Screen Printing

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Short History

Screen printing is a method for depositing a patterned layer onto various substrates by pressing a suspension, called the screen-printing paste, through a mesh onto the substrate. The earliest forms of screen printing began in China at the end of the first millennium, and consisted of weaving human hair across a wooden frame as a mesh, with leaves being attached to the hair as a stencil. Later, the process was adapted, by replacing the hair with a piece of silk mounted between two pieces of strong, waterproof paper with some openings cut into them. The paint flowed through the silk, leaving a motive on the substrate (made of ceramic or silk), identical to the openings cut in the paper. This technique, silk-screen printing, arrived in Europe in the late 18th century, but only saw widespread use in the 20th century thanks to the greater availability of silk from Asia. The first screen-printing machine was patented in 1907, and photo-imaged stencils, developed in 1910, led to greatly improved printing quality and control. Initially, silk-screen printing was used to decorate luxury wallpapers and later to print multicolor posters and textiles (Sheng, 1999). In the late 1930s screen printing was, for the first time, applied in the electronics industry as a method for manufacturing capacitor electrodes and later for the processing of hybrid circuit resistor-capacitor networks. Later, the electronics industry rapidly expanded screen printing as a method for packing electronic components in response to the need for the efficient, affordable, large-scale production of thick films. By the 1960s screen printing had become the dominant technology for fabricating printed-circuit boards, which are the basis for almost all consumer electronics (Cote, 1974).

Today, screen printing is integral to the fine arts and the textile industry for decorating fabrics as well as dominating the electronics industry as a mature technology for producing conductive patterns for electronic components, such as touch panels and solar cells, and for various thick-film electronic components, such as sensors and fuel cells.

Screen-Printing Process

Screen printing can be used to reproduce uniform layers or patterns on a substrate. In the conventional screen-printing process the paste is placed on the mesh of the screen mask and the flat substrate is placed under the screen mask. The substrate is held in the holder by a vacuum hold-down system during the printing. A small gap of 0.5–1 mm is kept between the mesh and the substrate. To deposit the pattern onto the substrate, the squeegee, which consists of a polyurethane rubber in a metal support, presses the paste through the open areas of the otherwise filled mesh with a certain speed and force onto the substrate, either manually or automatically. The typical speed ranges from a few to 300 mm s^{-1} while force ranges from 10 to 200 N. After the deposition, the screen mask is removed, leaving the paste on the substrate. The general principle of the screen-printing process is shown in **Fig. 1**.

The thickness per screen-printed layer is from a few micrometers to $\sim$ 30 μm. To achieve a thicker deposit, multiple printing steps are performed, including screen printing and curing of the first layer, followed by an overprint of the paste on the cured first layer and drying and curing of the second layer. This process is repeated until the target thickness is reached. At present, 35-micrometer-wide screen-printed lines are used in commercial printed electronics products, while 20–30-micrometer-wide lines are obtained under laboratory conditions for conventional screen-printing technology (Dorey, 2012; Tepner et al., 2019).

The quality of the printed pattern is affected by a combination of many parameters, including the printing parameters, the properties of the screen-printing paste, the properties of the mesh and the screen mask, and the properties of the substrate, all of which need to be optimized and properly adjusted for each individual application.

Screen Mask

The screen mask defines the pattern of the layer and affects the amount of ink deposited onto the substrate. The screen mask consists of a rigid metal frame onto which a mesh, coated with a photosensitive emulsion, is stretched. The common wire-to-frame angles are 22.5, 30 and 45°. The frame has to be flat and structurally stable to provide a stable mesh support that does not affect the dimensional accuracy. The common frame materials are die-cast or extruded aluminum.

The mesh is a weaved cloth of silk, synthetic fibers or metal threads with well-defined windows that reproduce the pattern to be printed. The pattern to be printed is made by coating the mesh with a photosensitive emulsion, usually a polyvinyl acetate or polyvinyl alcohol, sensitized with a dichromate solution. Then the pattern to be printed is masked with a photo-mask and the mesh is exposed to the ultraviolet (UV) light. The photosensitive emulsion that was not exposed to the UV light is washed out with water and becomes the area for printing. (Haskard and Pitt, 1997). A schematic presentation of a cross-section of a mesh is illustrated in **Fig. 2**.

