PulseForge Lift-Off: A Flashlamp Lift-Off Process

- **What is PulseForge® Lift-Off (PFLO)? How is it used in industry?**

  PulseForge Lift-Off (PFLO) is a flashlamp based lift-off process developed by NovaCentrix to address the industrial need to rapidly and economically release polymeric films from rigid glass carriers. Developed as a laser lift-off (LLO) alternative, some of the advantages of PFLO include: (1) Enabling higher throughput by large-area illumination of the substrates as opposed to highly localized illumination in LLO process. (2) Light absorber on glass carrier increases process reliability and yield by ensuring no direct illumination of the polymeric film and the device stack. (3) Resiliency to pinholes and particle defects on the polymeric film coating as the film does not see any illumination.

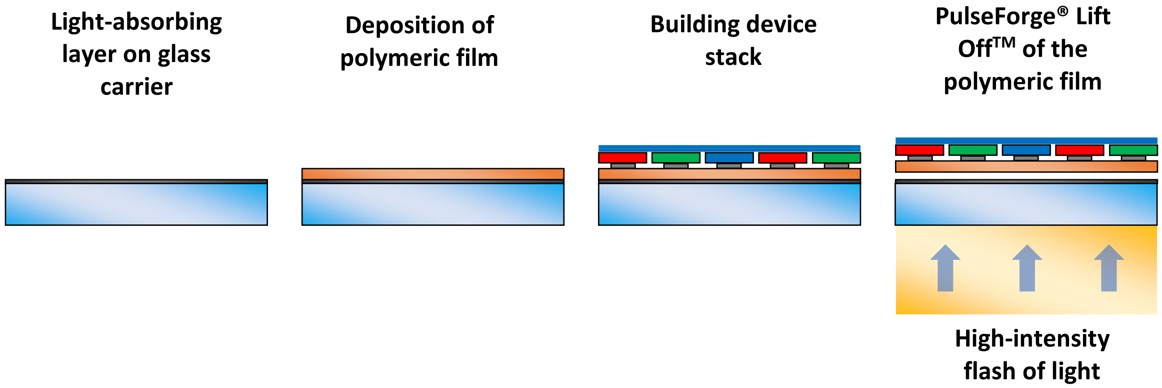
  Some industries that use PFLO are flexible display manufacturing, flexible sensors and batteries manufacturing, thin silicon wafer debonding in multi-layered 3D chip packages, and in other light-weight electronics packaging applications.

- **How does PFLO differ from LLO?**

  Instead of using an excimer laser beam, the PFLO process uses high-intensity light from a flashlamp to release a polymeric film from a glass carrier. The main difference between the excimer LLO and PFLO process is the presence of a light absorber layer on the carrier glass. Most, but not all, polymeric films have strong absorption of UV light, thus enabling the excimer laser beam (operating in UV) to be directly absorbed at the polymer-glass interface in LLO process. In contrast, the light from the PFLO process has a broader wavelength (mid UV to near IR). One of the primary functions of the coated absorber layer is to prevent the transmission of the light through the polymeric substrate. In addition, PFLO also relies on strong absorption of the light by the absorber layer to promote necessary heating for the release of the polymeric film.

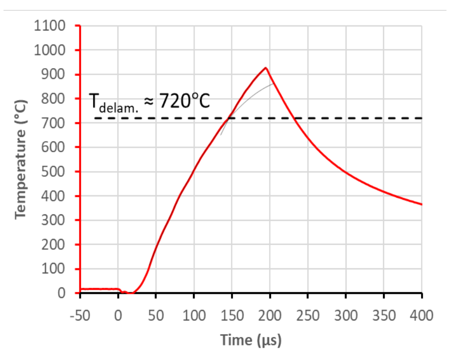
- **What is the mechanism of PFLO?**

  The key mechanism in PFLO is the thermal vaporization of the polymeric film at the polymeric film-absorber layer coated carrier glass interface. Consider the figure below, the carrier glass in the PFLO process is first coated with a thin film (100 nm – 300 nm) of light absorber layer. The polymeric film intended to be released is coated directly on the top of this layer and the device stack is built. The light absorber layer absorbs the high intensity light flashed through the glass to promote heating over a very short period of time (micro-seconds). Heat conduction from the absorber layer to the polymer layer vaporizes the polymer only at the interface, resulting in an adhesion loss of the polymer layer, which is then mechanically released. Further, as result of rapid thermal heating, thermal expansion mismatch between coated polymeric film and the absorber layer coated glass may assist in easy release of the polymeric film.

