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Application of a Pulse Programmable Fiber Laser to a Broad Range of Micro-Processing Applications

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Abstract

Spatial beam shaping has long been utilized to improve laser processes and has often generated spectacular improvements in the end results. Until recently the temporal shape of laser pulses has been limited by the design parameters of the laser cavities and shaping in the temporal domain has remained relatively unexplored. The advent of the MOPA fiber laser has opened the door to creating arbitrary temporal waveforms with shape, energy, and duration being entirely independent from the laser repetition rate and changeable “on the fly.” This new degree of freedom in the laser processing parameter space has not only enabled new and improved laser processes but provided a new tool to study the dynamics of the laser material interaction itself which can greatly speed process development. Furthermore having this flexibility allows a single laser to cover a range of process parameters that heretofore normally required using several separate laser system. In this work we report on the application of temporal pulse shaping to CIGS P2 & P3 processing, CIGS P1 processing (molybdenum on glass), a-Silicon P1 processing (ZnO on glass), c-Silicon via hole drilling for emitter wrap through (EWT) and other processes using the PyroFlex 25 pulse programmable fiber laser. The temporal pulse shaping feature of the laser is demonstrated as a tool to probe the process dynamics and speed up the determination of optimal process parameters. When applicable, results between the pulse shape of a traditional laser and an optimized laser pulse shapes are compared.

Introduction

The temporal shape of the Q-switched laser pulse is something researchers have long taken for granted. The hall mark rising edge and exponentially falling tail are familiar features have at one time or another been tasked with deriving from the fundamental

cavity gain and loss equation (1). When studying the material-laser interaction scientists have long characterized a process in terms of required pulse duration, peak energy and laser repetition rate (PRF) as it applies to the laser pulse. This was a natural way to characterize a laser process since in general the Q-switched pulse was the only type of pulse available and this gives a logical reference for other researchers who may wish to duplicate ones results. However in reality the features of a Q-switch pulse have nothing to do with an optimized laser process, they are simply an artifact of the construction of the laser that generated them.

In recent years lasers have been developed that have opened the door to greater flexibility in the temporal domain. Q-switched lasers have been developed that allow generation of multiple pulses with selectable delays (2), high power fiber lasers with MOPA configuration, seeded by single mode laser diodes or by mode locked seed lasers, have opened the door to even shorter pulse durations and increasing control of the shape of the resulting laser pulse. Until now however, all of these architectures have fallen short of providing a system that can produce a temporal pulse shapes arbitrarily tuned to match the exact requirements of a process. The PyroFlex 25 pulse programmable fiber laser (3) allows the process engineer to create an arbitrarily temporally shaped waveform with 1 ns resolution. Furthermore the shape can be programmed in seconds and changed “on the fly.” As we will see this feature enables extremely fast process development and optimization. This paper presents application of this truly novel laser technology to several materials and illustrates graphically the power of pulse shape programming.

CIGS P2 and P3 Processing

CIGS (CuInGaSe_2) has become an exciting material for the production of thin film PV panels. CIGS now holds the world record of 20.1% (4) efficiency for thin film single junction cell efficiency and has ostensibly taken the lead from the current thin film material of choice, CdTe, in mass produced module efficiency with the current record being 13.0% (5). With any new material comes new challenges and CIGS has been no exception. While laser scribing has long been the process of choice to form a-Silicon and CdTe monolithic interconnects (typically referred to as the P1, P2 and P3 scribe processes (6)), CIGS has until now defied laser processing for the P2 and P3 steps. The reason for this is twofold. First of all CIGS films are typically grown on a Molybdenum coated surface. This first layer of Molybdenum is opaque to laser light. Consequently the P2 and P3 scribes, where the absorber layer and then the top contact layer are cut, must be performed from the film side.

