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Scalable, High Power Line Focus Diode Laser for Crystallizing of Silicon Thin Films

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Invited Paper

Abstract

We present the design and performance of a diode laser module producing a high intensity line focus at 808 nm for material processing. The design is based on a linear array of 7 laser bars and beam forming optics featuring a micro-optic homogenizer. The module delivers a total output power of 900 W at 140 A and peak intensity created in the focus area of 10.3 kW/cm^2. Two systems with line length of 5 cm and 10 cm at a large working distance of 110 mm have been realized. The chosen concept allows scaling in length by joining multiple modules which is of interest for material processing in industrial applications. Application results from laser crystallization of amorphous silicon seed layers used in the fabrication of photovoltaic cells for solar panels are given.

Keywords: Laser diode; line focus; homogenizer; optics; laser crystallization; amorphous silicon; photovoltaic; material processing;

1. Introduction

Laser systems based on the direct use of laser diodes are gaining more and more attractiveness due to their advantages in performance, size and cost.

With fiber coupled power levels ranging from 4 to 10 kW at a corresponding beam quality of 30 to 100 mm mrad direct diode laser systems are now targeting applications like cutting and key hole welding previously mastered by solid state laser systems [1]. This largely has been enabled by the steady improvements in performance [2] with laser diode bars in the 9xx nm wavelength range now being rated at 200W and beyond for long term operation [3].

However, many applications do have special requirements. Area processes like crystallization of amorphous silicon targeting efficiency improvements in solar cells are aiming for scalability of the laser focus from millimeters

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to meters while maintaining medium power densities in the range of 5-20 kW/cm^2. Due to the reduced absorption of Silicon at long wavelengths the best trade-off between direct diode power and absorption is around 800 nm.

In this work we will present a high power laser diode head with scalable line focus. Due to the improvements in chip performance at 800 nm wavelength described in paragraph 2 and the use of water cooled microchannel heatsinks highest power per unit length are enabled. Eliminating the need for spatial multiplexing of laser bars in the vertical (fast axis) direction is seen as a significant way to reduce cost of direct diode systems. The design of the optical train and the efficient homogenization of the beam are described in paragraph 3. The performance of the laser diode head and the application results are summarized in paragraph 4 and 5. A summary concludes this communication.

2. Laser diode sources

2.1. Chip technology

The high power laser bars presented in this publication are based on Al(In)GaAs laser structures. This material system allows for a flexible design of the waveguide and the doping profiles enabling best optical, electrical and thermal performance. Careful optimization of mode distributions and doping profiles yielded Oclaro's high efficient Al(In)GaAs based laser structures, emitting in the 800 nm wavelength range.

From these wafers various multi element laser bars are processed using the Oclaro high volume and quality process technology [4] and the E2 facet passivation technology providing maximum protection from chip fails due to catastrophical optical mirror damage (COMD) [5]. Cavity length ranges from 1.8 to 2.4 mm depending on desired operation power and is optimized for best power conversion efficiency (PCE) at the given condition. According to the application, whether high brightness or high power operation is intended, the filling factors are varied from 30% to 80%.

2.2. Assembly technology

The most relevant specification for the assembly for a line generator application is a low bow of the bar in the final configuration of below 1 µm peak to valley, owing to the requirements of the fast axis collimation optics. Because of the high output power of the device and the mechanical rigidness required a hard solder assembly approach is chosen [6]. In order to match these requirements together an expansion matched heat sink is required, where in this case an expansion matched micro channel cooler design is used allowing the direct attachment of the laser bar to this heat sink.

Figure 1 shows a typical bow measurement for a 10 mm wide laser bar (mid) on micro channel cooler (left) as well as the distribution for 21 devices of the final configuration (right). The mean of the distribution of 0.65 µm and the narrow standard deviation demonstrate that the chosen assembly design is suitable for the application.

