The Midas Touch: Surface Processing With the UV Excimer Laser
Open Up Growth Markets and Drive Disruptive Innovations

Very much like the ancient king Midas who as the legend tells was able to transform ordinary material into gold by the touch of his hand, today’s excimer lasers are capable of transforming an un-specific material layer into a high value, functional surface by their unique beam properties.

Representing today’s most cost-effective and dependable pulsed, ultraviolet (UV) laser technology, excimer lasers enable disruptive innovation in various growth industries as diverse as the markets for flat panel displays, automobiles, biomedical devices and alternative energies.

It is the combination of two fundamental aspects, namely wavelength and output power, which determines the excimer laser’s unique value adding potential in high tech industries which more than ever have to balance product size-efficiency and performance demands with process speed and production costs. This article will try to provide an insight into some key applications of the excimer laser.

Transforming Surfaces Into Differentiators

Excimer lasers are narrowband, ultraviolet light sources providing the shortest laser wavelengths or, which is equivalent, the highest laser photon energies for commercial laser based manufacturing [1]. Since the optical resolution which is achievable in laser material processing is related to the laser’s wavelength, excimer lasers are among the most precise optical processing tools on the market. Depending on wavelength and material, with commercial excimer laser based material processing systems, feature sizes close to one micrometer as shown in Figure 1 are obtainable [2].

Moreover, while the short wavelength translates into smallest lateral structures, it is the strong material absorption of the correspondingly high photon energy (e.g. 5.0 eV for 248 nm or 6.4 eV for 193 nm) which translates into very limited vertical material impact. In fact, the depth resolution of excimer laser thin layer material processing is in the submicron range and can be as small as 50 nm per laser pulse depending on the material sample and the wavelength [3].

Excimer lasers enable unmatched high resolution optical processing both in the sidelong direction and in the vertical direction of the sample material. They are the ideal tools for functionalizing large surfaces via changing their microstructure.

In addition, excimer lasers are by far the most powerful ultraviolet lasers for commercial, laser based manufacturing.

The UV Technology Landscape

Today, the output power of an excimer laser at 308 nm can be above 500 Watt, as is shown in Figure 3, which shows a comparison of the achievable power levels of diode pumped and lamp-pumped solid state laser technology. State-of-the art excimer lasers...
Formula of Success: UV Without Detours

The fact that elevates excimer laser technology above all other UV technologies is that its underlying laser transitions are in the UV spectral range by nature. As a result, excimer lasers generate UV photons in the first place rendering them the most powerful and most stable UV laser sources on the market.

In contrast, concurrent UV generation concepts start with IR and visible lasers requiring subsequent non-linear frequency conversion inevitably inducing severe trade-offs as to the achievable UV output efficiency and UV output stability [4].

Boosting Product Performance With UV Power

The innovative potential of UV excimer lasers in today’s advanced manufacturing is best visualized in the applications given below. All of the following production examples have in common that an excimer laser based processing step is responsible for the achieved leap in performance.

Greener Diesel Engines

Diesel engines are among the world’s most significant contributors to fossil fuel in the transport sector. They are essential for both public and freight transport via road, rail and sea as well as in agricultural machines. Moreover, about 40% of the European automotive market is based on Diesel engines. Stricter environmental legislation demands for fuel saving and reduced environmental pollution as well as market demands for increased power and efficiency constantly force manufacturers to find innovative solutions.
Since Diesel engine technology uses high compression ratios, the tribological conditions of the pistons moving inside the cast iron cylinder liners are particularly arduous with respect to lubrication and wear.

Conventional Cylinder Wall Processing

The inner walls of conventional cylinder liners exhibit a communicating microchannel surface topography as shown in Figure 5 which are left over from mechanical polishing, the so-called honing process. As a consequence, the oil escapes along these microchannels during the piston's movements thereby severely reducing the desired lubrication effect between piston ring and cylinder wall. As a matter of fact, the friction between piston rings and cylinder liners can account for as much as 60 % of a Diesel engine's total frictional loss.