The material of the mesh is selected based on the properties of the paste and the target application. The material must be chemically inert with mesh openings that are as equal as possible, suitable mechanical properties and sufficient life time. The most frequently used materials for the mesh are polyamide (nylon), polyester and stainless steel. The polyamide and polyester are
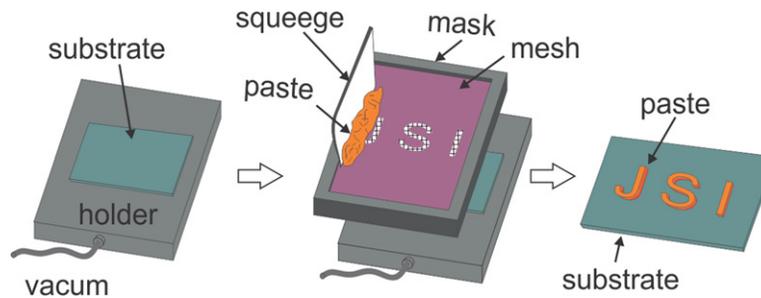
Fig. 1   Schematic presentation of the screen-printing process.
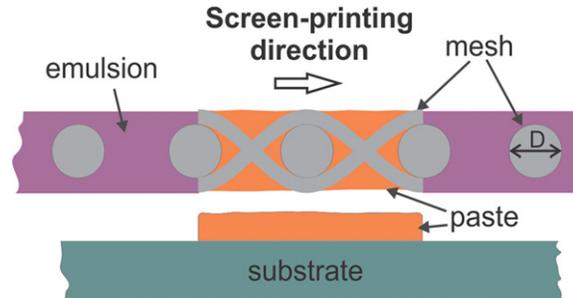
Fig. 2   Scheme of the cross-section of a mesh. D is the diameter of the mesh element.

available as monofilaments with diameters from ~ 30 µm to a few hundred µm. Both materials are resilient, strong and elastic, with a high extensibility of 4%–6%. The polyamide and polyester meshes easily deform, which results in a distorted shape and a relatively thin printed pattern. The higher elasticity of polyamide compared to polyester makes it possible to print on uneven substrates, but the tendency to absorb water limits the printing accuracy and consequently polyamide meshes are used less frequently than polyester. A polyester-based mesh is sufficiently flexible for printing on substrates with normal irregularities. It is characterized by a higher tension, better dimensional accuracy and longer life time compared to polyamide. Polyester-based meshes are used for applications where the high resolution of the patterns is not of paramount importance, but production costs need to be limited.

A mesh based on stainless steel is characterized by thin and uniform wires with a diameter from 15 µm, a consistent mesh thickness with evenly tensioned waves having a very low extension of 0.5% and a high tensile strength, which makes it possible to print patterns with high definition and good printing accuracy. The flattened standard stainless mesh, i.e., the calendared stainless-steel mesh, is thinner, smoother and more uniform than standard mesh and allows the printing of layers with excellent definition. The poor flexibility of the stainless steel means that it is possible to print solely onto flat surfaces, and thus the stainless-steel meshes are used for realizing very-high-resolution patterns on flat and relatively small surfaces (White, 1994). Stainless steel meshes are largely used in electronics.

The factors influencing the characteristics of the printed layers include many parameters, such as the number of mesh elements, i.e., wires or fibers, per inch (mesh count, M), the type and diameter of the mesh element, the tension, the wire-to-frame orientation, the type and thickness of the photosensitive material, the exposure time, the dimensional accuracy of the photomask etc.

For a given mesh count M [in^{-1}] the smaller diameter of the mesh element is reflected in larger mesh openings, which results in a larger volume of the printed paste. Thus, the mesh count is one of the factors controlling the thickness of the deposit. The percentage of open area (OA) is defined as $[1 - (M \times D)]^2$, where M is the mesh count and D [in] is the diameter of the mesh element. Knowing the OA, the mesh thickness (MT), and the thickness of the emulsion (ET) we can estimate the wet thickness of the printed pattern WT = (MT × OA) + ET. For most applications the ET is ~ 13 µm.

