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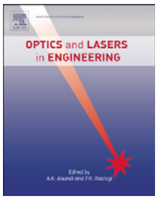

High resolution, low cost laser lithography using a Blu-ray optical head assembly

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We present a novel, cost-effective laser lithography system capable of producing periodic and non-periodic patterns with sub-micrometre feature sizes and periodicities. The optical head assembly of a Blu-ray disc recorder containing a 405 nm semiconductor diode laser and 0.85 NA objective lens was mounted on a motion stage and it was used to expose silicon samples covered with a mixture of SU-8 photoresist and photoinitiating chemicals. Experiments were carried out to demonstrate the lithographic capabilities of the system, and a smallest feature size of 450 nm was obtained. Grating structures were fabricated in order to demonstrate system capabilities.

1. Introduction

One of the most common lithography systems is optical projection, which uses an advanced optical design to expose a pattern onto a photoresists using a mask. It is capable of exposing large areas of resist and offers great repeatability, but its resolution is limited by the wavelength of light being used. Excimer lasers are the current standard, and feature sizes have reached dimensions below 100 nm [1]. Similar dimensions have been fabricated using X-ray sources instead of coherent light as the source of energy for these systems [2]. Masked systems tend to be expensive, so there is always a need for maskless, low cost, high resolution lithographic systems. Ion and electron beam lithography have been shown to produce features in the order of 10 nm, but their high complexity, high cost and low throughput limit their wider applications [3]. Another way of fabricating devices using maskless lithography is to use a laser source and scan it across the photoresist covered sample, or direct laser write. The resolutions that can be achieved with this technique are in the range of 0.5–1 μm depending upon the wavelength and focusing optics, and it has a high throughput and relatively lower cost.

The resolution in a direct laser write lithographic system is determined by the spot size of the beam, which is determined by the type of lens being used and the wavelength of the light, and is proportional to

$$\text{Spot size} = \frac{\lambda}{\text{NA}}, \tag{1}$$

where λ is the wavelength and NA is the numerical aperture of the lens [4].

The wavelength of the light is an important factor. Lower wavelengths can provide better resolution. Objective lenses with high numerical apertures are able to tightly focus the beam. The spot size is smallest at the focal spot, and the distance between the lens and the substrate must be accurately controlled. Just a few microns away from the focal spot in either direction causes the beam to become larger, thus, reducing the resolution of the system.

The cost of semiconductor laser diodes has decreased significantly in the last few years due to technological developments and also due to mass production and availability of shorter wavelengths in the UV-blue region. There are several uses for these diodes, but one of the most common is as light sources for reading and writing optical media such as compact discs (CD), digital video discs (DVD) and now Blu-ray discs (BD). The main difference between these media is their storage capacity, which is given by the size of the marks that are written onto the substrates. As marks get smaller, the storage capacity of the discs increases. However, in order to be able to read the data encoded in the smaller marks, lower wavelengths are necessary. The laser diodes went from 780 nm in wavelength for CDs, to 650 nm for DVDs and to 405 nm for BDs. The lower wavelength, combined with a high numerical aperture lens, allow BDs to store over 25 GB of information, compared to the 0.7 GB capacity for CDs and 4.7 GB capacity for DVDs [5–7].

The standard adopted for BD technology is to use objective lenses with 0.85 NA. This yields spot sizes of around 480 nm for a 405 nm wavelength, which highly correlates to the feature size that can be exposed on a resist. Objectives with higher numerical aperture reduce the tolerance for disc fluctuations and laser sources below

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405 nm are still not cost effective. While there are some techniques available to further reduce the spot size, such as solid immersion hemisphere and Weierstrauss sphere lenses and near-field optical head apertures, regular objective lenses are less expensive [4]. For current BD technology this is sufficient and widely available.

