Optical Smart Sensing

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Introduction

During the last 70 years, HORIBA has developed a large portfolio of optical technologies to meet the specific needs of the automotive industry, the environment, medical and material research. From Xray to Infrared, these technologies are widely used all over the world by leading end-users and organizations. Today, emerging applications, driven by the demand for faster data communication along with powerful artificial intelligence (AI) capabilities, high-performance and low-cost power conversion products for longer battery life, faster phones charging and electric vehicles (EVs) batteries, are creating new demand to the semiconductor industry.

Previously, these demands have been met through the continuous miniaturization of silicon-based complementary metal–oxide–semiconductor (CMOS) integrated circuits and by the development of a new generation of compound semiconductors. While for integrated circuits the technology enters the sub-2 nm node, with a lateral size of silicon transistors rapidly approaching its physical limits, leading to increased leakage current and degradation of mobility, the power and high frequency devices require a technology which is able to reduce the size of the devices, produced in large volume in existing fab.

These limitations of conventional silicon-based devices led to the exploration of new materials, such as 2D materials for the expansion below 2nm node and wide band gap compound semiconductors for the production of low-cost power and high frequency devices. For many field experts, the semiconductor industry is changing era from node era to the “Material Era”.

Adopting new materials in the semiconductor industry is a disruptive process. Thus, achieving desired yields and equivalent product quality requires smart manufacturing processes, which must include process control, chamber health monitoring and metrology.

While semiconductor metrology and inspection are essential for the management of the manufacturing process at all stages from R&D in the laboratory to prototyping, fabrication, assembly and packaging, and performance verification prior to final deployment, process monitoring is focused on yield improvement by monitoring the tool/chamber health, preventive maintenance for fault detection and for matching the performance of parallel tools/chambers at all production steps.

The production of the latest generation of devices requires sophisticated deposition, etching, lithography and chemical mechanical polishing tools. To support the deployment of smart processes in the semiconductor industry, HORIBA decided to leverage all its technologies for the development of a wide range of "Optical Smart Sensing" probes, by using the expertise of its global R&D organization (America, France, Japan and Germany) and by collaborating with leading research centers for semiconductors. These probes address the needs of the current and future needs for process monitoring and metrology. Some of them, will be briefly described in this readout.

Etching process

Dry etch is a critical step in the production of Semiconductor, MEMS, Photonics devices, Display and others. The production of the latest generation of devices requires sophisticated etching tools and involve complex processes. To avoid ordinary tool fluctuations, tool-to-tool variations, and tool/process variations after chamber maintenance, routine endpoint detection and chamber health monitoring are required to increase the yield.

Optical Emission Spectroscopy (OES) is a very flexible endpoint detection and plasma monitoring method, which measures the amplitude or amplitude-ratio changes of emission lines emitted by a plasma. OES is the technique with the greatest potential to satisfy the present and future requirements of plasma technology as all plasmas emit radiation depending on their gas composition and plasma parameters.

Figure 1 High throughput and high resolution optical emission spectrometer.

Because it is a rich real-time source of information for plasma etch and deposition monitoring, OES has been used for years by the Semiconductor industry. In reactive ion etching (RIE), induced coupled plasma (ICP) and deep reactive ion etching (DRIE) processes where endpoint monitoring is critical, OES is the preferred technique. It is noninvasive and easily adjusted for any chemistry or film to be etched. In addition to Endpoint monitoring, OES is used for detailed diagnostics such as tool fluctuations, tool-to-tool variations, and tool/ process variations after routine chamber maintenance or repair by means of plasma process-spectra matching.

Typical OES systems involve three main components, a spectrometer, a CCD array detector for recording emission intensity, and software for data processing. A fiber optic probe is used to collect the light at the window of a plasma chamber and transmit that light to the spectrometer. OES data is normally very high in dimensionality and volume, and data analysis and processing methods are required. Effective OES data processing methods could provide significant benefits for prediction of crucial system parameters, system condition monitoring, amongst other etch process control applications.

Figure 2 Optical fibered chemical concentration.

Because the open area becoming smaller and smaller (below 0.5%) OES spectrometers need to provide high throughput and high spectral resolution. To achieve this, specific gratings and optimized optical coupling are required. HORIBA with its long experience and leadership in designing diffraction gratings and optical design, developed a new compact generation of OES (Figure 1). Combined with a patented optical coupling and advance data processing, this new system is the right tool for end point detection and chamber health monitoring.

