HANDBOOK OF SENSORS AND ACTUATORS

Volume 1

Series editor S. Middelhoek

M. Prudenziati (editor)

Thick Film Sensors

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Thick Film Sensors

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Series Editor: S. Middelhoek, Delft University of Technology, The Netherlands

Introduction to the Series

The arrival of integrated circuits with very good performance/price ratios and relatively low-cost microprocessors and memories has had a profound influence on many areas of technical endeavour. Also in the measurement and control field, modern electronic circuits were introduced on a large scale leading to very sophisticated systems and novel solutions. However, in these measurement and control systems, quite often sensors and actuators were applied that were conceived many decades ago. Consequently, it became necessary to improve these devices in such a way that their performance/price ratios would approach that of modern electronic circuits.

This demand for new devices initiated worldwide research and development programs in the field of "sensors and actuators". Many generic sensor technologies were examined, from which the thin- and thick-film, glass fiber, metal oxides, polymers, quartz and silicon technologies are the most prominent.

A growing number of publications on this topic started to appear in a wide variety of scientific journals until, in 1981, the scientific journal Sensors and Actuators was initiated. Since then, it has become the main journal in this field.

When the development of a scientific field expands, the need for handbooks arises, wherein the information that appeared earlier in journals and conference proceedings is systematically and selectively presented. The sensor and actuator field is now in this position. For this reason, Elsevier Science took the initiative to develop a series of handbooks with the name "Handbook of Sensors and Actuators" which will contain the most meaningful background material that is important for the sensor and actuator field. Titles like Fundamentals of Transducers, Thick Film Sensors, Magnetic Sensors, Micromachining, Piezoelectric Crystal Sensors, Robot Sensors and Intelligent Sensors will be part of this series.

The series will contain handbooks compiled by only one author, and handbooks written by many authors, where one or more editors bear the responsibility for bringing together topics and authors. Great care was given to the selection of these authors and editors. They are all well known scientists in the field of sensors and actuators and all have impressive international reputations.

Elsevier Science and I, as Editor of the series, hope that these handbooks will receive a positive response from the sensor and actuator community and we expect that the series will be of great use to the many scientists and engineers working in this exciting field.

Simon Middelhoek

Preface to the Volume "Thick Film Sensors"

Planning this Book appeared soon a very timely enterprise. In fact thick-film technology has already gained a good rank in the families of advanced solid sensors technologies, but the acquaintance with its role and potentialities among sensor experts working both in academic institutions and R&D Labs. appears to be still limited, as witnessed by the restricted number of scientific publications and contributions presented at Conferences and Symposia, dealing with thick-film sensors in comparison to those dedicated to sensors obtained with other technologies.

Therefore a Book on thick film sensors seemed immediately a fine and unique chance of properly disseminating the data concerning the actual performances and applications of thick film sensors manufactured all over the world, as well as of presenting the ideas underlying the current activities in research and development of new devices and suggest possible directions for future areas of investigations.

The basic idea was to provide a guidance in the three major areas in which thick film technology contributes as a sensor technology, namely: hybrid circui[illegible] signal processing (in combination with either thick-film sensing elements or transducing elements derived from other technologies), creation of architectural structures (e.g. multilayer structures, integrated chips with chemical sensing elements, sensor arrays) and transducing elements derived from thick-film pastes.

However the unique properties and chances offered by thick-film technology for sensors manufacture might not be appreciated without emphasis on both scientific and technological features which are either common or distinguished from those of the major alternative technologies, namely silicon, thin films and ceramic, probably better known to most readers.

In this framework a survey of the thick-film processes is offered in Section I; no attempt has been made to give guidelines for the design of hybrid circuits, which can play a prominent role in hybrid integrated sensors, since excellent books in this area already exist. On the other hand some relevant comments on the strategy for designing microstructures of hybrid circuits are presented in Section II, with a general survey on thick film materials, for implementation of thick-film structures and conditioning circuits. The other Sections of the volume are organised according to a classification consecrated by time and convenience, i.e. according to the input energy converted in the output electrical energy/signal. So Sections III deals with devices for conversion of thermal energy (temperature, heat flow), Section IV describes sensors of mechanical quantities (force, pressure, distance, etc.), Section V is devoted to the conversion of chemical and biochemical quantities and Section VI deals with sensors of electromagnetic radiation. An extra Section has been included for dealing with sensors using high-T_c superconductors, an emerging area for sensors prepared with different technologies. Finally Section VIII presents a brief review of dissimilar themes, including actuators and ancillary parts of measuring systems, together with an attempt to envisage the way in which the technical and market evolution of sensors could continue to take advantage of thick-film technology.

