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A novel resist surface profilometer for next-generation photolithography using mechano-optical arrayed probe system

S. Takahashi [*], K. Watanabe, K. Takamasu

Department of Precision Engineering, The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-8656, Japan

Submitted by T. Masuzawa (1), Kanagawa, Japan.

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ABSTRACT

We propose a novel mechano-optical arrayed probe system, allowing a resist surface profile evaluation, which can be applied to on-machine measurement for a next-generation photolithography process of the semiconductor manufacturing. An experimental system, consisting of a white light interferometer and an arrayed probe unit supported on a SiC thin membrane, was newly developed, and fundamental experiments were carried out for verifying the feasibility of the new system. The experimental results suggest the proposed method is an effective resist surface profile evaluation technology with a vertical resolution of 10 nm over a horizontal range of tens of millimeters.

1. Introduction

As a result of the demand for high efficiency in the semiconductor manufacturing industry, nanometrology is rapidly gaining importance [1]. Especially in the photolithography process, measuring the surface profile of a photoresist layer on a wafer has become more and more important in order to expose a finer pattern with high reliability due to the smaller depth of focus of the lithography imaging system. Table 1 shows the measurement requirements of a photoresist surface profile for next-generation photolithography with a comparison of typical profilometers. The photoresist material is known as a kind of soft thin transparent film. Because its surface profile is very smooth [2], the required lateral resolution is not very high (500 μm), but a high vertical one (10 nm) is required. In addition, the applicability to both a transparent thin film and a soft material is strongly required.

Generally speaking, an AFM (atomic force microscopy), which is one of the highest resolution profilometers, can be used to take measurements by a mechanical probe with high accuracy [3–6]. However, the photoresist material is so soft that the AFM tip can damage it during a measurement [7]. Fig. 1 shows a scratch on the photoresist (chemical amplification resist of ArF) surface when an AFM tip with a diameter of 10 nm is pushed into the photoresist by a load of 0.5 μN in a contact mode operation. A dynamic mode operation can indeed be applied to a soft material nondestructively, but there is the problem that its measurement performance is strongly affected by an environmental disturbance such as those from humidity, or a static electric field. In addition, in the case of AFM, the measurement area is limited to micro-area measurements requiring a mechanical probe scan (Fig. 2(a)).

As another approach, an optical method, such as a confocal microscope [8], and an interferometer [9], can also usually be applied to measure a surface profile, with the advantage of nondestructivity, high sensitivity, and high-throughput characteristics [8–11]. But, in next-generation photolithography, the thickness of the photoresist layer will be less than 100 nm. Therefore it is very difficult to apply a conventional optical method because multiple interferences and reflections from the under layer of the transparent thin film obstruct the profile measurement with optical noise, making correct measurement very difficult (Fig. 2(b)).

For these reasons, it is difficult to directly use a typical conventional profilometer as the measuring instrument for a photoresist surface profile in next-generation photolithography. Thus, the purpose of this research is to develop a novel resist surface profilometer, which will overcome the difficulties mentioned above.

2. Resist surface profilometer based on mechano-optical arrayed probe system

Fig. 3 shows the basic concept of our proposed method which is based on a measurement principle that combines the advantages of an optical measurement and a mechanical probe measurement [12]. The design characteristics of the method are summarized as follows:

1. In order to prevent the optical method from causing a multiple interference effect, a mechanical probe is applied.
2. In order to prevent the mechanical probe from damaging a photoresist surface, the contact area between the probe tip and the surface is designed to be large enough in view of the required low lateral resolution.
3. In order to achieve the high-throughput characteristics, the mechanical probes are discretely arrayed in view of the required low lateral resolution. Here, each probe is attached on a thin membrane, allowing the function of two-dimensional support.

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[*] Corresponding author.

Table 1
Requirements of photoresist surface profilometer for next-generation photolithography with a comparison of typical profilometers.

	[Requirements]	AFM	Optical profilometer (interferometer)	Proposed profilometer using mechano-optical arrayed probe system
Vertical resolution	[10 nm]	0.1 nm	0.1 nm	10 nm
Lateral resolution	[500 μm]	0.1 nm	250 nm	500 μm
Measurement area	[30 mm × 30 mm]	Difficult (200 μm × 200 μm)	Depending on optical device	Depending on optical device
Applicability to transparent thin film	[Required]	Applicable	Difficult (due to multiple interference)	Applicable
Applicability to soft film	[Required]	Difficult (in contact mode)	Applicable	Applicable

4. In order to achieve the high-throughput characteristics, the entire height of arrayed mechanical probes is collectively measured at a time using an optical method.

