AUTOMATED NANO-DEFECT REVIEW OF MECHANICAL, ELECTRICAL AND CHEMICAL CHARACTERIZATION BY SCANNING PROBE MICROSCOPY

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Abstract - SPM technology is the most versatile tool born in the field of applied physics. SPM has now begun to be applied to high-tech industries such as next-generation semiconductor and display industries. With decreasing device sizes, nanometer-sized defects on the wafer substrates can already limit the performance of the devices. These defects' detection and precise classification require additional characterization methods with a resolution in the nanometer range. It is well known that Scanning Probe Microscopes (SPM) can measure not only surface morphology but also mechanical and electrical properties. However, the versatility of SPM is not fully utilized in industrial applications due to its various limitations. Various limitations include low throughput and tip life and laborious efforts to find the defects in inline automated defect review (ADR). This paper introduces the ADR SPM with mechanical and electrical characterization capability. In addition, newly developed Photonic induced Force Microscopy (PiFM) technology to obtain chemical signatures with 10 nm resolution.

Keywords - Scanning Probe Microscopy, Atomic Force Microscopy, Pinpoint Mechanical Analysis, Kelvin Probe Microscopy, Photonic Induced Force Microscopy

I. INTRODUCTION

Because the pattern size of the lithographic process continues to be smaller, defects that could previously be ignored have now reached levels that cannot be ignored compared to the pattern size. For example, a manufacturer can ignore a 10nm-sized defect in tens of microns-sized feature but no longer ignore it in a 50nm-sized pattern. As a result, defining the defect's identity and cause determines the engineering process's success. Nano meter size defects are too small so that they could be misclassified by automated optical inspection (AOI) and require post-processing for proper classification [1].

Analyzing surface morphology of nm-scale defects was successfully introduced using the automatic defect review (ADR) function of the Atomic Force Microscope (AFM), one of the Scanning Probe Microscopes (SPM) [2~4]. AFM is particularly advantageous because it not only directly measures the dimensions (height and width) but also provides physical properties of defects of interest together with providing reference information for other characterization tools. However, the versatility of AFM is not fully utilized in industrial applications due to the various limitations, including low throughput and limited tip lifetime, in addition to the laborious efforts to find the defects. In this paper, we introduce the true potential of ADR AFM as a post-inspection metrology tool for defect studies.

In addition, we explore the possibility of the advanced SPM technologies leading to defect analysis through the field examples of mechanical, electrical, and chemical characterization. This paper introduces the latest force volume method called "pinpoint nanomechanical mode," which quantitatively investigates a surface's mechanical properties [5]. It describes how the method can be used to analyze the stages at which defects are generated during the material surface processing. It is generally challenging to determine when the defect was generated during production solely from surface morphology observation. Here, we propose a way to resolve this issue using pinpoint nanomechanical mode. It gathers mechanical information on the surface and not only determines the characteristics of the defect but also repairs the defect through mechanical interaction.

The discovery of Electrical SPM technologies in the mid-1990s has made a remarkable contribution to maintaining device reliability in various industries such as semiconductor, solar cell, and hard disk drive manufacturing, among others [6,7]. The ever-shrinking dimensions of materials and devices in these industries have reached the limit of conventional test methods such that bulk property measurements can no longer describe their behavior. For this reason, measuring the local electrical properties of materials has become more effective than bulk property. Among SPM technologies, the most differentiated technology is the measurement of electrical properties at the nanometer level. Typical SPM electrical property measurement modes include Conductive AFM [8], Scanning Capacitance Microscopy (SCM) [9], Scanning Spreading-Resistance Microscopy (SSRM) [10], Kelvin Probe Force Microscopy (KPFM) [11~13], and Piezoresponse force microscopy (PFM) [14]. These electrical properties measurement modes are widely used in material research, but it is not widely used for industrial use until now. However, it is expected to become a reality soon as the demand for measuring

electrical properties in the nanoscale in the semiconductor industry is rapidly increasing.

