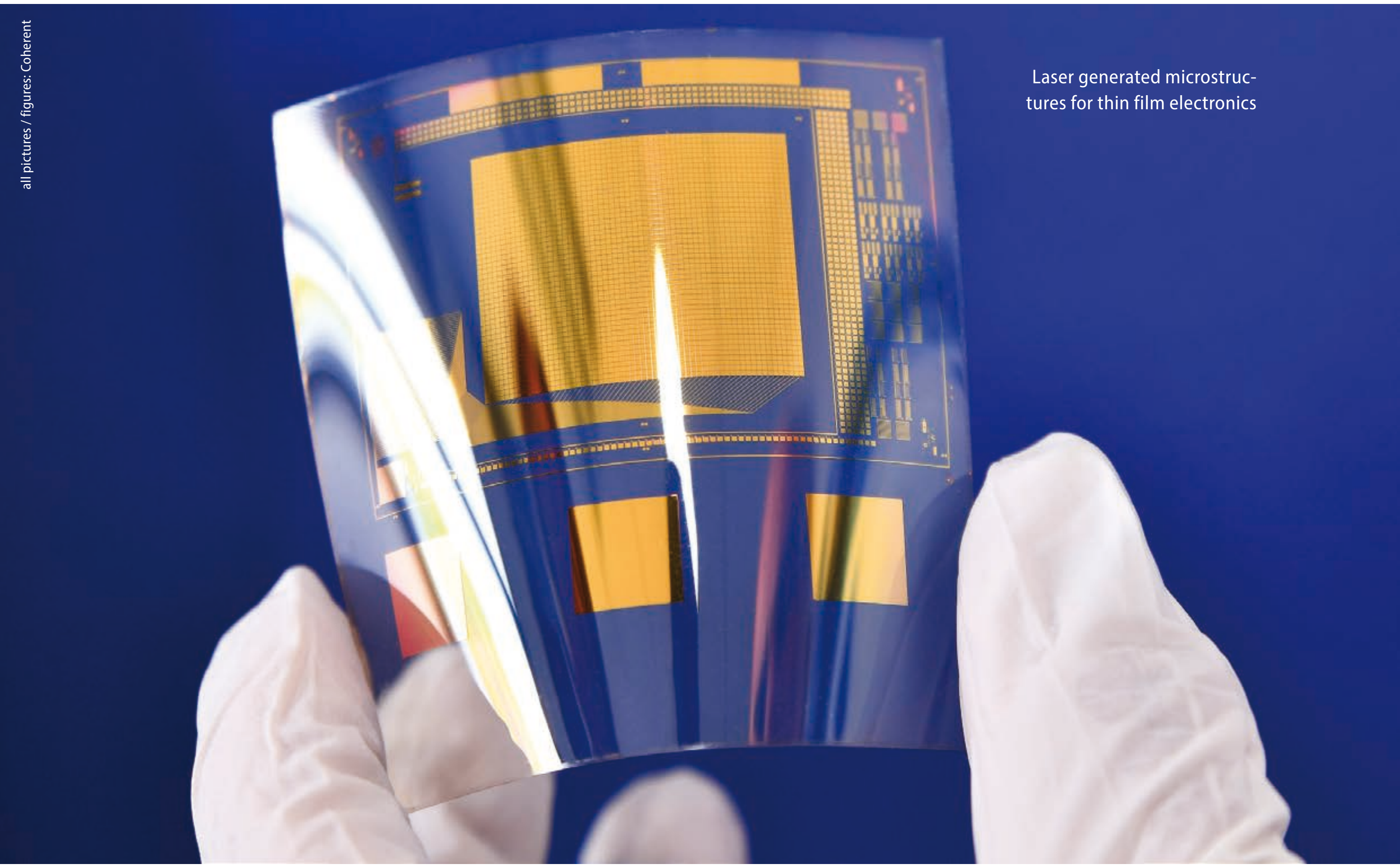

Laser generated microstructures for thin film electronics

The Antennae Challenge

USP lasers streamline micromachining of 5G phone antennae.

