MATERION

TECHNICAL PAPER

Coating Processes Evolve

Satisfying Special Optical Requirements

Author: Samuel Pellicori
Materion Coating Materials News

Today's coating processes provide the capability to produce anti-reflective (AR) coatings, bandpass filters, separation filters, high laser damage threshold coatings, mirror coatings, etc. with high precision and high yields. The production environment is based on batch-coating processes and component sizes that range from mm to meter. Generally, one function such as limited wavelength coverage is provided by the standard coating process.

The desire to incorporate optical coatings at the wafer-level stage was inspired by semiconductor manufacturing practices, and has led to an evolution in specialty optics requirements. Development of processes that would enable complex multi-layer coatings to be incorporated into wafer manufacture called for new thinking. It allowed for the reduction of deposition temperatures and incorporation of photolithographic steps to define smaller coated areas.

An example of the use of wafer-level integration and production is the manufacture of solar cells. The most efficient solar arrays in production are composed of multi-junction thin film PV cells such as: Cu(In,Ga)Se_2 (CIGS), $CuInSe_2$ (CIS), CuInSSe (CISS), and the GaAs-based compositions InGaP/InGaAs/Ge triple junction cells developed for space applications. The latter cells power orbiting missions for NASA, NOAA, DoD and for commercial applications in communication, entertainment and GPS satellites. The junction and absorber layers, buffer interlayers, contact electrodes, and AR coatings are all deposited at the wafer stage. Advances now allow for solar cell wafer diameters to be 150 mm.

In early 2000, promise of high density, high speed communications and data networks inspired the development of DWDM (dense wavelength division multiplexing) filter deposition and subsequent mm-sized dicing, with associated mounting and testing techniques. Currently, the proliferation of miniaturized spectral analytical instrumentation requirements and their expanding applications have inspired the introduction of wafer-level manufacturing processes for band-pass filters. This satisfies the needs of low-cost miniature non-scanning spectrometer applications.

Advances in Coating Technology Set the Stage for Miniaturized Optics Production

In the case of DWDM filters, where spectral bandwidths can be as narrow as 0.4 nm (0.02% relative to the center wavelengths near 1550 nm), the state of coating technology had to be quickly advanced over the existing pace of development in the 1990s [1]. As indicated by the name, many narrow spectral bands separated by small intervals are multiplexed and transmitted down a single fiber, then de-multiplexed at the receiver end – thus dramatically increasing the data capacity of a single optical fiber. This optics network is the backbone of Internet and other high data rate applications. Revolutionary improvements in: deposition process accuracy, precision, temporal stability and coating material consistency were necessary to make DWDM filters fulfill their promise. A greater understanding of the factors that influence coating performance at the nano-meter level was derived as a result.

Automated systems were built to combat the low in-spec yield from coating processes that existed. To create meaningful yields, more precise and accurate deposition processes and engineered target materials were designed. Costly automated coaters were developed and delivered. As the technology progressed and coating facilities began producing DWDM filters, the output eventually exceeded the demand. Fortunately for the general coating industry, this technology continued to mature and find new applications during the reset following the telecom bubble burst. Advances derived from the DWDM technology included deposition process control and monitoring of thickness and index, process automation and long-time stability, optimized materials preparation, and better optical and mechanical characterization tools. Wafer-level manufacturing procedures that were applied to DWDM manufacture were adopted. We can appreciate the results of these improvements today. Many sophisticated coatings with previously unapproachable requirements are being formulated using wafer-level manufacturing processes. These coatings produce high yields with uniform area coverage convenient for dicing to small sizes. One example is the optical filter used in the miniaturization of spectral analysis equipment that has transitioned from the laboratory to many other applications.

Hyperspectral Imaging and Data Collection Instrumentation

To maximize the information in a remote scene, it is necessary to obtain spectral as well as spatial imagery, preferably simultaneously. Hyperspectral data collection is used in imaging applications for: medical data collection, dental care and dermatology, agriculture health and irrigation-frequency monitoring, general machine vision applications, colorimetry for scientific and decorative purposes, pharmaceutical sorting, forensics analysis, monitoring of land and water resources, pollution detection, and art & currency forgery detection. Diverse markets such as clinical, handheld and overflight drone platforms are using these miniature spectral analyzing instruments with greater frequency.

Adapting Wafer-Level Processing to Other Applications

How is wafer-level filter/sensor processing being adapted to hyperspectral spectrometer applications?
Commercial and consumer digital cameras achieve limited spectral and spatial information using a mosaic pattern of RGB filters, known as the Bayer filter array, on their CMOS array at the focal plane. See Figure 1. This analysis and color synthesis technique is adequate for replicating the photopic vision response that the camera is intended to provide to the human vision system. Commercial camera RGB mosaic filters are produced with selectively absorbing dyes.

