PHOTONIC CURING FOR MILLISECOND-DRYING OF THIN FILMS

Stan Farnsworth and Kurt Schroder discuss the benefits of thermal processing

Photonic curing has been shown to be effective in heating inks and functional films to very high temperatures, in excess of 1000 degrees C, on low-temperature substrates such as polymers and paper. The use of this thermal processing method has been explored previously in the literature for sintering, annealing, and reacting materials such as metal-based electrically conductive inks. The authors have applied this technique to drying, and show that pulse conditions as well as pulse architecture play a key role in producing good results.

PHOTONIC CURING IS A HEATING PROCESS

Photonic curing is the high-temperature thermal processing of a thin film using pulsed light from a flash lamp. When this transient processing is done on a low-temperature substrate, such as plastic or paper, it is possible to attain a significantly higher temperature than the substrate can ordinarily withstand under an equilibrium heating source such as an oven. In this way, photonic curing is a non-equilibrium-based thermal processing method as the film is preferentially heated over the substrate.

Equilibrium-based processing methods, such as traditional ovens, heat both the thin film and the substrate to uniform elevated temperatures. The maximum temperature is often limited by the substrate. In contrast, photonic curing makes it possible to thermally process films and depositions on plastic and paper that previously required more expensive, rigid, high temperature substrates such as glass or ceramic. Typical processing times are about one millisecond or less, meaning that a quality photonic curing system can cure a wide range of films and depositions near instantly. Photonic curing, as a non-equilibrium process, also allows oven-capable materials to be processed much faster than with equilibrium-based oven heating.

As an example of photonic curing, consider the material stack in Figure 1.

Figure 2 shows the results of a 300 microsecond exposure of the stack by a photonic curing tool. The resulting thermal profile at various locations in the material stack is calculated with a thermal stack simulation (SimPulse™ by NovaCentrix) as real-time measurement methods are inadequate to capture this information.

The rapid temperature rise is a result of the films absorption of the flash lamp output. It continues to rise for the duration of the 300 microsecond flash lamp pulse. After the pulse's cessation, the surface is cooled due to conduction into the bulk of the substrate which prevents it from being damaged. After about 35 ms, the entire stack is in thermal equilibrium and has risen to only 90 degrees C.

(For extensive details on photonic curing including technical papers, articles, and patents, please refer to www.novacentrix.com .)

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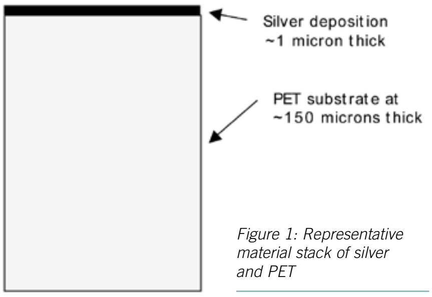

Figure 1: Representative material stack of silver and PET

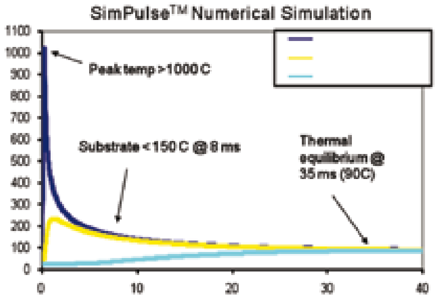

Figure 2: Thermal simulation of the photonic curing process (300 microsec, 1 J/cm2) for a 1 micron thick silver ink-jet film on 150 micron thick PET

Figure 3: Idealised, simplified depiction of a nanoparticle-based deposition of <1 micron thickness undergoing drying

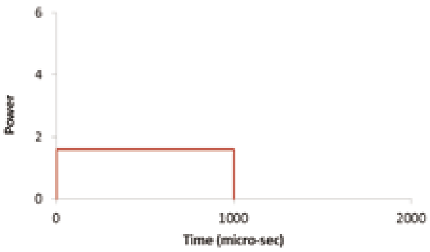

Figure 4: An arbitrary intensity and pulse length of a single light pulse, used for heating a thin film stack such as for drying of inkjet depositions

