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Stephan Mingels, Navas Kutty, Nicolaas Tack, Dries Bangels, Elias Janssens, Harro Hagedorn, "Production of dielectric filters with low defect levels for integrated optical devices," Proc. SPIE 12424, Integrated Optics: Devices, Materials, and Technologies XXVII, 124241J (17 March 2023); doi: 10.1117/12.2667774

SPIE.

Event: SPIE OPTO, 2023, San Francisco, California, United States

Production of dielectric filters with low defect levels for integrated optical devices

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ABSTRACT

We have assessed and reduced the particle count in coatings from a magnetron sputter coater used for production of optical coatings for applications in photonics and semiconductor industry. Results for particle levels in single layers from Al_2O_3, SiO_2, Nb_2O_5, Ta_2O_5, and TiO_2 showed semiconductor grade particle levels for the upgraded deposition system. Moreover, particle levels were also investigated for optical filter stacks deposited on bare Si, glass substrates and actual CMOS device wafers, which were used for the manufacturing of hyperspectral imaging (HSI) sensors. In all cases, low particle counts were detected in the optical filters as expected from the results obtained for the single layer. It could be shown that the coating on the device wafers had no negative impact on the production yield of the HSI sensors.

Keywords: dielectric optical filters, production yield, defect levels, filter-on-chip, hyperspectral imaging, fluorescence spectroscopy, sputter deposition, semiconductor manufacturing.

1. INTRODUCTION

Integrated optical devices for applications like hyperspectral imaging (HSI)[1,2], 3D sensing[3], fluorescence spectroscopy[4], or ambient-light sensing[5] require complex optical filter coatings. State-of-the-art vacuum coating machines based on plasma assisted reactive magnetron sputtering (PARMS) and equipped with an in-situ optical monitoring system (OMS) paved the way for extremely challenging dielectric filter coatings with highest optical performance and layer uniformity. Using this approach, the limiting factor for production yield is often only the defect level dominated by particles created during the process. Applications in photonics demand optical filter glasses that require highly complex layer stacks with total thicknesses of up to 50 µm. This makes it very difficult to maintain an acceptable surface quality. In other cases, devices with a high degree of integration are fabricated not by filter depositing on cover glass but directly on valuable sensors or imagers. Here the coating thicknesses might be well below 10 µm but the devices can have pixel sizes of down to a few µm leading to a high sensitivity against particle pollution.

To meet the demands of the industry for low-defect coatings, we have assessed and reduced the particle levels of a high vacuum deposition system for optical filter coatings used in precision optics and semiconductor industry. Results from the initial and the upgraded system for oxide layers from Al_2O_3, SiO_2, Nb_2O_5, Ta_2O_5, and TiO_2 as well as optical filter stacks on different substrates including CMOS device wafers for HSI are discussed.

2. EXPERIMENTAL

The experiments for the optimization of the production yield were performed using a HELIOS 800 sputter coater[6-8] as shown in Figure **1**. The process module of the HELIOS 800 is equipped with a turntable for the substrates, three magnetron sputter stations for physical vapor deposition (PVD), a plasma beam source (PBS) to support the process, two electrical heaters for coatings at elevated substrate temperatures T, a pyrometer for T-control, and an optical monitoring system (OMS)[9] for in-situ measurements of the coating thickness during deposition.

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Integrated Optics: Devices, Materials, and Technologies XXVII, edited by Sonia M. García-Blanco, Pavel Cheben, Proc. of SPIE Vol. 12424, 124241J · © 2023 SPIE
0277-786X · doi: 10.1117/12.2667774

Figure 1. Photo of a HELIOS 800 sputter coater with automated substrate handing system. In the picture the process module is open.

The turntable can be loaded with up to 12 substrates with a diameter of up to 200 mm. By spinning the turntable continuously during processing, the substrates are exposed to the other main components in the chamber. By means of the PVD stations sputter deposition of various materials can be performed in reactive and non-reactive processes. To form perfectly stochiometric oxide layers with optimized deposition rates, the machine is operated using plasma assisted reactive magnetron sputtering (PARMS). In PARMS, the PVD stations are equipped with metallic targets and operated with a mixed gas from Ar and O_2 while the process is controlled by using lambda probes. The lambda probes help to stabilize the process at the ideal working point where it is running as oxidic as possible without oxidizing the target surface which would result in low deposition rates. The process is supported by the PBS providing oxygen radicals.

