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Measuring the future - Nanometrology for advanced manufacturing of miniaturized devices

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Abstract
Nanometrology is a cornerstone of modern manufacturing, pivotal in enabling precise measurements and materials characterization at the micro- and nano-scales. Therefore, we provide a short perspective based on [1] that explores the crucial contributions of nanometrology to advancing the frontiers of high-tech manufacturing, with a particular focus on quality control of diverse material assemblies and hybridization. The cutting-edge contribution of nanometrology to the Internet of Things (IoT) is closely tied to the meticulous development of miniaturized devices. The assessment of novel scanning, sensor, and probing techniques generates valuable insights into measuring nanoscale device dimensions, architectures, composition, and properties, while reducing the influence of measurement distortions, noise, and high-aspect ratios. Furthermore, we guide interested readers through methods applicable for field-effect transistors (FET), n-type or p-type metal oxide semiconductor field effect (n/p-MOSFET), metal-insulator semiconductor field effect (MISFET), novel complementary metal oxide semiconductor field effect transistors (CMOSFET), as well as magnetoelectric (ME) micro and nanoelectromechanical systems (ME M/NEMS). In this regard, nanometrology will revolutionize advanced manufacturing of miniaturized devices by ensuring their quality, thus propelling industries towards unprecedented levels of precision, repeatability, and efficiency to meet the ultimate goal of far-field very low frequency (VLF) communication in IoT with minimal energy consumption, low power loss, and outstanding multifunctionality/versatility.

nanometrology, miniaturized devices, fabrication quality, resolution, uncertainty

1. Introduction

As technology advances, precise measurements at smaller scales become increasingly essential for scientific and technological innovation, driven by the downsizing of components and structures to nano-scale dimensions. Therefore, nano-metrology, a specialized branch of metrology, has emerged as a vital tool in the manufacturing of modern devices, enabling the precise measurement and characterization of their features at the nanoscale. Here, we provide a short perspective based on the full paper.[1] Hybrid metrology approaches have the potential to achieve critical sub-nanometer dimensions and can become key to successful nanoscale research and specialised manufacturing designed for the Internet of Things (IoT).[2]

Nanometrology offers suitable tools and methodologies tailored to overcome the limitations of conventional approaches, thereby ensuring the reliability and performance of multimaterial-based miniaturized devices, such as field-effect transistors (FETs), including junction FETs (JFETs) and insulated-gate FETs (IGFETs). Miniaturized IoT-grade devices that require novel nanometrology approaches include CMOS, which has recently moved from bulk optics to detecting optical beams with angular momentum, as well as metal-oxide-semiconductor FET (MOSFET), and novel complementary metal-oxide-semiconductor field-effect transistors (CMOSFET).[3]

Therefore, in [1] we looked beyond the horizon of nanometrology. Its future lies in the continued synergy of innovative measurement technologies and methodologies, setting the stage for more accurate, reliable, and efficient measurement solutions that will drive the next wave of technological breakthroughs.

2. Metrology at the nanoscale

While scaling of miniaturized IoT-grade devices continues to push boundaries deep into the nanoscale, it faces significant metrological limitations as it approaches atomic-scale dimensionality. Therefore, nanometrology tools are required to characterize the nanoscale doping gradients, electrostatic potentials, and material interfaces that govern the operation of MEMS or NEMS devices.

Both MEMS and NEMS combine electrical and mechanical components. However, controlling the quality of nano-component assembly in MEMS is challenging as these are microscopic devices with a characteristic length of less than 1 mm (but greater than 1 µm), while NEMS are nanoscopic devices with a characteristic length of less than 1 µm.[4]

In another example, polaritons generated and propagated in CMOS-compatible plasmonic ultrathin topological insulators can exhibit plasmonic figures of merit comparable to those of noble metals. However, developing reliable methods to track the spatial displacement of plasmonic angular momentum modes in a 100-nm-thick Sb_2Te_3 thin film is challenging.[5]

Alternative transistor architectures, such as Junction-less Transistors (JLTs) and Tunnel FETs (TFETs), are particularly attractive for ultra-low-power electronics. The critical challenge in TFET development lies in optimizing the tunneling efficiency, which is heavily influenced by the material selection, doping profiles, and junction geometry. This requires controlling the uniform doping of high-concentration channels to eliminate the need for source-drain junctions.[6]

Furthermore, integrating TFETs with silicon technology poses a unique metrology challenge, particularly overcoming silicon's indirect bandgap, which requires sub-nanometer resolution and traceability to ensure device reliability.