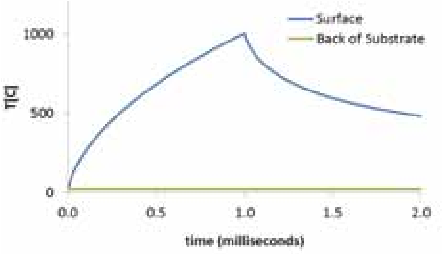

Figure 5: Graph showing the temperature versus time of a deposition and substrate system after irradiation by the single light pulse from Figure 4

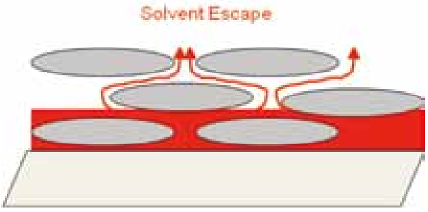

Figure 6: Idealised, simplified depiction of a micron-flake deposition of tens of microns thickness undergoing drying

Figure 7: Commercial screen-print silver ink at >10 microns thickness made up of micron-scale flakes after application of standard-structure photonic curing pulse. Note the occurrence of crater-like surface structures

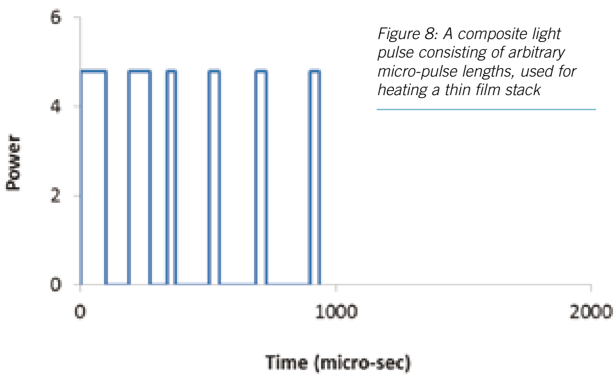

Figure 8: A composite light pulse consisting of arbitrary micro-pulse lengths, used for heating a thin film stack

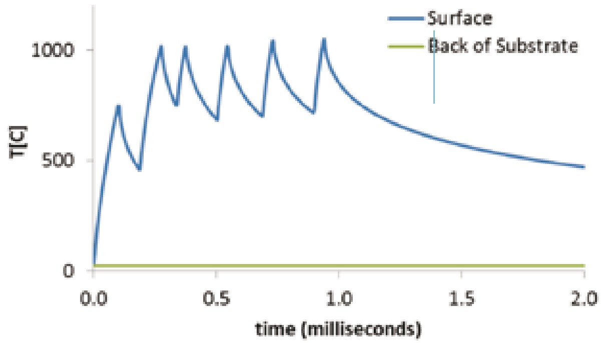

Figure 9: Graph showing the temperature versus time of a deposition and substrate system after irradiation by the composite light pulse from Figure 8

PHOTONIC CURING APPLIED TO DRYING

Thermally driven processes, such as drying (ie: driving off carrier fluids and solvent), are governed by the Arrhenius equation. The time for such a process to complete is related to the processing temperature in an exponential fashion. Hence, a small reduction in the drying temperature will require a significantly longer drying time and more energy, which translates to a more costly drying operation. It is well known that durations of five to 30 minutes or longer are often required for drying some inks, and this drying time results in the need for lengthy festooning ovens for production processing. Consequently, it would be desirable to provide an improved process for thermally processing thin films located on inexpensive substrates without extending the processing time. Photonic curing is such a process.

