FABRICATION OF THICK FILM CIRCUITS

by 1264

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A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

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KANSAS STATE UNIVERSITY
Manhattan, Kansas

1969

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CHAPTER I

INTRODUCTION

Thick film technology is one of the recent technologies used in the manufacture of integrated circuits. Although it was introduced as a production process only about six years ago, it has now become a leading subject for discussions not only in the electronic trade press but also at important technical conferences throughout the year.

The facts indicate that this technology will be around for a long time to come in the field of microelectronics where rapid developments in materials and technology continue to make processes obsolete at an alarming rate. Some of the main reasons for this are:

i) The yield is very high and this results in low running costs.

ii) The capital investment is low because the process does not require sophisticated machinery to produce sophisticated circuits.

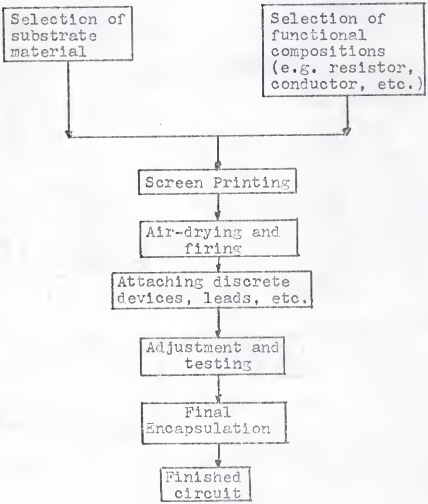
iii) The simplicity of the process makes it easy to understand and easy to translate it into sophisticated circuits, even for an electronics layman.

iv) It is easily adaptable to high speed, large scale, computer controlled manufacturing.

What are thick films?

"Thick films", in modern electronics literature, is a term which refers to the process (and the materials) used to manufacture one type of hybrid microcircuit. It does not signify the thickness of the film but rather the way it is made. It is 'screened and fired-on' film in contrast to thin films which are produced by other processes such as vacuum deposition, sputtering etc. It may be said that thickness of thick films may range from 100 A^{o} to few microns. Although the term "thick-films" has gained acceptance as a term describing the technology, some other terms are also used, viz., cermet films, screened and fired films, metal glaze films, etc.

Production of thick film circuits involves a number of unit operations as well as the selection of functional raw materials as illustrated in the following flow chart.



The purpose of this thesis is to demonstrate how simple it is to set up the process and how, without any special skill, sophisticated circuits can be fabricated in the simple set-up.

CHAPTER II

LITERATURE SURVEY

Although thick film production technology is only six years old, its principle is the same as the old graphic-arts process. Nevertheless, the parameters of thick film technology are more in number and are more critical as compared to those of the graphic arts process.

The properties of a thick film circuit depend a great deal on its parameters. It is therefore necessary that they should be fully understood by the circuit designer.

Substrates:

The substrates over which thick films are to be deposited should be chosen critically. This is because the yield is badly affected should the substrate become damaged in the process. The criteria (26) by which substrates are chosen are:

i) Thermal conductivity which must be compatible with those of inks.

ii) Size which depends on the type of packaging and the circuit complexity.

iii) Strength which should be enough to sithstand normal vibrations.

iv) Surface finish and flatness.

Alumina is the normal choice of the material for substrates because of following reasons.

i) Alumina is obtainable in consistent pure form.
ii) It has reasonably good surface finish as compared to glass, steatites and fosterites.
iii) It has better thermal and strength properties than those of glass.
iv) It has no toxicity hazard unlike beryllia.

Typical substrate specifications are as follows:

i) Alumina content (95%)
ii) Density (3.75 to 3.90 gm/cm^3)
iii) Dimensional tolerances: Along with the main dimensions, other specifications such as the number of holes and their pitch should also be stated.
iv) Surface finish: 'Peak or valley' distance should be within 20-30 microns.

Inks (or Compositions)

One of the most important parameters of thick film technology is ink. In fact, it would be no exaggeration to say that this technology owes its present day status to the developments in the various kinds of inks.

The two main inks required for making thick film circuits are resistor and conductor inks. As will be seen a little later, the properties of inks vary widely. However, they are all available in a paste form and mainly consist of:

i) Finely divided precious metal powders
ii) Special glass powders

iii) Temporary organic portion

iv) Solvent portion

These ingredients are mixed together to form a viscous paste. After the inks are deposited on the substrate, they are air-dried at 100 to 150 °C to get rid of the solvent which evaporates away. Then the inks are fired in a furnace (usually a continuous belt furnace) at temperatures ranging from 750 to 1100 °C, depending upon the exact composition. During firing the temporary organic vehicle decomposes and the specially formulated glass particles sinter into the surface of the substrate. As a result, the ink pattern now becomes a part of the substrate.

Resistor Inks

Chemically, resistor ink is very complex. The resulting parameters of the resistor are subject to variations in processing.

The important parameters (and their ranges) of thick film resistors are:

i) Resistivity: 1 ohm/sq. to 15-20 k ohms/sq.

ii) TCR: 25-50 to 200-300 ppm

iii) Noise: 25 db to 10-20 dB

iv) Stability: About 0.5% drift under normal operating conditions.

A number of inks are available with different values of sheet resistivity. They can be further blended amongst themselves to obtain intermediate resistivity values. Other factors which control resistor parameters are:

i) Screening direction

ii) Shape of the resistors (e.g. narrow, broad, short, long, etc.) has different effects with different inks.

iii) Adjacent components: for example, a previously deposited capacitor prevents screen forming at the surface due to its thickness. This leads to non-uniformity both in thickness and edge definition.

TABLE I. Commercially available resistor inks:

Vendors	Cost/gm.	Sheet resistivity	TCR	Composition
Du Pont	.70	100-15K	< 250	Ag Pd glass bound
Electro-chemicals	4.0	50-20K 50K-1M	< 100 < 300	Iridium family glass bound
Electro-science	.90	1-100K 100K-1M	< 250 < 250	Ag Pd glass bound
Alloys Unlimited	1.30	10-100M 1M-10M	< 250 < 500	New Composition (not Ag Pd)

Conductor Inks

Conductor patterns have to perform varied tasks such as terminating, interconnecting, providing connection pads which make contact to outside world, etc. The conductor ink is therefore required to possess many properties other than the basic one, viz., conductivity. These are:

i) High adhesion to substrate
ii) Compatibility with other printed materials
iii) Bondability to solder, ultrasonic bonding and thermocompression bonding.
iv) Resistance to solder 'leaching'.
v) Resolderability
vi) Resistance to ageing.
vii) Good line definition
viii) Resistance to migration under an electric field.
ix) Refirability

The following table compares various characteristics of conductors and resistors for two main kinds of inks. It also gives an idea of the diversity of tasks inks have to perform.

