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Investigation of Conductivity, Flexibility, and Thermal Curing Effects in Hybrid Graphene Nanoplatelet–Silver–Carbon Black Inks

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Graphene nanoplatelets, silver, carbon black, cyclic bending

Abstract

This paper presents a study on conductivity, flexibility and thermal curing effects on hybrid Graphene nanoplatelets-silver-carbon black conductive ink, aiming to optimize the inks performance for printed and flexible electronics. The hybrid conductive ink was formulated at room temperature and printed on the copper substrate using a manual stencil printing technique followed by thermal curing at 240 °C, 250 °C and 260 °C for five hours. The printed inks were subjected to cyclic bending tests and the electrical performance of the conductive ink was evaluated in terms of bulk resistance and resistivity. The results showed that samples cured at 260 °C exhibited the lowest initial average bulk resistance 2.1 Ω and resistivity 1.25 × 10^{-4} Ωm which indicate enhanced initial conductivity. However, after extended cyclic bending up to 16000 cycles, a significant increase in resistance to 3.7 Ω and resistivity 2.23 × 10^{-4} Ωm was observed. In contrast, samples cured at 250 °C initially showed higher average bulk resistance 3.4 Ω and resistivity 2.01 x 10^{-4} but experienced a significant decrease after 16,000 bending cycles to 1.8 Ω and 1.07 x 10^{-4} Ωm, suggesting possible conductive network reorganization under mechanical stress. Samples cured at 240 °C demonstrate moderate and more stable conductivity with less variation throughout the cycles, even the initial average bulk resistance 3.4 Ω and resistivity 2.01 x 10^{-4}. In conclusion, these findings highlight the critical role of thermal curing in achieving optimal ink performance, where both electrical conductivity and flexibility must be balanced. An ideal curing temperature around 250 °C offers a practical compromise between low resistance and structural integrity for applications in printed and flexible electronics. Further study is

recommended for samples cured at 250 °C to confirm the reproducibility of the observed resistivity reduction after long-term cyclic effects.

1. Introduction

The rapid development of flexible and printed electronics has increased the search for innovative conductive materials that combine excellent electrical performance with mechanical flexibility, processability, and cost-effectiveness. Conductive inks, usually formulated by dispersing metallic nanoparticles or carbon-based materials in suitable solvents, enable the direct patterning of electronic circuits on various substrates through scalable printing methods. This approach offers a scalable and economical alternative to conventional photolithographic techniques [1].

Recent advancements highlight the potential of carbon-based conductive inks, whose electrical conductivity and electrochemical performance can be enhanced by combining metallic nanoparticles as chemical modifiers [2]. Conductive inks have found broad application across technologies such as printed circuits, wearable electronics, flexible electrodes, electronic textiles, OLEDs, RFID tags, RF/microwave devices, memory storage, photovoltaic cells, and flexible displays [3].

Among carbon-based fillers, graphene-based inks have been comprehensively researched because of the excellent electrical conductivity. However, challenges such as poor dispersion stability, high annealing temperatures, and limited solubility in water restrict the practical application. As a result, hybrid formulations combining graphene nanoplatelets with metallic nanoparticles or conductive polymers are progressively explored to overcome these limitations [4]. Graphene nanoplatelets consist of multiple stacked graphene sheets offer high electrical and thermal conductivity, large surface area, and excellent mechanical strength [5]. The fundamental of graphene nanoplatelets with two-dimensional (2D) structure facilitates efficient electron transport, making them suitable for conductive ink systems in flexible and printed electronics.

With the aim of improving conductivity and filler dispersion, recent studies have focused on hybridizing graphene nanoplatelets with metal nanoparticles such as silver, gold, copper, and carbon-based additives such as carbon black. These combinations not only enhance filler network formation but also increase ink stability. Silver is often selected because of its superior properties in electrical conductivity and strong adhesion properties which are better than other metallic fillers in ink applications [6].

Carbon-based conductive materials including graphite and carbon black are widely used in printed electronics such as batteries, supercapacitors, sensors, PCB resistors, and heaters, as well as in emerging solar energy technologies [7]. A key advantage of carbon is its inert chemical nature, confirming compatibility with a wide range of chemicals and reducing the risk of degradation compared to metal-based inks [8]. Carbon black, particularly, is a cost-effective, zero-dimensional (0D) filler composed of porous agglomerates with high surface activity. Its addition enhances both mechanical reinforcement and conductive network formation through its structural “filling” effect [9]. Particle morphology plays a significant role in packing behavior as smaller carbon black particles promote better inter-particle interaction, increasing conductivity but also contributing to higher viscosity and film thickness [10].

Silver nanoparticles are widely chosen in conductive ink formulations because of the excellent electrical conductivity and ability to sinter at relatively low temperatures. These properties enable the use of silver nanoparticles on temperature-sensitive substrates, including in wearable electronics and biomedical devices [11]. Nevertheless, the high cost and sensibility to oxidation limit the usage in pure form, stimulating the development of hybrid systems that reduce silver content while retaining high performance.

Hybrid inks comprising graphene nanoplatelets, silver nanoparticles, and carbon black have emerged as a capable approach for optimizing ink performance. The combination of silver enhances electrical conductivity and mechanical strength, while carbon black contributes to improved filler dispersion, film uniformity, and structural integrity were critical for reliable application among various printing technologies. Generally, conductive inks consist of a matrix of conductive fillers, binders, solvents, and additives. Materials ranging from metals silver, copper, gold to carbon-based fillers such as graphene, carbon nanotubes, carbon black, conductive polymers, and oxide nanoparticles have been investigated for flexible, stretchable, and wearable electronic applications [12]. graphene nanoplatelets and silver flakes are particularly popular in stretchable conductive inks because of the combined electrical efficiency and mechanical robustness [13].

Despite these advances, there remains a need for systematic studies focused on optimizing filler ratios, processing parameters, and thermal treatment conditions to achieve an ideal balance between conductivity, flexibility, and stability. Understanding the interactions between graphene nanoplatelets, silver, and carbon black is essential for customizing ink formulations to specific functional requirements in emerging flexible electronic systems.

In this study, a hybrid conductive ink comprised of graphene nanoplatelets, silver nanoparticles, and carbon black is developed and described. The effects of varying curing temperatures and cyclic mechanical bending on

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the ink's electrical resistance and mechanical durability are evaluated. This work aims to identify optimized formulations and processing conditions that yield enhanced conductivity, flexibility, and thermal stability, contributing to the development of next-generation conductive inks for flexible and printed electronics.

