

The Pennsylvania State University
The Graduate School
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BEAM DELIVERY SYSTEM FOR LASER FIRED CONTACT

A Thesis in
Electrical Engineering
by
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ABSTRACT

A Laser Fired Contact (LFC) is a contact through the dielectric layer between the silicon wafer and back-side conductor layer produced by a laser-based technique. Such a technique holds promise to dramatically reduce the overall manufacturing cost of silicon based solar cells. As part of a parallel effort to investigate and optimize LFC technology, the work presented here looks at different technologies that can be used as part of a LFC beam delivery system to meet the desired production throughput. Two beam splitting technologies, diffractive optical elements (DOE) and microlens arrays, were evaluated and corresponding results are presented. The beam splitting technologies were tested with a Q-switched 532 nm Nd:YAG laser to produce an array of LFCs simultaneously.

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Additionally, I would like to thank BP Solar for funding the project and my education for the past year. I hope what I have done will aid in the advancement of LFC production technology. The project itself was a great learning experience. It was amazing to be surrounded by so many intelligent minds.

Finally, I would like to thank my parents for their support throughout the years.

Chapter 1

Project Description

In spring of 2009, the Applied Research Laboratory at Penn State was awarded a three year contract named “Investigation and Optimization of Laser Fired Contacts” by BP Solar. The contract was to take an in-depth look at laser fired contact (LFC) technology to develop optimal processing parameters, novel assessment techniques and rapid manufacturing processes.

For the first two years, the project was to be divided into two separate parts working in parallel with each other. At the third and final year, the two parts will be brought together to develop a prototype system for use at a manufacturing plant. Please refer to Section 4 of the project proposal¹ for detailed statement of work and timeline.

The first part, “Evaluation of Laser-Material Interactions, and Process Optimization”, seeks to find the optimal processing parameters that will produce the most desirable LFCs through the following steps:

1. Vary process parameters and system characteristics to optimize process conditions.
2. Employ material characterization techniques to evaluate the LFCs and to understand the relationship of laser processing conditions and efficiency.
3. Design test structures for electrical characterization of LFCs and surrounding Si quality.
4. Fabricate and characterize electrical test structures.
5. Fabricate and characterize PV cell with LFCs. [1]

¹ The project proposal is proprietary. Access to ARL network is required in order to view the document. The file is located at \\BP Solar\Administrative\Proposal - 2008-09\BP Solar Laser Fired Contacts White Paper - Final - 2008-10-03.pdf.

There are two students working together on this part, one responsible for steps 1-2 and the other responsible for steps 3-5.

The second part, “Laser Fired Contact Manufacturing Technology Development”, seeks to develop a rapid manufacturing process for producing LFCs through the following steps:

1. Design, build, and evaluate diffractive optics and other novel automation and beam delivery techniques to improve manufacturing processes. (this thesis)
2. Investigate process monitoring techniques, such as high speed video and capture of spectral process emissions, for quality control and as a means of gaining understanding of the process physics. [1]

There is only one student working on this part. This student must work closely with the student responsible for steps 1-2 of the first part to ensure smooth combination in year three.

This thesis will summarize the work performed on the second part step 1 after the first year. The purpose of this thesis is to educate the reader so that he/she may continue the work where the author has left off. Hyperlinks as well as e-mails are provided throughout. Although these have a potentially short shelf life, they are presented in hopes that they are useful for students following up on this research in the near future.

1.1 Silicon Solar Cell

It is necessary to have a basic understanding of how a solar cell works. As shown in Figure 1-1, a typical LFC based silicon solar cell consists of a front surface junction, or emitter region, for carrying the excited electrons to the load, an anti-reflective coating to help capture the maximum amount of sun light by minimizing reflection, a p-n junction,

or base region, for converting photons into excited electrons, a passivation layer for preventing spontaneous recombination of the holes, and a metal layer to complete the path to enable the excited electrons to recombine with the holes.

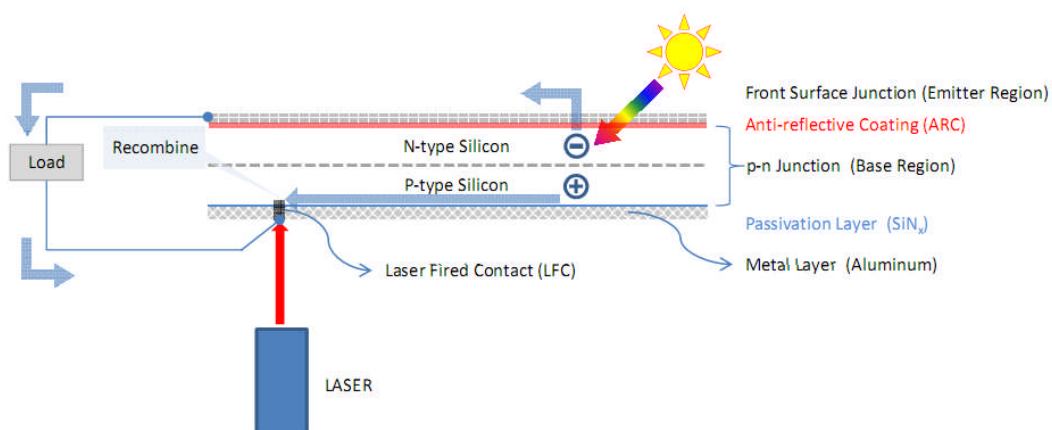


Figure 1-1. Silicon solar cell operation

In a typical LFC solar cell, the photons from sunlight hit the base region exciting the electrons and thus creating electron-hole pairs. Before they can recombine, the electric field in the p-n junction separates the electron-hole pairs forcing the electrons to migrate toward the front (emitter region) and the holes to travel toward the back (rear Al contacts). Then the electrons get carried off by the front surface junction and travel through the load. Finally, the electrons arrive at the backside LFCs to recombine with the holes to complete the circuit.

Please watch this 22 minutes video named “The Power of the Sun – The Science of the Silicon Solar Cell” produced by the University of California, Santa Barbara,

physics department (<http://www.youtube.com/watch?v=u0hckM8TKY0>)². Their website, <http://powerofthesun.ucsb.edu>, has a PowerPoint presentation of the video under “Instructional Materials” link.

1.2 Laser Fired Contact

As reported by Zhao et al [2, 3], surface passivation of PERL (passivated emitter, rear locally diffused) silicon solar cells have demonstrated cell efficiencies of nearly 25%. This is a significant improvement over traditional silicon solar cells where the backside metal layer is directly in contact with the heavily doped p-type silicon layer [1]. This achievement comes at the expense of added manufacturing complexity.

In an effort to reduce added manufacturing complexity while maintaining efficiency, Schneiderlöchner et al [4] proposed a new laser-based technique to create so called laser fired contacts. As shown in Figure 1-2, the traditional photolithographic process for manufacturing PERL silicon solar cells contains more steps than the proposed LFC process.

² This video is also located on the network at \\BP Solar\Beam Delivery\ZHua Work\Solar Cell\The Science of the Silicon Solar Cell.mp4.

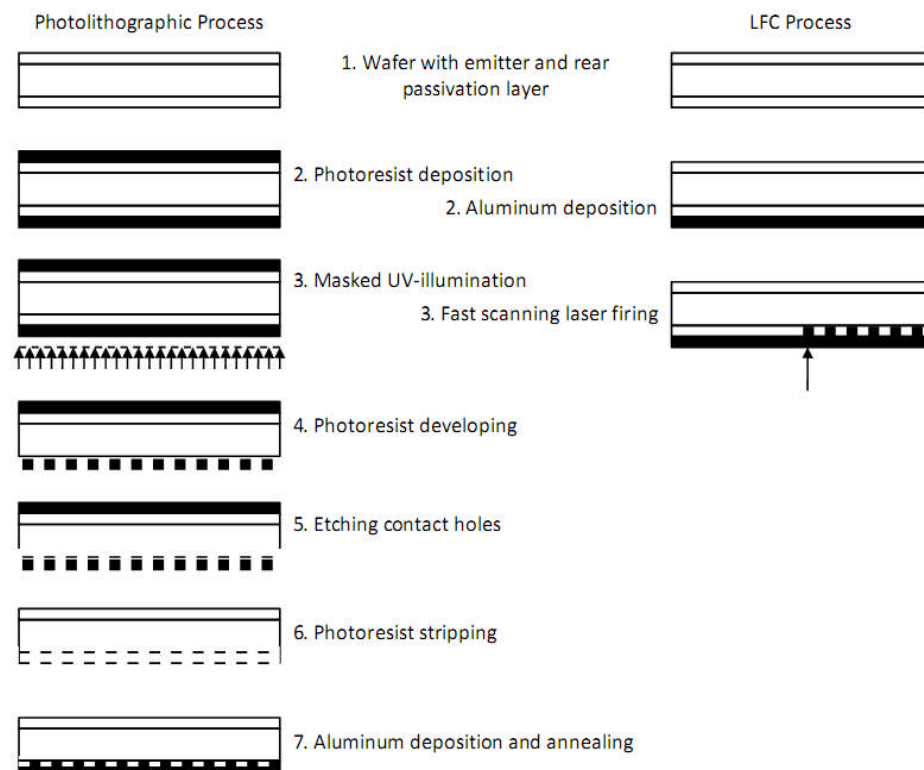


Figure 1-2. Photolithographic vs. LFC process [4]

On January 3, 2006, U.S. Patent No. 6,982,218, “Method of Producing a Semiconductor-Metal Contact Through a Dielectric Layer”, was issued by United States Patent and Trademark Office to Preu et al [5]. The patent contains a total of 16 claims with 1 independent claim and 15 dependent claims. Independent Claim 1 states:

“1. A method of electrically contacting a semiconductor layer coated with at least one dielectric layer, comprising: applying a metal layer on the at least one dielectric layer and temporarily locally heating the metal layer in a line or at a plurality of sites in a linear pattern or a plurality of sites in a dotted pattern on the semiconductor layer by means of a controlled source of radiation providing radiation to produce a local molten mixture consisting exclusively of the metal layer, the dielectric layer and the semiconductor layer at the line or at the linear pattern or at the dotted pattern to provide an electrical contact with controlled contact electrical resistivity between the metal layer and the semiconductor layer with the dielectric layer and the semiconductor layer being located directly

beneath the metal layer, which, upon solidification produces the electrical contact between the semiconductor layer and the metal layer of the controlled contact resistivity, and that both the surrounding dielectric layer and the semiconductor layer which are contacted are not changed by excessive heating during the local heating regarding the function thereof, beyond a region of the electrical contact.” [5]

In other words, the LFC process consists of first depositing a metal layer on top of the passivation layer of the silicon solar cell, then using laser to locally melt or diffuse the aluminum contact into the silicon base creating a p^+ alloy region.