This film side scribing requirement is itself not necessarily an issue until the properties of the CIGS film are considered. A critical feature of the CIGS film to the function of the solar cell is that it has high impedance. When the CIGS material is heated by a laser pulse, its stoichiometry undergoes a transformation and the material becomes highly conductive (7). This conductivity creates a severe problem for scribes that are supposed to be isolating such as the CIGS P3 scribe. For the P2 scribe conductivity is not the critical issue since it is by intent a conductive channel. However, the problem then becomes one of removing the material cleanly so that an appropriate low resistance contact can be made between the top layer of TCO on one cell to the bottom molybdenum layer on the next cell. In fact for the P2 scribe it has been suggested that decomposing of the CIGS to the conductive phase could be a desirable result in forming the “via” (7). Until now, there have not been any laser processes that have been accepted across the CIGS industry as sufficient for P2 and P3. Those processes that have been put forward by the laser industry are based on ps or even fs lasers (8). Even though some success has been reported with those laser sources they have generally been viewed as too expensive and not industrially robust. By contrast the PyroFlex 25, a robust and simple ns fiber laser, has proven a viable solution to the CIGS P2 and P3 scribing process where other fiber and Q-switched lasers have failed (9) (10).

The unique feature of the PyroFlex 25 laser is its ability to produce an arbitrary pulse shape. Perhaps the simplest shape that one can imagine would be a rectangular shape. As shown in Figure 1, a square shape is the simplest match to an idealized laser material interaction event. The light pulse rapidly turns on, rises up to a peak intensity that is just slightly higher than the process threshold, then immediately turns off. For comparison, Figure 1 also shows the overlay of how a more traditional Q-switched pulse would look compared to the process threshold.

Figure 1: Idealized laser-material interaction compared to Q-switched pulse shape.

Inspection of Figure 1 reveals that there is a substantial fraction of energy lost in the leading and trailing edges of the Q-switched pulse, since it is below the process threshold. Furthermore, a certain minimum amount of energy must be input while the pulse is above the process threshold to complete the process successfully. Figure 1 implies that a Q-switched pulse by its very nature, will deliver far more energy as well as a substantially overshoot of the minimum threshold intensity. The former contributes to excess heat deposition and the latter can result in unwanted damage, to non target layers in a thin film stack for example. This would not seem to pose a problem if one considers only the lower limit of the process threshold, however many processes (such as CIGS) have an upper limit, either in fluence, total energy input or both. If either the peak intensity limit or the total energy accumulation limit is reached the process also fails.

To test this supposition we use the unique capabilities of the PyroFlex 25 to create an idealized pulse that matches the hypothetical idealized rectangular process threshold. Total energy and pulse duration were optimized to maximize the total process window and the results are shown in Figure 2, note

the resulting clean fractured edges and the molybdenum with a complete absence of melted CIGS debris.

Figure 2: SEM of PyroFlex 25 CIGS P3 process result utilizing a rectangular temporally shaped pulse.

To test the supposition that the equivalent Q-switched pulse shape could not deliver the same process result, we again used the unique temporal pulse shaping capability of the PyroFlex 25 to create a Q-switched pulse shape. Again the total energy delivered was optimized in an attempt to find a process window in which the CIGS ablation process could work effectively. The result as shown in Figure 3, clearly indicates that compared to the rectangular pulse, there is effectively no process window in which enough energy is delivered to the material with sufficient peak energy to drive the process without exceeding the total energy input limitation. We conclude that the temporal shape of the laser pulse has a clear and profound impact on the process result. In this case, the result is nearly a factor of 10 improvement in depth of focus for the rectangular pulse over the Q-switched pulse.

Figure 3: Comparison of CIGS P2 process using an optimized rectangular pulse shape (left) and an optimized Q-switch pulse shape (right). The vertical axis depicts the process depth of focus.

Taking a closer look at the square pulse result and the Q-switch pulse result we can see that even in the very narrow parameter range where the Q-switch pulse gave interesting results, there is a profound difference in the groove morphology. Figure 4 clearly shows the presence of a larger amount of melted material in the groove and even indicates some melt occurring at the groove edge for the Q-switch pulse.

Figure 4: SEMs of CIGS P2 process results revealing the morphology of rectangular temporal pulse (left) vs. Q-switched shape pulse (right).

