Capacity Increase of Mask Aligner UV Curing Process with LED Technology

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Abstract — *Diabetes disrupts blood sugar regulation, and Continuous Glucose Monitoring (CGM) systems help manage it by tracking glucose levels in real-time. Improving CGM sensor production is crucial for meeting demand and quality. Challenges include ultraviolet (UV) exposure efficiency and production time. This project aims to enhance sensor fabrication using Light-Emitting Diode (LED) technology, a Definitive Screening Design (DSD), and reducing UV exposure. By doing so, production efficiency and sensor quality can improve, benefiting diabetes management. DSD identifies factors like UV intensity and solution parameters, optimizing them. LED tech is explored for better UV exposure. Analysis shows dose affects sensor quality, and optimal exposure times are found. LED use and UV parameter optimization promise significant improvements in CGM sensor fabrication, enhancing production efficiency and sensor quality for better diabetes management.*

Key Terms — *Light-Emitting Diode, Definitive Screening Design, Mask Aligner Curing*

INTRODUCTION

Diabetes disrupts the body's energy conversion process. Food breaks down into glucose, the body's primary energy source. Insulin, produced by the pancreas, regulates blood glucose levels. With diabetes, either insufficient insulin is made or it's ineffective, causing blood sugar levels to rise, leading to health issues. It has been estimated that 115.9 million adults have prediabetes and 29.3 million have been diagnosed with diabetes on the United States in 2024 [1]. In 2023, it was estimated that 529 million persons of all ages worldwide were living with diabetes [2]. It has been projected that this number will double to 1.31 billion or the year 2050 [2].

Continuous glucose monitoring (CGM) involves a device to seamlessly track blood glucose levels, also known as blood sugar, persistently throughout the day and night, helping people with diabetes to track in real time the blood glucose levels and its trends.

Medtronic (MDT) is a global leader in medical devices and therapies, offering solutions like insulin pumps, pacemakers, and diabetes treatments. MDT Diabetes is dedicated to easing the burden of diabetes through innovative technology and support. With over 40 years of experience, MDT excels in next-gen sensors such as CGM and intelligent dosing systems. Medtronic Juncos in Puerto Rico specializes in manufacturing CGM sensors, disposable components used with monitoring systems for continuous glucose monitoring. These sensors, with daily recalibration, enable closed-loop functionality for up to 7 days, providing continuous monitoring of glucose concentration for patients.

The sensor fabrication process involves crucial steps, including laser, electrochemical deposition, and enzyme-polymer slot coating. Among these, the enzyme-polymer slot coating step is particularly significant. It utilizes the NXQ800 Mask Aligner with a mercury light bulb to cure the solution by exposing it to an ultraviolet (UV) light source. This process typically takes 40-60 seconds per plate, with a total cycle time of 17 minutes. To meet increasing demand, additional equipment and workstations were replicated. However, there's potential to reduce UV exposure time. The primary objective of this project is to minimize UV exposure.

LITERATURE REVIEW

Sensor fabrication involves crucial steps like the "Slot Coating Process," a high-precision method for depositing a uniform wet film [3]. In this process, an enzyme-polymer mixture is prepared, coated onto sensor plates, and dried. Adding photo initiators to the formulation is crucial as they absorb light at various wavelengths, initiating crosslinking and curing. Optimal initiator concentration is key to ensure complete and efficient curing without blocking UV light [4].

UV curing processes utilize ultraviolet energy emitted by mercury vapor and UV LED lamp heads, characterized by irradiance, energy density, spectral output, and spectral irradiance. These parameters vary by lamp type, supplier, and design, influenced by integration and maintenance. Once properly matched and integrated, UV curing processes are repeatable with periodic measurement and maintenance.

A mask aligner plays two critical roles: it aligns the coated substrate precisely with the mask and exposes the substrate to light for pattern transfer. Alignment accuracy, facilitated by the mask and substrate holders, is crucial for complex device fabrication [5]. Automation in production can enhance efficiency. Pattern recognition technology detects alignment targets and orients the substrate and mask accurately. Automated handling systems for wafers and masks streamline loading and unloading. Currently, the aligner uses a mercury short arc ultraviolet lamp with a reflector, but UV LED modules offer an alternative option.

UV Mercury and UV LED technologies differ significantly [6]. UV Mercury Lamps use mercury vapor to emit ultraviolet light, while UV-LED modules utilize semiconductor materials. UV-LEDs are more efficient, lasting longer and emitting less carbon. They offer instant on/off capability and contain no toxic mercury.

METHODOLOGY

The process development for the Mask Aligner UV curing process using LED technology consisted of a robust analysis to identify optimal process conditions and confirm that these are capable of meeting process output requirements.

Definite Screening Design (DSD)

Definitive screening designs (DSD) require few runs, utilize three levels of continuous factors, and estimate main effects, interactions, and quadratic terms. They help identify factors with significant effects on a response, allowing the study of multiple factors in a small experiment. DSDs offer advantages over standard designs by avoiding confounding and identifying nonlinear effects. Two dummy factors were added to meet the minimum requirement for analysis. The four control factors shown in Table 1 were included in the DSD.

