Thick-film – a mature technology at the cutting edge of advances in the electronics industry

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Abstract

For decades, thick-film technology has proven to be a dependable, cost-efficient method for highly reliable electronic circuitry and components. Hybrid microelectronics was the first major application for fired thick-film materials, finding its way into military and aerospace applications, where reliability is paramount. Inner and outer electrodes for passive components have been another traditional thick-film market. One of the main advantages of thick film is that it is an additive process, where the various conductor, resistor, and dielectric pastes are screen-printed and fired or cured in succession to form the circuit. This results in cost-efficient processing for the circuit manufacturer. Patterned screens are relatively easy to manufacture, allowing for flexibility in circuit design, and screen printing allows for flexibility in feature sizes from hundreds of microns down to 30 microns or less.

The main drivers in electronics today are miniaturization – higher circuit density, adaptation to new forms such as 3D and flexible substrates, and ecological factors such as reduced energy consumption, waste reduction, and reduction in the use of toxic substances (RoHS – REACH). Thick film has evolved to address these main drivers and due to its reliability, flexibility, and adaptability, The technology has found new applications. 5G telecommunications utilizes highly conductive silver coatings on signal filters for low losses. Automobiles have historically used thick film technology in fuel/air sensors, air bag deployment sensors, and electronic control units (ECUs). Current vehicles have become computers on wheels and have multiple driver assistance sensors (ADAS), e.g. lane departure warning, blind spot monitoring, automatic braking, regenerative braking, and fully autonomous driving. Both fired and non-fired thick-film technology is enabling these developments. Also in the automotive space, applications include thick film heaters for cabin comfort, heaters keeping ADAS sensors free from frost and snow, and heaters for battery management systems (BMS) in electric vehicles. Polymer thick-film (PTF) pastes for cured (90 – 250ºC) electronic circuitry on temperature sensitive polymers have also been around for decades, used in membrane touch-switch keypads and similar circuity. Recently, new applications have emerged for PTF in printed electronics, where the ability to develop flexible, highly durable pastes is enabling new applications in flexible displays, medical monitoring, and performance enhancement in sports.

As the megatrends continue to drive the advancement in technologies, the versatility, reliability, and adaptability of thick-film technology is expected to continue to facilitate these advancements. Heraeus Electronics, with its extensive portfolio of thick-film pastes and matched systems, is primed to support these advancements.

Key words

Advanced, automotive, communications, flexible, heaters, medical, reliability, screen printing, thick-film

I. Introduction

Thick-film technology has been in existence for decades or even centuries depending on the definition. The first documented examples of screen printing, the primary application method for thick-film pastes, was developed in China 3000 years ago for "silk-screening" pigments. Printing metallic films onto ceramics has been demonstrated since the 1930s, with the use of fired thick-film for electronic circuitry developed in the mid 1950's, gaining commercial traction in the 1960's [1]. The non-fired analog of thick-film, polymer thick-film, first appeared in a patent issued in 1944 and has since allowed for printing electronic circuitry onto temperature sensitive substrates such as polyethylene terephthalate (PET) [2]. Since then, thick-film technologies have proven to be a dependable, cost-efficient, and highly reliable method for forming electronic circuitry and components. Hybrid microelectronic circuits were the first major application for fired thick-film materials and has been heavily used in military and aerospace applications, where harsh conditions are often encountered and reliability is paramount. Polymer thick-film enabled membrane touch switches for keyboards, which became widespread in the 1980s [3]. Inner and outer electrodes for passive components have been another traditional thick-film market.

The main drivers in today's electronics are miniaturization, higher circuit density, higher communication frequencies, adaptation to new forms such as 3D, flexible and stretchable substrates, and ecological factors such as reduced energy consumption, waste reduction, and reduction in the use of toxic substances, especially Pb and Cd, driven by RoHS and REACH [4,5]. Thick film technology is equipped to address these challenges as well as others in the future. Thick film has evolved and will continue evolve to facilitate advancements in telecommunications, aerospace, automotive, displays, consumer electronics, and the medical space. Heraeus Electronics, with its extensive and evolving portfolio of thick film pastes and matched systems, will be at the cutting edge of supporting these technological advancements.

