# Effect of Stretchable Circuit Deformation on Its Electrical Performance for Automotive Lighting Application

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ABSTRACT

*The purpose of this paper is to investigate the effect of the stretchable circuit deformation during a thermoforming process on its electrical performance for automotive lighting. The thermoforming process was carried out using a mould that was developed based on commercially available automotive lighting product. The circuit was printed on a 2-D thermoplastic substrate using screen printing technique before transformed into 3-D shape through the thermoforming process followed by LEDs assembly. The quality of the product were characterised before and after the thermoforming process by measuring the resistance and resistivity of the circuit. Voltage drops and luminance each of the LEDs resulted from the deformation of the circuit were compared with the current automotive lighting product. The study shows that the new design with stretchable material has similar performance with previous design in terms of electrical performance. These findings will encourage further development of new design of automotive lighting in the future.*

**Keywords:** *Stretchable circuit, Thermoforming, and Circuit Deformations*

## Introduction

Electronic devices have been developing from time to time due to various factors such as low manufacturing cost, long-time endurance, environmentally sustainable production methods, recycling, lower energy consumption and higher efficiency, and the complex integration of electronics systems. These can be achieved through alternative technique and advance materials. One of the alternative techniques is advanced circuit printing used to prepare conductive patterns directly on flat or even curved surfaces. Printing techniques such as screen printing, gravure printing, and ink jet are normally used to construct electronic circuits [1]–[4]. Polymeric

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silver inks have been introduced as the advance material that can be stretched and conform to shape of substrate.

Many researches have been studying the silver inks printed on stretchable substrate like polydimethylsiloxane (PDMS) to form conductive patterns [5]–[8]. The pattern was characterised in term of resistance changes when subjected to a certain percentage of stretch level. The silver was chosen and normally used as the conductor rather than gold and copper in the ink because gold price is very expensive while the copper is easily oxidised upon air exposure. In addition, silver has the lowest bulk resistivity of all the elements which is 1.6 x $10^{-8}$ Ωm [9], [10]. The conductive inks basically comprise of polymer matrix, conductive fillers, solvents and additives. The conductive fillers play an important role in order to determine the electrical and mechanical properties of the printed pattern which depend on the particle content, size and form [11].

Curing process of the printed pattern requires certain temperature and time to produce a good conductive pattern. During the curing process, particles of conductors are heated at desired temperature to form interconnections which is called sintering process. The sintering depends on a few factors such as organic molecules the particle surfaces, particle size, pressure, atmospheric gas, temperature and sintering duration [12]. Increase in sintering temperature and time had reduced electrical resistance of the printed conductors [3], [13]. Most researchers investigate sintering of silver particles at low temperature in order to widen application of printed silver inks on thermoplastic substrates that has low glass transition temperature, $T_g$ [3].

The purpose of the study is to investigate effects of stretchable circuit deformation during a thermoforming process on its electrical performance using silver ink printed on a flat thermoplastic substrate. The product of new method is compared to an existing automotive lighting design in order to meet standard automotive lighting requirements.

## METHODOLOGY

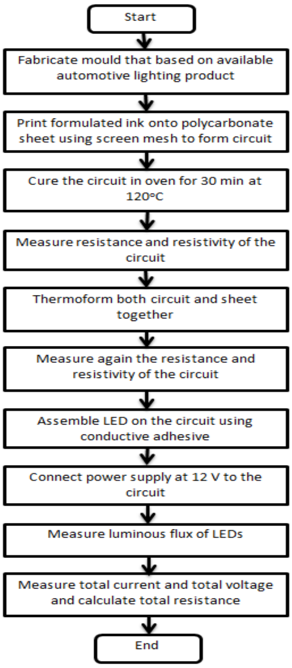
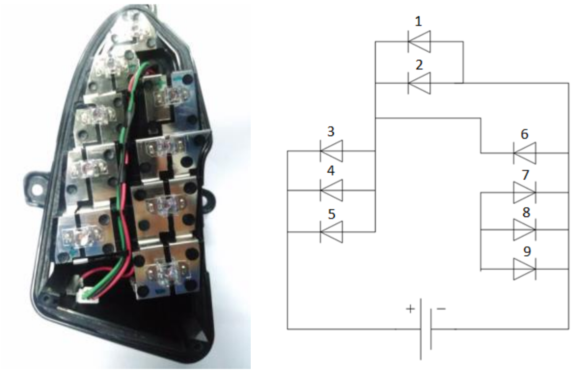



Figure 1: The whole process flow of manufacturing of new design automotive lighting and its performance measurement.