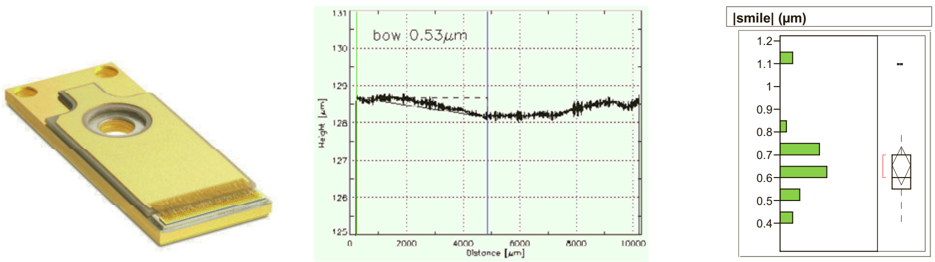

Fig. 1. Left: Bar on expansion matched microchannel cooler. Mid: Bow measurement of a 10 mm wide laser bar. Right: Distribution of the bar bow (smile) of 21 devices with a mean value of 0.65 µm.

Primary requirement for a high operation output power is the control of the thermal management of the device, where the key parameter to reduce the thermal load on the assembly is the electrical to optical power conversion efficiency of the semiconductor. The efficiency improvement achieved by the careful optimization of the epitaxial design is demonstrated in Figure 2 on the basis of a 19 element 30% filling factor bar on a passive assembly. Even though the cavity length of current design (solid line) is increased by 50% over the previous work (dashed line) to efficiently remove the heat load, the differential efficiency is improved by close to 10% to 1.3W/A with the operation voltage reduced at the same time. As a consequence the overall power conversion efficiency of the device is increased by 6% absolute to almost 60%.

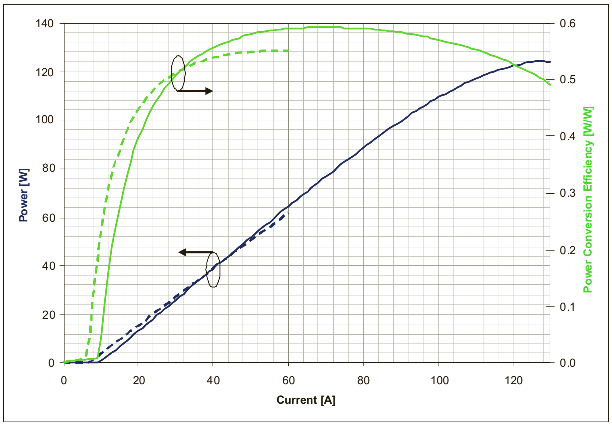

Fig. 2. Power (left scale) and power conversion efficiency (right scale) as function of drive current for previous chip design (dashed line) and this work (solid line). Differential efficiency and power conversion efficiency have been improved by careful optimization of the epitaxial design.

The application of the highly efficient epitaxial design to a device designed for the high power line source is shown in Figure 3: The 50% filling factor device mounted on a micro channel cooler can be operated at output powers in excess of 180 W and is suitable for reliable operation in the package at 140 W output power.

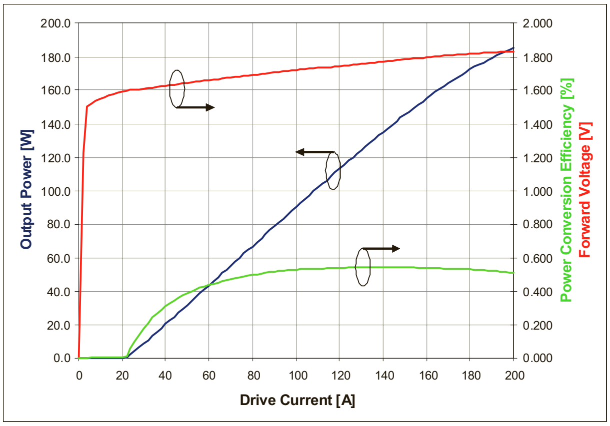

Fig. 3. Power (blue), voltage (red) and power conversion efficiency (green) vs. drive current of a 50% filling factor 808 nm bar on micro channel cooler at 25° C water temperature.

2.3. qCW Application

Further developments based on the presented chip technology are targeting qCW operation at 500 W output power. Epitaxy and device design are further optimized to enable higher output powers while maintaining the high efficiency, while resonator length, filling factor and assembly were maintained from the previous devices. The characteristics of the qCW adapted device operated at 500µs long pulses with 15 kHz repetition rate are plotted in Figure 4 (left). A maximum power of 592 W and a maximum power conversion efficiency of 60% are achieved. The differential efficiency of this device is 1.37 W/A at 30 °C base plate temperature.