2. Materials and Method

The Graphene Nanoplatelets with a particle size of 25 µm with a surface area of 150 m^2/g as in Fig. 1(a), silver acetate 99.99 % trace metal basis acid silver salt as in Fig. 1(b), and denatured ethanol 99.9% as in Fig. 1(c) were used in this study. All materials are obtained from Merck KGaA, Darmstadt, Germany. Besides, the carbon black with density of 1.16 g/ml, sheet resistance 55Ω/sq. at 50 µm film thickness and water based as in Fig. 1(d) was from Bare Conductive, United Kingdom. The sonication technique using an ultrasonic bath was implemented for the primary fabrication process. The Graphene Nanoplatelets and carbon black are used as conductive fillers, whereas silver acetate was used as precursors to metallic silver and ethanol was used for dispersion.

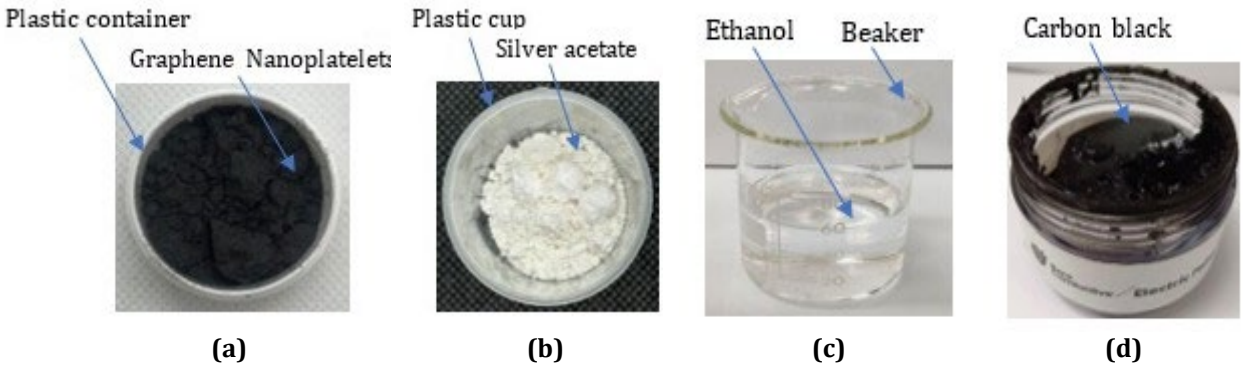

Fig. 1 *(a) Graphene Nanoplatelets 25 µm; (b) Silver acetate; (c) Ethanol 99.9%; (d) Carbon black*

2.1 Preparation for Graphene Nanoplatelets-Silver Hybrid Powder

The graphene nanoplatelets-silver hybrid powder and graphene nanoplatelets-silver-carbon black hybrid conductive ink were prepared according to a previous study [14] to enhance electrical and mechanical properties of conductive ink [15]. The formulation of graphene nanoplatelets-silver hybrid powder was shown in Table 1. Almost, for every 0.005 g of graphene nanoplatelets powder, 5 ml ethanol and 0.042 g silver acetate were used to fabricate the hybrid powder.

Table 1 *Graphene nanoplatelets-silver hybrid powder formulation*

Graphene Nanoplatelets (g)	Ethanol (ml)	Silver Acetate (g)
0.005	5	0.042

The graphene nanoplatelets were measured 0.06 g and dissolved in 60 ml of ethanol in a beaker as in Fig. 2(a). The graphene nanoplatelets mixture was covered with aluminum foil as in Fig. 2(b) and prepared with sonication method using an ultrasonic machine for 70 minutes for a well dispersed of the graphene nanoplatelets particles. Aluminum foil was used to protect the mixture from light to avoid degradation of some components which affect dispersion stability and to prevent contamination from dust or other environmental factors. After sonication for 70 minutes, 0.504 g of silver acetate was added to the mixture, which was then sonicated for an additional one hour for the silver acetate to be well-dispersed and begins to react to form nanoparticles in the mixture.

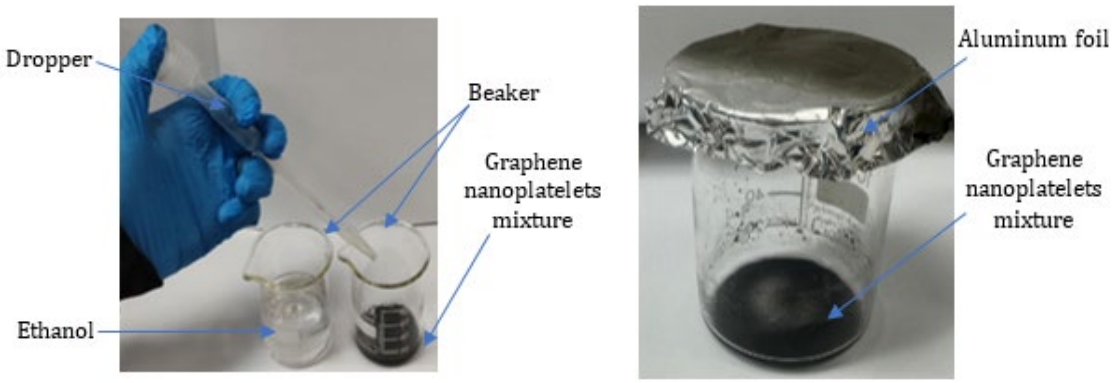

Fig. 2 *(a) Dissolving graphene nanoplatelets in ethanol; (b) Graphene nanoplatelets mixture*

The dispersibility between the graphene nanoplatelets -silver in ethanol was monitored during the sonication process. The sonication process was performed using ultrasonic machine shown in Fig. 3(a). The graphene nanoplatelets-silver mixture was then heated on a hotplate under constant stirring 200 rpm at 70 °C using a magnetic stirrer to achieve a complete blending. This process facilities the dispersion and homogenization of the graphene particles within the solution for a well-mixed and uniform distribution of the graphene. Fig. 3(b) shows the magnetic stirrer used in the experiment. The stirring process was done until the remaining components graphene nanoplatelets-silver particles form a paste-like texture as shown in Fig. 3(c).