Even if care has been paid to present an up to date report of the present state of thick-film sensors and the actual trends, some matter could not be dealt with because of the industrial value of several sensor programmes; moreover it is presumable that the present contents will become obsolete or surpassed by new findings and achievements in a short time, since evolution of thick-film sensors proceeds apace today in many R&D Laboratories and academic institutions actively involved in studies on new thick-film materials, structures and evaluation of thick-film sensors performances.

No attempt has been made to compel the various authors to use a single standard system of units and symbols; but it is though that the reader will be not confused or frustrated by the changes included in the various contributions.

The book might have been a more informative and comprehensive volume if experts in specific topics could have contributed as authors; unfortunately some of them have be compelled to recede the invitation, or even withdraw from the commitment to participate, for various reasons.

I would take the opportunity here to thank Prof. S.Middelhoek for his invitation to edit this volume. It is my pleasure to thank my colleague Prof. Bruno Morten for his encouragements, critical reading of contributions, and chiefly for the silent and appreciable support in continuing the academic activities which I have not attended during the period of planning and editing this volume. Many thanks to Profs. D.Andreone, G.Gallinaro, C.M.Mari , M.Mascini, S.Pizzini for the critical reading of contributions. The assistance of my graduate students (especially M.Bersani) and fellowship Dr.G.M.Mihai, in editorial passages is greatly acknowledged.

Maria Prudenziati
Modena

February 1994

Contents

Section I. THICK FILM TECHNOLOGY

Thick-film technology
N.M. White

Thick Film Sensors / M. Prudenziati (Editor)

Thick film technology

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INTRODUCTION

The history of thick film technology can be followed back to the 1950s when it was envisaged that the thick film process would merely be a replacement for the printed circuit board process. Many of the early resistor materials were based on silver, carbon and various copper oxides and they exhibited inferior electrical characteristics to those of the competing technology. With the advent of the semiconductor integrated circuit in the 1960s and the appearance of palladium-based resistor materials the thick film *hybrid* circuit materialised. It soon became clear that the result of fabricating together components made by different technologies could open up a whole new field of electronics.

Even in the mid-to-late 1960s, thick film processing was capable of producing fine line conductor geometries, thereby allowing a high component packing density on a single substrate. As we shall see in later sections, the essence of today's modern thick film process is almost identical to that used thirty years ago. However, modern thick film paste compositions allow an expansion into areas which, in the early days, must have seemed nothing more than an academic pipe-dream.

1. FUNDAMENTAL ASPECTS OF THE PROCESS

A thick film circuit is normally considered to be one which comprises layers of special inks (or pastes) deposited onto an insulating substrate. With the addition of integrated circuits, and sometimes films formed by other technologies, a hybrid circuit is realised. One of the key factors which distinguishes a thick film circuit is the method of film deposition, namely screen printing, which is possibly one of the oldest forms of graphic art reproduction. The deposition process for a thick film circuit is essentially identical to that used for traditional silk screen printing. The main differences being the screen materials and the degree of sophistication in the printing machine. A typical thick film screen consists of a finely woven mesh of stainless steel, nylon or polyester, mounted under tension on a metal frame. The mesh is coated with an ultra-violet (UV) sensitive emulsion onto which the circuit pattern can be formed photographically. The finished stencil has open mesh areas through which the desired pattern can be printed and is held in position at a distance of around 0.5 mm from the top surface of the substrate. The ink is placed on the opposite side of the screen and a squeegee traverses the screen under pressure, thereby bringing it into contact with the substrate and also forcing the ink through the open areas of the mesh. The required circuit pattern is thus left on the substrate. The next stage of the process is to dry the film to remove the organic solvents from the paste. This task can be performed in a conventional box oven but is more often accomplished with an infra-red belt drier. After this stage the dried film is relatively immune to smudging and the substrates can be handled. Sometimes it is permissible to screen print the next layer directly after the drying stage, but this really depends on the nature of inks being deposited.

The films themselves contain fine powders which must be exposed to a high temperature in order to form a solid, composite material. This is often referred to as *sintering*, and is achieved in a belt furnace. The furnace operator has control over a number of parameters including peak temperature, dwell time and throughput speed. Some inks are very sensitive to variations in these parameters whilst other types show little dependence on process parameter variations. All thick film inks contain glass, and during the firing cycle the glass melts and forms a mechanical key at the film-to-substrate interface and also provides a suitable matrix for the active material of the film. The result is a fired composite film which is firmly bonded to the substrate. Further screen printed layers may be added after firing if necessary.