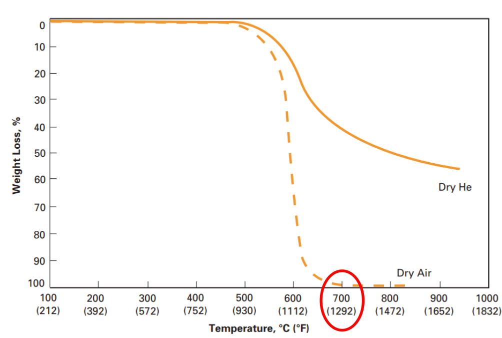


- **What is the estimated local temperature rise on the absorber layer?**

  The peak temperature achieved on the absorber layer during the PFLO process is typically higher than the degradation temperature of the polymeric film. This high temperature is achieved for only a short period of time (100-200 µs). As the time period of lift-off is very short, and there is no thermal contact between the absorber layer and the device stack after the process, the device stack remains relatively cool. To understand this, consider the real-time temperature measurement data (see below) obtained during PFLO of the standard polyimide (PI) coating as an example. In-situ temperature measurements were made at the absorber/PI interface using a temperature sensor with the same sensing element as the typical absorber layer material. A temperature rise of up to 950°C was recorded over ≈ 150 µs. The temperature is then quickly conducted away from the interface. The peak temperature is above the degradation temperature of the PI (Kapton) as shown below in the TGA data, indicating that the lift-off (delamination) could've occurred at around 720°C. Any residual heat after the lift-off on the absorber layer is conducted to the glass carrier as there is no thermal contact between the absorber layer and the polymer.



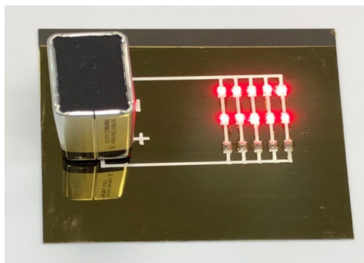
Real-Time temperature measurement



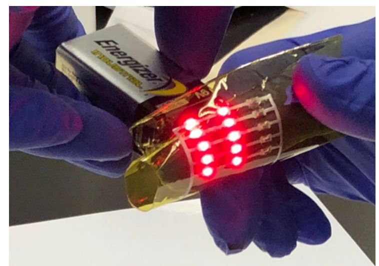
Thermogravimetric analysis of Kapton

- **Why does the top of the device stack remain cooler? What is the temperature achieved on the top of the device stack during PFLO process?**

  PFLO process is a self-limiting process, as soon the polymeric film is released from the absorber layer coated glass substrate, the thermal transport towards the bulk of the film is limited due to poor thermal contact between the released polymer and the substrate. Consequently, any residual heat on the absorber layer is quickly conducted into the glass carrier substrate instead of to the device stack. Thermal conduction from absorber to carrier substrate continues until they equilibrate. All these factors play a vital role in keeping the top of the device stack relatively cooler. For instance, the LED array developed on the coated PI film (shown below) is still functional after the PI film with the device stack was released using PFLO process. Besides this, our recent studies with in-situ temperature measurements have shown that the temperature achieved on the top of the device stack is not greater than 80°C.



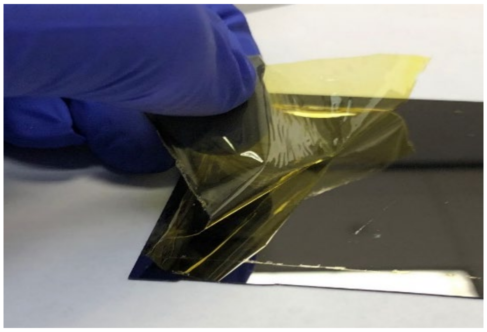
Before PFLO



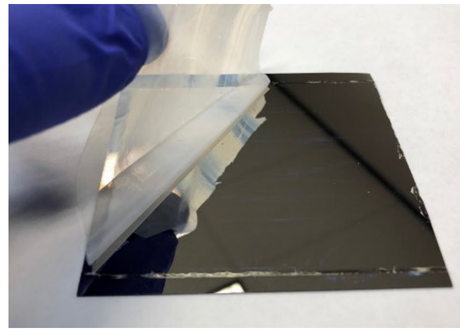
After PFLO

- **Can different types of polymers be released without having to change the structure of the lift-off substrate and the lift-off equipment??**