The HELIOS 800 used for the investigations was equipped with an automatic substrate handling system, which has a central chamber with a robot and three load-lock chambers. The machine was installed in a 200 mm semiconductor facility with a bay/chase configuration. While the process module was in a cleanroom with class ISO 3, the area around the handling system had a quality of class ISO 1 eliminating the risk of particle pollution of the samples during loading.

The particle performance of the HELIOS 800 was tested before and after applying the upgrades. In all cases, two PVD stations were equipped with Si and Ti targets. In the remaining PVD station, targets from Al, Nb, or Ta were mounted. Before each test series of a particular material, clean chamber screenings and virgin targets were installed. To guarantee a standardized test procedure independent form other aspects like the substrate quality or the optical appearance of the coating, 100 nm thick single layers of the individual materials were deposited on semiconductor grade 200 mm Si wafers. The number of particles with a diameter > 0.16 µm were measured prior and after the deposition by means of a KLA Tencor SP1 DLS inspection system with an edge exclusion of 5 mm. By calculating the difference of the counts in both measurements the number of added particles from the HELIOS 800 was derived. The particle tests were performed evenly distributed over the lifetime of the target. Between the tests, other runs were performed using the same process parameters as for the particle tests. For the particle results from the individual wafers, the average for each investigated coating material was calculated. The corresponding estimated standard deviation was taken as the measurement error.

Based on the findings from the particle tests on single layers with the initial setup of the tool, upgrades were implemented to reduce the particle count. The main goal was defined to reach on average less than 100 added particles with a diameter of 0.16-3 µm in a 100 nm thick single layer independent of the lifetime of the targets. These rather small particles were considered since they provide higher counts than larger ones helping to generate sufficient statistical data for the evaluation of the experiments. To reach the goal, different hardware upgrades at the PVD stations, the PBS, the turntable, the targets, the chamber screenings, the handling system, and the substrate holders were tested. For each individual material the process was adjusted for a minimized particle count while preserving the high grade of the optical properties of the layers. Moreover, a well-defined maintenance procedure and way of working was established to stabilize the low particle levels. During this work, more than 1200 coated particle wafers from over 900 runs were measured and analyzed.

To test the particle performance not only for single layers but also for optical filters, a 602 nm thick layer stack composed of in total 464 nm SiO_2 and 138 nm Nb_2O_5 was deposited on 6 Si wafers with diameter of 200 mm. The coated wafers were measured by means of a DIOPTIC ARGOS measurement system after the deposition. This device can detect and categorize particles in the µm-range. For the measurements an edge exclusion of 10 mm was used. The test was performed before and after upgrading the sputter coater. By means of the raw particle data, a theoretical scrap level for hypothetic device wafers each having 6397 dices with a size of 2.4×2.1 mm^2 was calculated. A rather strict specification for the good dices was chosen. Dices were considered as scrap if one or more particles larger than 2.5 µm were detected in its area.

The particle performance of the upgraded HELIOS 800 for coatings on device wafers was evaluated by producing HSI sensors. As basis commercially available 200 mm CMOS wafers containing 228 sensors with 2 MP were used. The details of the coating are reported elsewhere[10]. The production yield loss due to particle contamination of the wafers causing blind pixels in the sensors was assessed by wafer level testing in a custom-designed measurement setup.

Finally, the particle pollution in rather thick layer stacks was investigated. An 11 µm thick design was chosen which was composed of SiO_2 and Nb_2O_5 with total thicknesses of 7 µm and 4 µm, respectively. The deposition was performed on Ø1" × 1.1 mm glasses from D263. Besides the upgraded system, two other HELIOS sputter coaters were used for the trials: an older HELIOS system as well as a partially upgraded one. The tests with the partially upgraded system were carried out right after cleaning of the process module while those with the fully upgraded system were performed at the end of the lifetime of the targets and the chamber screenings. The resulting particle counts were measured in an area with a diameter of 20 mm in the center of the substrates using the DIOPTIC ARGOS system.

