Microelectronic Engineering 142 (2015) 64–69

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Electron beam mastering system using a vacuum-compatible hydrodynamic spindle

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ARTICLE INFO

Article history:
Received 2 June 2015
Received in revised form 24 July 2015
Accepted 28 July 2015
Available online 3 August 2015

Keywords:
Electron beam lithography
Rotational mastering
Vacuum-compatible spindle
Ionic liquid

ABSTRACT

Nanoscale patterning used in disk media is a promising technology for storage devices (patterned media) and optical devices (Fresnel lens, X-ray zone plate). Electron beam (EB) lithography is a candidate technique for writing nanoscale patterns. Patterned media and X-ray zone plates are fabricated using an EB mastering system with a vacuum chamber. The EB mastering system requires a positioning mechanism to put a workpiece such as a semiconductor wafer in an appropriate position. This positioning mechanism must be vacuum-compatible and have properties such as low out-gassing and high positional accuracy. We propose an EB mastering system using a compact hydrodynamic spindle lubricated by an ionic liquid, which has a low vapor pressure. In addition, this spindle could be easily installed as an attachment to an existing scanning electron microscope (SEM). In our experiments, the proposed EB system could fabricate concentric circular grooves with a width of 40 nm, track pitch of 180 nm and a diameter of 1200 μm under a vacuum pressure of 10^{-4} Pa. It was confirmed that the ionic liquid had no effect on the EB machining in the SEM and that the proposed hydrodynamic spindle was very suitable for creating an EB mastering system that was simple, small and able to achieve high accuracy.

1. Introduction

The technique of lithography is important for nanoscale fabrication that is often used for making storage devices (such as patterned media) and optical devices (such as Fresnel lenses and X-ray zone plates). An X-ray zone plate consists of a number of nanoscale circular grooves [1,2]. Optical disks also use circular grooves and circular pit patterns with nanoscale track pitch to store very large amounts of data on them. To fabricate these precise circular grooves and pit patterns, both a rotational mechanism with high positional accuracy and a light source with a short wavelength such as a deep ultraviolet (UV) laser or an electron beam (EB) are needed, as described in Fig. 1. Table 1 summarizes rotational mastering devices for optical disks reported in the literature. These devices usually use a fluid-lubricated spindle to achieve precise rotational movement and to fabricate nanoscale circular grooves and patterns. Takeda et al. [3] investigated the use of a rotational mastering system for high-density storage disks using an air spindle and deep-UV light, and reported that the proposed system could fabricate fine pit patterns with a track pitch of 300 nm. Many researchers have studied mastering devices that used an EB operated in a vacuum chamber at a pressure less than 10^{-3} Pa. Accordingly, a vacuum-compatible spindle was necessary, and an aerostatic spindle was usually used in these EB mastering devices. Ogata et al. [4] designed a rotational EB mastering system using an air spindle with a noncontact labyrinth seal and fabricated rotary encoder gratings with a grating pitch of 1.57 μm under vacuum conditions of less than 2.0×10^{-5} Pa. Wada et al. [5,6] and Kitahara et al. [7] designed an aerostatic spindle with a viscous seal system for an EB recorder. The proposed EB recorder could fabricate pit patterns with a width of 12.5 nm and a track pitch of 35 nm. In addition, it was reported that the viscous system could maintain a vacuum pressure of the order of 10^{-4} Pa during spindle rotation. Furuki et al. [8] and Takeda et al. [9] proposed a local vacuum mechanism for an EB recorder using a differential pumping system. The pressure between a semiconductor wafer and the EB column head was sealed by the proposed local vacuum mechanism and was maintained at a value less than 10^{-3} Pa. Accordingly, this mechanism had the advantage that an aerostatic bearing for rotational movement could be operated in the open air and a vacuum-compatible aerostatic bearing was not needed, although a local vacuum mechanism was still necessary. However, it was obvious that these vacuum-compatible mechanisms require a large space for the viscous seal regions and a complex structure for the tubing of the vacuum pumps [10,11].

Therefore, we developed an EB mastering system with a hydrodynamic spindle using an ionic liquid as a lubricant that has low vapor pressure [12]. An ionic liquid has previously attracted attention as a lubricant for use in high-vacuum situations [13–15]. However, to the best of our knowledge, there has been no previous report of a hydrodynamic

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http://dx.doi.org/10.1016/j.mee.2015.07.014
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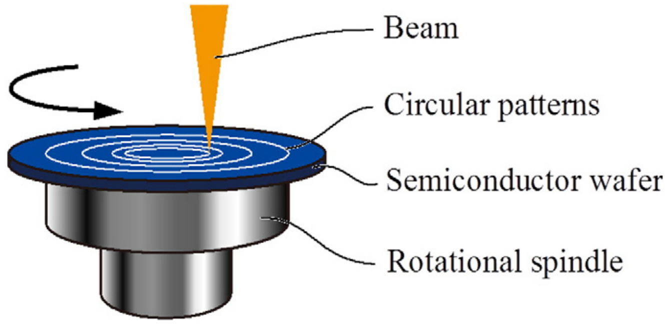

Fig. 1. EB mastering device using a rotary mechanism.

spindle using an ionic liquid as a lubricant for an EB mastering system. The hydrodynamic spindle could make the rotational mechanism for a vacuum compact and simple, because a seal system with several steps of exhaust vacuum pumps and viscous seal regions like a vacuum-compatible aerostatic bearing was not required. In this study, we propose an EB machining system using a hydrodynamic spindle as the rotational stage. The spindle that we developed could be installed as an attachment to the vacuum chamber of a scanning electron micro scope (SEM). It was experimentally confirmed that the proposed system could fabricate precise circular grooves with a width of 40 nm and a track pitch of 180 nm, and it was very useful for making the rotational EB recorder simple and small.

