Automotive electronics: Gearing up
CARS AND CHIPS: HOW AUTOMOTIVE INNOVATION IS DRIVING SEMICONDUCTOR MANUFACTURING

A Letter from Ali Salehpour

Technology trends sometimes have a way of sneaking up on us. For the past few years, chip manufacturers have focused on supplying ICs for the latest smartphones, tablets, PCs, and other consumer electronics. Now, even as that market seems to have leveled off, the automotive segment continues to grow, fueled by a myriad of convenience and safety innovations as well as the pursuit of self-driving cars. As a result, automotive semiconductor revenue is growing at nearly twice the rate of the overall semiconductor market.

That’s why automobiles take center stage in this issue of Nanochip Fab Solutions. Our cover story, “Driving Innovation,” discusses the automotive industry in this milestone period, heralding decades of change—change that will directly impact semiconductor manufacturing.

In a recent presentation at imec-ITF 2016, in Brussels, Audi executive Berthold Hellenthal noted that today 80% of all automotive innovations depend on semiconductors. Everything from sensors and 3D video cameras to night vision and long-range radar relies on ICs. And this dependency touches every aspect of the automotive business, including quality, costs, and supplies.

German consultants PwC (whose figures Hellenthal cited at imec) estimate that electronic components, which currently represent less than 30% of a vehicle’s manufacturing cost, will represent 50% by 2030. Nanochip Fab Solutions examines both technology and market drivers behind this projected growth. Our readers will soon learn why the need to supply ICs for electric vehicles (EVs), self-driving vehicles, and advanced driver assistance systems (ADAS) features is tightening the relationship between automakers and chip manufacturers more than ever.

We also look at the interesting phenomenon of manufacturing new, highly sophisticated ICs, such as advanced power devices and MEMS for auto sensors, using more cost-effective legacy tools. One article, for example, explores how the MEMS industry is getting a boost from companies interested in using the piezoelectric effect and new materials like scandium to build next-generation microphones and fingerprint sensors—two high-volume products that could have a major impact on 200mm semiconductor manufacturing. While challenges remain, Applied is now working with leading technologists to develop a new class of MEMS devices that leverage this important technology.

Our article on FabVantage 360 introduces a new benchmarking service that gives customers a “big picture” view of their fab operations, enabling them to see how their tool performance compares to the world’s best-in-class facilities. This capability touches on an issue that is particularly important to automotive device manufacturers: the ability to ensure the safety of devices they produce for automotive applications through critical analysis of process control (FDC) and detection of deviations early in the production process rather than later at final test.

Finally, two related articles introduce Applied Materials’ redesigned 200mm Centura Epi chamber and Vita controller for 200mm Applied Producer tools. The new Epi chamber delivers the superior quality thick epi required for MEMS and other power device applications without compromising results for thinner layers. The Vita controller, previously available for 200mm Centura and Endura systems, has now been extended to 200mm Producer tools, enabling high resolution and data clarity, with total recipe transparency and backward-compatibility with the original software.

Cars and chips. Less than a decade ago this would not have been the most obvious of pairings, but this will be a key driver of our industry today. And as you’ll read in the following pages, we’ll better fasten our seatbelts and gear up: it’s going to be an exciting ride!
NEW HIGH-PRODUCTIVITY EPI CHAMBER FOR THICK SILICON EPITAXY

BY CARLOS CABALLERO

Semiconductor technology is undergoing a sea change as proliferating mobile technologies and the growing Internet of Things broaden the use of semiconductors in more products across more market segments than ever before. Among many design and manufacturing changes, these forces are stimulating the fabrication of devices in which performance is enhanced by using much thicker films than are typically associated with semiconductors. Applications calling for thick epitaxial silicon (Si) can now benefit from a versatile new single-wafer chamber specifically designed for that purpose. A new Centura Epi chamber has a >6 µm/min growth rate that enables more than 100 µm of silicon epitaxy in a single pass through exceptional chemical efficiency, delivering both high productivity and lower cost of ownership.

Today’s semiconductor industry may be more dynamic than ever before. While leading-edge chip designers explore the far frontier of scaling below 10nm, a growing variety of devices are being fabricated using films that are thousands of times thicker. Thick, doped epitaxial Si forms electrical isolation for high-voltage, faster-switching power semiconductors, such as insulated-gate bipolar transistors (IGBTs), used in appliances, stereos, trains, etc. It also improves device performance and lowers manufacturing costs of price-sensitive sensors and actuators by incorporating microelectromechanical systems (MEMS) in power-efficient, “smart” applications.

Commercially viable manufacturing of power devices and advanced MEMS requires epitaxial Si 30–150 µm thick to be grown on systems that deliver high productivity at the lowest possible cost of ownership. Many of these devices can be cost-effectively manufactured on 200mm systems and are rejuvenating the market for this equipment. Applied Materials actively supports the expansion of 200mm technologies and has enhanced the capabilities of several of its 150mm and 200mm systems—including its widely used 200mm Applied Centura Epi chamber—to meet evolving industry requirements.

A pioneer in epitaxy and the market leader in epitaxial deposition equipment, Applied Materials has leveraged its long-established expertise in materials engineering to redesign the 200mm Centura Epi chamber specifically for superior quality thick Si (20–100µm) without compromising its already excellent results for thinner layers (<20µm). The new 200mm Applied Centura Epi chamber features process kit modifications that combine to enable (1) growth of up to 100 µm of Si in a single pass; (2) shorter clean time compared to that of a standard chamber; (3) multi-wafer processing between cleans (for <20µm); and (4) significantly lower consumable costs.
Once an epitaxy tool is fully depreciated, running cost has a major direct impact on profitability, so tight control of consumable costs is critical to overall profitability.

UPGRADING THE CHAMBER

Power devices and MEMS require extremely uniform epitaxial Si and resistivity of less than 2%. To meet these demands, key hardware and software components of the standard 150mm and 200mm Centura Epi chambers were upgraded for the new Epi chambers.

Chamber: Process kit geometries were modified to achieve a smaller boundary layer, i.e., zone of highest precursor concentration above the wafer surface. This promotes faster film growth by more effectively containing the trichlorosilane (TCS) Si precursor in the reaction space above the wafer surface. The resulting boost in chemical efficiency reduces the volume and cost of TCS required by the process.

Several design changes to other components improve laminar gas flow to facilitate higher growth rates, improve uniformity of film growth and resistivity, and reduce unintentional coating of chamber components, including the upper and lower dome. Reduced coating is particularly important in ensuring good temperature uniformity and stable film growth across the entire wafer.

Motorized Susceptor Lift: The Applied Centura Epi system can accommodate up to three of the newly-designed chambers. In each chamber, a wafer rests in a pocket on a susceptor that rotates while precursor gas is injected into the chamber and the epitaxial process takes place. Exact positioning of the wafer is essential for optimizing within-wafer uniformity and wafer-to-wafer repeatability of the process. Therefore, in the new chambers, the conventional pneumatic susceptor lift has been replaced with a motorized lift whose speed can be much more carefully controlled to avoid wafer movement within the susceptor pocket (see figure 1). A new susceptor-leveling mechanism complements the motorized lift to enhance positioning repeatability (see figure 2).

Reliable centering of wafers also minimizes bridging, i.e., the tendency of wafers to stick to the susceptor. This effect can occur when the susceptor surface is exposed between the edge of the wafer and the pocket sidewall, allowing epitaxial growth to spread over this area.

Closed-loop dome temperature control: This new software feature has the dual benefit of improving on-wafer performance and boosting system productivity. Maintaining a stable process environment temperature (see figure 3) is important for promoting the desired single-crystal growth. Closed-loop temperature control also helps minimize coating of the dome.

Minimal coating has implications for both film quality and system productivity. Producing thicker films requires longer process times, increasing the possibility that coatings or byproducts will build up on chamber surfaces.

The thicker the deposits, the greater the risk that the material will flake off and fall onto the wafer, creating yield-limiting defects.

From a productivity standpoint, a thin coating can be removed speedily and with a small volume of hydrochloric acid (HCL). This contributes to lowering the cost of consumables, and lessens the system’s potential environmental hazards. For thinner epitaxy (<20µm), negligible dome coating allows throughput of three wafers between chamber cleanings rather than only one, as is typically the case.