The output power of 592 W corresponds to a power density at the facet of 73 mW/µm for this device. Previously, power densities of 88 mW/µm were achieved under CW operation conditions optimized for heat removal [7]. The highest power density we achieved for this kind of device was obtained for a bar with 30% filling factor (Figure 4 - right). This device reached 290 W output power at 260 A drive current operated under 500 µs pulse width. The corresponding power density is 101 mW/µm indicating peak output powers in excess of 800 W are achievable with high filling factor bars at 808 nm.

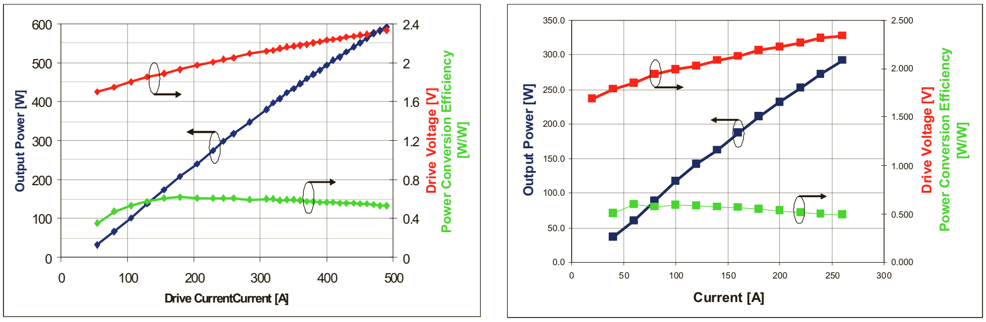

Fig. 4. Output characteristics power (blue), voltage (red) and power conversion efficiency (green) vs. drive current of two lasers with different vertical designs optimized for high facet power density. The left plot shows the result for an 80% filling factor bar reaching 592 W output power (500µs pulse length, 15 Hz repetition rate, 30°C heat sink temperature). The plot on the right shows a 30% filling factor device that can be operated up to 290 W output power at 500µs at 20 Hz representing an even higher power density.

3. Optical design

The general design approach is shown in Figure 5. The optical power is generated by an array of broad area laser bars, LBA. Each laser bar is collimated in the fast axis direction by a micro-optic cylindrical lens (FAC). Slow axis collimation is not applied. The thus shaped output of the laser bar array propagates to the input plane of a so-called imaging homogenizer [8,9,10]. This arrangement consists of a specially designed micro-optic lens array (MLA) and a cylindrical macro lens, denoted the Fourier lens (FL). The cross-sections of the homogenizer and the Fourier lens do not depend on the y-coordinate; hence they only act in the lateral directions. The corrugated front surface of the homogenizer decomposes the laser bar array output into a large number of beamlets, each having the same lateral divergence 2β (the vertical divergence is not affected and given by the FAC). The back surface of the homogenizer in combination with the Fourier lens defines an optical system that superimposes the images of all beamlets in the so-called homogenization plane (HP) coinciding with the front focal plane of the Fourier lens. The lateral extent of this image, defining the length of the line focus, is given by

$$L = 2 f_{FL} \tan(\beta) \quad (1)$$

with f_{FL} the focal length of the Fourier lens. Thus the design of the Fourier lens allows for scaling of the individual laser array. A further cylindrical lens, the Fast Axis Focusing lens (FAF), is used to vertically concentrate the line focus in the homogenization plane.