CIGS Mini-Module

In partnership with NREL the PyroFlex CIGS processes were applied in the manufacture of mini demonstration solar modules with monolithic series interconnects (9), (10). Two fully laser scribed modules were prepared as well as two modules with mechanical P2 and P3 scribes. The mechanically scribed modules and the laser scribed modules were found to have nearly identical performance with the laser scribed modules yielding slightly better performance on an average.

NREL Mini-Module Efficiency
Solar Flux $\sim 790\text{W/m}^2$

Figure 5: All laser scribed mini-module with 10 cells (Top Left). High magnification optical image showing laser P1, P2 and P3 scribes (Top Right). Comparative efficiency curves for all laser scribed and mechanically scribed modules (Bottom).

CIGS P1 – Moly on Glass

We have already discussed CIGS P2 and P3, but there was also an interesting discovery during the P1 scribing step. This particular Moly on Glass is applied in two layers with different stress in each layer. It was found that a process could be developed that quickly and cleanly removed the first Moly layer in a brittle fracture manner however the second layer would ablate with terrible quality.

Figure 6: Wyko interferometric images of ablation in dual layer molybdenum. Left: Clean ablation of the top moly layer only by a single laser pulse. Right: Clean ablation of top moly layer with "eruption" of bottom moly layer.

Figure 6 shows that the moly in the second layer has clearly melted and shows classic solid to liquid phase transformation with high ridge of re-solidified melt at the edge of the spot (right) where as the first layer has broken away cleanly with sharp edges (left). After much work we theorized that heat transfer from the ablated top layer to the bottom layer causes heating of the bottom layer resulting ultimately in melting or substantial softening that spoils the brittle fracture process. To test this hypothesis we ran the following experiment graphically illustrated in Figure 7:

1. Single Pulse is created and optimized
2. The single pulse is split into two.
3. Each half pulse ran with a variable delay between pulse and the resulting processed characterized.

Figure 7: Dual layer moly experiment utilizing the PyroFlex 25 pulse programming feature to create a double pulse with arbitrary delay. A long time delay between pulses allows the bottom layer to cool so that the second pulse can introduce high strain and brittle fracture in the bottom layer, without melting.

Referring to Figure 7, when the delay is zero we see the characteristic clean top layer removal and messy bottom layer removal. As the delay increases, the condition of the bottom layer progressively changes, until at about 125 ns ablation stops altogether in the bottom layer. Then at an even longer delay of 275ns ablation begins again but now with the property of brittle fracture and less evidence of phase transformation. We conclude that the time delay between first and second pulse allows the residual heat from the first pulse to diffuse away so that the second pulse acts on material that is once again cool

and therefore subject to the same brittle fracture mechanics as the first layer. For comparison we processed with a single pulse (30uJ-left) , a double pass (15uJ-middle) and a double pulse (275 ns delay and 15uJ per pulse-right). The results are shown in Figure 8 and clearly indicate that the double pulse and double pass results have similar morphology. This leads us to conclude that our model is a good indicator of the physical mechanisms behind this ablation.

Figure 8: Comparison of single pulse results to double pulse results. Note that a single pass with a delayed double pulse (right) gives similar results to using a single pulse with a double pass (middle).

ZnO on Glass (a-Silicon P1)

Another interesting application of the PyroFlex 25 is in the ablation of ZnO from glass at 1064nm in what is typical of an a-Silicon P1 process. The main obstacle to overcome with removing the ZnO is microcracking in the glass substrate. Fluence and total energy input high enough to remove cleanly all of the ZnO typically results in micro-cracking of the glass substrate which is unacceptable in a solar panel that should have at least a 20 year useful life time. To tackle this problem we utilized the unique pulse programming characteristics of the PyroFlex platform to investigate the physics of this ablation problem and devise a solution. In the course of our testing it was observed that 100ns pulses and longer, gave a very clean ablation result but with significant prevalence of microcracking as shown in Figure 9. On the other hand short pulse durations removed almost all of the material with no cracking but with significant residue left behind.

Figure 9: Observation of single pulse interaction with ZnO film on glass at different square pulse durations and energies.

