A Unique Laser Process for Rapid Patterning of Thin Films

Picosecond laser pulses enable high throughput, spallation - a single step, dry process with the highest edge quality for patterning ITO and other films resulting in superior resolution and reduced linewidths. This approach is ideal for touch screens and other display applications.

Overview

It is the goal of this article to provide a reference for identifying spallation applications which are likely to require a picosecond laser, and not to provide an overview of all lasers which can perform spallation. In fact, the decision to use either a picosecond or nanosecond laser is not always obvious, requiring collaborative applications lab tests with multiple technologies to identify the best possible fit. In particular, thin film removal is a very good example of the complex matrix of parameters which are often highly interconnected. These require significant experience with a wide variety of laser types to demonstrate the ideal source given the balance between line width, material thickness, composition of adjoining materials, film composition, and the pattern density.

For example, it is well-established that the nanosecond 355 nm Coherent AVIA laser is a cost-effective system for easily removing ITO with high speed. However, thick ITO (>30 nm) may experience burr which degrades the pattern, making it visible to the human eye. Additionally, laser pulse energy must be carefully controlled to avoid glass substrate damage due to the strong material removal capability. Nanosecond excimer lasers can provide even higher throughput if the line pattern density line is high enough to capitalize on mask imaging which ablates large area patterns in a single shot.

By comparison, the picosecond Talisker laser is the focus of this article because it offers excellent removal depth control without the risk of damage to the glass substrate. The selectivity from a picosecond laser is especially useful when removing multiple layers with precise depth control; providing very clean removal edge and almost no burr even with >70 nm ITO film thickness.

These advantages are a result of the very short interaction time between the laser and the material, which make the picosecond laser the best solution for applications requiring stringent edge quality and depth control.

The Need for Thin Film Patterning

The fabrication of microelectronic devices and flat panel displays requires patterning of thin films of dielectric, metal and/or semiconductor materials typically in alternating layers. For example in touch screens, it is necessary to scribe completely through transparent conductive oxide films with a linewidth and precision of around 100 microns. Initially, the majority of this patterning was performed using some type of photolithography, a traditional technique involving multiple steps, including photoresist (PR) coating, baking, exposure, developing, material etching and PR stripping. This is a complex process requiring large capital investment in equipment, high fabrication costs (including masks and large volumes of wet chemicals), high maintenance charges, and long fabrication times.

Photolithography is perfect for smaller devices such as logic and memory chips. But for larger area products such as displays and touch screens, where high throughput and fast processing have to be combined with sub-100 micron linewidths, the picture is more nuanced. As a result, alternative patterning methods based on laser micromachining have been gaining wider acceptance because these methods involve much fewer individual steps and avoid wet chemistry, except where post-process cleaning is required. Moreover laser patterning can be very flexible, supporting easy (software) pattern changes. (A standout and already well-established example being laser direct imaging used to pattern state-of-the-art multilayer PCBs.)

For the display and touch screen markets, a new direct patterning process called spallation is enabled by the latest generation of ultrafast (picosecond) industrial lasers. This novel manufacturing process can selectively remove thin films (up to a few hundred nanometers) with the required spatial resolution and

without damage to the underlying layers. Moreover, spallation is a single-step dry process that leaves almost no debris, meaning that no post-processing (cleaning) is usually required. In this whitepaper, we explore the advantages of this process which can be applied to metals, dielectrics and transparent conductive oxides (TCOs). We will also present data obtained with a unique picosecond laser – the Coherent Talisker – a laser that provides ideal output characteristics for volume manufacturing using spallative patterning.

Laser Spallation Theory

Spallation relies on vaporizing a small amount of material at the interface of two layers with very different absorption characteristics at the laser wavelength. As shown qualitatively in figure 1, the laser enters the target via a layer that is fairly transparent, e.g. glass. And the beam delivery optics are setup so the laser beam waist (i.e. highest intensity) is focused at the interface between this transparent layer or substrate and the next layer which must be a strongly absorbing, e.g., metal. All the pulse energy from the laser is thus absorbed in the first few nanometers of the absorbing layer. Because the absorption occurs at an enclosed interface, there is nowhere for the expanding vaporized material to escape.

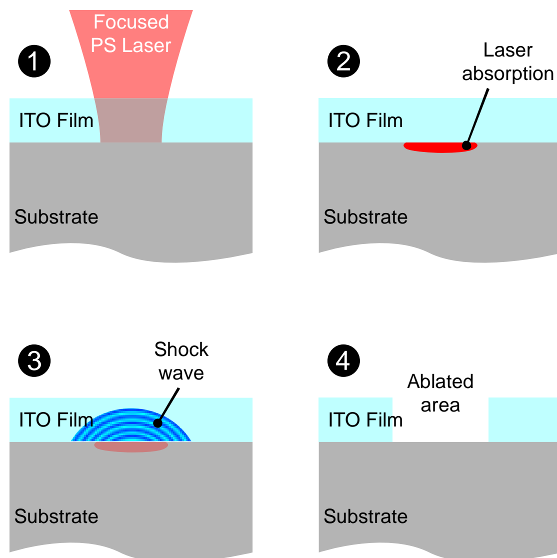

Figure 1. *In spallation 1) a focused laser beam is absorbed at an interface, 2) heating occurs in a thin layer, 3) a shock wave expands out, and 4) the thinner layer is blown off.*

As a result, this catastrophic expansion of atomized material creates a shock wave that blows off the thinner of the two layers. And just as important, this laser spallation process minimizes damage to the surrounding and underlying materials making it ideal for most thin films used in the electronics and display industries.

