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Effect of Silver Filler Morphology on the Conductivity of Screen-Printable Silver Inks

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Abstract: Conductive inks are essential for developing flexible and wearable electronic devices, where printability and electrical performance must be finely balanced. However, achieving high conductivity while minimizing costly silver filler content remains a key challenge in ink formulation. In this work, we demonstrate that a simple ball-milling process transforms spherical silver particles into platelet-shaped fillers, dramatically enhancing conductivity at equivalent filler loading. The resulting inks show a reduction in sheet resistance from ~180 Ω/□ to ~ 0.57 Ω/□ at 70 wt% filler content, with improved performance attributed to surface-to-surface contact between platelets. Moreover, we show that filler content influences not only electrical conductivity but also ink viscosity, with the 53.8 wt% formulation achieving a practical balance between conductivity, processability, and cost. This morphology- and composition-controlled ink design offers a scalable strategy for manufacturing high-performance, cost-effective conductive inks suitable for next-generation printed electronics.

Keywords: Ag conductive ink, Platelet-shaped filler, Ball milling, Screen printing, Electrical conductivity

Conductive inks are essential functional materials widely used in printed electronics, including flexible circuits, RFID antennas, wearable sensors, and electromagnetic shielding layers [1]. Among various conductive fillers, silver (Ag) has garnered the most attention due to its exceptional electrical conductivity, oxidation resistance, and compatibility with a range of printing processes [2]. In particular, silver-based inks are favored in screen-printing applications for their ability to form robust, high-conductivity pathways even at low processing temperatures [3]. A critical factor governing the performance of conductive inks is the morphology of the metallic fillers. Traditional silver inks often employ spherical or near-spherical particles, which form electrical pathways primarily through point-to-point contacts [4]. In contrast, morphology-engineered fillers such as flakes, platelets, or wires can offer larger contact areas and more efficient conduction networks, enabling superior electrical performance even at reduced filler loadings [5].

Recent studies have explored the use of anisotropic fillers such as nanowires, flakes, and platelets to improve the conductivity of printed traces [6,7]. These investigations have demonstrated that modifying the aspect ratio and contact

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geometry of fillers can significantly improve ink performance. For instance, flake-like particles can form surface-to-surface contacts, facilitating better electron transport than their spherical counterparts. However, the widespread application of anisotropic fillers remains limited due to their complex and often costly synthetic processes, which hinders large-scale industrial adoption [7].

In this work, we present a straightforward and scalable ball-milling approach to convert commercially available spherical silver powders (~1 μm) into platelet-shaped fillers. These platelets were incorporated into a silver-based conductive ink formulation composed of dimethyl glutarate (DG), ethyl carbitol acetate (ECA), and a polymeric binder (BNMR-215-40, BN Chemical). For comparison, a control ink was prepared using unmodified Ag particles dispersed by magnetic stirring, maintaining identical ink composition and silver content (70 wt%). Notably, the ink containing silver platelets exhibited a dramatically lower sheet resistance (~0.57 Ω/□) compared to the particle-based ink (~180 Ω/□), which is attributed to improved surface-to-surface contact among the anisotropic fillers. To further assess performance with respect to silver content, four different Ag platelet inks (20, 25, 53.8 and 70 wt%) were screen-printed onto fabric substrates using a uniform dot array pattern. As expected, a decrease in silver content led to an increase in sheet resistance and a reduction in ink viscosity. These findings highlight the critical role of filler morphology in determining ink performance and provide practical insight for designing cost-effective, printable, and scalable conductive inks that meet diverse application requirements in flexible and wearable electronics.

