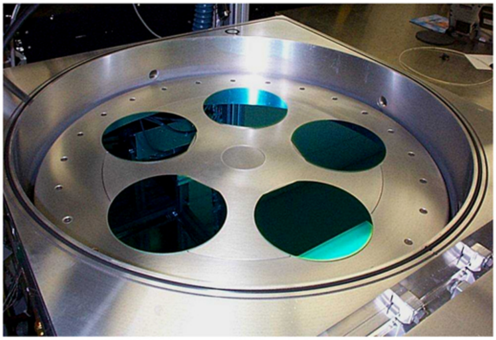
Batch-deposition module cuts downtime and material waste

Maximizing yield, increasing throughput and reducing scrap is becoming increasingly critical for GaAs device manufacturers as customers demand cheaper products. **David Lishan** from Unaxis, **Mike Fresina** of RF Micro Devices and their colleagues describe how a large PECVD module has more than proved its worth in a high-volume production environment.



The large-area batch PECVD system – used to deposit SiN_x films – holds up to five 150 mm-diameter GaAs wafers.

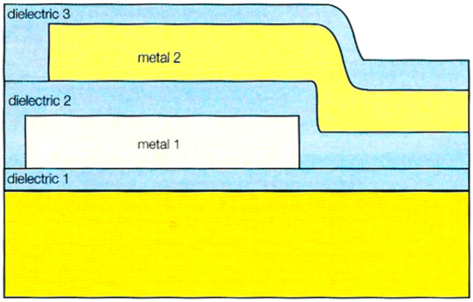


Fig. 1. Silicon nitride is used for passivation (dielectric 1), MIM-capacitor (dielectric 2), and glassivation (dielectric 3) applications.

With the average selling price of many compound semiconductor devices sliding by up to 20% year after year, it is becoming ever more critical for chip makers to improve margins by maximizing wafer yield, throughput and manufacturing uptime, while reducing the amount of scrap material produced.

Investment in a new, larger tool to increase manufacturing capacity is part of the solution, but the economics of nearly all device production requires attention to a myriad of variables in cost-of-ownership calculations. As might be expected, process system performance provides many of the critical variables. Obtaining a favorable cost analysis for tool operation implies systems that guarantee long uptimes and high throughput while maintaining a low level of scrap. Critical though this data might be for making decisions relating to production and capacity, collecting it is usually a tedious process and as a result such information is often unavailable.

Several years ago, Unaxis introduced a production batch plasma-enhanced chemical vapor deposition (PECVD) module for silicon nitride (SiN_x) deposition. Using the same basic technology and process regimes of earlier systems, a new, larger module has now proved itself under high-volume production conditions, and the data presented here confirm its usefulness.

Controlling film thickness

PECVD SiN_x is used in many different III-V-based devices such as MESFETs, HBTs and HEMTs in the roles of passivation and encapsulation (figure 1). In particular, the large dielectric constant of SiN_x makes it attractive for use as an intermetallic insulator material in metal–insulator–metal (MIM) capacitors. To meet circuit and device-design criteria as a capacitor dielectric, SiN_x film thickness and insulator properties need to be tightly controlled.

A SiN_x deposition process was developed for GaAs monolithic microwave integrated circuits (MMICs) and used in high-throughput batch PECVD production at RF Micro Devices. PECVD is well suited to the low-temperature constraints of GaAs-device manufacturing, as the technique allows growth of high-quality SiN_x films below 400 °C with deposition rates of approximately 100 Å/min.

The PECVD system uses a conventional parallel-plate configuration operating at 13.56 MHz. Dilute silane in nitrogen and ammonia are combined in a plasma to form the SiN_x film. Nitrogen is used as a carrier gas, and it is also introduced as a separate gas in the deposition process. It is possible to control the film stress over a stress range of about –300 (compressive) to 300 MPa (tensile) by modifying the plasma chemistry [1].

Controlling film stress is critical because it strongly influences the mechanical integrity and electrical characteristics of the manufactured device. It is is also useful for maintaining either low composite stress in device layers or for introducing a desired level of stress to define specific film properties. A stress of around zero ensures that even relatively thick SiN_x films will have a small absolute stress.