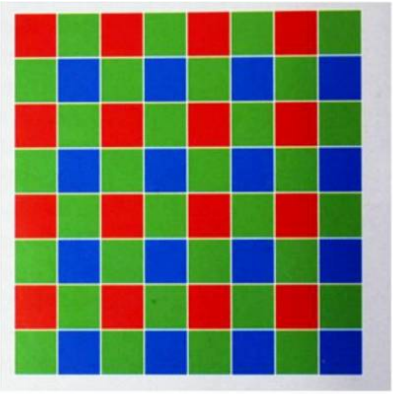
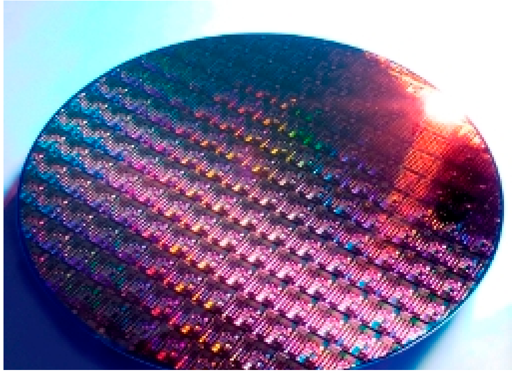


Figure 1. Bayer RGB filter pattern used on the focal plane of consumer digital cameras is produced by colored dyes over pixel-size areas.



Imaging applications exist at wavelengths shorter and longer than the visible spectrum, and include multiple narrow passbands for a more complete spectral analysis. Interference filters patterned and deposited using photolithographic techniques produce small filters that are able to cover a wider spectral range with greater efficiency than is possible using colored dyes. This approach is replacing the instruments that are currently based on small diffraction gratings to disperse the spectrum. These are used with a linear silicon CMOS linear array that produces only the spectral dimension. With linear array as the sensor, 2D imaging is only possible by mechanically scanning the optical system over the field of view. Spatial and time-dependent information is therefore temporally separated from the spectral information. Integration of bandpass filter arrays with 2D sensor arrays adds the spatial dimension. The concept is not new; a wedge-filter spectrometer was patented in 1990 **[2]**. The operational advantage over diffraction-grating instruments is that both the spatial and spectral data images are simultaneously obtained. The 2D data set is called a hyperspectral cube.

Miniaturizing Spectrometers through Wafer-level Integration Processes

The current direction is to produce miniature spectral imaging sensors by employing wafer-level production and assembly techniques to simplify integration and lower manufacturing costs. Miniaturization of filters through wafer-level integrated technology and the availability of high pixel density sensor area arrays are combined to produce miniature 2D spectrometers.

Today, it is possible to obtain a spectral imaging instrument with no moving parts that fits in your hand and covers visible wavelengths. Sensing shortwave IR wavelengths to ~ 1.7 µm is also possible with InGaAs sensor arrays. Military and NASA/NOAA applications include handheld bio/chem agent detection and weather/water monitoring using arrays working at mid-wave (3 – 5 µm) and thermal IR (8-12 µm) wavelengths that are mounted on drone platforms.

Wafer-level processing is the industry standard for producing large quantities of CMOS sensor arrays. Pixel sizes one-half the size of the photo-sensors on human retinas are possible in densities of 25 Mpixels in a 24 mm standard photographic format, although different pixel sizes are available. The density of film emulsions is thereby being reproduced on CMOS sensors. Imaging instruments that require the highest spatial resolution can use these pixel densities to maximum advantage; however, most spectral imagers do not employ them because signal-to-noise (SNR) value is reduced and the large volume of generated data is not required for spectral analysis.

Another reason they are not used is their limited ability to define sharp physical edges in the photolithographic process. This is due to the ratio of coating thickness to pixel size, a parameter that is limited by lift-off techniques. Consequently, more often used are pixel sizes in the range 5 to 20 µm. Software permits binning of blocks of pixels to obtain higher SNR under low-light level conditions, especially for astronomical imaging.

Creating Miniature BP Filters & Their Use as Spectral Imagers

In contrast to DWDM filter production where single passbands are deposited on individual substrates and subsequently diced to small filters, multiple passbands are deposited on a single substrate to produce a filter array of different spectral passbands. The filter array can assume different configurations. It might be linear, i.e., one-dimensional and use a wedged filter that provides continuous spectral bandpasses as defined by individual pixels or a defining mask, see Figure 2, or a configuration where different spectral bands cover rows of mating sensor pixels in a staircase configuration, as in Figure 3 [3], or a mosaic of pixel-sized, pixel-positioned tiles as shown in Figure 4.

Figure 2: By wedging the filter design thicknesses, the transmitted wavelengths vary continuously as illustrated, from shortest on the left to longest on the right. The wedge is shown from its edge and pass bands are dispersed along the X-axis of the 2D sensor array. The Y-axis is into the paper, and spatial scanning of the field of view will be along the X-axis to create a hyper spectral image.