Another important parameter is the size of the mesh openings, which must be at least 3–5 times larger than the size of the particles or agglomerates in the screen-printing paste.

Properties of the Screen-Printing Paste

A stable and homogeneous paste is of great importance to the screen printing of uniform patterns in a reproducible manner. Furthermore, the paste needs to be formulated in such a way that it possesses good printability and provides uniformity and a good aspect ratio of the printed pattern.

The paste consists of an active material distributed in a certain solvent. In the case that the active material is a powder, the particles sediment over time, if gravity overcomes the Brownian motion. In addition, the particles spontaneously agglomerate as a
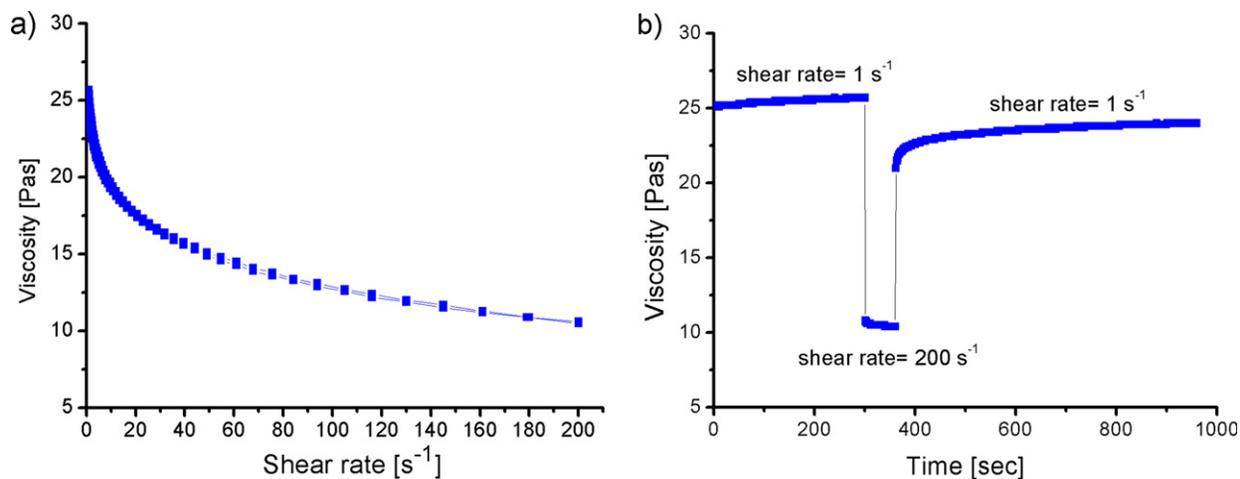
Fig. 3 (a) Viscosity of the ceramic paste (60 wt% of $K_{0.5}Na_{0.5}NbO_3$ and 40 wt% organic phase) as a function of shear rate. (b) Viscosity of the ceramic paste as a function of time and shear rate.

result of the van der Waals attractive forces. The sedimentation and agglomeration reduce the quality of the printing pattern and need to be avoided. To prevent agglomeration and sedimentation of the particles it is necessary to introduce repulsive forces between the particles, either by charging the particles or by preventing their close approach with steric hindrance.

In electrostatic stabilization, the interactions between the particles and the solvent yield a charge on the surface of the particles as a result of the ionization of the surface groups, ion adsorption, dissolution of the ions or the isomorph substitution of ions. Electrical repulsion is an important type of stabilization for particles dispersed in water-based systems or in liquids with a moderate polarity, like alcohols. In these systems the stability of the particles is controlled by the particle size, ion type, its concentration and the value of the zeta-potential. The zeta-potential of a particle with an absolute value over 25 mV results in a stable suspension.