TABLE II. Comparison of Ag:Pd and Au:Pt conductor inks

Characteristic	Ag:Pd	Au:Pt
i) Flow Control	In formula	May require thickening
ii) Porosity	Very dense	Somewhat porous
iii) Adhesion-tensile	2300-4000 psi.	2500-4000 psi.
iv) Compression resistance	150K psi.	85K psi.
v) Chip strength (3 pads)	300 gms.	240 gms.

TABLE II. (Cont'd)

Characteristic		Ag:Pd	Au:Pt
vi)	Flow change, humidity	none	observed
vii)	Conductivity(untinned)	6-10 times greater	
viii)	Tinned TCR	7-11%	18-19%
ix)	Resistor drift	Equivalent	slightly better
x)	Resistor TCR	Equivalent	no electrical difference
xi)	Resistor cracks		
xii)	Contact resistance		
xiii)	Interface hotspot		
xiv)	Intermetallic problems	better	
xv)	Tinning yield		
xvi)	Corrosion		
xvii)	Migration		better
xviii)	Volatility	non volatile	volatile
xix)	In house resistor compatibility		incompatible
xx)	Settling in jar	no settling	settling
xxi)	Paste consumption	30% less	
xxii)	Cost	$10/oz.	$60/oz.
xxiii)	Resistance scaling		better

<u>Special Inks</u>

a) High adhesion conductor ink

The package configurations require lead terminals which are subjected to bending and peeling stresses. This led to the development of high adhesion inks.

b) Fine line printing conductor ink

Until recently, most conductor lines used to be 50 mils wide. As the electronic circuits diminished in size, line width of conductors also had to be reduced and lines narrower than 10 mils were required. This special requirement led to the development of high viscosity fine line printing conductor inks.

c) Inks for eutectic and thermocompression bonding

These inks of gold and gold alloys are designed to provide easy die bonding of transistor chips and integrated circuit dice to thick film microcircuits.

d) Crossover ink

This ink provides an insulating layer between conductor compositions and is printed after the first conductor pattern is fired. The crossover ink is a viscous paste containing a glass phase finely divided in an organic vehicle system suitable for screen printing. It has a low value of K (approximately 6 to 9),dissipation factor less than 2% at 10 kHz. and has excellent compatibility with conductor inks.

e) Dielectric inks

As may be expected, this ink has high value of K (from 400 to 500). It also has low dissipation factor (less than 2%) and low TCR

Typical capacitors have a fired thickness of 2 mils.

Capacitance densities ranging from 4000 to 10,000 pf/sq. cm. can be produced depending on electrode materials, dielectric thickness and firing temperature.

The bottom electrode is printed and fired before cofiring the top electrode and the dielectric, thus only two firings are needed to make a capacitor.

f) Encapsulating ink

This ink is designed to provide a moisture and gas resistant coating over resistor inks. It is fired at 500 °C and thus changes in the previously deposited resistor values are minimized. The surface of the encapsulant exhibits a matte texture. Resistor trimming by air abrasion techniques can be accomplished through the fired encapsulant. The coating also serves as a protection for the resistor against grit abrasion from overspray during trimming.

Process Variables

The technique of depositing ink on to a substrate through a screen using a squeegee is called screen process printing. This is an important process and has many parameters (11,17) which have to be controlled critically to obtain a good yield.

The first step is the preparation of screens. The two methods of screen preparation are called "Direct stencilling" and "Indirect stencilling". These will be discussed in detail in the next chapter.

The prepared screen is placed in a machine called a screen printer which may be manual, semi-automatic or automatic depending on the rate of production. In this machine the pattern on the screen is printed with the appropriate ink on properly aligned substrates.

The screen process printing is not so complicated as compared to most other production processes in the electronics industry. Even so, there are numerous small detail factors which may cause variations in the expected results. Some of such factors, conveniently grouped, are outlined below.

A) Squeegee area variable factors
    1. Type of material, hardness, etc.
    2. Size and shape of edge
    3. Method of applying pressure
    4. Amount of pressure applied
    5. Uniformity of travel
    6. Speed of travel
    7. Ratio of squeegee size and stroke to screen size
    8. Cleaning of screens

B) Screen area variable factors
    1. Mesh count
    2. Wire diameter
    3. Type and thickness of pattern coating
    4. Alignment of pattern with mesh
    5. Flatness of screen
    6. Tension in mesh
    7. Method of mounting of mesh and frame.

C) Ink area variable factors

  1. Composition of inks
  2. Vehicle used
  3. Viscosity of ink
  4. Rheology
  5. Homogeneity

D) Substrate area variable factors

  1. Materials used
  2. Surface finish
  3. Camber
  4. Parallelism of surfaces
  5. Tolerance of dimensions

E) Printer or Printing equipment

  1. Off contact v/s contact operation
  2. Parallelism of screen to substrate locating and positioning surface
  3. Parallelism of squeegee to screen and work holder throughout its travel
  4. Rigidity of frame-work holding screen, squeegee and work holder in proper relation
  5. Type of work holder for substrate
  6. Method of registering screen and substrate
  7. Speed of operation

F) Post-Print area of variable factors

  1. Method of handling
  2. Timing
  3. Settling

4. Type of dryer
5. Drying cycle
6. Furnace design
7. Firing cycle
8. Air flow
9. Method of trimming

Theory of Screen Process Printing

It is clear from the above that squeegee area variables are more critical than the rest. In order that their effect is minimized if not eliminated, a thorough knowledge of squeegee printing is necessary.

Assuming off-contact printing, the squeegee may be assumed to deflect the screen as shown in Fig. 1. The amount of deflection depends on the 'breakaway' distance or off-contact

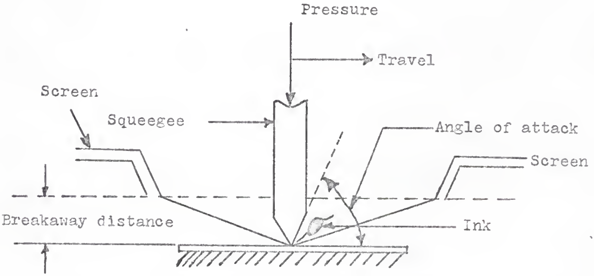


Fig. 1. Terminology of screen process printing

setting. The point of contact between the screen and the substrate moves across the screen as the squeegee is wiped for printing. It is assumed that at this point of contact the squeegee fills each mesh opening with ink which is later deposited on the substrate in the form of individual miniature columns when the screen snaps away behind the squeegee (see the figures 2 and 3).

