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In-line metrology of nanoscale features in semiconductor manufacturing systems

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ABSTRACT

Quality control and defect monitoring are of great importance to the semiconductor industry. This article presents a system to enable inspection of nanoscale features in-line with nanomanufacturing processes. The ultimate goal of this research is to integrate this metrology system into current semiconductor manufacturing processes to enable true in-line wafer inspection and quality control. In the system presented in this paper, AFMs that have been shrunk down on to a single MEMS chip are used to scan the surface of a sample. A flexure-based mechanism allows the MEMS-based AFM to be positioned over a millimeter range of motion, with nanometer level precision when properly actuated. The performance of the system in areas such as positioning repeatability, AFM stability and measurement resolution are evaluated in this study. Owing to the small size of single-chip AFM (1 million times smaller than a conventional AFM instrument), it is a good candidate for multipoint detection. Overall, the system presented in this paper significantly shortens inspection time and dramatically decreases the setup time required for an AFM to load, approach, and measure a sample making in-line inspection of nanoscale features in semiconductor manufacturing systems feasible.

1. Introduction

Nanoscale manufacturing techniques enable technologies used in many aspects of daily life. The most common use of nanoscale manufacturing is in the production of integrated circuits (ICs) and microchips, which consist of billions of transistors and other electronic components in a small area (in mm^2 scale). These transistors are typically patterned in batches on silicon wafers and the critical dimension (CD) of these transistors has fallen from the micron scale to tens of nanometer over the last 25 years. In addition to the semiconductor manufacturing industry where many nanofabrication technologies were initially developed for the mass production of integrated circuits, many new nanomanufacturing processes are emerging for the photonics, energy, and healthcare industries where more complex three-dimensional structures are required [1–3]. As features continue to decrease in size and increase in complexity quality control and yield analysis become increasingly difficult. Therefore, metrology for nanopatterning is an important issue for detecting errors and reducing waste before the patterned wafer moves on to the next processing step.

Measurement of manufacturing processes can be performed either in-line as part of the manufacturing process or off-line in a separate process. Unfortunately, no methods currently exist to measurement nanoscale features in-line with high-rate nanomanufacturing processes. Therefore, inspection, if it is done at all, generally takes place offline using slow metrology methods such as atomic force microscopy (AFM) or scanning electron microscopy (SEM). However, in-line semiconductor inspection has several real advantages compared to off-line inspection. First, in-line inspection eliminates steps such as sample loading and unloading from the main assembly line for inspection. This results in an increase in throughput of chips that can be handled per unit time. In-line wafer metrology also decreases the time required to observe problems in the manufacturing process. As such, defects in masks and dies can be detected sooner and remedied earlier to increase yield. Finally, in-line inspection can be used to implement statistical process controls in order detect equipment issues before they lead to defects in the final manufactured product.

The limiting factors to enabling in-line nanoscale metrology are the resolution of the metrology tools and the total time required to take a measurement sample using present technologies. Decreasing the total time required to prepare and measure a sample is the key to enabling in-line inspection in nanofabrication. While a number of technologies are capable of imaging nanoscale features, advances

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in atomic force microscopes (AFMs) show promise for enabling true in-line metrology. High-speed AFM imaging techniques have been in development for many years. Currently, two methods exist for increasing AFM scanning throughput [4]. One method is to utilize an array of cantilever scanning tips instead of the traditional single tip. A second method for increasing throughput is to increase the scanning speed of a single tip. This method requires an increased resonant frequency because most of the commercial AFM instruments are already operating at frequencies close to their resonant frequencies. One way to increase the resonant frequency of the sensing cantilever is to reduce the dimensions of the AFM system. Conventional AFMs have a large number of components and have large moving masses but if the system is scaled down into a single MEMS chip it becomes possible improve the scan speed of the AFMs. This miniaturization also allows multiple, independent AFMs to be assembled into the production line enabling metrology to be directly embedded into nanomanufacturing system.

In this paper, we propose a new method for semiconductor metrology which incorporates multiple single-tip AFMs attached to a stage which can be rapidly brought into contact with the wafer to be measured [5]. In a typical inspection system, it is desirable to measure the same points on the wafers for each inspection. Therefore, the positioning repeatability of the AFM cantilever relative to the sample in an AFM system needs to be better than the scanning range of the AFM system, which is typically on the order of a few microns. In order to achieve this level of repeatability, a kinematic coupling is used to repeatably position the AFM stage relative to the wafer mounting stage. The AFM inspection system itself utilizes MEMS-based components such as flexures, actuators, and sensors to drive a microscale cantilever for high speed measurements [6]. This method allows for the rapid measurement of nanoscale features over the surface of a wafer. In the system presented in this paper, each single-chip AFM is mounted on a 2D stage that allows course-positioning translation over a 1 mm range and nanometer repeatability when the stage is lifted to accommodate a wafer sample. The presented system uses flexure bearings because of both the mechanical simplicity and high precision of flexures [7]. Moreover, because of the compact nature of the flexural bearing system, the inspection system presented in this paper has the potential to simultaneously utilize multiple MEMS-based AFMs within the confined area of the wafer surface in order to increase the area that is measured within a single metrology step. However, this paper focuses on the operation of a single AFM chip within the inspection system and presents the performance of the single-chip AFM inspection system including the error motion of X-Y flexure system, the repeatability of translation in each axis, and the stability of the single-chip AFM operation. Moreover, this paper investigates the cycle time and imaging resolutions of measurement with the system and proves the feasibility of the system for in-line inspection of nanoscale features.