This study used a commercially available product shown in Fig 2.(a) as a benchmarking model which comprised of LEDs assembly as illustrated in Fig 2.(b). The geometry of the model was measured by using the coordinate measuring machine (CMM) and transferred into Solidworks where the 3-D CAD model was developed. Once completed, the drawing file was converted into IGS file, which to be used by a CNC machine to fabricate the mould from an aluminium block. Several holes 0.3 mm diameter were drilled at specified mould geometry in order to remove air between the mould surface and the sheet during the thermoforming process. In addition, it also facilitates the sheet to deform according to the mould geometry.



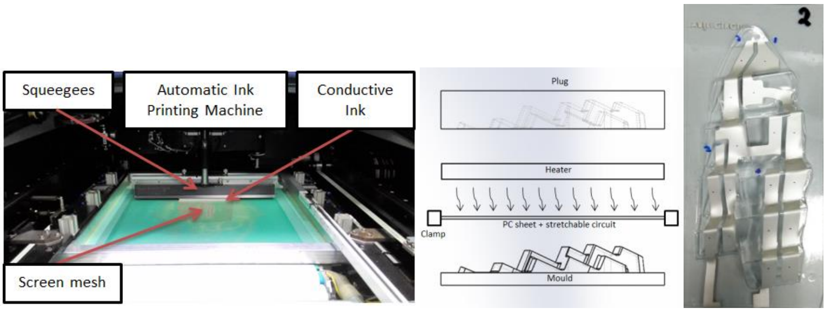

(a) (b)

Figure 2. (a) The original design of automotive lighting (b) Schematic diagram of the circuit with LEDs arrangement.

Polycarbonate (PC) sheet was chosen as a substrate due to its excellent mechanical properties, chemical stability and high electrical insulation [14]. 1 mm thick sheet of PC was cut into 220 mm x 250 mm squares using a shear machine. The dimension of the sheet used was based on the mould and clamping size of the thermoforming machine. The sheet was pre-dried before the thermoforming process to eliminate blisters or bubbles from moisture [15].

The sheet was placed on the machine's conveyor where there was suction pressure under the sheet to keep it in position during printing process. The screen frame was inserted into machine's slot above the sheet position as shown in Fig 3.(a). The ink was printed on the polycarbonate sheet using screen printing technique. A screen with a meshed pattern was used during the printing to get a desired electronic circuit shape. The sheet with the printed circuit was cured in an oven at temperature 120$^{o}$C for 30 minutes to make sure the ink totally solidified with desired properties [16] and then it was cooled freely at ambient temperature.

In the thermoforming process, the setup arrangement of the machine could be illustrated as in Fig 3.(b). The distance between the heating element and the sheet was 60 mm and the distance between the sheet and the mould was 150 mm. The thermoforming process started with the heating process after the sheet had been clamped. The sheet was heated up to 155$^{o}$C for 33 s in order to achieve a softening point [17]. The sheet was deformed according to the geometry of the mould and left to be cooled. The thermoforming product was removed from the mould and trimmed to discard unwanted parts. The finished product of new automotive lighting is as shown in Fig 2.(c).




(a) (b) (c)

Figure 3. (a) The printing process of conductive ink on the thermoplastic sheet (b) The arrangement of material and apparatus during the thermoforming process (c) The new design automotive lighting product.

The resistance and the resistivity of the circuit were measured before and after the thermoforming process. The resistance was measured by connecting multimeter probes at each end of the circuit traces and the resistivity was measured by using four point probes at specified positions where only at flat areas as shown in Fig 4. These readings were recorded before and after the thermoforming process and the percentage differences were identified.

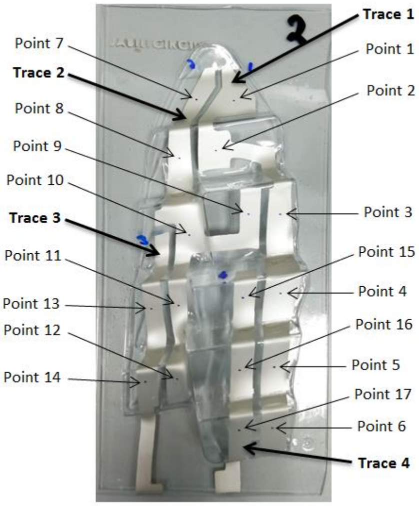



Figure 4: The resistance and resistivity measurements at specified traces and the point locations throughout the circuit.

