Advanced process control – lessons learned from semiconductor manufacturing

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ABSTRACT

Advanced Process Control (APC) has become an indispensable cornerstone of today's semiconductor manufacturing. With roots in chemical processing, APC has not only proven itself in semiconductor manufacturing, but has potential to enhance yield in adjacent industries, such as photovoltaics. This paper gives a short introduction to APC, including its key elements, and proceeds to illustrate examples and success stories from the application of APC in semiconductor manufacturing. Based on these application examples, the lessons learned are summarized and the potentials of APC for PV are derived.

Introduction

Semiconductor manufacturing consists of hundreds of process steps, with the entire device processing time, from blanket wafers to packaged chips, usually taking six to eight weeks. Fig. 1 shows a schematic of the general semiconductor fabrication process. In order to satisfy device quality requirements and to maintain high yield, a very tight control of every single process step is required and implemented in the production lines.

Photovoltaic devices, particularly thin-film cells but also mono- and polycrystalline cells, also have quite a demanding multilayer structure. The individual manufacturing processes, often bearing similarities to semiconductor production, are set to provide the desired layer thicknesses, homogeneity and composition, the crystal phases and the crystal structure defining the cell properties. Even the smallest process variations can affect the cell structure, and more importantly, the cell properties. Continuously increasing quality and cell efficiency requirements, combined with the enormous price pressure, require a very high process stability and fast reaction concerning process variation and drift. Therefore, as was seen in the semiconductor manufacturing industry, tight process control will gradually become vital in the photovoltaic industry to establish and to maintain high quality and high efficient production with increased yield.

Introduction to advanced process control

The semiconductor industry has always taken measures to ensure high quality productivity by increasing process control, as is the case in other branches of manufacturing industries. Common approaches include statistical process control, the use of neural networks – especially in high-dimensional problems, and advanced process control (APC).

The fundamental goal of APC is twofold: to obtain measures for process control closer to the process and to automate control actions. Fig. 2 illustrates how the increasing value of a semiconductor wafer can increase the potential loss in case of error. To minimize loss, the early application of appropriate measurement and control methods is necessary.

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APC comprises control methods that act directly on processes. The most important methods can be summarized as follows:

- *Methods for statistical process control (SPC)* SPC is a well-established technique of using statistical methods to analyze process or product metrics to take appropriate actions to achieve and maintain a state of statistical control and continuously improve the process capability. Many SPC tools are based on the so-called Western Electric Rules [1].
- *Methods for fault detection (FD), fault classification (FC) and fault prediction (FP)* FD is the technique of monitoring and analyzing variations in tool and/or process data to detect anomalies. FC builds on that and covers techniques of determining the cause of a fault once it has been detected. Both methods are often used together as ‘fault detection and classification’ (FDC). FP is the technique of monitoring and analyzing variations in process data to predict anomalies and faults before they actually occur.

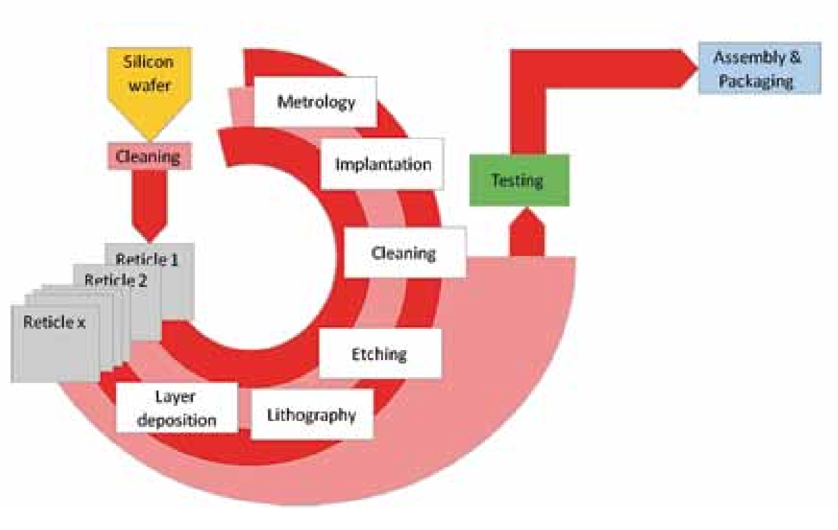


Figure 1. General fabrication flow of microelectronics devices.

