Design Considerations for Quasi-Continuous, Inline Measurement in Roll-to-Roll Nanomanufacturing

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ABSTRACT

This work aims to (1) review pertinent needs in the metrology landscape for evolving roll-to-roll nanofabrication processes and current art solutions which attempt to address these applications, and (2) posit precision design considerations which may enable a new class of tools for semi-continuous sampling of moving webs in R2R manufacturing with traditionally slower approaches that can achieve low levels of measurement uncertainty and resolve sub-diffraction features, patterns, or critical dimensions.

1. INTRODUCTION

Roll-to-roll (R2R) fabrication of nanofeatured products promises to enable devices which meet or exceed the performance of traditionally wafer- or glass panel based manufacturing. Further, through the use of thin, flexible substrates, R2R fabricated products inherent the advantageous mechanical properties of the substrate and R2R processing significantly lowers device costs [1]–[4]. From functionalized materials like anti-fouling or anti-microbial coatings to displays, and even compute, logic, or memory, the driver for more compact, higher performance, and lower cost products has led to a significant amount of community interest in research to enable R2R processing techniques which can successfully bridge the lab-to-fab valley of death towards high volume manufacturing (HVM) [5]–[9]. While implementation of these techniques has occurred, widespread adoption, specifically for nanometer scale patterns, is still limited in a significant manner — process metrology [10], [11]. Fig. 1 shows three areas of research need by a National Institute of Standards and Technology (NIST) analysis of future advanced R2R fabrication [12]. Without a comprehensive solution which can address these hurdles, R2R fabrication of nanoscale patterns and products could easily fail to come to fruition.

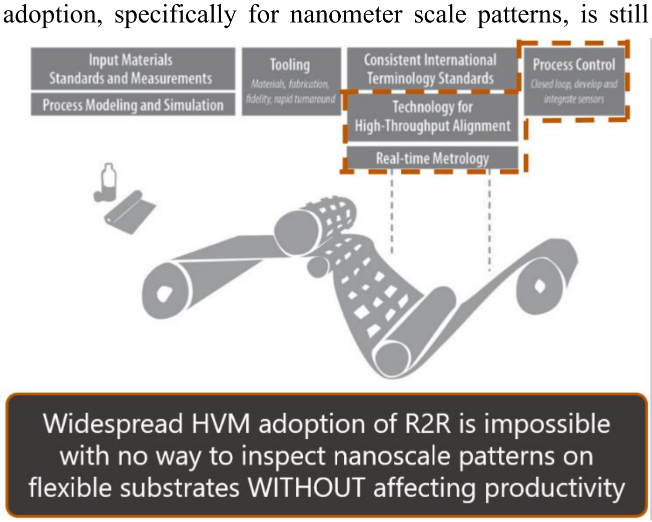

Figure 1: Major areas of research focus for advancing R2R manufacturing

1.1 The Metrology Landscape in R2R Nanopatterning

A significant body of work for R2R nanometrology focuses on optical or photonic methods given their non-contact and high throughput properties, and promising results have been presented in specific use cases [13]–[17]. For example, hyperspectral scatterometry has been demonstrated with accurate results and has become a staple of wafer based HVM over the last decade [18], [19]. This approach has been successfully extended to the R2R environment for in-line process control [20] in addition to methods like diffractometry for both substrate and master imprint template monitoring [21]. While these techniques have proven to be precise and non-destructive at throughputs commiserate with R2R manufacturing, these approaches can only resolve collections of features - spatial resolution is still inherently diffraction limited. This restricts applications for tasks such as defect root cause analysis that require direct nanoscale topography data, and further, requires a measurement calibration library, typically a time consuming and computational expensive process to build. While direct measurement of nanoscale features is common in rigid-substrate manufacturing with tools such as atomic force microscopes (AFMs) and scanning electron microscopes (SEMs), there exists a gap when it comes to R2R due to the inherent difficulty in out-of-line sampling [22], [23].

Where in wafer-based manufacturing it is trivial to take a single wafer for out-of-line inspection in a separate, slower, and more precise measurement tool, the opposite is true of R2R. As a sample may only be physically cut out of a web or roll of material, this procedure is often only possible after an entire roll of material has been processed – potentially leading to large amounts of waste if a process shifts out of control at the beginning of a roll and is not caught until an out-of-line sample is measured at the end of processing of a roll of material. As new and increasingly effective hybrid metrology methods develop, the importance of this gap in capabilities increase. Hybrid metrology, or a measurement approach where multiple tools, each with its own inherent measurement advantages, are used as inputs to a some sort of algorithm, be it a black-, grey-, or physics-based-box, to decrease overall measurement uncertainty [23]. The aim of this approach is the creation of an system which seamlessly integrates information from multiple tools and informs closed loop process control, as is shown in Fig. 2 [24]. This could thus aid in improving yields to the point of economic viability for often nascent R2R processes, however, the lack of available high-resolution, direct topography measurement tools compatible with a R2R architecture has prevented full adoption of hybrid metrology frameworks in current art.

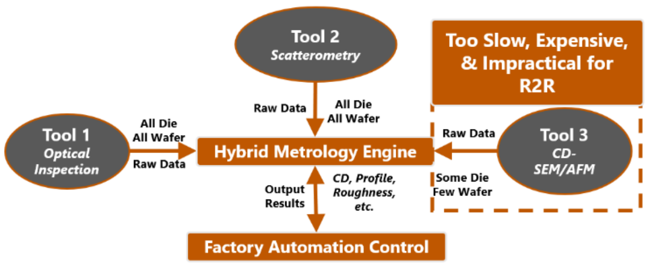

Figure 2: Cartoon schematic outlining the basic process flow for hybrid metrology approaches in high-volume semiconductor manufacturing.

DESIGN FOR QUASI-REALTIME SAMPLING

In order to enable inline sampling with a throughput which will not affect overall R2R processing speed and a level of precision on the same order of magnitude of traditional AFM and SEM tools, a new framework for process metrology is required [25]. Two primary domains must be considered – web registration and regulation, and single chip atomic force microscope (sc-AFM) probe positioning. This presentation will focus on performance of the sc-AFM measurement probe and approaches for the machine structure, sensing, and actuation strategy for both unwind/rewind roller stands and the probe positioning system shown in Fig. 3, with the goal of providing an order-of-magnitude increase in the available process metrology data for yield enhancement and process development in comparison to traditional high-precision, and critically, out-of-line based sampling.

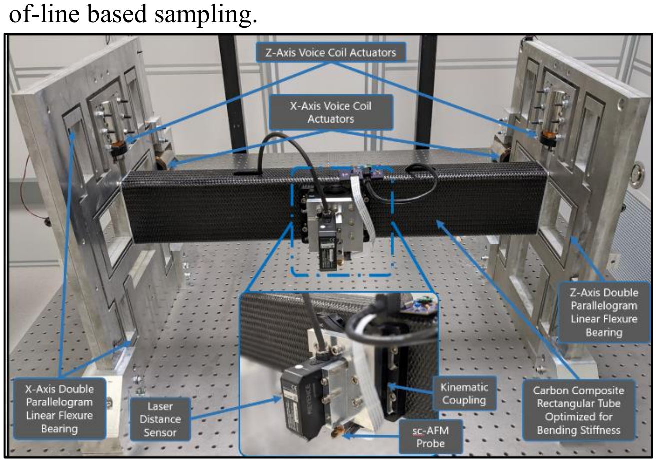

Figure 3: Preliminary upgraded sc-AFM probe positioning setup

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