For thick film hybrid circuit applications further production stages are needed. Active devices such as transistors, integrated circuits, diodes etc. are usually soldered on to the thick film conductor pads. There are a number of different ways of applying the solder; one possible method is to screen print using a special type of screen and printable solder paste. Some hybrid circuits also require the addition of naked chips which need to be mounted and wire bonded out to suitable substrate connections. Inevitably, there is always tolerance of around ± 20% on a thick film resistor and for some applications this is not acceptable. A further processing step is needed for trimming the resistors, and this is accomplished using either a laser or an air-abrasive technique. The penultimate processing stage involves packaging the thick film circuit. The hybrid circuit designer is faced with a wide range of different packages and careful choice must be made. The decision will largely be influenced by the required application of the circuit, but the usual engineering compromise of quality and cost prevails. After the circuit has been fabricated, the final step is to assess the quality and ensure that the performance is within specification.

2. DESIGN AIDS

Generating the artwork for thick film screens was once a time consuming task. The master pattern was produced by one of several methods including tape strips and decals, drawing and inking and cut-and-peel techniques using materials such as Rubylith and Stabilene. Each of these methods offers its own advantages but, in general, it is difficult to achieve sharp edges, positional accuracy and uniform density with these techniques. Correcting for even the most minor errors can prove to be a tricky and often time consuming task.

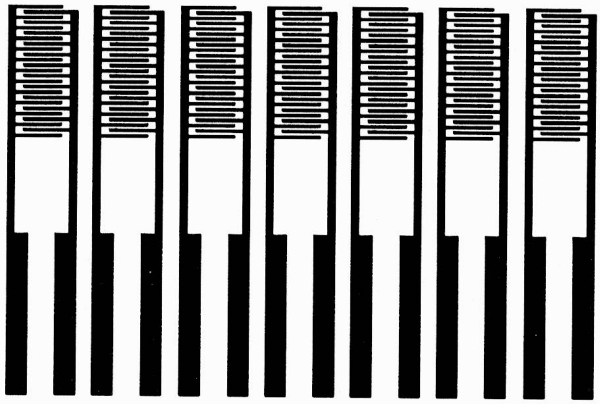

Figure 1. Computer generated layout of a sensor array.

Modern desk-top computer systems possess excellent graphics facilities and allow a variety of input devices (mouses, joysticks, trackerballs etc.) to be used. Many commercially available software draughting packages exist which allow the thick film engineer to produce computer-generated artwork in a fraction of the time needed with some of the manual techniques described above. Figure 1 shows a thick film layout for an array of interdigitated electrode patterns used for a number of sensor applications [1]. The track width and spacing of the 'fingers' of the electrode pattern are 200 microns wide. A drawing like this can be generated in a matter of minutes with the most basic of software packages. Use of facilities like the step-and-repeat command allow areas of the design to be copied quickly and efficiently. A similar layout produced by cutting and peeling a Rubylith sheet would take significantly longer.

Once the design has been completed on a suitable software package, the next step is to verify that the design rules regarding track width, track spacing, etc. are not violated. Different thick film manufacturers will have different design rules depending on the quality of the processing facilities available to them. However, as discussed later in § 9.1, there are some sophisticated software packages available specifically for thick film hybrid circuit design, which provide, amongst other facilities, the ability to automatically check the layout against a set of design rules which can be modified to suit each individual users' processing capabilities. Assuming the computer layout conforms to the design rules then the next phase in the design process is to generate a hard copy of the design. The exact form of this copy can take one of several forms depending on the equipment available to the user. For example, many thick film screen manufactures will accept artwork in either positive or negative form scaled up by 2, 4, 5 or 10 times the required size. This was certainly a common method for screen generation when cut-and-strip processes were used, because the magnified artwork is subsequently reduced photographically thereby minimising errors which may have occurred on the original artwork. With the advent of accurate photoplotters, it is now possible to take the layout and accurately reproduce it on photographic film directly, so that it can be developed and fixed ready for screen manufacture. Alternatively, conventional office equipment like laser printers and plotters can be readily used to generate magnified images of the required layout which are of acceptable quality to be sent directly to the screen manufacturer.