Figure 1 illustrates the overall fabrication process of silver-based conductive inks with controlled filler morphology, followed by their screen printing onto fabric substrates. Initially, the spherical silver particle-based ink was prepared by mixing Ag powder (70 wt%) with dimethyl glutarate (DG), ethyl carbitol acetate (ECA), and a polymeric binder (BNMR-215-40) in a glass vial. To promote dispersion, 30 mL of acetone was added as a co-solvent. The resulting mixture was stirred on a hot plate at 60°C using a magnetic stirrer for 24 hours to achieve uniform blending. In contrast, platelet-type Ag fillers were prepared via a ball-milling approach. Specifically, Ag powders (10 g, 20 g, 35 g, and 70 g corresponding to 25 wt%, 40 wt%, 53.8 wt%, and 70 wt%, respectively) were added to a Nalgene bottle containing DG, ECA, and the polymeric binder along with zirconia balls as the milling medium. After adding 30 mL of acetone, the mixture was subjected to ball milling at 170 rpm for 24 hours. Upon completion, the zirconia balls were separated and rinsed with acetone to collect any remaining ink. The collected ink was subsequently stirred again at 60°C for an additional 24 hours to ensure complete dispersion and viscosity stabilization. For screen printing, polyurethane-coated fabric substrates (50 denier) were cut into 10 cm x 10 cm squares. The conductive inks were then printed using a stainless-steel mesh screen (325 mesh count) to form uniform circular dot arrays. After printing, the samples were dried in an oven at 150°C for 10 minutes. This screen-printing process enabled direct comparison of particle-based and platelet-based silver inks under identical

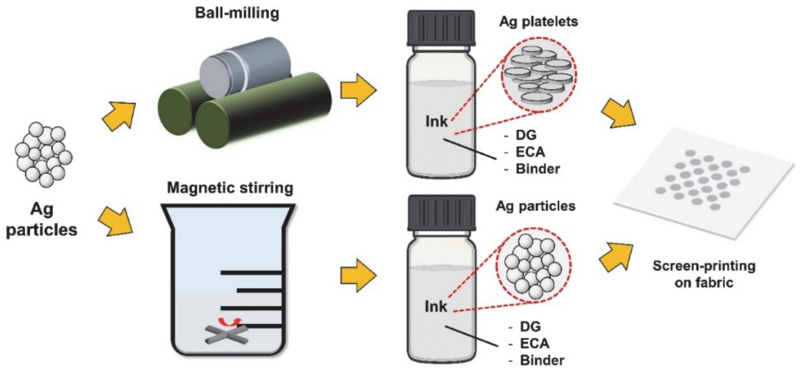

Fig. 1. Schematic illustration of the fabrication process for silver-based conductive inks with controlled filler morphology and their screen printing onto fabric substrates. Spherical silver particles were used for the control ink, while platelet-shaped fillers were obtained via ball milling.

geometries and post-treatment conditions, serving as a reliable platform for evaluating the effects of filler morphology and content on conductivity and printability.

The morphological and structural characterization of silver fillers with different geometries is presented in Fig. 2. The overall morphology and size distribution of both spherical silver particles and platelet-shaped silver fillers were examined using scanning electron microscopy (SEM, JSM-IT700HR, JEOL). A low-magnification SEM image of the spherical Ag particles is shown in Fig. 2(a), while a higher-magnification image in Fig. 2(b) reveals their uniform and nearly isotropic shape. The particle size distribution, obtained by measuring 100 randomly selected particles, is plotted in Fig. 2(c), indicating an average diameter of 1.16 ± 0.13 μm. In contrast, Fig. 2(d) and 2(e) display the morphology of silver platelets obtained via ball milling. These images reveal a flattened, anisotropic shape with significantly increased lateral dimensions compared to the original particles. The transformation from spherical to platelet morphology can be attributed to the severe plastic deformation induced by repetitive mechanical impact and shear during ball milling. Given the ductile nature of metallic silver, the particles undergo lateral compression and deformation rather than fracturing, resulting in platelet formation. The lateral size distribution of the platelets, also based on measurements from 100 samples, is presented in Fig. 2(f), yielding an average dimension of 2.9 ± 0.27 μm. To confirm the crystal structure of both fillers, X-ray diffraction (XRD) analysis was performed using a Rigaku MiniFlex 600 diffractometer, as shown in Fig. 2(g). Both the Ag particles and Ag platelets exhibit sharp diffraction peaks at approximately 38.1°, 44.3°, 64.4°, and 77.5° in 2θ, corresponding to the (111), (200), (220), and (311) planes of face-centered cubic (FCC) metallic silver (JCPDS No. 04-0783). No noticeable difference in peak positions or intensities was observed between the two filler types, and no secondary phases were detected, confirming that the ball-milling process preserved the phase purity and crystallinity of the silver materials.