The spot size described in Eq. (1) relates to the full width of a focus beam, measured at the first minimum of an ideal airy disc, allowing for the possibility to fabricate feature sizes smaller than the spot size. Feature sizes below 100 nm have been reported for similar types of combinations of objective lenses and 405 nm semiconductor laser sources, but using an organic resist and thermal lithography [8]. Due to the beam's Gaussian distribution, it is possible to fabricate such small sizes where the energy within the distribution is sufficient to expose these resists. As described below, we decided to use a thin SU-8 resist because of its availability.

Direct laser write systems have been designed with 405 nm diodes. A blue-laser mastering system [9], which used a 405 nm GaN diode, a 0.95 NA objective lens and inorganic photoresist was used to produce 130 nm wide features on a ROM disc mounted on a spindle motor. There are commercial systems like MicroWriter from Lot-Oriel [10] which has a large number of 405 nm diodes to achieve high-writing speed of 375 mm^2/min at a 5 μm resolution and in another high-resolution (0.6 μm) configuration at 3 mm^2/min. MicroLab from SVG Optronics [11] is a similar system with different options, capable of producing 280 nm features at 4 mm^2/min. Heidelberg Instruments offers a tabletop laser pattern generator, μPG 101 [12], which can produce 3 μm features at 30 mm^2/min and 1 μm features at 3 mm^2/min and it uses a 405 nm diode laser, with the possibility of using a 375 nm diode laser. These commercial systems offer a high writing speed, high resolution and a variety of patterns that can be written. However, their costs are high (hundreds of thousands of US dollars) so alternative system configurations have been reported.

A low-cost (~$1000) interference lithography system with a 405 nm GaN semiconductor laser diode in a Lloyd's mirror configuration has been reported to be able to generate periodic patterns with a 300 nm period using PFI-88 photoresist [13]. A similar, cost-effective ($15,000) setup using an AlInGaN 405 nm diode was used to make periodic patterns with periods between 290 and 750 nm over a large area on AZ5214-E resist [14]. While interference lithography systems are low-cost and simple, they have the limitation that the patterns that can be reproduced are only periodic and determined by the interference patterns of the laser beams.

We report a cost-effective direct write lithography system which uses the optical head assembly from a Blu-ray disc recorder ($40), capable of generating both periodic and non-periodic, high-resolution structures. In order to read optical media, the optical head assemblies in Blu-ray drives contain a semiconductor laser diode, an objective lens of 0.85 NA [6,7] and photodetectors to read the signal, along with other mechanical and optical elements. All the optics are mounted on a sled which scans the rotating optical disc in order to read the tracks that have been recorded on it, and the optical head is properly designed and aligned to be able to focus the laser spot to the smallest size possible. Because of this design, it is possible to use the whole head assembly to focus the light of the diode onto a substrate and use it to expose photoresist without an external objective lens or the need to align it to the laser source. Within the optical head, focusing of the objective lens is carried out through an actuator mechanism that obtains data from the photodetectors and adjusts the position and tilt of the mounted objective lens. Some Blu-ray drives contain three diodes in order to offer backward compatibility and be able to read older optical media like CDs and DVDs. For our experiments, only the 405 nm laser diode was powered using a current source.

The described system is an alternative to using a conventional semiconductor laser diode and objective lens because of its simplicity and cost-effectiveness. In order to power the laser diodes, it is required to supply a constant current so that fluctuations in the current do not damage the diode. A current regulator driver can be assembled from simple electronics to power the diode, or alternatively, it can be purchased as an integrated circuit board and connected to the diode. Then it is only necessary to provide 5–7 V using a voltage source. While even conventional batteries can be used, for our experiments we used a laboratory current source so that the current could be accurately controlled.

2. Experimental

In order to focus the beam of the optical assembly on the substrates, the position of the objective lens in the actuator mechanism was fixed and the whole assembly was mounted on a motion stage and moved in position relative to the sample. By varying the position of the assembly to the samples the correct focal position was determined. In order to generate patterns, the samples were mounted on a two axis motion stage and scanned on a plane perpendicular to the laser beam. Experiments were carried out in order to determine the best focal distance and capabilities of the system, as described in the following sections.