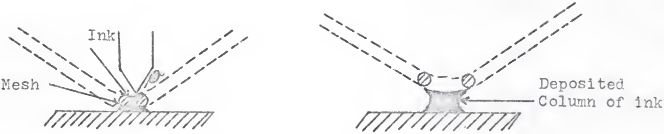


Fig. 2. Depositing of a "column of ink"

It may be noted that: -

i) A moving blade under pressure but perpendicular to the screen will not force ink through the mesh.

ii) Mosts inks will not themselves flow through the mesh because of their viscosity.

iii) A squeegee with an attack angle will force the ink through the mesh only when it is moved across the screen.

iv) A squeegee is restricted by the mesh from pushing the ink directly down the substrate.

This discussion may be summarized to explain the mechanism of printing as follows:

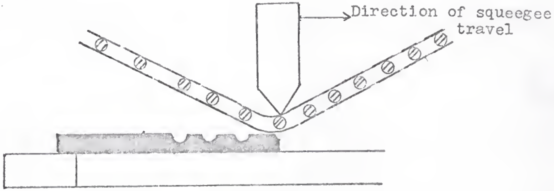


Fig. 3. Deposition of a series of ink columns

A hydraulic pressure on the ink is developed by the squeegee pressure and the movement of the squeegee. The pressure is a function of the attack angle. This pressure is responsible for filling up the openings of the mesh with ink. The transfer of ink on to the substrate takes place by the combined action of reduced hydraulic pressure (reduced when squeegee moves further away) and the snap back in the mesh.

Trimming of resistors

The component value obtained by screen printing and subsequent firing is only approximate. To get the desired accuracy, the resistor has to be trimmed. Trimming is a process in which some of resistor material is abraded away, whilst monitoring the resistance until the required value is reached. Usually the abrasion is carried out by forcing a jet of alundum powder through tiny nozzles. This process is called sandblasting.

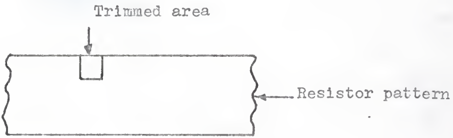


Fig. 4. Resistor trimming

The eroded area appears as a halo around the cut edge of the resistor and contributes to the resistor drift. Hence this area is kept to a small percentage of total resistor area. A resilient coating applied to the resistor prior to its trimming minimizes this effect.

Although sandblasting is the main tool for abrading, it is not free from problems: trouble is encountered with dust and non uniform stress in substrates. To avoid these problems an ultrasonic chisel may be used. A laser beam may also be used to remove a complete thickness or to irradiate the whole surface without heating the material below. In a more recent technique, the basic structure of the resistor is altered by a high voltage, high frequency pulse. It is conjectured that this current alters the band structure between particles. This effect is not subject to subsequent annealing.

Packaging

There are no standard packages for large area thick film hybrids. Instead, there are a number of packaging approaches and a large variety of special packages. In any case either

The substrate becomes a part of the package or it is enclosed by the package. If the substrate is enclosed inside the package, it is attached to the package by

i) Sticking together the bottom surface of the substrate to the appropriate surface of the package, or

ii) Brazing the internal leads of the package to the terminal pads on the substrate after slipping the substrate under the internal leads. These internal leads function both as electrical connections and as mechanical attachments of the substrate and the package.

One of the least expensive methods of sealing the thick film circuits is to use a plastic or epoxy coating. Before moulding the fully assembled circuit in the epoxy, the flying leads from chips are coated with a silicone material which remains soft during the entire life of the device. This inexpensive process is not proven reliable and hence is not yet accepted as adequate protection for military and space applications.

For reliability, the most suitable method of packaging is placing the thick film circuits inside hermetically sealable packages. Typically, the packages have a ceramic or a metal base and a ceramic or glass lead frame around the periphery. The leads pass through a metal or a ceramic lid, a metal sealing frame and glass metal region to the outside.

Discrete Components

The hybrid thick film circuit is the result of efforts to diversify the utility of thick films. It is a combination of a thick film network and discrete devices. The attached discrete devices may be active or passive. In order to achieve maximum volumetric efficiency, most of the attached components should be of same height.

The hybrid approach is often considered a means to improve systems packaging. Thus the use of discrete components revolves around the systems packaging concept. It is also desirable to have as few attached passive components as possible inside the module. Frequently active components are preferred to passive ones for cost considerations. For example, a transistor which sells for 12¢ a piece in large quantities may replace a 10 microfarad capacitor costing 55¢ a piece in large quantities.

Capacitors

Capacitors, less than a few hundred picofarads in value, are generally screened by the thick film process. However, for close tolerances and large value capacitors, it is cheaper to use capacitor chips of barium titanate. These chips can be obtained in sizes from .02 by .02 inch to .125 by .125 inch with values from 10 picofarads to 5600 picofarads.

Active components

Signal diodes and small signal bipolar transistors form the bulk of active devices used in thick film hybrids. Other specialized devices such as field effect transistors, microwave transistors, etc. have recently become available and are playing a very important role in hybrid circuit work. These devices may be classified into four major categories. Within each category there are numerous package variations. The five categories are:

i) Conventional chips

The chips have planar structure and are produced by the manufacturer for his own use. In general, the contact material is aluminum but gold is also used in special cases. The topside contacts are connected to other components by means of some form of wire bonding.

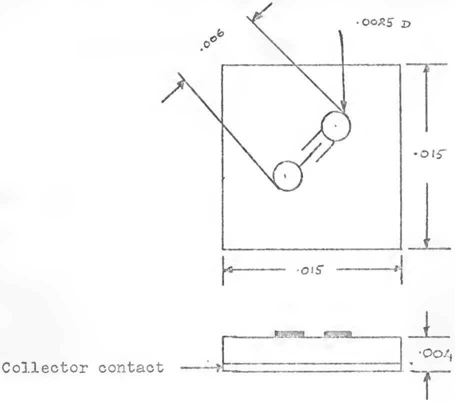


Fig. 5. Typical conventional chip

ii) Flip chips

The flip chips are designed specifically for use in hybrid circuits. All contacts are on the same side of the chip and

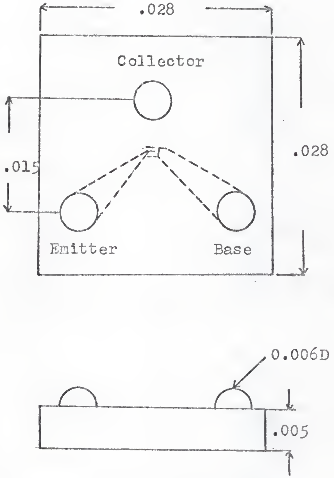


Fig. 6. Typical flip chip

consist of protrusions from its surface. The protrusions are solder-clad spheres or pillars about 6 mils in diameter. They are called flip-chips because they are "flipped" over in mounting so that the contacts touch corresponding conducting lands on the substrate. Then, on application of heat, the solder flows from contact to land.

iii) Ceramic flip chips, Channels, LIDs

This approach combines some of the advantages of conventional chips and flip chips. Fig. 8 shows a typical configuration.