To investigate the effect of filler morphology on electrical conductivity, two types of inks—one containing spherical silver particles and the other containing silver platelets (each with 70 wt% silver filler)—were screen-printed onto fabric substrates, and their sheet resistances were measured. Figure 3 compares the sheet resistance of both silver inks. As shown in Fig. 3(a), the ink based on spherical Ag particles exhibits a relatively high sheet resistance of approximately 180 Ω/□, whereas the ink containing platelet-shaped Ag fillers shows a dramatically lower sheet resistance of ~0.57 Ω/□. This substantial reduction is attributed to the morphological transformation induced by the ball-milling process, which significantly alters the percolation behavior of the conductive network.

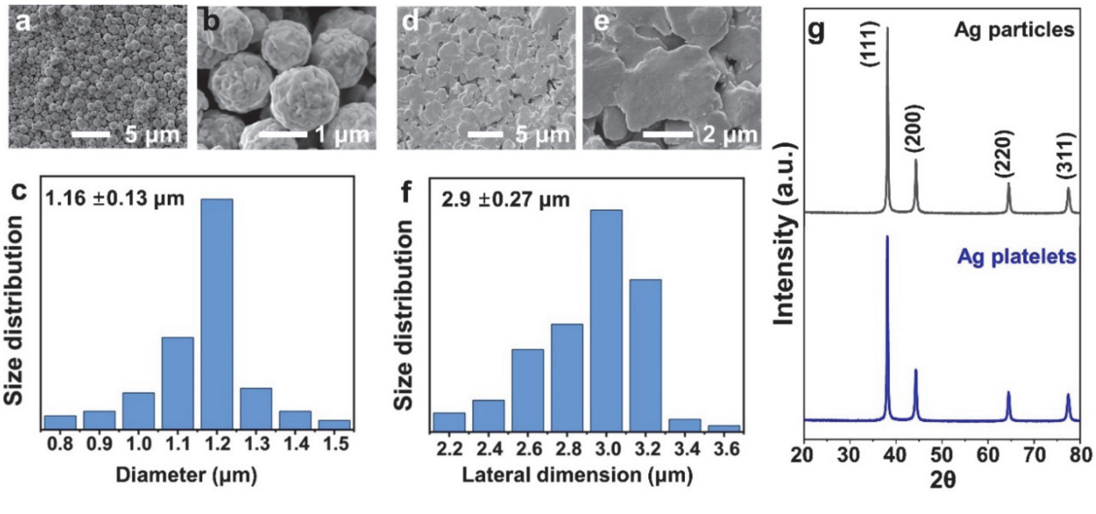

Fig. 2. (a,b) SEM images of spherical silver particles at low and high magnifications, respectively, (c) particle size distribution of spherical Ag particles, (d,e) SEM images of platelet-shaped silver fillers obtained via ball milling, (f) lateral size distribution of silver platelets, and (g) XRD patterns of both spherical and platelet-shaped silver fillers, confirming the face-centered cubic (FCC) structure.

The improved conductivity observed in the platelet-based ink stems from a fundamental difference in the nature of the electrical pathways. As schematically illustrated in Fig. 3(b) and 3(c), spherical particles primarily form point-to-point contacts, resulting in limited and discontinuous conduction paths with high contact resistance. These narrow and unstable bridges impede efficient electron transport across the printed pattern. In contrast, the platelets-shaped fillers enable surface-to-surface contact across broader areas, promoting the formation of more continuous, densely interconnected conductive networks. The planar geometry of the platelets not only reduces interfacial resistance but also increases the probability of electron hopping or tunneling between adjacent fillers, thereby improving overall conductivity. This result clearly demonstrates that the anisotropic filler morphology, achieved through a scalable and low-cost ball-milling process, plays a pivotal role in enhancing the electrical performance of conductive inks, even when the silver content remains constant. These findings highlight the importance of morphological engineering in designing high-performance, cost-efficient conductive inks for printed electronics.