Besides, HORIBA is also working on other technologies such as Non-Dispersive InfraRed absorption, to improve endpoint detection for low open area. This new technology will be described later in a separate paper.

A dry etch process is always followed by a photoresist stripping and cleaning step. Photoresist stripping, or simply ‘resist stripping’, is the removal of unwanted photoresist layers from the wafer by using a chemical. The objective is to eliminate the unwanted remaining photoresist material from the wafer as quickly as possible, without allowing any surface materials under the resist to get attacked by the chemicals used. To monitor the cleaning and resist stripping process, HORIBA developed a wide range of chemical concentration monitors to measure the concentration of various chemical. HORIBA’s chemical concentration monitors can measure single components as well as up to eight components simultaneously (Figure 2).

Deposition Process

Atomic layer deposition (ALD) is rapidly becoming a standard technique for a wide range of thin film materials and is an essential tool in the semiconductor industry. ALD relies on self-limiting surface reactions of two gaseous reactants in sequential mode to obtain sub-nanometer control of the thickness and conformity of a thin film. The physicochemical properties of the deposited films depend mainly on surface decomposition reactions and growth mechanisms. Therefore, it is important to monitor the flow rate of the reactant gases and fully characterize and understand these processes by utilizing metrology tools that shorten the process optimization cycle and provide real-time monitoring and control in a production environment.

Spectroscopic ellipsometry is a sensitive non-destructive, noncontact, and non-invasive optical technique which is based on the change in the polarization state of light as it is reflected obliquely from a thin film sample. Ellipsometry uses a model-based approach to determine thin film, interface, and surface roughness thicknesses, as well as optical properties (and much more!) for thin films ranging in thickness from a few A to several tens of microns. Spectroscopic Ellipsometry is widely used in the semiconductor industry for the quality check of the different material used during the manufacturing process of a device. It is also used for real time growth monitoring for process optimization and development of new materials.

To monitor the ALD deposition process, traditional spectroscopic ellipsometers are facing some limitations due to the data acquisition rate (0.5 s per spectra) which is not compatible with the frequency of the sequential mode used in this process. To overcome this, HORIBA with its long experience in spectroscopic ellipsometry developed a new generation of spectroscopic ellipsometers capable of acquiring data with a high accuracy at a high speed down to 5 ms per spectra. This new patented technology based on spectral polarimetry (Figure 3) has the merit of no moving parts and fast data acquisition. Currently at a research level, this technology was used to monitor the growth of Al_2O_3on saphire. Preliminary results are shown in Figure 4.

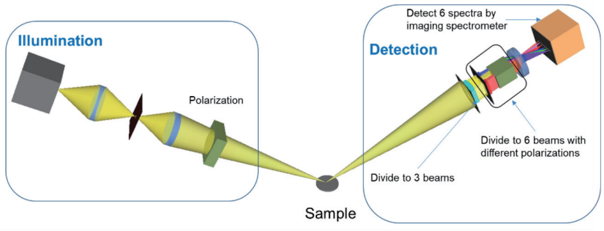

Figure 3 Schematic diagram of the fast ellipsometer.

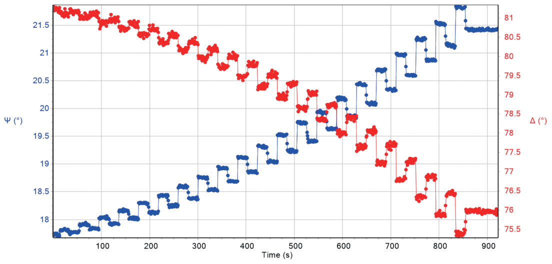

Figure 4 Real time of the Ellipsometric parameters (Y, D) during the ALD deposition of Al_2O_3 on saphire.1&2 are deposition step and 3&4 are passivation step