Excimer Laser Cylinder Wall Processing

Post-treatment of the cylinder liners with the UV photons of a 308 nm excimer laser and nitrogen-assist gas completely changes this surface situation from structurally unfavorable to structurally entirely beneficial as depicted in Figure 6 below.

The short wavelength, high energy photons of the excimer laser strongly interact with the cast iron material of the cylinder liner and produce a different surface via three effects:

(1) Selective melting to a depth of ca. 2 µm leads to an overall smoothening of the cylinder liner's surface.
(2) Due to the opening of graphite inclusions close to the surface, located grooves are formed acting as oil reservoirs.
(3) The nitrogen-assist gas atmosphere induces an additional surfaces hardening due to the formation of nitrides and subsequent enrichment in the molten surface.

Comparative Diesel engine test bench programs have been conducted. These test results show the percentage reduction in wear of an excimer-laser-treated cylinder compared to a conventionally honed cylinder. Depending on the duty cycle, the UV excimer laser process step leads to a relative wear reduction of up to over 85 % for both the cylinder liners and the piston rings. Moreover, the oil consumption is reduced by ca. 75 % compared to conventional mechanical honing [5].

The excimer laser process step thus improves fuel efficiency and decreases long-term wear, which in turn reduces oil consumption and particulate emissions helping to save our resources and to protect our climate.

For the engine manufacturer the economical benefit of the excimer laser process is twofold: he can easier meet legislation demands and as well clearly differentiate his product in a competitive market.

Brighter Displays

The global flat panel display industry has experienced tremendous growth over the last decade in all display segments extending from small size mobile phone and car navigation displays via medium size television and notebook displays to large size home entertainment and advertising panels. Emerging display technologies such as Organic-LEDs or displays based on flexible substrates (see Figure 7) will further drive industry's rapid growth. Flat panel display manufacturers face demand for features such as decreasing power consumption, faster response times, enhanced contrast and better resolution which puts stringent requirements to the thin film silicon backplanes.

As a consequence, an increasing number of faster, brighter displays is encountering the performance limits of conventional amorphous silicon backplanes.

**UV Laser Technologies**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Excimer Technology</th>
<th>UV-DPSSL</th>
<th>Lamp-pumped Nd:YAG laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available UV Wavelengths</td>
<td>351 nm 308 nm 248 nm 193 nm 157 nm</td>
<td>355 nm 266 nm</td>
<td>355 nm 266 nm 213 nm</td>
</tr>
<tr>
<td>Power Range</td>
<td>up to 540 W</td>
<td>30 W</td>
<td>4 W</td>
</tr>
<tr>
<td>Energy Range</td>
<td>up to 1100 mJ</td>
<td>0.3 mJ</td>
<td>up to 180 mJ</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>variable, 1 to 600 Hz</td>
<td>variable, 1 to 300kHz</td>
<td>fixed, 10/20 Hz</td>
</tr>
<tr>
<td>Shot-to-Shot Stability</td>
<td>0.5 to 1.0 %, rms</td>
<td>5 to 10 %, rms</td>
<td>5 to 10 %, rms</td>
</tr>
<tr>
<td>Long-Term Drift</td>
<td>0.1 to 0.5 %, rms</td>
<td>2 to 5 %, rms</td>
<td>5 to 10 %, rms</td>
</tr>
<tr>
<td>Beam Profile</td>
<td>homogeneous flat-top</td>
<td>near-Gaussian</td>
<td>distorted Gaussian</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>10 to 20 ns</td>
<td>30 to 100 ns</td>
<td>5 to 8 ns</td>
</tr>
</tbody>
</table>

**TABLE 1: Comparison of UV technologies showing performance parameter ranges of UV excimer lasers versus frequency-converted lamp-pumped Nd:YAG lasers.**
Conventional Silicon Backplane Processing

In active matrix displays silicon forms the basic conductive layer which is conventionally created via a high temperature-high vacuum chemical vapour deposition process. Unfortunately, silicon layers obtained with this technique are largely amorphous in nature which implies severe limitations as to the pixel switching speed and the overall electrical consumption of a flat panel display.