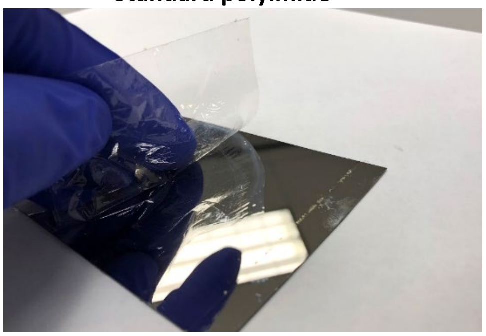
  Presence of the light absorbing layer enables the PFLO process to be polymer agnostic. A wide variety of both thermoset and thermoplastic polymeric films have been tested with PFLO and have been successfully released from the same carrier substrate. Some of the polymeric films that were released using PFLO are shown below. These films were released using the same PulseForge equipment.



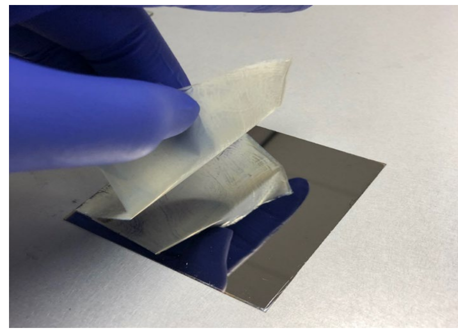
Standard polyimide



Polyurethane



Clear polyimide



Polyester-based proprietary polymer

- **What's the minimum polymer coating thickness that is viewed as viable for PFLO process?**

  We have achieved reliable PFLO for a wide range of polymeric films between 8 and 15 µm thick. Our recent studies have shown that some polymers could be as thin as 3 to 5 µm. It's possible to go thinner if the polymeric film is tailored for this process.

- **Is the PFLO process capable of releasing patterned polymeric films?**

  One of the key characteristics of PFLO is that there is no direct exposure of the light to the polymeric film. Large-area illumination of the light on to the absorber layer facilitates release of the polymeric film via uniform heating across the entire absorber layer. Therefore, as long as the polymeric film is coated on the top of the absorber layer, patterned or unpatterned, the PFLO process is capable of releasing the film. Thus, patterning of the polymeric film becomes trivial in the PFLO process.
  In addition, our recent studies with several collaborators have revealed that, patterned polymeric films filled with a secondary polymer can also be released without the need for altering the process conditions. This indicates that regardless of the absorption cut off wavelength of the polymer, the absorber layer provides the necessary heating to vaporize the interface and release the film.

- **Can light-sensitive polymers be released using PFLO?**

  The absorber layer coating on the glass substrate has near 0% transmission of light. This ensures that the polymer of interest doesn't see any light. So, in principle, light-sensitive polymers can be released using PFLO.

- **What are the typical materials used as the light absorber in PFLO?**

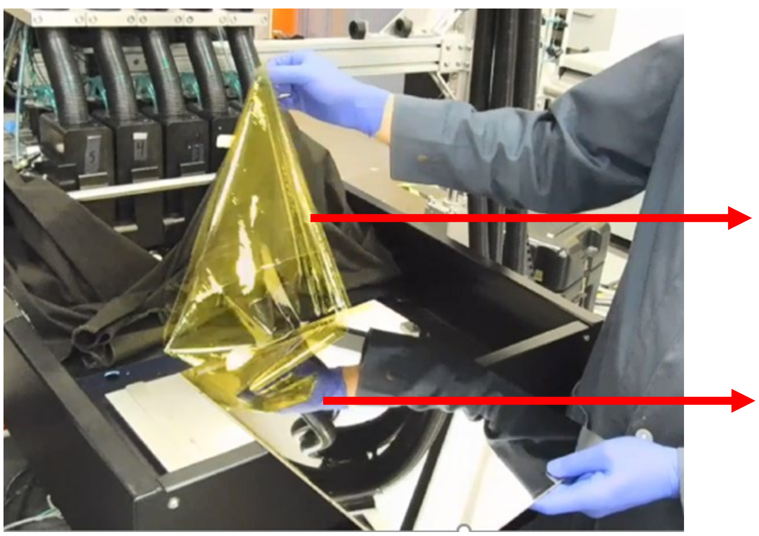
  There are quite a few different metals and coatings we've tried including copper, molybdenum, and tungsten. Amongst them, tungsten is more robust and absorbs a higher fraction of light. As such, it has been used more extensively for this work.