II. Advantages of Thick-film

One of the main advantages of thick film is that it is an additive process, where the various conductor, resistor, and dielectric pastes are screen-printed and fired (or cured) in succession to form the circuit. This results in cost-efficient, easily scalable processing for the circuit manufacturer as well as reducing waste associated with subtractive methods. Patterned screens are easy to manufacture, allowing flexibility in circuit design, and screen printing allows for flexibility in feature sizes from hundreds of microns down to 30 microns or less. Screen and emulsion technologies in combination with thick film advancements have facilitated miniaturization via line width reductions as well as lower costs. For instance, Asada Mesh has demonstrated screen printed silver conductor grids ranging from 37 to 22 µm [6]. In Fig. 1, Fraunhofer ISE has demonstrated screen printed 19 µm silver conductor contact lines for a PERC photovoltaic cell [7].

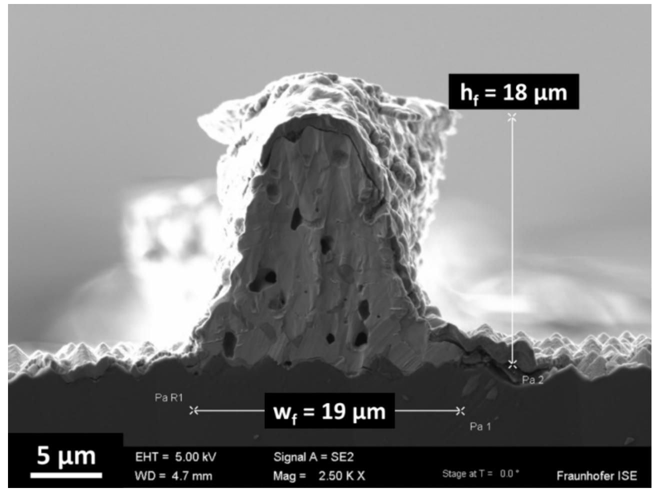

Fig. 1: cross-section of a screen printed silver conductor as demonstrated by Fraunhofer ISE [7]

Thick film paste technology may be adapted to many application methods besides screen printing. Spraying, dipping, syringing, and pad printing are common printing technologies. Printed Electronics may utilize gravure, flexographic, and offset printing.

Proper paste formulation and process optimization ensure matched conductor-resistor-dielectric systems which permit the substrate or device manufacturer to use the same equipment to deposit sequential layers of materials to produce their circuits. Thick film is a versatile technology as demonstrated by its application on a wide variety of substrates. High temperature ceramics such as aluminum oxide (alumina) and aluminum nitride are most common, but matched systems on steel and aluminum are available, which allow for newer thick-film heaters. Fig. 2 shows a hybrid microelectronic circuit, which typically use conductors, resistors, dielectric, and an overglaze [8].

Fig. 3 shows a comparison between the various conductor metallizations. Each metallization has its advantages and disadvantages. Gold is used in the highest reliability applications where the high cost of the bullion is more than justified with low resistivity and exceptional chemical resistance, however it exhibits poor solderability and solder leach resistance. Silver is much less expensive, is solderable, and has the highest conductivity of all the metals; yet it suffers from silver migration, a phenomenon where the silver will migrate from one conductor line to another when exposed to humidity or water, resulting in a short circuit. Migration is alleviated through the addition of palladium or platinum with the penalty of higher cost. Platinum, although expensive, has excellent environmental resistance and is an excellent metal for use in low ohmic resistors with the ability to provide a safety margin for temperature over-run due to its high temperature coefficient of resistance (TCR), 3927 ppm. Copper by far is the lowest cost conductor and is nearly as conductive as silver, but due to it being easily oxidized at elevated temperatures, must be processed and cured or fired in a nitrogen or reducing atmosphere. Copper is also prone to oxidation and environmental corrosion, requiring an overglaze that prevents exposure to air and moisture. The wide variety of properties given by the various metallizations gives the thick film paste user a toolbox for their specific application.