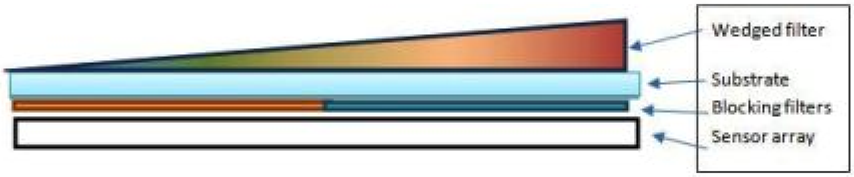


Figure 3: Multiple discrete pass bands are defined by rectangular filters whose wavelength increases as thickness increases from left to right. To create a spatial map or hyper-spectral image, the filtered array is scanned along the plane of the paper (the X-axis) The filters cover pixel columns along the Y-axis.

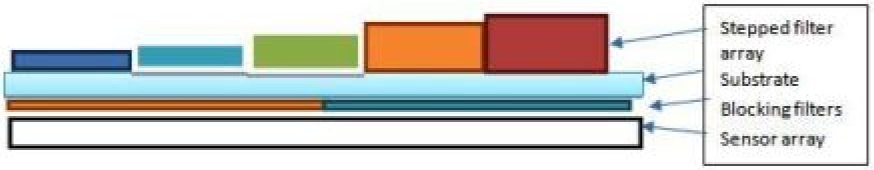
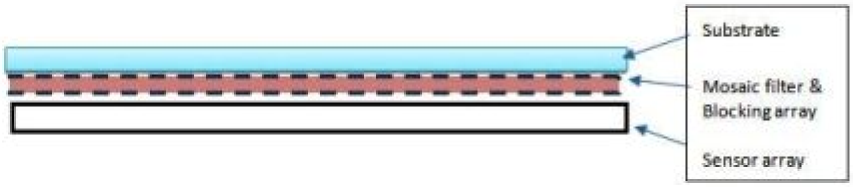


Figure 4: Hyper-spectral imager using a mosaic of individual bandpass filters, similar to the configuration of Fig 1. More wavelengths can be defined according to the desired pattern of filters. This configuration does not require scanning to produce an image, and trades the highest potential spatial resolution for snapshot imaging. It is the most complicated filter pattern to make for achieving individual pixel coverage.



Each configuration requires sequential masking steps that individually define and cover specific areas of the sensor array to map the passband locations and their physical sizes to the array of pixels. This is necessary because production of multiple filter patterns is sequential, and problems at any step of the filter deposition process can cause production failure that results in low- or no- yield.

The spectral filter array can be laid out in either of the two patterns previously mentioned. For the staircase architecture, consisting of parallel rows of pixels covered by strips of individual passbands or a wedged filter, the assembly needs to be optically or physically scanned in the cross-column direction. This allows for the collection of spectral data on the same scene area and provides spatial dimension. This is time-sequenced imaging.

Pseudo-simultaneous or staring imagery is possible with individual pixelated passband filters in a mosaic pattern, similar to the Bayer camera filter concept. In this architecture, the spatial resolution is reduced because each wavelength is sensed by its own pixel. The individual passband filter covers only the area of one µm-sized pixel or a block of such pixels. Thus, high accuracy is required in the photolithographic process to achieve high spatial resolution with minimal physical artifacts such as edge sharpness at the micro-meter level. Consequently, process yield is a large factor in production cost.

Interference filters are constructed from multi-layers of alternating refractive index. Commonly used materials for visible through SWIR wavelengths (400 nm to ~3000 nm) are Tantala (Ta_2O_5) with index ~2, and Silica (SiO_2) with index ~1.45. Metal targets of Tantalum and Silicon (available through Materion Advanced Materials) are reactively sputtered by DC magnetron to produce dense, non-absorbing, environmentally stable oxide compounds that compose the multi-layer coating designs. Since patterned lift-off is required in the steps to define specific filter areas of different design wavelengths (thickness), the preferred process is sputter deposition in order to maintain sufficiently low-temperatures that can be tolerated by photolithographic chemistry.

Future Challenges

The rapid development of coating deposition technology and coating materials prepares the industry to take on new challenges. Key among these is the evolution from individual macro substrates to micro-dimensions deposited at the wafer substrate level. The integration of wafer processing technology and optical coating technology has resulted in production-ready, miniaturization-enabling applications not previously possible.

References

1. Pellicori, Sam, *Coating Materials News* V11, Issue 2, June 2001
2. US Patent 4,957,371. Wedge-Filter Spectrometer, Samuel F. Pellicori and Aram M. Mika, 1990
3. Provoost, Ian, *Photonics Spectra*, p 46-50, April 2015

Principal Contributor
Samuel Pellicori, Pellicori Optical Consulting, Santa Barbara, CA
Phone: 805.682.1922, Email: pellopt@cox.net

Materion Advanced Materials Group
2978 Main Street
Buffalo, NY 14214
+1 800.327.1355
www.materion.com/advancedmaterials

Material Advanced Materials Group is a global supplier of premier specialty materials and services. Our offerings include precious and non-precious thin film deposition materials, inorganic chemicals and microelectronic packaging products. In addition, we offer related services to meet our customers' requirements for precision parts cleaning, precious and valuable metal reclamation and R&D. We support diverse industries including LED, semiconductor, data storage, optical coatings, large area glass and aerospace.