1.3 System Requirement

Based on email communications with BP Solar, the required throughput in the production line is one wafer per second [6]. A processed wafer is defined as having 124×124 LFCs in a matrix pattern with 1 mm spacing between each other on a $125 \times 125 \text{ mm}^2$ area. This is not the required throughput for each machine. If a single machine cannot achieve this throughput, additional machines can be used in conjunction.

At the time of the project proposal, the estimated processing time per wafer can be calculated as follows:

$$(124 \times 124) \times 0.0001 \text{ sec} + 124 \times 0.050 \text{ sec} = 7.7 \text{ sec}$$

The first term 124×124 is the total number of LFCs required in a typical $125 \times 125 \text{ mm}^2$ cell. With a galvanometer system scanning at a speed of 10 m/s [7], the laser would have to operate at a pulse repetition frequency (PRF) of 10,000 Hz to ensure 1 mm spacing or 0.0001 seconds per LFC. The final term $0.050 \text{ sec} \times 124$ is the total acceleration and deceleration time exhausted for the galvanometer to switch between lines, 0.050 seconds

per line for a total of 124 lines [6]. The resulting 7.7 seconds per wafer means it will require 8 machines working in conjunction to achieve the desired throughput. It is desirable to reduce the number of machines required to achieve the desired production rate in order to reduce cost and complexity and improve system robustness.

1.4 Approach

Figure 1-3 shows a high level schematic of a proposed beam delivery system to meet the desired production rate. The system is divided into two parts: Beam Splitting and Scanning.

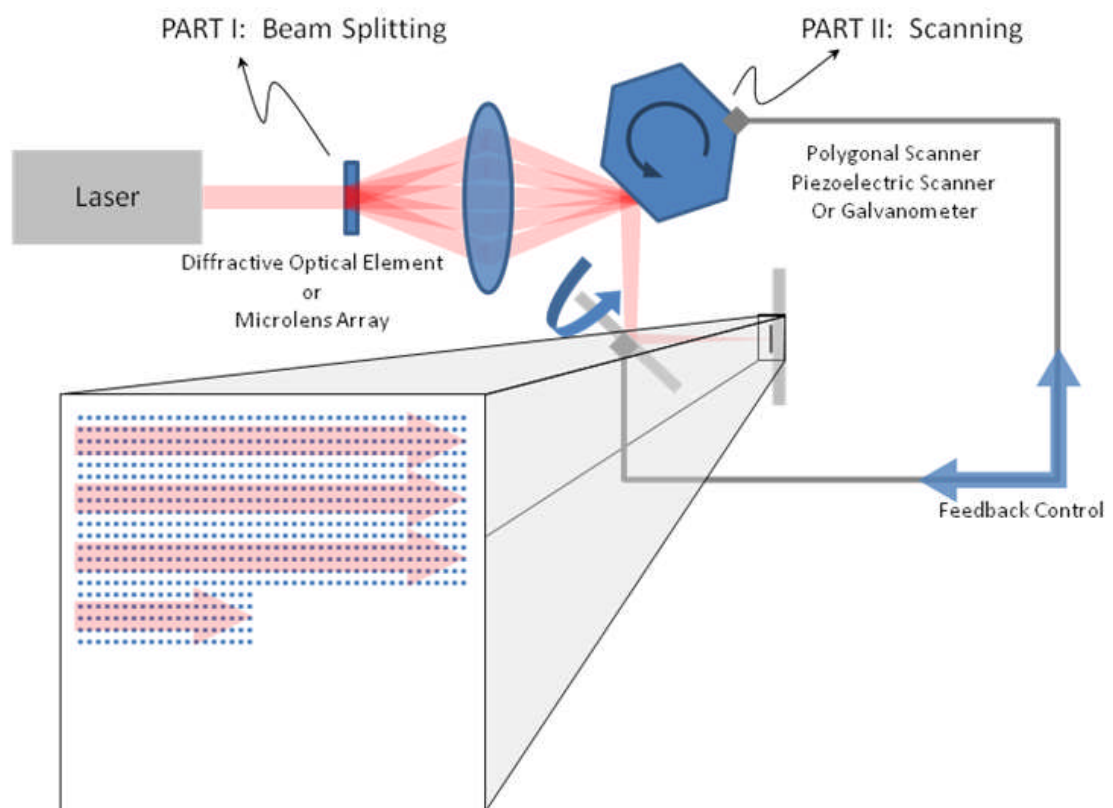


Figure 1-3. Proposed beam delivery system schematic

By splitting the input beam, PART I of the proposed system simulates the effect of having multiple machines given that the laser system can produce enough power. PART II of the proposed system utilizes different scanning technologies to further reduce the acceleration and deceleration time. For example, in the case of a polygonal scanner which guides the beam by rotating at a constant velocity, there is no acceleration or deceleration time.

Chapter 2

Beam Splitting

Two elements, a diffractive optical element (DOE) and microlens arrays, were evaluated as part of the beam splitting investigation. Since they are both microoptical elements, it is appropriate to first introduce microoptics.

“Microoptics: From Technology to Applications” by Jürgen Jahns et al. [8] classifies elements based on the different surface profiles as shown in Figure 2-1.

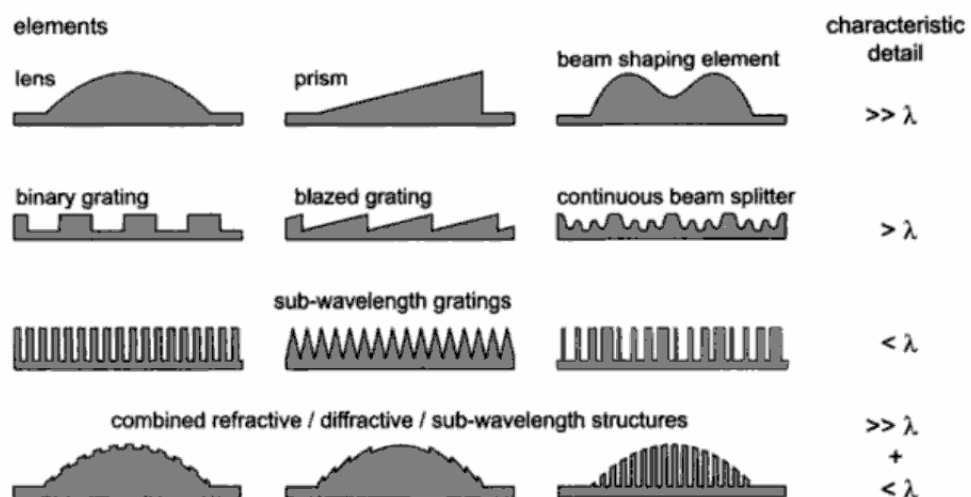


Figure 2-1. Profiles of optical elements [8]

From top to bottom, the first class consists of elements with characteristic details much larger than the wavelength of light. Since a geometrical optical approach is sufficient to design and model these elements, they are called refractive optics. Microlens arrays fall into this class of elements [8].

The second class consists of elements with characteristic details slightly larger than the wavelength of light. Since diffraction of light is the basis for the functionality of these elements, they are called diffractive optics. DOEs fall into this class of elements [8].

The third class consists of elements with characteristic details smaller than the wavelength of light. Since no propagating diffraction orders exist for normal incidence and the elements act as an effective medium, they are called artificial materials [8].

The forth class consists of elements that are the combination of all three classes mentioned above [8]. In addition, the referenced book contains detailed information regarding design, modeling, fabrication and application for the different classes of elements mentioned above.

2.1 Diffractive Optical Element

“Diffractive Optics: Design, Fabrication, and Test” by Donald O’Shea et al. [9] is a great reference book for learning about diffractive optical elements. For the interest of this project, it is necessary to review Chapter 1, 5 and 7 of the book.

Chapter 1 gives a brief introduction to the field and provides a description of the theoretical basis for the operation of diffractive optical devices. Chapter 5 introduces the design of diffraction gratings and gives an example of 1×3 grating analysis in detail. Finally, chapter 7 takes a detailed look at the most common fabrication method of diffractive optical elements: photolithographic fabrication.

2.1.1 Background

This section will review and discuss relevant literature listed in Table 2-1. Literature 1-3 from the list are referenced by the project proposal. Literature 3-5 from the list are all work published by Dr. Jun Amako of Seiko Epson Corporation. Amako has performed extensive work on using DOEs for manufacturing processes. Amako provided a custom diffractive beam splitter which will be discussed in the next section.

Table 2-1. Relevant literature on diffractive optical elements

	Title	Author
1	One step marking process with fiber laser and Diffractive Optical Elements	Estelle Clauss et al.
2	Periodic structures with arbitrary shapes recorded by multiple beam interference	Ch. Weiteneder et al.
3	Use of non-digitized diffractive optical elements for high-throughput and damage-free laser materials processing	Jun Amako et al.
4	Versatile light-control schemes based on diffractive optics for laser drilling, cutting and joining technologies for microelectronic and micromechanical components and devices	Jun Amako et al.
5	Direct laser writing of diffractive array illuminators operable at two wavelengths	Jun Amako et al.

“One step marking process with fiber laser and Diffractive Optical Elements” by Estelle Clauss et al. [10] proposes an alternative marking process over the traditional scanning processes using a high power near infrared fiber laser and DOEs. The authors present both simulation and experimental results using proposed alternative marking processes to demonstrate its feasibility. The main focus of the paper is surveying the

impact of varying both grating fill factor³ and laser power level on the quality of reconstructed images.