- **How is the absorber layer deposited on the glass? Does any of the absorber layer also lift-off?**

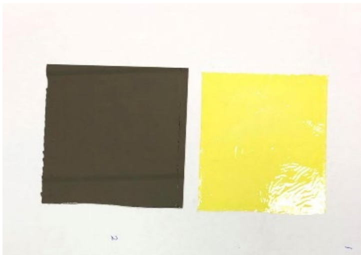
  The absorber layer is sputter-coated on the glass substrate. If there is no polymer coating on top of the absorber layer, it's possible to overheat the metal layer which results in flaking of the absorber layer. However, under typical lift-off conditions, the absorber layer is undamaged and reusable.

- **Are the carrier surfaces damaged or modified during the process? Is there a polymeric residue leftover on the substrate? Do you have any images of the carrier surface after processing? Can these carrier substrates be reused? If yes, what number of repetitions is it expected to achieve?**

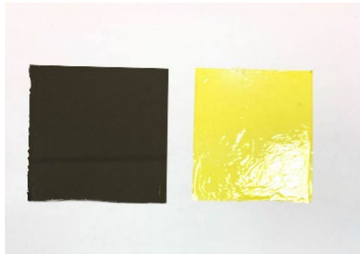
  Under typical lift-off conditions, no damage on the carrier surface is observed after lifting of the polymeric film. Consider the image shown below, the carrier surface looks clean and undamaged after the lifting off 10-12 µm thick PI. PulseForge Lift-off is a clean process leaving no residue of the polymer behind. There are some polymeric formulations that will decompose more aggressively, leaving a residue on the absorber layer, those formulation are best to be avoided. An image below shows the glass substrate after lift-off below.



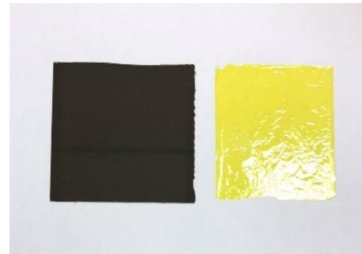
  The carrier substrates are reusable. Reusability of the carrier substrate was investigated by releasing a coated PI film (10-12 µm thick) for up to 10 lift-off iterations with the same processing conditions. Visually, no damage was observed on the coating and the average sheet resistance of the absorber layer remained consistent throughout the experiment indicating no micro crack formation in the coating (see below).
  Pinhole formation on the absorber layer coating, primarily due to dust particles is the most prominent reason of carrier surface degradation. The pinhole defects are addressed by processing in a dust-free environment.