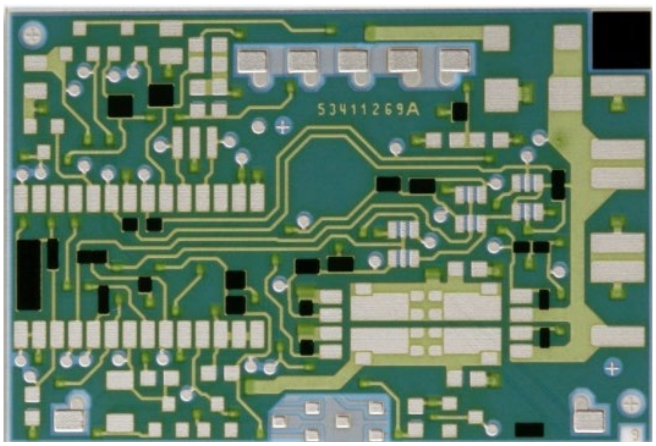

Fig. 2: A typical hybrid circuit. Image courtesy of Continental Automotive GMBH

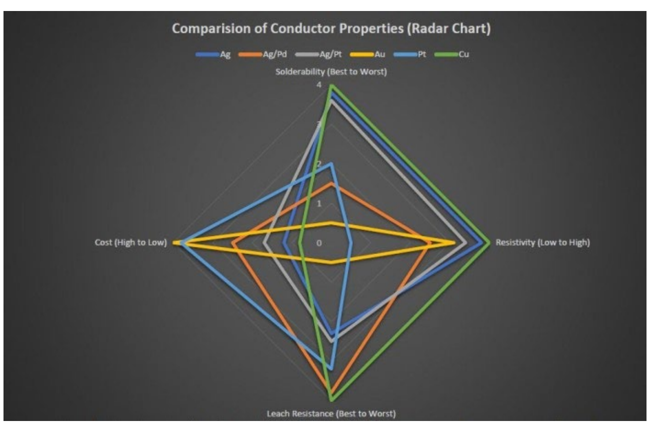

Fig. 3: comparison of conductor properties [9]

Fired thick-film resistors, depending on the resistive filler and application, are available ranging from <0.1 Ω/□ to >1.0 E6 Ω/□ as well as all decades in between. Dielectric pastes are based on the substrate, the metallization being used, firing or curing temperature, and other key application parameters such as break-down voltage and leakage current. This extensive portfolio of pastes gives the circuit designer the flexibility required to build the required circuit.

Polymer thick-film pastes are not fired, but cured at low temperatures, allowing application onto temperature sensitive substrates such as polyethylene terephthalate (PET), polyethylene napthalate (PEN), polyimide, and FR4. Polymer thick-film conductors are largely based on silver with copper starting to emerge as a metallization, resistors based on carbon, and dielectrics allow the circuit designer to build a complete thick-film system for their application.

III. Thick-film in Current and Future Electronics

A. Automotive

Vehicle electronics need to be reliable over an extended temperature range. Depending on the application, this may range from -40 to 80ºC to -55 to 150ºC. Also, the thick film must survive harsh conditions such as the environment and vibration from operating the vehicle. Therefore, the devices and raw materials used must be reliable up to thousands of temperature cycles and 85ºC 85% relative humidity aging as well as other severe electrical testing [10,11]. Thick-film technology has demonstrated proven reliability over the years to perform under these conditions.

Automobiles have historically used thick-film technology in fuel/air sensors, air bag deployment sensors, exhaust sensors, ECU's, and fuel level senders. For fuel level senders, gasoline is particularly corrosive, as it contains sulfur compounds, organic acids, water, and alcohols. This requires thick-film conductor metallizations that are highly resistant to these compounds. Silver migration creates reliability issues with fuel level senders, requiring alloys based on AgPd and, where silver-free alloys are required by the OEM, AuPtPd. As vehicles become fully electric, materials for fuel level senders will be phased out and replaced by thick-film materials supporting the electric vehicle (EV) market, especially thick-film based heaters and sensors as well as displays and touch screens.

Over the years, vehicles have become computers on wheels and have multiple driver assistance sensors, for instance, lane departure warning, blind spot monitoring, automatic braking, and regenerative braking. Already in beta testing are vehicles that are fully autonomous and drive themselves. Still more sensors are required to support safe autonomous driving, for instance lidar, radar, merged lidar-radar, and ultrasonic sensors [12]. Both fired and non-fired thick-film technology are enabling the new sensors.

Non-fired and in some cases fired thick film pastes are also used for heaters for cabin temperature control, rear window defogging, and seat heaters New and near-future applications for thick-film heater pastes, both fired and non-fired, are heaters required for warming sensors in cold environments, heaters to warm batteries in electric vehicles, side mirror deicers, LED headlamp deicers, steering wheel warmers, other in-cabin warmers, and sensor warmers. Positive temperature of coefficient (PTC) carbon resistor pastes are most appropriate for these types of heaters as they self-regulate to a specific temperature without additional controls.