In particular, high performance displays offering increasing brightness and resolution do ultimately rely on fast switching and smaller transistors and therefore on electron mobilities way beyond the ca. 1 cm²/V-sec as provided by conventional amorphous silicon backplanes.

Excimer Laser Based Silicon Processing

An additional UV excimer laser process step (as depicted in Figure 8) transforms the low electron mobility silicon into an enabling thin film which supports fast voltage switching of high resolution AM-LCDs as well as the required current driving of emerging AM-OLEDs.

The transformation of the amorphous silicon layer is obtained by selectively annealing and recrystallizing the amorphous silicon layer with the effect that a highly ordered microstructure is achieved. Due to the short wavelength of 308 nm and the small penetration depth, the underlying glass substrate is not affected by the high power excimer laser beam [6].

On account of the multihundred Watt output power, fast large area processing is possible. Dramatically increased electron mobilities of above 100 cm²/V-sec which are two orders of magnitude higher than those of amorphous silicon layers are the result. The polysilicon layer shown in Figure 9 permits electrons to move more easily through its highly ordered lattices.

The UV excimer laser process step, thus enables faster, brighter, thinner and more lightweight AM-LCDs and AM-OLEDs which rely on high electron mobility to enter the market.

Additionally, due to its low temperature annealing characteristics, the excimer laser surface transformation represents the basis for disruptive display technologies such as bendable electronic books or newspapers using flexible polymer type substrates instead of rigid glass panels.

Enhancing Light Capture of Solar Cells

Despite the strong annual market growth of the photovoltaics industry, the road to grid parity for photovoltaic power generation will be difficult, likely needing another five or more years to be competitive in an unsubsidized manner and on large scale.

Accordingly, the photovoltaic market is driven by ongoing process optimization and material improvements which improve cell efficiency, as well as glass, wafer, and contact grid improvements in order to enhance the fraction of light captured.

Conventional Silicon Wafer Etching

As of today silicon based multicrystalline solar cells form the major basis of commercial large scale production. Wire sawing is used to cut silicon ingots into wafers. This process induces small cracks penetrating around 10 µm deep into the wafer surface. Saw damage has to be removed from the wafer surface, because it reduces the mechanical strength of the wafer and increases recombination in the surface region. Fast solution etching is conventionally used for saw damage removal. Due to locally differing etch rates on account of crystallographic orientation or impurities, randomly distributed indentations of a few microns (see Figure 7) show up throughout the surface which are unfavorable as to light reflection losses [7]. To create highly efficient photovoltaic cells it is, however, necessary to reduce light reflectivity on the surface.

Excimer Laser Patterning of Etch Barriers

An enhancement of the overall light absorption of the solar cell is obtained by introducing an excimer laser based process step. By large area mask projection machining of a SiNx etch barrier with excimer laser wavelengths of 308 nm or 248 nm, a regular pattern is created on the surface of a solution-etched multicrystalline silicon wafer.
tern of holes is created. Solution etching via the excimer laser ablated SiNx barrier ultimately translates into the very regular honeycomb structure which is shown in Figure 12 below.

A hexagonal pattern with 30 µm pitch is created from etching with a SiNx barrier containing precise excimer laser ablated holes of 10 µm in diameter [8].

The honeycomb surface obtained by the excimer laser process steers incoming light back to the glass-air interface at a grazing angle, that allows the light to undergo virtually total internal reflection, thus directing it back to the cell surface. After encapsulation the total light reflectivity was reduced from 34 % to 11 % resulting in a significant overall cell efficiency gain of 0.4 %.

With state-of-the-art excimer lasers providing multihundreds of Watts output power and multihundred Hertz of pulse repetition rate, process speeds for large-area SiNx UV patterning are as fast as a few seconds per solar cell (156 mm x 156 mm).

FIGURE 12: Regular honeycomb surface structure as obtained after excimer laser patterning a SiNx etch barrier layer and subsequent etching of a multicrystalline silicon wafer.