2.1. Optical head

The laser system that was selected for these experiments was the sled assembly SF-AW210 for a 6 × Blu-ray burner drive (purchased from lasersurplusparts.com) and can be seen in Fig. 1. The optical head contains three semiconductor diodes to read different optical media, and the individual optical paths of each diode are shown with arrows. The optical path of the 405 nm diode, which was the only one required for these experiments, has to travel through the optics labelled in the diagram. As light leaves the diode it goes through a diffraction grating "a" and through a cube beam splitter, "b". The lens "c" collimates the beam and then partially reflecting mirror "e" separates the beam to photodetector "d", for output beam control, and turning mirror "f". The beam then travels in a direction normal to the diagram (into the page), and the path is described in the inset. Mirror "f" directs the beam into LCD optical element "g" which corrects the beam for wavefront aberration. Finally, the beam goes through the objective lens "h", which is mounted on an actuator system that can tilt the lens, or move it horizontally or vertically to micro-focus. In an optical drive, the light would then reflect from the disc, and then back to the same elements until it reaches photodetector "d" to be able to read the signal [15,16].

When separated from the optical system, the 405 nm diode laser can output well over 300 mW at a drive current of 250 mA, but for optimal duration and performance the manufacturer suggests currents below 100 mA for about 100 mW of output power. An extracted 405 nm diode from a spare optical head was powered by a current regulating driver system (Rckstr driver, purchased from lasersurplusparts.com), which has a potentiometer in order to adjust the maximum current to be delivered to the diode. The current was set to 96 mA and the diode was measured to produce about 90 mW of optical power.

However, within the head, most of the power is lost as the light goes through all the optical elements described previously, so in order to prevent these losses, a few elements were removed. The purpose of this diffraction grating "a" is to split the beams into a central 0th order and two diffracted orders (±1, with higher orders ignored). The two side orders travel through the optical head along with the central beam and are later used to correct the position and tilt of the objective lens through the focusing servo mechanism by keeping the intensity of the two side order beams equalized [16]. For our purposes we did not require to include these side beams, so this grating was removed. Beam splitter "b" was also removed since it is

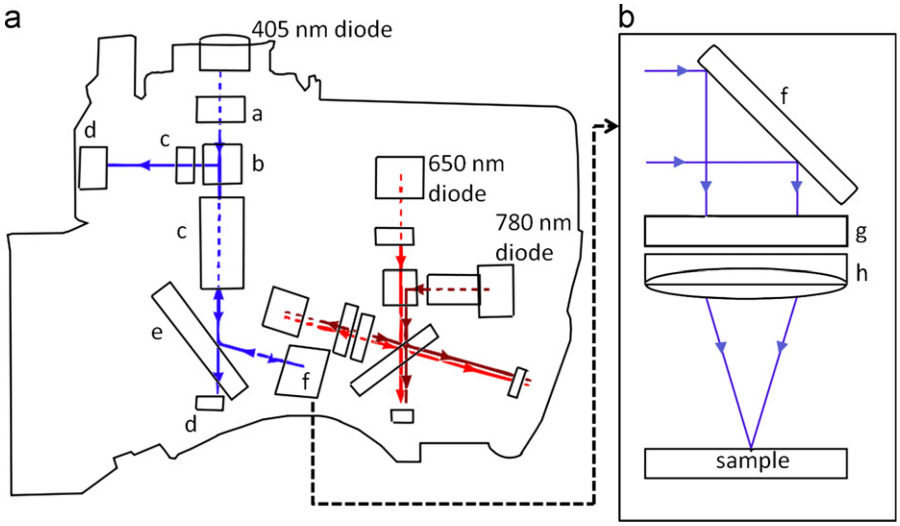

Fig. 1. (a) Top view of SF-AW210 optical head schematic. (b) Side view of 405 nm path after beam reflects from turning mirror "f". Original image courtesy of "Sci.Electronics.Repair FAQ" at www.repairfaq.org. Copyright © Sam Goldwasser and Karol Luszcz.