B. Communications

5G communications support the Internet of Things (IoT) through increased connectivity and higher data transmission rates. 5G signal filters utilize highly conductive silver coatings for low losses. These are typically fired thick-film silver conductor pastes. These pastes are expected to be used well into the future as frequencies increase. IoT applications are forecasted to increasingly use flexible hybrid electronics as they are light weight and may replace printed circuit boards according to Dr. Matthew Dyson of IdTechEx [13].

The ceramics used in LTCC are dielectric powders specifically designed for low losses in high-frequency applications and cast into tapes. Emerging in the LTCC space is the use of photoimageable pastes, where etching may be used to build structures finer than screen printing with high edge resolution, for instance 20 um or less. These finer features are especially relevant for high frequency communications up to 100 – 300 Ghz, the vision for 6G communications [14]. Embedded thick-film conductors are already used in LTCC with resistors being actively researched.

Communications devices such as smart phones all have passive components as well as other circuitry that requires thick film materials. A common theme in components is as the electronics miniaturize, the components also have to miniaturize, increasing the demands on the thick film pastes used. Case sizes as small as 006003 (150 x 75 µm) are now available. Thick-film technology continues to rise to the challenge faced in miniaturization of these components through pastes designed for thinner lines and defect-free end terminations.

C. Power Electronics and Renewable Energy

For decades thick-film silver conductors have been used as the front side contact fingers for solar cells and are considered the largest market for conductive inks and pastes [15]. Aluminum thick film pastes are used for the rear metallization. Photovoltaic thick-film pastes are a rich subject that is well represented in the literature [16,17,18]. Thick film has also found its way into power electronics, where not only high electrical conductivity but also thermal conductivity are required. Heraeus has developed a thick-print copper system for bonding copper sheets to alumina and aluminum nitride substrates as a replacement to direct copper bonded substrates (DCB) [19]. Newer thick-film technologies for bonding copper foil to silicon nitride and aluminum nitride, which are highly thermally conductive ceramics, are under development and targeted to replace active metal brazed substrates (AMB) as the most advanced, cost savings solutions for power electronic substrates.

Another use of thick film in power electronics is sintered silver and copper pastes for die attach. These metallizations, typically grouped with assembly materials, are syringe or stencil printed, then sintered at 200 – 250ºC, which results in a metallization approaching the bulk properties of silver or copper while providing excellent die shear adhesion to the substrate. Sinter pastes provide a lead-free alternative to the lead-containing solders commonly used in die attachment.

D. Thick-film in Medical Applications

One of the older thick film applications is glucose testing strips, where silver-silver chloride paste for the counter/reference electrode and carbon-graphite paste for the working electrode are printed onto a polymer substrate. The first electrochemical glucose strip on the market (Fig. 4), made by ExacTech, came available in 1988; now there are numerous suppliers. [20]

Fig. 4: ExacTech glucose sensor

Silver-silver chloride and carbon pastes are also used in continuous glucose sensors as shown in this thesis [21]. There are numerous continuous sensors on the market, for instance the Dexcom G6, the Abbott Freestyle Libre, and the Eversense CGM system. Although the electrode compositions are proprietary, they likely contain thick-film electrode pastes containing silver-silver chloride and a conductor paste for the working electrode.

One of the future growth areas projected for the near and intermediate term are flexible/stretchable electronics for wearable skin patches as well as smart clothing. Here, the printed electronics must be flexible and somewhat stretchable over numerous cycles without losing electrical performance [22]. The patches and clothing, already in existence, will find more widespread application for medical monitoring and performance monitoring for athletics and exercise. Polymer thick film pastes are already used in different types of diagnostic equipment involving blood samples to detect illnesses and will also find more widespread adoption in the medical space.

E. Printed Electronics – New Form Factors

In-mold electronics (IME) is a technology that has been around for several years, however it is finally finding increasing application in automotive, white goods, and consumer electronics. Dr. Dyson mentions that the integration of electronics into molded plastic panels reduces weight and provides a simpler assembly process with lower manufacturing cost while providing excellent in-cabin aesthetics. The thick film pastes used are developed to withstand the thermal-forming process, which uses pressure as well as temperatures above the softening point of the polymer [23].