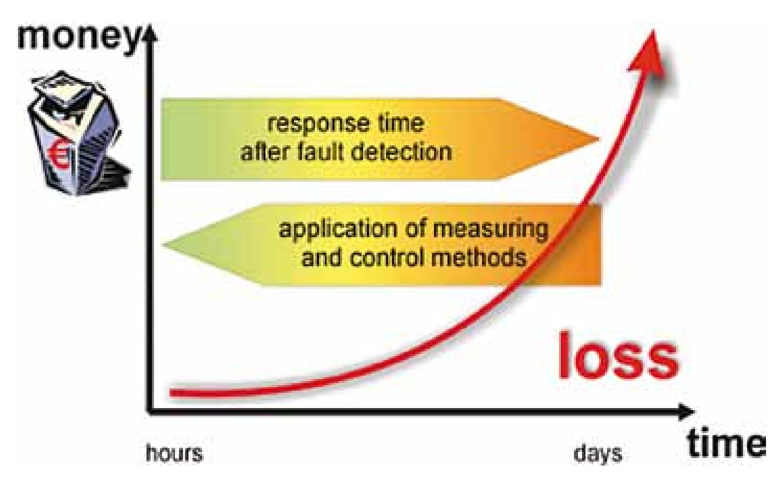


Figure 2. Correlation between the time of error detection and occurrence of loss.

- *Methods for run-to-run control (RtR)* RtR is the technique of modifying recipe parameters between production runs to improve processing performance. A 'run' can be a batch, lot, or an individual wafer. In serial processing this method can just be applied between two measurements.
- *Methods for virtual metrology (VM)* VM is the technique of deriving wafer parameters or product parameters from existing manufacturing parameters or from upstream metrology (e.g., process state, additional sensors, temperature, pressure, gas flow etc.) by using physical models.

It is obvious that the proper application of these methods relies heavily on the availability of data throughout the fab. Those data may come from the manufacturing equipment (e.g., equipment health indication, uptime data), from the process (e.g., temperature, pressure), or from the wafer (e.g., layer thickness, layer composition). In order to be able to apply control algorithms, 'quality parameters' have to be identified as well as 'tuneable parameters'. Quality parameters describe whether a production run was successful; tuneable parameters are parameters that can actually be adjusted to adapt a process. In addition, wherever data are collected, specific emphasis must be put on data quality (e.g., accuracy, resolution, correct time-stamping, context information), because every control measure can only be as good as the data upon which it relies.

Fig. 3 depicts some of the aforementioned elements of APC in an abstract process flow. This is independent from an actual implementation in semiconductor or PV manufacturing, as data about processes and product properties are collected by sensors and dedicated metrology. The data from the sensors are used for a simple 'go/no go' decision at process *n*, based on the knowledge of whether or not a certain quality parameter is beyond a defined limit. Both process and metrology data are used to feed a run-to-run control algorithm to adjust tuneable parameters of process *n* to adapt to changes in quality parameters detected at the post-process metrology or previous metrology step. This is either called feed-forward or feedback control, based on the metrology step used for automated adjustment of recipe parameters. A combination of both feed-forward and feedback is possible.

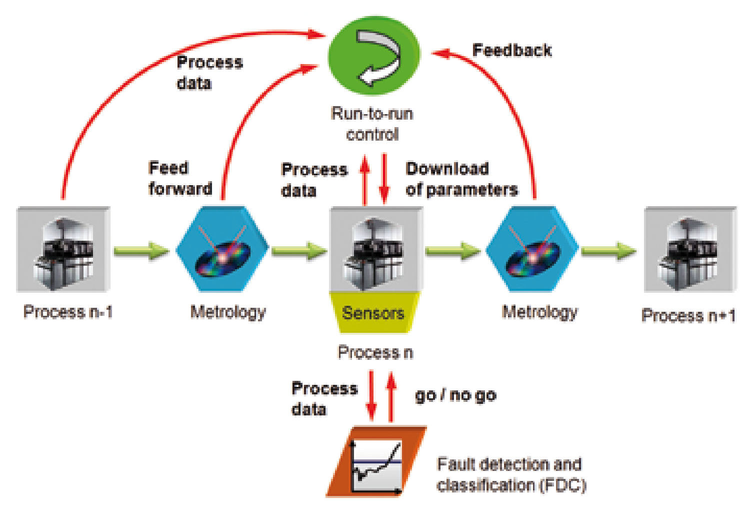


Figure 3. Interaction of APC elements.