Nine LEDs were assembled on the product by using conductive adhesive to attach the LEDs' joints to the circuit through dispensing technique. The product was heated again in the oven at 120$^{o}$C for 10 minutes to cure the adhesive for obtaining good electrical conductivity.

The completed product was connected to power supply at 12 V supported by a driver of the current product in between the connection to control the current flow into the circuit. During the power connection, the voltage and the current were measured using the multimeter and illuminations given out by the LEDs were measured by using Integrating Sphere of FEASA spectrometer as depicted in Fig. 5. The Integrating Shpere was placed upon each LED and the readings were recorded with integration time 300 ms. These measurements were compared with that of the current product.

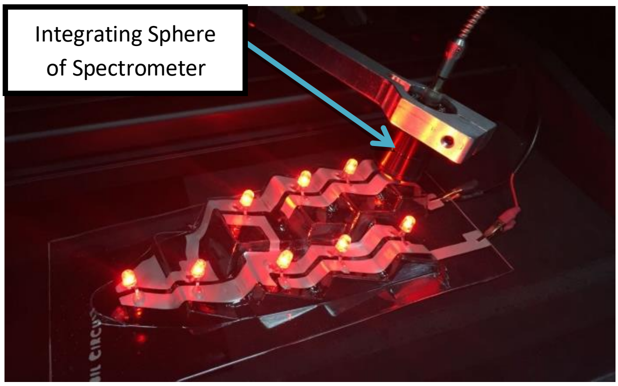



Figure 5: LEDs illumination measurement using FEASA Spectrometer.

## Results and Discussion

Table 1 shows the resistances of the circuit before and after the thermoforming process. The resistances increased for each trace after thermoforming process with maximum percentage up to 380%. During the thermoforming process, each of the traces in the circuits undergoes stretching and deformation according to the mould shape. As consequences, the circuit’s resistance became higher because the silver flakes interconnections became loose which reduced the current paths and more obstacles introduced. However, the circuit was heated initially before deforming during the thermoforming process. This heating process enhanced the conductivity of the circuit since the silver flakes had been through sintering process where they were partially melting and fusing together [18]. Thus, the silver flakes coalesced to form more current paths and made the resistance became lower. This could be proven as illustrated in Fig. 6 where the resistivity of the circuit mostly decreased after the thermoforming process.

The sintering process and the deformation of the stretchable circuit occurred sequentially which could affect the resistance of the circuit after the thermoforming process. The deformation of the circuit gave significant effects at bending areas as illustrated in Table 2 with maximum recorded resistance of 1.6 Ω. Even the measurement at corner areas were small, their resistance readings were higher than at flat areas which are only 0.4-0.5 Ω. The findings indicate that the changes in resistance of the circuit depend on the level of circuit’s deformation and amount of heat applied on the circuit. Generally, the more the circuit being deformed the higher the circuit’s resistance will be and the longer the heating time of the circuit the lower the resistance.

Table 1: Resistance readings before and after thermoforming process

| Trace | Resistance Before Thermoformed, (Ω) | Resistance After Thermoformed, (Ω) | Percentage Difference, (%) |
|---|---|---|---|
| 1 | 1.0 | 4.8 | 380.0 |
| 2 | 0.9 | 3.1 | 244.4 |
| 3 | 1.0 | 4.3 | 330.0 |
| 4 | 0.8 | 2.8 | 250.0 |

Table 2: Resistance readings at each corner area

| Corner No | Resistance (Ω) |
|---|---|
| 1 | 1.0 |
| 2 | 0.9 |
| 3 | 0.7 |
| 4 | 1.6 |
| 5 | 1.0 |
| 6 | 0.7 |
| 7 | 1.3 |
| 8 | 1.3 |
| 9 | 0.9 |
| 10 | 0.8 |
| 11 | 1.4 |
| 12 | 1.0 |
| 13 | 0.6 |
| 14 | 0.6 |

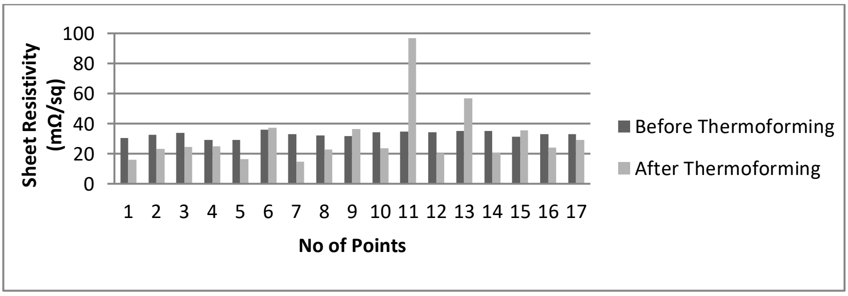



Figure 6: Sheet resistivity readings obtained before and after the thermoforming process