Lithography process

A pellicle is a membrane used to protect the photomask from contamination during high-volume semiconductor manufacturing. It is mounted a few millimeters above the surface of the photomask. Highly particle free and transparent pellicle is critical to enable high yield and throughput in advanced semiconductor manufacturing. While for Deep Ultraviolet (DUV) lithography, there are established material for the pellicle, Extreme Ultraviolet (EUV) process requires the development of new materials as 13.5nm light is absorbed by most of them. In addition to transparency, stringent thermal, chemical, and mechanical requirements must be achieved. We have seen tremendous progress in carbon nanotube membrane development in the past year and, based on our strong collaborations with our partners, we believe that it will result in a high-performance pellicle solution in the near future. Beside the transparency, one of the challenges during the lithography process, is the particle inspection onto the pellicle and frame and the pellicle health monitoring during the lifetime of its use. To improve the lithography process yield, HORIBA, after more than 40-year experience in photomask inspection by laser scattering technology, has developed a new Particle detection system integrating several proprietary technologies to count, localize and identify the particles, while at the same time evaluating the health of the pellicle. This system (Figure 5) is based on a modular design approach, combining several HORIBA proprietary technologies such Laser scattering, Raman Spectroscopy and Spectroscopic Ellipsometry. It allows the user to evaluate the particle distribution on a pellicle with a high efficiency (minimizing the false detection), to identify the particles location and composition and to evaluate the health of the pellicle.

Figure 5 Photomask inspection system with particle remover and metrology probes.

Chemical Mechanical Polishing

The chemical mechanical polishing (CMP) is a polishing process which uses a chemical slurry formulation and mechanical polishing process to remove unwanted conductive or dielectric materials on the silicon wafer, achieving a near perfect flat and smooth surface upon which layers of integrated circuitry are built. The process involves both chemical attack and abrasive removal by using CMP slurry. The CMP slurry, a polishing powder, can be divided into oxide slurry and metal slurry depending on the film to be polished. The use of CMP slurries, and number of CMP steps in Integrated Circuit processing is growing exponentially. As, it is becoming a critical step for the manufacturing leading edge devices, slurry quality control is critical to achieving the lowest defectivity and cost of ownership. To monitor the quality of the slurry, HORIBA by using its expertise in Laser scattering and Dynamic scattering technologies (Figure 6) has developed a smart particle size analyzer which integrated in the CMP tool provide in real time the particle size distribution form few tenth of nm to several microns. Traditional laser scattering method is limited to particle bigger than 80 nm and not able to analyze multi-model size distributions with a high resolution as most CMP slurries contain a mixture of particle sizes. To overcome this challenge, HORIBA developed a new sensor based on the measurement in real time of the optical absorption of a solution under Centrifugal sedimentation. The dynamic measurement of the light optical absorbance variation due to a particle crossing the light beam is correlated to the particle size distribution by using a dedicated mathematical model. This new technology allows the quality control of the slurry with a high accuracy. In Figure 7, is displayed the picture of the system.


Figure 6 Dynamic Light Scattering particle size analyzer.


Figure 7 Dynamic absorption particle size analyzer.

Material characterization

High quality materials are necessary to improve the performance and reliability of the devices. The reliability of the devices is tightly related to the presence of defects such as dislocations, stacking faults or non-uniformity of thickness, composition and properties, which can be created during the different technological steps followed to build up the device.

Raman Spectroscopy and photoluminescence are non-destructive and non-invasive light scattering technique, whereby a sample scatters incident light from a high intensity laser light source (Figure 8). Most of the scattered light is at the same wavelength (or color) as the laser source and does not provide useful information. However, a small amount of light is scattered at different

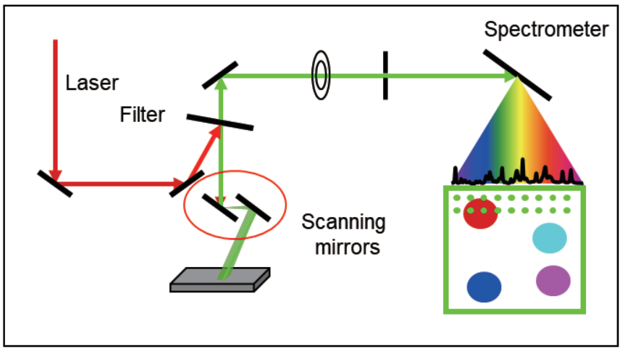

Figure 8 Schematic diagram of the Raman/PL probe.

wavelengths (or colors). While in Raman spectroscopy, the emitted spectrum is a fingerprint of the chemical structure, phase, polymorph, crystallinity, and molecular structure of the sample, in photoluminescence the emitted light is a fingerprint of the bandgap and electronic properties of the materials. Both techniques are analytically very powerful, as they provide information with submicrometric spatial resolution on defects and material properties. While in R&D both technologies are used for process optimization and the development of new materials, in production only low throughput photoluminescence systems are used for quality control of compound semiconductors. To be used in production for screening 2D materials at the different steps of the devices production without damaging the sample, high sensitivity Raman spectroscopy, and high throughput (fast measurement time) system is required.