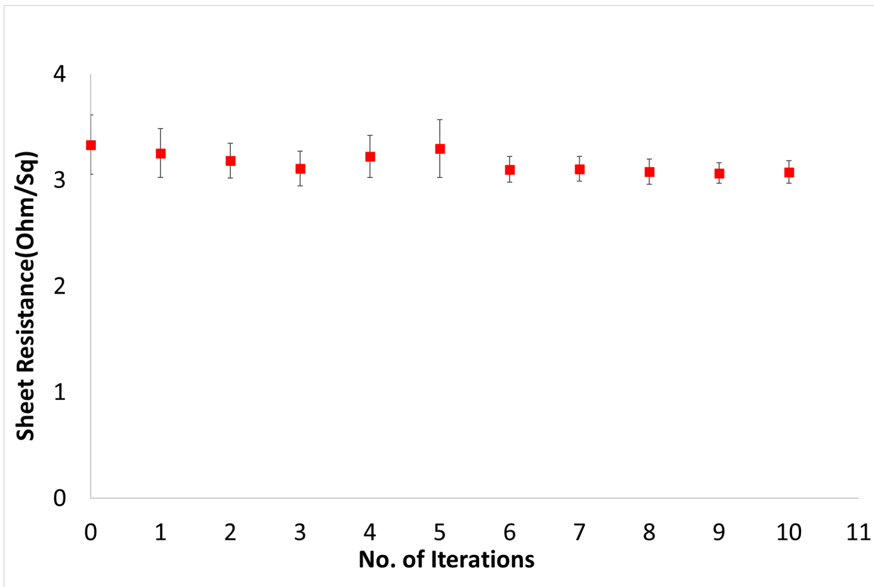
After 1st lift-off



After 5th lift-off



After 10th lift-off



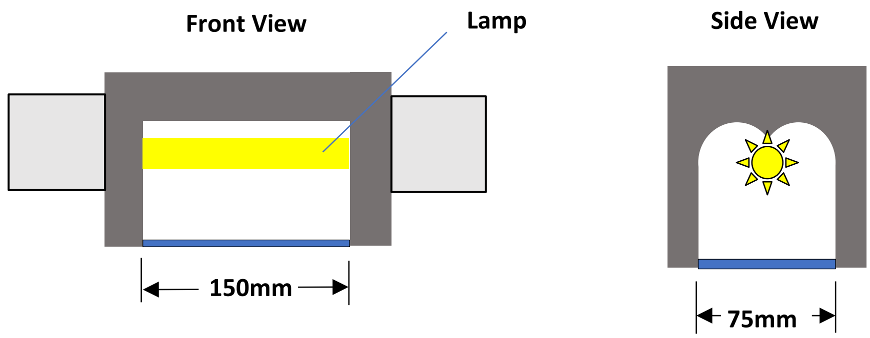
Average sheet resistance of the absorber layer coating

- **Are all PulseForge systems capable of PFLO?**

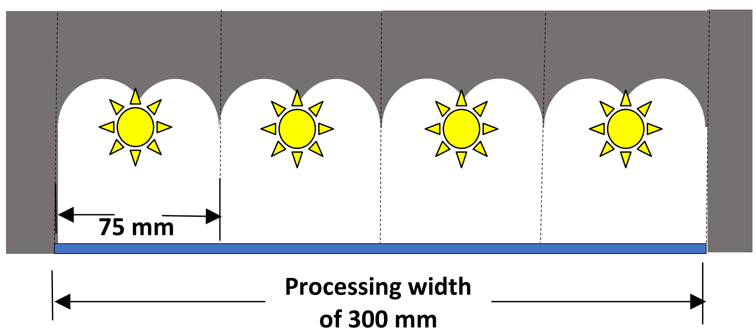
  PFLO is a high radiant intensity process and the particular PulseForge® tool used should be capable of delivering higher than 45 kW/cm^2 of radiant power. Not all the PulseForge® tools are capable of delivering this level of intensity. Therefore, high instantaneous power systems, generally termed as PulseForge® 1300 for R&D level and PulseForge® 3300 for production level applications are deemed suitable for PFLO process.

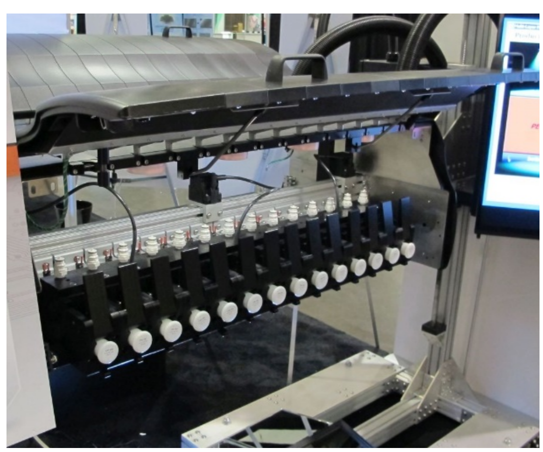
- **What is the maximum irradiation area and repetition rate? Are irradiation areas overlapped for double exposure?**

  The irradiation area on our single lamp PulseForge R&D scale tool is 75 mm x 150 mm when operated in the fixed mode of operation, e.g. with a stationary stage. The same tool has the capability to irradiate across an area of 150 mm x 300 mm when operated in the once through mode of operation, e.g. motorized stage. Once through mode involves the use of the conveyor to run a sample placed on the processing table underneath the flash lamp housing. In this case, larger irradiation area (150 mm x 300) mm can be achieved by stitching the subsequent flashes of light over the large sample as the sample processing table moves underneath the flash lamp housing.