This analysis led to an epiphany in our understanding of the ablation mechanism. What we discovered was that the material was 90% removed in the first 5ns and an additional 50 ns to 100% was required to remove the material completely. Furthermore at 50 ns no cracks were observed but for 100 ns cracks appear in the glass substrate. At the same time through research on the materials we discovered that ZnO melts at 1975 Celcius and also decomposes at about 1975 Celsius yielding Oxygen and Zn gas (11). We then hypothesized the following model for this laser material interaction:

1. Material is heated rapidly to its melting point resulting in rapid decomposition and physical ablation up to 5ns.
2. Some material is left at edges where fluence is lower and only partially decomposes leaving whitish residue
3. Additional energy input out to 100ns, keeps remaining ZnO above its decomposition temperature until all ZnO has decomposed into Zinc vapor and oxygen leaving a clean but cracked surface.

With this model we then predicted after 10 ns, when most of the work was done, it was not necessary to keep the fluence so high, but rather only to keep the ZnO near its melting point so that the decomposition could go forward. To test this we again used the unique pulse shaping capabilities of the PyroFlex25 to progressively turn down the “heat” after the first 10 ns while holding the total energy input constant. A matrix of experiments was executed to explore the process parameter space as depicted in Figure 10. The intent is to decompose the remaining ZnO without overheating the glass.

Figure 10: Pictorial diagram of how the pulse shape was changed to explore the process parameter space. Vertical axis peak intensity and horizontal axis pulse duration.

Finally the process was repeated with an equivalent shaped Q-switch pulse for reference. The comparison between the q-switched, square, and shaped pulse are shown in Figure 11.

Figure 11: ZnO on glass removal. Results comparison of three types of laser pulses all constructed with the PyroFlex pulse programming feature at equal energies. Q-switched pulse (left), Square Pulse (middle), shaped pulse (right).

Figure 11 shows clearly that the Q-switched shape pulse results in the worst cracking and worst overall quality, the square pulse shows less cracking and better quality, and the shaped pulse shows no cracking and excellent edge quality.

Laser Fired Contacts (LFC)

In the process of laser fired contacts a laser pulse is fired at a c-silicon substrate in order to “punch a hole” through an insulating passivation layer and simultaneously form a conductive channel through that layer by alloying the metal on one side of the passivation layer with the Silicon on the other side. In this process the damage to the underlying layer should be minimized (12). While full disclosure of the experimentation and process developed is beyond the scope of this paper the unique properties of the

Pyroflex25 laser platform were once again utilized to improve the understanding of the physics at work in the LFC process. Similar to the ZnO experiments we divided a square pulse of 250 ns total duration up into several parts and examined the appearance of the sample after each part of the total pulse had interacted with the material. The resulting “time lapse” pictures of the process Figure 12 yielded two very important clues to the physics of the process.

Figure 12: Pulse duration experiment for laser fired contacts. Peak power is held constant and pulse duration is allowed to increase from 75 to 250 ns.

First of all, when the pulse duration exceeded 125 ns and 325 uJ it appears that ablation began. However upon closer inspection it was realized that the phenomenon was actually dewetting and “rollback” of the metal layer not ablation. It was clear that this phenomenon was detrimental to the process because the metal has to remain in the laser interaction zone to form the conductive via alloy. Seeing that the metal is tending to leave the reaction zone and leave quickly was a significant discovery and suggests that modification of the silicon surface energy so that the metal would tend to wet it would be beneficial. The second key piece of information that was gleaned from this study was the approximate quench rate for the material (how long it takes to cool after the pulse is gone). To study this the pulse was divided into two parts with a variable delay as shown in Figure 13. The delay was varied through the maximum range of the laser and the resulting de-wetting area was plotted in Figure 14. Fitting this data to an exponential curve then gives an indication of how long it takes for the material to cool back down to approximately its baseline temperature, about 450 ns.

Figure 13: Quench rate study for LFC. Delay between pulses increases downward and to the right. As the delay between the two pulses increases, the effect of the second pulse on material diminishes due to thermal diffusion of the energy from the first pulse.

Figure 14: De-wet area as a function of delay between two pulses. Fitting the curve to an exponential function and adjusting the last “infinity” delay point to the curve indicates how long it takes for the material to completely cool between pulses. In this case the cooling time was determined to be about 450 ns.