3. RESULTS

The results of the particle investigations on single layers from Al_2O_3, Nb_2O_5, and SiO_2 are summarized in Figure 2. In (a) the counts for the defects with Ø = 0.16-3 µm are shown. In the initial configuration of the sputter coater, average particle counts of 3500 ± 3000, 312 ± 227, and 1170 ± 1030 were measured for Al_2O_3, Nb_2O_5, and SiO_2, respectively. After upgrading the system, the particle counts were drastically reduced resulting in average values of 38 ± 23 for Al_2O_3, 72 ± 24 for Nb_2O_5, and 98 ± 88 for SiO_2. In (b) the counts for the particles with Ø > 3µm are displayed. Here a significant improvement for the three materials is visible as well. For Al_2O_3, Nb_2O_5, and SiO_2 the number of added particles were reduced from 29 ± 40 to 19 ± 18, 40 ± 18 to 13 ± 6, and 88 ± 57 to 21 ± 20, respectively.

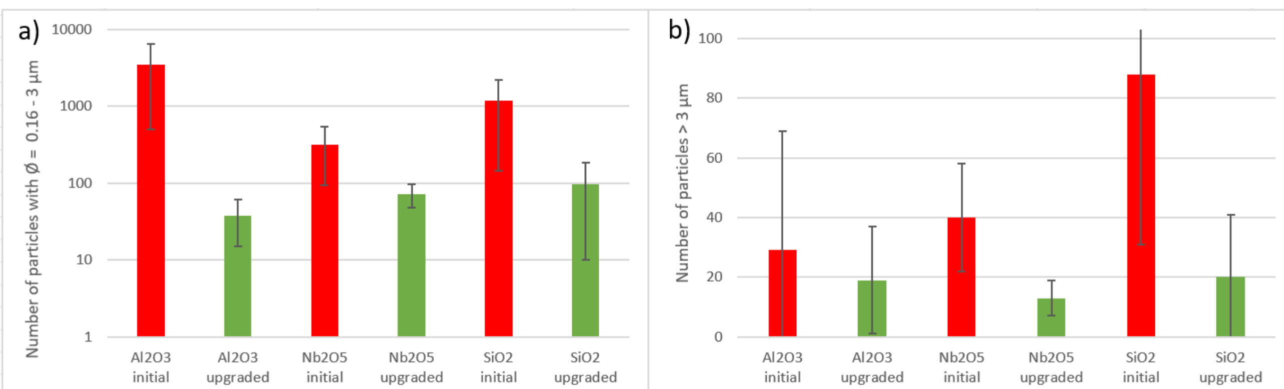

Figure 2. Comparison of the average number of particles detected in 100 nm single layers from Al_2O_3, Nb_2O_5, and SiO_2 deposited on Ø200 mm Si wafers using a HELIOS 800 sputter coater in the initial version and the upgraded version. In (a) and (b) the number of particles with a size of Ø 0.16-3 µm and > 3 µm are displayed, respectively. The error bars indicate the calculated standard deviation. It should be noted that the scale of the ordinate is logarithmic in (a).

Besides these three materials TiO_2 and Ta_2O_5 were tested too. For TiO_2 a remarkable reduction of from 86000 ± 12000 to 46 ± 36 particles with Ø = 0.16-3 µm was achieved as reported in another publication[11]. For Ta_2O_5 a good result of 28 ± 22 for the 0.16-3 µm and 22 ± 22 for the particles > 3 µm was achieved for the upgraded system. In summary, the defined goal of achieving less than 100 particles with a size of 0.16-3 µm was achieved for all tested oxide layers.

The results for the 602 nm thick optical filter stack are shown in Figure 3. In (a) the count for all particles larger than 2.5 µm are plotted for the initial and the upgraded setup. For the initial setup average particle counts of more than 200 for a size of 2.5-6 µm and about 28 for a size of more than 6 µm were recorded. By upgrading the HELIOS 800 system the particle count could be strongly reduced to less than 15 adders in total. In this case, no particle larger than 16 µm was detected on one of the wafers. The theoretical scrap level of the hypothetic device wafer in (b) shows a relative high ratio of about 4.3 ± 1.3 % of all dices polluted by particles for the initial setup of the sputter coater. In contrast, the upgraded setup shows a much lower scrap level of around 0.4 ± 0.4 %. This means that the amount of scrap of the devices would have been reduced by a factor of 10 by using the upgraded HELIOS 800.