Examples and success stories for the application of APC

Examples of successful application of APC in the semiconductor environment are manifold. However, not every single application is transferable to other production environments. The following sections focus on deposition and metallization processes, often based on plasma-enhanced methods, which are important techniques both in semiconductor manufacturing as well as in the photovoltaic industry. Common quality parameters for these processes may be identified in both industries, and features such as deposited thickness, homogeneity of layer thickness and layer composition can act as quality parameters to optimize anti-reflective coatings (ARC). In the semiconductor industry, the tight control of critical dimensions is also a very important issue.

Integrated metrology as enabler for APC

In a straightforward approach, these parameters may be measured by standalone metrology tools and the measured quality parameter of the substrate or device under investigation may serve as an input parameter to control a process and the respective equipment. Interestingly, for large substrate areas and high-throughput production processes in particular, it turned out to be more efficient to measure parameters that may serve as input for a control strategy more closely to the equipment (see Fig. 2).

In semiconductor processing, integrated metrology (IM) has proven to be an enabler for APC and to provide substantial benefits in process development as well as in volume production. Several prerequisites are necessary for the successful and effective implementation of IM. These include: the availability of solutions for mechanical integration and automation of sensors or measurement equipment; the availability of analysis methods to correctly measure inside an equipment or process environment; and the efficient connection to a data framework enabling fab-wide APC strategies. In the past, various IM solutions were developed for different process classes in the semiconductor industry, e.g. plasma processing, lithography, thermal deposition and oxidation processes, and implant. Retrofit solutions for IM integration may be applied for existing equipment, but the most efficient approach is development of

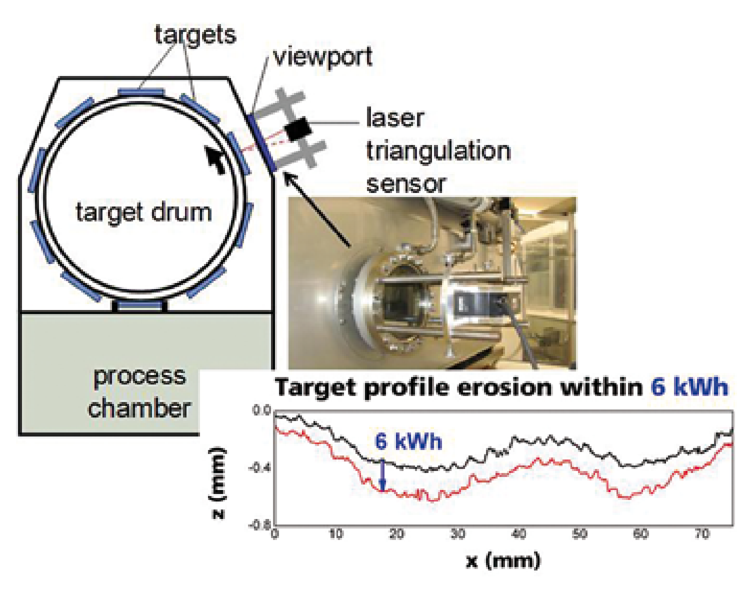


Figure 4. Laser-triangulation system for the target control in dynamic linear magnetron sputtering. The difference between the black and red curve represents an energy usage of 6kWh.

IM and APC strategies at the early stage of the process equipment development.

Example 1: Control of sputter erosion

In sputtering processes, the cathode material (target) is removed by accelerated ions in the plasma, and the removed material is then deposited on the wafer. During that process, the target is eroded and, as a consequence, the envisaged process result on the wafer is influenced by this erosion. Additionally, the use of magnetic arrays (magnetrons) behind the target, used to enhance the deposition rate, causes inhomogeneous erosion resulting in the formation of deep grooves in the target surface and leading to unpredictable process results in homogeneity and composition. Exceeding the target lifetime may also result in contamination of the deposited layer by sputtering the backing plate.

