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Development of a vacuum-compatible hydrodynamic spindle using an ionic liquid as a lubricant

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ABSTRACT

The importance of beam machining and extreme ultraviolet lithography technologies in the area of precise and fine machining used for high-density optical discs, integrated circuits and patterned media of hard disc drives (HDDs) is rapidly increasing.

In this paper, a very simple vacuum-compatible rotary spindle is proposed that uses an ionic liquid as a lubricant with a very low vapor pressure. The usefulness of the proposed spindle lubricated by an ionic liquid was experimentally confirmed by measuring the partial pressures of outgassed products during rotation of the spindle in the vacuum chamber, measuring the accuracy of movement of the rotary table and machining circular grooves by an electron beam in a scanning electron microscope (SEM). It was found that the proposed spindle could be used in vacuum, and the partial pressures of outgassed products were almost the same as those of a clean, empty vacuum chamber. In addition, it was confirmed that by using the proposed spindle, circular grooves with diameters of 200 and 400 μm, 450 nm width and 40 nm depth could be machined on a photoresist surface coated on a silicon wafer in vacuum of an SEM.

1. Introduction

The importance of beam machining and extreme ultraviolet lithography technologies in the area of precise and fine machining used for high-density optical discs, integrated circuits and patterned media of hard disk drives (HDDs) is rapidly increasing. These machining technologies require in vacuum, and accordingly, they use vacuum-compatible precise moving mechanisms using aerostatic bearings.

Several reports on noncontact seal systems have proposed the use of aerostatic bearings in vacuum. Pollock [1] proposed a linear gas journal bearing with an integrated seal for a high-vacuum ion implantation chamber. This seal system had four axially spaced annular grooves to prevent air leakage into the vacuum chamber. Yokomatsu et al. [2] proposed an aerostatic journal bearing to achieve higher accuracy of the linear or rotational motion of the positioning mechanism in a vacuum chamber than conventional contact-type bearings. This aerostatic journal bearing also integrated several exhaust stages of viscous seals and exhaust grooves. Bisschops et al. [3] presented a positioning mechanism that was movable in a vacuum chamber for a lithographic projection apparatus using electron beams and ion beams. Yoshimoto et al. [4] investigated the effects of various design parameters of the seal system on the degree of vacuum in a vacuum chamber by installing vacuum-compatible aerostatic journal bearings, theoretically and experimentally. Heidler et al. [5] designed a two-stage exhaust seal system and experimentally confirmed that the designed vacuum-compatible aerostatic guide could maintain a vacuum level of the order of 10^{-4} Pa during the experiment. Wada et al. [6,7] conducted electron beam machining using a vacuum-compatible aerostatic spindle for next-generation high-density optical discs in vacuum, and they reported that 12 nm-wide grooves could be formed on a wafer surface. However, vacuum-compatible aerostatic bearings need a multistage seal system that consists of several viscous seals, exhaust tubes and vacuum pumps to maintain a high degree of vacuum in a chamber, and therefore, this seal system is very complicated and requires large amounts of space for seal regions and tubing.

It is well known that ionic liquids have a very low vapor pressure, and many works on the performance of ionic liquids used in vacuum

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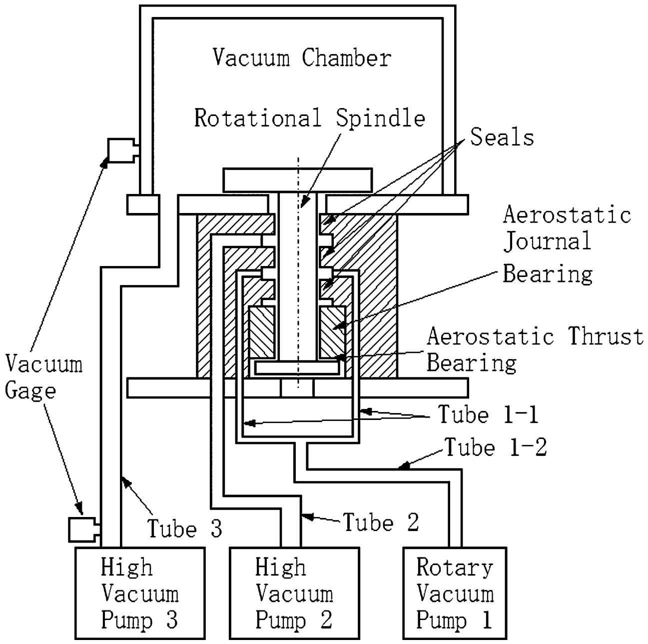

Fig. 1. Rotary table structure using vacuum-compatible aerostatic bearings.

have been published. Street et al. [8] investigated the tribological performance of ionic liquids in vacuum and reported that ionic liquids had friction properties and lifetimes comparable to or better than several commonly used space oils. Morales et al. [9] used an ultrahigh vacuum spiral orbit tribometer and reported on the advantages of ionic liquids in vacuum and also observed that ionic liquids had lower friction coefficients and longer lifetimes than the commonly used perfluoropolyalkylether (PFPE) space lubricants.

