The effect of different shape pattern of metal interconnects on the electrical and mechanical properties of stretchable conductive circuit

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ABSTRACT

Electrically conductive adhesive (ECA) had been extensively studied to replace the Sn/Pb solder mainly found in printed circuit boards (PCBs) because of their harmful action towards human health and environment. In the production of stretchable PCBs, ECA mainly comprises of metallic filler and polymer matrix should perform good electrical and mechanical properties when straining being loaded. Therefore, determining the optimum shape pattern to be printed will contribute toward the desired traits of stretchable PCBs. In this study, commercial silver ink and thermoplastic polyurethane (TPU) as substrate was used. The ink was printed on the substrate by doctor-blade technique with different shape patterns with varies widths (1mm, 2mm and 3mm): (a) straight, (b) zigzag, (c) square and (d) sinusoidal. Then measurement of sheet resistance by four-point measurement was conducted on unloaded and loaded straining of shape pattern. This study exhibited that 3mm width zig zag shape pattern can elongate the highest straining (5% strained) compare than others patterns. In the meanwhile, straight and square shape pattern did not tolerate to any deformation which when straining at a minimum elongation of 0.1mm, the conductivity already lost. In conclusion, further study purpose, more analysis were suggested like analysis on the silver composition, curing temperature variation as well as the distribution of stress in printed shape pattern by 3D Finite Element Analysis (FEA) can be done for the more reliable study.

KEYWORDS: *shape, sheet resistance, elongation, silver, thermoplastic polyurethane*

1.0 INTRODUCTION

Globally, electronic industry had been leading in term of the fastest growth since the last two decades (Poh-Kam, 1995). The rapid growth and advancement of the electronic sector make their availability widespread to the public. However, they reach limitation when it comes to environmental context. For instances, printed circuit boards (PCBs) are known to contained heavy metal reported causing harmful towards human health and environment when improper disposable practice worldwide (Hadi, Xu, Lin, Hui, & Mckay, 2015). Therefore, proper studied on the electrically conductive adhesive (ECA) growing interest among researchers as they had been observed to potentially substitute the Sn/Pb solders in PCBs (Jagt, 1998; Lee, Chou, & Shih, 2005). ECA comprise of conductive filler which serves as an electrical conductor and polymer matrix for mechanical support in them as well as solvent and additives also included as part of ECA

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components. Stretchable polymer, thermoplastic polyurethane (TPU) has low elastic modulus and high stretchability was used in this studied. Conductive filler had been extensively studied for example carbonous material (graphene (Liang et al., 2009), carbon nanotube (CNT) (Sandler, Kirk, Kinloch, Shaffer, & Windle, 2003) and metallic material (copper (Ho et al., 2010; Lin & Chiu, 2008), silver (Lee et al., 2005; Merilampi, Laine-Ma, & Ruuskanen, 2009)). Among all the conductive fillers, silver is the most robust and excellent conductivity with sheet resistance typically 0.01-0.04 Ω/□ at dry thickness 25 µm of ink layer (Merilampi et al., 2009) and also perform good chemical durability (Lee et al., 2005). Fabricating electronic circuits can be made by several printing techniques like screen printing, gravure printing and inkjet printing (Khan, Lorenzelli, & Dahiya, 2015; Yoon et al., 2011), which all these techniques allowed integration on several materials such as paper, plastic and fabrics. However, for this work, printing was done by doctor-blade printing as it is simple, fast and low cost, besides this technique is favoured for small scale experimental as low material consumption compared to screen printing and others (Ghediya & Chaudhuri, 2014). There are many studied had been successfully investigated on the important parameters (particle content, size and form) affecting electrical and mechanical properties of the pattern (Dziedzic, 2007; Hicks, Allington, & Johnson, 1980; Lin & Chiu, 2004). However, main challenges are when it involved the production of stretchable PCBs, which definitely need conductive patterns and substrate to withstand several degrees of stretching manner before lost its conductivity. Therefore, a printed pattern should free from any defects such as porosity and cracks as well as must perform good adhesion between substrate and pattern. The design of shape pattern comparison had been studied by the previous researchers, but mainly they only focusing into the sinusoidal and horseshoe shape pattern (Abu-khalaf, Saraireh, Eisa, & Al-halhouli, 2018; Gonzalez et al., 2008). In their comparative studied, the parameters were varies based on the amplitude, width of lines, cycles and inner radius. Meanwhile, in this study, we are focusing into a comparison of definitely different shape (straight, zigzag, square and sinusoidal) to determine the optimum shape suitable for stretchable electronic application. Thus, the objective of this study is to investigate the effect of different shapes patterns with different width ranging between 1mm to 3mm on the conductivity performance upon stretching.