There are several options available to help monitor the target erosion state, including modelling the target erosion by using equipment data like operating hours and RF power. However, a direct measurement of the target erosion is advantageous and more accurate. To this end, a measurement system based on the principle of laser-triangulation was developed for the assessment of new equipment for linear dynamic magnetron sputtering. The measurement system was adapted to a viewport and enables the profile analysis of the sputter target surface and the determination of the surface erosion, which is not visible to the operator (see Fig. 4). By means of the measurement system, it is possible to control the process parameters based on the current target profile. The application of end-point control enables the optimum usage of expensive target material. With a resolution of 0.1µm, the measurement system is capable of reducing the safety margin in target thickness for the prevention of contamination to a third of its former value. Given the extremely thin targets used by the tool, this could result in savings of up to 5-10% of target material as well as a significant reduction in downtime and maintenance effort.

Example 2: Control of homogeneity and plasma composition

A frequent problem in plasma processing is the control of plasma composition and plasma homogeneity, especially in large-volume reactors. Multichannel optical emission spectroscopy (OES) is a powerful measurement method of controlling these parameters. In OES, the light spectrum emitted from the plasma is analyzed and the chemical species in the plasma are identified from the characteristic emission lines. By comparing the spectra at different locations in a reactor, the homogeneity of the plasma may be controlled.

A low-cost OES system was applied in a two-channel configuration to support process development for a new 300mm mini-batch plasma furnace for thin-film deposition, as shown in Fig. 5a. An innovative solution for spectrometer integration was developed to measure the spacing of a stacked electrode assembly. Light from the plasma was guided to the spectrometer through quartz rods, applying the principle of total internal reflection. The spectrometer controls were fully integrated into the furnace control software. By applying an advanced algorithm for spectrum analysis, the

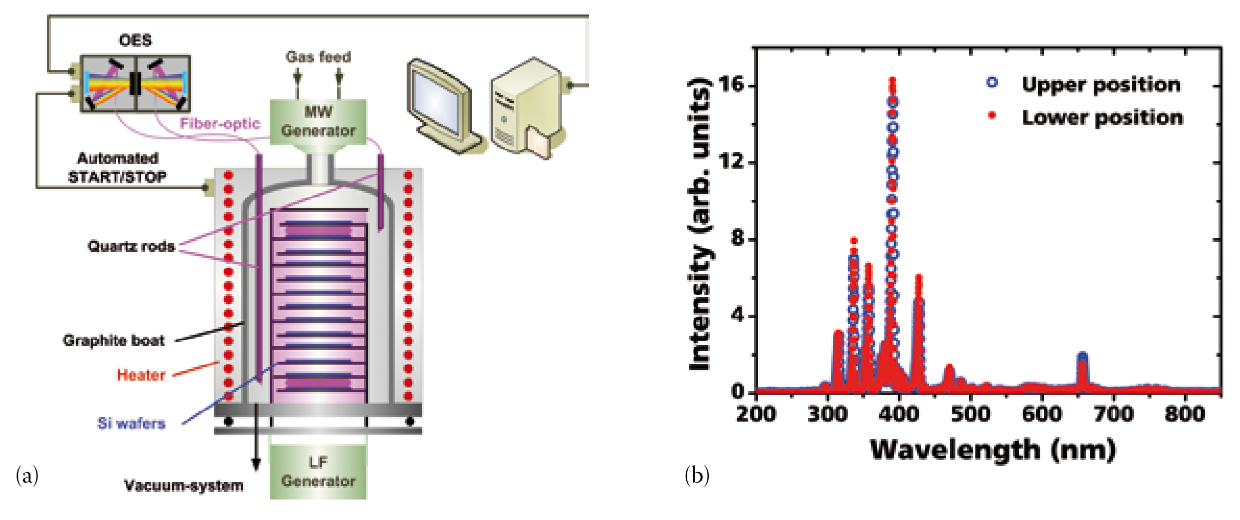
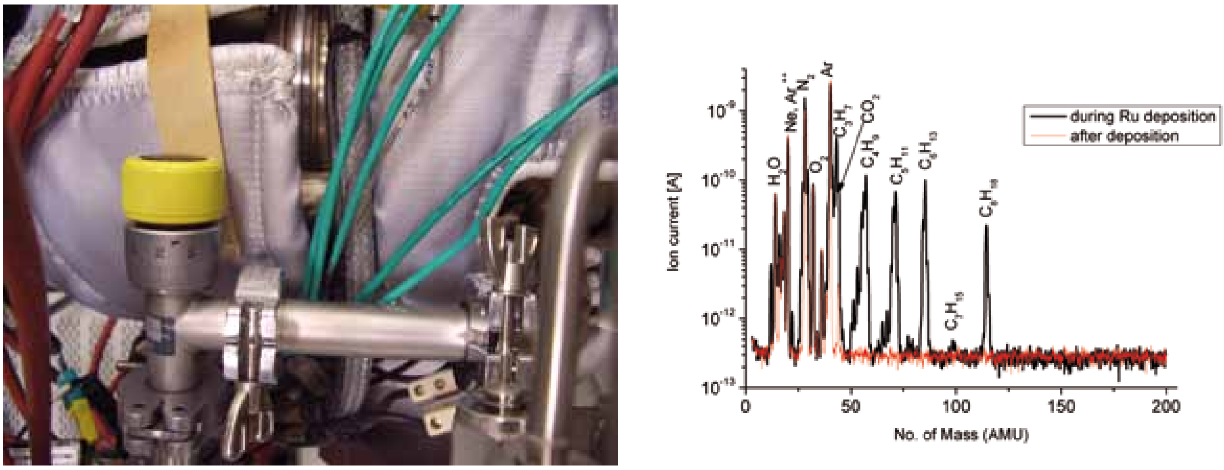