Building on the confirmed advantage of platelet-shaped silver fillers for enhancing electrical conductivity, we next investigated the effect of filler content on both printability and film uniformity. From an application standpoint, reducing the amount of silver filler is highly desirable for lowering material costs, as silver is most expensive component in conductive inks. However, such reduction may adversely affect the electrical performance and printability of inks. Therefore, to evaluate this trade-off, silver inks containing platelet-shaped fillers at varying concentrations (20 wt%, 25 wt%, 53.8 wt%, and 70 wt%) were formulated and screen-printed onto polyurethane-coated fabric substrates. As shown in Fig. 4(a), a dot-array stencil mask (10 mm diameter, 10 mm spacing) was used to ensure consistent printed geometry across all samples. The resulting printed patterns are displayed in Fig. 4(b), demonstrating that all formulations produced uniform and well-defined circular dots on the fabric without smudging or edge bleeding. These results confirm that the platelet-based silver inks maintain good printability and shape fidelity even at reduced filler contents.

Figure 5 presents a comprehensive comparison of the electrical conductivity and viscosity of conductive inks formulated with platelet-shaped silver fillers at varying

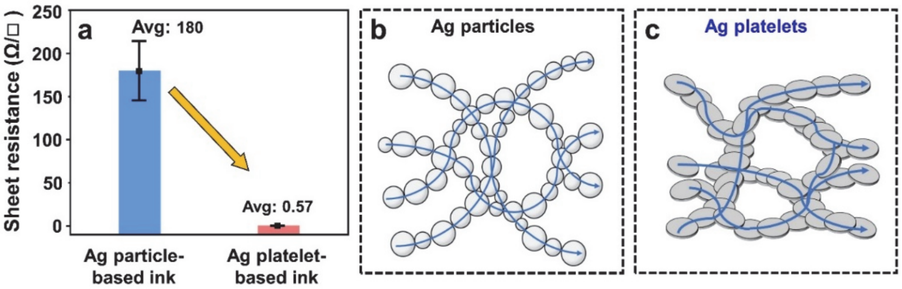

Fig. 3. (a) Sheet resistance of inks containing spherical Ag particles and platelet-shaped Ag fillers (each with 70 wt% silver content), (b,c) schematic illustrations of electron conduction pathways: (b) point-to-point contact in spherical particle networks and (c) surface-to-surface contact in platelet networks.

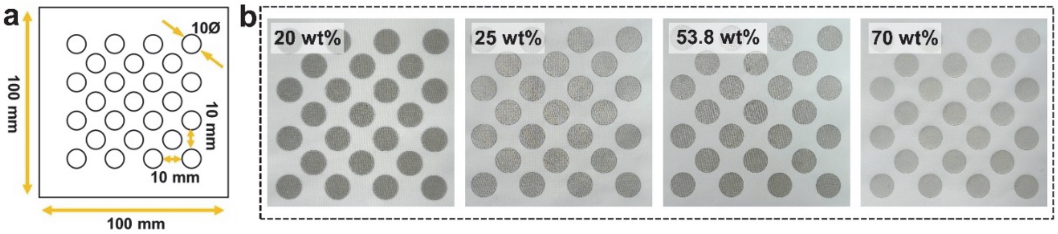

Fig. 4. (a) Schematic of the dot-array pattern (10 mm diameter, 10 mm spacing) used for screen printing and (b) optical images of screen-printed patterns on fabric substrates using inks with varying Ag platelet contents (20 wt%, 25 wt%, 53.8 wt%, and 70 wt%).