Because of this property of the ionic liquids, we proposed a vacuum-compatible hydrodynamic spindle using an ionic liquid with few contact parts to simplify precision mechanisms used in vacuum. There are plans to apply this spindle in the manufacturing of a next-generation high-density optical master disc with a track pitch of less than 100 nm using electron beams. The proposed hydrodynamic spindle does not need a seal system, although vacuum-compatible aerostatic bearings do. Accordingly, the structure of the proposed spindle could be very simple and miniaturized because a seal system is not needed. In this work, we experimentally investigated changes in the vacuum level and partial pressure of outgassed products in a vacuum chamber during the operation of the proposed hydrodynamic spindle. In addition, the accuracy of movement of the proposed rotary spindle in open air was measured, and circular groove machining was conducted by using an electron beam in a scanning electron microscope (SEM). It was experimentally concluded that the proposed spindle was very suitable for precision mechanisms in vacuum.

2. Proposed vacuum-compatible hydrodynamic spindle using ionic liquids

The geometrical configuration of the vacuum-compatible aerostatic spindle [4] applied in vacuum is shown in Fig. 1. As seen in the figure, in the case of a rotary spindle using vacuum-compatible aerostatic bearings, a seal system with several exhaust stages is needed; this system consists of several viscous seal regions, exhaust tubes and vacuum pumps. Accordingly, it is obvious that this system needs much space for the seal regions and tubing in addition to several vacuum pumps.

The geometrical configuration of the vacuum-compatible hydrodynamic spindle proposed in this paper is shown in Fig. 2.

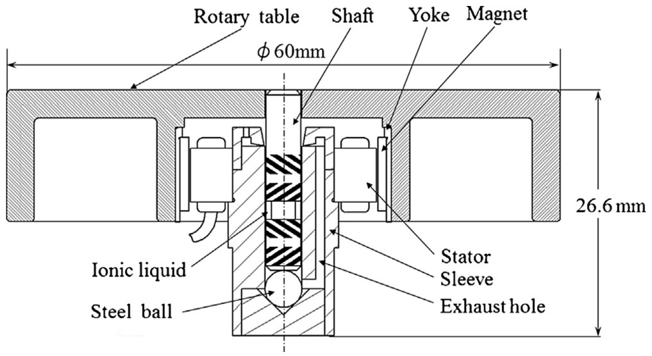

Fig. 2. Proposed rotary table structure using ionic liquid as a lubricant.

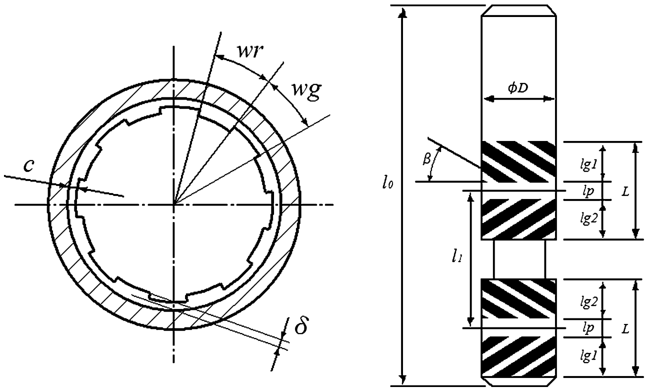

Fig. 3. Detailed design parameters of herringbone-grooved journal bearings.

In the proposed spindle, an ionic liquid with a very low vapor pressure was used as a lubricant. The spindle was radially supported by two herringbone-grooved journal bearings, and its weight was supported by a steel ball located at the bottom. Contamination might be produced by the direct contact between the spindle bottom and the steel ball. However, the effect of contamination on the bearing performance might be small in the proposed spindle because the spindle weight is very small, and the contact area is immersed in an ionic liquid. Accordingly, no seal system such as viscous seals, tubes and vacuum pumps was needed, and the structure of the proposed spindle became very simple and small. An exhaust hole was formed in the housing to exhaust residual air bubbles in the bearing clearance to the open air. The rotary spindle was driven by a brushless direct current (DC) motor designed for use in vacuum without organic glue. The DC motor was installed at the middle part of the spindle. The geometrical configuration and the detailed design parameters of the herringbone-grooved spindle are shown in Fig. 3. The design parameters of the herringbone-grooved spindle are indicated in Table 1, and to determine the design parameters of its journal bearing, the static characteristics of the bearing were

Table 1
Principal dimensions.

Shaft diameter, D [mm]	4.0
Bearing length, L [mm]	5.0
Shaft length, l_0 [mm]	19.5
Bearing span, l_1 [mm]	6.9
Groove region length $lg1$ [mm]	2.05
Groove region length $lg2$ [mm]	1.95
Plain region length, l_p [mm]	1.0
Bearing clearance, c [μm]	3.0
Number of grooves, n_g	8
Groove angle, β [deg]	30.0
Groove depth, δ [μm]	10.0
Groove width ratio, α (=$wg/(wg+wr)$)	0.5