Analysis of technical and economic market conditions affecting metrological equipment used in microelectronics

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Abstract. The issues of changing the requirements for metrology tools caused by scaling of integrated circuits are considered. Key factors leading to the increasing number of sensors are the need in the earliest possible detection of deviations of process parameters, as well as the need to avoid occurrence of defects. Undoubtedly, artificial intelligence, machine / deep learning, and big data technologies will play a crucial role in improving the efficiency of metrology tools. Improved efficiency will increase the yield, reduce the time for development and introduction of new products and, as a result, it will increase the profitability of businesses.

1. Introduction
Metrology tools help to achieve a suitable output level that ensures profitability as they control and monitor major processes in production. However, the use of metrology tools in microelectronics is getting much more complicated due to the growing scaling of integrated circuits and the development of 2.5D and 3D structures in production. As new topological standards are being designed at a considerable rate, the complexity of forming suitable elements grows, which results in implementation of more requirements for quality control. There is a need to develop new approaches and create a new type of metrology which will be able to combine the expanded use of sensors, machine learning tools / techniques and artificial intelligence systems.

2. Market outlook
It is expected semiconductor control and measurement equipment market will expand at a compound annual growth rate (CAGR) of 7.9% - from approximately $3.36 billion in 2019 to $5.3 billion in 2024. The market for this equipment is highly monopolized - three leading suppliers (KLA-Tencor, Hitachi High-Technologies and Applied Materials) account for more than 60% of the industry’s revenues [1].

The market can be classified by types of products - optical, electron-beam and other equipment, and by application - equipment for monitoring wafers, crystals of integrated circuits, cases, etc. The largest sector of semiconductor control and measuring equipment is plate inspection tools - It accounts for more than 70% of sales. Also, important areas of application are housing and testing of integrated circuits [1].

3. Major trends
1. As the minimum dimensions of topological elements of integrated circuits decrease (scaling), design processes, metrology and final control are becoming more unified. This helps to increase the yield and reduce the time to launch new or upgraded product.
2. With a decrease in the minimum size of topological elements (also scaling), the sensitivity of integrated circuits to emerging defects increases. Therefore, providing production lines with metrological defect detection tools is becoming not only necessary, but also useful.

3. One of the main driving factors in the development of design technologies and metrology is the evolution of the mathematical apparatus. As part of the development process, several stages of data review can be carried out in order to improve functionality and ensure that the initial design matches what is formed on the integrated circuit chip.

4. The problems associated with various types of defects are exacerbated with an increase in the density of elements and a decrease in their topological dimensions. What was not a problem at the level of 28 nm technologies, for example, an imperfectly formed topological element, at the level of 7 nm technologies can cause a clear or hidden defect.

5. The currently used fault detection and classification functions and the corresponding sensors do not solve all the problems of the process. An increase in the degree of their integration into the technological process is required. Integrated circuit designers began to pay more attention to the presence of the necessary sensors and reliable data that can be linked to a specific process.

6. Metrology generation of large amounts of data requires the use of local servers or cloud computing. In most production operations, this would be the middle step between sensors and cloud storage, but silicon plants (contract manufacturing of integrated circuits) always resisted storing any data in public clouds (data protection and intellectual property requirements). As a result, manufacturers themselves have to decide which data needs to be processed immediately and which data can be processed later.

7. The stricter requirements for the variability of process parameters occur at all levels - from batch to batch of plates, from plate to plate, on the plate itself, at the crystal level, as well as at levels of non-uniformity of line edges (resist) / non-uniformity of line width / local reproducibility critical sizes - LER / LWR / LCDU. Some of the data points used today are seen as an opportunity to control the process more efficiently. This requires an understanding of how the data must be used.

8. Sources of variability of process parameters range from impurities in the materials used to before these materials are used in the process. So, at each new technological level, thin films should be formed with much greater accuracy than at the previous level - due to an increase in tolerance requirements. This complicates the use of existing tools for metrology and control, requires the development of new tools.

9. When reducing the size of topological elements to 5 nm or less, everything becomes even more complicated. When entering the structures of the next generation of circular gates with topologies of 3 nm or less, this trend continues. This transition only looks like a modification of FinFET - not only are the requirements tightened, but the shutter architecture is much more complicated, it has no analogues in previous experience.