In steric stabilization the particles are covered by a layer of uncharged polymers, either through the adsorption or through chemical grafting. The polymer layer physically prevents the close approach of the particles. To keep the particles well dispersed in a solvent the polymer must be strongly adsorbed on the particles, must completely cover the surface of the particle, while the concentration of the non-adsorbed polymer must be low. Steric stabilization is appropriate for stabilizing the particles in low-polarity solvents.

Electrosteric stabilization is a combination of the electrostatic and steric stabilization mechanisms. It utilizes a polyelectrolyte with a long-chain polymer and a functional group. The functional group can dissociate in the solvent, thereby creating charged moieties that contribute to the electrostatic effect, while the polymer chains contribute to the steric hindrance. Examples of polyelectrolytes are polyacrylic acid with a carboxylic group that dissociates at high pHs and polyethylene amine with an amino group that dissociates at low pHs.

The printability of the paste is directly related to its rheological properties, in particular to the shear-rate-dependent viscosity and thixotropy. During the printing process the paste is mechanically forced through the mesh. The resistance of the paste to flow is determined by means of viscosity, defined as the ratio of the shear stress (τ) to the shear rate ($d\gamma/dt$). A high viscosity means a high resistance to flow and vice versa. The viscosity of the paste can be independent of the shear rate (Newtonian behavior), shear-thinning where the viscosity decreases with the shear rate or shear-thickening where the viscosity increases with the shear rate. The composition of the screen-printed paste should be designed to be shear-thinning (**Fig. 3(a)**). The paste is put on the mesh before printing and while it rests, the viscosity of the paste should be high. During printing under the pressure of the squeegee, the viscosity of the paste should decrease to be able to flow through the mesh. However, once the pattern is formed on the substrate, the viscosity of the paste must increase within a short time period to maintain the high-definition shape of the pattern (**Fig. 3(b)**). The printing step takes into the consideration the change in viscosity with the shear rate, while the last step includes the change in viscosity with time, evaluated as the thixotropy. Thixotropy covers the reduction of the structural strength of the paste by a shear process and the structural regeneration of the paste in a subsequent period of rest (Mezger, 2006). The shear rate during printing is typically between 100 and 1000 s^{-1}, and pastes with a viscosity up to 150 Pas at 100 s^{-1} are generally suitable for screen printing (Reed, 1995).

Chemical Composition of the Screen-Printing Paste

The composition of the paste for screen printing is complex and consists of an active material, solvent and various additives, such as a dispersant and a binder. The solvent serves as a dispersion medium for the active material and a medium to dissolve all the other components. Traditionally, organic-solvent-based pastes have been used for screen printing. Terpineol (2-(4-methylcyclohex-3-en-1-yl)propan-2-ol) and texanol (2,2,4-trimethyl-1,3-pentanediol monoisobutyrate) with boiling points of 219 and 254°C,
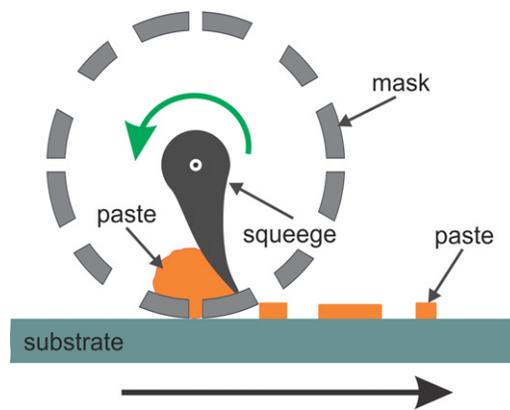
Fig. 4   Rotary screen printing.

respectively, are commonly used solvents. As the major phase the solvent dictates the properties of the paste, in particular the drying and wetting behaviors. If the drying rate is too fast, defects can form in the printed pattern, while a slow drying rate results in a wet pattern for a long time and consequently difficult handling of the sample, possible phase separation and losing the accurate dimensions of the printed pattern. Wetting is an important parameter that controls the dispersion of the active materials in the solvent and also the behavior of the paste on the substrate. The contact angle Θ measures the wetting tendency of a liquid on a solid and is related to the surface energies of solid-vapor γ_{SV}, solid-liquid γ_{SL} and liquid-vapor γ_{SL}: $\cos\Theta = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}}$.