Base: Ceramic
Contacts: Gold
Encapsulation: Epoxy or open

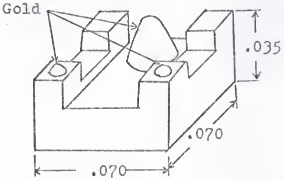
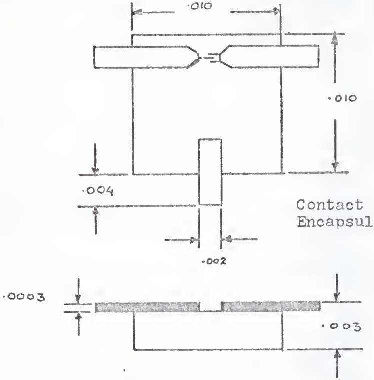


Fig. 7. Typical ceramic flip chip

A ceramic block has metallized lands for mounting on a conventional chip and making wire bonds to it. After mounting and encapsulating the chip in the ceramic, it may be "flipped" and attached to the circuit on the substrate by soldering. It is also called a "LID" for "leadless inverted device".

iv) <u>Beam lead devices</u>

Beam lead devices eliminate the need for large bonding pads. Their name is derived from their leads which are relatively large and heavy. They are formed by multiple vacuum evaporations before the slice is subdivided into chips. Beam lead chips can be made smaller than conventional chips. These devices are used in high performance applications since their parasitics are very low.



Contact material: Gold
Encapsulation: S_1O_2, Glass; or other insulator

Fig. 8. Typical beam-lead device

Mounting and Bonding Techniques

The passive and active devices are attached to the substrate by one of the following methods.

i) Alloying: This is the most satisfactory method for mounting conventional chips. The chip is held against a hot substrate (heated to 380-450 °C) until the gold-silicon eutectic alloy on its back surface melts and flows. "Scrubbing" the wafer back and forth may be sometimes necessary to promote the melting.

ii) Conductive epoxy: The high temperatures required for alloying can be avoided by using conductive plastics. However, these epoxies are not too reliable in long term stress, and their contact resistance is high. Even so, they offer a neat solution to otherwise a difficult problem.

iii) Thermocompression bonding: This bonding is based upon the principle that two reasonably clean metal surfaces form a molecular bond under sufficient heat and pressure.

Ball and stitch bonding (fig. 9) is probably the most widely used version of thermocompression bonding. It is extremely reliable when properly done.

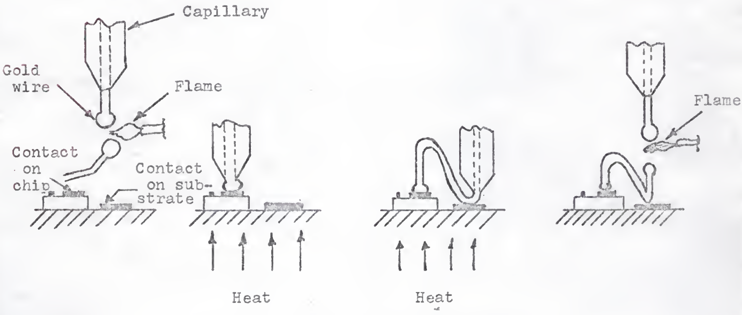


Fig. 9. Ball and stitch bonding

iv) Ultrasonic bonding: This is used when bonding aluminum and aluminum or when heat must be avoided. The aluminum wire is forced against a pad by a tool which is then vibrated in a direction parallel to substrate ultrasonically (usually at 60 kHz.) The locally produced heat and the pressure cause two parts to bond.

v) Soldering and welding: The advantages of soldering are low temperature and simplicity of equipment. With properly controlled spot welding the heat can be confined to a very localized area.

Multilayer Techniques:

Multilayer techniques are the outcome of attempts to maximize device density on surfaces of ceramic substrates. One approach is "Surface screening". In surface screening, different layers such as conductor layer, resistor layer, etc., are screened and fired alternately. It was two main problems.

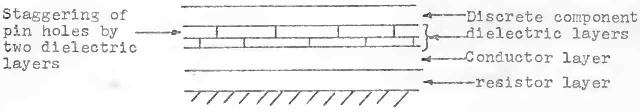


Fig. 10. Pin hole problem

The first one is the pin-hole problem which can be solved by screening two dielectric layers (fig. 10) so that no pin holes

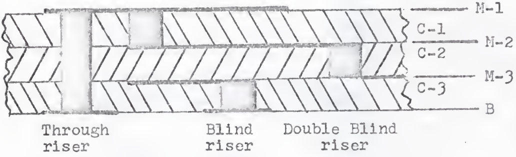


Fig. 11. Buried layer terminology

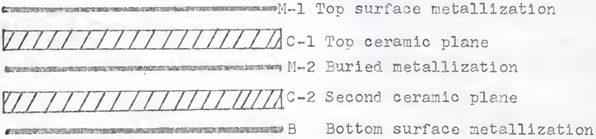


Fig. 12. Buried layer terminology

overlap. But this gives rise to the second problem, viz., excessive thermal stress in the substrate.

The second approach is to bury the interconnecting wiring in alumina. Highly conductive buried metallization and small diameter riser holes allow active and passive components to be positioned with close proximity.

Semifinished multilayer structures (22) are available. These contain only buried wiring and conductive risers and can be further processed for individual needs, by screening and firing on top and bottom layers. Ref. (22) gives details of the design of thick film circuits using multilayer techniques.