The authors stated there are generally two types of DOEs: the Fourier and the Fresnel type, corresponding respectively to the Fourier and Fresnel scalar diffraction approximations [10]. The DOEs considered for this project are Fourier type. They are phase-only elements which focus the diffracted waves in the far field. Hence a Fourier convex lens is required in combination with the DOE to bring the diffracted wave into the near field for processing. To evaluate the marking process, the paper presented simulated diffraction efficiencies using GSOLVER[®] software and marked four different encoded dot matrixes using a 1081 nm ytterbium doped IPG CW fiber laser, model YLR-200-SM-CW, on photograph paper as shown in Figure 2-2.

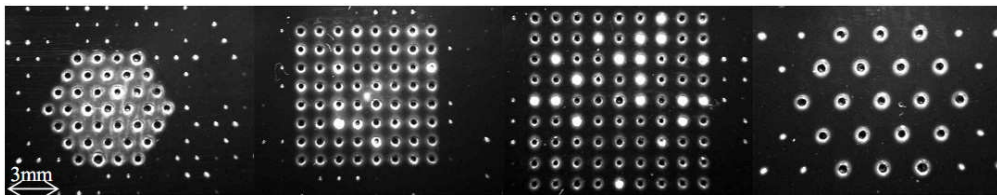


Figure 2-2. The four encoded dot matrixes reconstructed in the focal plane, laser power 83 W [10]

The authors observed that by increasing the fill factor, the number of points that can be marked increases. Moreover, the authors stated the total number of marked points can be adjusted by tuning the grating factor, the distance between marked points can be adjusted by tuning the focal length, and the size of the marked points can be adjusted by tuning the laser wavelength.

³ “Wavefront discontinuities that are due to structure depth. The efficiency is reduced by the amount of the ‘fill factor’, the ratio of the width Λ of the emerging beamlet to the grating period Λ .” See Reference 9. O’Shea, D.C., *Diffraction optics : design, fabrication, and test*. Tutorial texts in optical engineering. 2004, Bellingham, Wash.: SPIE Press. xii, 241 p.33

“Periodic structures with arbitrary shapes recorded by multiple beam interference” by Weiteneder et al. [11] proposes a multiple beam interference lithography method named Fourier synthesis for producing surface relief DOEs. The paper contained extensive mathematical derivations and theory regarding the proposed fabrication method, but it did not contain any information on using DOEs for beam splitting or materials processing. For the interest of the current project, this paper is not relevant.

“Use of non-digitized diffractive optical elements for high-throughput and damage-free laser materials processing” by J. Amako et al. [12] presents the advantages of using continuous surface-relief DOEs over their binary counterpart. From a series of comparison studies, the authors concluded that analog DOEs offer better performance than the binary DOEs in terms of light-use efficiency, SN^4 and fan-out uniformity when used as a beam splitter. It is important to note that for analog DOEs, the higher order diffraction orders are suppressed as opposed to the binary DOEs. However, because analog DOEs have a very small tolerance in fabrication errors, they are more expensive to manufacture than the binary ones. In fact, most vendors do not offer analog DOEs.

The authors designed the analog DOEs with a Fourier-iterative method and fabricated finished designs using laser direct writing technology. Two types of analog DOEs were designed, fabricated, tested and compared to their binary counterparts: Fourier type and Fresnel type. The authors differentiated the two types by their functionality: the Fourier type has only splitting function and the Fresnel type has both

⁴ SN – The ratio between the minimum of the fanout beam intensities and the maximum of higher-order diffraction intensities.

splitting and focusing functions. The Fresnel type elements' optical responses are less sensitive to fabrication errors than the Fourier type elements [12].

“Versatile light-control schemes based on diffractive optics for laser drilling, cutting and joining technologies for microelectronic and micromechanical components and devices” by J. Amako et al. [13] presents four laser-based processes implemented at authors' manufacturing plant: 1) laser drilling of silicon wafers for inkjet printers; 2) laser cutting of metal films for mobile phones; 3) laser soldering of quartz oscillators for wristwatches; and 4) laser sealing of packages for electronic components. The authors demonstrated use of DOEs can achieve high throughput while reducing cost in mass production processes.

Figure 2-3 shows two fundamental optical configurations for Fourier type DOEs used as beam splitters.

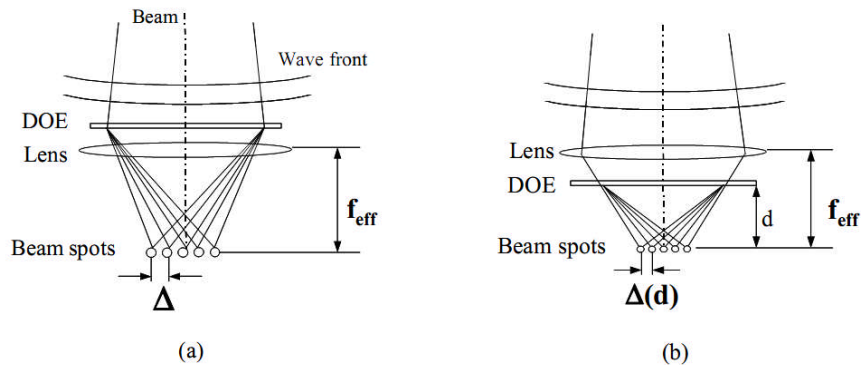


Figure 2-3. Optical configurations for diffractive optics [13]

To achieve maximum distance between beam spots “ Δ ”, the DOE is placed in front of the focusing lens as shown in Figure 2-3(a). This distance is given by

$$\Delta = \lambda f_{\text{eff}} / p \quad (1)$$

where λ is the wavelength, f_{eff} is the effective focal length of the beam delivery optics, and p is the grating period. If the DOE is placed behind the focusing lens as shown in Figure 2-3(b), then the distance between beam spots can be adjusted as a function of the DOE position on the optical axis, d given by:

$$\Delta(d) = \Delta d / f_{eff} \quad (2)$$

If an array of beam spots is scanned across the target plane to form scan lines, then the distance between scan lines drawn by two adjacent beam spots can be adjusted by rotating the DOE about its center given by:

$$\Delta(\theta) = \Delta \cos(\theta) \quad (3)$$

where θ is the rotation angle. The authors also noted that it is impossible to get rid of the 0th order beam completely due to fabrication errors. Therefore odd split element is the preferred choice since it incorporates the 0th order beam as part of the fan out beams. Since the 0th order beam stays on the optical axis despite diffraction, it can be used to align the diffracted beam spots [13].

“Direct laser writing of diffractive array illuminators operable at two wavelengths” by J. Amako et al. [14] presents DOEs that work at two different wavelengths. The DOEs were designed using simulated-annealing method and fabricated using direct laser-writing method. Specifically, the authors demonstrated 9-split DOEs with the same pitch for wavelength combinations such as 1064/532 nm, 1064/355 nm and 1064/266 nm.

2.1.2 Vendors

This section will review and discuss the DOE vendors listed in Table 2-2.

Table 2-2. DOE vendors

	Name	Phone	Web Address
1	MEMS Optical, Inc.	256-859-1886	http://www.memsoptical.com/
2	StockerYale Inc.	514-685-1005	http://www.stockeryale.com/
3	TESSERA	704-887-3154	http://www.tessera.com/
4	HOLOEYE Photonics	+49 (0) 3063923667	http://www.holoeye.com/

MEMS Optical, Inc. is a U.S. based microlens and DOE manufacturer. They offer custom design DOEs costing around \$20,000~\$25,000 for a single 8" fused silica wafer. Depending on the size of the DOEs, multiple elements may be obtained per wafer. The standard fabrication technique is photolithography. The procurement lead time, including design, is around 6-8 weeks. The cost per element will decrease with increase in order volume. A design report will be provided for every custom order. The sales representative contacted was Mary Beth Key. Her email address is mbkey@memsoptical.com and phone number 256-859-1886x141. Aside from custom design, the company also offers a catalog of stock products including diffusers, beam splitters, and refractive microlens arrays for testing purposes. The stock diffractive beam splitters cost \$500 each and are designed for 633nm wavelength only. Since the company focuses on custom designs, they do not maintain detailed information for the stock products. The customers can trade out stock elements with the company if necessary.

StockerYale, Inc. is a UK based microlens and DOE manufacturer. They offer custom design DOEs with limited capabilities. The sales representative contacted was Carlos Martinez. His email address is cmartinez@stockeryale.com and phone number 514-685-1005. This company cannot meet the demands of current project.

TESSERA is a U.S. based microlens and DOE manufacturer. They offer custom design DOEs costing around \$20,000~\$40,000 for a single 6" wafer. The custom design process includes first initiating a customer requirement document (CRD) which would commit all pertinent specifications to a document. Then non-recurring engineering (NRE) occurs for layout, development, and fabrication of custom DOEs, including fabrication of multiple prototypes. The first deliverable of NRE typically takes place 1-2 weeks after receipt of order, and includes CRD sign off and 30% payment of NRE fee. The second deliverable of NRE takes place 8-10 weeks after CRD sign off, and includes delivery of prototype parts and payment of NRE balance. The sales representative contacted was Heather Geddings. Her email address is hgeddings@tessera.com and phone number 704-887-3154. This company appeared to be well suited for this project. A preliminary specification sheet has been filed with the company.

HOLOEYE Photonics is a German based DOE manufacturer. They offer custom design DOEs costing around \$10,000 for a 50 mm diameter element. Dr. Andreas Hermerschmidt was the primary contact and is an expert in the field of DOEs. His email address is andreas.hermerschmidt@holoeye.de and phone number +49 (0) 3063923667.

2.1.3 Experimental Results

Two different DOEs have been procured and evaluated: one stock beam splitter DOE purchased from MEMS Optical, Inc. and one analog diffractive beam splitter (DBS) borrowed from Dr. Jun Amako.

The specifications provided by MEMS Optical, Inc. on the stock beam splitter DOE are listed in Table 2-3.

Table 2-3. Stock beam splitter DOE specifications

Part #	Material	Pattern	Full Angular Divergence	Efficiency	Wavelength
1006	Fused Silica	Line 5	0.8°	78%	633nm

The company could not provide additional information regarding the design of DOE, so SEM images as shown in Figures 2-4 to 2-6 were taken to determine more details. It revealed that the DOE is a binary element with approximate grating period of 180 μm .