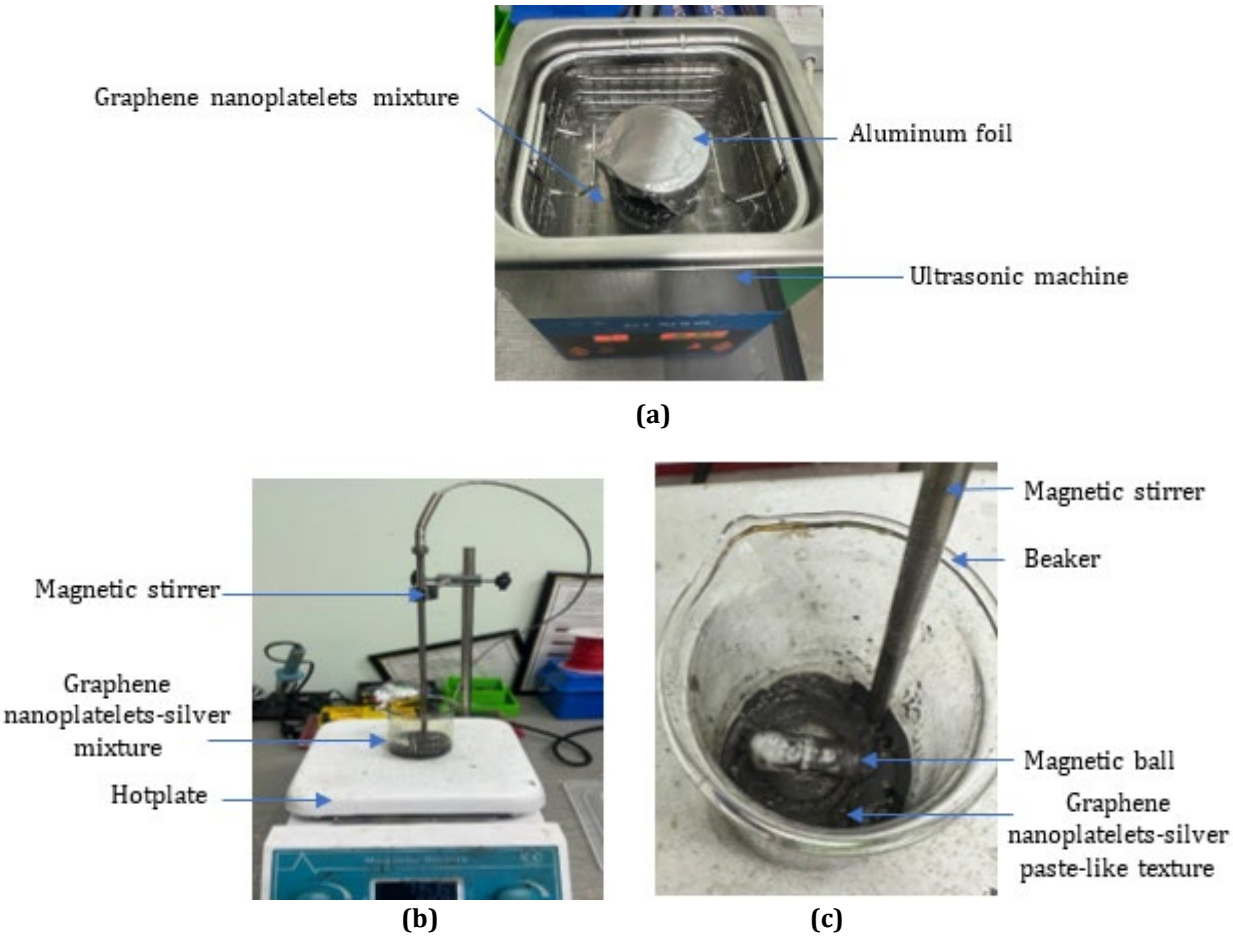

Fig. 3 *(a) Ultrasonic machine; (b) Magnetic stirrers; (c) Graphene nanoplatelets-silver paste-like mixture*

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The graphene nanoplatelets-silver mixture was collected as in Fig. 4 (a) in a ceramic pestle for curing process in an oven. The mixture was cured for one hour at 250 °C using a reflow oven to make sure all traces of solvent were completely removed. The one-hour duration enables the entire volume of the material to be uniformly dried and sintered. Finally, the dried hybrid powder was collected, cooled down, and pounded into a fine powder using a mortar as in Fig. 4(b).

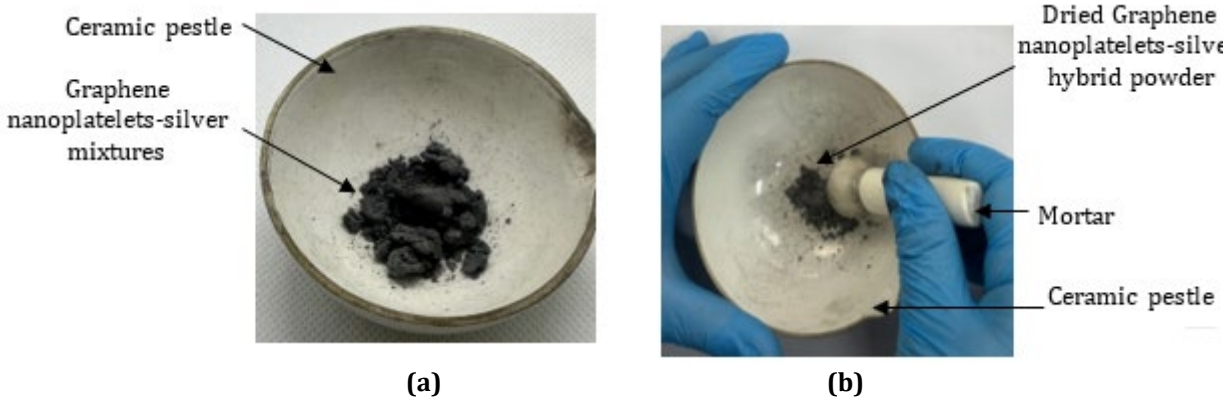

Fig. 4 *(a) Graphene nanoplatelets-silver particles collected; (b) Pounding process of graphene nanoplatelets-silver hybrid powder*

2.2 Preparation of Graphene Nanoplatelets-Silver-Carbon Black Conductive Ink

The graphene nanoplatelets-silver-carbon black conductive ink was prepared according to the formulation in Table 2. Generally, for every 0.005 g of graphene nanoplatelets powder, 0.4292 g of carbon black were added to produce the graphene nanoplatelets-silver-carbon black conductive ink. The weight of graphene nanoplatelets used for this preparation was 0.06 g (0.005 g x 12), therefore 5.1504 g of carbon black conductive paint was used to fabricate the graphene nanoplatelets-silver-carbon black hybrid conductive ink. Carbon black was measured in Thinky mixer cup using a digital analytical balance as shown in Fig. 5(a) and graphene nanoplatelets-silver-carbon black powder was added to carbon black as in Fig. 5(b) for conductive ink fabrication.