IMPROVING PERFORMANCE

As summarized in table 1, the modifications described earlier enable Applied’s new epi chamber to satisfy all key market requirements by mitigating the major challenges posed by thick epitaxy. It achieves an unmatched growth rate of high-quality Si, formed with excellent thickness and doping uniformity and negligible defectivity. In addition, it ensures repeatable wafer placement and eliminates bridging, which are both essential for high-yield volume manufacturing. Moreover, this industry-leading performance is delivered at a lower cost of operation than competing alternatives offer.

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Figure 4 illustrates the higher growth rate produced by the new, smaller Centura Epi chamber and more efficient chemistry, while figure 5 shows the uniformity of thickness and resistivity achieved. The new chamber offers the versatility of equally good results for both thick and thin epitaxy (see figure 6). Resistivity targets are reached rapidly and remain stable throughout the entire growth process (see figures 7–8).

SUMMARY

With the introduction of the new Centura Epi chamber, Applied Materials has significantly upgraded its workhorse 150mm and 200mm Centura Epi chambers to meet the industry need for cost-effective production of thick Si in power-device and MEMS applications. In a 500-wafer marathon, the redesigned chamber demonstrated a >6μm/min growth rate in producing 100μm-thick blanket silicon—triple that of batch technology. In addition, its chamber design and shorter process times promote optimum efficiency and productivity of the TCS precursor, a cleaner chamber, and lower consumption of HCL used in removing dome coating. These economies offer the competitive benefits of a lower cost of consumables relative to batch systems, as well as higher throughput.

For additional information, contact carlos_caballero@amat.com
The MEMS industry is getting a push from companies interested in taking advantage of the piezoelectric effect to build next-generation microphones and fingerprint sensors—two high-volume products that could have a major impact on the 200mm semiconductor landscape.

New materials and architectures for MEMS microphones and fingerprint sensors—both major revenue streams for the MEMS industry—use the piezoelectric effect: the ability of certain materials to generate an electric charge in response to applied mechanical stress (see sidebar, “The Piezoelectric Effect”).

Though challenges remain, technologists are working with Applied Materials to develop a new class of MEMS devices that leverage this important technology.

**HIGH SNR MICROPHONES**

MEMS-based microphones—one of the highest-volume MEMS devices produced today—are undergoing a seismic shift in capabilities (see figure 1). A move is underway from single parallel-plate, capacitive-coupled microphones to piezo-based microphones, soon to be followed by electrostatic comb-finger-based designs and then optical-based devices. While it is the piezo-based design that has captured attention recently, experts agree it will take time to develop the necessary materials and process technologies required to mass produce the devices with high reliability.

A recent forecast by Yole Développement (Lyon, France) puts shipments of MEMS microphones in 2016 at over 4.4B units, exceeding 7B units by 2020, a nearly 14% compound annual growth rate (CAGR) over the forecast period.

**IMPROVED SNR OPENS DOORS**

Matt Crowley, CEO of Boston-based Vesper, a piezo-MEMS microphone startup, expects that the increased SNR capability (beyond 70dB) of next-generation microphones “will open up numerous additional applications in consumer and industrial markets,” ushering in an era of voice-activated, recognition-based technologies.

PVD-sputtered piezo materials, including scandium-doped aluminum nitride (ScAlN),[1] are enabling much of this improved performance. Theoretical calculations demonstrate that the higher the scandium concentration, the more the SNR will increase. Crowley calculates that for every 5% of scandium (Sc) there is a corresponding increase of 1dB of SNR, which is significant from both application performance and manufacturing standpoints.

Today there are readily available single-alloyed targets containing less than 10% Sc. However, for higher concentrations the target alternatives are not well developed. Applied Materials, in conjunction with target manufacturers, is tackling the development of higher-concentration Sc-doped single-alloy targets, as well as the robust deposition processes needed to deliver them in a manufacturing environment. The goal is to enable deposition processes to support Sc concentrations up to 43%—the empirically proven limit before there is a roll off in the achieved piezoelectric coefficient.

**Figure 1. Microphone architectures that leverage new materials and new sound-wave detection schemes promise increased signal-to-noise performance. (Source: IHS)**
PIEZO EFFECT BOOSTS MEMS MICROPHONES, FINGERPRINT SENSORS

RELIABLE FINGERPRINT SENSORS

Capacitive fingerprint sensors are being used increasingly in smartphones and other mobile devices (see figure 2). However, from a manufacturability standpoint, their popularity is due simply to the CMOS compatibility of their device structure. Despite this, the capacitive-type fingerprint sensor is prone to reliability issues caused by moisture, dirt and other surface contamination on fingers, and therefore is ripe for reinvention. Enter the piezo-based fingerprint sensor, where Sc also plays a role.

Unlike capacitive-based fingerprint sensors, piezo-based devices detect the electrical impedance of both ridges and gaps on the epidermal layer of skin. Furthermore, ultrasonic sense mechanisms provide the ability to acquire images beneath the skin’s surface for optional additional security (see figure 3, which shows a conceptual diagram of a piezo-based fingerprint sensor).

The key to enabling this functionality lies in the choice of piezoelectric materials, including aluminum nitride (AIN), scandium-doped aluminum nitride (Sc-AIN) and other members of a CMOS-compatible class of PVD-sputtered materials with the right electrical and mechanical characteristics.

Professor David Horsley of the University of California at Berkeley's Sensor and Actuator Center (BSAC) points out that ultrasonic receiver sensitivity lies in the combination of high piezoelectric coefficients affording the transmitter sensitivity and a low relative permittivity. These, in addition to a higher electromechanical coupling coefficient for AI films, have shown that increased percentages of AlN films doped with Sc, have increased up to 20% in AlN films have been experimentally demonstrated to improve device performance, with an almost linear increase in performance for continued increases in Sc concentrations.

For equipment OEMs the challenge becomes how to deliver robust, reliable sputtering processes for these films. Sc-doped AlN films are currently available as single-alloyed targets with Sc concentrations of less than 10% for use in RF filter devices.

Applied Materials is working closely with materials innovation provider Materion Corporation (Cleveland, Ohio) to develop single-alloy targets of ScAlN, with concentrations exceeding 20%. This development work will apply to multiple MEMS applications from RF filters to micro-machined ultrasonic transducers (pMUTs) to high-force piezoelectric actuators.

Once suitable target materials have been developed, process development begins. Hardware elements are refined in concert with process recipe conditions to achieve the deposition rates, nonuniformities and across-wafer stress levels required to meet the on-wafer film requirements.

MEMS SENSORS SNIFf EXHAUSTS

There are other trends likely to have notable effects on the MEMS industry. The recent automotive emissions scandals have had a positive effect on the automotive MEMS market, prompting increased adoption of more advanced exhaust after-treatment systems, such as the selective catalytic reduction (SCR) system based on MEMS sensors. Industry analysts estimate that improved emissions control alone may account for an additional dozen sensors or more per vehicle.

Humidity sensors, which aid in controlling in-cabin HVAC, are featured in more than 20% of vehicles today, and that number is rising. Sensors also play a role in improving the safety and lifetime of the battery pack in electric vehicles.

Whether it’s expanded functionality in the latest smartphone, advanced driver awareness systems, or regulatory forces driving market trends in passenger safety and emissions control (as is the case in the automotive market), the next generation of MEMS-based device applications will rely heavily on new materials and processes. And all of these applications must be developed on robust, reliable and competitively priced platform solutions.

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(1) Scandium is a chemical element with symbol Sc and atomic number 21. A silver-white metallic d-block element, it has historically been sometimes classified as a rare earth element, together with yttrium and the lanthanoids. (Source: Wikipedia)


Figure 2. The conceptual capacitive sensor shown has an array of 57,000 pixels; each pixel is a capacitive device with CMOS control circuitry underneath the MEMS structure. While popular, this architecture is prone to security flaws and reliability issues caused by dirt and moisture. (Source: Solid State Fingerprint Scanners: A Survey of Technologies, Philip D. Wasserman, Guest Researcher, NIST, Gaithersburg, MD, December 26, 2005)

Figure 3. The piezo-based fingerprint sensor is positioned above CMOS circuitry. (Source: Applied Physics Letters 106, 2015)
When working on a painting, artists regularly step back from the canvas to refocus and evaluate their work. Only by taking a broad view can the artist determine what’s working, what’s not, and what to do about it. Similarly, fab managers can “step back” from their overall operations to evaluate process and equipment performance. Which tools are underperforming? Are equipment constants set correctly? Could a comparison to best known methods (BKMs) help? How could uptime improve? Is my fab output as high as it could be—and am I maximizing ROI?