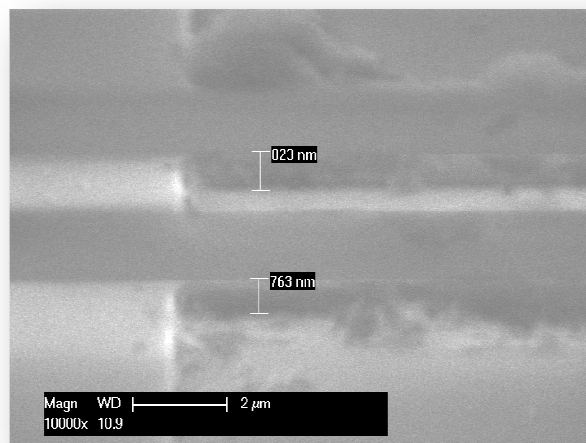


Figure 2-4. SEM image 1 of DOE

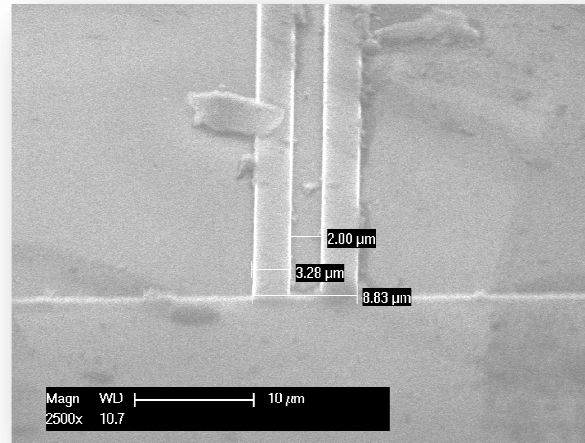


Figure 2-5. SEM image 2 of DOE

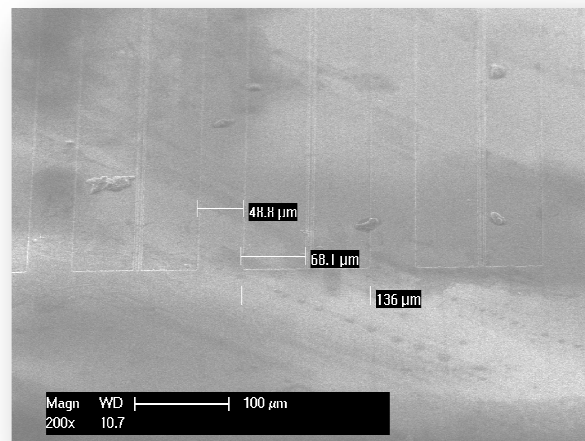


Figure 2-6. SEM image 3 of DOE

The full angular divergence can be calculated using the grating equation [9]

$$m\lambda = \Lambda \sin \theta_m \quad (4)$$

where λ is the wavelength of incident light, Λ is the grating period, and θ_m is the angle of diffracted order m . Using $m = \pm 2$ for a line 5 pattern, $\Lambda = 180 \text{ um}$ and $\lambda = 633 \text{ nm}$, the full angular divergence of the DOE is calculated to be 0.8° which matches the company specification.

The element is then modeled in the GSOLVER[©] software⁵ using the structure details from the SEM images. The resulting diffraction efficiencies at various wavelengths corresponding to commercially available lasers are shown in Figure 2-7.

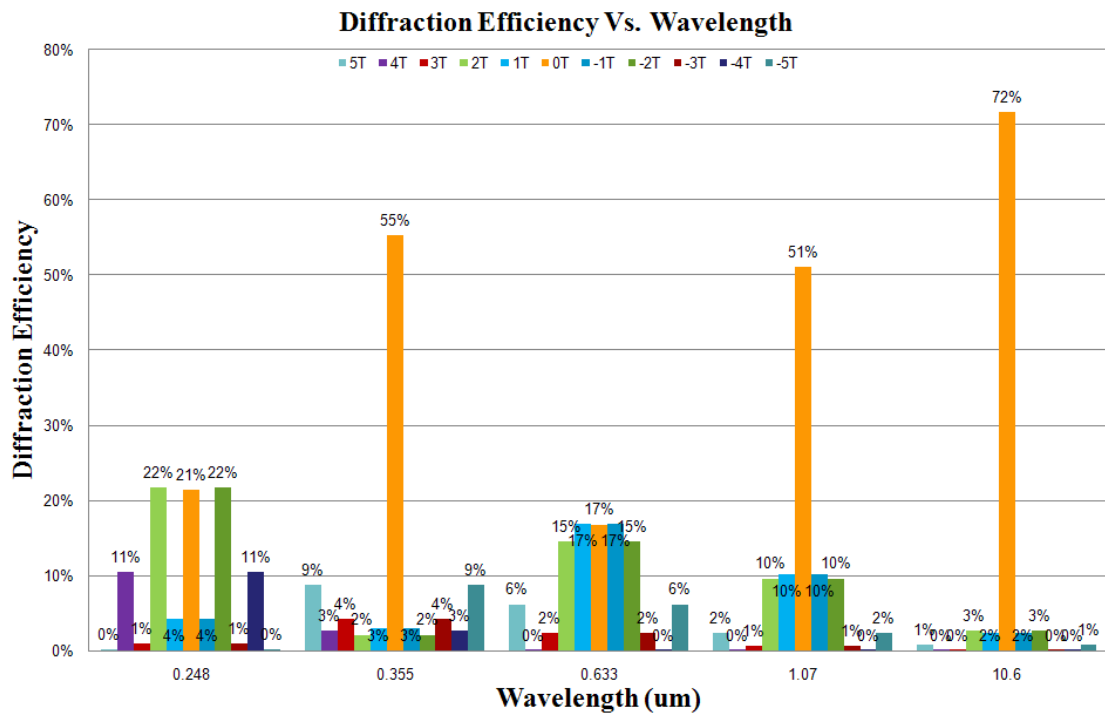


Figure 2-7. Diffraction efficiency vs. wavelength

At the design wavelength of 0.633 um, the diffraction efficiency split evenly across the center five diffraction orders matching the company specification. As expected, the 0th order beam dominates at different wavelengths such as 0.355 um, 1.07 um and 10.6 um.

⁵ ZEMAX[®] cannot model the DOEs correctly because its algorithm is based on ray tracing.

However, at 0.248 μm wavelength, the diffraction efficiency is spread evenly across 0 and ± 2 diffraction order rendering the DOE suitable as a line 3 beam splitter at this wavelength.

To evaluate the DOE's performance for processing LFCs, the optical setup as shown in Figure 2-8 was used.

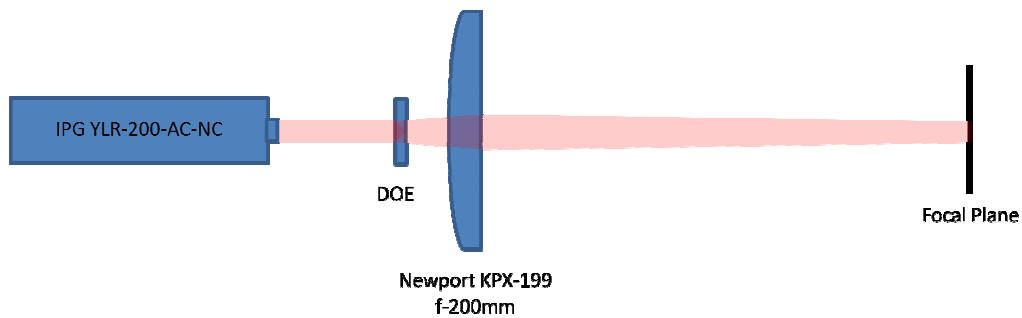


Figure 2-8. Optical setup for LFC processing with DOE

The laser beam from IPG YLR-200-AC-NC single mode fiber laser arrives on the DOE at normal incidence. A Newport KPX-199 f-200 mm lens was placed behind the DOE to focus the diffracted beams onto the wafer at the focal plane. The laser characteristics are listed in Table 2-3.

Table 2-4. IPG YLR-200-AC-NC specifications

Characteristic	Conditions	Min.	Max.	Test Results	Unit
Operation Mode				CW	
Tuning range of output power		10	110	10-110	%
Nominal output power	Setpoint = 100% CW	200.0		204.9	Watts
Maximum output power	Setpoint = 110% CW			225.7	Watts
Emission wavelength (λ_c)	Setpoint = 100% CW	1065.0	1080.0	1070.2	nm
Emission linewidth ($\Delta\lambda$)	Setpoint = 100% CW		4.0	3.6	nm
Beam diameter		6.95	7.65	7.17	mm
Beam waist diameter	w/f = 200mm	35	43.0	42.1	μm

Because the laser used for processing operates at 1070 nm wavelength and the DOE is designed for 633 nm wavelength, it will not perform according to the company's specifications. Using the grating equation, the DOE's full angular divergence for 1070 nm wavelength was calculated to be 1.36° . Compared to 0.8° at 633 nm, it is 1.7 times wider. Figure 2-9 shows a comparison between the marked spots using the 1070 nm laser and the focused aiming beam at 633 nm on Zap-it[®] paper.



Figure 2-9. Diffracted patterns for 1070 nm and 633 nm

As expected from calculated diffraction efficiencies of Figure 2-7, the 0th order beam dominates at 1070 nm causing a deeper burn than the rest of the marked spots.