Table 2 *Graphene nanoplatelets-silver-carbon black conductive ink formulation*

Graphene Nanoplatelets (g)	Ethanol (ml)	Silver Acetate (g)	Carbon black (g)
0.005	5	0.042	0.4292

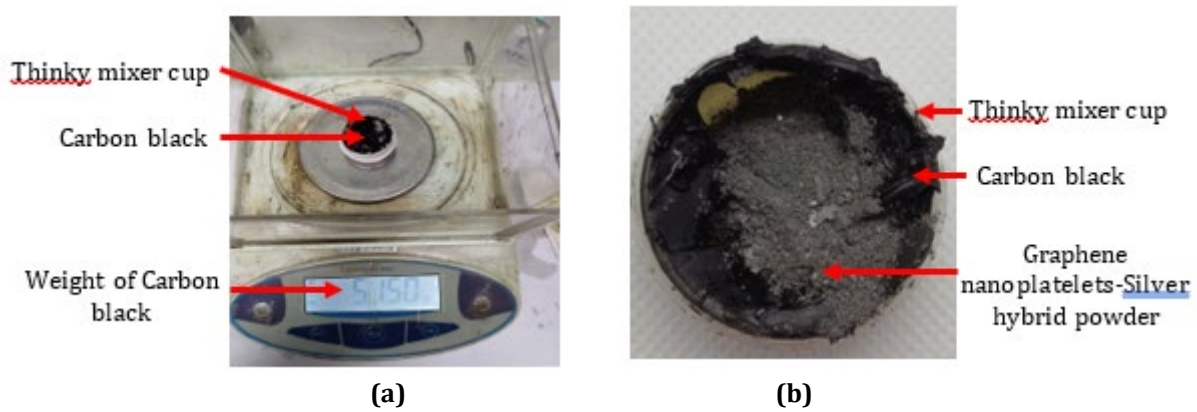

Fig. 5 *(a) Carbon black measuring process; (b) Addition process of Graphene nanoplatelets-silver hybrid powder to carbon black*

The total weight of the mixture with the Thinky mixer cup and holder were measured on a digital scale to set the weight estimator. The Thinky Mixer ARE-310 as shown in Fig. 6 was used to blend the graphene nanoplatelets-silver-carbon black mixture for three minutes at 2000 rpm to produce the conductive ink.

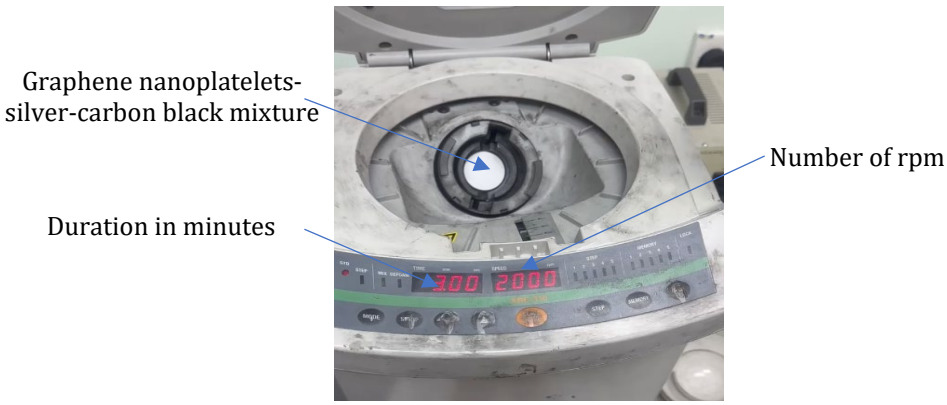

Fig. 6 *Thinky mixer ARE-310 for graphene nanoplatelets-silver-carbon black conductive ink blending process*

2.3 Resistivity in Hybrid Graphene Nanoparticles-Silver-Carbon Black Conductive Ink

The screen-printing method as illustrated in Fig. 7 was used to prepare the conductive ink patterns. The pattern was printed with mesh stencil [16], with a thickness of 60 µm ± 2 µm, sized 0.3 cm x 0.3 cm on a copper substrate [17]. The prepared test patterns and dimensions presented in Fig. 8. The test pattern was selected to be square (area 0.09 cm^2) and was used to measure the electrical properties of the conductive ink. The ink was printed at five designated points and cured in a Reflow oven at a temperature of 240 °C, 250 °C [18] and 260 °C for five hours to study the thermal curing effect on electrical resistivity. The Fig. 9 shows the printed conductive ink for curing process.

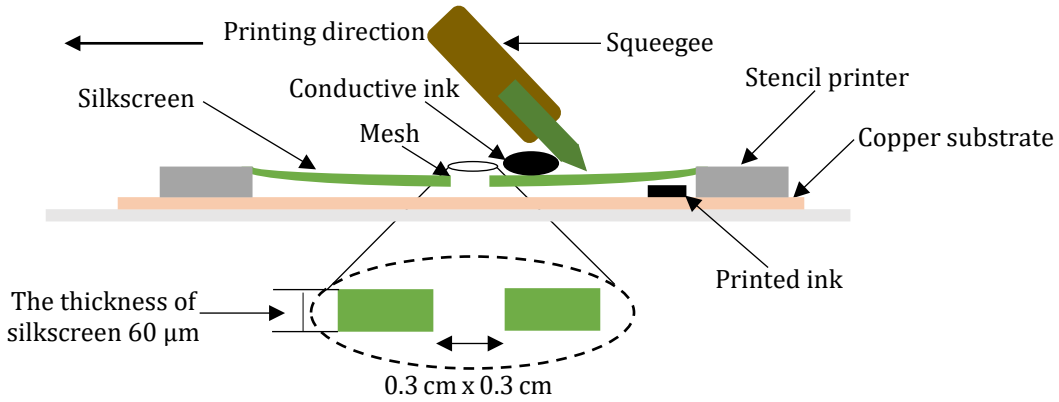

Fig. 7 *Process schematic of screen-printing using silkscreen and squeegee*

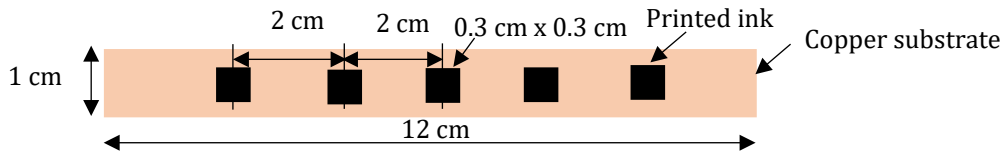

Fig. 8 *Dimensions of conductive ink on 12 cm x 1 cm copper substrate with 2 cm distance from each other*