2.0 EXPERIMENTAL

2.1 Test samples and patterns

The doctor-blade printing was used to print conductive silver ink pattern on the polymeric substrate: thermoplastic polyurethane (TPU). The commercial silver ink used in this study and the curing condition was at 120^{o}C by an oven.

The prepared test patterns are presented in Figure 1 (a) straight, (b) zigzag, (c) square and (d) sinusoidal. All the patterns have length 6 cm and vary line widths: 1mm, 2mm and 3 mm.

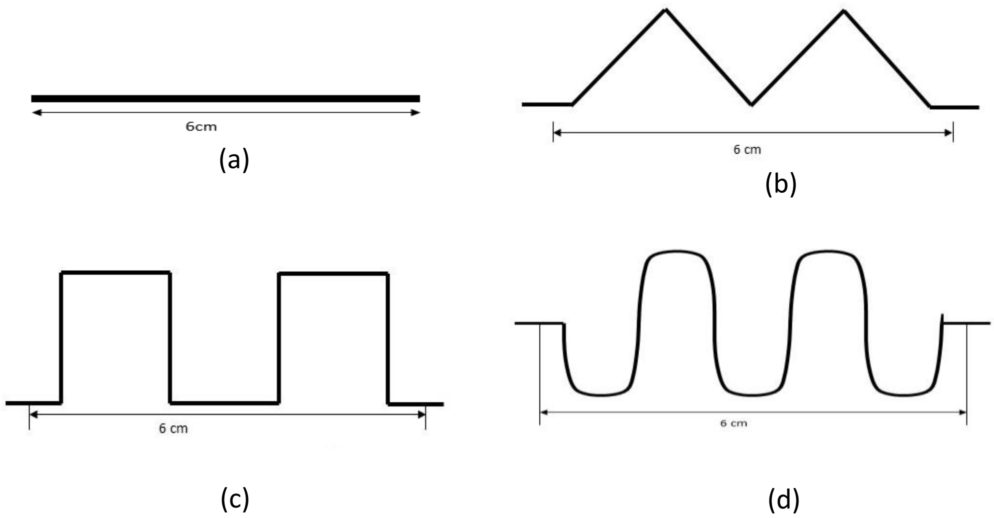

Figure 1. Shape and dimensions of prepared patterns

2.2 Measurements

Sheet resistance was measured in unloaded conditions by using four-point measurement method for 6cm length of the sample. The measurement was conducted by DC power by supplying 10 mA of current along the pattern by connecting alligator clips at each end of the pattern. Then, the measurement of voltage was performed by using accuracy multimeter. The sheet resistance was obtained by integrated measured voltage results into equation (1):

$$Rsquare = cf \times \frac{V}{I} \tag{1}$$

Where cf is correction factor, R_{square} is sheet resistance, V is a voltage between inner probes and I is applied current. The correction factor was assumed to be $\frac{\Pi}{\ln 2} = 4.53$ (Kalavagunta, A., & Weller, 2005). The resistance of the conductor was measure when tensile test performed to investigate the electrical performance during stretchability. Each sample was strained until the conductivity was lost. The straining was conducted by manually stretching, which the stretched sample was fixed on the glass slide by clipped each end by using paper clipper and further measurement on the specific point of each pattern was conducted in the same manner during the unloaded condition.

3.0 RESULTS AND DISCUSSION

The sheet resistance of the different shapes with different widths: 1mm, 2mm and 3mm are presented in Figure 2. The sheet resistance of the samples at unloaded condition was smaller for the sample with a straight line. In this study, the length of each pattern is being fixed to 6cm (refer to Figure 1) for consistent straining of the shape pattern. However, if a total of pattern length is being considered, hence square, sinusoidal and zigzag having much longer length when measured. According to Pouillet's law, the resistance of the material is directly proportional to the length. Thus, square, sinusoidal and zigzag displayed larger resistances than straight shape pattern. Besides, the plots exhibited incline trend of measured sheet resistance when increasing the width in all shape patterns. This due to the more metallic silver particle content in a larger width than smaller, hence showed good conductivity performance. However, in this studies, observation on the ability of each shape pattern to stretch is much interested which further discussed in Figure 3 and 4.