3. Hybridized nanometrology for miniaturized devices

An ideal reference metrology (RM) system provides International System of Units (SI)-traceable measurements with known and sufficiently low uncertainty. A nanometer-level measurement uncertainty (MU) in critical dimensions (CD) metrology tools is essential for controlling the manufacturing of products with CDs below 100 nm. Two key factors emerged as particularly significant: sample-to-sample measurement bias variation and sampling uncertainty.[7]

Recently, hybridized metrology tools have emerged, aiming at enhancing the accuracy of high-throughput inline or reference metrology tools by integrating measurements from another technology. In this regard, the possibility of hybridizing metrologies was thoroughly reviewed in Ref. [1], and here we present a shortened key discussion. These techniques leverages the strengths of multiple measurement techniques to minimize the uncertainty of a particular measurement.[1]

Figure 1 illustrates the fundamental relationship between analytical resolution, detection limits, analytical spot size, and metrology footprint, highlighting why hybridized metrology approaches are increasingly important for advanced nanoscale characterization. Such integration is particularly important for advanced semiconductor devices, MEMS/NEMS technologies, and IoT-oriented miniaturized systems, where accurate dimensional and functional characterization is essential for ensuring device performance, energy efficiency, and manufacturing reliability [1]. Effective control of CD is essential for successful nanoscale operations. Through extensive research and daily application in the semiconductor industry, it became evident that additional MU components need to be considered.[8]

According to **Figure 1A,** techniques with extremely high spatial resolution often operate over limited sampling areas and may suffer from reduced throughput or sensitivity to measurement noise and surface distortions. Conversely, methods capable of rapid large-area inspection may lack the spatial precision required for sub-nanometer characterization. This trade-off motivates the integration of complementary metrology techniques that combine high-resolution local measurements with statistically relevant large-area analyses.

Figure 1B further demonstrates how the metrology footprint varies as a function of spatial resolution. The footprint defines the effective interaction area between the measurement system and the analyzed structure, directly influencing measurement uncertainty, feature detectability, and reproducibility.

For instance, Scanning electron microscopy (SEM) can achieve resolutions of several nanometers. The total measurement uncertainty (TMU) of CD at SEM is influenced by variations in feature shape caused by changes in the lithography scanner's focus.[9] However, SEM can be hybridized with Atomic Force Microscopy (AFM). In atomic force microscopy, critical dimensions (CD AFM) are often required to evaluate the TMU of the system under test.[9]

In general, CD AFM is a strong candidate for linewidth reference metrology due to its low sample-to-sample bias variation and high sampling efficiency. Sampling efficiency is the degree of sample averaging inherent in a single measurement.[9]

SEM hybridised with Transmission Electron Microscopy (TEM) to enable lower sample-to-sample bias. Although TEM can serve as a reference tool, it is a costly and time-consuming option.[1]

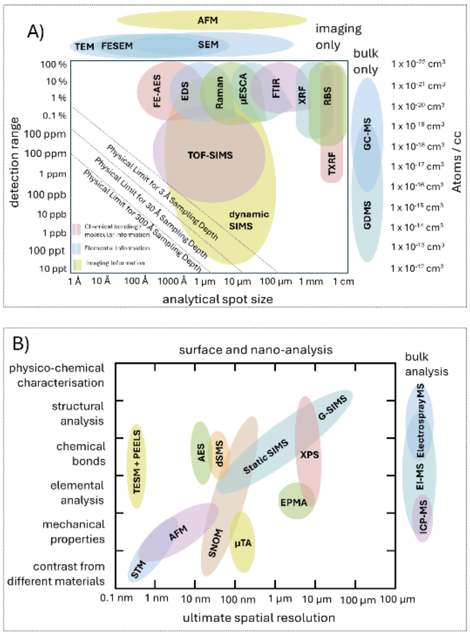

Figure 1. A) Analytical resolution of various measurement techniques versus their detection limits related to analytical spot size and number of features in the detection area. B) Metrology footprint as a function of special resolution, adopted from Ref. [1].

4. Summary

Advances in metrology have been pivotal in driving groundbreaking development in nanoscale materials and device fabrication over several decades. As device dimensions continue to shrink and architectures become more complex, no single measurement technique can simultaneously provide high spatial resolution, large-area coverage, low uncertainty, and sufficient sensitivity to detect critical nanoscale features. In hybridized metrology frameworks, combining techniques with different footprints and sensing principles enables more reliable multidimensional characterization of complex nanoarchitectures, high-aspect-ratio structures, and heterogeneous material assemblies.

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