This article introduces a new Applied Materials benchmarking offering, FabVantage 360, which for one fab uncovered opportunities to increase output by 25% as well as reduce particles and defects.

FABVANTAGE 360 — A BROADER PERSPECTIVE

To help fab executives answer the questions above and gain a better perspective on their operations, the Applied Materials FabVantage Consulting Group has developed a new assessment capability, FabVantage 360. This offering provides a differentiated benchmarking capability to identify opportunities relative to world-class performance and BKMs for evaluated toolsets. Unlike conventional FabVantage assessments, which normally focus on a specific area of concern (such as tool output), a comprehensive FabVantage 360 evaluation delivers a much broader perspective. By taking a wider view, FabVantage 360 can identify more opportunities for tool and fab improvement and help better estimate the impact of these improvements.

Holistic Approach

A FabVantage 360 assessment compares equipment performance against similar tools across the installed base and relative to proprietary BKMs. The analysis provides a holistic view of a tool’s performance and can indicate factors that may be interdependent or hidden when the focus is limited to specific performance challenges. It also enables customers to prioritize improvement projects by quantifying the magnitude of each identified opportunity. For example, an analysis may reveal that suboptimal cleaning practices are resulting in throughput loss, higher particles, and lower uptime.

Comprehensive Scorecard

To complete an assessment, the FabVantage 360 team develops a comprehensive scorecard that benchmarks a customer’s fab performance on about two dozen metrics. The scorecard covers metrics in four categories of tool performance—configuration, maintenance, unit process, and output (see table 1). Together, these categories give a picture of a tool’s impact on fab variability, yield, and output. The metrics are scored on a scale of 0%, representing worst in class (WIC), to 100%, representing best in class (BIC).

Typically, fab executives engage in a FabVantage 360 assessment when they need to identify opportunities to improve performance of equipment that is bottlenecked or critical for yield performance. The FabVantage 360 analysis quantifies gaps in each tool-performance metric, augmented by deep domain knowledge.

EXAMPLE SCORECARD

Figure 1 illustrates sample sections from a FabVantage 360 scorecard for a 300mm HDP UltimaX chamber used for STI gapfill in a logic fab. The results shown are representative and used for illustrative purposes only. Sections highlighted include (A) configuration, (B) maintenance, (C) unit process, and (D) output.

<table>
<thead>
<tr>
<th>This Metric Section...</th>
<th>Scores the Tool On...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration</td>
<td>Implementing equipment upgrades, matching equipment constants and software across the fleet, and using the latest software revision.</td>
</tr>
<tr>
<td>Maintenance</td>
<td>The preventive maintenance (PM) checklist, PM green-to-green (GtG) time, 1st time PM success, and the use of BKM parts.</td>
</tr>
<tr>
<td>Unit Process</td>
<td>Particle performance and implementation of fault detection and classification (FDC).</td>
</tr>
<tr>
<td>Output</td>
<td>Uptime and other equipment states, uptime variability, throughput, and tool dedication.</td>
</tr>
</tbody>
</table>

Table 1. Metrics for tool performance used in FabVantage 360 assessments.
A. Configuration – Sample Evaluation

### Hardware Upgrades

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Execute/Time</th>
<th>GIG</th>
<th>Throughput</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Short Nozzle Symmetric Gas Ring, Top Q2</td>
<td>0</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>2. Low Centering</td>
<td>0</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>3. RPS Bypass</td>
<td>12</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>4. Minimum Contact LL Films</td>
<td>0</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>5. Minimum Contact Buffer Blade</td>
<td>0</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>6. Cover Wafer Station</td>
<td>0</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>7. LRF+ Nozzles</td>
<td>0</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>8. LT Baffle</td>
<td>8</td>
<td>67%</td>
<td>67%</td>
<td>67%</td>
</tr>
<tr>
<td>9. Cool Gas Feed Block</td>
<td>8</td>
<td>67%</td>
<td>67%</td>
<td>67%</td>
</tr>
</tbody>
</table>

### Software Tools

- Installed on All Chambers
- Installed on Some Chambers
- Not Installed

<table>
<thead>
<tr>
<th>Tool</th>
<th>TOTS</th>
<th>STCKS WITH LATEST VERSION</th>
<th>STCKS WITH EARLIER VERSION</th>
<th>STCKS WITH INCOMPATIBLE %</th>
<th>INSTALLED %</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>100%</td>
</tr>
</tbody>
</table>

Nine upgrades are available for the 12 UltimaX chambers. Only the RPS Bypass is installed across all chambers getting the full defects, cost, and throughput benefits. Some chambers have the GT baffle (#8) and the cool gas feed block (#9) upgrades. Other upgrades are not installed, therefore missing opportunities to reduce defects. Similarly, not all tools have the latest software installed therefore missing on latest features and causing variation across tools.

C. Unit Process – Sample Evaluation

### FDC Practices

<table>
<thead>
<tr>
<th>Practice</th>
<th>Customer</th>
<th>WIC</th>
<th>BIC</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of Critical Sensors Monitored</td>
<td>57%</td>
<td>15%</td>
<td>100%</td>
<td>14%</td>
</tr>
<tr>
<td>% of Monitored Sensors That Are Critical</td>
<td>78%</td>
<td>15%</td>
<td>100%</td>
<td>56%</td>
</tr>
<tr>
<td>Data Sampling Rate Vary by Sensor</td>
<td>All sensors collected at 1Hz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use of UVAs, EHMs, and/or MVAs</td>
<td>UVAs used, but not EHMs or MVAs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fleet-based/Chamber-based Control Limits</td>
<td>Chamber-based</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strategy for Defining Stats and Setting Limits</td>
<td>All limits are at 3 sigma; do not vary limits by recipe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monitoring Windows</td>
<td>Monitor both steady-state and transitions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use of Golden Tools/Golden Reference Traces</td>
<td>No golden tool or reference trace</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use of Interuption Based on FDC Alarms</td>
<td>0.2 Engineer is notified</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A FabVantage 360 assessment also evaluates FDC practices by comparing the sensors the customer monitors against the list of sensors critical to the performance of a specific process. The assessment also compares general FDC practices to BIC's and highlights areas of opportunity. This figure shows that the customer is monitoring only 51% of critical sensors and can improve sampling data rates as well as golden references. Under Particles, it also identifies a high particle count of 24 vs. benchmark of 5, representing an opportunity to reduce particles by 80%.

D. Output – Sample Evaluation

### Uptime Performance

<table>
<thead>
<tr>
<th>Customer</th>
<th>WIC</th>
<th>BIC</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uptime %</td>
<td>90.2%</td>
<td>86.4%</td>
<td>93.5%</td>
</tr>
<tr>
<td>Scheduled Down %</td>
<td>6.5%</td>
<td>6.6%</td>
<td>2.2%</td>
</tr>
<tr>
<td>Unscheduled Down %</td>
<td>3.3%</td>
<td>6.3%</td>
<td>3.2%</td>
</tr>
<tr>
<td>Uptime Variability</td>
<td>0.2</td>
<td>0.25</td>
<td>0.04</td>
</tr>
</tbody>
</table>

### Throughput & Dedication

<table>
<thead>
<tr>
<th>Customer</th>
<th>WIC</th>
<th>BIC</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of Product/Recipes Run on All Tools</td>
<td>75%</td>
<td>75%</td>
<td>100%</td>
</tr>
</tbody>
</table>

To evaluate output performance, the FabVantage team assesses scheduled downtime, unscheduled downtime, and throughput against benchmark levels. FabVantage experts also analyze production runs to highlight hidden tool dedications. The analysis uncovers opportunities for process optimization and matching, leading to a more balanced utilization across tools, and therefore better cycle time through the equipment set.

Figure 1. A FabVantage 360 assessment involves collecting detailed tool data from customers in exchange for providing a comprehensive scorecard that identifies tool performance gaps relative to BIC. This example illustrates the data used to generate the scorecard, along with a summary spider chart that graphically shows performance gaps.
Vita’s high computational bandwidth brings a growing number of advanced capabilities to Applied’s popular and versatile legacy platform.

**KEY TAKEAWAYS**

As shown in figure 1D, the customer’s uptime is 90.2%, within the benchmark range but scheduled downtime is close to the worst end of the benchmark, offset by good performance on unscheduled downtime. The performance metrics give another perspective on the PM performance with long green to green times and a low PM success rate.