(Does not add any value).c-Silcon Edge Isolation

In the manufacture of crystalline solar cells it is necessary to cut a thin groove around the edge of the wafer to isolate the front contact from the back contact. The challenge with this process is to remove phosphorous doped silicon without allowing further diffusion of the phosphorous deeper into the wafer. Even though there are many established laser processes for this in the industry, we have utilized the rapid pulse shape programming capabilities of the PyroFlex 25 to characterize the laser parameter space to identify the optimal conditions. For three different stage speeds and fixed average power on the work surface, Figure 15 indicates that the groove depth is approximately a linear function of the pulse duration and Figure 16 shows the corresponding groove morphology. This

relationship holds true until the onset of “self sealing” of the trench. The last point in each series represents the last pulse duration before self sealing onsets. Our interpretation of the self sealing phenomenon is that the groove becomes too deep for the material to be effectively expelled. Typical groove width was about 30 μm .

Silicon Groove Depth at Constant 15Watt Power on Work Piece

Figure 15: Relationship between groove depth and pulse duration. Note: Laser PRF was adjusted to hold the power constant for each pulse duration. The single circle, triangle and square are the results from a chair shaped pulse and the small square green point represents a burst of three pulses. Highest efficiency was achieved using a 250 ns pulse at 350 mm/s.

Figure 16: Morphology of grooves corresponding to Figure 15. The best grooves are circled in green.

Figure 17 shows the resulting isolation from a test sample with the optimized 250 ns waveform. The highest isolation corresponded to the pulse condition that gave the deepest groove which was the 250 ns pulse duration and 400 mm/s. In addition the values of isolation achieved were consistent with the best industrial laser processes in use in the industry (13) and the corresponding process speed of 350 mm/s is also consistent with what is currently used in the industry (14). However the average power required for the process was only 15 watts which is a factor of 2-4 lower than is generally used.

Figure 17: Isolation resistance and groove depth as a function of stage velocity for the optimal pulse duration of 250 ns.

Silicon Via Drilling for Emitter Wrap Through (EWT)

Another process of interest is known as Emitter Wrap Through (EWT) (15). In this process thousands of holes have to be drilled through at wafer in 1 to 2 seconds time. The PyroFlex pulse programmable feature was used to optimize the drilling rates for this process (16). As part of this study the drilling rates at a fixed power for a given pulse duration were characterized as shown in Figure 18. Collection of all of the data in Figure zzz was accomplished with same Pyroflex 25 laser over the course of a few days highlighting the extremely flexible nature of the laser.

Figure 18: Drilling speed for EWT solar cells as a function of pulse duration. Data courtesy of Fraunhofer USA.

Alumina Ceramic Cutting

In another application that highlights the value of pulse shape programming, we studied the grooving of alumina ceramic. Through a survey of pulse duration it was found that for a given fluence, a 10 ns pulse gave the best and most consistent cuts about 20 um wide as shown in Figure 19.

Figure 19: Grooves cut in alumina ceramic utilizing the PyroFlex 25 laser

PyroFlex Pulse programming was then used to create several shaped pulse variants. It was found that through pulse shaping the cutting rate was doubled however for as the groove grew deeper the morphology of the groove was degraded as material began to re-solidify and plug the groove . Figure 20 shows the effect of pulse shape on the cutting rates.

Figure 20: Effect of pulse shape on the cutting rate for alumina ceramic.

Conclusions

The PyroFlex 25 pulse programmable fiber laser has proven to be a flexible tool for studying the laser

material interaction and finding the temporal pulse shapes that best match a process threshold profile. In some cases the best temporal pulse shape was found to be simply a square shaped pulse, in other cases the ideal pulse shape was more complicated. In other cases a burst of pulses proved to be ideal. The on demand pulse programming feature allows a unique opportunity to study the laser material interaction in a way not practical with other lasers. Several other materials have been successfully processed with the PyroFlex 25 including P1, P2 and P3 processes for CdTe, TCO on polymer, and various metals. In all cases the pulse programming features have proven to be invaluable in speeding process development time and finding the optimal temporal shape for a process.

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