A more quantitative explanation shows that this process can occur when the laser pulse duration is less than the thermal/acoustic response times of the material, allowing the thin film to be essentially spallated with a single laser pulse [1]. Let us consider the case of a silicon dioxide thin film of thickness, t ~100 nm and a laser pulse duration of 10 ps.

The speed of sound in ITO, *c*, is ~4100 m/s, using equations from [2] and material property date data from [3], so the characteristic acoustic relaxation time, *A*, is given by:

$$A = t / c \qquad (1)$$

The thermal diffusivity of silicon dioxide is κ ~0.013 cm^2/s, which in equation (2) gives a thermal relaxation time, τ of 1.9 ns. So both the thermal and acoustic relaxation times are longer than the 10 picosecond laser duration, meaning that this thin film can be successfully removed by laser spallation.

$$t = \sqrt{4\kappa\tau} \qquad (2)$$

The thermal diffusivity of silicon dioxide is κ ~0.009 cm^2/s, which in equation (2) gives a thermal relaxation time, τ of 2.8 ns. So both the thermal and acoustic relaxation times are longer than the 10 picosecond laser duration, meaning that this thin film can be successfully removed by laser spallation.

In addition to producing clean edges with thicker films, spallation is also very fast in terms of throughput versus laser power. In conventional laser machining processes, the overall speed is limited by the total amount of material to be vaporized. However in spallation, only a small amount of material is vaporized, typically with a single laser pulse at each location, but the entire thickness of the target film is completely – and cleanly – removed with no melted and/or recast debris.

An Optimum Laser for Thin Film Spallation

To optimize laser spallation for high throughput manufacturing requires consideration of the pulse

duration, pulse energy, repetition rate and the laser beam quality. As we have seen from the sample calculation, the acoustic/thermal relaxation timescales of most materials are of the order of several 10’s of picoseconds. The optimum laser therefore is one with a pulse duration of less than 10’s of picoseconds. Nanosecond laser pulses are too long to produce good spallation results, even at ultraviolet wavelengths, and the high cost of femtosecond lasers (vs. picosecond) is not justified by any advantage for spallation.

Pulse repetition rate is a laser parameter that is important for both results and costs. Specifically, to reach a certain power level in a fast pulsed laser, the laser can be designed for very high repetition rate or high pulse energy. The simplest laser capable of delivering picosecond pulses is called a mode-locked fiber laser. These lasers deliver pulse repetition rates in the tens of MHz range. This is not suitable for thin film spallation where the goal is one laser pulse at each location with minimum overlap between adjacent pulses. Depending on the focused spot size, the maximum speed of galvanometer mirror scanners is compatible with a pulse repetition rate of around 200 kHz. (Applying additional pulses at the same location after film removal is a waste of laser energy and will often damage the substrate layer and/or underlying layers.) So a mode-locked fiber laser can only be used for thin film spallation if the pulse rate is reduced by an external device, wasting over 95% of the total laser power.

Figure 2, *The Coherent Talisker is a turnkey picosecond laser for applications including spallation.*

The pulse repetition rate is an important laser parameter. High repetition rate mode-locked picosecond lasers result in extremely high pulse overlap and damage to underlying layers, preventing selective removal of a given thin film. To ensure clean selective removal, a single laser shot with minimal pulse overlap is required and the Talisker repetition rate of 200 kHz allows scribe speeds of several meters per second.

And lastly, mode-locked fiber lasers tend to produce poorer quality output beams, as measured by the parameter M^2. Meaning the beam profile is messy compared to a perfectly circular $M^2 = 1$ beam. Plus the output beam of fiber lasers tends to wander over time. This limited beam pointing stability is detrimental when processing large area panels that require a long throw-distance for the beam.

On the other hand, picosecond laser amplifier systems based on bulk optics can deliver near ideal performance for laser spallation in terms of pulse energy, repetition rate, beam quality and beam pointing. They are better suited to scientific applications because they are more complex and often more costly than fiber lasers and require periodic re-alignment.