Possible issues causing poor PM performance are using non-BKM parts and not following prescribed PM procedures, such as not replacing parts at the recommended frequency and not performing prescribed calibrations. High particles are also a result of poor PM procedures, not leveraging defect-reduction upgrades, and setting equipment constants incorrectly.

Another cause of poor PM performance and high particles relates to matching issues on tools. In this example, software revision does not match across all tools. This, combined with incorrectly set equipment constants, may explain the high tool dedication, which in turn reduces the output of the fleet.

With a FabVantage 360 assessment, these calculations can be illustrated in a SEMI E10 Equipment States chart that shows the productive time of the tool and a breakdown of nonproductive time. As seen in figure 2, low throughput causes total tool productivity of only 63.6%, although the tool is utilized for 80% of the time. This example highlights a hidden opportunity to increase output by 25% by improving maintenance practices and equipment setup. Additional opportunities exist to reduce particles and defects, and improve process control with better FDC practices.

**CONCLUSION**

It is said that French artist Henri Matisse was notorious for spending extended periods of time looking at his paintings, reflecting on what he had done while plotting his next stroke. He would hold his paintbrush at a distance from the canvas and move it slowly through the air to try out different movements before committing to the next stroke on the canvas.[1]

Similarly, a FabVantage 360 evaluation provides customers with a “big picture” view of their fab situation, enabling them to plot their next “stroke” of improvement gains. The FabVantage 360 evaluation provides valuable data for use in prioritizing projects and quantifying ROI. It offers an easy, effective way to reveal how a customer’s tool performance and fab operations compare to the world’s best-in-class facilities.

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**Figure 2.** Example of a SEMI E10 Equipment States chart from a FabVantage 360 assessment which indicates that this fleet of four tools suffers from low productivity.

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**GET MORE FROM 200MM PRODUCERS WITH VITA CONTROLLERS**

Many users of Applied Materials 200mm Centura and Endura systems who have comprehensive service agreements are already realizing significant improvements thanks to Applied’s Vita controller, which enables implementation of advanced sensors and other capabilities (see Nanochip Express, April 2016 at www.appliedmaterials.com).

The Vita controller is a powerful embedded system that replaces a number of obsolete, performance-limiting components in the VME architecture, including the single-board controller (SBC). It also upgrades other parts originally shipped with these legacy tools.

Vita controller retrofits, which are performed by Applied Materials service personnel, have led to substantial gains in performance, productivity, throughput, tool stability, system availability, and reduction of overall cost of ownership for customers’ manufacturing equipment.

Now, similar benefits are available to users of Applied Materials 200mm Producer tools when the system is combined with...
Applied’s advanced services and data analysis capabilities under a service agreement. The Vita controller provides higher resolution and data clarity, enabling unmatched Producer performance, with total recipe transparency and backward-compatibility with the original software. With high computational bandwidth and access to tool data at up to 10 Hz with no dropouts (see table 1), Vita enables users to fully implement a wide spectrum of advanced services available under Applied Materials service agreements. These include tool optimization, sophisticated process modeling, and high integration with Applied’s fabwide automation and equipment engineering system (see figure 1). Vita enables users to fully implement a wide spectrum of advanced services available under Applied Materials service agreements. These include tool optimization, sophisticated process modeling, and high integration with Applied’s fabwide automation and equipment engineering system (see figure 1).

Table 1. The table compares performance of 200mm Producer tools equipped with the original SBC versus those with the new Vita controller. The higher resolution and faster speed of the Vita system generates much better data, which can be used to increase tool performance.

<table>
<thead>
<tr>
<th>SBC (1Hz)</th>
<th>Vita (10Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td>1 data point per 1.8 sec</td>
</tr>
<tr>
<td>Data Accuracy</td>
<td>56%</td>
</tr>
<tr>
<td>Data Quality</td>
<td>49% to 67%</td>
</tr>
<tr>
<td>Chamber Pressure Output Data</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. Compared with the original SBC for 200mm Producer tools, the new Vita controller offers greater data resolution, enabling significant reductions in particles and greater uniformity in lot film thickness.

Table 2. Significant performance advantages were demonstrated in beta tests by Applied 200mm Producer tools equipped with the new Vita controller.

![Graph showing particle reduction and stability improvements with Vita compared to SBC.](Image)

VITA FOR PRODUCER

The Applied Materials 200mm Producer platform was introduced in 1998. Today, more than 1,000 of these tools are at work in fabs around the world providing a comprehensive portfolio of dielectric CVD thin-film solutions while meeting customers’ need for high productivity. The enduring popularity of this platform is evidenced by the still-high demand for refurbished and new 200mm Producer systems. Within Applied Global Services, the Equipment Products Group (EPG) is dedicated to ensuring that legacy platforms such as Applied Materials 200mm Producer tools continue to benefit from continuing innovative equipment designs, many of which have evolved from newer 300mm tools. High-value upgrades based on state-of-the-art 300mm tool designs are released regularly, ensuring that Applied Materials tools can perform at the highest levels for many years to come.

Development of the Vita controller for Producer was initiated in 2015, and the new controller was fully released in January 2016. During months of beta testing at multiple customer sites, 200mm Producer tools equipped with the Vita controller demonstrated the same characteristic benefits seen now on more than 300 Vita-equipped Endura and Centura tools. These include significant throughput improvements (in excess of 2%), faster data sampling rates, improved data quality, and gains of up to 37% in the speed at which they are able to communicate with factory automation systems (see table 2). All refurbished and new Applied Materials 200mm Producer systems shipping from the company’s Austin, Texas, manufacturing site are now equipped with the Vita system.

Table 2. Significant performance advantages were demonstrated in beta tests by Applied 200mm Producer tools equipped with the new Vita controller.

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>BEFORE</th>
<th>VITA</th>
<th>DURATION GAIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recipes Upload From the Tool to the Server</td>
<td>58.5s</td>
<td>27.48s</td>
<td>53%</td>
</tr>
<tr>
<td>Recipes Download From the Server to the Tool</td>
<td>127.54s</td>
<td>15s</td>
<td>88%</td>
</tr>
</tbody>
</table>

![Graph showing processing time improvements with Vita compared to SBC.](Image)

SERVICE COLLABORATIONS FOR BETTER, FASTER RESULTS

The Vita controller makes it possible for Applied Materials to maximize the performance of legacy tools under service agreements and enables a faster return on investment (ROI) for customers.

Tools covered by Comprehensive Service Agreements receive the expertise of the company’s specialized TechEdge service engineers, who can help fully optimize their system’s capabilities (see figure 2). With the benefit of legacy tools and their processes can be uncovered and addressed quickly and effectively. These include arcing, excursion management, chamber/tool matching, throughput, recipe optimization, defect reduction and thickness uniformity, among others.

Applied Materials offers this unique combination of control technology and expertise so that users who want to optimize their legacy equipment cost-effectively can implement modern monitoring and control techniques, thereby improving yields, output and overall cost of ownership faster and to a greater degree than otherwise.

Customers have had such notable success with Vita controller retrofits that Applied Materials is working on further developing the system to extend its use to a broader array of legacy equipment.

For additional information, contact florent_ducret@amat.com

![Graph showing wafer output improvements with Vita compared to SBC.](Image)

Figure 2. Applied’s TechEdge service engineer teams combine extensive analytical skills with deep process tool expertise and detailed knowledge of advanced production technologies to quickly and effectively troubleshoot tools with the Vita controller. These upgrades allow the tools to be optimized in ways that weren’t possible with the SBC, leading to higher productivity.
CARS AND ELECTRONICS CONVERGE

BY DAVID LAMMERS

Fortunately for the semiconductor industry, the outlook for automobiles includes an unprecedented array of innovations that require significantly greater numbers of electronic devices. From the cameras, sensors, and image processors needed for advanced driver assistance systems (ADAS) in conventional autos, to sophisticated power electronics used in electric vehicles (EVs) and advanced sensor technologies for autonomous “self-driving” vehicles, the automotive and semiconductor industries are more tightly linked than ever.

There is strong evidence that the worldwide automotive industry is in a milestone period, one that heralds significant changes that will span several decades. One powerful force behind these events is the fast-forming consensus that climate change is real, with the gases coming out of tailpipes as one of the causes. Little wonder, then, that the smog-challenged Chinese government is pushing adoption of EVs and ADAS-capable cars and highways, or that a China-based EV vendor, BYD (it stands for Build Your Dreams) is building battery-powered buses at its factory near Los Angeles.