The chemical property analysis on the nanometer scale has been a long-cherished desire for researchers to develop and study mixed compounds. Raman measurement technologies such as Micro-Raman [15], Nano-Raman [16], and Tip Enhanced Raman Spectroscopy (TERS) [17~18] were expected to realize this possibility, but they have yet to be applied to the industry due to their weak signals. Fourier-transform infrared spectroscopy (FTIR)[19] is a technique used to obtain an infrared spectrum of absorption or emission of a solid, liquid, or gas which allows us to analyze the distribution of different chemical species within the sample. It is difficult to use FTIR to analyze the nanoscale sample due to its beam spot resolution. Photo-induced force microscopy (PiFM) overcomes the resolution limit of FTIR by using mechanical instead of optical detection to measure the near-field optical interaction between the tip and sample. PiFM allows AFM to easily detect the local polarization of the sample by tip-enhanced optical illumination mechanically to increase resolution dramatically by eliminating the problem of background scattering [20~21].

This paper introduces the potential application of the electrical and chemical characterization of ADR, eventually leading to failure analysis. The advanced automated process and SPM-based physical property measurements enable ADR SPM to complement any manufacturing control toolset and provide applied physical solutions to the semiconductor industrial problems.

II. DETAILS EXPERIMENTAL

2.1. AFM Automatic Defect Review Process

In the manual AFM defect review, a wafer is inspected by an inspection tool, and engineers search for defect location manually and collect the images at the AFM. In order to help to find the defects easily, the defect locations sometimes require an additional search using an optical microscope and marking the defect for AFM. The coordinate alignment, defect search, and defect imaging and classification are the essential automated components of the ADR AFM procedure. Fig. 1 indicates the automated process of ADR AFM, which is locating defects of interest (DOI), performing the survey scan, and imaging. In ADR AFM, DOI coordinates from the inspection tool are initially imported, followed by coordinate alignment in AFM. Locating the defect in ADR AFM requires the ability to read the coordinates from any inspection tool and to minimize the stage positioning error by coordinate alignment. Due to the various coordinate systems used in inspection tools by different manufacturers, the ADR AFM can accommodate either Cartesian or polar coordinates in different directions. The alignment is performed in two steps. A coarse alignment, called circle alignment, is performed to determine the sample's amount of translation and rotation. Three random wafer edges are used for finding the center of the wafer, and the notch is used as the angular reference between the tools. In order to minimize the positioning error, a second alignment is performed, called fine alignment. If the wafer has any markers (e.g., alignment or fiducial markers), their coordinates from the inspection tool are used as references for fine-tuning the initial alignment and minimizing the positioning error between ADR AFM and the inspection tool.

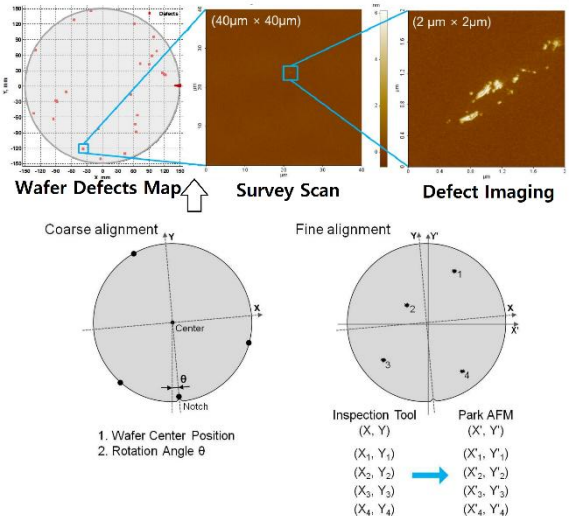


Fig.1.Automatic defect review (ADR) process of locating the defect, imaging, and analysis and alignment procedure used in ADR AFM to minimize the positioning error of locating the defects based on the coordinates provided by inspection tool. Coarse alignment for finding the center of the wafer and its rotation and fine alignment by using large defects to correct for skewness of inspection tool coordinate system are performed.