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The high frequency antennae and circuits that enable 5G connectivity require more complex shapes and finer details than earlier devices but USP lasers enable these patterns to be created in a single dry process that can cut copper, insulator and adhesive layers without any thermal damage.

The advent of 5G technology is predicted to have a revolutionary impact on society as "everything communicates with everything" at unprecedented speeds; for example, this will deliver more than ten times reduction in latency times compared to 4G LTE. Yet in all this high-speed digital revolution, a key component is still analog – the miniaturized phone/device antennae and circuit boards that must be optimized for high frequency operation. These antennae involve complex shapes fabricated from laminates of necessarily dissimilar materials: thin copper conductor supported on a tough organic (e.g., modified polyimide, liquid crystal polymer) insulator, often including a bonding (adhesive) layer. In this article, we see why micromachining with ultrashort pulse lasers (USP) is poised to play a critically role in the mass fabrication of these RF elements. Beyond this application where antennae and circuits will have to be manufactured in huge quantities, the demonstrated ability of USP lasers to cut multiple dissimilar layers in a single dry process also has broader applications in other areas of microelectronics and MEMs.

In its simplest form, an antenna is an electrical conductor attached to components such as capacitors and resistors that tune the circuit to resonate in a specific frequency range, i.e., to build up signal intensity in response to an oscillating incoming field of electromagnetic radiation (RF or microwave) at that frequency. Conversely, an oscillating electrical signal in a similar driver circuit will cause an antenna to emit radiation at that resonant frequency. The efficiency of both detection and transmission are strongly influenced by the impedance, orientation and shape of the antennae relative to the direction and any polarization of the incoming waves.

The high-speed promise of 5G is predicated on an enormous increase in bandwidth, which has several consequences for antennae design and fabrication. First, it requires transmission to be shifted to higher frequencies compared to 3G and even 4G LTE, i.e., from RF into the microwave domain, which means the antennae elements have to be physically smaller to maintain efficiency. And at the same time, a key part of 5G will be the ability of mobile devices to simultaneously exploit signals from different transmitters, based on frequency, directionality and polarization effects. In a smartphone, this requires incorporating multiple miniaturized antennae with complex 2D (and even 3D) shapes and spatial details that allow all this signal multiplexing with the requisite sensitivity. These shapes support so-called MIMO operation: multiple signals in, multiple signals out for the same antenna. Existing antennae already support 2×2 and even 4×4 MIMO function, but 5G is looking to increase this type of multiplexing further. Lastly there is the ubiquitous challenge of minimizing weight and overall size in a densely packed device such as a phone, which must also include 4G antennae for the foreseeable future.

Each antenna element is a laminate of a thin layer of copper bonded to a polymer substrate (typically tens of micrometers in thickness) which acts as both impedance matching insulator and structural support for the copper. Several of these elements can then be encapsulated to provide MIMO functionality. The polymer is usually a modified Polyimide (mPI) or liquid crystal polymer (LCP) since these tough plastics have excellent electrical and thermomechanical properties that match the copper, while being very stable when exposed to humidity and immune to damage (with the notable exceptions of boiling acid or alkali). Further details are proprietary to the antenna manufacturers but usually also involve some type of bonding compound between the copper and polymer layers.

Laser micromachining

The diminutive dimensions, thinness, and modest value of the antenna elements mean that they have to be patterned from a copper on polymer laminate substrate mounted on some type of sacrificial tape or other carrier to simplify downstream handling. The alternative of cutting before laminating is not a practical option because some of the laminating process is thermal in nature, resulting in material shrinkage after lamination. There are several techniques that can be used to fabricate small devices from a sheet substrate, including lithography, laser micromachining, mechanical cutting, and electrical discharge machining (EDM). Lithography is well proven and widely used throughout electronics manufacturing and could easily provide the requisite spatial resolution but is not ideal for this application. It would require multiple wet chemistry steps and could only pattern the copper; another process would still be required to pattern the polymer. Mechanical cutting is not practical as it could not provide the resolution to create the tight curves and other details. EDM only works on conducting materials, so like lithography it would be limited to the copper. However, laser micromachining is well-proven at this spatial resolution, and can machine both metals and polymers, making it the obvious choice. But this application does present some challenges.