There is a virtuous cycle developing, one that benefits semiconductor suppliers focused on automotive electronics. New ADAS safety features, such as automatic emergency braking systems (EBS), are attracting car buyers (and insurance companies) who want to avoid costly crashes. Beyond that self-interest, governments are stepping in: the US National Highway Traffic Safety Administration (NHTSA) will require automatic emergency braking as a standard feature on new cars by 2022, for example.

However, visions of self-driving electric vehicles cruising around while their owners take care of email must be balanced against the realities of high development costs, the need for infrastructure improvements, and the impact on modern family budgets. As University of Michigan Professor James Moyne notes, “There is a small percentage of people, myself included, who make car-buying decisions based on ecology, but most people vote their pocketbooks. If gas is cheap, they will go with what keeps money in their pocket. If gas is $5 a gallon, that’s a motivator for people to get hybrids or electric cars.”

Indeed, EV sales are in the early stages. Navigant Research predicts the US market—the largest for plug-in EVs—will go from about 133,000 sold in 2014 to between 860,000 and 1.2 million sold in 2024. In a good year, total car sales in the US hit 17 million.

Yet the net effect of all this is the creation of strong demand for automotive electronics (see “Automotive ICs Lead Market Growth” on page 25 of this issue of Nanochip Fab Solutions).

48 V MILD HYBRIDS

While progress in the ADAS and EV fields garners much of the media attention, gasoline-powered cars are also adopting new technologies. One development that is seldom discussed but important to the semiconductor industry, is the advent of conventional gas-powered cars that receive supplemental electrical propulsion from a 48 V lithium-ion battery and an intelligent energy-capture system. Major car manufacturers are designing cars with a 48 V power network and high-performance lithium-ion battery that will complement today’s 12 V battery, which would continue to handle traditional loads such as lighting, ignition, entertainment, audio systems, and electronic modules.

“The main bottlenecks [facing automotive electronics], are the sensor fusion, image processing, and power computing.”

– Guillaume Girardin, Yole Développement
Peter Harrop, chairman of market research firm IDTechEx, said these “mild hybrids” will begin to hit markets next year or in 2018. The 48-V battery will be linked to a reversible motor-generator that will capture braking energy and other forms of kinetic energy, storing it in the battery for use when the vehicle is stopped or running at low speeds. Because so much pollution is caused by cars stuck in urban traffic jams, Harrop claims that 48 V systems “will probably contribute more to emissions reduction in the next 15 years than all EVs—strong hybrids and pure electric—combined.”

Ford Motor Company, for example, is working with automotive suppliers on a 48-V split-voltage prototype car that reduces fuel consumption by 25%. The car can begin moving in stop-and-go traffic without running the gas engine, powered solely by the battery and a small electric motor. Carmaker Audi estimates a carbon dioxide savings that reduces fuel consumption by 25%. The car can begin moving in stop-and-go traffic without running the gas engine, powered solely by the battery and a small electric motor. Carmaker Audi estimates a carbon dioxide savings that reduces fuel consumption by 25%. The car can begin moving in stop-and-go traffic without running the gas engine, powered solely by the battery and a small electric motor.

Dave Eggleston, Vice President of Embedded Memory Technology at GLOBALFOUNDRIES, said automotive MCUs are driving much-higher amounts of embedded memory. “A car with advanced automation systems will have an estimated 300 million lines of code across 50 distributed systems. "Saying that a car is a smartphone on wheels completely underestates the complexity," Eggleston said. “For something like emergency braking, the speed of decision-making has to be very fast, so you need on-chip integration, including the embedded memory and analog. We’ve also integrated RF into the platform, so the automotive SoC designer now has the key elements of fast compute, motor control, and wireless connectivity.”

**DEEP LEARNING FOR AUTONOMOUS CARS**

The concept of augmenting (or replacing) the human driver implies an artificial intelligence (AI), based on what is now being referred to as “deep learning.” The AI applications used in augmented driving are accelerating development of a new class of processors, optimized for deep-learning algorithms. NVIDIA, for example, has attracted many of the leading carmakers to its Drive PX 2 development platform, made at TSMC on its 16nm FinFET-based technology. Based on a combination of graphical processing engines and general-purpose processing cores, the NVIDIA platform delivers up to 24 trillion “deep-learning operations" per second. These are specialized instructions that accelerate the math used in inference engines. In order for cars to drive themselves, the on-board intelligence must quickly learn how to address unexpected road debris, erratic drivers, and construction zones. Vision systems must develop to the point where they can handle rain, snow, fog, and difficult lighting conditions such as sunrise, sunset, and extreme darkness.

“Drivers deal with an infinitely complex world," said NVIDIA CEO Jen-Hsun Huang. Autonomous vehicles must be “continuously alert,” and eventually achieve “superhuman levels of situational awareness,” he added. It is little wonder, then, that TSMC co-CEO Mark Liu recently said that automotive semiconductors, for both enhanced safety and improved infotainment systems, “will certainly speed up the adoption of TSMC’s leading-edge technology.”

**SENSOR FUSION**

Emergency braking is among the currently available ADAS options—along with lane-departure warning systems, adaptive cruise control, backup alerts, and parking assistance. It’s based largely on cameras and other sensors, according to Yole Development analysts Guillaume Girardin and Eric Mounier, who noted in email exchanges with this author that “many other advanced autonomous driving capabilities will arrive in the near future.”

The successful proliferation of ADAS vehicles will depend in part on the ability of designers to reduce costs, especially for light-detection and -ranging (LIDAR) modules, and high-end GPS. The LIDAR on Google’s self-driving car uses 64 lasers to map the physical world, collecting more than a million data points on its surroundings every second and costing about $50,000. The next-generation Google car, the Yole analysts said, will have an $8,000 version, “still way too expensive for wide consumer adoption.”

Much of the work required for autonomous vehicles depends on sensor fusion, which means integrating LIDAR with ultrasonic sensors, radars, cameras, and inertial sensors. “All of them must be working simultaneously, with redundancy,” according to Mounier and Girardin. But these “direct” sensors won’t be enough. The cars will also need to rely on “indirect” sensors—the sensors of other vehicles—because cars will operate in an “Internet of Things” connected mode.

**SOPHISTICATED COMMUNICATIONS SYSTEMS**

The technology for this is already in reach. Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) capabilities may draw on cellular networks, including the still-under-development 5G wireless standard, to connect to other cars and infrastructure. Peter Rabbeni, senior director of RF technologies at GLOBALFOUNDRIES, said “to make autonomous vehicles a reality requires some pretty sophisticated communications systems. We have to make the cellular system reliable enough for autonomous vehicles, and achieve very high data rates delivered to many, many users.”

Rabbeni said GLOBALFOUNDRIES has deployed its silicon-germanium (SiGe) process for automotive radar transmit-and-receive functions being rapidly deployed for range sensing and detection. The foundry expects to provide automakers with MCUs based on its 22FDX process, which uses fully depleted silicon on insulator (SOI) to reduce power consumption and stay within the thermal envelope permitted by automakers. Moreover, at the 22nm node GLOBALFOUNDRIES is planning to switch from embedded flash to MRAM for its automotive processor manufacturing. “Because traditional e-flash is more difficult to integrate at smaller nodes,” Rabbeni said.

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**Figure 1.** Yole predicts “massive opportunities” for sensor providers as cars adopt assisted-driving features. (Source: Yole Development)
It is clear that cars are driving sensor and semiconductor technologies, ranging from new generations of power devices (see “Automotive Power Device Market Amps Up” on page 28 of this issue of Nanochip Fab Solutions) to embedded memory, processors, and MEMS sensors (see “Piezo Effect Boosts MEMS Microphones, Fingerprint Sensors” on page 8 of this issue of Nanochip Fab Solutions).

In remarks at a Global Semiconductor Alliance (GSA) meeting in Europe, Markus Tremmel, a senior Bosch technology manager, said the semiconductor industry needs to provide more sophisticated processors to support deep learning. “Current microprocessors are not suited to do [deep learning algorithms] efficiently,” Tremmel said in a report by EE Times Europe. “We need new microprocessor architectures.”