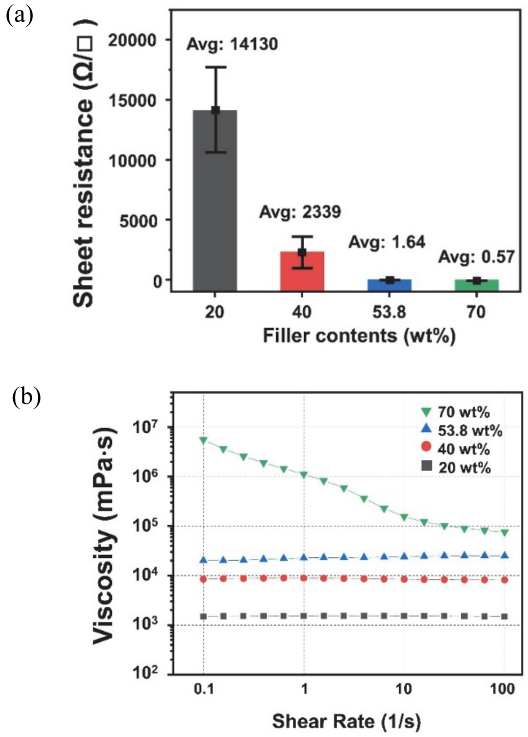

Fig. 5. (a) Sheet resistance of conductive inks as a function of filler content (20 wt%, 40 wt%, 53.8 wt%, and 70 wt%) and (b) viscosity profiles of corresponding inks as a function of shear rate.

concentrations. As shown in Fig. 5(a), the sheet resistance decreases significantly with increasing silver content. At 20 wt%, the ink exhibits a high sheet resistance of approximately 14,130 Ω/□, which drops sharply to 2,339 Ω/□ at 40 wt%. Notably, further increases in filler content to 53.8 wt% and 70 wt% result in much lower resistances of 1.64 Ω/□ and 0.57 Ω/□, respectively. This trend indicates that the percolation threshold for continuous conductive pathways is reached between 40 and 53.8 wt%, beyond which additional filler has a diminishing effect on conductivity enhancement. The rheological behavior of these inks is shown in Fig. 5(b). The inks containing 20 wt%, 40 wt%, and 53.8 wt% Ag platelets display nearly constant viscosities across the entire shear rate range, indicating Newtonian-like behavior. In contrast, the ink with 70 wt% filler exhibits a pronounced shear-thinning response, with viscosity decreasing by nearly two orders of magnitude from low to high shear rates. This non-Newtonian behavior is attributed to strong interparticle interactions and the formation of a transient network structure at high filler concentrations. Under shear, this network is disrupted and aligned, resulting in reduced viscosity. Taken together, these results highlight the trade-off between electrical performance and rheological behavior. While higher filler contents significantly reduce sheet resistance, they also increase viscosity and introduce non-Newtonian flow characteristics, which may affect processing and printability. Importantly, the ink with 53.8 wt% filler offers a balanced compromise, achieving near-minimum sheet resistance with manageable viscosity, making it a promising formulation for practical screen-printing applications.

In conclusion, we demonstrated the significant impact of silver filler morphology and content on the electrical and rheological performance of screen-printable conductive inks. A simple ball-milling process was employed to convert spherical silver particles into platelet-shaped fillers, resulting in a dramatic reduction in sheet resistance from ~180 Ω/□ to ~0.57 Ω/□ at the same filler content (70 wt%). This improvement is attributed to the enhanced surface-to-surface contact between platelets, which facilitates efficient electron transport. We further investigated the effect of silver content using platelet-based inks at 20-70 wt%. As filler content increased, sheet resistance decreased sharply and plateaued above 53.8 wt%, indicating saturation of the conductive network. Rheological measurements revealed that inks with lower filler contents exhibited Newtonian-like behavior, whereas the 70 wt% ink showed pronounced shear-thinning due to strong interparticle interactions. These results highlight the importance of morphological control and filler loading optimization to balance conductivity, viscosity, and printability. Overall this work offers a cost-effective and scalable strategy to improve the performance of silver-based conductive inks, providing valuable insights for the design of printable materials in flexible and wearable electronics.

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