Table 1
DSD Control Factors and Levels

Control Factors	Low Level	High Level
UV Exposure Intensity Percentage (%)	30	70
UV Exposure Dose (mJ/cm^2)	300	1000
Solution weight to weight ratio	4.75	5.25
Solution Thickness (Categorical)	1	3

In the DSD analysis, two factors were studied: visual inspection and exposure time. Visual inspection is crucial, with sensors undergoing 100% inspection post-mask aligner process. The goal of the DSD was to identify factors significantly impacting visual inspection. Besides enhancing yield by reducing inspection-related scraps, minimizing cycle time is also a priority. Ultimately, the aim is to optimize visual inspection output in the shortest time frame.

Confirmation Run

To ensure validity, reliability, and reproducibility, a confirmation run validates experimental results and optimization findings. Following the response optimizer's results, input parameters were defined. The confirmation run aims to establish a process range for UV intensity. The input parameters used for the confirmation run are shown in Table 2.

Table 2
Confirmation Run Settings

Run	Input	Recipe Setting Value
Low Settings		
1	UV Exposure Intensity Percentage	60 %
	UV Exposure Dose	300 mJ/cm^2 (fixed)
	UV Exposure Time	17 seconds
Nominal Settings		
2	UV Exposure Intensity Percentage	65 %
	UV Exposure Dose	300 mJ/cm^2 (fixed)
	UV Exposure Time	15 seconds
High Settings		
3	UV Exposure Intensity Percentage	70 %
	UV Exposure Dose	300 mJ/cm^2 (fixed)
	UV Exposure Time	14 seconds

RESULTS

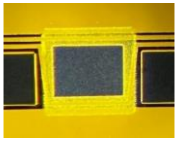
Definite Screening Design (DSD) Results

With an R-squared value of 87.78%, the visual inspection rating model instills greater confidence in the obtained results. The exposure time response model resulted in a very high R-squared of 99.74%. This is to be expected since exposure time is a calculated value that depends on the UV exposure intensity and dose. The UV intensity used in the equation is obtained experimentally using a UV intensity meter depending on the intensity percentage value included in the recipe.

Confirmation Run Results

As part of the confirmation run, three settings were used. For each setting, the input parameters for UV exposure intensity percentage, UV exposure dose, and UV exposure time were specified. Table 3 shows the results for the confirmation run. Showing a 99.67% for low settings, 99.46% for nominal settings and 99.52% for high settings.

Table 3
Confirmation Run Results

Process Output	Run	Results		
		Number of Samples Tested	Number of Samples Passed	Process Yield%
Visual Inspection: Complete and symmetric Solution patterning on electrode 	1	610	608	99.67%
	2	557	554	99.46%
	3	620	617	99.52%

CONCLUSION

After comparing UV curing technologies, significant differences emerge in process inputs and subsequent improvements. Table 4 shows the distinct parameters between Mercury UV Curing and LED UV Curing, showcasing variations in UV exposure intensity, exposure dose, and exposure time. Notably, LED UV Curing offers a fixed exposure dose and shorter exposure time, promising operational advantages.

Table 4
Comparison of Input Values between Technologies

Parameter	Process Window Setting/Range Mercury UV Curing	Process Window Setting/Range LED UV Curing
UV Exposure Intensity mW/cm^2	7 - 12.9 mW/cm^2	18 to 21 mW/cm^2
UV Photo Mask P/N	T8769-009 Fixed	T8769-009 Fixed
UV Exposure Dose (mJ/cm^2)	350 – 1350 mJ/cm^2	300 mJ/cm^2 (fixed)
Print Mode	Pressure Contact	Pressure Contact
Selective UV Exposure Time (sec)	UV Exposure Dose / UV Exposure Intensity	UV Exposure Dose / UV Exposure Intensity

The nominal UV exposure dose for other Mercury UV equipment is 450 mJ/cm². This indicates that at normal operating range, UV LED curing technology offers advantages in cycle time. Assuming robot velocities are the same for both technologies, only the UV exposure time per plate will be used to compare cycle times. Additionally, the exposure time will be fixed to the value used during normal operating conditions. UV exposure intensity depends on the measured intensity using the meter; therefore, this value could vary.

Lot cycle time was calculated assuming the exposure of 16 substrates. Time related to the aligning process and pick and place process was not considered. Only exposure of plates was used to calculate approximate cycle time. As seen in Table 5, there is a significant improvement in the exposure time per plate during normal dose settings. Contrary to the UV Hg lamp, the UV LED lamp does not degrade over time. Therefore, the UV intensity should not change drastically so process cycle time should be constant depending on the normal setting for UV LED intensity defined during Process Validation activities. That means that the UV LED technology gives us more control in terms of our process settings and provides a significant improvement in cycle time.

Table 5

Process Cycle Time Window at Normal UV Exposure Dose

Parameter	Hg Curing	LED curing
UV Exposure Intensity mW/cm^2	7 - 12.9 mW/cm^2	18 to 21 mW/cm^2
UV Exposure Dose (mJ/cm^2)	450 mJ/cm^2	300 mJ/cm^2
UV Exposure Time (sec)	35 to 64 seconds	14 to 17 seconds
Process Cycle Time	560 to 1024 seconds	224 to 272 seconds

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