Laser micromachining is the obvious choice to perform the necessary cutting/scribing (scribing involves a selective removal of layers without damaging the under layers). Nanosecond (Q-switched) lasers could readily provide the required spatial resolution, but not in a single process. The problem is that the copper and polymer have very different ablation thresholds. This is the minimum fluence required to begin removing material – as liquid, particulates and vapor. Depending on the application, the optimum laser fluence is seven times the ablation threshold. Increasing the fluence toward ten times over threshold and beyond does not improve process speed, it just results in more localized heating, increasing the heat affected zone (HAZ). This is the material adjacent to the cut, scribe or hole that is degraded by thermal effects, for example charring in paper and plastics, creation of a glassy phase in ceramics, or melting in the case of semiconductors.

With a small electromagnetic device like a phone antenna, the HAZ must be minimized to avoid functional damage or the potential for reduced reliability and lifetime. But ablation threshold for copper and polymers

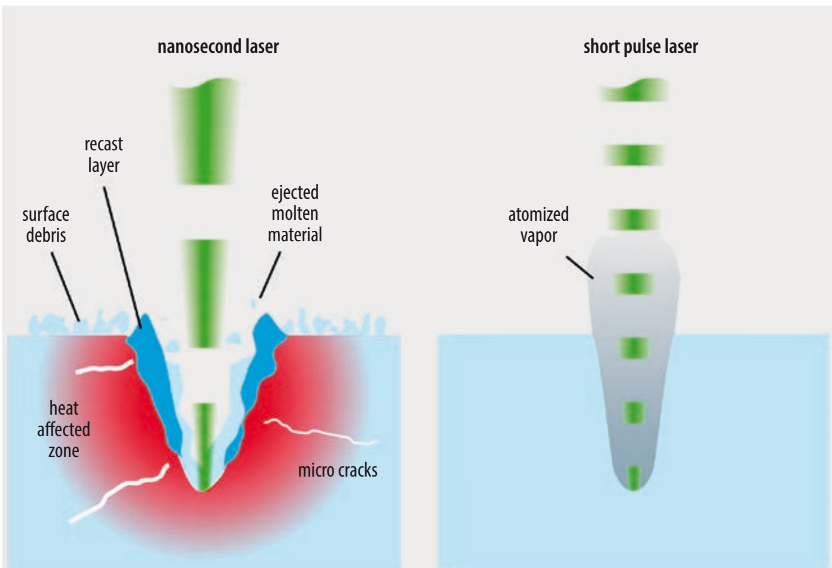

Fig. 1 With short pulse lasers, much of the pulse energy is carried away in the ejected material, resulting in a major reduction in the heat-affected zone in virtually all materials.

are quite different. If a nanosecond laser process were optimized for ablating the copper, it would be very difficult to prevent significant HAZ damage in the polymer. Conversely, the optimum fluence to machine the polymer would leave the copper unaffected. With nanosecond lasers, the antennae would have to be patterned in two separate processes with two different laser setups, adding to the process cost and requiring that tight registration is maintained throughout.

USP vs. nanosecond lasers

Fortunately, the HAZ problem can be eliminated using USP lasers – namely picosecond lasers – with ultraviolet output. The use of short pulses results in a "colder" process. That is because the pulse duration is shorter than the thermal diffusion time in the target material. In other words, much of the pulse energy is carried away in the ejected material, before it has time to spread and cause a HAZ (**Fig. 1**). USP lasers based on mode-locking generally have much smaller pulse energies than nanosecond Q-switched lasers, making them well-suited to machining thinner substrates as in this application. Moreover, this reduced pulse energy is also offset by the fact that USP lasers are capable of much higher pulse repetition rates, which support processing in fast multiple passes, further minimizing HAZ issues.