Table 3 shows the measured total voltage supplied to the new design automotive lighting is slightly higher than that of the current design automotive lighting but with the same amount of current flow into the circuit. The driver primarily regulated the current output which required by the LEDs to function. Electrical characteristics of LEDs are less affected by voltage fluctuation because they are current devices that require a constant current for their operation. Therefore, to deliver 0.013 A of current to the circuit, the driver needed to convert the power supply voltage from 12 V to 5.417 V without damaging the circuit system. From the total voltage and current obtained, the total resistance for the whole circuit could be determined and showed that no significant difference between new design and current design. Based on Ohm's law, the changes in resistance will be small when the changes in voltage are small because the resistance is directly proportional to the voltage.

Table 3: Electrical properties measurements of the circuits

| Sample | Measured $V_t$ (V) | Measured $I_t$ (A) | Calculated $R_t$ (Ω) |
|---|---|---|---|
| Current Design | 5.315 | 0.013 | 126.55 |
| New Design | 5.417 | 0.013 | 128.98 |

Figure 7 shows the luminous flux of light that produced by the LEDs of the current design and the new design when connected to the power supply. The luminous flux is an amount of light energy emitted per second in all direction. The luminous flux depends on how much the current received by the LEDs. Increase in the amount of current will increase the luminous flux of the LEDs. Since LEDs 6 and 7 possessed the highest voltage drop among the LEDs as depicted in Fig. 8, they received more current that passed through the LEDs which cause the LEDs 6 and 7 became brighter than other LEDs which had more than 0.4 lm. Generally, most of the LEDs have slightly different in luminous flux which cannot be detected by visual inspection in term of their brightness. The difference gaps between new design and current design in term of luminous flux were considered small and did not affect the performance of the lighting.

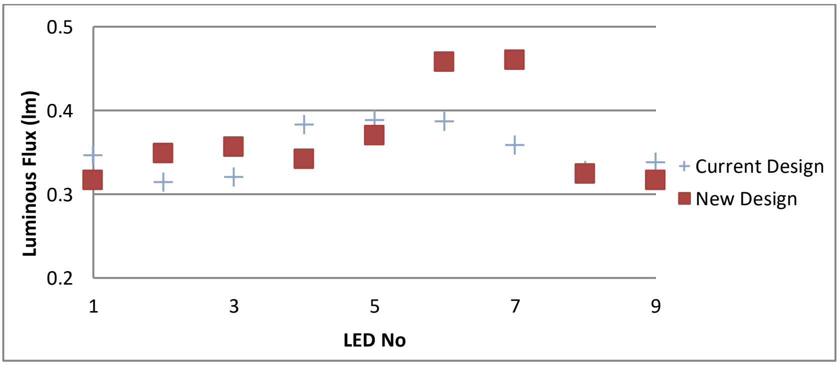



Figure 7: Luminous flux readings for each LED

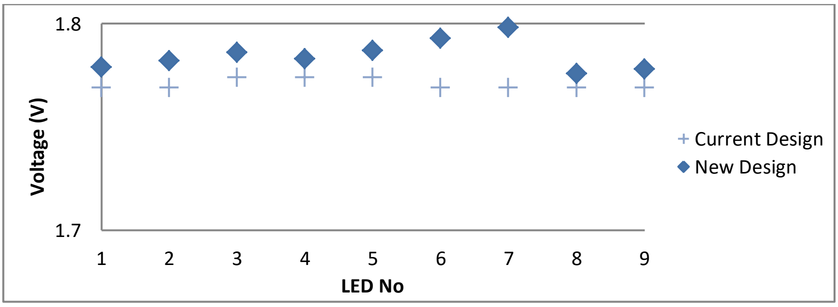



Figure 8: Voltage readings for each LED

## Conclusion

This study has shown the characteristics of the new automotive lighting design in terms of electrical performance. Even the circuit of the new design undergoes deformations due to the thermoforming process which involve stretching and bending at some areas, it still can provide a good conductivity since the calculated total resistance of the new design circuit is slightly higher than current design circuit which are 126.55 Ω and 128.98 Ω respectively when connected to the power supply. In general, the comparison of the electrical performance between the new alternative design and the benchmark design of the automotive lighting shows that there was no significant difference found between these two lighting designs. Thus, the thermoforming process can become the alternative method in manufacturing of automotive lighting using the stretchable circuit.

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