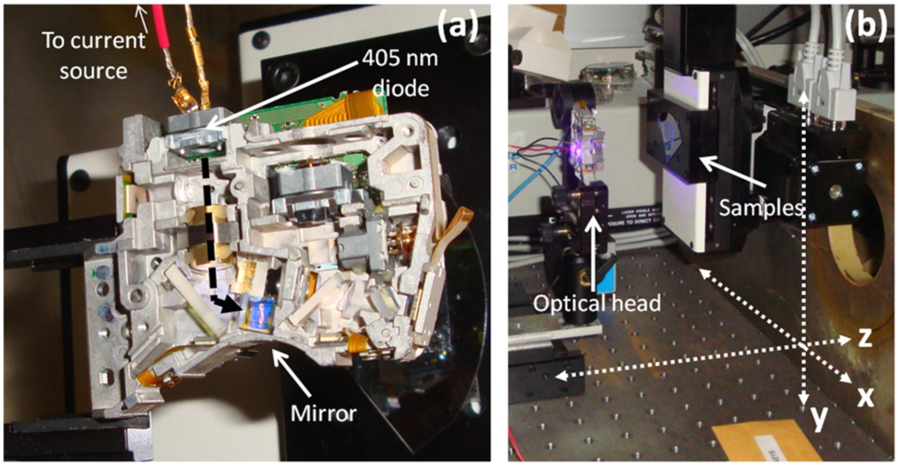

Fig. 2. (a) SF-AW210 optical head with diffraction gratings and beam splitter removed. The wires power the diode and connect it to the current regulating driver. The optical path is shown with the arrow. (b) Experimental setup, showing the SF-AW210 optical head on a kinematic mount and on a one axis stage. Samples were mounted on the vertically-oriented two axis stage. The orientation of the axes is shown.

used to split the beam and send a beam to a detector for output control. The same current regulating driver was used to power the 405 nm diode and the power was measured to be about 8 mW after going through the head. Fig. 2(a) shows the sled after these elements were removed. Furthermore, the actuator mechanism was fixed to prevent movement of the objective lens.

2.2. *Direct laser write experimental setup*

The samples were mounted on a computer-controlled, high-precision two axis stage (Newmark Systems, NLS4-2.5-16-1) and moved to have the laser beam scan the samples. The laser head system was mounted on a computer-controlled one axis stage (Aerotech, ALS130-050), which allowed for precise determination of the focal distance by running resolution tests at different positions with respect to the samples. In addition, the laser head system was mounted on a kinematic mount to adjust tilt and ensure that the beam is perpendicular to the motion of the vertically mounted two axis stage. The setup and axes orientation is shown in Fig. 2(b).

[100] silicon wafers were diced to obtain 1 cm^2 samples. The samples were first cleaned using the RCA method and dried. Since the negative photoresist SU-8 is not very sensitive to light with wavelength above 400 nm, additional photoinitiating chemicals must be added [17]. A solution of SU-8 photoresist (SU-8 2000.5, MicroChem), a photoinitiator (HNU-470, 0.2 wt% of SU-8, Spectra Group Limited) and a coinitiator (OPPI+N DMMA, 2.5 and 2 wt% of SU-8, Spectra Group Limited) was magnetically stirred for one hour and then spin-coated on the silicon samples at a speed of 3500 RPM. The coated samples were then pre-baked on a hot plate at 95 °C for 60 s. Profilometer measurements confirmed that the resist had a thickness between 400 and 500 nm. The samples were then stored in Petri dishes covered with aluminium foil to prevent accidental exposure of the resist. The samples were then mounted on the XY stage and scanned with the laser for different experiments. Following the laser scanning process, a post-exposure bake was performed on the samples at 95 °C for 60 s. Development was done by submersing the samples in SU-8 Developer (MicroChem) for 45 s, and then they were rinsed with fresh SU-8 Developer for 5 s and finally rinsed with DI water for 10 s and dried with N_2.