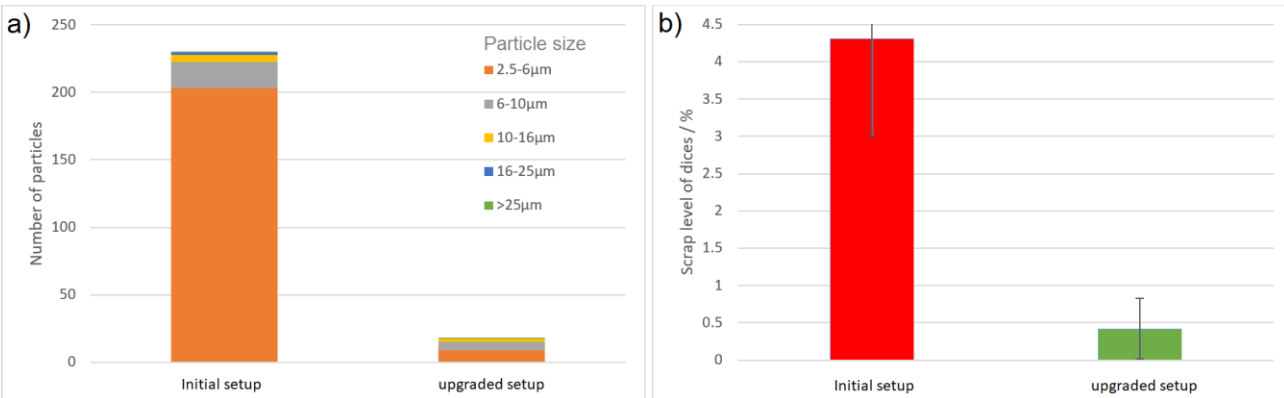

Figure 3. Average number of particles measured in an approximately 602 nm thick layer stack from SiO_2 and Nb_2O_5 deposited on 6 pieces of 200 mm wafers using the initial and the upgraded HELIOS 800 (a) and corresponding theoretical scrap level due to the particle pollution (b). The particle counts were recorded in an area with a diameter of 180 mm in the center of the wafers. The error bars in (b) indicate the calculated standard deviation.

The results for wafer level testing of the actual HSI devices are displayed in Figure 4. On average 142.5 of 228 imagers, i.e., 62.5 % on the 6 device wafers were found to be usable to manufacture HSI imagers. Most of the defects of the devices (31.5 % on average) were found to be of electrical nature which is clearly related to the manufacturing of the CMOS devices rather than to the optical coating. A smaller number of devices were defect due to particles blocking pixels (6.0 % on average). It is likely that these particles are not only originating from the optical filter coating but also from other manufacturing steps in the production line. The total production yield of 62.5 %, however, is remarkable since it is even slightly higher than the typical yield of the raw CMOS devices without any optical coatings which is only around 60 %. This means that there is no evidence for a reduction of the yield during the production of the HSI imagers due to the coating by the HELIOS 800.

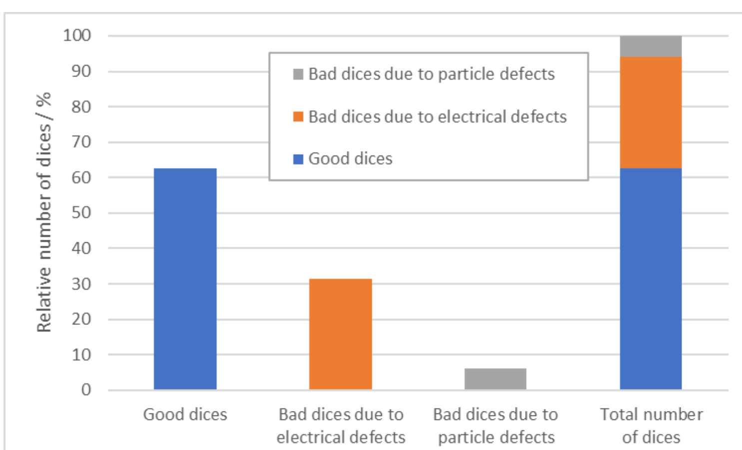

Figure 4. Average production yield values obtained by wafer level testing of a device wafer with 228 CMOS imagers coated with a 1 µm thick optical filter by means of a HELIOS 800 sputter coater.