Figure 5. Image (a) shows integration of the optical emission spectrometer into a 300mm mini-batch plasma furnace for thin-film deposition. The graph in (b) shows the coincidence of the emission spectra measured at the upper and lower electrode position for optimized plasma homogeneity.



(a)

(b)

Figure 6. Adaptation of the mass spectrometer port to a flange of the MOCVD reactor (a). The graph in (b) depicts the mass spectrum of the precursor and carrier gases during ruthenium deposition and on completion of the process.

plasma generated by two different plasma excitation sources could be optimally adjusted and controlled in composition and homogeneity vs. the reactor volume using one key number. Fig. 5b shows the comparison of the spectra of an $N_2/NH_3/He$ plasma recorded at the upper and lower electrode and with optimized homogeneity of the plasma composition.

The measuring plasma composition and uniformity approach can be easily transferred to other plasma equipment. The advantage for an established process is that the plasma composition that directly influences layer thickness and composition can be controlled in real time. Deviations in the plasma composition and uniformity may be easily detected, preventing misprocessing of subsequent wafers. Enormous cost savings can be achieved if the approach is applied during process development. Further processing of device structures is necessary to assess electrical layer properties and homogeneity of processing for the deposition processes described here. Using this OES solution over two days, a total of 400 process settings were investigated from which 10 processes were selected for further process assessment on device structures.

Example 3: Process stabilization and cost optimization in chemical vapour deposition (CVD)

An important issue during process development and actual processing is to achieve stable process conditions at optimized cost. An important factor in many processes is the avoidance of overhead process times and the reduction of precursor or gas consumption. In order to maintain the process results, while addressing these objectives, precise process knowledge is vital. The application of integrated metrology supports these objectives since important process parameters can be measured directly on the equipment. For example, a deposition module for pulsed MOCVD was optimized for deposition of thin ruthenium films applying mass spectroscopy which was integrated in the MOCVD module (see Fig. 6a). By integrating mass spectroscopy, the stabilization times and precursor injection parameters were optimized for the complex deposition processes, which consist of a sequence of single steps.

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Fig. 6b shows the mass spectrum taken during a ruthenium deposition process with N_2, O_2, Ar, CO_2, H_2O and octane with its fragments, which serves as a measure for the precursor in comparison to the remaining gas composition that is present after completion of the deposition [2]. By simultaneously measuring the concentration of the reactive species in the reactor, important deposition mechanisms can be investigated and optimized gas and precursor flow settings can be derived. With optimized precursor and carrier gas adjustment and stabilization time, processes with optimized layer quality at optimized throughput can be achieved. For example, the process investigated here yielded a reduction of process duration up to 20% by optimized gas adjustment.