2.2. Pinpoint Mechanical and Electrical Measurements

AFM has become a fundamental tool for studying nanomechanical properties such as Young's modulus and adhesion force on a nanometer scale for various samples like polymers, 2D materials, or biological samples. Traditionally, force-volume mapping is used to measure quantitative mechanical properties. For that, isolated force-distance measurements are conducted at a defined number of pixels. The cantilever is pressed onto a surface until a previously defined threshold, the setpoint force, is reached. During the approach and retraction, the cantilever deflection is measured as a function of the z height. Subsequently, the cantilever is moved to the next pixel, where another force-distance curve is measured. Conventionally, it takes at least a few hundred milliseconds to collect a single force-distance curve, which scales up to several hours when recording whole images with thousands of pixels. PinPoint nanomechanical mode was developed to accelerate conventional force-volume mapping while maintaining high precision and accuracy. Similar

toregular AFM scanning mode, a customizable channel selection allows obtaining various quantitative mechanical data in combination with high-resolution topography and functional electrical data like conductivity and capacitance.

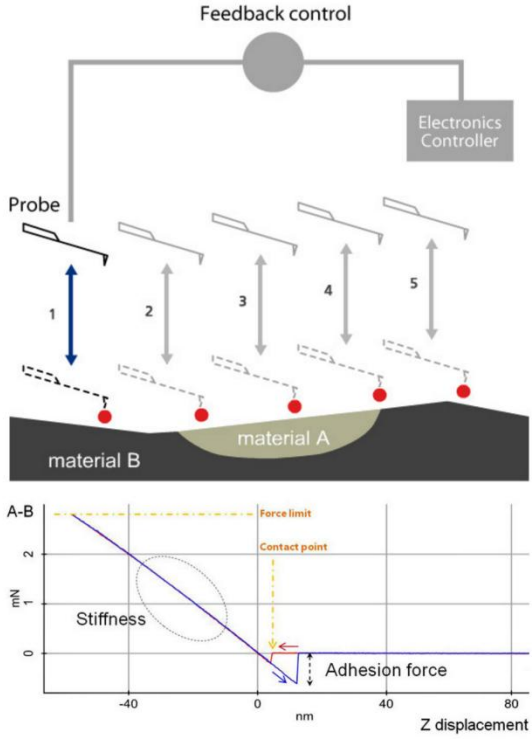


Fig.2.A schematic representation of PinPoint mode operation. The probe approaches towards the sample surface until a pre-defined force threshold is reached, and at each point force-distance curves are taken to calculate the nanomechanics each point. Then the probe retracts away from the surface and move to the next pixel. The process repeats to collect the topography map and the nanomechanical response map.

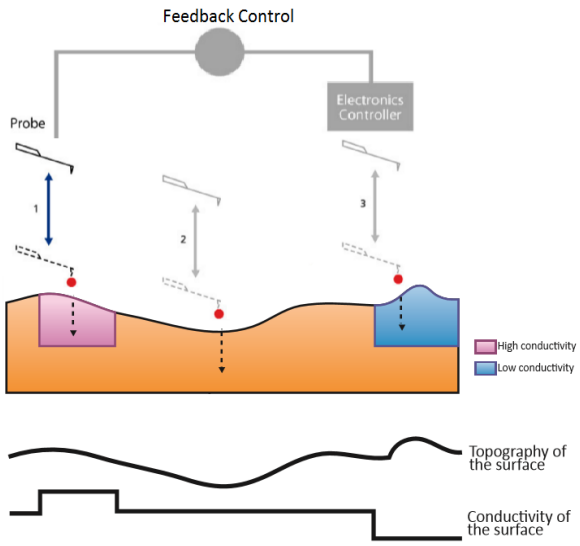


Fig.3.Principles of PinPointConductive AFM. This diagram demonstrates the feedback-controlled approach and retraction of a C-AFM probe at multiple sites along a sample's surface. Feedback control from the AFM system's controller allows this technique to acquire both surface topography and conductivity data as in traditional C-AFM and tapping C-AFM, but without the drawbacks.