The use of shorter wavelengths, i.e., ultraviolet, is also well-known to reduce HAZ effects as the UV pulses' high energy photons can directly break interatomic bonds in most materials, so that some of the material is removed in a photolytic process, rather than a thermal process. The use of a shorter wavelength also supports a larger depth of focus, thereby increasing the process window. The combination of short pulse width and short wavelength make the picosecond UV laser an ideal candidate for micromachining the copper/LCP or copper/mPI laminates in this application.

Until recently, however, USP lasers with ultraviolet output were limited in their average power, which ultimately determines process throughput in micromachining. And in a mass production application like this, process throughput is critical. However, by drawing on many years of technical leadership in numerous types of ultraviolet industrial lasers, engineers at Coherent have solved the problems that limited power scaling in previous USP ultraviolet lasers. For example, avoiding contamination of optical surfaces was identified as a paramount consideration in achieving high reliability and long laser lifetimes. Consequently, the latest lasers use only low- or no-outgassing materials in the sealed laser cavity to avoid contamination as well as active cleaning of the cavity. An example of this power scaling is the HyperRapid NX which is available with up to 30 W of output at a wavelength of 355 nm. This enables scan speeds of several meters per second with about ten passes needed for the latest antenna designs.

These lasers are designed for simple integration into existing cutting/scribing machines already in use by antennae manufacturers, lowering the barrier to adoption by both tool builders and end users.

Real-time pulse control

This new generation of USP lasers includes a novel pulse control feature called Pulse EQ, which further enhances their capabilities in this type of complex shape cutting or scribing application. Specifically, where the beam is rapidly scanned across the substrate (or sometimes vice versa), this inevitably involves finite acceleration and deceleration rates so that the motion in straight lines is faster than the motion around tight curves and corners.

This is potentially problematic since excessive pulse to pulse overlap can lead to thermal accumulation and the production of HAZ in delicate materials like organics, even with the small thermal load created by USP ultra-

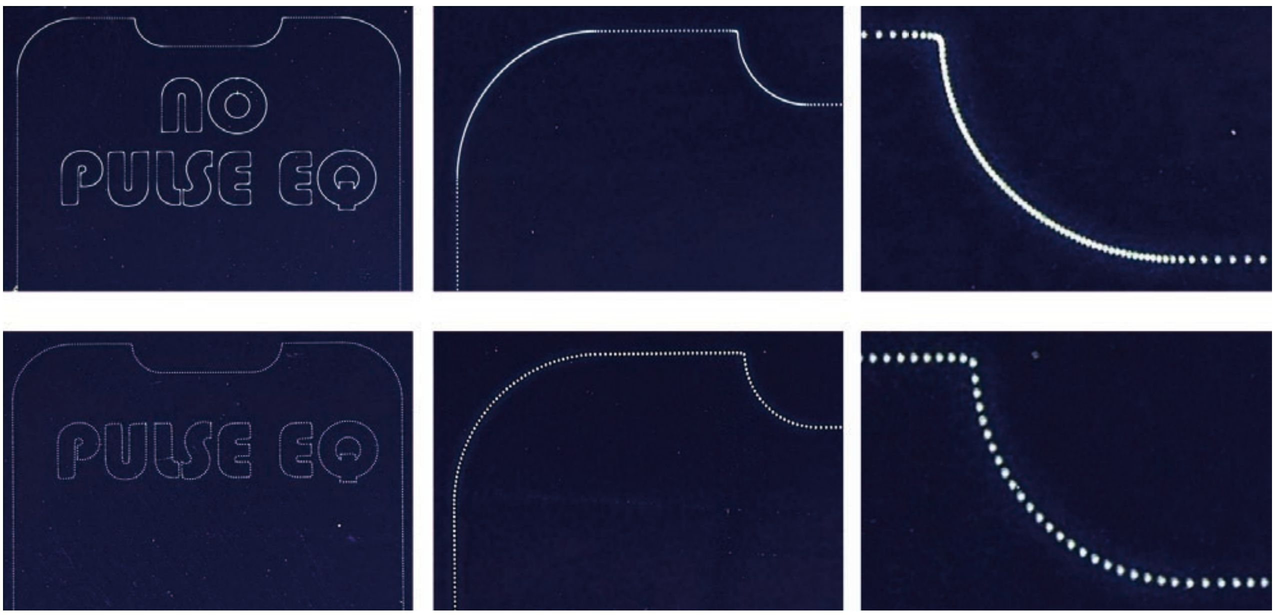

Fig. 2 Demonstration of the benefit of active pulse rate control by real time feedback with a single pass over a sample of thin SiN layer on Si using a HyperRapid NX laser with 355nm wavelength and a scan speed of 12 m/s.