The patterns were then optically observed under a microscope. Higher resolution SEM micrographs were taken with a V Zeiss Supra SEM in order to observe and measure the resist line dimensions. The optical diffraction characterisation was done using a Lexel Ar-ion laser operating at a wavelength of 488 nm.

3. Results

Several experiments were carried out to determine the best working distance from the laser head assembly to the sample, by monitoring the position of the laser along the Z axis. A working distance of approximately 2 mm was determined to be ideal, but needs to be adjusted since the high numerical aperture of the objective lens in the laser head system focuses the beam in a very narrow window.

In order to control the energy delivered to the sample, it is possible to control the scanning speed of the stage and the input current to the laser diode. A speed of 15 mm/s was determined through speed tests to be the most appropriate for the experiments, which was the fastest possible speed for the XY stage used in the experiment. The input current controls the optical power of the laser, but it was set to 96 mA as a maximum value for the current in order to maximise the diode's lifetime. Any input voltage above 7.5 V would deliver 96 mA of power, which outputs about 8.1 mW of 405 nm light on the sample. The input voltage was varied to control the input current and thus the optical power. Table 1 shows the effect of the input voltage and optical power on the resolution. Fig. 3(a) shows lines exposed at 5.1 V, with a width of 450 nm.

Square-wave surface-relief gratings were fabricated in order to verify the repeatability of the experiments, with a period of 5 μm. The grating equation,

$$d(\sin\theta_i + \sin\theta_d) = m\lambda, \tag{2}$$

can be used to predict the dependence of the diffracted angle θ_d to the incident angle θ_i. Diffraction angles for several orders were measured from the diffraction pattern of the fabricated 5 μm gratings using 488 nm light, and they closely follow the angles predicted by the grating equation.

Table 1
Resolution as a function of incident power.

Input voltage (V)	Optical power (mW)	Best resolution (μm)
7.5	8.1	24.5
6.5	6.2	22.9
6.0	4.1	16.9
5.5	2.2	2.08
5.2	1.0	1.13
5.1	0.7	0.45

In order to have a high diffraction efficiency, the duty cycle of the gratings must be 50% for the line. Also, the diffraction efficiency is also dependent on the grating line depth. For a square-wave profile for the gratings, the best efficiency is achieved when the ratio of the grating line height h to the period d, (h/d) is about 1.55 and diffraction efficiency is around 88.5% for the first order [18].

The linewidth can be controlled using three methods. The first method is to control the incident light power. Several samples were exposed at different input voltages in order to determine the appropriate voltage to produce gratings with a 50/50 duty cycle. A voltage of 5.6 V was determined to produce lines that were 2.5 μm in width. The second method involves studying how the development time affects the linewidth. Diffraction efficiency was measured *in situ* by submerging exposed substrates in developer and measuring the diffracted power as a function of the development time. When the measured signal becomes highest, it indicates the point at which the duty cycle is 50/50. The efficiency increased from $t=0$ s to 25 s and then decreased as time increased. Consequent samples were developed for 20–25 s and the produced lines were around 2.5 μm in width with 50% duty cycle. The third way to control the linewidth is to expose the samples at a position that is near but not exactly at the focal spot. Fig. 3(b) shows an sample with a linewidth close to 2.5 μm, which was fabricated using the first method.

The diffraction efficiency was measured for samples that had a linewidth of 2.5 μm. The 488 nm beam of an Ar-ion laser at a power of 5.3 mW was focused using a 35 mm focal length lens on the gratings and the diffracted power was measured. The first order diffraction efficiency was measured to be on average 9.5% for angles between 0° and 50°, while the total efficiency was measured to be 23%.

