Ultramicroscopy 158 (2015) 8–16

Contents lists available at ScienceDirect

Ultramicroscopy

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

Atomic force microscope caliper for critical dimension measurements of micro and nanostructures through sidewall scanning

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ARTICLE INFO

Article history:
Received 22 November 2014
Received in revised form
29 May 2015
Accepted 9 June 2015
Available online 17 June 2015

Keywords:
Atomic force microscope
Dual probe
Caliper
Critical dimension
Sidewall
Micro and nanostructures

ABSTRACT

A novel atomic force microscope (AFM) dual-probe caliper for critical dimension (CD) metrology has been developed. The caliper is equipped with two facing tilted optical fiber probes (OFPs) wherein each can be used independently to scan either sidewall of micro and nanostructures. The OFP tip with length up to 500 μm (aspect ratio 10:1, apex diameter ⩾10 nm) has unique features of scanning deep trenches and imaging sidewalls of relatively high steps with exclusive profiling possibilities. The caliper arms–OFPs can be accurately aligned with a well calibrated opening distance. The line width, line edge roughness, line width roughness, groove width and CD angles can be measured through serial scan of adjacent or opposite sidewalls with each probe. Capabilities of the presented AFM caliper have been validated through experimental CD measurement results of comb microstructures and AFM calibration grating TGZ3.

1. Introduction

Critical dimensions (CDs) such as line width (LW), line width roughness (LWR), line edge roughness (LER) and CD angles have increasing impacts on performance of shrinking nano-devices, e.g. photonic devices [1,2], nanometer-scale electronics [3], plasmonics and nanophotonics [4], semiconductor fabrication processes with deep reactive ion etching (DRIE) [5] and focused ion beam (FIB) milling [6] result in extremely high-aspect-ratio structures [7]. Similarly, in the recently invented FinFET, tremendous effects of the gate surface roughness on the performance of the device have been observed [8]. The emerging next generation of nanodevices has overemphasized the need for more powerful metrology instruments.

Photon-based microscopies have been traditional ways for CD metrology. Conventional optical microscopy has inherent optical diffraction limitation while scatterometry require priori sample surface information and rigorous modeling for data extraction [9,10]. Electron-based metrology instruments, including CD scanning electron microscopy (CD-SEM) [11] and transmission electron microscopy (CD-TEM) [12], are commonly used methods. However, applications of the CD-SEM and CD-TEM are limited by their inherent two-dimensional (2D) measurements. In addition, sample preparation for the CD-TEM is time consuming, destructive and costly. Soon after invention [13], atomic force microscope (AFM) has been regarded as an important techniques for CD metrology. The realization of CD-AFM is a breakthrough as it provides the three-dimensional (3D) topography of patterns with high spatial resolution, well suitable for CD metrology. Unfortunately, conventional AFM probe is aligned normal to the sample surface and cannot provide enough information on the sidewalls. To trace a solution to this problem, numerous CD-AFM techniques have been developed during last two decades. K. Murayama et al. developed tilt angle scanning method to image sidewall topography of fine patterns [14]. M. Watanabe et al. developed step-in mode with CNT probe for sidewall measurement [16]. CNT tips mounted on standard AFM silicon cantilever were also utilized for CD measurements [16,17]. With this technique the AFM can scan narrow patterns, but during CNT tip assembly, it is difficult to control the angle and length of the CNT. In addition, the CNT probe suffers from imaging instability in tapping mode [18]. In other investigations, probes with special tip geometries, e.g. flared tip [19], trident shaped probe [20], boot-shaped tip [21,22] and assembled probe [23] were used to scan steep sidewalls. Their application is limited to specialized measurements or provide low surface resolution due to comparatively big tip radius and a complex blind estimation would be required for accurate CD measurements [24,25]. M. Fouchier et al. proposed a technique by tilting the sample for sidewalls imaging [26,27]. This approach is suitable for sidewall scan with a complex calibration routine [28]. Recently, a three-dimensional (3D) AFM has been developed to scan undercut

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http://dx.doi.org/10.1016/j.ultramic.2015.06.007
0304-3991/

sidewalls with nanometer precision [29]. It demonstrates great potential to CD metrology of the sidewall structures. To measure the linewidth of high aspect-ratio features a dual probe AFM caliper was proposed [30]. However, the study presents a conceptual prototype which lacks experimental validation of the caliper's performance.

LW and LWR measurements have been challenging in semiconductor metrology. In SEM or TEM, these CDs are difficult to measure in top-down view whereby overhang or re-entrant sidewall features hinder visibility. Similarly, cross-section view cannot visualize nonlinear features along view-axis so that the sample needs to be cut into sections for complete feature characterization. On the other hand, conventional CD-AFM with a single probe cannot measure LWR and LW due to its inability to simultaneously scan both sidewalls. Although CD-AFM with flared tip has capability to scan both sidewalls, its applications are limited due to short and large blind areas.

We report an dual-probe AFM caliper that is able to serially scan adjacent or opposite sidewalls without specimen rotation. The line width (roughness), line edge roughness and CD angle can be precisely measured by the accurately calibrated caliper. With two tilted OFPs of relatively long tips, the AFM caliper is more scalable and efficient than the conventional CD-AFMs to characterize sidewalls of micro and nanostructures.