Mechanism of Conduction in thick Film Resistors:

As mentioned earlier, thick film resistors are chemically very complex. The precious metals in a resistor ink, are generally palladium and silver. Since the firing is done in an oxidizing atmosphere, the following two reactions take place.

$$\text{i)}\qquad Pd \xrightleftharpoons[550\ ^{o}C]{O_2} PdO$$

$$\text{ii)}\qquad PdO + Ag \xrightleftharpoons[650\ ^{o}C]{O_2} PdAg + O_2$$

The reactions do not reach completion while the substrate is in the firing zone of the furnace. The amount of silver also controls the degree of reaction and hence the amount of PdO present in the final form. Thus the sheet resistivity and the TCR are determined mainly by the temperature profile to

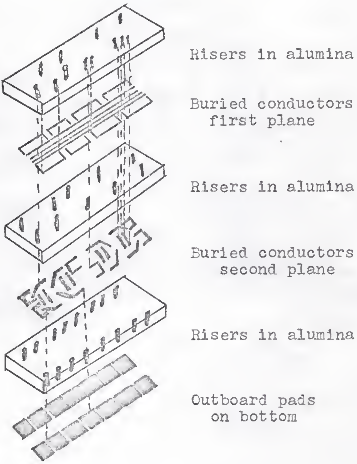


Fig. 13. Multilayer ceramic wiring structure (DDU) general purpose for four digital ic's

which the ink pattern is subjected and the amount of silver present.

Although the conduction phenomenon in thick film resistors is complex, it is reasonable to assume that conduction consists of three components.

i) Metallic conduction in the alloy PdAg,

ii) Semiconduction in the oxide PdO, and

iii) Quantum - mechanical conduction in the glass.

It is interesting to note that while the metallic conduction exhibits positive TCR, the latter two conducting modes exhibit negative TCR.

CHAPTER III

MANUFACTURING EQUIPMENT

As mentioned earlier, the cost of setting up a line for the manufacture of thick film circuits is relatively low. The following two tables (1, 25) represent the equipment required to set up such a line. It is very interesting to note that the total cost for these separate lines is the same, viz., $50,000.

TABLE III. Cost of manufacturing equipment I

Screening machine	$ 5000
Kiln	$ 13000
Hot plate for airdrying substrates	$ 200
Abrader for trimming	$ 10000
Soldering machine	$ 11000
Miscellaneous	$ 20000
Total	$ 50000

TABLE IV. Cost of manufacturing equipment II

Dispersing equipment	$ 1500
Jar rolling mill	$ 500
Stencil screens	$ 500
Screen printing machine (2)	$ 13000
Drying oven (2)	$ 4500
Continuous belt lehr (2)	$ 25000
Adjusting equipment	$ 1000

TABLE IV. (Cont'd)

Soldering equipment		$ 3000
	Total	$ 50000

N.B. In this table two screening machines, two drying ovens and two furnaces are included to maintain a continuous flow of two kinds of circuit patterns, e.g. resistor and conductor patterns, simultanuously.

The equipment for producing thick film circuits is far from standardized. However, the equipment is selected to perform following main functions:

A. Testing substrates
B. Paste preparation, viscosity control, etc.
c. Screening, control of paste deposit, etc.
D. Firing, temperature and time control
E. Adjustment (Trimming)

Testing Substrates

i) Surface finish: True surface finish is conveniently measured by a method which uses the light sectioning tester principle. Ref. 26 gives different photographs which illustrate the nature of surface and fissures between the grains detected by this method.

The flatness is probably the least controlled parameter in the manufacture of substrates. At present obtainable surface flatness is .005 in./in. and this presents problems in obtaining a meaningful snap-off distance between the screen and the substrate, (The snap-off distance is usually between .020 in. and .1 in.) and results in squeegee deformation.

ii) Expansion coefficient: The effect of expansion coefficient is to generate stress in glaze film resistors on cooling, and thus affect the contact resistance between the metal grains in the glaze. This is clearly seen in the following table.

TABLE V. Effect of expansion coefficient of substrate material on contact resistance

Material	Expansion Coeff.	Contact Resistance	TCR
Al_2O_3	7×10^{-6}	250 ohms/sq.	+ 175
Zircon	4×10^{-6}	100 ohms/sq.	- 800

Paste Preparation

Although in many cases it is not necessary to disperse the inks before using them, dispersion may be needed in some inks. The dispersion is done in a jar rolling mill. These are available from \$ 200 to \$ 1,500, depending upon the number of rollers and the sophistication.

Viscosity Measurement: The viscosity of the ink has to be properly controlled to obtain reproducible printed film thickness.

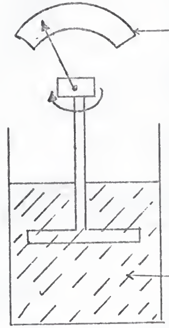


Fig. 14. Viscosity measurement

A Brookfields viscometer, for example, works satisfactorily for this purpose. Principle: (Fig. 14) A spindle is rotated in the ink and the torque necessary to overcome resistance to induced movement is recorded on a dial. The reading on the dial gives a measure of viscosity.

Screen printing equipment

The main functions of screen printing equipment are:

i) Holding the screen frame

ii) Positioning the substrate precisely below the pattern on the screen

iii) Precise adjustment of the snap-off distance

iv) Maintaining the squeegee pressure, squeegee stroke and the squeegee speed to proper adjusted values.

v) Maintaining proper amount of ink per unit area of the screen for each printing stroke.

vi) Automatic feeding and stacking of the substrates.

The last two functions are optional. Dietch (10) describes a screen printer with six squeegees and automatic feeding and stacking arrangements.

Firing Furnace:

The firing of the printed substrates determines the quality and reproducibility of thick film circuits. The most suitable furnace is probably the continuous belt furnace, also called conveyor furnace or lehr. Basically, this type of furnace consists of an internal ceramic shell (muffle). The muffle is divided (fig. 15) into three sections, namely, preheat zone,

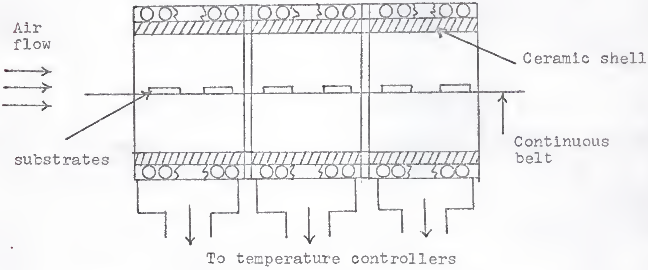


Fig. 15. Section of a typical firing furnace

firing and holding zone and cooling zone. The furnace is usually heated with resistance elements which are separately controlled to give correct temperatures in different zones. This ensures constant temperature profile in the furnace and hence the reproducibility of the circuit properties.

Trimming Equipment:

The main function of the trimming equipment is to precisely control the area of the resistor being removed. The control system of the equipment is therefore required to start and stop the abrasive flow through the nozzle so that the resistor is trimmed to a value which is within the tolerances. Following are the critical parameters of the trimming machine.

i) Distance from the shut-off valve to the nozzle tip
ii) Air pressure
iii) Size and shape of abrasive particles
iv) Area of nozzle opening
v) Distance between nozzle and the resistor pattern
vi) Response of the valve

It may be noted that valve distance and air pressure are first order variables.