Wafer type W1B as shown in Figure 2-10 was used for the experiment and the resulting LFCs with processing conditions are shown in Figure 2-11.

e-beam Al (0.5 μ m)
PECVD a-Si:H (100nm)
FZ p-Si wafer (375-525 μ m)
e-beam Al (0.5 μ m)

Figure 2-10. Description of wafer W1B

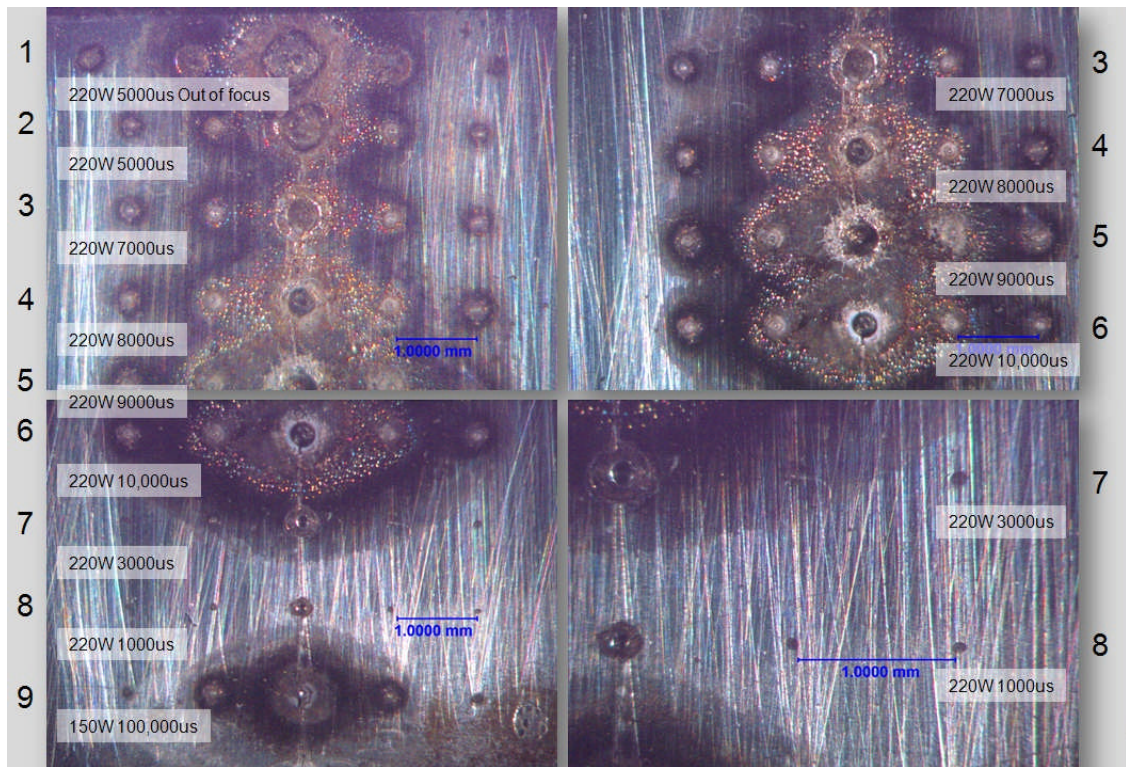


Figure 2-11. LFCs with corresponding processing conditions

The processing conditions are the laser output power and pulse duration for marking the corresponding LFCs. The top left image shows resulting LFCs from processing conditions 1-5, the bottom left image shows resulting LFCs from processing conditions 6-9, top right image shows resulting LFCs from processing conditions 3-6 and bottom right image shows resulting LFCs from processing conditions 7-8. Because the 0th order beam carries more than 50% of overall power, it ablated the most materials and shattered the wafer⁶. Nevertheless, processing conditions 8 showed that 1st and 2nd order diffracted beams with equal diffraction efficiencies produced similar LFCs as predicted with the GSOLVER[®] result. This supports that using DOEs at wavelength other than designed

⁶ The shattered wafer is not visible from the images because it was glued onto a base plate.

wavelength do not perform according to specifications, but marking multiple LFCs simultaneously using DOEs are possible if the DOEs are properly designed for the processing wavelength.

It is apparent from these results that a custom designed DOE is necessary to further the investigation. Dr. Jun Amako of Seiko Epson Corporation, he agreed to provide an analog diffractive beam splitter (DBS) for us to run some tests. Figures 2-12, 2-13, 2-14 and 2-15 are the DBS specifications.

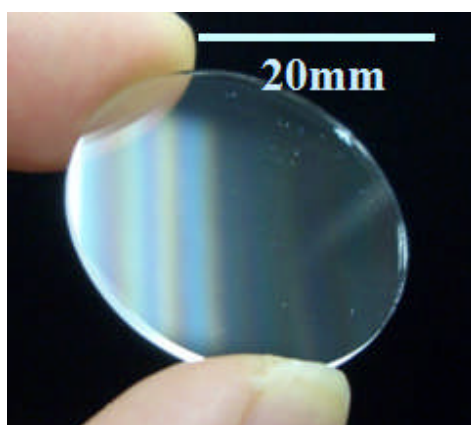


Figure 2-12. Diffractive beam splitter

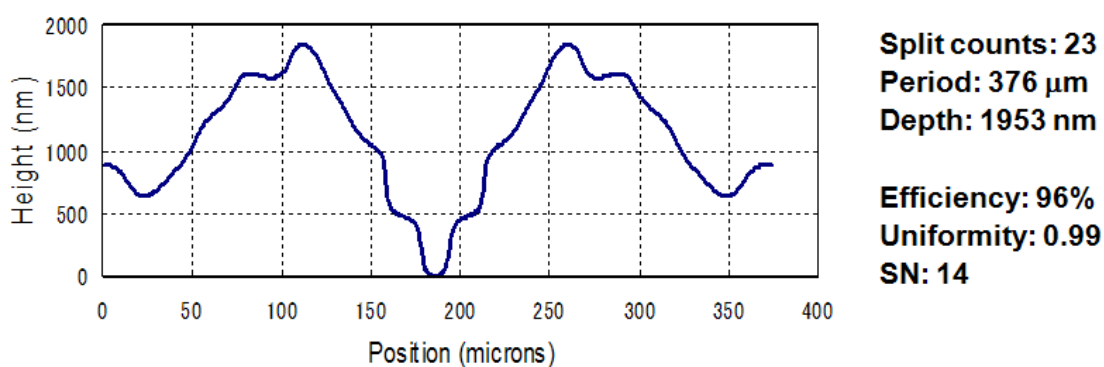


Figure 2-13. DBS designed profile⁷

⁷ Uniformity – Min. of arrayed beams divided by Max. of arrayed beams.

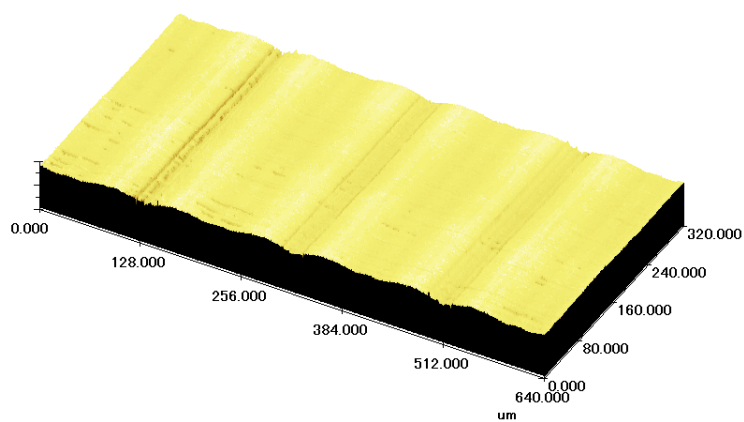


Figure 2-14. DBS measured profile

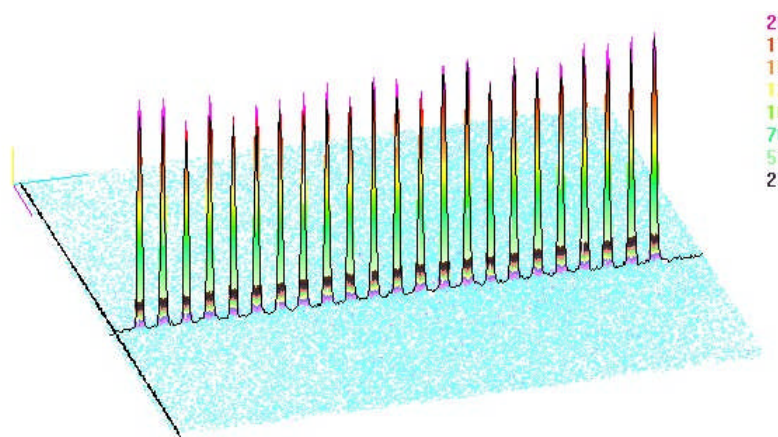


Figure 2-15. DBS measured intensity distribution

The DBS is designed to operate at wavelength of 532 nm and has a split count of 23. The optical setup as shown in Figure 2-16 was used to evaluate the DBS for processing LFCs.

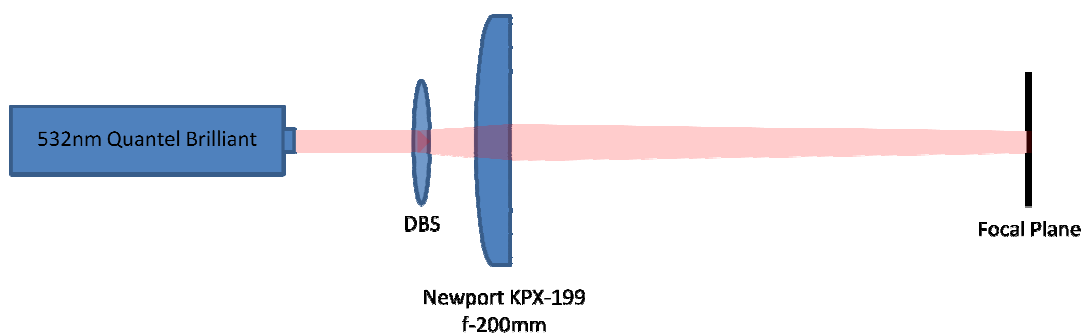
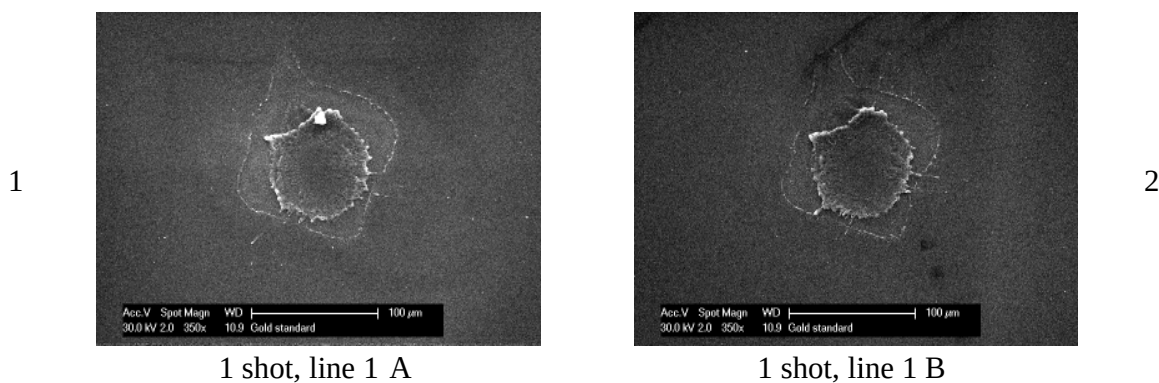
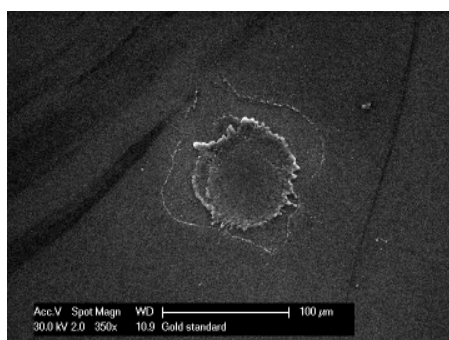