10. The importance of data collection coverage is growing. It is often unknown what the problems are and where they arise; therefore, an increase in both the number of samples and the amount of data is required. When it comes to resolution of the order of 1 nm, the level of the plate is 1012 pixels. Such huge volumes of data need to be filtered on an admission basis, since some of them must be analyzed immediately, some of them in comparison with other data, and some accumulated.

11. Implementation of methods printing of circuit boards instead of using fabrication methods could potentially reduce energy consumption by approximately an order of magnitude [2].

4. The impact of metrology on microelectronics

1. The use of advanced metrology tools, characterized by the use of modern mathematical methods, allows to prevent low-quality products from entering the market. So, due to such funds, in the first quarter of 2019, TSMC managed to remove a batch of plates from processing due to problems with resistance [1].

2. The expansion of the widespread use of sensors provides an idea of what happens at any given time in the manufacturing process. Modern sensors are characterized by an increase in speed and a decrease in size.
3. Reducing defects due to methods such as:
   - careful control of the technological process with the help of programs for its continuous improvement to reduce accidental defectiveness (basic methods are used to increase the yield, such as monitoring tools during processing);
   - implementation of the process of sampling data by metrology at a level sufficient to ensure traceability of the process (other approaches are still being developed).

4. Dependence of yield on the placement of crystals on the plate and the diameter of the processed plate. From a statistical point of view, latent defects, the formation of which must be avoided, are easier to find by outliers / dips in the picture obtained from the data points. To clarify the information received, it can be combined with the data obtained by electrical methods, which will improve the input for making decision on the crystal on the basis of the “fit / not fit” principle.

Figure 1 illustrates the time dependence of yield depending on the location of the crystal [3].

![Figure 1. Comparison of the yield at the center and along the edge of the plate during the development of a new device as a function of time.](image)

5. Increased yield due to redefinition of the purpose of the crystals. Creation of reliable metrology methods that distinguish non-catastrophic defects from catastrophic ones. When using such techniques, we can talk not about culling crystals, but about redefining the scope of their final application [2].

5. Standard and advanced metrology techniques

1. For manufacturers of integrated circuits at FinFET, manufacturers require tools in five main categories - measuring critical dimensions, determining the composition of measured structures, the presence of dopants, stress states and electrical characteristics. Each of the categories provides for the presence of several different types of metrology tools in both laboratory and factory conditions.

Figure 2 shows the main metrology technologies that measure the parameters of integrated circuits in laboratory and factory conditions [4].

2. In the field of CD-SEM (scanning electron microscopy of critical sizes) evolutionary improvements continue. For its radical improvement in critical size metrology, Applied Materials and ASML are developing a new class of tools based on the use of electron beams [5].

3. One of the directions for improving critical size scatterometry (OCD) is low angle x-ray scatterometry (CD-SAX). It was assumed that CD-SAX will replace OCD, but the power of the X-ray source CD-SAX is still insufficient, the size of the radiation beam is not suitable for logic devices.

4. CD-SAX is used in the manufacture of memory circuits. Lam Research Corporation and the U.S. National Institute of Standards and Technology (NIST) in 2018 presented a report on the use of CD-SAX to control hard masks based on amorphous silicon. The developers claim that thanks to CD-SAX
they were able to measure the profiles of 2D and 3D structures, having received detailed information. Rigid masks based on amorphous silicon play an important role in the production of memory.

![Figure 2. Basic metrology technologies used in laboratory and factory conditions.](image)

5. A promising method in metrology is machine learning, using special algorithms to solve some problems and adjust metrology parameters. This technique is intended for technological levels with topologies of 7 nm or less. GlobalFoundries and Nova presented the results of their research on the use of machine learning as an additional method to OCD.

6. The use of techniques such as machine learning and measurement physics modelling in combination with process information would not only solve metrology problems, but could help develop completely new measurement techniques for these end of roadmap devices [6].

6. Conclusion

The variability of the process parameters, the increasing complexity of designs and rapidly evolving technologies make the metrology of integrated circuit crystals an extremely labor-intensive and knowledge-intensive task. To make sure that yield is guaranteed and the launch time for new products is getting shorter, it is necessary to create valid methods and means of metrology.

An increase in the number of sensors requires the expanding use of artificial intelligence and machine learning tools to solve metrology problems currently present in industry.

The value of metrology cannot be underestimated, from the initial stages of processing a plate to the analysis of the formed crystal of integrated circuits. Companies will benefit from linking production with design and metrology processes.

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