Brian Matas, who tracks automotive applications at IC Insights, said automotive processors will need a sharp boost in computational power in order to handle inputs from multiple high-precision sensors, and to execute powerful algorithms that respond quickly to different driving conditions. Yole’s Girardin put it only slightly differently: “The main bottlenecks [facing automotive electronics] are the sensor fusion, image processing, and power computing.”

Jeff Bier, a veteran analyst who tracks embedded vision markets, said vision algorithms “are typically quite demanding of processor performance, and getting that performance at low cost and low power usually involves some sort of heterogeneous processor, a CPU coupled with some sort of coprocessor.”

These stringent processor demands are being met by consumer-oriented companies such as NVIDIA, with its graphical processing expertise, and by the traditional automotive semiconductor suppliers. Akhilesh Kona, senior analyst for automotive semiconductors at market research firm IHS, said chip suppliers with consumer backgrounds “clearly lead on outright performance” in image processing. However, traditional automotive IC suppliers are far more familiar with functional safety standards and how to handle inputs from sensors in an engine, for example.

Yole’s Girardin said: “Two approaches are contending with each other. One is with a central processing unit combined with ’dumb’ sensors, an approach which requires high transfer rates, and a big processing unit with multipurpose skills. The other approach deals with a ’delocalized’ intelligence in each sensor.” Girardin said the recent evolution of computing “gives credit to the second option,” with computing intelligence close to the sensors.

LANE MARKINGS AND INFRASTRUCTURE

The demands on semiconductor suppliers are mirrored by the need for cities and national governments to think about outdated roads and signage. Infrastructure and regulatory challenges are likely to lag behind the purely technical development of cars that can “see” far down highways and streets.

The infrastructure situation may be worse in China, where the central government is seeking to take the lead in self-driving technologies. Junyi Zhang, a partner with the consulting firm Roland Berger, commented in a New York Times report that people, animals, three-wheel rickshaws, and trucks all converge on China’s roads, which also have poorly marked lanes.

“It is harder in China, where many roads have pedestrians, bicycles, low-speed vehicles and high-speed vehicles all mixed together,” Zhang said. “It is a very complicated environment, and many don’t ride or drive to the same standard.”

How long will it take before self-driving cars populate roads? The Yole analysts said the answer depends largely on the regulatory environment and legal considerations.

“For completely autonomous vehicles in all conditions, we don’t expect such vehicles before 15 to 20 years,” they said, though adoption could come faster if regulations are quickly put in place.

For additional information, contact nanochip_editor@amat.com

Infrastructure and regulatory challenges are likely to lag behind the purely technical development of cars that can “see” far down highways and streets.

In the current slow-growth period for the overall semiconductor industry, the automotive IC sector is a relatively bright light. With electric vehicles (EVs) and advanced driver assistance system (ADAS) features leading the way, analysts say the semiconductor content in vehicles is set to increase at a healthy pace.
Dave Pahl, vice president of investor relations at Texas Instruments, recently estimated a new car now has about $350 in semiconductor content, on average. “That’s a number that’s been growing very nicely,” Pahl said.

For makers of cameras and other automotive sensors, the growth rates are enticing, Yole Développement, the Lyon, France-based market research firm that tracks “More Than Moore” markets, predicts that the market for sensor modules for autonomous cars will grow from $38B in 2015 to more than $35B in 2030, providing “massive opportunities for sensor manufacturers and the semiconductor industry,” said Guillaume Girardin, a Yole analyst and co-author, with senior analyst Eric Mounier, of the report “Sensors and Data Management for Autonomous Vehicles.”

Gartner automotive electronics analyst James Hines, speaking at a SEMI event in Austin last year, predicted that automotive semiconductor revenue will grow at nearly twice the rate of the overall semiconductor market through 2018. Semiconductors aimed at ADAS features and EVs, he predicted, “will grow at above the automotive market average.”

Automotive semiconductors “are one of last bastions of profit, and provide good returns on investment,” said IC Insights analyst Brian Matas, an author of the firm’s report on IC growth markets. Matas said the strong dollar exchange rate impacted last year’s automotive IC market, as sales in yen and euros translated into fewer dollars. That held down growth in the 2015 market to just 1%, with $20.8B in automotive IC sales, even as unit shipments grew at a healthy pace.

Besides the exchange rate factor, car manufacturers asked for lower unit prices in return for relatively long buying cycles, he said. Nevertheless, IC Insights does see solid growth in the automotive semiconductor sector. “We definitely see this market on the rise,” Matas said, “with an average growth rate of 6.7% through 2019.”

IC Insights said “intelligent cars are the catalyst” for much of the growth in the market for 32-bit MCUs, set to increase 8% this year (see Figure 1). Features such as self-parking, advanced cruise control, and collision-avoidance rely on 32-bit MCUs. Three of the top five suppliers to the 2015 automotive IC market (see Figure 2). With its acquisition of Freescale Semiconductor, NXP becomes the leading automotive IC supplier. (Source: IC Insights)

Jim Feldhan, president of Semico Research, said automotive ICs account for about 10% of the overall chip industry now. “While the automotive pie is getting bigger, it still does not rival the market for mobile ICs. Profits are relatively good but the car companies tend to hit you down on price. Once a vendor is designed in, the good thing is that they probably are locked in for a number of years.”

Tony Massimini, who tracks the MCU market for Semico Research, said while automotive MCUs account for only 10-11% of unit volume, they will represent 36% of MCU revenues, which is $5.7B dollars.

WSTS sees steady growth
With semiconductor sales slowing recently for smartphones, tablets and PCs, cars—along with virtual reality—have captured tablets and PCs, cars, along with virtual reality—have captured

The World Semiconductor Trade Statistics (WSTS) Council predicts little growth for this year’s worldwide semiconductor market, just 0.3% to $336B. Next year will be a bit better, with a 3.7% growth rate to $347B in 2017 revenues.

According to WSTS, automotive ICs accounted for about 7.3% of the 2015 global IC market, a relatively small percentage compared to computer and communication ICs. However, the rate of growth is impressive: back in 1998 automotive ICs were only 4.7% of the total semiconductor market, and WSTS expects that share to increase to 8.1% by 2019.

The wave of consolidation in the industry last year also changed the top ranking in the automotive sector, which had $20.5B in 2015 sales. Matas noted that NXP’s $11.8B acquisition of Freescale Semiconductor—completed on April 1, 2016—makes it the leading automotive IC supplier. In automotive IC sales last year, Freescale was the third-ranked and NXP the fifth-ranked supplier, giving the combined company more than 17% market share last year and vaulting NXP past Renesas.

“About half of the automotive IC supplier base is made up of other companies such as Texas Instruments and Analog Devices,” Matas said, adding that it took more than $1.3B in automotive IC sales to make the top-five supplier list in 2015.

For additional information, contact namochp_editor@tmat.com

Figure 1. Installed capacity leaders per wafer size as of December 2014

Figure 2. With its acquisition of Freescale Semiconductor, NXP becomes the leading automotive IC supplier. (Source: IC Insights)
Automotive power electronics are emerging as one of the semiconductor industry’s key drivers. These electronics include power devices that are at the heart of a new breed of electric vehicles (EVs) capable of going 200 miles or more between charges.

Although unit shipments of smartphones have been much higher than automobiles (1.4B\textsuperscript{1} versus 88 million in 2015\textsuperscript{2}), automobiles have much higher semiconductor content. Automotive power ICs are showing healthy growth, with an estimated 8% CAGR for the automotive power IC sector over the 2015–2020 period.\textsuperscript{3} Battery-powered EVs are particularly strong drivers of the sector: a May 2015 Teardown.com report on the BMW i3 electric vehicle revealed more than 100 power-related chips in the bill of materials.

Unlike typical logic transistors that follow Moore’s Law scaling, power device FETs typically use much older technology nodes, such as 200nm (and smaller) wafers. Nevertheless, since the late 1980s power devices have continuously evolved. For example, thick PVD aluminum on the order of 3–12µm must be deposited on both the front- and backside of the device in order to provide heat dissipation and improve electrical performance. If not deposited properly, thick aluminum can be prone to whiskers and dislocations leading to catastrophic device failure. The Applied Endura PVD HDR Al reactor ensures that such defects are minimized while providing for improved electrical performance.

Some improvements and adjustments to etch processes have been necessary to accommodate these schemes, which involve higher aspect ratio structures. Improved epitaxial Si films and optimized implant doping profiles also have enabled performance gains.