The pinpoint conductive AFM mode operates in an approach-retract manner, ensuring a frictionless operation that eliminates the lateral force due to continuous tip-sample contact (Fig. 3). In addition, the contact time and contact force between the tip and sample surface are controllable, allowing the acquisition of accurate and reproducible electrical data even with soft samples, such as polymers.

2.3. Chemical analysis of Photo induced force microscopy

Photoinduced force microscope (PiFM) combines optical absorption spectroscopy with AFM to produce chemical imaging and a 3D topographical image. As the laser light excites material-specific polarization, PiFM detects the photo-induced molecular polarizability by mechanically detecting the force gradient from the optically driven molecular dipole and its mirror image in the metallic tip [22, 23]. The cantilever is driven at f1 while the excitation laser is modulated at fm. Since the illumination source is modulated at fm, frequency mixing produces a sideband component at f1−fm = f0 inducing Q-enhanced cantilever vibration at f0. Lock-in detection of the cantilever motion at f0 generates the background-free PiFM signal corresponding to the nanometer-scale conventional FTIR signal (Fig. 4).

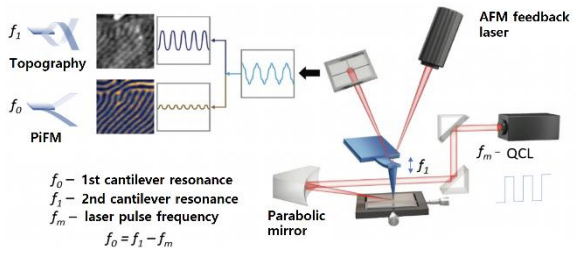


Fig.4.A schematic representation of Photonic induced Force Microscopy (PiFM) mode operation. The incident mid-IR laser is electrically triggered to pulse at fm = f1 – f0 where f0 and f1 are the first and second resonance frequency of the cantilever. The topography of the sample is measured at f1, and the photo induced dipole-dipole interaction force is measured at f0

III. RESULTS AND DISCUSSION

3.1. Pinpoint electrical analysis of ZnO nanorod

Zinc Oxide (ZnO) nanorods are widely used due to their unique electrical and optical properties. They are utilized in a electronics, optics, photonics, and photocatalysis. However, the electronic performance of these devices are often linked to the presence of surface defects and changes to the surface, which are not observable when performing bulk measurements. We demonstrate that Pinpoint Conductive AFM can measure the current distribution of a ZnO Nanorods in high resolution. The pinpoint conductive AFM provides a controlled and frictionless measurement that allows to measure the topography and conductivity of a sample with minimized measurement artifact (Fig. 5).

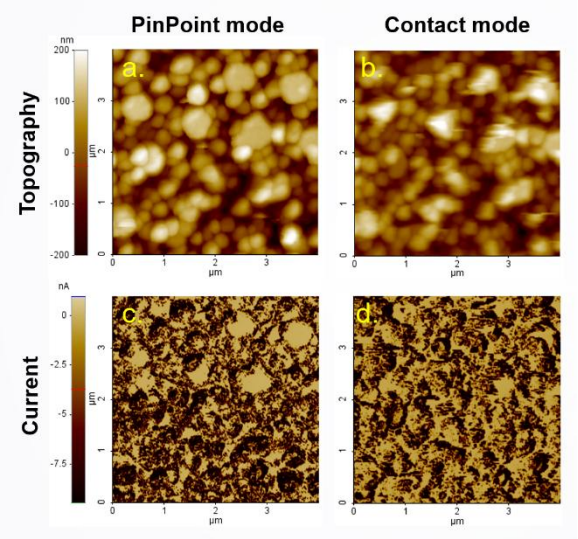


Fig.5. 1.) Data acquired using pinpointconductive AFM (Topography: a, Current: c.) 2.) Data acquired using contact conductive AFM (Topography: b, Current: d)Scan size: 4 x 4 µm, image size: 256 x 256 pixel.