Film specifications for the batch PECVD production solution exceed the requirements for most MMIC applications. In general, SiN_x film specifications cover within-wafer, wafer-to-wafer and batch-to-batch film thicknesses, since a highly uniform target film thickness

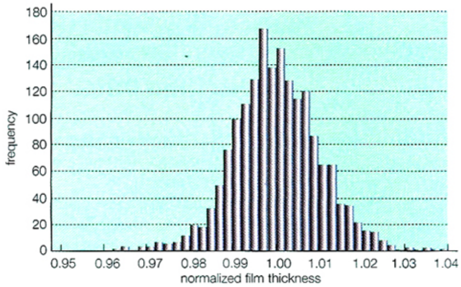


Fig. 2. A near-Gaussian distribution of the deposited SiN_x film thickness indicates sufficiently high reproducibility for the batch PECVD process with more than 1700 samples collected.

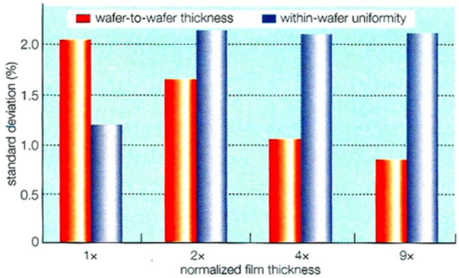


Fig. 3. Variations in the within-wafer (blue) and wafer-to-wafer film thickness (red) were well within the 2.5% target range. Keeping within this range is essential to meet capacitance design criteria.

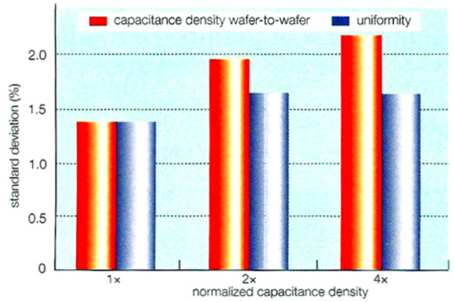


Fig. 4. Capacitance density, an important indicator for device performance characteristics, showed adequate reproducibility within a single wafer (blue) and between different wafers (red).

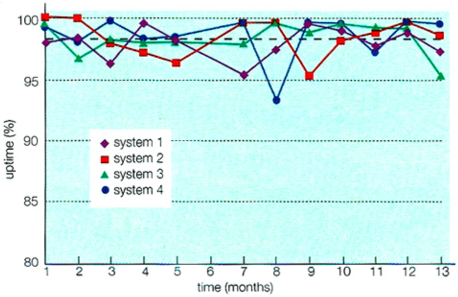


Fig. 5. As well as film uniformity and quality, uptime is crucial for GaAs-device manufacturers. Four batch PECVD systems were monitored over 13 months, resulting in an average uptime of 98%.

is essential for meeting capacitance design criteria. Statistically speaking, the standard deviation of a film thickness must be within 2.5% of the specified target.

To establish whether these targets had been successfully met, more than 1700 samples of film thickness were collected over a more than a year using a spectroscopic reflectometer (figure 2). The data shown correspond to SiN_x films deposited on five different systems and have been normalized to the target thicknesses. The narrow, near-Gaussian distribution levels reveal a normalized standard deviation of 0.0097, and this confirms a tight distribution around the target film thickness.

Similar results to this have been found with three other film-thickness goals that spanned a range of between one and 10 times the thickness of the thinnest film. For proprietary reasons, the film thicknesses shown in figure 3 have been normalized to the thinnest film produced (that is, film thicknesses were two, four, and nine times that of the thinnest film).

Wafer-to-wafer thickness reproducibility was also demonstrated to be within the 2.5% target window (figure 3). More important was that the within-wafer uniformity over the measured production runs also met the required level of reproducibility. All of this was achieved, in part, because the reactor encourages deposition uniformity owing to the careful design of a showerhead for process-gas introduction and the use of a unique pumping manifold.

Reproducible film quality

Being able to reproduce high-quality film is as important as meeting film-thickness targets. In the case study presented in figure 4, the films were used as capacitor dielectrics. Wafer-to-wafer capacitance-density reproducibility is presented for three different films and, as with the film-thickness measurements, the capacitance-density figures are normalized to the smallest value. Again, the reproducibility surpasses the 2.5% specification goal for both capacitance density and for wafer-to-wafer uniformity.