3. SCREENS

The screen defines the pattern of the printed film and also meters the amount of paste which is deposited. It is a very important part of the screen printing equipment, and is essentially a stencil through which the paste is forced during the printing process. The most common type of screen comprises a frame, normally cast aluminium, onto which a finely woven mesh is stretched. The mesh itself is usually based on a plain weave pattern as depicted in figure 2. Some important properties of the screen mesh are: the size and density of the mesh strands (usually quoted in terms of lines per inch), the tension, the orientation and the mesh material.

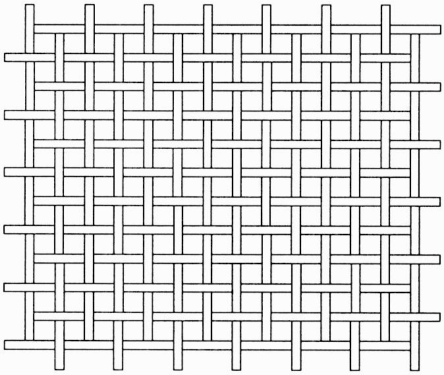

Figure 2. A plain weave pattern for a typical thick film screen.

The selection of a suitable mesh count for a screen is a very important criterion. Factors which may influence this choice include the required line definition of the pattern and the type of paste being used. For general purpose work a typical mesh count might be 200 strands per inch. The mesh opening depends on the mesh count and the filament diameter. For a given mesh count, the smaller the filament diameter, the larger the mesh opening which will therefore allow a greater volume of ink to be deposited onto the substrate. Hence, the mesh opening provides one of the means of controlling the thickness of the deposit.

Figure 3 shows a cross-section of a mesh and defines some of the terms used. One common term is the percentage open area of mesh which is defined as follows:

$$\text{Percentage open area} = \frac{100A^2}{(A+D)^2}$$

where A is the mesh aperture and D is the filament diameter.

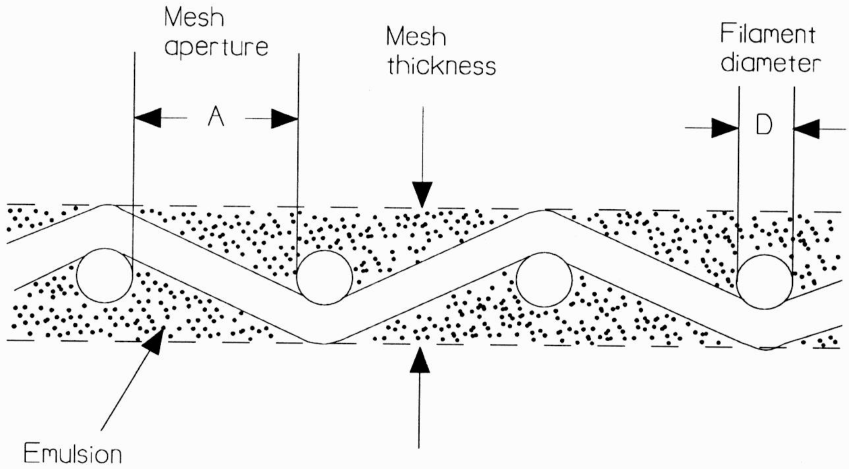

Figure 3. Cross-section of a screen mesh.

It is possible to obtain the screen mesh aligned in several orientations, the most common three mesh angles are 45^0, 90^0 and 22.5^0. A number of factors need to be considered when choosing the mesh angle. A 45^0 mesh provides the maximum flexibility for the stretched fabric but may produce a serrated edge on conductor lines which are aligned in parallel or at 90^0 with the direction of the squeegee. It is possible that a 90^0 mesh angle may cause a fine line to disappear altogether if the filament coincides with the line. In view of these matters the 22.5^0 mesh angle was adopted as a compromise.

The screen emulsion is usually a polyvinyl acetate or polyvinyl alcohol sensitised with a dichromate solution. Many screen manufacturers apply the emulsion by hand coating, a skilled process which can accurately produce a standard range of thicknesses (typically 13 to 23 microns).

3.1. Mesh materials

The three most common materials used for thick-film screen meshes are polyester, nylon and stainless steel. Each has its own advantages and disadvantages but before these are discussed in detail it is important to mention some of the fundamental requirements for all screen fabrics.

The screen acts as a metering device to control print thickness, and hence it is essential to ensure that the mesh material achieves uniformity of the printed deposit. Therefore the mesh material must be precisely and evenly woven and possess uniform mesh apertures. The fabric should also have suitable flexibility to enable good contact over all areas of the substrate. This is particularly important if the substrate itself is not exactly flat. Sometimes (though not very often) there are requirements to print onto non-planar substrates (even cylindrical!). The fabric