4. Discussion

Voltages below 5.1 V were not taken into account in Table 1 since they produced underexposed lines, which resulted in SU-8 that was not crosslinked and which washed away upon development of the samples. Also, the threshold voltage for the operation of

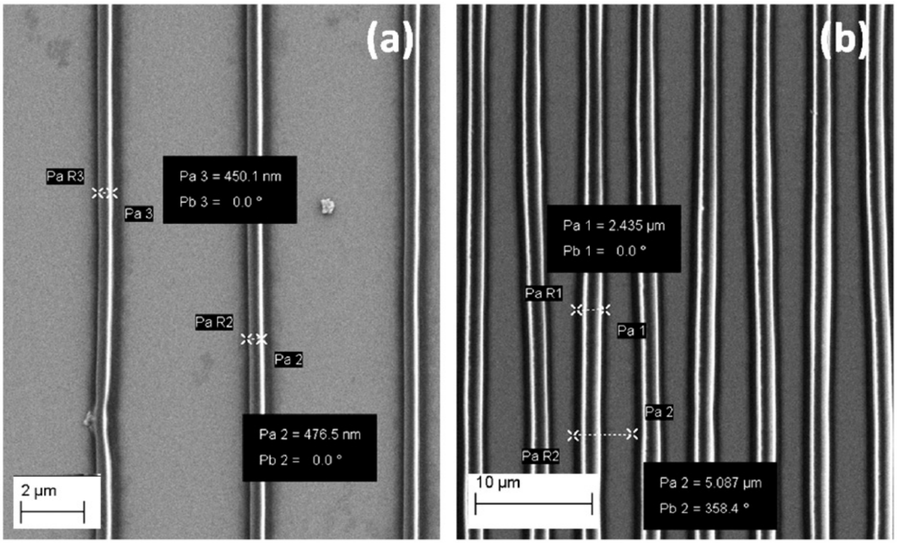

Fig. 3. Scanning electron micrographs of (a) exposed lines at varying focal distances showing 450 nm features; and (b) 5 μm grating structure with duty cycle close to 50/50. Scale bars are shown as insets.

the 405 nm diode within the SF-AW210 head occurred at about 5.0 V. Neutral density filters could have been utilised to further reduce the power, but due to the short working distance between the optical head and the samples, it was not possible to carry out such an experiment. At voltages of 5.1 V and at the right focal spot, 450 nm wide lines were exposed, but as soon as the focal spot was modified slightly, no lines were observed after development.

The measured efficiencies are lower than the model because losses are occurring due to grating imperfections and because the (h/d) ratio is not ideal, but further experiments can be carried out to increase the efficiency of the gratings. It can be further increased by performing reactive ion etching on the fabricated gratings, in order to create grooves in the silicon substrate. For a 5 μm period, the trenches should be 7.75 μm deep, but in our case they were only 450 nm on average, which means that the ratio (h/d) is 0.09. The measured efficiency for the first order efficiency was about 9.5%, which is in accordance to the plot presented by Moharam and Gaylord [19], which describes how the (h/d) ratio affects the diffraction efficiency of different diffraction orders.

Focusing was done using a computer-controlled stage, but further investigation can be done in order to use the actuator mechanism already present in the optical head. This mechanism can adjust the lens for microfocusing, and if the signal from the photodetectors can be analysed, it would be possible to add an autofocus feature, in the same way a conventional optical drive would.

While we used the high power diode laser and laser head from a Blu-ray recorder, it is also possible to use the assembly from a conventional Blu-ray disc reader, since they are mass produced for video gaming consoles (PlayStation 3 and Xbox 360) and home video players. Because of the widespread use of this technology, the optical assemblies can be purchased as a package to repair malfunctioning assemblies in the consoles and home entertainment systems and are sold at very low prices. They are therefore very low-cost alternatives to purchasing a separate objective lens and semiconductor laser diode, which can cost thousands of dollars, as compared to these low-cost, alternative optical heads ($10–$40). If one were to fabricate a similar system from individual components, one would need a 405 nm laser source and driver and an objective lens, with the added need to align them. Typical, commercial 405 nm laser diodes with power between 50 and 100 mW cost between $3000 and $25,000, which include the driver and module. Commercial 0.85 NA objective lenses cost between $200 and $3000.