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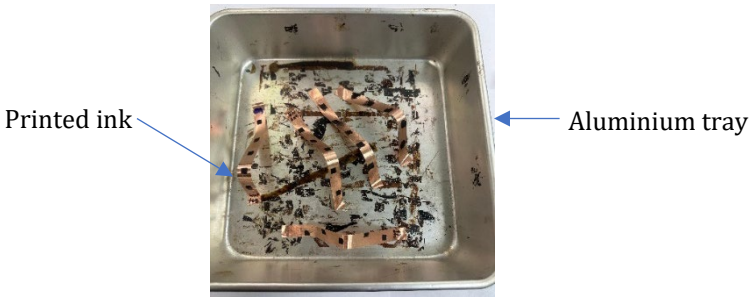


Fig. 9 *Printed conductive ink for curing process*

The cyclic bending test was conducted for 1000, 2000, 4000, 8000, and 16000 cycles using the cyclic bending test equipment [19] as shown in Fig. 10(a) to the printed conductive ink to evaluate the mechanical flexibility and electrical conductivity under repeated deformation. The resistance of each conductive ink was assessed at four selected points (1,1) (2,2) (3,3) (4,4) as described in Fig. 10 (b) using a Two-Point probe [20]. The surface structure of the paste was then examined using a light microscope.

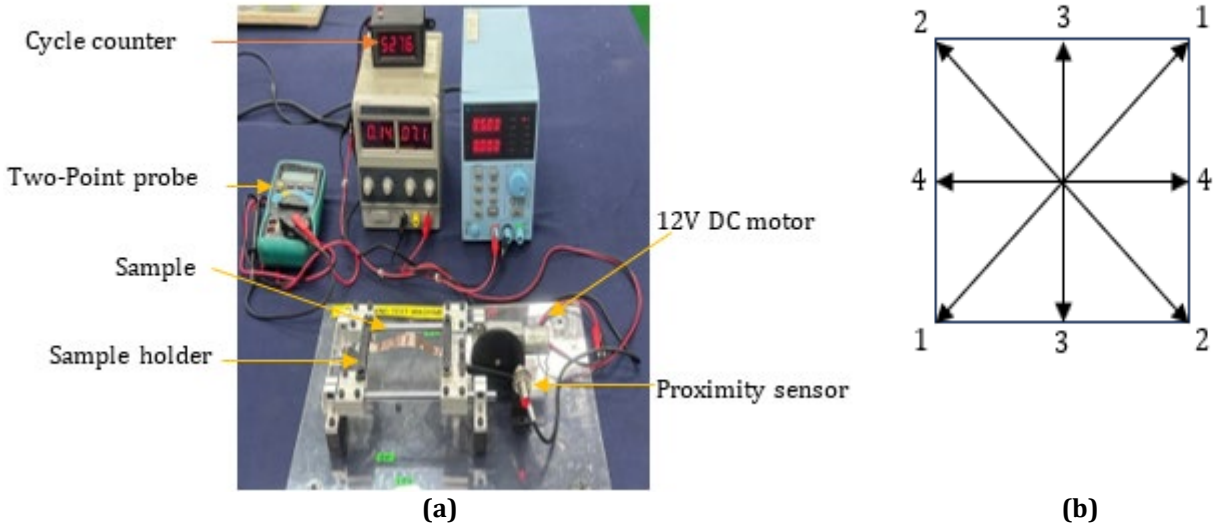


Fig. 10 *(a) Cyclic bending test equipment; (b) Four points measurement of resistance*

3. Results and Discussion

The graphene nanoparticles-silver hybrid powder was prepared by adding 60 ml ethanol into the graphene nanoparticles in a beaker and the mixture was subjected to 70 minutes of sonication in ethanol using ultrasonic machine. After the sonication process, 0.504 g of silver acetate was added into the solution, which was then sonicated again for another one hour. After the sonication process, the graphene nanoparticles-silver mixture was heated on a hotplate under a constant stirring 200 rpm at 70 °C using a magnetic stirrer to dissolve the ethanol then cured in the oven for one hour at 250 °C to make sure the ethanol dissolved completely. Fig. 11 shows the mixture after the curing process. The materials are stuck together but in a fine structure and the pounding process detached the powder.

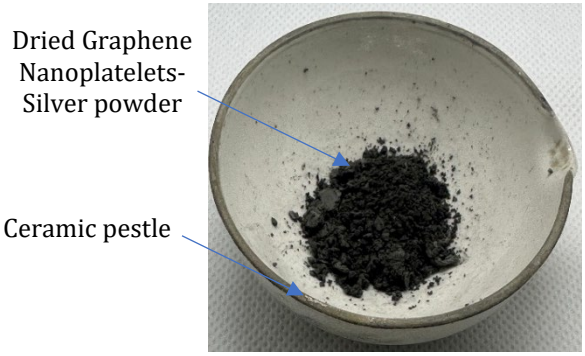
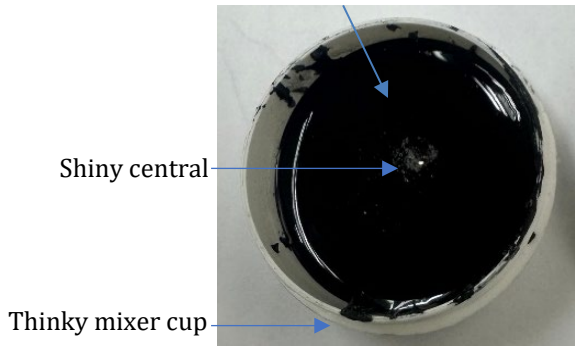


Fig. 11 *Graphene nanoplatelets-silver powder after one hour cured at 250 °C*

The powder was added to 5.150 g of carbon black conductive paint to fabricate the graphene nanoparticles-silver-carbon black conductive ink. Table 3 shows the result of the ink fabricated. The image shows a viscous black conductive ink fabricated using a combination of three materials that stated previously. The deep black color indicates a high concentration of conductive carbon materials, and the shiny central region suggests the presence of metallic particles, probably developing from the partial reduction of silver acetate to metallic silver. The ink appears to have a uniform dispersion with no visible large agglomerates showed effective mixing and dispersion of the fillers. The adhesion of ink to the side walls of the container indicates good viscosity for printed electronics applications.