Flexible electronics, in addition to facilitating medical and athletic monitoring, also allows for foldable/bendable displays and flexible touch screens. Curved displays have already hit the market and are a feature of IME. In September 2019, the first foldable smart phone – tablet was launched as published by LOPEC [24]. Dr. Klaus Hecker of LOPEC further elaborates that foldable and rollable touch screens will become more readily available, further elaborating that the efforts on foldable rollable displays are now on industrializing the manufacture of the displays [25]. Flexible curved touch screens are already found in luxury automobiles and expected to proliferate in the future [26].

F. Thick-film in smart packaging

As reported by Transparency Market Research, thick film-based Printed Electronics enables smart packaging technologies, for instance, prescription reminders, freshness indicators, temperature indicators that show if a product was subjected to unusually hot or cold temperatures, and other product information. Temperature controlled films are used to coordinate shipping logistics for temperature sensitive products [27].

The printed silver antenna for RFID tag has been a focus of Printed Electronic since the early 2000s. However, smart tags with silicon electronics and the supporting conventional circuitry are still used in inventory control of pallet-level goods as well as high value items and RFID toll passes for vehicles. Many in the industry have proposed that an RFID tag must be a penny or less in order to make it into packaging, currently using graphic bar codes that are virtually free. The industry has largely moved on to other applications, but fully printed RFID tags with antennae and organic transistors remains in the background.

G. Thick-film Heaters

More demanding performance and new, unique form factors are expanding the use of thick film materials into new heater applications. The latest thick film heaters are thinner, designed in any shape, and provide higher reliability which opens new markets for customers to be competitive. Thick film technology provides outstanding heating uniformity for devices with matched material systems on a variety of substrates including alumina, aluminum nitride, and several grades of aluminum and steel substrates. This gives the heater manufacturers the flexibility to design heaters over a wide temperature range [28].

As reported by Mordor Intelligence, thick film heaters on steel promise to yield a new class of heaters for numerous applications. Circuits made using the technology can operate at temperatures up to 400°C and target various automotive applications. The devices are produced by combining a thick ceramic dielectric glaze with stainless steel with the resistive material printed on top and, depending on the application, an overglaze. These heaters can be welded, and holes may be added for mounting [29].

In addition to the fired thick-film heaters, Heraeus has polymer thick-film curable materials for heaters printed on PET, PEN, nitrile, and FR4. These are designed to have operating temperatures ranging from below 100 to 250ºC [30]. These types of heaters are used in automotive, which has been discussed earlier, and may be used in other applications, for instance warmers in clothing.

H. Passive Components

Resistors, capacitors, inductors, and other components are needed for each and every electronic circuit. Thick-film pastes are widely used in passives, which use a variety of different printing methods: screen printed inner electrodes, dipped outer electrodes, and spraying. Miniaturization and cost down pressure requires manufacturers to have a large volume, efficient manufacturing process in order to compete as well as the ability to print and apply smaller electrodes and handle smaller parts. This requires pastes that have sufficient green strength to handle the customer's manufacturing process. Also, the pastes must be RoHS – REACH compliant. The Heraeus offering of termination and metallization pastes, with the exception of PZT pastes, are fully RoHS and REACH compliant and have excellent green strength following deposition and drying [31]

Most capacitors are based on base metals, however some of the high reliability and power capacitors as well as other types of passive components will use precious metals to avoid oxidation and possible environmental attack in more severe applications. Precious metal pastes based on silver, silver-palladium, and silver-platinum-palladium are used in PZT components, resonators, filters, capacitors, resistors, varistors, and inductors. Flexible silver termination materials are especially appropriate for vibration sensitive applications, for instance automotive circuitry.

IV. Conclusion

Thick-film technology has continued to show its resilience in keeping up with current megatrends as well as anticipating the future evolution of electronics. From the fully connected automobile as well as other forms of transportation to the infancy of 6G telecommunications and continued growth and required connectivity in the Internet of Things, thick-film continues to be the go-to technology for high reliability and ease of incorporation into the manufacturing process. Medical sensors and monitoring will continue to be a robust market for thick film materials as will be aerospace, displays, and a variety of thick-film heaters serving numerous heating applications. Heraeus will continue to serve these markets through cutting edge products that are RoHS – REACH compliant and show exceptional reliability regardless of the application.

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