5. Conclusions

We have demonstrated a cost-effective lithography system using the optical head assembly of a Blu-ray drive capable of producing sub-micrometre (450 nm) features on a standard SU-8 photoresist. The cost of the system, excluding the motion stages, is less than $100. By controlling the motion of the XY stages, different patterns can be generated and the systems resolution would be in part determined by the accuracy of the stages. While high precision motion stages can be expensive, they are not necessary if the patterns have feature sizes that are in the range of several micrometres. It would also be possible to utilise the existing motion axes from Blu-ray drives and combine them for a cost-efficient solution to having expensive motion stages. The area that can be exposed with our system is limited by how accurately we were able to align the stage with the laser assembly in order for the exposure to be planar. Higher diffraction efficiency gratings can be generated using this system, by fabricating deep trenches and making the grating linewidth be half the period of the gratings. Furthermore, aluminium can be evaporated on the gratings to increase reflectivity and, hence, diffraction efficiency.

References

[1] Rai-Choudhury P. Handbook of microlithography, micromachining and microfabrication, vol. 1. SPIE Press; 1997. (Monograph PM 39).

[2] Samson JAR, Edereer DL. Vacuum ultraviolet spectroscopy II. Academic; 1998.

[3] Watt F. Nucl Instrum Methods Phys Res B 1999;158.

[4] Ohtsu M, editor. Progress in nano-electro-optics III, 95. Springer Verlag; 2002.

[5] Blu-ray, Blu-ray Disc, 2010. Available at 〈http://www.blu-ray.com/faq/〉.

[6] Blu-ray Disc Association, "White Paper Blu-ray Disc Format: Physical Format Specifications for BD-RE," 2010. Available at 〈http://www.blu-raydisc.com/Assets/Downloadablefile/BD-RE_physical_format_specifications-18325.pdf〉 [downloaded October 28, 2011].

[7] Blu-ray Disc Founders, "White Paper Blu-ray Disc Format: Key Technologies," 2004. Available at 〈http://www.disc-group.com/wp-content/uploads/2011/05/Blu-Ray-5-Key-techno-1.147KB.pdf〉 [downloaded October 28, 2011].

[8] Usami Y, Watanabe T, Kanazawa Y, Taga K, Kawai H, Ichikawa K. Appl Phys Exp 2009;2:126502.

[9] Kouchiyama A, Aratani K, Takemoto Y, Nakao T, Kai S, Osato K, et al. Jpn J Appl Phys, Part 1 2003;42:769.

[10] LOT-Oriel Group Europe, "MicroWriter^{TM} Laser Lithography System," 2010. Available at 〈http://www.lot-oriel.com/files/downloads/dmo/eu/MicroWriter_Laser_Lithography_System_eu.pdf?phpMyAdmin=gjwRNLwKd0p,,aCaCB54evpHoQ2〉 [downloaded October 20, 2010].

[11] SVG Optronics, "MicroLab: Laser Pattern Generator on curve surface," 2010. Available at 〈http://www.svgoptronics.com/MicroLab.pdf〉 [downloaded October 20, 2010].

[12] Heidelberg Instruments, μPG 101 The Tabletop Laser Pattern Generator, 2010. Available at 〈http://www.himt.de/factsheets/ muepg101.pdf〉 [downloaded October 20, 2010].

[13] Fucetola CP, Korre H, Berggren KK. J Vac Sci Technol B 2009;27:2958.

[14] Byun I, Kim J. J Micromech Microeng 2010;20:055024.

[15] Goldwasser SM. Sci.Electronics.Repair FAQ, 2011. Available at 〈http://www.repairfaq.org/sam/sf-aw210.jpg〉 [downloaded October 28, 2011].

[16] Goldwasser SM. Sci.Electronics.Repair FAQ, 2010. Available at 〈http://www.repairfaq.org/sam/cdfaq.htm#cdfun〉 [downloaded October 28, 2011].

[17] Chanda D, Abolghasemi LE, Haque M, Ng ML, Herman PR. Opt Express 2008;16:15402.

[18] Gaylord TK, Moharam MG. Proc IEEE 1985;73:894.

[19] Moharam MG, Gaylord TK. J Opt Soc Am 1982;72:1385.