CHAPTER IV

EXPERIMENTAL RESULTS

Apparatus

It is obvious that a educational laboratory cannot offord the sophisticated equipment used in industry. It was mentioned earlier that making thick film circuits is simple and cheap. This will now be demonstrated in following pages where the method of making thick film circuits in Thin Film and Solid State Laboratory of Kansas State University is described.

Most of the equipment used for this purpose was built from scrap. A machine previously used for zone refining silicon ingots, donated by Western Electric to Kansas State University, was converted for use as a base to hold the screen and the substrate.

The screen was clamped to a metal base which could be raised or lowered by means of a two way switch and variac. The substrate was held to a substrate holder by vacuum. A solid cube of aluminum with two holes drilled at right angles in adjacent surfaces as shown in Fig. 16, was found to be most suitable as a substrate holder. The substrate holder was made to rest on a metal plate fixed on top of a metal frame, made from aluminum channels. This frame was held down to the machine bed by bolts and nuts. A hole was drilled in the metal plate to provide a vacuum connection to hold down the metal cube. Although this

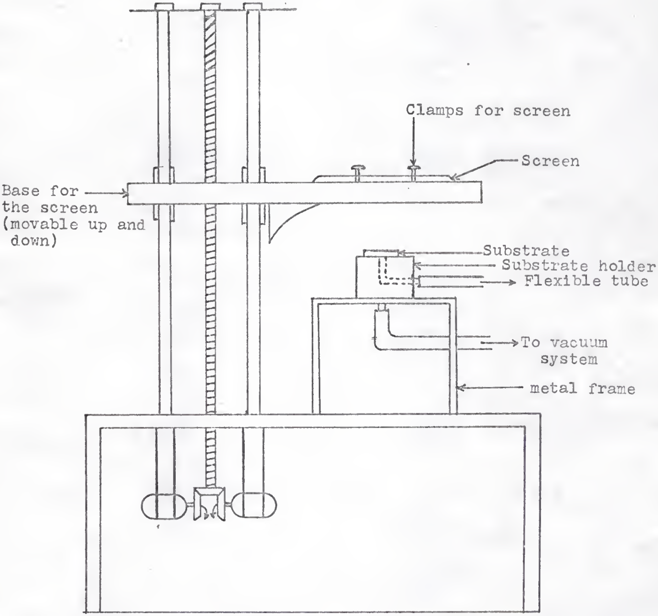


Fig. 16. Schematic of apparatus for screen printing

arrangement does not give much holding power, it certainly provides enough resistance to movement due to accidental touches to the substrate holder after it is aligned with the pattern on the screen.

For firing purposes, a furnace was borrowed from the Nuclear Engineering department. Fig. 17 shows the arrangement for firing the printed substrates. A rheostat is connected in series with the furnace windings for controlling temperature of the furnace.

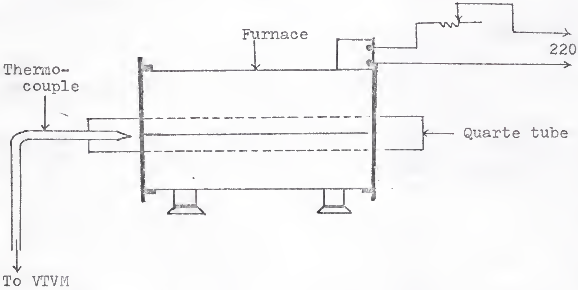


Fig. 17. Schematic drawing of firing apparatus

The temperature was measured by the voltage developed across a thermo-couple made simply by welding alumel and chromel wires at one end. The voltage measurement was done on a VTVM which was calibrated in degrees centigrade.

Two types of inks, viz., the resistor R 13-A and the conductor C-4020 ink (supplied by Alloys Unlimited) were used. These inks need no dispersing or any other treatment prior to their use of printing. One inch square substrates were used. They do not need any cleaning when used for the first time. The reclaiming of badly printed substrates was done by using acetone and photoresist stripper.

The printing was done manually with a squeegee having a neoprene blade fixed to a wooden handle. 200 mesh size screens were used to make stencils. The indirect method of screen preparation was preferred (to the direct method) because it was found to be simpler, less messy and quicker. Colorgraph (type 4570) film was exposed and developed for the indirect (transfer) method. For details see the section on experimental procedure.

It can now be appreciated that the thick film process is cheap by noting that the cost of the above apparatus is only the cost of inks, stencil film and few hours of metal work. The simplicity of the process will become apparent in next few pages.

Experimental Procedure

The procedure used to make thick film circuits in the Solid State Laboratory of Kansas State University is may be summarized as follows:

1) Prepare circuit layout
2) Photoreduce positive of the circuit layout
3) Prepare stencil

4) Transfer stencil to the screen

5) Print circuit on substrate

6) Airdry and fire the substrate.

Preparation of circuit layout

With the present set-up of the photoreduction camera in the laboratory, possible photoreduction ratio is from 8:1 to 10:1. The available substrate size is 1" by 1". With these considerations, maximum size of the circuit layout can be from 8" by 8" to 10" by 10". In preparing the layout following points are borne in mind:

i) The terminations of the circuit, at which connections to the outside world will be made, should be easily accesible.

ii) If any 'outboard' devices such as transistors, diodes, etc. are to be added later on, the conductor pads (where the leads of these devices are soldered) should be so located that there will be no undue stress on the leads when they are being soldered.

If more than one device is to be soldered, their locations should be such that different leads can be soldered with ease.

After a rough sketch of the layout is made with these considerations, the circuit layout is drawn to scale. A separate layout is made for resistor and conductor patterns. Since the ink R 13-A (Alloys Unlimited) is used for resistor patterns in the laboratory, the length of the resistor paths should contain as many squares as the value of the resistor in k-ohms assuming that length of a side of the square is equal to the width of the line. For example, a resistance of 47 k-ohms will require a pattern 9.4" long, assuming its width to be .2". These dimensions refer to the size of the layout. It may also be mentioned that lines, 10 mils wide, can be printed in this set up with a little practice.

After the patterns are drawn to scale, they are painted black, preferably with India ink. Instead of painting, black tape may be used to get better positives or best of all a mechanical scribing machine can be used with "rubylith" sheet.

