measurements should be useful in identifying the processes that affect strain and hence impact the reliability and the operation of III-V devices.

Acknowledgment

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REFERENCES

[1] M. Oudart, J. Nagle, J.W. Tomm, S. Bull, and E.C. Larkins, “Failure prediction of high-power laser bars” in *Quantum Well Laser Array Packaging*, J.W. Tomm and J. Jiménez, eds (McGraw-Hill, New York, 2007), pg. 246.

[2] D.Lisak, D.T. Cassidy, and A.H. Moore, “Bonding stress and reliability of high power GaAs-based lasers”, IEEE Trans. Components and Packaging Technologies vol. 24, no. 1, pp.92-98, 2001.

[3] S.-L. Chuang, A. Ishibashi, S. Kijima, N. Nakayama, M. Ukita, and S. Taniguchi, "Kinetic model for degradation of light emitting diodes”, *IEEE J. Quantum Electron.* Vol. 33, no.6, pp. 970-979, 1997.

[4] S.K.K. Lam, R.E. Mallard, and D.T. Cassidy, "Analytical model for saturable aging in semiconductor lasers” *J. Appl. Phys.* vol. 94, n° 3, pp. 1803-1809, 1990.

[5] D.T. Cassidy, S.K.K. Lam, B.Lakshmi, and D.M. Bruce, "Strain mapping by measurement of the degree of polarization” *Appl. Opt.* vol. 43, n° 9, pp. 1811-1818, 2004.

[6] P.D. Colbourne and D.T. Cassidy, “Observation of dislocation stresses in InP using polarization-resolved photoluminesence”, *Appl. Phys. Lett.*, vol. 61, no. 10, pp. 1174-1176, 1992.

[7] P.D. Colbourne and D.T. Cassidy, “Dislocation detection using polarization-resolved photoluminescence”, Canadian J. Phys., vol. 70, pp. 803-812, 2002.

[8] P.D. Colbourne and D.T. Cassidy, “Imaging of stresses in GaAs diode lasers using polarization-resolved photoluminescence”, *IEEE J Quantum Electron*., vol. 29, no. 1, pp. 62-68, 1993.

[9] J.-P. Landesman, D.T. Cassidy, J.W. Tomm, and M.L. Biermann, “Strain measurement” in *Quantum Well Laser Array Packaging*, J.W. Tomm and J. Jiménez, eds (McGraw-Hill, New York, 2007), pg. 102.

[10] M.A. Fritz and D.T. Cassidy, “Extraction of bonding strain in diode lasers from polarization-resolved photoluminescence measurements”, *Microelectronics Reliability*, vol. 44, pp. 787-796, 2004.

[11] M.A. Fritz and D.T. Cassidy, “Photoelastic effect from die bonding of diode laser”, *Appl. Opt.*, vol. 43, no. 1, pp. 160-166, 2004.

[12] S.K.K. Lam, D.T. Cassidy, and R.E. Mallard, “Characterization of SiOx/Si/SiOx coated n-InP facets of semiconductor lasers using spatial resolved photoluminescence”, *Jpn. J. Appl. Phys*., vol. 44, no. 11, pp. 8007-8009, 2005.

[13] J.W. Tomm, J. Jiménez, M. Oudart, J. Nagle, E.C. Larkins, and S. Bull, “Degradation modes and related defects in high-power lasers bars” in *Quantum Well Laser Array Packaging*, J.W. Tomm and J. Jiménez, eds (McGraw-Hill, New York, 2007), pg. 351.

[14] P.D. Colbourne and D.T. Cassidy, “Bonding stress measurements from the degree of polarization of facet emission of AlGaAs superluminescent diodes”, *IEEE J Quantum Electron*., vol. 27, no. 4, pp. 914-920, 1991.

[15] B.W. Hakki, P.E. Fraley, and T.F. Eltringham, “1.3 μm laser reliability determination for submarine cable systems”, *AT&T Technical Journal*, vol 64, no. 3, pp. 771-807, 1985.

[16] M.A. Fritz and D.T. Cassidy, “Cooling rate in diode laser bonding”, *IEEE Trans. Comp. Packag. Technol.*, vol. 27, no. 1, pp. 147-154, 2004.

[17] O. Rehioui, L. Bechou, T. Fillardet, A. Kohl, D.T. Cassidy, Y. Deshayes, Y.Ousten, G. Volluet, and H. Moisan, “Benefits of individual emitter electo-optical characterizations in packaged high power laser diode bars for space applications”, International Conference on Space Optics, 14-17 October 2008, Toulouse, France.

[18] G.B. Morrison, D.T. Cassidy, J.E. Johnson, M. Sipics, H. Wang, and R. Wolf, “Bonding-induced strain effects in InP DFB components soldered p-side-up on AlN substrates”, *IEEE J. Quantum Electron.*, submitted for publication October 2008.