This new method is expected to be applied not only to a soft material nondestructively, but also to a transparent thin film without a multiple interference effect and a mechanical probe scan.

3. Development of fundamental experiment system for validation of proposed concept

In order to verify the validity of the proposed concept, we developed a fundamental experiment system. The schematic diagram of the developed system is shown in Fig. 4. This system mainly consists of (1) a mechano-optical arrayed probe unit using a thin membrane, (2) a Zαβ-position/attitude control unit for the mechano-optical arrayed probe unit, (3) a XYZαβ-position/attitude control unit for a specimen, and (4) a white light interferometer as the optical profilometer for the arrayed probes.

Fig. 5 shows the detailed specification of the mechano-optical arrayed probe unit. Here, as the support for discretely arrayed probes, a SiC (silicon carbide) thin membrane with a thickness of 1 μm is employed in view of the fact that its fabrication technique was previously established in the field of an X-ray proximity exposure process. Each probe is made of a hard baked resist with a diameter of 50 μm and height of 38 μm, and the pitch of the arrayed mechanical probes is set at 500 μm based on the requirements in Table 1. In addition, in order to decrease the optical noise and provide a high sensitivity for measuring the height position of each mechanical probe with the optical method, the top of the mechanical probe is covered with a highly reflective coat of Ta (tantalum). Because of the first step for validation of the proposed concept, these probes are designed to be arrayed in 5 × 5 grids, meaning that the measurement area is 2 mm × 2 mm.

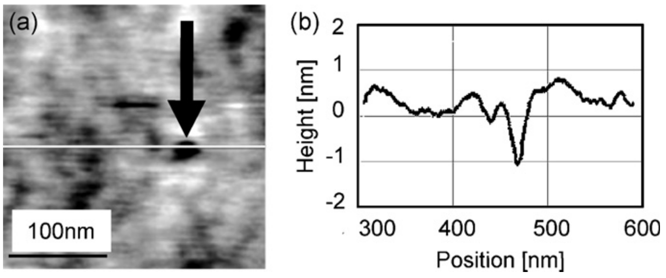

Fig. 1. Scratch on photoresist surface caused by AFM tip (tip diameter <10 nm, load 0.5 μN). (a) AFM image. (b) Cross-sectional profile of the white line of figure (a).

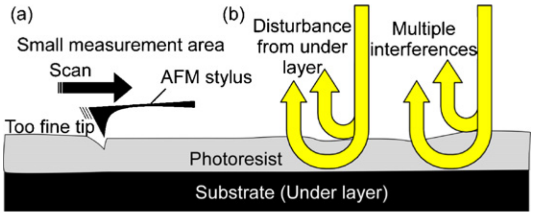

Fig. 2. Problems of conventional profilometer for photoresist surface. (a) AFM. (b) Optical method.

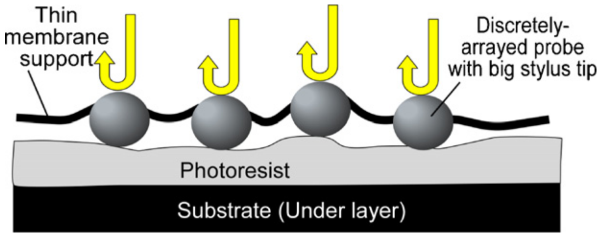

Fig. 3. Concept of the proposed method based on mechano-optical arrayed probe system.

Fig. 6 shows the fabrication process of the mechano-optical arrayed probe unit. After forming a SiC layer of 1 μm and a Ta layer of 100 nm in thickness on a silicon substrate, the thick posi-resist film was coated. By the photolithography and the hard baking process, discrete-arrayed probes with a top of tantalum are fabricated (I–III). In addition, by processing anisotropic wet etching on the backside of the silicon substrate with an area of 3.7 mm × 3.7 mm (IV), the mechano-optical arrayed probe unit using a SiC membrane can be fabricated. Fig. 7(a) and (b) show optical microphotographs, and Fig. 7(c) shows a SEM photograph of the fabricated unit.