2. System configuration and methods

2.1. Setup of the AFM Caliper

The AFM caliper is developed on a home-built dual-probe AFM [31,32]. New probe holders were designed and each has a rotating lever that can be used to tilt the OFP at angles of 0–90°. Fig. 1 shows the schematic diagram of the caliper composed of two facing optical fiber probes (OFPs), namely Left OFP (OFP-L) and Right OFP (OFP-R). Each probe has an independent optical lever with a laser source and a PSD (PSD I and PSD II). OFP-L is mounted on a x–y–z micropositioning stage I (MP I) for coarse positioning. OFP-R is supported by x–y–z nanopositioning stage II (NP II; $10 \times 10 \times 10\ \mu m$ of travel range and 0.1 nm of motion resolution) that is further assisted by x–y–z micropositioning stage II (MP II). NP II and MP II are used to drive OFP-R with nanoscale resolutions. Sample is placed on a set of two independent stages x–y–z MP III and x–y–z NP I ($75 \times 75 \times 75\ \mu m$ travel range and 0.1 nm motion resolution). Image scan can be accomplished by OFP-L and OFP-R independently and coordinately driving both nanopositioning stages.

An optical microscope ($20\times$) is used for coarse aligning the caliper, as well as locating the laser spot on each probe and desired pattern on the sample. An oscillation controller (Dual-OC4) is used to control the probe dynamics and a high-speed (2 MHz maximum sampling rate) data acquisition system is used to record data from the PSD. A multi-thread planning and control system has been developed for the feedback control on the y-axis and raster scan of the sidewalls on xoz plane. The control system allows programming of complex tasks of caliper alignment, image scan, data acquisition and processing.

2.2. Description of the optical fiber probe

Optical fiber probes (OFPs) (Nanonics Imaging Ltd., stiffness: 3 N/m) are used in the proposed AFM caliper. Each OFP can be used for imaging surface topography with nanometric resolution. Force modulation and intermittent contact modes are available for a variety of surfaces and for a range of materials and structures.

Fig. 2(a) shows an optical microscope image ($20\times$) of the OFP, which has a cantilever length of ~1000 μm, a tip length of up to 500 μm and tip diameter ≥10 nm. Compared with standard silicon AFM probes (with a tip length of 10–20 μm), the OFP tip has unique features of scanning sidewalls (tens of micrometers). Its high-aspect-ratio (10:1) tip provides distinctive profiling possibilities. Fig. 2(b) represents a frequency spectrum of the first bending mode of a typical OFP (the resonance frequency $f_0 = 63.351$ kHz and quality factor $Q = 202$). The OFP has a comparable Q factor to that of the conventional silicon probe. The Q factor control is not mandatory for the normal-speed intermittent-contact-mode AFM imaging since sensitivity and response time are balanced. The OFP has potential to scan the sidewall without any alterations to the system, even at larger tilted angles, e.g. more than 47° with a tip length of 500 μm, a cantilever length of 1000 μm and a mounting angle of 8°.

2.3. AFM imaging with the optical fiber probe

Fig. 3 shows the schematic and working principle of the OFP. Deep trenches can be scanned by the vertically installed OFP

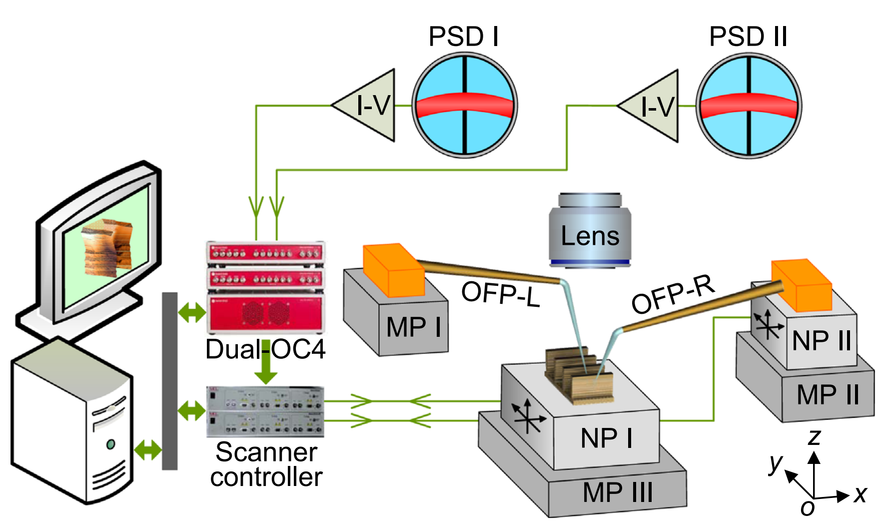

Fig. 1. System configuration of AFM dual-probe caliper. Three x–y–z micropositioning stages, MP I, MP II and MP III are used for course positioning of OFP-L, OFP-R and the sample, respectively. Two x–y–z nanopositioning stages, NP I and NP II are used for image scan and caliper alignment, respectively. Probe dynamic control is performed by an oscillation controller (dual-OC4) with laser feedback from PSD I and PSD II. CD measurements are accomplished by a multithread planning and control system.