Consider the idealised, simplified deposition of nanoparticle-based ink, such as by ink-jet, in a drying state, depicted in Figure 3. In such a system, the carrier fluid solvent vapours have a short escape path through the thin (<1 micron thick) deposition. Because of the nanometre-scale size of ink-jet nanoparticles, the tortuosity is also very low (even in cases of agglomeration). Consequently, the system is readily heated and dried using photonic curing. A typical standard pulse profile structure for drying such a system is shown in Figure 4, showing a one millisecond pulse duration and arbitrary units of power. The thermal response for such a pulse is depicted in Figure 5.

In Figure 5, note that the time duration of the pulse of light must be shorter than the thermal equilibration time of the entire stack or the photonic curing effect cannot be realised, and one is again limited to the equilibrium thermal limit of the substrate.

MICRON-SCALE FLAKES

Now consider a deposition composed of micron-scale flakes such as by screen-printing which may be tens of microns thick. The thickness through which the exiting carrier solvent vapours must pass is much greater. Additionally, the micron-scale flakes provide much greater tortuosity than the nanometre particles. This scenario is illustrated in Figure 6.

When we apply the type of standard pulse structure seen in Figure 4 to dry an actual screen-print deposition, the results are less than satisfactory. The observed crater marks in Figure 7 are typical of an initial skinning effect during drying, wherein the topmost layer of the deposition is dried and perhaps even sintered. This closes the travel path for the underlying carrier fluids as they volatilise and erupt through the surface. Consequently, as the deposition becomes thicker, it becomes more and more problematic to remove the solvent with a simple pulse structure from a flash lamp.

We have determined that a shaped pulse structure on the same timescale as a single pulse is better able to process thicker films without damage. Figure 8 depicts such a shaped or segmented profile, composed of multiple light pulses in a specified timing.

When this type of pulse input is entered into the thermal stack simulation, the thermal profile shown in Figure 9 results. Although the peak temperature reached and total pulse length are identical as in Figure 5, the simulation in Figure 9 shows the film is allowed to release solvent or ‘breathe’ during the heating process instead of after, thereby preventing damage. Furthermore, the amount of time spent at elevated temperature is actually longer than in Figure 5, resulting in increased solvent removal for the same input energy. The exact configuration of this profile is heavily dependent on the thermal properties of the target material and the details of the pulse power and segmentation applied. Timing of each individual pulse is controlled to the micro-second by software and is predicted by the thermal stack simulation. To affect such drying requires the use of a photonic curing tool with micro-second control and maximum configurability of each pulse event.

Importantly, as can be seen in the thermal results, the composite pulse sequence is still at a time scale below the thermal equilibration time for the materials. By judiciously tailoring the pulse conditions, it is possible to construct a pseudo ramp-and-soak processing step. This type of processing is well suited for drying applications and is more effective than having multiple simple low power pulses. The composite pulse, like a simple pulse, can furthermore be synchronised to a high-speed web for uniform cures over an arbitrarily long length.

The result of an optimised composite, segmented pulse profile on an identical screen-printed film is shown in Figure 10. As can be seen, the cured print is defect free.

SUMMARY

The authors have described the photonic curing process and applied that process to the drying of silver-based conductive inks. Thin nanoparticle depositions such as that applied by ink-jet are effectively dried with a simple pulse structure. Thicker depositions such as those applied by screen-print and including micron-scale flakes may require the use of an optimised shaped pulse consisting of multiple smaller pulses. The requirements of a photonic curing tool to effectively develop and deliver an optimised shaped pulse structure are quite rigorous and additionally require the use of thermal simulation to optimise the process. ■

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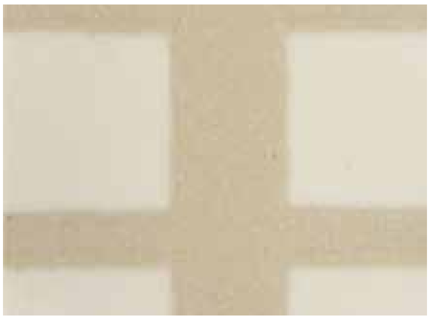

Figure 10: The same print as shown in Figure 7 except it has been dried with an optimised composite pulse structure. Note the avoidance of drying defects

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