A small contact angle indicates that the liquid spreads on the solid surface, which results in poor definition of the pattern, while large contact angles with well-defined drops of liquid indicate a poor wettability of the solid. The wettability of the solid can be improved by surfactants, whose short-chain molecules consist of hydrophobic (oil-soluble) and hydrophilic (water-soluble) parts. Such molecules have a tendency to adsorb very strongly at the solid-liquid or vapor-liquid interfaces, causing the removal of the hydrophobic part from the aqueous media, while the hydrophilic part remains in the water. They form new surfaces with a lower energy, which improves the wettability (Hunter, 2009). The approach to enhance the wettability of the paste on the substrate is also to clean the substrate with solvent or to treat the substrate with plasma.

Dispersants are added to screen-printed pastes to increase the repulsive forces between the particles and thus to improve the long-term stability of the paste. Dispersants are long-chain molecules that adsorb onto the particles and stabilize the particles using a steric or electrosteric mechanism. The dispersants, such as polyethylene glycol, pentastearic acid oligomer, and alcohol poly-oxyethylene phosphoric acid ester, with a content of a few wt%, are frequently used in screen-printing pastes. The dispersant also decreases the viscosity of the paste, which makes it possible to process the paste with a large number of particles, i.e., a higher solids load. The maximum acceptable solids load in the paste is determined by the particle size and the particle size distribution, as well as by the amount of solvent and additives. Typical solids loading ranges from 40 to 60 wt%. The patterns fabricated with a low solids loading have a tendency to crack and delaminate due to the large shrinkage of the pattern during the drying and debinding processes, while high-solids-loading pastes result in a thicker layer with a high surface roughness.

Binders are additives used in screen-printing pastes to improve the particle network in the as-printed pattern and thus provide the strength for handling. The binders consist of polymer molecules that adsorb onto the particles and bridge the particles. They prevent the formation of defects and enable adhesion of the paste to the substrate after drying. The binders can be roughly classified based on the composition of the inorganic and organic binders or based on the structure of the particle and molecular types. In screen-printing pastes the organic, molecular-type binders are the most frequently used, e.g., ethylene cellulose, polyvinyl butyral, polyvinyl acetate, and polymethyl metacrylate. The amount of binder in the paste, commonly added in the amount of 1 wt%, has an impact on the rheological properties of the paste. Too high an amount of the binder can affect the printability and reduces the quality of the printed pattern.

Water-based systems for screen printing have been investigated less intensively, regardless of increasing environmental and health concerns. For example, the screen printing of Ag nanoparticles was realized by dispersing 77 wt% of the particles in a mixture of water and polyethylene using polyacrylic acid as a dispersant (Hyun et al., 2015).