Figure 2-16. Optical setup for LFC Processing with DBS

The laser beam from the Quantel Brilliant Q-switched Nd:YAG laser arrives on the DBS at normal incidence. A Newport KPX-199 f-200 mm lens was placed behind the DBS to focus the diffracted beams onto the wafer at the focal plane. The Quantel Brilliant laser is a 532 nm frequency doubled Nd:YAG laser. It has a repetition rate of 10 Hz, energy per pulse of 165 mJ, beam diameter of 6 mm and pulse duration of 4 ns. Wafer type W1B was used in this experiment and SEM images of the resulting LFCs are shown in Figure 2-17.

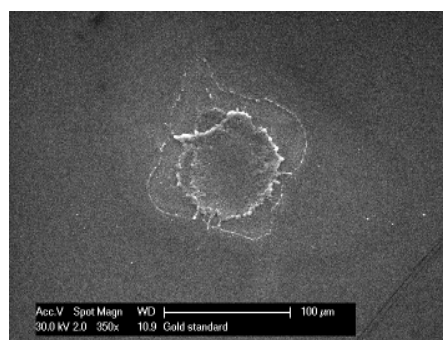


3



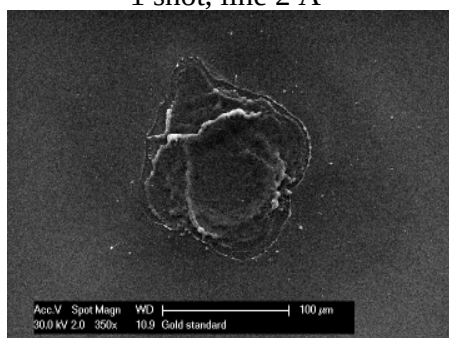
1 shot, line 2 A

4



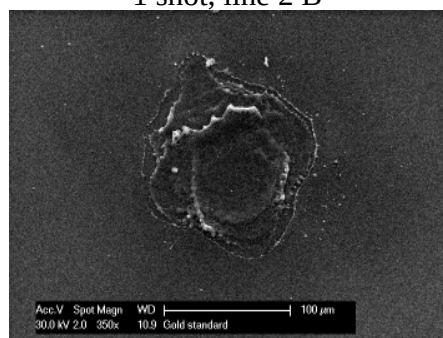
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5



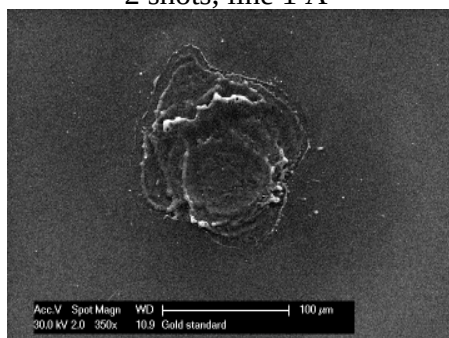
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6



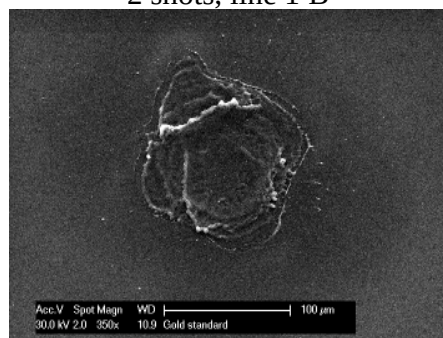
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7



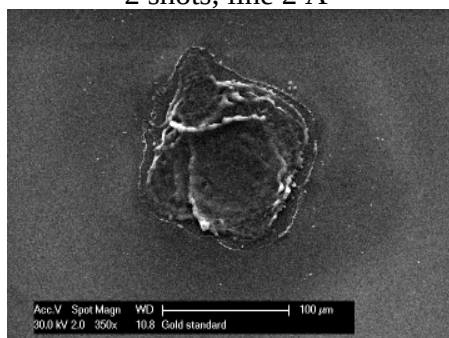
2 shots, line 2 A

8



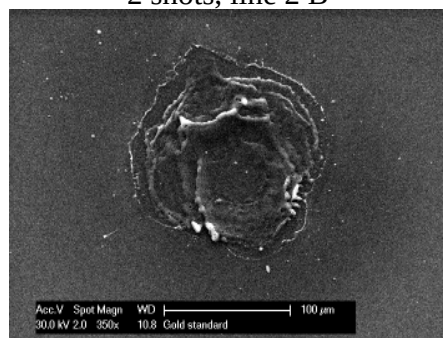
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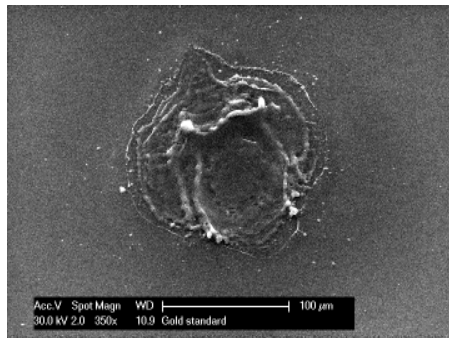
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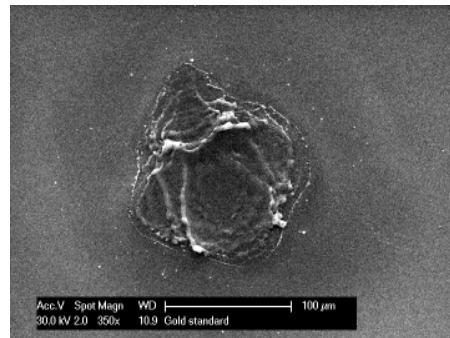
3 shots, line 1 B

11



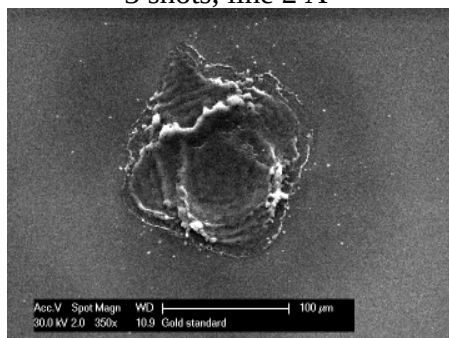
3 shots, line 2 A

12



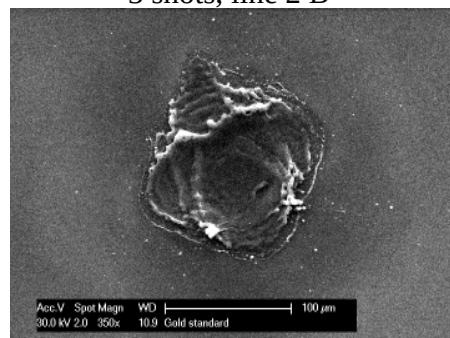
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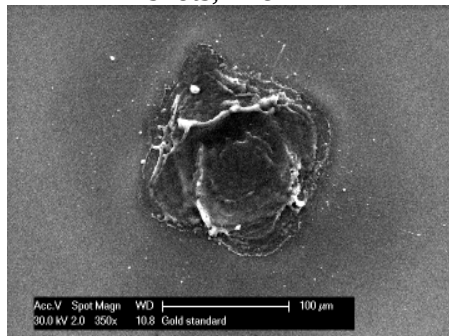
4 shots, line 1 A

14



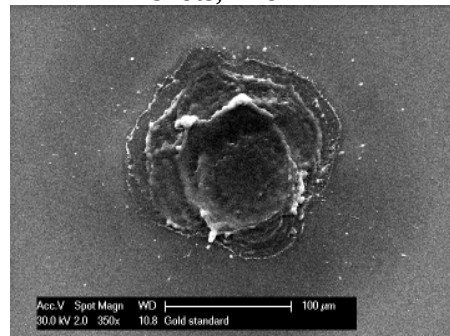
4 shots, line 1 B

15



4 shots, line 2 A

16



4 shots, line 2 B

Figure 2-17. SEM images of LFCs using DBS

Since the DBS splits the input beam into 23 diffracted beams in a line pattern, 2 lines for each of the 4 laser conditions, totaling 8 horizontal lines of LFCs were marked on the wafer. Each row in Figure 2-17 represent the SEM images of 2 randomly chosen LFCs from the same line. The LFCs from the same line (1&2, 3&4, 5&6, 7&8, 9&10, 11&12, 13&14, 15&16) are all comparable to each other which mean the diffracted beams have uniform intensity as predicted. The LFCs from the same laser conditions (1-4, 5-8, 9-12,

13-16) are all comparable to each other which mean the marking process has repeatability. The depth of LFCs increased uniformly as more shots of laser pulses were fired which means the depth of LFCs are proportional to the total energy delivered to the sample.