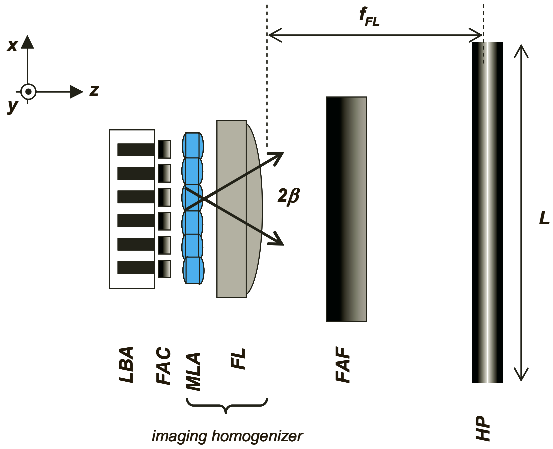

Fig. 5. Schematic outline of the optical system. LBA=laser bar array, FAC=fast axis collimation lens, MLA=micro optic lens array (homogenizer), FL=Fourier lens, FAF=fast axis focussing lens, HP=homogenization plane. L = length of the line focus. f_{FL}=focal length of FL. 2β is the lateral divergence of the beamlets formed by the front surface of the homogenizer.

The final vertical width of the beam of an individual laser bar depends on a number of factors: the near field characteristics of the laser bar, the optical magnification provided by the FAC and FAF lenses, the planarity of the laser bars ("smile"), and the imperfections related to the FAC lens and the assembly process.

A) The combination of the FAC lens and the FAF lens generates a fast axis magnification of 44 in the line focus position. A typical near field spot size in the fast axis of the laser diode with 1 µm diameter will result in a line width of 44 µm in the working plane of the system.

B) As described earlier, the smile of the laser bars can be designed to amount to less than 1 µm. From the magnification of the laser bar geometry, the contribution of smile to the linewidth of the laser bar is approximately of the same order as the vertical nearfield dimension, i.e. 44 µm.

C) Imperfections of the lens design and the beam being not completely diffraction limited result in an additional broadening of the linewidth. An image of an individual laser bar consisting of 25 emitter is depicted in

Figure 6 illustrating the situation.

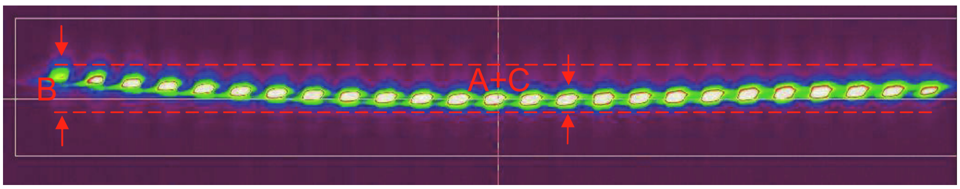

Fig. 6. Image of an individual laser bar consisting of 25 emitters illustrating the individual contributions for linewidth broadening: Magnification (A), Smile (B) and Optical Imperfections (C). For this picture no homogenizer is used.

Figure 7 shows an example of a typical individual laser diode bar with a line width in the focus position of ~165 µm given by the sum of the vertical spot size, the smile and the distortion through the optical elements.

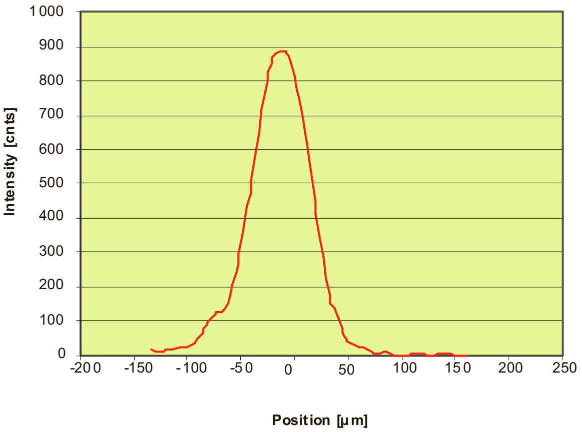

Fig. 7. Typical example for the integral linewidth (165 µm) of an individual laser bar

4. Laser head with line focus

The optical train described in the previous paragraph is integrated in a compact housing with mechanical dimensions (LxWxH) of 277 x 99 x 36 mm (w/o electric pins) resulting in a size of less than 1000 cm^3. Each laser head includes a linear array of seven laser diode bars. Due to the scalable design of the laser head and the high power laser bars that have been used two different laser lines with 10 cm and 5 cm line width have been realized.