The role of standards in APC

To support the cost-effective application of metrology as both an enabler of APC and of actual APC systems, the semiconductor industry developed a host of standards covering different aspects of APC. SEMI (Semiconductor Equipment and Materials International, [3]) coordinates the elaboration, synchronization and distribution of standards both for semiconductor manufacturing and PV, some of which are mentioned here:

- Standards for APC:
  - SEMI E133 defines the capabilities of APC systems as well as their interaction between each other and the fab environment.
  - SEMI E126 defines commonly-used quality parameters related to the success of process runs, for individual equipment groups such as etch, CVD, deposition or diffusion.
- Standards for (integrated) metrology:
  - SEMI E127/E131 comprises specifications for communication and interface requirements for integrated metrology.
  - SEMI E141 acts as guide for the specification of ellipsometer equipment for use in integrated metrology.
- Standards for equipment automation, data acquisition and data quality:
  - A SEMI guideline defines quality of protocols, quality of data and test procedures for verification.
  - SEMI E5/E30 define the well-known 'SECS/GEM' interface for equipment communication; several standards (SEMI PR8/E121/E125/E132) specify the higher-performing 'Interface A' (often referred to as 'equipment data acquisition,' or EDA).

The so-called 'PV Group' at SEMI takes care of standards for the photovoltaics industry, particularly standards from the realm of equipment automation and process control systems that are already being (re-)used in or adapted for the photovoltaics industry. SEMI PV2, the Guide for PV Equipment Communication Interfaces, for example, builds on some of the aforementioned semiconductor standards.

Lessons learned and potentials of APC for PV

It is obvious that findings from the semiconductor industry cannot be reused like for like in the photovoltaic industry. Although both the processing schema and the cost schema are way too different to simply enable duplicate solutions, the principle techniques, methods and algorithms can be applied.

Thus some overall 'lessons learned' can be summarized that hint at the potential for APC in PV:

1. **Know your process**. A sound process understanding is required to identify the right quality parameters characterizing the quality of a product, to measure them and to build models and algorithms for sustainable APC control. As shown earlier, (integrated) metrology may help to deepen process knowledge.
2. **Use data you already have**. In each fab, a huge variety and number of data are available – from sensors and metrology to equipment and logistics. Before adding new data sources, it is better to link existing ones to allow full extraction of information.
3. **Keep things simple and inexpensive**. In the examples discussed, it was shown that the quick integration of a mass spectrometer fostered process understanding and allowed for an optimized process setting. 'Inexpensive' is certainly a different absolute figure in different processing environments, but one should be aware that a simple sensor can suffice in place of a full-featured set of metrology equipment for the measurement of one important quality parameter and setting up an APC capability.
4. **Go for low-hanging fruits**. As for most things in life, the 80:20 rule holds also for APC – experience shows that for the final 20% of solutions, 80% of the effort has to be spent. Thus, it is better to start with well-understood processes and problems, implement simple sensors, use linear algorithms, etc., and then build on the success achieved with those solutions.
5. **Make use of standards**. Smart people have invested a lot of time in thinking out scenarios and requirements. Using standards wherever possible helps to keep things complete and to keep implementation costs low due to the use of compliant and exchangeable IM/APC entities.
6. **Take care of data quality**. Every control action is only as good and as reliable as the data flowing into it.

Up to now, one could argue the necessity of implementing APC into photovoltaic production processes. Many claim it is semiconductor centred and too costly. But discussions on high-cost also plagued APC in semiconductor manufacturing from the very beginning – and today, every fab has APC applications implemented in its production flow. Indeed, the changing political and economical environment, paired with increasing technological demands and shrinking process windows (e.g., PVD or CVD thin multi-layer deposition, high temperature anneals, or patterning by laser scribing) also inherent in PV will see APC become a tool of ever-increasing importance to keep production cost low and yield high.

Specific, cost-efficient APC solutions for PV will be developed and applied, since many of the more expensive solutions from semiconductor manufacturing cannot simply be reused. But the transfer of APC from semiconductor manufacturing to PV production is not a one-way street: many of the smaller European semiconductor manufacturers have begun to ask for cheaper APC solutions than those applied by the big high-volume manufacturers. Thus, a huge field of joint development, networking and interlinking in APC with sharing efforts and sharing cost may yet evolve here.

Acknowledgment

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