Advancing Superconductor Commercialization

The emerging high temperature superconductor (HTS) industry drives solutions ranging from magnetic energy storage to electrical energy transport grids operating at current densities 100 times higher than conventional copper based systems. Resulting technological advantages of using HTS based systems which are operable with liquid nitrogen cooling are higher efficiencies, higher currents, fields and forces, higher power densities, smaller weight and size as compared to conventional technologies. This is illustrated in Figure 13, showing the amount of copper cable necessary to carry as much current as the small HTS tape containing a 1 µm thick superconducting YBCO layer.

FIGURE 13: A thin HTS tape can carry as much power as the much larger copper wire shown.

The future cost and energy saving potential of HTS is enormous and makes them a first choice solution for breaking technological barriers. Pivotal to HTS commercialization are cost-efficient, high-performance thin film deposition technologies [9].

Conventional Metal Organic Deposition of HTS Films

Among the most promising chemical processes of depositing superconducting metal oxide films, is metalorganic deposition (MOD). In conventional MOD an organic precursor solution containing the appropriate metal atoms (typically Y, Ba and Cu) is used for dip coating the substrate layer. Subsequent, repetitive heating and baking steps at high temperatures of 500°C and 1000°C are needed for organic solvent removal and oxidation, respectively. While a solution based deposition is an inherently fast process, the crystalline structure and hence the current density performance of the obtained YBCO layers is unsufficient. This problem cannot be overcome even by time-consuming, repetitive heating and baking steps.

Excimer Laser Assisted Metal Organic Deposition

The excimer laser’s enabling capability to speed up overall processing time and to boost thin film performance has been demonstrated by Japanese researchers at AIST and JSW. With their ELAMOD (Excimer Laser Assisted MOD) method time-consuming heating and baking is replaced by fast 308 nm-large-area excimer laser illumination resulting in five times faster processing speed and three times higher performance of the superconducting films. The performance leap due to bond breaking and reformation in the YBCO layer as induced by the UV excimer laser light is visible in Figure 14 by the strong color change.

For the excimer laser illuminated YBCO films when cooled with liquid nitrogen, critical current densities above six million Acm⁻² are measured (see Figure 15) ranking ELAMOD among the most promising approaches for large-scale superconductor commercialization such as pulsed excimer laser deposition (PLD).

As a matter of fact, ELAMOD achieves the largest current density ever achieved with a chemical solution deposition process [10].

Also in this final example of the looming HTS market, the increased process speed due to the excimer laser implementation leads to severe cost reduction and enables economical mass-production of high-quality superconducting thin film devices and tapes via mask patterning and via reel-to-reel architectures, respectively [11].

Future applications comprise superconducting fault current limiters for stabilizing electric power grids as well as patterned microwave filter and antennae structures for enhanced mobile communication capacity in congested urban areas.
Market Trends and Perspectives

Excimer lasers surpass all other laser and non-laser technologies when it comes to precise, large-area processing. The superior performance as well as the state of maturity of excimer lasers is most prominently seen in the excimer laser volume markets, namely micro lithography and vision correction. Without the 248 nm and 193 nm deep-UV wavelengths and the high output power delivered by excimer lasers, microlithographic chip-making industry had not been able to maintain pace with Moore’s Law realizing in-
tegrated circuit feature sizes which are now ten million procedures performed since its introduction.

In times where overcoming material limitations becomes ever more demanding UV excimer laser technology is once again seen at the forefront of cutting edge industrial la-
sor solutions. As has been shown, various mature and emerging high-technology products of the display, automotive, and renewable energy industry (see Figure 16) are lifted over seeming-
ly inherent performance barriers by the Midas touch of excimer laser UV photons.

Miniaturization and use of thin film tech-
nology in particular is an ongoing trend seen in industrial manufacturing. Drivers of thin film technology use are cost saving aspects as e.g. in the photovoltaic market where the multicrystalline silicon makes up ca. 50 % of the final module costs but also functional as-
pects as e.g. in the display market requiring oxide layers which are conductive and yet thin enough to be optically transparent. In selectively patterning, illuminating and an-
nealing these thin functional layers which exhibit a mere thickness between 50 nm and 2 µm over large areas the excimer laser with its unparalleled UV power will continue to lead its trump.

References

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