In order to precisely control the tilt attitude of the mechano-optical arrayed probe unit, three piezo actuators (Newport Corp.: PZA-12) with a resolution of 30 nm over 12.5 mm travel are employed, as shown in Fig. 4. An angle resolution of 100 nrad for the tilt attitude control of the unit can be achieved. On the other hand, the specimen is set on a vacuum chuck attached to the

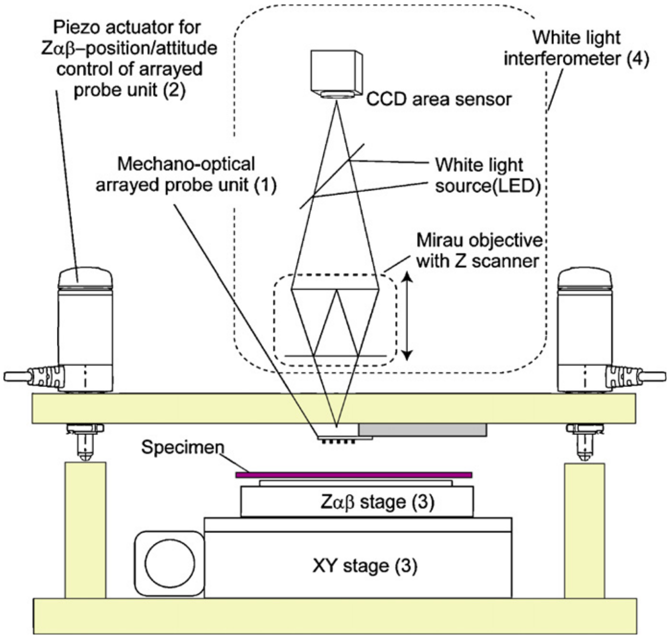

Fig. 4. Schematic diagram of developed mechano-optical arrayed probe system.

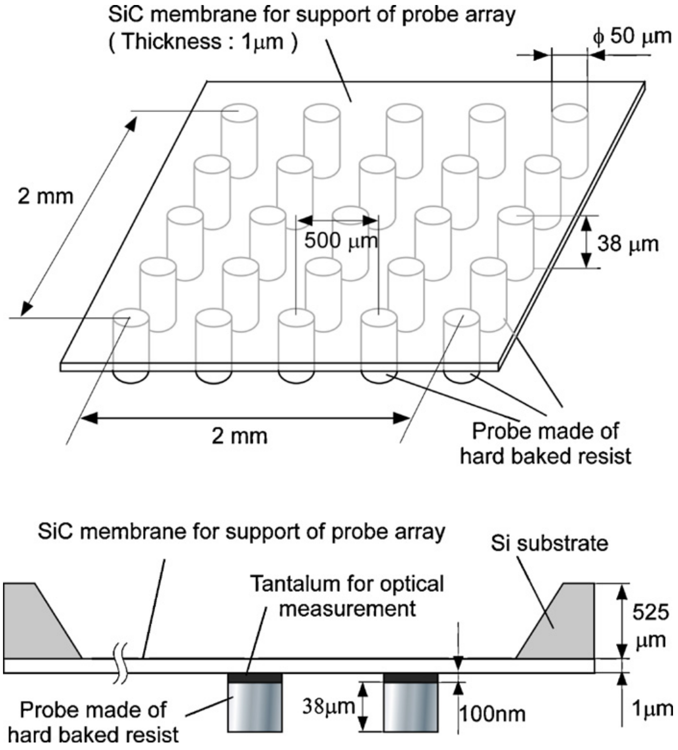

Fig. 5. Mechano-optical arrayed probe unit using SiC membrane.

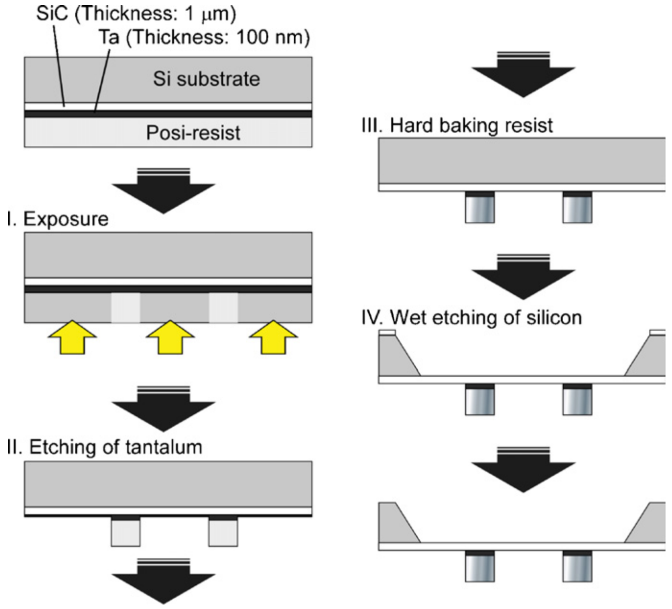

Fig. 6. Fabrication process of mechano-optical arrayed probe unit using SiC membrane.