Table 3 *Result of graphene nanoplatelets-silver-carbon black conductive ink*

Sample	Graphene Nanoplatelets (g)	Ethanol (ml)	Silver Acetate (g)	Carbon Black (g)	Observation
1	0.06	60	0.504	5.150	Graphene nanoplatelets-silver-carbon black conductive ink 

The effect of curing temperature on the morphology and performance of the conductive ink was evaluated using light microscope after thermal treatment at 240 °C, 250 °C, and 260 °C. Table 4 shows the image of surface structure of the conductive ink under a light microscope after curing at 240 °C, 250 °C, 260 °C.

At 240 °C, the ink surface exhibited a rough and cracked texture, showing insufficient curing. This can be attributed to the incomplete thermal decomposition of silver acetate, which limits the formation of conductive metallic silver. Furthermore, remaining solvents may increase viscosity, prevent proper particle dispersion and lead to concentrated agglomeration. At 250 °C, the ink displayed a darker and more uniform surface with a metallic shine, suggested optimal curing. At this temperature, silver acetate possibly decomposed completely, formed well-dispersed metallic silver particles that contributed to improved electrical conductivity. Solvent evaporation was also more efficient, reduced viscosity and enhanced filler interaction and film uniformity. At 260 °C, the cured ink appeared more compact but showed minor surface texture and micro-cracks, probably because of over-curing and thermal stress. Although higher temperatures promote complete silver formation and compression, excessive thermal input may have introduced shrinkage-induced cracking or degradation of binder components. In general, 250 °C provided the best balance between silver formation, structural integrity, and film uniformity.

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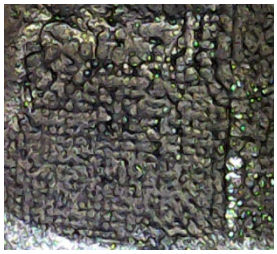
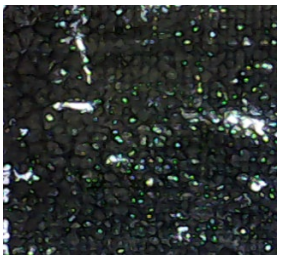
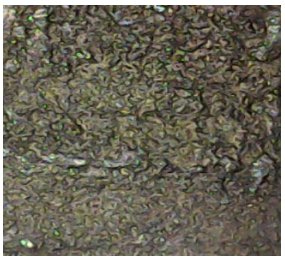
Table 4 *The image of surface structure of graphene nanoplatelets-silver-carbon black conductive ink under a light microscope*

Curing Temperature (°C)	Graphene Nanoplatelets (g)	Ethanol (ml)	Silver Acetate (g)	Carbon Black (g)	Observation
240	0.06	60	0.504	5.150	
250	0.06	60	0.504	5.150	
260	0.06	60	0.504	5.150	

The average bulk resistance of of graphene nanoplatelets-silver-carbon black was evaluated after curing at 240 °C, 250 °C and 260 °C as shown in Table 5. At both temperatures 240 °C and 250 °C the average bulk resistance was 3.4 Ω, indicate moderate electrical conductivity. In this case silver acetate expected began decomposing into metallic silver, but the process may have been incomplete or limited by particle sintering, especially at 240 °C. In addition, higher viscosity at lower temperature can delay uniform filler dispersion and interconnection which leads to isolated conductive region and increase resistance. At 250 °C, even though the surface morphology improved as observed microscopically, the electrical performance remained like that at 240 °C perhaps because of residual porosity. Whereas, curing at 260 °C resulted in lower average bulk resistance 2.1 Ω, reflecting enhanced conductivity. This can be attributed to the complete decomposition of silver acetate and improved sintering of metallic silver particles, which enhances filler-to-filler contact. The higher temperature reduces viscosity further, thus better flow and compaction of conductive fillers, while the improved thermal conductivity of the metallic and graphene components helps distribute heat more uniformly across the film. Although the risk of micro-cracking, the increased particle connectivity and packing density at 260 °C balanced structural weaknesses led to the lowest observed bulk resistance.

Table 5 *Average bulk resistance of of graphene nanoplatelets-silver-carbon black at different curing temperatures*

Graphene nanoplatelets-silver-carbon Black			
Temperature °C	240	250	260
Bulk resistance (Ω)	3.4	3.4	2.1

Table 6 shows the average resistance and resistivity before and after the cyclic bending test cured at 240 °C for five hours. The electrical stability of the of graphene nanoplatelets-silver-carbon black conductive ink was evaluated through repeated cyclic bending tests from 1000 and up to 16,000 cycles. From the observation, the resistance values fluctuated slightly during the cycles, with an initial resistance of 3.4 Ω increasing to a maximum of 4.2 Ω at 4,000 cycles and then the resistance decreased to 3.1 Ω at 16,000 cycles, consistent to the lowest

recorded resistivity of 1.84×10^{-4} Ωm. This trend suggests that the conductive network may have undergone compaction or rearrangement during cyclic bending, led to improved electron pathways over time. Similar behavior has been observed in stretchable carbon-based inks, where initial plastic deformation and alignment of nanomaterials result in consistent electrical performance under cyclic strain. Fig. 12 illustrates the graph of hybrid conductive ink.

Table 6 *The average resistance and resistivity of hybrid of graphene nanoplatelets-silver-carbon black at 240 °C for five hours*

Cycle	Resistance (Ω)	Resistivity (Ωm)
0	3.4	2.01 x 10^{-4}
1000	3.8	2.31 x 10^{-4}
2000	3.6	2.13 x 10^{-4}
4000	4.2	2.52 x 10^{-4}
8000	3.7	2.20 x 10^{-4}
16000	3.1	1.84 x 10-4