2. Background

Geometric dimensions such as line edge roughness and sidewall angle are measured to ensure that tolerances are being maintained in nanomanufacturing processes. There is an extremely low margin for defect error in the manufacture of components such as processor dies. Producing components such as patterned media for memory requires excellent uniformity and tolerances for individual defects are somewhat relaxed [8]. The ideal nanomanufacturing metrology system would be capable of rapidly characterizing nanometer scale local defects and feature uniformity over a patterned area of a few hundred centimeters squared. Present technologies are limited to either high throughput metrology of average features or extremely low throughput metrology of individual features. Table 1 provides a comparison of existing metrology technologies and Fig. 1 illustrates resolution and throughput within metrology technologies. Note that the scanning areas are not standardized but the throughput must be based on not only the ratio of area and scanning speed, but also the sample preparation and uploading/unloading operation. Table 1 and Fig. 1 are just showing an approximation in scan time, the actual scan time is highly depending on the whole sample area in measurement. However, Table 1 tells that the bottleneck of throughput is the setup time, which takes up most of the measuring cycle time in each metrology technology.

Optical scatterometry is a metrology technology that can be utilized to measure average feature geometry with sub-nanometer resolution [12]. Optical scatterometry equipment detects changes in reflected light and through computational analysis of the reflected light yields information on average geometry [15]. Advanced metrology systems based on optical scatterometry are used in industry to detect overlay errors and add only 15 s of overhead per wafer [16]. Optical scatterometry is capable of high-throughput metrology with nanometer resolution, but its use is limited to determining average dimensions of dense repeated patterns.

Instruments such as the scanning electron microscope (SEM), scanning tunneling electron microscope (STEM) and atomic force microscope (AFM) are routinely used to characterize individual features at the nanometer scale. It is possible to resolve features down to the angstrom level with STEM and AFM and to the single nanometer level with SEM [9]. Presently all of the systems that are capable of resolving individual nanoscale features are used offline and are not suitable for in-line metrology in nanomanufacturing systems. Electron microscopes generally require vacuum [17] and use high energy electron beams that can damage sensitive substrates [9]. Furthermore, electron microscopy is only suitable for conducting samples.

Atomic force microscopy shows promise as a technique to enable high throughput nanometer scale in-line metrology. As compared to other metrology technologies such as optical scatterometry and SEM, the limitations of AFM are not inherent to its operating principle. The challenges of range and scanning speed can be solved while maintaining the basic operating mode and high resolution of a traditional AFM system. AFM metrology typically uses a single oscillating cantilever beam to laterally scan the surface of a sample. Current AFM systems are not suitable for in-line metrology due to limited lateral range and relatively slow scanning speed. The scan speed of AFMs are typically on the order tens of microns per second [4] due to attenuation of resonant stage frequencies at higher speeds. As the scan speed approaches the resonant fre-

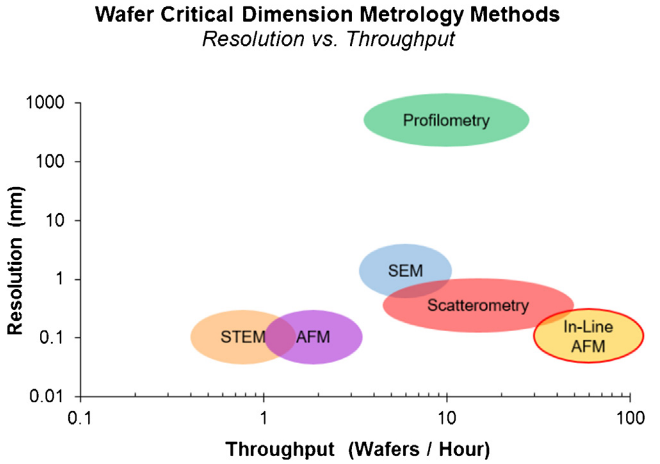

Fig. 1. CD Metrology Resolution vs. Throughput.