XYZαβ-position/attitude control unit. This unit consists of an XY stage (COMS Co. Ltd.: PT100C-50XY) with a resolution of 1 μm over 50 mm travel and a Zαβ stage (PI Corp.: P-541.TCD) that includes integrated capacitive sensors with a resolution of 0.8 nm (80 nrad) over 100 μm (1 mrad) travel. The experimental setup is interfaced with a PC through a GPIB interface protocol using LabVIEW software. This system allows us to move the mechano-optical arrayed probe unit towards the specimen while keeping its surface horizontal.

As the optical method for detecting the vertical position of each probe, a white light interferometer (Zygo Corp.: New View 6300), which can detect height information with a height resolution of 0.1 nm and profile heights ranging from 1 nm to 150 μm, is employed because of its highly vertical resolution in this fundamental experiment system.

4. Verification experiments on the developed mechano-optical arrayed probe system

4.1. Validation of fundamental function of mechano-optical arrayed probe system

In order to verify the fundamental function of the mechano-optical arrayed probe system, an experiment measuring the profile of the top surface of the thin SiC membrane was carried out. Fig. 8 shows the white light fringes on the thin SiC membrane surface that were obtained with the video CCD as the mechano-optical arrayed probe unit was moved towards the sample in a push operation. After a probe contacted the sample surface, the white light fringes on the membrane began to change, meaning that the thin SiC membrane is flexibly deflected as the arrayed probe unit contacts the sample. That is to say, a shape-following for the sample can be achieved with the 1-μm-thick SiC membrane of the developed device under this condition. By analyzing each interferogram using a computer with a frequency domain analysis [13], we can get a three-dimensional profile of the top surface of the arrayed probe unit, as shown in Fig. 9. From this figure, it can be seen that all arrayed probes contacted on the sample surface, and the vertical position of each probe top can be simultaneously detected.

4.2. Validation of repeatability using the optical flat

In order to verify the reliability of the developed system, a fundamental experiment for evaluating its repeatability was carried out using an optical flat, surface flatness of which was λ/20 (Sigma koki., Co. Ltd.: TFA-50-C08-20). This experimental procedure is as follows:

1. The tilt of the optical flat is adjusted horizontally based on the white light interferometer using the XYZαβ-attitude/position control unit (Fig. 4 (3)).
2. The mechano-optical arrayed probe unit approaches the optical flat horizontally using the Zαβ-position/attitude control unit (Fig. 4 (2)).

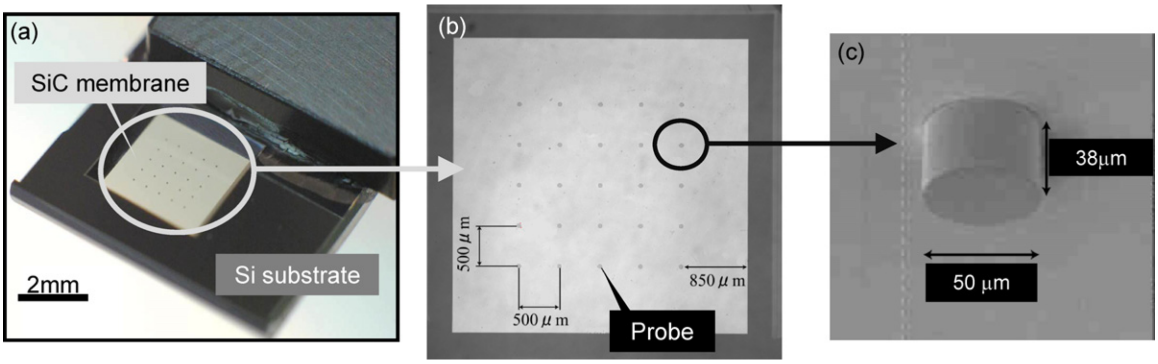

Fig. 7. Fabricated mechano-optical arrayed probe unit using SiC membrane. (a) Overview image. (b) Top view image. (c) Hard baked resist probe observed with SEM.