Power device manufacturers continue to look for more improvements. According to publicly available reports, Hitachi’s high-conductivity IGBT employs a separate floating p-layer to improve gate controllability and turn-on voltage. ABB Semi is creating P-piller implants under the trench gates to create a super-junction effect to enable higher switching speeds. Wafer are being thinned across the board to help reduce stored charge for high-speed switching.

Fuji Electric has recently developed a seventh-generation IGBT with a thinner drift layer, smaller trench pitch, and optimized field-stop layer.

However, the consensus among experts is that the performance envelope for silicon devices has been pushed nearly to the limit. Power devices are limited by intrinsic silicon properties, so each subsequent stage of progress provides only marginal improvements.

### III–V POWER DEVICES

The power IC industry is looking to new wide bandgap (WBG) materials to take performance to an entirely new level. Silicon carbide (SiC) and gallium nitride (GaN) are the top candidates today, each with their own set of pros and cons. These are compound semiconductor materials that provide much higher bandgap and breakdown fields, taking power device performance to a level where silicon simply cannot compete. They are widely considered to herald the next era of power devices, the next big inflection.

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\textsuperscript{1} Source: Yole Développement and Applied Materials

\textsuperscript{2} Source: Nanochip Fab Solutions

\textsuperscript{3} Source: NANOCHIP
Infl ections bring new challenges, and WBG power ICs are no exception. Cost is the biggest obstacle today, including manufacturing-related challenges from wafer warpage and high rates of defects associated with substrate and epitaxial processing. Currently, a 6-inch SiC substrate + epi wafer costs in the thousand-dollar range, according to market research firm Yole Développement (Lyon, France). And that cost can multiply quickly with more stringent device defect requirements.

There are other challenges in subsequent process fl ow steps. For example, high-temperature anneals nearing the 2,000°C range are required. Typical anneal reactors for Si come nowhere near this regime. Implanting into SiC is also quite complex.

Encouraged by the potential of WBG power devices, several companies, consortia, and university research centers are focused on solving their challenges. In fact, both SiC and GaN products are available today, albeit in limited quantities. However, costs must come down signifi cantly before the benefi ts of WBG—including power savings, simplifi ed circuitry, and reduction in module size—can provide a meaningful return on investment compared to silicon substrates.

Take, for example, a typical automobile inverter box that may contain 40 or more power transistors and diodes. Moving to SiC enables simplifi ed circuitry, fewer components, and an overall module size reduction of up to 80%. It is this intersection of device size, materials cost, and energy savings that must be satisfi ed to create a meaningful value-add compared to silicon power devices (see Table 1).

Fortunately, other steps in the semiconductor processing fl ow, such as CVD, PVD, etch and CMP, are relatively straightforward for WBG power devices because the general process fl ow is very similar to that of silicon. Process tuning is required along with minor hardware changes, but existing technologies can be adapted to WBG processing.

GaN-based power devices have great potential for high-voltage automotive applications, but GaN brings its own list of challenges, including wafer costs and eff ective production of GaN-on-GaN structures (a bulk GaN substrate with GaN epi). Only 2-inch bulk GaN wafers are available today. Moreover, with current architectural limitations, GaN devices are normally ON, which introduces reliability issues and limits market acceptance. Enhancement-mode GaN devices would be needed to overcome this shortcoming.

Therefore while the performance benefi ts of WBG devices are undeniable, it is an open question whether they can overcome the cost challenges and achieve high volumes.

In a recent power device seminar at Applied Materials, Stanford University Professor Jim Plummer suggested that for these devices to achieve success in the marketplace, it would make sense to identify a new space where silicon doesn’t compete. This would enable increases in manufacturing volume, which Plummer said would then help reduce wafer costs.

For additional information, contact benjamin_lee@amat.com

Table 1: Both GaN and SiC have superior bandgap and breakdown properties compared with today’s silicon-based power devices. (Source: F. Iacopi, et al, MRS Bulletin, May 2015, courtesy of Jim Plummer, PhD, Stanford University)

<table>
<thead>
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<tr>
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<tr>
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<td>Electron mobility at 300 K (cmm²/V·s)</td>
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<tr>
<td>Saturated (peak) electron velocity (10⁶ cm/s)</td>
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<tr>
<td>Relative dielectric constant</td>
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<td>Thermal conductivity (W/cm·K)</td>
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* Values of corresponding heterostructures


Potential challenges, such as scaling and reliability, are being addressed by GaN and SiC device manufacturers and materials suppliers. GaN on Si has already entered ramp-up production at SPTS Technologies, while SiC and its derivatives are progressing through production ramps at various companies, including Wolfspeed and Cree.

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Table 1: Both GaN and SiC have superior bandgap and breakdown properties compared with today’s silicon-based power devices. (Source: F. Iacopi, et al, MRS Bulletin, May 2015, courtesy of Jim Plummer, PhD, Stanford University)
Combining state-of-the-art scanning electron microscopy (SEM) with large-scale display vacuum platforms, EBR is a new approach that can shave several months from the average LTPS display fab ramp time of 15 months (see figure 1). Assuming a factory output of 30,000 displays/month, a 3-month savings for example, would be equivalent to $250 million in added revenue.

Applied Materials is developing inline EBR technology (see figure 2) as a better, faster way to discover and address the root causes of killer defects in mobile display production, which is characterized by an increasing number of process steps that can generate more—and smaller—particles and new types of defects.

Killer defects, or electrically active faults, destroy pixels and reduce yield. It can be difficult to determine their origin because while they may be symptomatic of a problem with a tool or process that negatively impacts yields on an ongoing basis.

Before EBR, however, it is possible to offline SEM analysis does enable root-cause analysis, a crucial linkage is lost by having to break the substrate into pieces: it’s impossible to compare the inline defect to an end-of-line array test, because the defect location on the full panel can no longer be determined.

As a result, insight into the source(s) and kill ratio of the defects is lost, making discovery a problematic and time-consuming process. Using EBR, however, it is possible to determine which defects are killer defects without breaking the substrate for analysis. Moreover, because production continues while random samples are inspected, any lots that have been processed during that time may suffer from the same problem and have to be scrapped.

**MINIMIZE KILLER DEFECTS IN REAL TIME**

To address these issues, Applied Materials has introduced an analytical approach based on EBR technology that will help LTPS display manufacturers minimize killer defects in real time when a process or tool is not performing to specifications (see figure 4). EBR makes use of both optical imaging analysis and SEM/energy-dispersive X-ray (EDX) tools. It can handle LTPS panels up to Generation 6 (1850mm x 1500mm) with no need to break them into pieces. The overall approach is to isolate the most probable source of a defect (e.g., a CVD, PVD, etch, photolithography, or other process step), select the best sampling plan to isolate and monitor the defect, and then quantify the number of lots impacted.

Sample substrates are inspected after each process step. Automated optical inspection is used to generate a map of defects on these wafers. The wafers are then reviewed with the EBR SEM tool, and the results of that inspection are overlaid with the results of the optical inspection so that the EBR results can be analyzed to determine the composition and size of the defects (see figures 5 and 6). These tests can and should be repeated after each process step.

A focused electron beam stimulates atoms in the sample with uniform energy. The atoms instantaneously send out X-ray radiation in characteristic signatures unique to each element, as shown in the graph. This information will enable users to “work backward” from the defect to determine where it is coming from so that the problem can be fixed quickly. In this way, the tool or process step that is most likely to be

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**Figure 1:** Excursion management improves fab ramp time and overall yield.

**Figure 2:** Applied Materials EBR platform.

**Figure 3:** In conventional LTPS display manufacturing, LTPS panels have become so large that in order to inspect one using a SEM tool it must be broken into pieces and each piece examined separately. Crucial information that may give insight into the source(s) of the defects is therefore lost.

**Figure 4:** Yield excursion identification and correction cycle. (Source: AKT)
the source of the problem can be more readily identified, along with the best set of lots to measure. The resulting information is then fed into the fab’s yield-management system (see figure 7).

All not defects are killer defects, and the EBR technology under development at Applied Materials will make kill ratio analysis possible. The kill ratio is the percentage of defects from a group of different types of defect that destroy a pixel. From left to right above, the process begins with an optical defect map. Next, EDX analysis classifies the defects as to type. Then, a focused ion beam is used to perform an array test. The “dead” pixels identified by this test are compared with the classified defects and a kill ratio is determined for use as a metric to improve yields.