To achieve these requirements, HORIBA by using its long experience in Raman spectroscopy, is developing a new generation of Raman and photoluminescence probes which combined with a fast data acquisition system, allows the user to evaluate the composition and localize defects on a large wafer at a high speed with a high sensitivity and without damaging the sample.

These new probes are compact and fully automated. They are based on the use of patented HORIBA technologies for fast laser scanning and on the fly data acquisition processing. Performances like evaluating the quality of 2D materials deposited on a 12” wafer size have been achieved in less than 100s for 49 points. Such performances, allow the user to optimize their deposition process and can also be used for screening defects in the production line with a high throughput. In Figure 9,10 are displayed the distribution of the composition of germanium composition in a film of $Si_{(1-x)}Ge_x$ deposited on a 8” c-Si wafer size and the intensity of the Raman D band of a graphene film deposited on a 12” wafer size have been achieved in less than 100 s, to be replaced by 12” wafer size have been achieved in less than 2 nm.

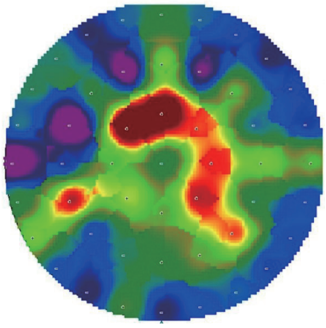

Figure 9 Germanium composition in $Si_{(1-x)}Ge_x$ as measured by Raman spectroscopy

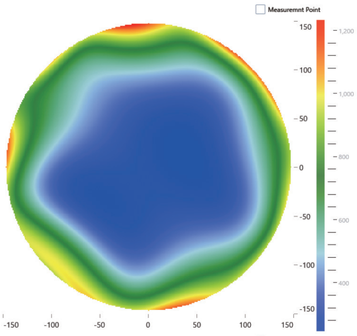

Figure 10 Defects distribution of a graphene film deposited on c-Si as measured by Raman spectroscopy (D band intensity)

As the current yield of the deposition tools of 2D, is not very well controlled, Integrated metrology is needed to monitor the quality of the deposited material. Thanks to the compactness of these probes, they use as integrated metrology can be considered.

Besides the defects, contamination and impurities which might happened during the different step of the manufacturing process, are also a concern in the semiconductor industry. X-ray fluorescence (XRF) is a non-destructive elemental analytical technique to identify what elements are contained and to determine how much concentration of the elements are contained in a material. It is based on the measurement of the fluorescence signals emitted from a material under X-Ray excitation. Among XRF analyzers, energy dispersive X-ray fluorescence (EDXRF) analyzers are more suitable for screening materials from the initial stage to the end.

Figure 11 Bench-top Micro-XRF analyzer.

Since 1956, HORIBA continuously developed Energy Dispersive XRF analyzers. HORIBA XRF analyzers can be used for metal film thickness, failure analysis and for the detection of impurities and contamination. HORIBA XRF technology can be used in-line and off-line. In Figure 11, is provided an image of the bench-top system used for failure analysis.

Conclusion

In this material “era” where integration of new materials is required, the control of the different processes involved in the manufacturing of semiconductor devices is critical. HORIBA with its long expertise in developing solutions for flow control and material characterization are addressing these new needs with innovation. For each step of the production process, HORIBA is able to provide a solution capable to provide valuable information on the process tool by collecting data around the process chamber and by analyzing the results of the process with analytical technologies. To achieve this, HORIBA is strengthening its global R&D organization and collaboration with key R&D organizations and will continue to look for innovative technologies.

* Editorial note: This content is based on HORIBA’s investigation at the year of issue unless otherwise stated.

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