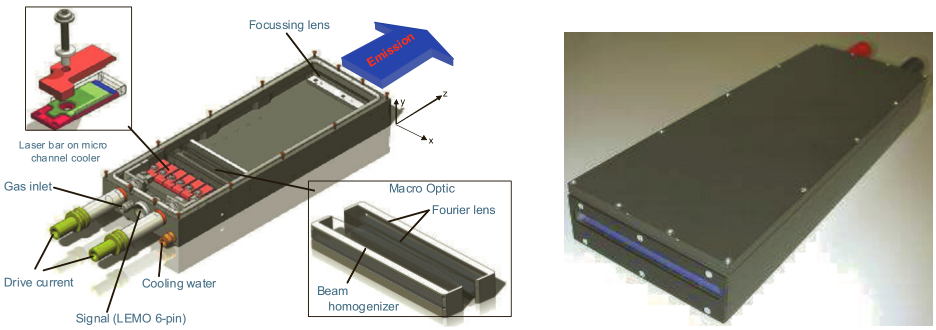

Fig. 8. Compact 1000 cm^3 laser head with line focus.

900 W of optical output power at 808 nm wavelength has been obtained at a drive current of 140 A (Figure 9). The focal plane of the system is located 110 mm in front of the laser head allowing a remarkable large working distance. For the 10 cm wide line, the peak power density in the homogenizing plane amounts to 6 kW/cm^2 at a line width of 250 µm full width at $1/e^2$ intensity. For 5 cm laser line the peak power density has been further increased to

10.3 kW/cm^2 at 140 A drive current. The intensity pattern in Figure 10 shows good homogenization of the seven laser diode bars with a ripple of +/-3% rms at 120A drive current.

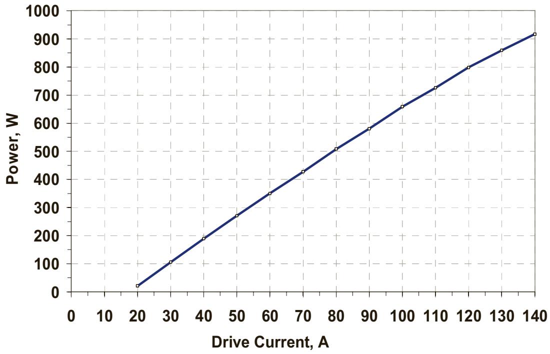

Fig. 9. Output power as function of operating current for a collimated laser head.

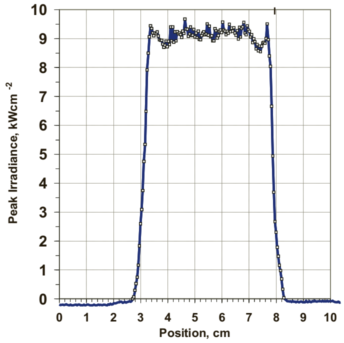

Figure 10: Slow axis intensity distribution at 120A

In this case the line width amounts to 400 µm full width at 1/e^2 intensity. A 2-dimensional intensity plot is shown in the insert of Figure 11 indicating multiple lines. A more detailed analysis through the imaging of the beams from each of the individual laser bars reveals excellent geometrical alignment for four of the seven laser bars. With corrected overlay a line width of 250 µm is expected with the peak intensity increasing to 12-15 kW/cm^2. Further work will also address the geometrical overlay of the laser lines generated by multiple laser heads to increase power density or to extend the length of the laser line.

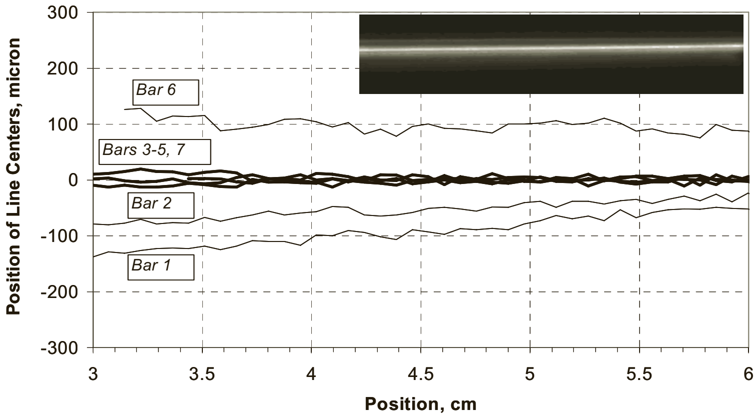

Fig. 11. Geometrical location of the peak intensity of the seven individual laser bars (main figure) and 2-dimensional intensity profile of the complete laser line generated from all seven laser bars (insert).