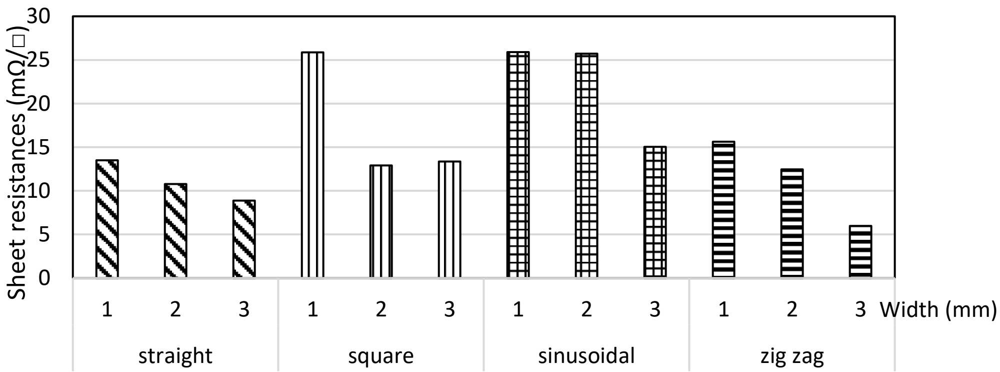

Figure 2. Sheet resistance of different shapes with different widths at the unloaded condition

Figure 3 gives a picture of the relation between the shape of the pattern and the maximum elongation for a different shape. 3mm width of zigzag shape showed the highest elongation (0.3mm/5% strain) before it fails. These plots show a clear trend which is a directly proportional relationship between elongation and reading sheet resistance. This explained that shape pattern cannot withstand any further elasticity hence lead to plastic deformation that expressed in term of fracture presence. The fracture cause restriction of currents from transpassing along the printed circuit. Besides, straight and square shape pattern giving early failure as they not allowed deformation to occur. This is due to the

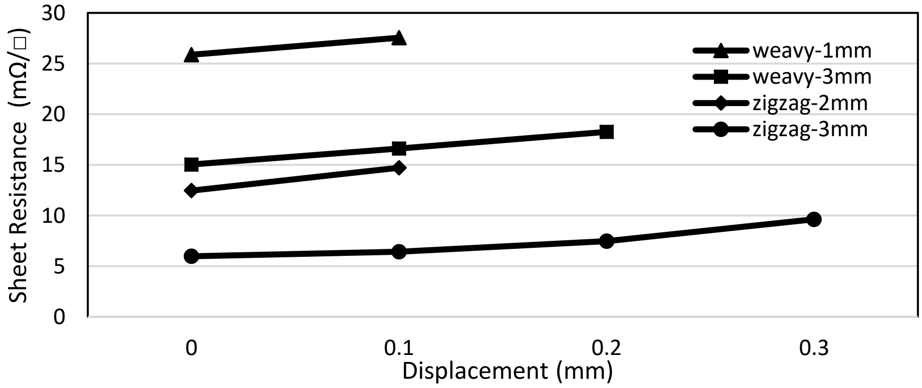

Figure 3. Sheet resistance of different shape when elongate at different displacement

high concentration of stress exist in the region of printed shape pattern that parallels to the applied load. Moreover, it also supported with the properties of metal conductors that typically have limited elastic ranges, therefore they required proper shape design in fabricating the conductive circuit for the stretching to be possible (Gonzalez et al., 2008). Furthermore, larger width of shape pattern (3mm) can allow the production of conductivity up till 0.2mm and 0.3mm elongation for sinusoidal and zigzag shape pattern respectively before failed. We believe this observation result from the small fractures in the printed shape pattern upon stretching do not individually span the width of the circuit, instead of, the fractures are spread out over a large area, hence allowing conductivity around their edge. This small fracture allowed to spread in the long distance manner when shape pattern having larger width but not in the smaller width of shape pattern due to the fractures tends to concentrate or spread in short distance manner because of small area present. Many intensive studied had been done on the sinusoidal shape (Abu-khalaf et al., 2018; Gonzalez et al., 2008). The evaluation was done by Mario and his team on the horseshoe design, present that semicircle design ($\theta=0^{o}$) will have small resistivity as well as smaller elongation (Figure 5). Besides that, they also described the width of metal track was defined as an important parameter in allowing high deformation of the structure (Gonzalez et al., 2008). Thus, this explained the reason why sinusoidal shape pattern in this work (Figure 4) perform low deformation when stretching and elongation possible only in the highest width (3mm) of sinusoidal shape pattern. Furthermore, Figure 4 and 5 present that zigzag shape showed the highest elongation compare than other shapes while maintaining the smallest measurement of sheet resistance. This counter the theory discussed before on the parameter (radius and joining angle) that are needed to consider for designing a shape pattern which zigzag shape did not have. Instead of, zig-zag shape pattern showed high deformation performance due to the slanted shape (45^{o}) which allowed the shape to has less stress in that reading point region compared to sinusoidal shape which accumulated plastic strain located mostly at the meander part of the shape which leads to fracture when load applied which can refer in Figure 6.