The topography data measured using the two techniques are shown in Figures 5a and b. The images revealed that the scanned area of the sample is composed of tendril-like structures that are grouped, pointing in an upright position. Each hexagonal nanorod's cross-sectional shape is observed with diameters varying from 200 to 800 nm and heights ranging from 30 to 200 nm. The topography data measured by contact AFM has poor quality compared to pinpoint AFM due to lower spatial resolution and artifacts visible in some areas of the image. Such quality can be attributed to continuous tip-sample contact that produces high frictional force leading to damage to both the tip and the sample, and a low signal-to-noise ratio that intensively degrades the accuracy of the acquired measurement. The current distribution of the sample is shown in figures 5c and d. The intensity of the shading correlates to the degree of surface conductivity. In this experiment, the darker regions represent a higher surface conductivity, while lighter regions represent a lower surface conductivity. The absolute value of the current for an individual nanorod ranges from 0 to 9 nA. By comparing the results of the two techniques, pinpoint conductive AFM shows more sensitivity in detecting local conductivity variations, and contact conductive AFM shows less conductivity with fewer features. Shorter contact time during the measurement may contribute to the poor image quality. Pinpoint electrical mode also demonstrated that the ZnO nanorods with smaller diameters are more conductive than those with larger diameters.

3.2. Photo induced force microscopy (PiFM) of a defect on a Si wafer.

As shown in Fig. 6, the surface topography and chemical analysis of an unknown defect on a 300mm wafer was measured using the AFM and PiFM mapping modes. These observations provide nanometer scale confirmation of the defect and its identification. AFM topography (Fig.6a) and PiFM images at 780 cm^{-1} ((Fig.6b) and 930 cm^{-1} (Fig.6c) of unknown defect on a 300mm Si Wafer. PiFM images demonstrated (Fig.6b) that the unknown defect responds at 780 cm^{-1}. PiFM point spectra at point 1 showed a strong peak at wavenumber 780cm^{-1}. As a result of the analysis, the defect is estimated to be a SiC component.

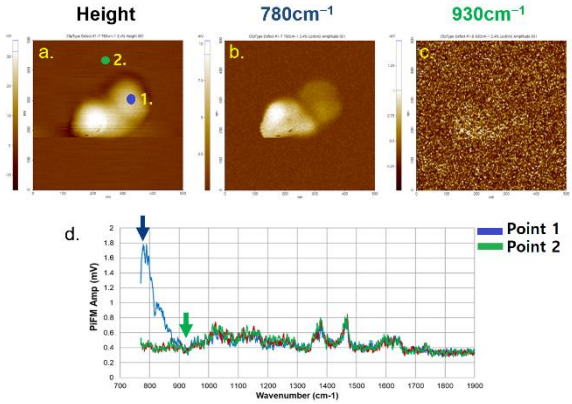


Fig.6. AFM topographical image (a.), Photo induced force microscope images at 780 cm^{-1}(b.) and at 930 cm^{-1}(c.) and IR spectroscopy data(d.) of SiC defect on Si Wafer at points 1 and 2.

IV. CONCLUSION

As device size becomes smaller and smaller, the role of AFM as an accurate and high-resolution technique becomes essential. The ADR AFM can complement the defect review process as a non-destructive, high-resolution technique by providing three-dimensional information on the defects. Additional functional analysis of SPM technology can significantly enhance the analysis of the defect and provide more concrete clues to improve the engineering process. Pinpoint nanomechanical and electrical mode will successfully provide researchers with critical material property information to better understand their samples at the nanoscale. Chemical analysis on the nanometer scale of PiFM will provide clues that can be modified more strongly than any measurement technology. As such, the development of SPM technology will provide an opportunity to solve various problems in the high-tech industry.

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