5. Application

For various applications, e.g. thin film solar cells, multicrystalline silicon thin films on glass are required [11]. These films should have grain sizes exceeding the film thickness of 100 nm to 2 µm by far. Therefore grains above several 10 µm are preferred. Diode laser crystallization is an interesting method to prepare these films by crystallization of amorphous silicon films (a-Si) via the melt [12, 13]. This is an industrially viable method on large areas, e.g. for solar cells. The excimer laser crystallization method already established for flat panel displays leads only to grains below 1 µm in size. This is due to the short pulse duration of several 10 ns which leads to a rather high cooling rate after the pulse so that the melt gets undercooled by several 100°C and extremely high nucleation rates of crystallites follow. As a consequence small grains below 1 µm in size are generated.

By the diode laser crystallization method a line focus 100 to 500 µm in width is scanned across the a-Si film at rates between 0.5 to 5 cm/s to melt the a-Si material. This leads to an irradiation time in the ms range so that an appreciable part of the energy heats the surface region of the glass substrate. Due to that the cooling rate in the melt is relatively slow and a low nucleation rate results and large grains in the 100 µm range are generated. However, the wavelength of diode lasers is not well absorbed by silicon. One has to use the shortest available wavelength near 800 nm. The thickness of the films has to exceed about 100 nm in order that enough of the light is absorbed. Moreover, interference effects are important so that the exact film thickness is crucial. To avoid cracks in the glass substrate and in the film some preheating is required. The precise temperature depends on the softening point of the glass used. This preheating is also helpful by increasing the absorption of the laser light in the silicon film.

Figure 12 shows as an example an optical micrograph of a 480 nm thick silicon film after diode laser crystallization. As a substrate 3.3 mm thick borosilicate glass (Schott borofloat 33) was used. The a-Si film was deposited by electron beam evaporation. Crystallization was performed by scanning the line focus of a 810 nm wavelength diode laser (line length 10 cm, line width about 250 µm) at a rate of 5.5 mm/s across the film. The maximum power density at the line center was 6.5 kW/cm². The substrate was preheated to 600°C. In the figure the scanning direction is vertical. As can be seen the crystallization leads to grains 50 to 200 µm in width and several 100 µm in scanning direction. TEM investigations [12] showed a rather low number of extended defects such as dislocations.

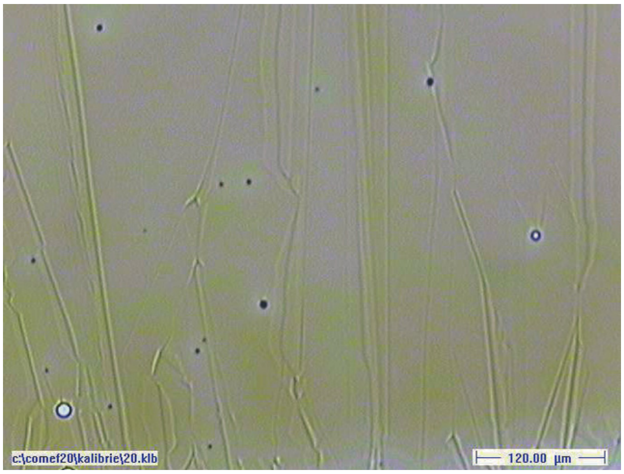

Fig. 12. Diode laser crystallized silicon layer on glass.

6. Conclusion

A scalable high power line focus diode laser for crystallizing of silicon thin films has been demonstrated. A cost effective path to direct diode material processing is the use of one-dimensional laser bar arrays enabled by the high power bars developed for this application. The optical design and the beam homogenization have been discussed and the effectiveness has been demonstrated in a laser diode head and through the application in crystallization of amorphous silicon on glass for use in thin film solar cells.

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