2. Hydrodynamic spindle used in the proposed EB mastering system

We designed a hydrodynamic spindle for the proposed EB mastering system. Fig. 2 shows the geometrical configuration of the spindle including displacement sensors for measuring rotational accuracy. This spindle consists of a shaft with herringbone grooves, hydrodynamic bearings, a rotary table and a built-in type brushless DC motor (Winbel Co., Nagano, Japan). The DC motor was designed for use under high-vacuum conditions, with no oil or glue included.

The rotary table was made of aluminium to avoid magnetization by the permanent magnet of the DC motor. In addition, a yoke was set inside the rotary table to avoid distortion of the electron-beam by the motor's magnetic field.

The spindle is simple and compact as seen in Fig. 2 because of no seal system is needed while the seal system has to be included in a vacuum compatible aerostatic bearing which consists of viscous seals, tubes and vacuum pumps. The hydrodynamic bearing had a 3 μm gap and was filled with an ionic liquid. The herringbone grooves formed on the shaft generated the hydrodynamic pressure by shaft rotation. The gap and the herringbone grooves were designed according to narrow groove theory [16], taking into account the viscosity of the ionic liquid. By using the ionic liquid with a very low vapor pressure (less than 1.0×10^{-10} Pa) as the lubricant, the hydrodynamic spindle could be used in a high-vacuum environment. Table 2 shows the physical properties of the ammonium-based ionic liquid used in this study. The performance of a hydrodynamic spindle is greatly affected by lubricant temperature because of associated viscosity changes. It was considered that in this instance the fabrication time would be very short and there would be a minimal change in the temperature of the ionic liquid in the gap by the heat generated by motor rotation. The ionic liquid used in this study had a halogen atom in the anion. It has been reported that this kind of ionic liquid produced decomposition products under metal-to-metal contact conditions in a vacuum [15]. In this spindle, the weight of the shaft and the rotary table were supported by a steel ball, and decomposition products might be produced from the contact point. However, there may be little effect by the decomposition products because the direct contact point was immersed in the ionic liquid, and the weight of the shaft and the rotary table were relatively small.

3. Experimental set-up and results

3.1. Rotational accuracy of the spindle

The displacement sensors for measuring radial and axial rotational accuracies of the spindle were arranged as indicated in Figs. 2 and 3. The spindle had no special control of the jitter associated with motor rotation. In previous research [12], the radial rotational run-out of 30 nm could be achieved during 14 rotations at 410 rpm. It was experimentally verified that the radial rotational run-out directly affected the minimum groove width fabricated by the EB system.

In addition, the axial run-out accuracy represented the displacement in the vertical direction of the rotary table and affected the dose. When these run-out accuracies are improved, the width and depth of a groove are closer to the design values. As mentioned above, the radial and axial run-outs were measured by two capacitive displacement sensors (Micro Sense 3401HR; Japan ADE Ltd., Tokyo, Japan). The resolution of the sensor was 3 nm and the response frequency was 100 kHz. A brushless DC motor driver (HC6250B-PT; Hokuto Co., Nagano, Japan) was used for the spindle but did not have a rotary encoder and a feedback control system. The rotational accuracy was measured in the air because the sensors could not be set in a vacuum chamber.

Fig. 4 shows the radial and axial run-outs of the spindle for a range of rotational speeds from 500 to 3000 rpm with an increment of 500 rpm. These run-outs were measured under two conditions: one with the semiconductor wafer sample set on the rotary table and the other without the sample on the table. The wafer mass was 0.86 g and the size was 10 × 10 × 0.8 mm. The target values for radial and axial run-outs were set to 40 nm and 50 nm, respectively.

The value of the axial run-out was almost constant with respect to rotational speed, and there was little difference between the two conditions. The radial run-out increased with rotational speed because of imbalance of the rotational table. Under the condition without a sample, axial and radial run-outs less than 40 nm could be achieved simultaneously. Therefore, it was considered that that this spindle would be very suitable for nano-scale EB mastering applications.

Table 1
Rotational mastering system reported in literature.

	Type of the rotational mechanism	Track pitch (Minimum)	Width of machined grooves (Minimum)	Rotational speed	Machining environment	Beam spot diameter
Proposed system for EB recoder(12)	Hydrodynamic ionic liquid spindle	180 nm	40 nm	410–3000 rpm	5.0×10^{-4}–1.0×10^{-5} Pa	10 nm
Blue-ray disk recoder	Plain bearing, aerodynamic spindle	320 nm	About 150 nm	10,000 rpm maximum	In the air	500 nm
Deep UV recoder(3)	Aerostatic spindle	300 nm	About 150 nm	–	In the air	–
EB recoder(4)	Aerostatic spindle	–	1.57 μm	300 rpm	Less than 2.0×10^{-5} Pa	100 nm
EB recoder(5–7)	Aerostatic spindle	35 nm	12.5 nm	5–3000 rpm	Less than 1.0×10^{-4} Pa	4 nm
EB recoder(8–9)	Aerostatic spindle	160 nm	About 80 nm	~3600 rpm	Less than 10^{-3} Pa	About 50 nm