By achieving the desired process stability, a high yield is ensured. After device performance, yield improvement is often considered to be the next most critical goal in a manufacturing environment. Device-function requirements, along with process capability determine the level of qualified product. Reproducibility within upper and lower bounds, as described by statistical process control, is determined by many variables, including maintenance schedules and process stability (of gas flow, pressure, RF power and

temperature, for example).

In this case, the reproducibility is attributed to a highly robust system and routine maintenance procedures. The tighter the capacitance distribution, the better the final product yield will be of devices with crucial characteristics such as high efficiency and high gain.

The batch deposition module used in this work was intended not only to provide SiN_x films of the required quality, but also to increase throughput. To do this, it uses an appreciably larger chamber than is typical, and can, therefore, accommodate significantly more wafers in each batch. The two standard batch sizes are eight 100 mm-diameter wafers and five 150 mm-diameter wafers. Available on a cluster tool platform, the large-area PECVD batch system offers fully automated, cassette-to-cassette processing, and batches are loaded from the cassettes using a rotating indexer in the process chamber.

Equally important to the throughput figures used in cost-of-ownership calculations is the system's operational uptime. Figure 5 shows the uptime of four different batch PECVD systems recorded over a period of a year. Except for a single month on system 4, where the operational uptime dipped to 93%, the uptime performances were consistently above 95% with an average uptime of more than 98%. Scheduled maintenance time is counted as downtime, as described in the international semiconductor guidelines provided by Semi E10-0701. This preventative maintenance averaged approximately 2% of measured downtime per system over the reviewed period.

Interpreting these uptime figures requires at least a rudimentary understanding of the maintenance cycle and practices involved when using a batch deposition module. The PECVD reactor includes several features to maintain system cleanliness that all serve to enhance yield and minimize system downtime. For example, the chamber walls and the upper gas-distribution electrode of the reactor are heated to minimize particulate formation during SiN_x deposition. As might be expected, SiN_x is deposited on the wafer and also on exposed surfaces in the chamber. If this material were allowed to build up indefinitely, issues with process repeatability and particulate control would arise.

Preventative measures

To help maintain consistent levels of efficiency, the standard PECVD SiN_x process incorporates both a regular *in situ* clean and a manual cleaning process. The *in situ* clean is performed more frequently (after approximately 1.5 μm of deposition) and is based on a fluorine plasma etch.

Uptime performances were consistently above 95% with an average of greater than 98%.

To achieve and consistently maintain the reactor in a clean, known state, an automatic plasma etch-back sequence is integrated with an optical emission spectrometer (OES). The OES ensures that effective *in situ* cleaning is completed in the shortest possible time. Typical *in situ* cleaning proceeds at a rate of approximately 2500 Å/min and thus cleaning takes around six minutes or about 4% of the deposition time. As a result, manual cleaning has to be carried out only once a year.

A number of important features are available on the batch PECVD system to improve system maintainability and uptime. These were all implemented based on experience with the standard PECVD system and include clean-chamber design. Modifications were made to minimize the number of parts of the reactor that tend to collect deposited material and become difficult to clean. A heated top electrode improves processing ability and system cleanliness, while port access to the main pump manifold allows for easier manual cleaning of the main vacuum manifold.

Now proved at various customer production sites, we conclude that the batch PECVD system provides advanced III-V device manufacturers with a high-throughput solution for depositing high-quality SiN_x at low process temperatures. Extensive testing has demonstrated that these results are not only repeatable for production with 150 mm-diameter substrates, but they are also achieved with uptimes of approximately 98% and with negligible scrap generation. ●

Reference

[1] K D Mackenzie, B Reelfs, M Devre, R Westerman and D J Johnson 2004 *Proc. CS Mantech Technical Digest* pp319–322 .

David Lishan, Ken Mackenzie and Dave Johnson are with Unaxis Wafer Processing in St Petersburg, Florida. Mike Fresina, Doug Wend and John Erickson are with RF Micro Devices in Greensboro, North Carolina. E-mail David Lishan at david.lishan@unaxis.com or Mike Fresina at mfresina@rfmd.com.