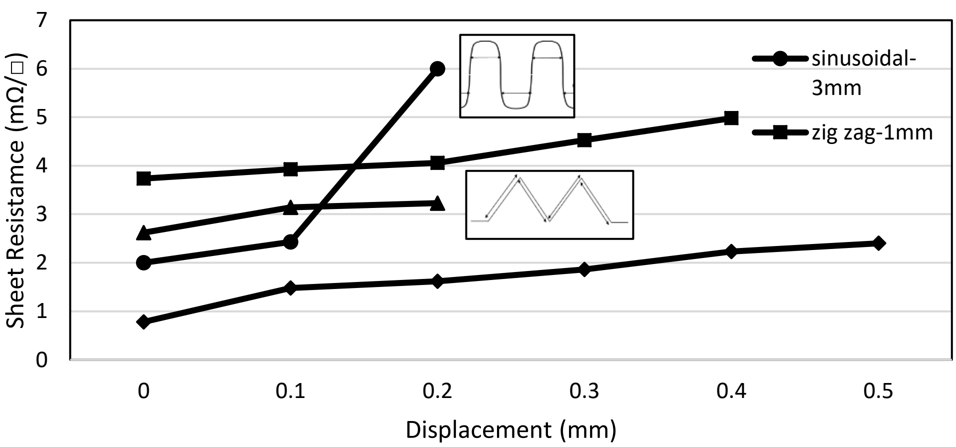

Figure 4. Sheet resistance of different shape at point parallel to the applied stretch

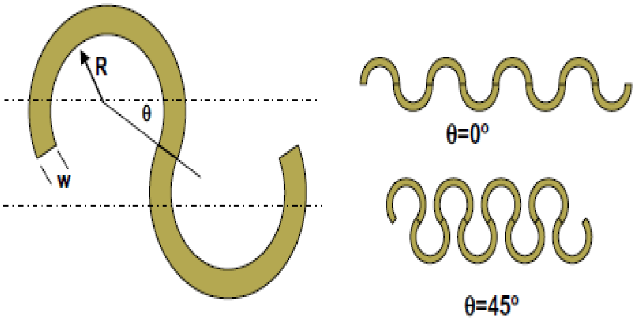

Figure 5. Definition of horseshoe design by its inner radius (R), joining angle (θ) and width of metal track (w) (Gonzalez et al., 2008)

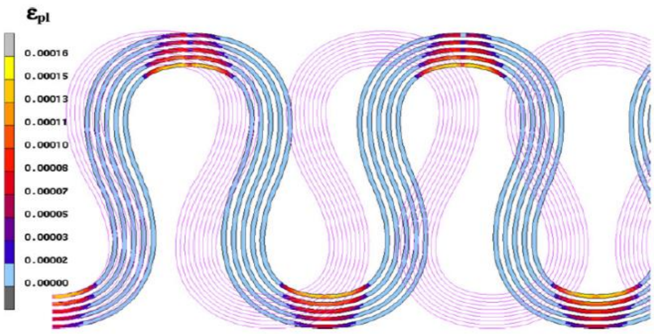

Figure 6. Plastic strain distribution in a multi-track horseshoe conductor design (Gonzalez et al., 2008)

4.0 FURTHER OUTCOMES

Although zigzag pattern showed better performance of stretchability when comparing with different shape pattern in these studies, maximum 5% strained is too little for it to be integrated into a daily application. When comparing with other study, the maximum strain can reach about 80% strained which indicate better mechanical performance and able to maintained low sheet resistivity (Merilampi et al., 2009). Further studied needed in term of ink characterization for silver composition percentage and also curing temperature variation as these greatly affected sheet resistance of the pattern. The silver composition (at a concentration about 10-30 vol%) is important to analyze for determining the percolation threshold for electrical transportation phenomena (‘tunneling') to be performed (Hu, Karube, Yan, Masuda, & Fukunaga, 2008; Sevkat, Li, Liaw, & Delale, 2008). The curing temperature also affected the sheet resistance as it contributes toward different evaporation rates of potentially available solvent in ink composition. Moreover, performing 3D Finite Element Analysis (FEA) will give thermo-mechanical modelling of sample pattern which displayed the distribution of stress or strain in different parts of a structure, thus making studies more reliable.

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