Obtaining the positive

The circuit layout is placed on a well illuminated translucent glass mounted vertically on a steel stand. It is then photoreduced 8 or 10 times by a camera which can be moved in horizontal direction. The exposure time is kept 3 seconds. (assuming that circuit pattern is made up of black tapes)
The exposed photochemical film is then dipped in three different solutions in following sequence.

i) Developer - 3 minutes. ii) Stop bath - 10 seconds. iii) rapid fixer - 10 minutes. The negative film thus obtained is now washed in water for 30 minutes and then hung up vertically for natural drying.

The positive is then obtained by contact printing. The exposure time is kept at 1/2 second. Good results may also be obtained by placing the negative and the photochemical film under a heavy, flat sheet of glass. The exposed photochemical film is developed and fixed as before.

Preparation of stencil

There are two methods of preparing the screen for printing.

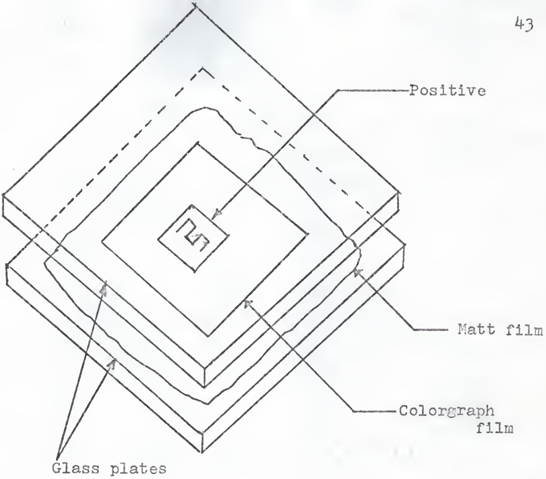
i) Direct method: In this method, the screen is coated with an emulsion which is photosensitive when dry. The coated screen is then exposed to ultraviolet light through the positive. The screen is then sprayed with lukewarm water to open the pattern areas.

ii) Indirect or Transfer method:

In this method a Colorgraph (type 4570) is exposed and developed as explained below to make a stencil. This stencil is then transferred to the screen as explained in step 4.

The Colorgraph film (type 4570) is exposed through the positive in a contact printer. Alternately the arrangement shown in Fig. 18 works very well. In this arrangement, the positive is placed over the Colorgraph film which is placed over a matt film with its emulsion facing the matt film. The three films (viz. positive, Colorgraph, and matt films) are sandwiched between two glass plates which are firmly held by means of clips. This ensures intimate contact between the positive and the backing of Colorgraph film. Note: A clean, soft tissue paper may be used instead of matt film.

This assembly is then exposed to ultraviolet light at a distance of 6-8 inches for 2-4 minutes. The exposure time



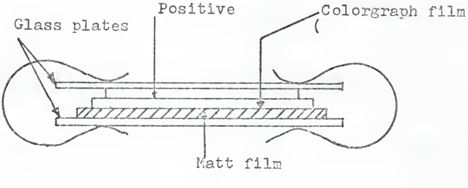


Fig. 18. Arrangement for exposing the 'transfer' film

depends on required thickness of the stencil. However, for off-contact printing, the exposure time is kept small for small details.

The exposed film is then removed carefully and placed horizontally on its backing film in a trough containing a specially prepared developer. The developer is prepared by dissolving 2½ ounces of proprietary developer 'A' (supplied by the manufacturer in powder form) in one gallon of water. The time for developing the film in this solution is kept from 25 seconds to 2 minutes depending upon exposure time and the minuteness of the details.

The developed film is splashed in water at about 105-110 °F till most of the gelatin is removed. The splashing is continued in another trough containing water at 85-90 °F till all unexposed areas become clear. The film is next dipped several times is 25% alcohol solution. This helps to keep small areas open and increase the drying rate. The alcohol solution may also be sprayed to clear the details fully.

This is an important step and following precautions are taken to get good results quickly.

i) Care should be taken to see that there are no dust particles in between the positive and the Colorgraph film which would lead to vents in the stencil.

ii) Splashing should be done with great care as gelatin is very likely to be damaged if it accidently touches any material other than water.

iii) Gloves should be worn when using developers to protect the hands.

Transfer of the Stencil to screen

Before mounting the stencil on a screen, the latter is cleaned thoroughly with detergent and hot water and rinsed to remove all foreign particles. Finally, the screen is fully dried by placing under a sun lamp.

Next the stencil (developed and splashed Colorgraph film) is placed on its back on a flat surface. The screen is carefully positioned over it and gently lowered into contact with the gelatin. Great care must be taken while lowering the screen to see that the gelatin, which is loose on the backing film, is not disturbed. Excess moisture is absorbed from other side of the screen by a napkin. If there is a slight rubbing action between the screen and the film, small details are in danger of being lost. The screen is weighted slightly for first 15 minutes and moderately for next 1-2 hours.

When all the moisture in the gelatin has dried up (this may require mild heat from sun lamp), the backing film is carefully removed, leaving the stencil on the screen. The stencil may be further heated by a sunlamp to remove any traces of moisture left on the screen.

Printing the circuit

The stencilled screen is clamped to the screen base in the machine described earlier. A substrate is positioned on the substrate holder and the vacuum pump is turned on. The substrate is thus held to the substrate holder. The screen base is then lowered till the screen is above the substrate at a distance of 1/32 or 1/16 inch depending the required thickness of the film.

Sufficient ink is placed on one end of the stencil. Care is taken to see that the ink in the bottle is not contaminated in any way. The squeegee is held firmly on the screen and moved across the stencil at a constant speed, the squeegee always being in contact with the screen. An additional stroke may be necessary for additional thickness.

The screen base is then raised and the substrate is carefully slid away. Before printing the circuit pattern on another substrate, the screen is cleaned on its underside so that the next pattern in not fuzzy.

In this equipment alignment of screen and substrate is a matter of trial, error, and judgement. But once correct alignment is obtained, the position of substrate and substrate holder can be marked so that subsequent substrates are printed without much difficulty.

Airdrying and firing

After the circuits are printed, they may be left overnight for drying. Alternately, they may be kept under a sun lamp for quick drying. The drying may be recognized by dull reflection of light from the ink pattern.

For firing the ink pattern, the furnace is turned on with the external resistance shorted for quick heating. When the temperature reaches 700 °C, resistance is added and adjusted to get the desired peak temperature at the center of the furnace.

The substrate is inserted from one end of the quartz tube and is pushed 2 inches every 7-8 minutes until it reaches the center of the quartz tube where temperature is the highest. The substrate is kept at this place for 15 minutes, and then advanced as before. This procedure gives a profile which roughly matches with that given by the manufacturer of inks.