The particle results for the 11 µm thick optical coatings are depicted in Figure 5. For the older HELIOS machine high particle numbers of more than 200 of a size > 2.5 µm were recorded in the rather small measurement area with a diameter of 20 mm. For the partially upgraded machine the counts appear to be strongly reduced especially for Run 1 performed right after cleaning of the process module. Here only around 40 added particles > 2.5 µm were measured. However, the next two runs show an increasing particle count reaching around 90 particles of this size for Run 3. This effect might be related to the increasing pollution of the machine. In contrast, the fully upgraded machine shows much lower and more stable particle counts of around 25 pieces with a size > 2.5 µm. This is remarkable since these tests were performed at the end of the lifetime of the targets and with a heavily coated machine.

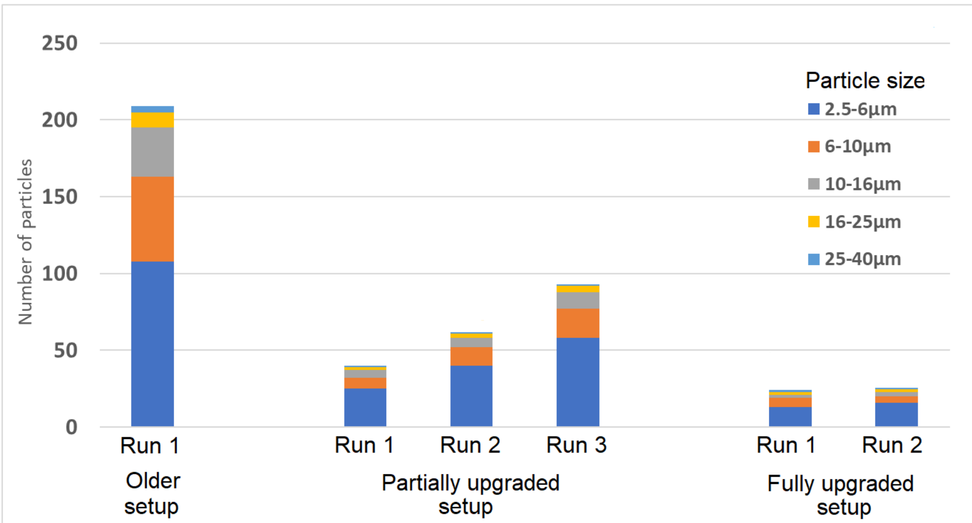

Figure 5. Exemplary particle results for an approximately 11 µm thick layer stack from SiO_2 and Nb_2O_5 deposited on Ø1" glasses by means of different HELIOS sputter coaters. The measurements were performed in an area with Ø = 20 mm in the center of the substrates. Each column represents one glass coated in one run. The results of one run using an older version of the HELIOS sputter coater (left), three consecutive runs with at partially upgraded system (middle), and two consecutive runs with the fully upgraded system (right) are shown.

4. CONCLUSION AND OUTLOOK

A comprehensive assessment of the particle counts in single layers from Al_2O_3, Nb_2O_5, SiO_2, Ta_2O_5, and TiO_2 deposited by means of a HELIOS 800 sputter coater was performed in a semiconductor facility. For the initial setup of the system, rather high particle counts were obtained, which are not suitable for the production in a semiconductor environment. By upgrading the hardware, the processes and the maintenance procedure of the machine, semiconductor grade particle levels could be achieved and stabilized of the full lifetime of the regarding sputter targets. Moreover, deposition of optical layer stacks with a thickness of 602 nm, 1 µm and 11 µm were tested using the initial and the upgraded system. In general, the particle counts in the layer stacks appeared to be much lower with the upgraded system compared to the initial one. This enabled the production of HSI imagers without any evidence of a reduction of the production yield induced by the deposition from the HELIOS 800.

In the next step, the upgrades implemented to the HELIOS 800 will be transferred to the larger HELIOS 1200 system capable to produce on substrates with diameters of up to 300 mm. It is expected that the combination of these upgrades and the sputter-up configuration for the HELIOS 1200 helps to further reduce the particle count especially for particles in the µm-range.

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