In addition to organic-solvent- and water-based systems, polymerizable pastes can be used for screen printing. The composition of such a paste is complex and contains monomers, polymers, initiator, active material such as particles and additives to enhance certain properties, for example, shelf life, adhesion, and wettability. Most formulations contain a complex mixture of numerous monomers and oligomers to obtain suitable rheological properties of the paste for the printing process. The monomers and oligomers are predominantly acrylates that undergo radical polymerization initiated by reactive species from the initiator. The common initiators generate radicals under thermal or ultraviolet (UV) curing. Thermal curing needs temperatures up to 200°C and curing times up to a few tens of minutes, while UV curing requires exposure of the paste to UV light, commonly in the range of 200–400 nm for less than 1 min (Licari and Swanson, 2011). The advantages of UV curing are the almost instant drying of the paste, solvent-free pastes, adhesion of the paste to various substrates, low costs and a fast production process (Edison, 2010; Hutchinson, 2010).
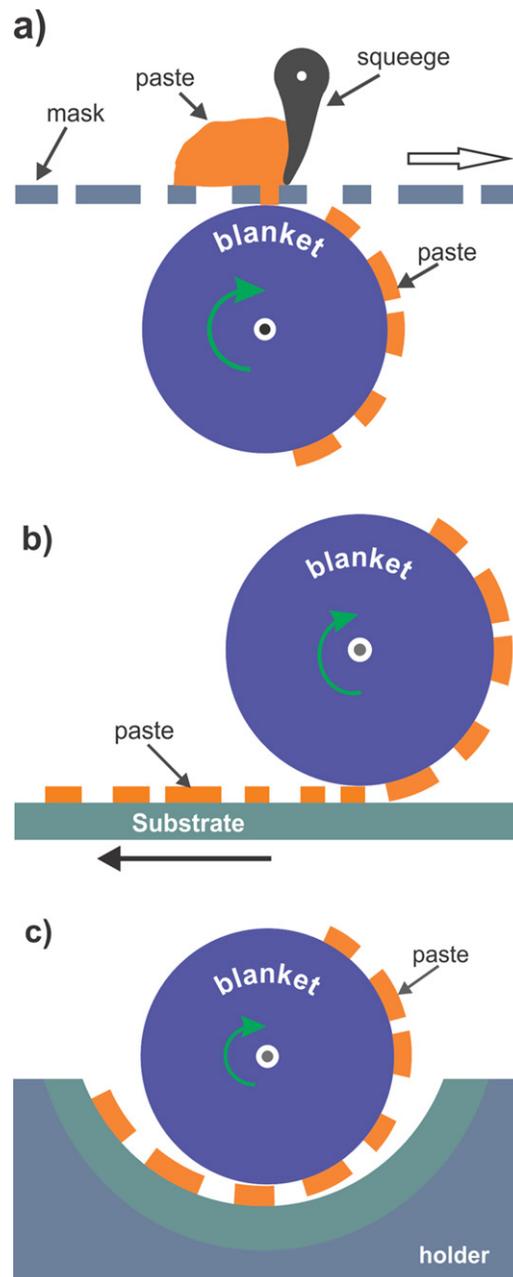
Fig. 5 Schematic presentation of screen-offset printing. (a) Screen-printing of the paste onto a blanket. Transformation of the paste to the flat (b) and curved surface (c).

The typical method for the preparation of the paste includes the weighting of the constituents and their homogenization in a three-roll mill. This mill is composed of three rollers rotating in opposite directions at different speeds relative to each other that squeeze the material through the adjustable gaps and thus mixes, disperses or homogenizes the paste.

Alternative to Traditional Screen Printing

Rotary screen printing uses the same principle as conventional screen printing, but in this case cylindrical-shaped masks are utilized as illustrated in **Fig. 4**. A paste is located inside the cylinder together with a squeegee at a fixed position. As the screen rotates with the same speed as the substrate the paste is continuously pressed through the mesh by the squeegee forming a pattern onto the substrate.

Rotary screen printing is widely used in the textile industry and recently in electronics for the metallization owing to the fact that it is a continuous process that allows for a high printing speed up to 1700 mm s^{-1}, and thus, reduced costs. However the cylindrical masks are quite costly and difficult to clean (Lorenz *et al.,* 2017).

Screen-offset (SOS) printing and screen-offset curved-surface (SOS-CS) printing are based on screen printing the paste onto a cylindrical silicon blanket (**Fig. 5(a)**) and the subsequent transformation of the paste onto the substrate. In SOS printing the substrate is flat, while in SOS-CS printing the substrate is curved (**Fig. 5(b)** and **(c)**).

In the first step the paste is put on the flat mask, which moves as a consequence of the rotation of the blanket. The squeegee is at a fixed position and forces the paste through the mesh openings onto the blanket. The pattern printed onto the silicon blanket retains its original shape due to the ability of the blanket to absorb the solvent from the paste. In the next step the pattern is transformed from the blanket to the flat or curved substrate.

This technique enables the printing of patterns with thicknesses of 5–7 μm and a minimum line width of ∼15 μm. The pattern is characterized by a rectangular and well-defined shape. Multiple printings (2 passes) results in thicker patterns of 12–15 μm and a similar rectangular shape. This technique is highly applicable in the electronics industry in response to the growing demands for printing low-width, high-thickness patterns on curved surfaces (Nomura *et al.,* 2018).

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