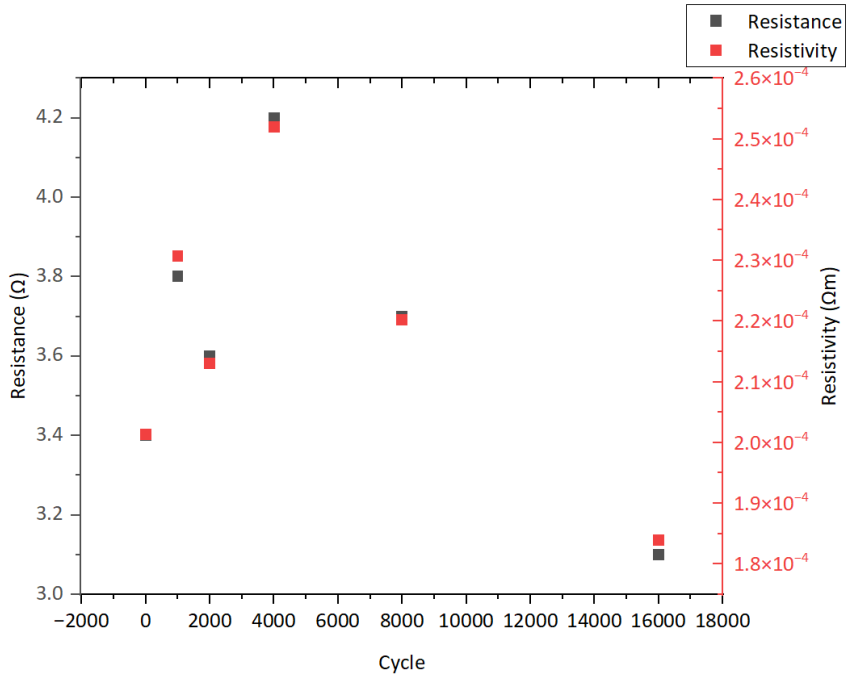


Fig. 12 *The graph of of graphene nanoplatelets-silver-carbon black average resistance and resistivity cured at 240°C for five hours*

As shown in Table 7 and Fig. 13, the of graphene nanoplatelets-silver-carbon black samples cured at 250 °C exhibit a different trend compared to those cured at higher temperatures. Initially, resistance and resistivity increase slightly with cycles, attaining a maximum of around 8000 cycles. However, at 16,000 cycles, both parameters drop sharply with resistance falls from 4.1 Ω to 1.8 Ω, and resistivity decreases from 2.47×10^{-4} Ωm to 1.07×10^{-4} Ωm. This unexpected reduction suggests possible reorganization or compaction of conductive pathways because of the prolonged thermal and mechanical stress, improved electron transport. Such behavior indicates a complex interaction between curing temperature, network evolution, and mechanical durability.

During the cyclic mechanical stress, the conductive fillers within the polymer matrix straighten because of micro-level vibrations and compressive forces. At 250 °C curing, the polymer binder retains some flexibility that allows movement of particles within the matrix and this stress promotes better alignment of the filler and improved the conductive pathways which reduces overall resistance. Repeated mechanical stress physically compacts the ink film if the curing left some voids or weak inter-particle connections. This compaction under cyclic stress reduces gaps between conductive particles and increasing the number of contact points for electron to flow and enhanced percolation network for efficient current conduction.

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Table 7 *The average resistance and resistivity of hybrid of graphene nanoplatelets-silver-carbon black cured at 250 °C for five hours*

Cycle	Resistance (Ω)	Resistivity (Ωm)
0	3.4	2.01 x 10^{-4}
1000	4.0	2.37 x 10^{-4}
2000	4.0	2.41 x 10^{-4}
4000	3.5	2.09 x 10^{-4}
8000	4.1	2.47 x 10^{-4}
16000	1.8	1.07 x 10^{-4}

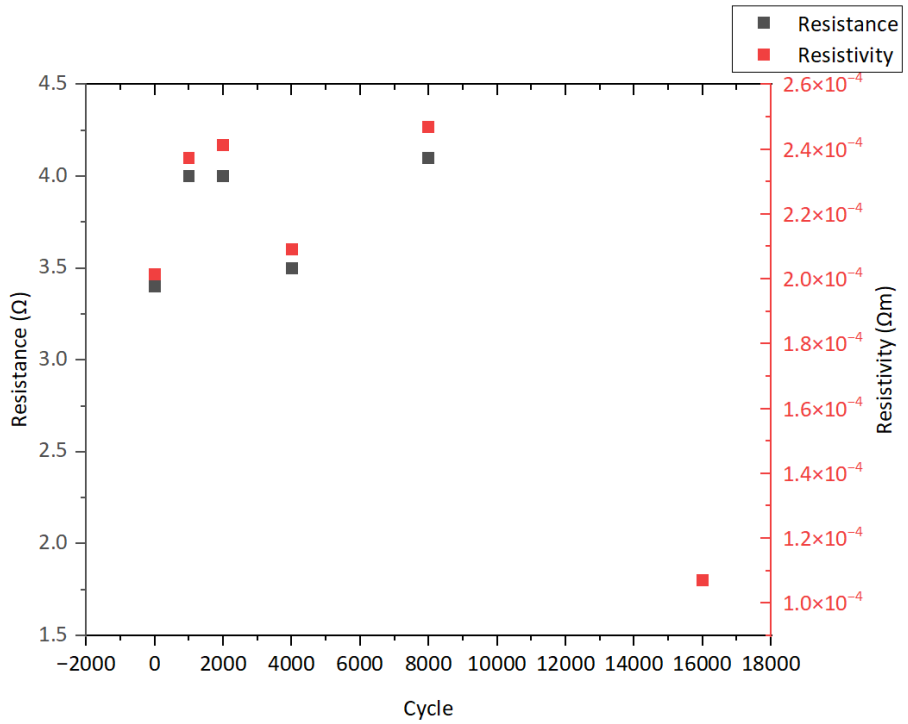

Fig. 13 *The graph of of graphene nanoplatelets-silver-carbon black average resistance and resistivity cured at 250°C for five hours*

Table 8 and Fig. 14 show the average resistance and resistivity of the of graphene nanoplatelets-silver-carbon black film cured at 260 °C for five hours. Initially, both resistance and resistivity fluctuate slightly because of minor structural or contact resistance variations within the ink. However, at 16,000 cycles, a significant increase in both resistances from 2.1 Ω to 3.7 Ω and resistivity from 1.25 × 10^{-4} Ωm to 2.23 × 10^{-4} Ωm is observed. This trend indicates potential degradation mechanisms such as micro-crack formation, interfacial delamination, or conductive pathway disruption because of the cyclic stress, which affects the stability of the conductive ink.