It’s important to note that particles aren’t the only source of killer defects. The new Applied Materials EBR technology can help identify other sources as well, such as ineffective laser annealing, by monitoring grain size uniformity after excimer laser annealing, effectively enabling process control to monitor the performance of the laser.

**Looking Forward**

With some 20 years of innovation and experience with inline SEM-based inspection techniques in the semiconductor industry, the company is now extending those capabilities to the manufacturing of LTPS displays for better and faster root-cause analysis of defects, and for greater control of LTPS grain sizes.

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AERIS-S TECHNOLOGY: INCREASE SUBFAB SAFETY, REDUCE EMISSIONS

By Andreas Neuber, Michael Cox, John Dickinson, Jim L’Heureux and Dustin Ho

The fabrication of advanced gate stacks and complex device geometries increasingly depends on new processes, chemistries and materials that generate substantial volumes of hard-to-treat and potentially dangerous waste byproducts in chamber effluent.

High-aspect-ratio processes (HARP) and “dirty” chemistries—such as flowable CVD (FCVD) based on low-thermal-budget chemical reactions—generate large volumes of byproducts that can clog forelines, gate valves and pumps. Meanwhile, low-material-efficiency processes such as atomic layer deposition (ALD) deposit only a small fraction of the gaseous source material onto the wafer; the rest must be removed from the waste stream. Finally, SiGe, III-V, and other alternative materials and highly reactive precursors may pose safety and operational concerns if they are energetic, pyrophoric or toxic to humans, as many are.

This means it is no longer enough to simply meet governmental emissions regulations, despite how difficult that can be under these new manufacturing conditions. To be successful in today’s hyper-competitive markets, semiconductor manufacturers must place greater emphasis on hazardous material management when treating chamber effluent so that subfab utilities and subsystems remain safe, available, cost-effective and efficient—even under heavy factory loads.

Applied Materials is now developing a promising solution for these challenges: Applied Aeris-S abatement technology.

This new solution operates by converting problematic materials into compounds that can be managed and transported more easily and safely for abatement (either locally or in the central scrubber). Aeris-S technology also improves subfab safety by reducing the levels of flammable, explosive or toxic exhaust gases and the accumulation of potentially hazardous reactive solids downstream of the chamber.

Initially focused on HARP applications, the new Aeris-S technology is currently undergoing beta testing at a number of fabs. The system builds on the success of the Applied Aeris-G pre-pump plasma abatement system, some 2,000 of which are installed at fabs worldwide. Using Aeris-G units has enabled fabs to meet increasingly strict emissions regulations and reduce their carbon footprints while maximizing system uptime and reducing overall costs.

Like the zero-footprint Aeris-G units, the new Aeris-S units sit in the existing pump footprint for each chamber but are placed before the pump so they can treat the actual process gas volume, a much smaller and more concentrated gas volume than what is treated by traditional post-pump abatement technology (see figure 1).
However, Applied’s Aeris-S technology brings powerful capabilities to the more challenging abatement requirements at the leading edge of semiconductor manufacturing. For example, the Aeris-G and Aeris-S technologies employ different plasma sources.

Existing Aeris-G units use an inductively coupled plasma source to actively manage process effluent and reduce solids accumulation. This is a more effective solution than passive microwave-based pipe-heating and post-pump purging systems. Aeris-G units virtually eliminate volatile organic compounds (VOCs) and COx from tool exhaust because no fuel is used. They also eliminate NOx emissions because effluent is treated before it is diluted with N2 purge gases. Aeris-G technology demonstrates typical destruction removal efficiencies (DRE) greater than 99% for SF6, CHF3, C2F6, CF4 and C3F8, and greater than 95% for CF4.

By contrast, Applied’s new Aeris-S technology employs a higher-power magnetically confined and capacitively coupled plasma source to dissociate complex molecules, and precipitate and evaporate solids. It features high flow rates (100 slm) and a wide operating range. These features allow users to manage and prevent accumulation of solids in and beyond the foreline, increasing uptime and availability and reducing costs. In addition, these features drive reactions that turn harmful compounds into less harmful ones, reducing potential risks to maintenance personnel.

Results from the beta tests indicate that Aeris-S technology can effectively treat high volumes of effluents with a wide range of chemistries and foreline pressures. It can significantly lengthen preventive maintenance (PM) intervals for pumps and post-pump abatement equipment, and improve subfab safety by reducing hazardous levels of exhaust gases and downstream accumulations of reactive solids.

Both Aeris-G and Aeris-S units are synchronized with chamber operation and operate on-demand. This can lower the overall utility cost of ownership by up to 70%.

**HOW IT WORKS**

To more clearly illustrate the working principle of Aeris-S technology, consider a HARP process that incorporates a TEOS deposition step. The waste stream from TEOS breakdown on the wafer and in the chamber comprises the following molecules: TEOS, which is Si(OC2H5), along with CO, HCOOH, CO2 and CH4. (See figure 2, step 1.)

TEOS and its byproducts are toxic or flammable and the goal is to eliminate them from the waste stream. Applied’s Aeris-S technology performs a two-step process to eliminate TEOS during the cleaning process. First, the Aeris-S converts it into SiO2, which is much easier to handle and is deposited on the pump shields and in the foreline.

Second, NF3 is introduced into the Aeris-S system as a source of highly reactive fluorine radicals (figure 2, step 2). The Aeris-S activates the NF3. Some of the F radicals recombine and don’t react anymore, but some of them convert the SiO2 into SiF4. This removes the SiO2 buildup, and leaves SiF4, which a fab’s central scrubber can manage easily.

The concentration of SiF4 in the effluent can be seen as an indicator of cleaning efficiency (i.e., more SiF4 in the effluent means that more SiO2 effluent has been converted). The removal efficiency of Aeris-S units in beta tests is shown in figure 3.

Applied’s new Aeris-S technology is designed for low operating costs and has a flexible architecture for easy cleaning and maintenance. The units are externally programmable to control reagent flow, power and purge functions, and can interface with production tools from Applied Materials or other manufacturers, as well as a fab’s host computer system.

It is always Applied Materials’ goal to have increased uptime, higher efficiency and lower operating costs go hand-in-hand with good environmental stewardship and safe operating practices. The new Applied Aeris-S technology will help ensure that customers continue to enjoy those benefits no matter how complex semiconductor fabrication becomes.

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NEW PREVENTIVE MAINTENANCE SERVICE OPTION

Preventive maintenance (PM) can maximize tool availability and minimize the risk of sudden increases in operating costs—provided it is timely and effective. Data from Applied Materials Managed Service Agreements shows that tools which receive appropriate PM according to Applied’s guidelines demonstrate an average improvement in scheduled uptime in the range of 3-5% over those which do not.

Customers covered by Applied’s Managed- or Performance Service Agreements already receive PM services as an integral part of their support programs. In addition, up to 60% of tools are covered only by Applied’s new product warranty or Standard Agreements already receive PM services as part of the program.

Applied’s new product warranty or Standard Agreements already receive PM services as part of the program.

Applied PM Services offer First Time Right performance. Applied’s assurance of consistently high-quality service. The goal is to minimize scheduled downtime through repeatable task performance. This means that if the initial chamber requalification process is unsuccessful and attributable to an improperly performed PM, Applied will support the subsequent efforts to successfully recover and return the chamber to production status. Applied offers this service at a cost savings over standard transactional services that include parts procurement, cleaning, and materials management tasks as required to sustain predictable operability.

This level of support is made possible by Applied’s extensive global parts infrastructure and efficiencies, and by the high level of training provided to field service technicians, most of whom are local to customers’ fabs. For example, Applied’s Tech Guides training team uses virtual reality simulations and other advanced teaching methods to bring our trainees “inside the chamber” and optimize their understanding of Applied Materials hardware and proprietary technologies. The combination of greater parts efficiencies and expert staff training helps customers reduce the costs and risks that stem from improperly performed PM tasks, which can arise from errors in workmanship, part failures, or use of parts that prevent chamber recovery to production status. It also frees up a lab’s own service technicians for other tasks.

Applied Materials has demonstrated that it can deliver repeatable, predictable and fast results using a methodological approach to PM execution based on industry-wide best practices, intimate tool and process knowledge, and high-quality parts and process cleaning protocols.

Thus, customers who contract for the new Applied PM Services option can expect to achieve greater tool stability and availability, and to benefit from more predictable operating costs.

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