For production level tools, we can concatenate multiple lamps together resulting in a common optical cavity to process a much wider area with an overall 2-D exposure that is even more uniform than a single lamp configuration. Consider the example shown below, in this case, we can concatenate 4 lamps, each of which is 75 mm wide, together to define a processing width of 300 mm. The pulse rate of the flashlamps can be synchronized with the conveyance rate to stitch the pulses together and thereby processing any length of materials that's desired in the production scale.





Photograph of a 14-lamp system displayed at IDTechEX 2016

- **Are there any inline process QC checks?**
  There is a photodiode associated with each lamp that records output of the lamp after each pulse. On production level systems, this photodiode can be monitored to ensure pulse to pulse

consistency. This can alert the technician of a possible issue if it detects any inconsistency in photodiode output.
Additionally, we have a bolometer that can be used to accurately measure the pulse energy (fluence) and if required, the capacitor bank voltage can be digitally adjusted to target the desired energy level, thus providing a closed-loop operation of the equipment in the field.

- **What environmental controls are in effect during operation of the machinery? Inert, clean, or otherwise? Could this device operate in inert (argon) atmospheres / or vacuum?**

  The system can be installed in a variety of conditions and will work as intended. Almost half of our installed systems are in cleanrooms, but this is not necessary. There are several systems installed in humidity-controlled environments and some of them in very humid factories. All the systems are operating as expected. If there is a desire to operate in an inert atmosphere, we recommend installation of flash head outside of the reaction vessel and illumination through a quartz window into the chamber. Systems with such design are being deployed in the semiconductor industry.

- **What is the typical throughput rate for the PFLO process? How fast could a G6 glass panel be processed**
  The speed is dependent on the processing condition. Under typical conditions for the PFLO, the equipment can operate at around 6 m/min. When operated under these conditions, we can process a G6 panel in around 15 – 20 seconds.

- **Can you provide some examples on different sized production level PulseForge equipment for PFLO and how many Gen 6 (1.5x1.8m) substrates can be processed per month on a single system?**

  Different sized production level PulseForge equipment can be developed to meet a target production volume. These are mostly sized on the number of lamps used in the flash head. Following are some of the examples on different sized equipment and an estimated number of Gen 6 (G6) substrates they can process per month:

  Assuming that the production plant runs 24h per day and 7 days week …

Number of lamps	Processing width of illumination area (mm)	# of passes necessary on a G6 panel	Estimated takt time per G6 panel (sec)**	Estimated # of G6 panels processed (30 days)*
4	300	6	80	30000
8	600	3	40	60000
21	1,575	1	15	172000

The smaller equipment (4-lamp) would need to be rastered across the sample with multiple passes to completely lift-off a G6 panel, while the larger equipment (21-lamp) can process the G6 panel in a single pass. Besides enabling faster processing, larger equipment can reduce the number of flash overlap (raster) regions on the substrate due to minimal number of passes.

**Note that these estimated time and numbers do not take substrate handling (load/unload) time into account.

- **Are there any associated consumable costs associated with PFLO process? Are there downtime considerations from preventive maintenance (PM) that would affect productivity?**

  The cost of replacing the flash lamps is the most significant consumable cost to consider. The flash lamps have a specific lifetime and under typical lift-off conditions, these lamps can last an average of 100,000 pulses before they are replaced.

  The lamp replacement dictates the PM schedule for the system. On a typical production level system in the field, a PM stop is scheduled every two weeks to check the health of the lamps. On average, lamps are replaced every four to eight weeks. PM steps to check the health or replace 6 lamps on a system is an estimated at 30 minutes.