Under repeated cyclic bending, the flexible substrate undergoes mechanical stress, and this stress initiate tiny cracks within the ink matrix at weak points such as particle interface. The micro-cracks grow and interrupt the continuity of the conductive pathways thus increasing the resistance. The conductive ink is composed of different materials; the bending stresses lead to poor adhesion at interfaces between the fillers at the ink substrate interfaces. As delamination progresses, electrical contact between particles destroys and increases resistivity. The conductive network relies on fixed contact between fillers to allow electron transport. When deformation occurs, the contact moves or separates and this leads to fewer percolation paths thus increasing resistance. The repeated bending executes cyclic stress on the film and over time this stress causes material fatigue. Curing at 260 °C for five hours might initially enhance bonding and conductivity by promoting good inter-particle contact and solvent evaporation however such a high temperature cure may also make the ink more brittle decreasing the ability to hold strain during cyclic bending. The increase in average resistance and resistivity is associated with the deformation of the conductive pathway of the ink, which can lead to cracks formation or gaps in the ink layer [21].

Table 8 *The average resistance and resistivity of hybrid of graphene nanoplatelets-silver-carbon black cured at 260 °C for five hours*

Cycle	Resistance (Ω)	Resistivity (Ωm)
0	2.1	1.25×10^{-4}
1000	2.3	1.37×10^{-4}
2000	1.9	1.17×10^{-4}
4000	2.1	1.28×10^{-4}
8000	2.3	1.40×10^{-4}
16000	3.7	2.23×10^{-4}

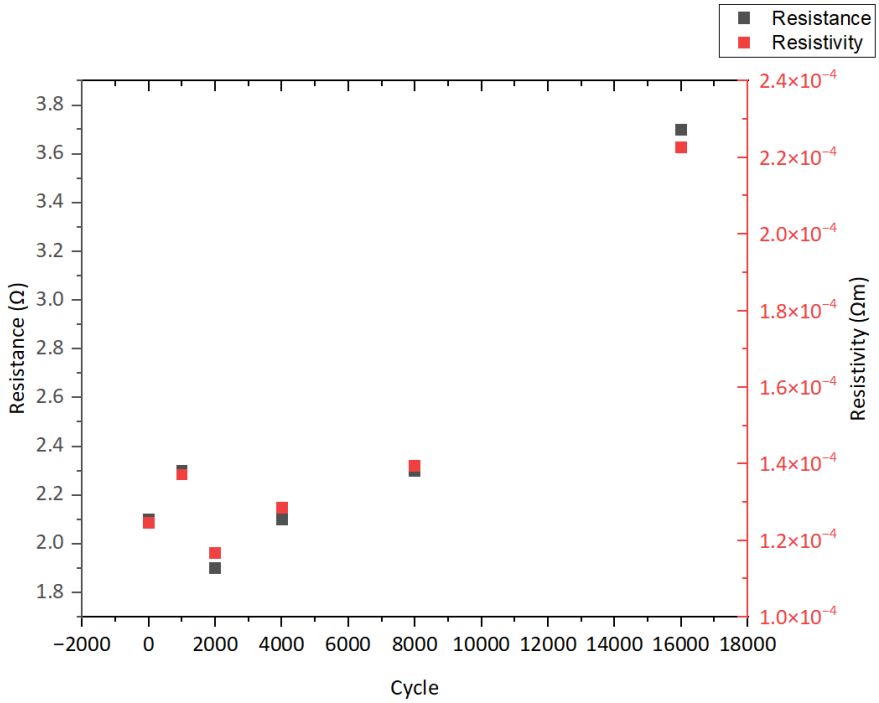

Fig. 14 *The graph of of graphene nanoplatelets-silver-carbon black average resistance and resistivity cured at 260°C for five hours*

The electrical conductivity of the conductive ink is strongly influenced by the thermal conductivity of its constituent materials during the curing process. Both graphene nanoplatelets and silver have naturally high thermal conductivity with approximately 2000–5000 W/m·K for graphene and ~429 W/m·K for silver which helps efficient and uniform heat distribution across the ink film. This condition assists the complete thermal decomposition of silver acetate into metallic silver, improves solvent evaporation, and enhances particle mobility, reduced viscosity and enable denser packing of conductive fillers. These thermal effects improve the interconnectivity between graphene nanoplatelets, silver, and carbon black particles, led to a more continuous conductive network. The average bulk resistance of the ink decreased from 3.4 Ω at 240 °C and 250 °C to 2.1 Ω at 260 °C, indicates that higher curing temperatures enhance conductivity through improved particle sintering and contact. However, excessively high temperatures can introduce thermal stress and micro-cracks because of rapid shrinkage or binder degradation.

Comparing of graphene nanoplatelets-silver conductive ink with of graphene nanoplatelets-silver-carbon black conductive ink, the graphene nanoplatelets-silver delivers very high thermal and electrical conductivity but may suffer from issues related to particle agglomeration, poor film uniformity, and thermal stress during curing. The addition of carbon black in the of graphene nanoplatelets-silver-carbon black system improves dispersion, thermal stability, and film morphology by increasing viscosity and modifying density. Although the peak conductivity may be slightly lower, the overall system is more uniform, and flexible therefore more suitable for scalable, printed, and flexible electronics applications.

4. Conclusions

A conductive ink composed of graphene nanoplatelets, silver acetate, and carbon black were successfully formulated and evaluated under different thermal curing conditions. The results demonstrated that curing temperature has a significant influence on the microstructure of the ink, electrical performance, and mechanical

properties. As the curing temperature increased from 240 °C to 260 °C, the average bulk resistance decreased from 3.4 Ω to 2.1 Ω, indicating enhanced electrical conductivity because of the complete thermal decomposition of silver acetate into metallic silver and improved interconnection among conductive fillers. At 250 °C, the ink exhibited good surface uniformity and balanced properties, which is suitable for flexible electronics applications. However, curing at 260 °C, while yielding the lowest resistance, introduced minor micro-cracking because of the thermal stress that effect the mechanical flexibility. These findings highlight the critical role of thermal curing in achieving optimal ink performance, where both electrical conductivity and flexibility must be balanced. An ideal curing temperature around 250 °C offers a practical compromise between low resistance and structural integrity for applications in printed and flexible electronics.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Mazilah Abu Bakar, Mohd Azli Salim, Nor Azmmi Masripan, Alan Watson;* ***data collection:*** *Mazilah Abu Bakar;* ***analysis and interpretation of results:*** *Mazilah Abu Bakar, Mohd Azli Salim, Nor Azmmi Masripan, Chonlatee Photong;* ***draft manuscript preparation:*** *Mazilah Abu Bakar, Mohd Azli Salim, Chonlatee Photong. All authors reviewed the results and approved the final version of the manuscript.*

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