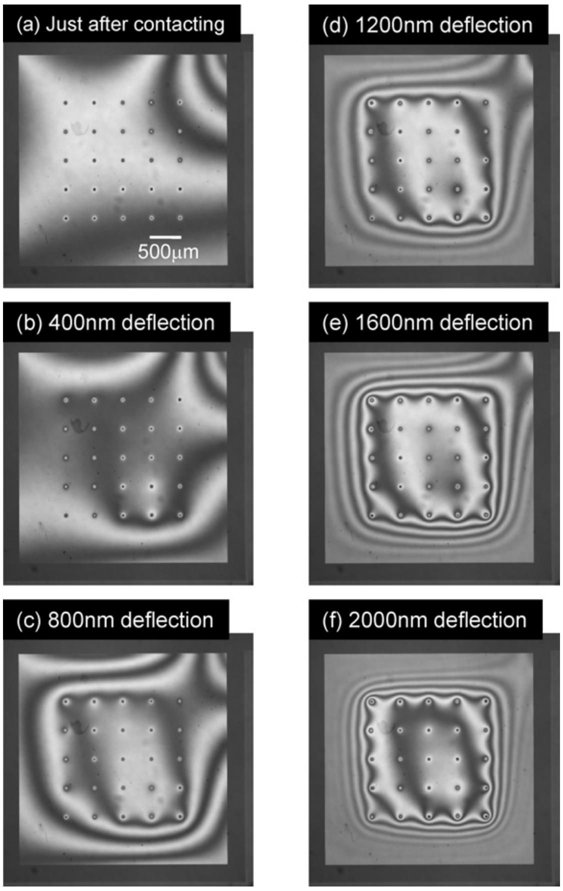

Fig. 8. White light fringes on the SiC membrane surface in moving down the mechano-optical arrayed probe unit.

3. After the first probe is contacting the optical flat, the mechano-optical arrayed probe unit keeps approaching in 10 μm travel, confirming that all probes are contacting on the optical flat.
4. With the white light interferometer, the height of each probe is simultaneously measured.

Tables 2 and 3 show the averaged values and the standard deviations of the height of each probe obtained from eight measurements. Here, “column” and “row” mean the horizontal position of the arrayed probe, and the relative values based on “column 3” were calculated in each row in consideration of slit-like shape of exposure are of scanners. From these results, it is true that each probe’s height is different from the others, mainly due to an individual difference caused in the fabrication process of the mechano-optical arrayed probe unit, but the repeatability of each probe is less than 10 nm. Since it is possible to calibrate the probe length differences using a proper standard, these results suggest that a vertical resolution of 10 nm can be realized with the mechano-optical arrayed probe system. In addition, the horizontal measurement area of this method does not depend on the measurement time of the probe scanning, but on the optics of the white light interferometer. In this case, the horizontal resolution of the optics is required to be at most 10 μm in view of the diameters of the probes. Therefore a horizontal range over tens of millimeters is expected to be realized.

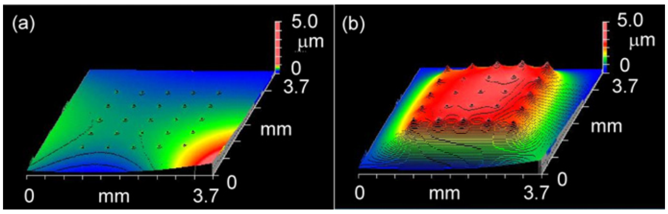

Fig. 9. Three-dimensional profile of the SiC membrane obtained by analyzing the white light fringes. (a) Just after contacting. (b) 3 μm deflection.

Table 2
Height value (nm) of each probe averaged from eight measurements.

	Column 1	Column 2	Column 3	Column 4	Column 5
Row 1	76.1	56.8	–	−61.9	−108.5
Row 2	52.0	64.0	–	−41.0	−85.8
Row 3	−40.4	11.3	–	6.6	4.8
Row 4	−139.9	−53.6	–	1108.8	50.8
Row 5	−249.8	−74.1	–	61.5	195.4

Table 3
Standard deviation (nm) of each probe height in eight measurements.

	Column 1	Column 2	Column 3	Column 4	Column 5
Row 1	4.1	1.2	–	3.3	5.1
Row 2	3.9	1.4	–	1.4	4.3
Row 3	6.0	0.8	–	1.2	5.1
Row 4	3.2	0.8	–	2.5	1.5
Row 5	4.8	2.4	–	6.0	5.8

5. Conclusions

We proposed a novel profilometer for a photoresist surface evaluation of a next-generation photolithography process based on a measurement principle that combines the advantages of an optical measurement and a mechanical probe measurement. Based on the proposed concept, a first prototype of a mechano-optical probe system using a thin membrane has been developed, and the feasibility of the new system has been evaluated by performing fundamental experiments using an optical flat. The results confirmed that the mechano-optical probe is capable of evaluating a surface profile at a time without a multiple interference effect and a mechanical probe scan. Its repeatability is less than 10 nm with a horizontal range of 2 mm. These results suggest that the proposed method has the potential of providing an on-machine measurement of a photoresist surface profile in a next-generation photolithography process.

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