violet lasers. The only way to ensure consistent edge quality throughout is to deliver a constant pulse-to-pulse overlap, optimized for a particular material target. This new pulse control capability enables the repetition rate to be directly controlled in real time directly addressing this potential problem by slaving the laser repetition rate to feedback signals from the scanners. This ensures that the pulse-to-pulse overlap stays at the constant amount that has been determined to be optimum for each application.

Just as important, this comprehensive pulse control functionality includes real-time pulse energy control. With most pulsed lasers, changing the pulse repetition rate usually causes variations in the pulse energy with slower rates delivering more energetic pulses. This could negate some of the benefit of real time repetition rate control. But the pulse control feature also allows the user to select a constant pulse energy option, where the pulse repetition rate can be varied from single shot to 1.6 MHz with no effect on pulse energy.

A single pass with a 30-W ultraviolet USP laser (Coherent HyperRapid NX) processing a Si-on-SiN sample is chosen to highlight the pulse ablation pattern in these microscope images (**Fig. 2**). The upper scan was performed without the pulse control feature engaged and shows increased overlap at curves and corners. This is particularly noticeable with the alphanumeric symbols where the ablation results are very non-uniform and depend on the curvature. The lower scan was performed with the pulse control feature engaged. The lower right panel clearly shows the uniformity of pulse spacing and the end result can be seen in the alphanumeric symbols which are ablated with near perfect uniformity.

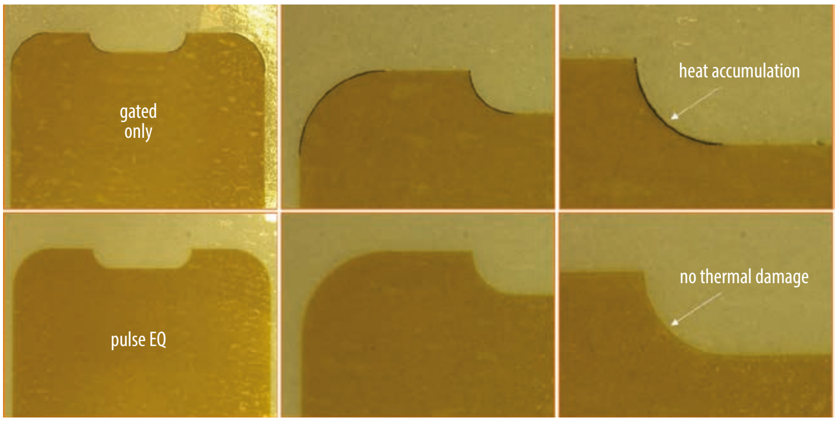

Fig. 3 The effects of pulse control for cutting polyimide on top of a polymer based carrier substrates are clearly visible.

This translates into real results on actual laminate samples similar to those used to create antennae, namely thick polyimide supported on a polymer-based carrier material (**Fig. 3**). Again, the upper images show the results of cutting performed without pulse control. The heat accumulation is clearly evident in the form of charring which is present on the curved edges but not the straight-line cuts. The lower images show the same shaped cuts performed under identical conditions but this time with full pulse control invoked. The edge quality is uniform throughout and exhibits no thermal damage.

Summary

Proponents of 5G connectivity predict a revolutionary impact and benefit on virtually every aspect of our lives. The quantum leap in speed and bandwidth requires new components and sometimes even new ways of fabricating these components. This example shows how next generation industrial lasers are now ready to produce next generation antennae for 5G.

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