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

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ABSTRACT

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