2.2 Microlens Array

Spot array generation using microlens arrays is achieved using a fly's eye condenser setup consisting of two identical microlens arrays and a condenser lens. Fly's eye condensers have been used for homogenization in lighting systems for over a hundred years. Recently, SUSS MicroOptics, a Swiss based microoptics company, developed fused silica based microlens arrays for beam homogenizing and spot array generation of high power laser beams.

2.2.1 Background

This section will review and discuss literature listed in Table 2-5.

Table 2-5. Relevant literature on microlens arrays

	Title	Author
1	Refractive Micro-optics for Multi-spot and Multi-line Generation	Maik Zimmermann et al.
2	Laser Beam Homogenizing: Limitations and Constraints	Reinhard Voelkel et al.

“Refractive Micro-optics for Multi-spot and Multi-line Generation” by Maik

Zimmermann et al. [15] presents the usage of microlens arrays as a fly’s eye condenser to shape laser beams into an array of spots, a matrix of spots, a square-flat-top or a line-flat-top. The authors discussed the theories of operation and presented micro structuring and micro drilling results from applying shaped laser beams onto different materials.

As shown in Figure 2-18, the fly’s eye condenser consists of two identical microlens arrays positioned focal length apart from each other and a convex lens directly behind the second microlens array.

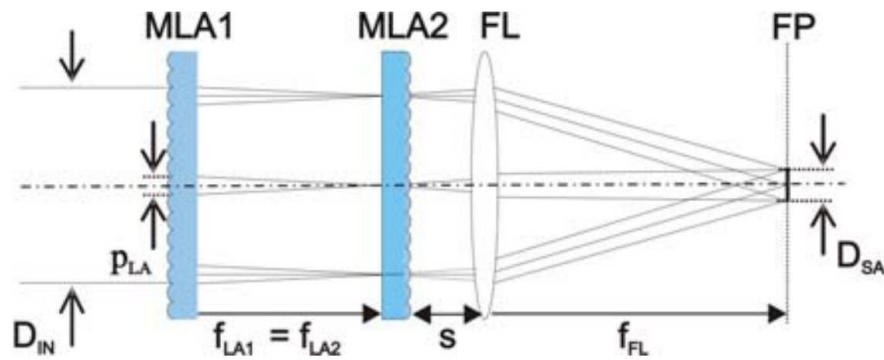


Figure 2-18. Fly’s eye condenser schematic [15]

The first microlens array, MLA1, splits the incident laser beam into an array of beamlets and focuses them into the second microlens array, MLA2. The second microlens array, MLA2, act as field lenses and project the focused beamlets into infinity. The convex lens, FL, focuses the beamlets at its focal plane, thus superimposing them. If the incident laser beam is coherent, $M^2 < 10$, then the superimposed beamlets will interfere with each other producing sharp peaks, thus producing spots. On the contrary, if the laser beam is

not coherent, $M^2 > 10$, then the superimposed beamlets will simply overlap producing a uniform intensity profile. This is the case of flat-top generation.

The number of points N formed by a fly's eye condenser is given by

$$N = \frac{p_{LA}^2}{\lambda \cdot f_{LA1}} \quad (5)$$

where p_{LA} is the pitch of the lens array, f_{LA1} is the focal length of the first microlens array, MLA1, and λ is the wavelength of the incident laser beam. The period of generated spots, Λ_{FP} , is given by

$$\Lambda_{FP} = \frac{\lambda \cdot f_{FL}}{p_{LA}} \quad (6)$$

where f_{FL} is the focal length of the convex lens, FL. Finally, the envelope of the generated spots, D_{SA} , is given by

$$D_{SA} = p_{LA} \frac{f_{FL}}{f_{LA2}} \quad (7)$$

where f_{LA2} is the focal length of the second microlens array, MLA2. [15]

“Laser Beam homogenizing: Limitations and Constraints” by Reinhard Voelkel et al. [16] presents usage of microlens arrays as a fly's eye condenser for laser beam homogenization. For the most part, the content of this paper is similar to the previous literature. It contained additional contents such as discussion of fly's eye condensers using non-periodic microlens arrays and usage of rotating diffusers with fly's eye condensers for uniform illumination. These applications are not relevant to this project.

2.2.2 Vendors

SUSS MicroOptics, <http://www.suss-microoptics.com/>, pioneered the field of homogenizing laser beams using microlens arrays. Their catalog of microlens arrays in fused silica can be used for homogenizing high power laser beams from wavelengths of 193nm to IR. Although custom design elements are available, the stock elements from the catalog should suffice in meeting the demands of most applications. The sales representative contacted was Jürgen Rieck. His email address is rieck@suss.ch and phone number +41-32 -7205428. He is the expert on fly's eye condensers.

2.2.3 Experimental Results

A fly's eye condenser, Flat-Top 5, from SUSS MicroOptics has been procured and tested. The company specifications are listed in Table 2-6.

Table 2-6. Fly's eye condenser specifications

Part #	Pitch	ROC	Divergence Angle	AR-Coating	Array-Size
19-0225-100-000	250 μ m	0.75mm	$\pm 5^\circ$	no	10mm $\times$ 10mm $\times$ 2.25mm

The procured fly's eye condenser is a fused silica element with cylindrical lenses on both sides acting as the first and second microlens arrays respectively. The company's 3D rendering of the element is shown in Figure 2-19.

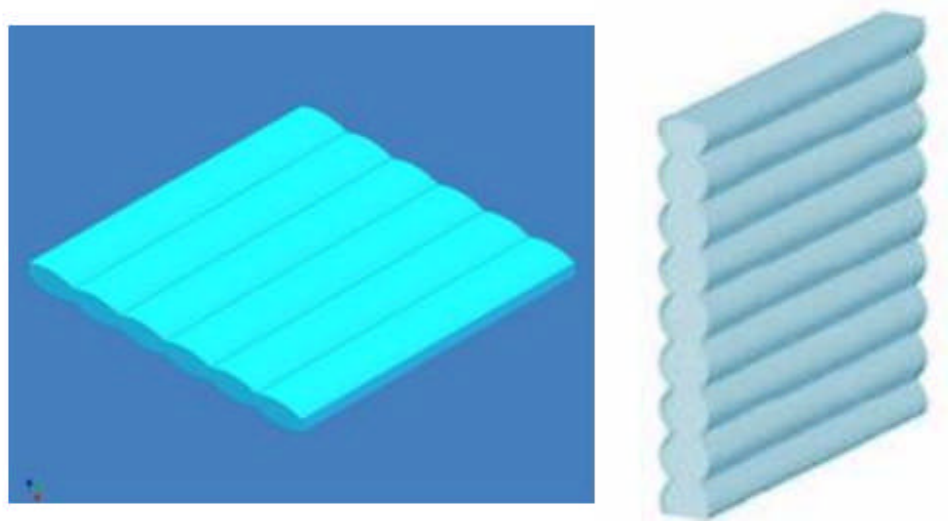


Figure 2-19. Fly's eye condenser model [17]

The effective focal length of the microlens is given by [17]

$$f_E = \frac{ROC}{n_1 - 1} \quad (8)$$

where ROC is the radius of curvature and n_1 is the refractive index of the bulk material.

Using $ROC = 0.75$ mm and $n_1 = 1.46071$ for fused silica at 532 nm wavelength, the effective focal length, f_E , of the microlens is calculated to be 1.62 mm. Using equations (5) through (7), the number of points, N , is calculated to be 72, the period of generated spots, Λ_{EP} , is calculated to be 0.43 mm and the envelope of the generated spots, D_{SA} , is calculated to be 30.7 mm.

To evaluate the microlens array's performance for processing LFCs, the optical setup as shown in Figure 2-20 was used.

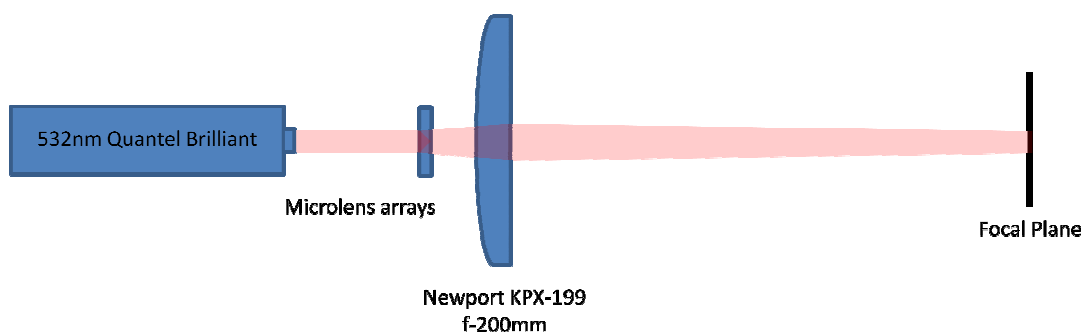
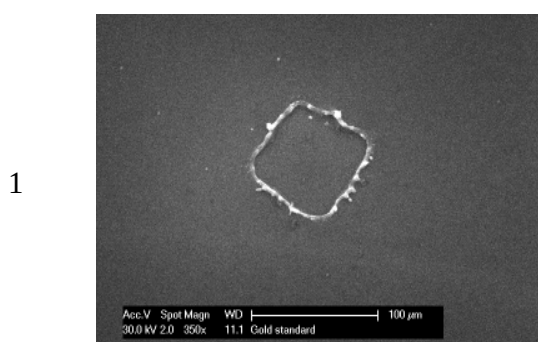
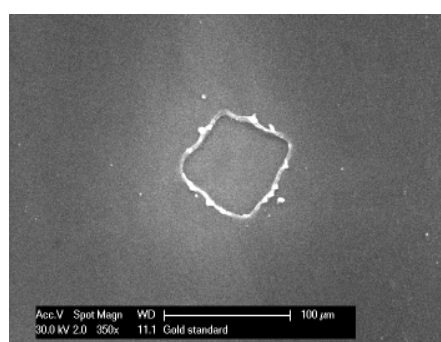


Figure 2-20. Optical setup for LFC Processing with microlens arrays

The laser beam from the Quantel Brilliant Q-switched Nd:YAG laser arrives on the microlens arrays at normal incidence. A Newport KPX-199 f-200 mm lens is used as the condenser lens. The Quantel Brilliant laser is a 532 nm frequency doubled Nd:YAG laser. It has a repetition rate of 10 Hz, energy per pulse of 165 mJ, beam diameter of 6 mm and pulse duration of 4 ns. Wafer type W1B was used in this experiment and SEM images of the resulting LFCs are shown in Figure 2-21.