In response to this situation, Coherent developed an optimum picosecond laser for laser spallation based on a hybrid approach. The Talisker laser uses a simple and robust fiber laser oscillator whose output repetition rate is slowed before the pulse energy is boosted by a traditional amplifier based on bulk optics. Both the oscillator and amplifiers are ruggedly integrated within a single compact laser head – see figure 2. The end result is a laser with an optimized 200 kHz pulse repetition rate, and an ideal pulse duration of 10 ps, a highly focusable beam with a M^2 value of $M^2 < 1.3$, and excellent pulse-to-pulse stability <2%. The average power of 16W for IR (8W at 532 nm and 4W at 355 nm) of the Talisker laser translates into pulse energy of several 10’s of µJ, resulting in plenty of power overhead for selective removal of thin films.

Test Data Examples

Extensive tests on selective thin film removal have been carried out in Coherent’s applications labs using an off-the-shelf Talisker picosecond laser, which clearly demonstrate that this picosecond laser is well-suited for enabling high quality features to be scribed. For example, figure 3 shows single pulse removal of ITO from SiN with a linewidth of 25 µm, and figure 4 shows similar results for removing ITO from SiO_2 with a linewidth of less than 9 µm. Also, figure 5 shows selective removal of 0.5 µm aluminum from SiO_2 yielding electrically isolated scribes of linewidth ~6 µm at a scribe speed of 1 m/s. The low pulse-to-pulse stability <2% is clearly evident from these scribes.

These images show the scribes as created with no post-process cleaning whatsoever. In these cases, there is no visible damage to the underlying layers nor any debris/molten material on the surface. As already noted, this is of critical importance since the presence of melt or laser ablated particle debris can negatively impact performance of products such as touch screens. Also, the high repetition rate of the laser (200 kHz) supports scribe speeds of several m/s for this new selective patterning method making it very compatible with other fab processes.

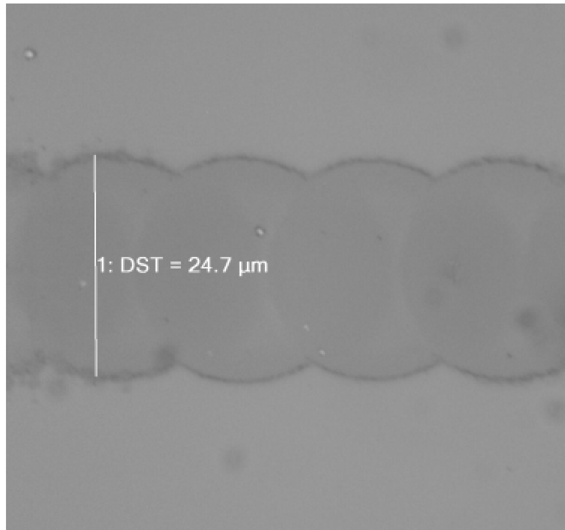

Figure 3, *Selective removal of ITO from SiN using 532 nm, 200 kHz, 5 µJ pulses at a scribe speed of 3 m/s.*

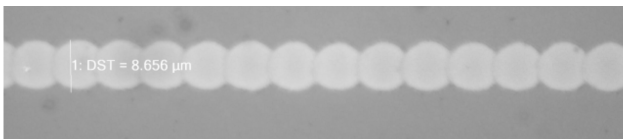

Figure 4, *Selective removal of ITO from SiO_2 using 355 nm Talisker, 200 kHz, 0.8 µJ pulses at a scribe speed of 1.5 m/s.*

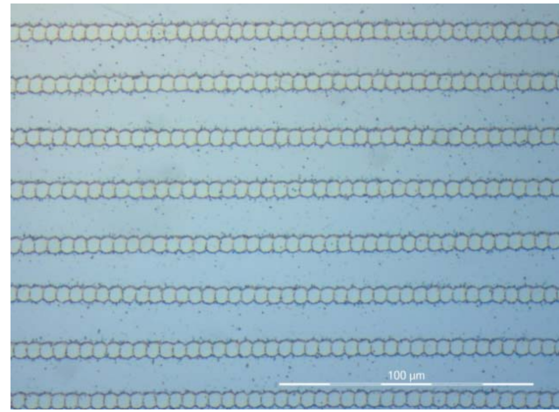

Figure 5, *Selective removal of 0.5 µm aluminum from 0.5 µm SiO_2 using 355 nm 0.7 µJ ps pulses at a scan speed of 1 m/s. This scribe was electrically tested and found to be isolated.*

Conclusion

A new process called laser spallation is ideal for many thin film patterning applications in the fabrication of displays and related products. This process is optimized by use of a picosecond pulsed laser with fairly specific output parameters. However, these output parameters are not readily obtained from either traditional (bulk optics) or fiber-based lasers. But Talisker, a new laser based on a hybrid technology approach, delivers near ideal output for both the fine patterning quality and high speed demanded for many of today's touch screen patterning applications.

References

[1] D. M. Karnakis et al., "Ultrafast Laser Patterning of OLEDs on Flexible Substrate for Solid-state Lighting," Journal of Laser Micro/Nanoengineering, vol. 4, pp. 218-223, 2009.the art performance in all these areas from a single product.

[2] ://hyperphysics.phy-astr.gsu.edu/hbase/sound/souspe2.html

[3] http://www.mit.edu/~6.777/matprops/ito.htm