Overview of the IEEE/LEOS Summer Topical on Optical Sensing in Semiconductor Manufacturing

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Optical sensing technologies are emerging as tools in several widespread areas of semiconductor manufacturing. In many ways, photons are the ideal probe for semiconductor materials and devices. Photon probes are nondestructive, non-contact diagnostics that can interact with spinning wafers in chemically corrosive environments. Light is easily generated, steered, and detected over a broad range of energies, so it can be used to monitor different aspects of the same process. The corresponding broad wavelength range means that the probe is sensitive to a broad range of length scales. Finally, light is particularly appropriate for probing materials destined for use in optoelectronic and photonic devices, where the interaction of light with the material provides the basis for device operation.

This topical meeting brought together experts in a number of areas where optical sensing is having an impact. These areas include detection of trace impurities in gases, plasma diagnostics in silicon etching, scatterometry applied to wafer and processed chip characterization, epitaxial growth monitoring, wafer temperature measurement, and post-growth materials characterization. The talks were designed to give attendees an overall perspective in these technologies as well as address future trends. Most of the participants were presenting their work in a broader forum than it had seen before and, as audience members, were able to learn something new. Virtually every talk was followed by several minutes of questions and discussion.

The conference had representatives from a number of industries, including gas manufacturers (Air Liquide, Matheson), gas purity instrumentation companies (Meeco, IRGas, Southwest Sciences, CIC Photonics), epitaxial equipment manufacturers (Emcore, EPI [Applied-EPI]), semiconductor device or epitaxial wafer manufacturers (IQE, Motorola, Lucent, Nortel), and characterization equipment manufacturers (Oriel, Bio-Rad). Government laboratories and universities were also represented well (NIST, Sandia National Laboratories, Air Force Research Laboratories (Wright Patterson), National Physical Laboratory (Great Britain), the Center for High Technology Materials at the Univ. of New Mexico, Princeton, MIT, North Carolina State Univ, Univ. of Texas Austin, and Arizona State). This topical meeting was also responsible for two of the three industrial sponsors for the topical meeting series.

The conference began with the technologies that are perhaps furthest along in their development- the use of light to determine gas composition. Chris Hovde of Southwest Sciences gave an invited talk on the use of multipass absorption cells to measure trace concentrations of water vapor based on wavelength modulation spectroscopy using near-infrared diode lasers. They have demonstrated a detection limit of 0.2 ppb. There were several additional contributed papers in this subject area, covering tunable laser spectroscopy of gases for trace contamination analysis, ring-down cavity absorption measurements, FTIR spectrometry for gas impurity analysis, and trace gas detection with quadrupole mass spectroscopy. There are several companies selling instrumentation based on these techniques with detection limits in the range from 0.2 to 20 ppb, and at least two national laboratory programs to provide traceability for calibrations. Although an obvious application of this technology is the measurement of the purity of incoming gas cylinders, the instrumentation is also as a diagnostic tool on the exhaust line of a process chamber. Trace moisture measurements in that location can determine the moisture introduced by a new wafer load or determine when the chamber has been adequately purged following a vent cycle. The latter application points to the other application of infrared spectroscopy- monitoring processes, typically plasma etching or deposition, by measuring concentrations of key chemical compounds in the reaction chain. Harold Anderson of the University of New Mexico gave an invited talk on the use of mid-infrared (3-12 μm) diode lasers to follow CFx radical formation during plasma etching of silicon. The optical sensing tool functions both as a research tool to identify the reaction mechanisms and as a process tool for endpoint and fault detection.

Other talks addressing the diagnosis of silicon materials and device processing provided further examples of the versatility of optical sensing. Harland Tompkins of Motorola Labs described the widespread use of spectroscopic ellipsometry and reflectometry as a diagnosic tool for the varied thin-film deposition processes that occur in silicon circuitry manufacture. In his invited talk, he gave examples of the use of these techniques to monitor thickness and uniformity of everything from thermal oxides and silicon nitrides to thin metal films. Bob McNeil of the University of New Mexico presented an invited talk on scatterometry as a diagnostic for photoresist profiles on test patterns in production silicon wafers. Because in this case, the light used in probing the surface is not formed into an image, features on the order of 50 nm or less can be detected with light of a wavelength ten times the feature size- well beyond the imaging diffraction limit. Contributed talks also described how scatterometry compares (favorably!) with more cumbersome electron microscopy and atomic force microscopy measurements of critical dimensions in periodic patterns, and how polarization scatterometry can be used to distinguish subsurface defects from particulate contamination and surface roughness in silicon wafer inspection. Finally, invited speaker Lucymarie Mantese of the University of Texas, Austin, described research in using nonlinear processes to monitor surface reactions using the example of silicon/germanium growth on silicon.