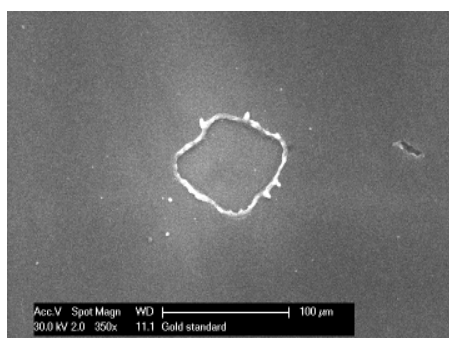


1 shot, line 1 A



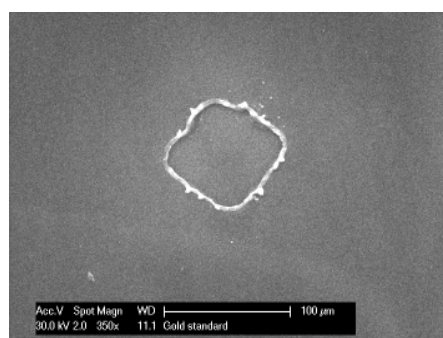
1 shot, line 1 B

3



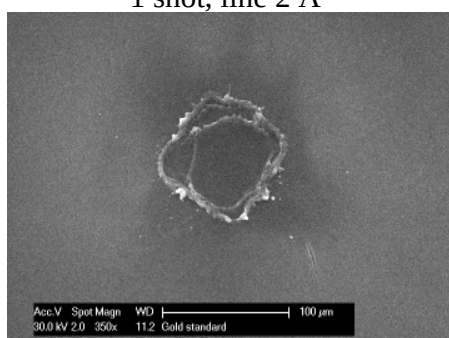
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4



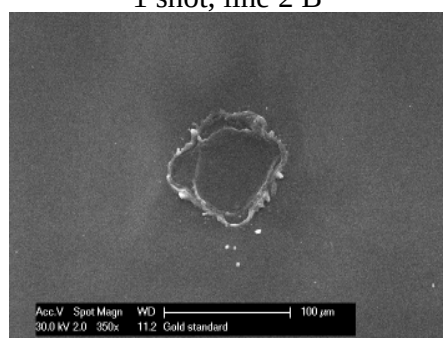
1 shot, line 2 B

5



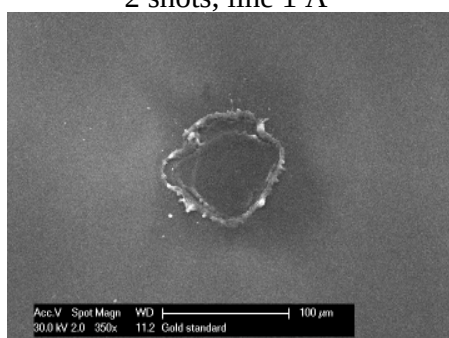
2 shots, line 1 A

6



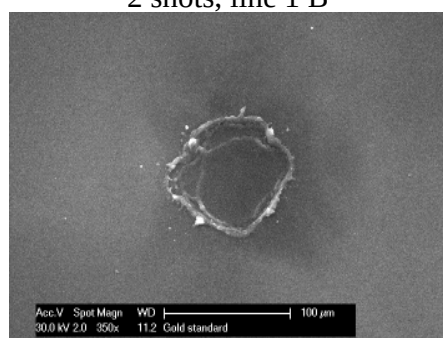
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7



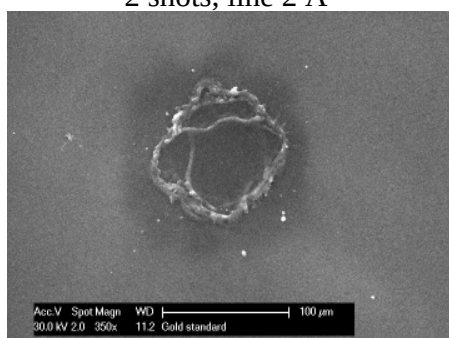
2 shots, line 2 A

8



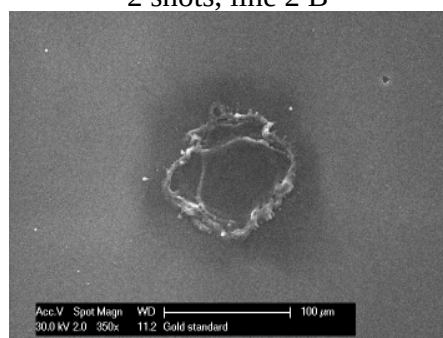
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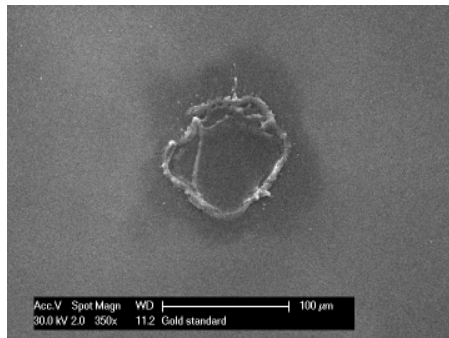
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10



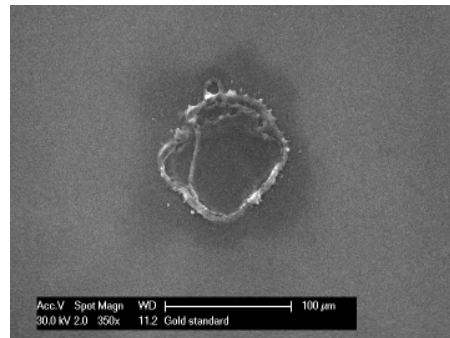
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11



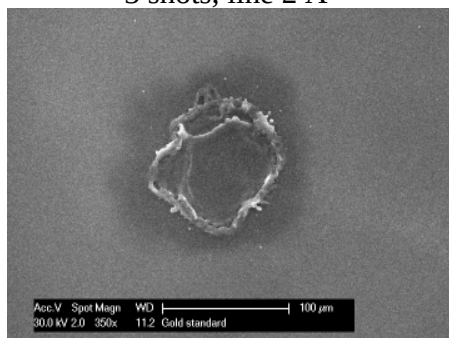
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12



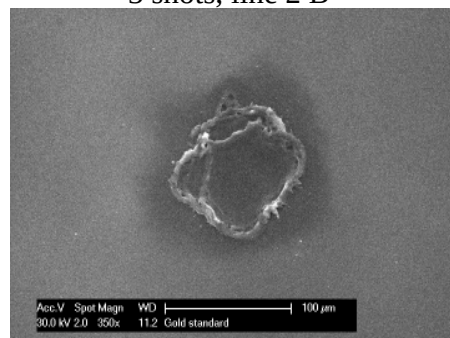
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13



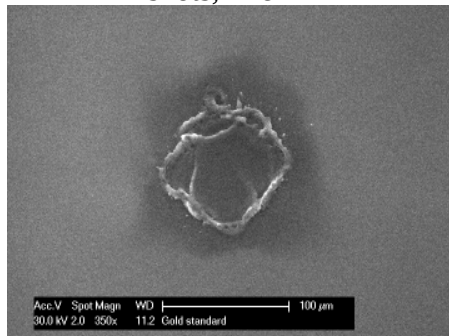
4 shots, line 1 A

14



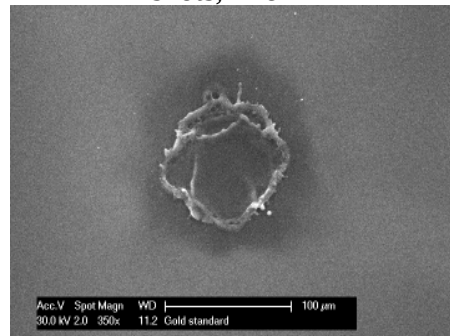
4 shots, line 1 B

15



4 shots, line 2 A

16



4 shots, line 2 B

Figure 2-21. SEM images of LFCs using microlens arrays

Since the fly's eye condenser generates $N = 72$ spots in a line pattern, 2 lines for each of the 4 laser conditions, totaling 8 horizontal lines of LFCs were marked on the wafer.

Each row in Figure 2-21 represent the SEM images of 2 randomly chosen LFCs from the same line. The LFCs from the same line (1&2, 3&4, 5&6, 7&8, 9&10, 11&12, 13&14, 15&16) are all comparable to each other which mean the generated spots have uniform intensity. The LFCs from the same laser conditions (1-4, 5-8, 9-12, 13-16) are all

comparable to each other which mean the marking process has repeatability. The depth of LFCs increased uniformly as more shots of laser pulses were fired which means the depth of LFCs are proportional to the pulse energy. The depths of LFCs here are shallower compared to the ones processed using DBS. This is because the microlens arrays has a split count of 72 where DBS only has 23.

2.3 Summary

The results from both DBS and microlens arrays showed similar trends proving both technologies are viable beam delivery options for manufacturing LFCs. Although both technologies can achieve near perfect efficiencies and uniform intensities across spot arrays, there are fundamental differences between them causing advantages and disadvantages.

Due to the wavelength dependency of the diffractive optical elements, each element has to be custom designed and manufactured to fit the specific laser system and application. This is costly. On the up side, the custom designed element has much fewer design constraints and limitations than a stock product.

Microlens arrays can operate at a range of wavelengths and stock elements are readily available. It is a much cheaper option compared to the custom designed DOEs. However, they have more design constraints and limitations. For example, the number of spots generated by a fly's eye condenser is fixed based on the laser wavelength and the microlens arrays' specifications. The period of generated spots is dependent on the focal length of the condenser lens, the laser wavelength and the pitch of the microlens arrays.

Therefore careful considerations must be taken into account when selecting which technologies to use in the final beam delivery system.

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