Epitaxial growth monitoring is an area where optical sensing has been making the transition from the laboratory to the production environment in recent years. Optical sensing works well in both of the two common growth techniques for III-V semiconductors, organometallic vapor phase epitaxy (OMVPE) and molecular beam epitaxy (MBE). The invited talk by Bill Breiland of Sandia National Laboratories described how normal-incidence optical reflectance spectroscopy (ORS) has become a standard pre-run calibration tool for both OMVPE and MBE growth machines at Sandia. Breiland also described work in emissivity-corrected pyrometry for temperature measurements, this being a natural extension of ORS as the equipment and geometry are similar. Dave Aspnes of North Carolina State University, presented an invited talk on the more general case of polarized light probes, including spectral ellipsometry and reflectance difference spectroscopy. Both these techniques are more surface-sensitive than ORS, a feature that can be exploited for thin layer growth while admittedly complicating the analysis. Both Aspnes and another invited speaker, Kurt Eyink from US Air Force Research Labs, gave examples of using in situ spectral ellipsometry for real-time control the composition of homogeneous layers. One interesting point made by both presenters is that hysteresis is often observed when ramping flux in either MBE or OMVPE to produce graded structures- the cell or flow controller settings are rarely exactly the same after the returning to the initial composition even within a single run. Contributed talks in this area covered production needs for in situ monitoring (mostly hints as the true needs are considered proprietary), high-accuracy composition measurements with ORS, and doping level measurements with Raman spectroscopy.

The conference ended with talks on optical methods of measuring what is arguably the single most important process parameter- temperature. Shane Johnson of Arizona State gave an invited talk on band edge thermometry, a recently developed technique in which the temperature of a semiconductor wafer is determined from in situ measurements of its band gap. This technique is applicable over a broad range of temperatures, from room temperature to epitaxial growth temperatures (800 °C or more), but it is particularly valuable at the low end of the temperature range where pyrometric techniques become difficult. This primary alternative, emissivity-corrected pyrometry, was covered in a contributed paper showing the significant improvement in temperature control of OMVPE wafers over thermocouples and conventional pyrometry, as well as being mentioned in both talks on ORS.

From molecular spectroscopy to phonon spectroscopy, surface dust to moisture contamination, characterization of single crystal thin films to photoresist profiles- there was something for just about everyone at this topical meeting. I hope those of you who were not able to attend the meeting will enjoy this collection of papers.

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Real-Time Control of Substrate Temperature Using Band Edge Thermometry

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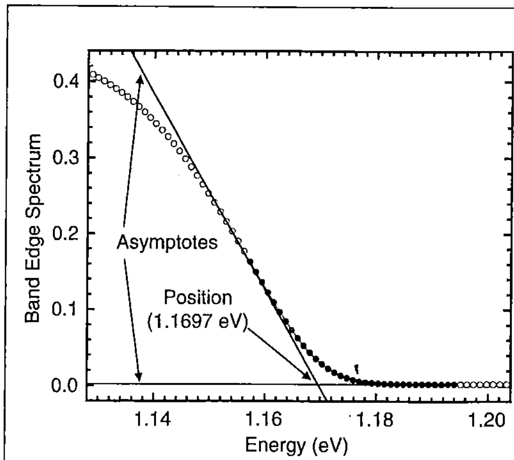
The sensitivity of material properties to growth temperature means that an accurate and reliable method for measuring substrate temperature is essential during epitaxial growth. Recently, optical methods have been developed that overcome some of the limitations of thermocouples and pyrometers [1-3]. Pyrometry for example, does not work at low temperatures, is affected by surface roughness, window coating, and substrate emissivity changes during growth. Since both rotating and radiatively heated substrates are preferred during epitaxial growth, physical contact between the substrate and the temperature sensor is not practical. Therefore, thermocouples are radiatively coupled to the substrate and typically have a large temperature offset compared to the substrate. This offset depends on the substrate and heater temperatures, the substrate doping level and type, the back surface texture of the substrate, and the changing absorptance and emittance of the epilayer during growth.

In these new optical methods, substrate temperature is inferred from the onset of transparency of the substrate itself. The band edge of III-V semiconductors (which cuts off exponentially) broadens and shifts to lower energies with temperature [4]. In practice, substrate temperature is inferred from the spectral position of various points in the diffuse reflectance spectrum [1] or transmission spectrum [2,3]. The onset of



▼ *Figure 1. The position of the spectrum and hence substrate temperature is given by the intersection of the asymptotes of the knee region of the spectrum. The knee region is shown by the solid dots.*