Fabrication of Resistor Patterns

As mentioned earlier, the most important component in a thick film circuit is the resistor. Since most of the important circuit functions depend on two resistor parameters, resistivity and TCR, they were first investigated. The ink R-13 A supplied by Alloys Unlimited was used this purpose.

Resistor lines of varying widths were printed on a number of substrates. The widths of these lines were 100, 75, 50, 25, 20, 15, 12 and 10 mils. Four lines were printed on one substrate to reduce the number of substrates used.

After air drying the resistor lines, conductor patterns printed to terminate the resistor lines. The conductor pattern was designed to give a uniform length of 0.6 inch for all resistors. After air drying the conductor patterns, the substrates were fired at a peak furnace temperature of 800 °C. (The manufacturer recommends firing temperatures of 750 and 850 °C for resistor and conductor inks respectively.) The simultaneous firing of resistor and conductor inks was done mainly for simplicity and also to reduce possible thermal stresses resulting from two firings.

It was found that the resistivity varies over a wide range, from 0.4 K ohms/sq. to 5.8 K ohms/sq. This was expected for following two reasons:

i) The 'Snap-off' distance and hence the thickness of resistor films cannot be controlled precisely in the simple laboratory set-up.

ii) The temperature profile in the furnace is, at best, only approximate.

The TCR values for resistors of different widths also varied over a wide range, from -76.4 to 109 ppm/^{o}C. However, these values are well within the limit specified by the manufacturer (±150).

The effect of screening direction on the resistivity and TCR was also investigated. Since it is impossible to control precisely the direction of squeegee movement in a manual operation, three resistor patterns, as shown in fig. 19, were printed with the squeegee movement as shown to get following three directions.

i) 'Along-the-length' direction

ii) 'Across-the-length' direction

iii) '45^{o} to the length' direction or oblique direction

It was found that resistivity values were considerably higher when the direction of squeegee movement was along the length. The resistivity values for this direction ranged from 5.8 K ohms/sq. to 17.2 K ohms/sq. as compared to the range .49 to

7.6 K ohms/sq., obtained for 'Across-the length' direction.

The effect of screening direction on TCR was just the same. The TCR values ranged from 11.2 to 255 ppm/°C for 'Along-the-length' direction as compared to the range 0.5 to 156 ppm/°C in 'Across-the length' direction. It is very interesting to note that both the TCR and the resistivity values for oblique screening direction were found to be in between the respective values obtained for other two directions.

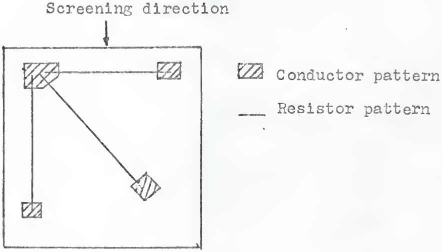


Fig. 19. Resistor pattern used to study effects of screening direction on resistivity and TCR

Fabrication of Inductors and Capacitors

The inductors were printed in form of a number of square turns with leads connected at the center of the square and the outside end of the square. Two types of inductors were printed. The first type consisted of 7 turns of conductor lines, 20 mils wide and spaced 20 mils apart. The second type consisted of 10 turns of 12 mils wide conductor lines spaced 12 mils apart. Their inductances were found to be 19.3 and 20.3 microhenries, and their Q's were respectively 60.5 and 36.4 at 10 MHz.

It may be mentioned here that the 'yield' was better and the results were more consistent when these inductors were screened in direction of the diagonal.

The printed capacitor consisted of 10 pairs of parallel "plates", formed by two 20 mils wide conductor lines spaced 20 mils apart, connected in parallel. The resulting capacitor looks like a comb and has a capacitance of 16.6 picofarads.

Fabrication of Starvation Amplifier

Beynon, et al. (2) describe the design and fabrication of a thin film starvation amplifier. Fig. 20 shows the circuit and the voltage gain-frequency response the conventional starvation amplifier. It was decided to make the same amplifier using the thick film method so that a direct comparison could be made. Since the resistor ink R-13 A gave only 1 K ohm/sq., the width of resistor lines had to be restricted to 12 mils to accommodate all the nine resistors on 1" x 1" substrate. However, some resistors had small values and the width of these resistors was kept as high as 50 mils to get a small number of squares such as 4.7, 1, etc.

After designing the layout, the circuit was printed and fired as explained earlier in the section on experimental procedure. Then all the resistor values of different circuits were compared to the resistor values in fig. 20 and the

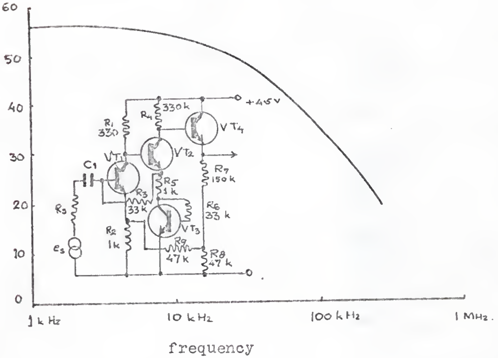


Fig. 20. Voltahe gain-frequency response of starvation amplifier

substrate with the closest tolerances in critical resistors (R_7, R_9, R_2) was selected for adding on discrete BC 122 transistors. Any harmful excessive ink pattern, such as conductor ink shorting resistors, was abraded away by creful use of a diamond point scriber. This scriber was also used to trim the wider resistors. (Note: The scriber may be used for resistors as narrow as 12 mils but extreme care must be taken as slightest over-travel of the scriber may result in an open circuit.)

The transistor leads were then soldered to the proper conductive pads and leads were attached. The soldering has to be done with a small soldering iron and with great care as there is a danger of cracking the substrate due to uneven expansion. (One substrate cracked for this reason.)

The amplifier was then tested. The results are tabulated so that direct comparison can be made with thin film and conventional amplifiers.

TABLE VI. Comparison of performance of a starvation amplifier made by conventional, thin film and thick film methods

Parameters	Conventional amplifier	Thin film amplifier	Thick film amplifier
Voltage gain at 1K Hz.	56 db	46 db	54.4 db
-3 db point	15 kHz.	not mentioned	57 kHz.
Nominal drain current	25 microamps	50 microamps	40 microamps
± 20% change in supply voltage at temperatures -40 to 150°C changes voltage gain to	within 1 db	within 1 db	5 db fluctuations in the gain at temperatures above 60°C

The higher drain current may be attributed to the tolerances in the resistors, while the high fluctuations in the gain at higher temperatures were probably due to bad quality of soldering. It may be noted, however, that voltage gain at 1 kHz roughly matches with that of the conventional amplifier and is considerably higher than that of the thin film amplifier. The voltage gain-frequency response for the thick film amplifier,

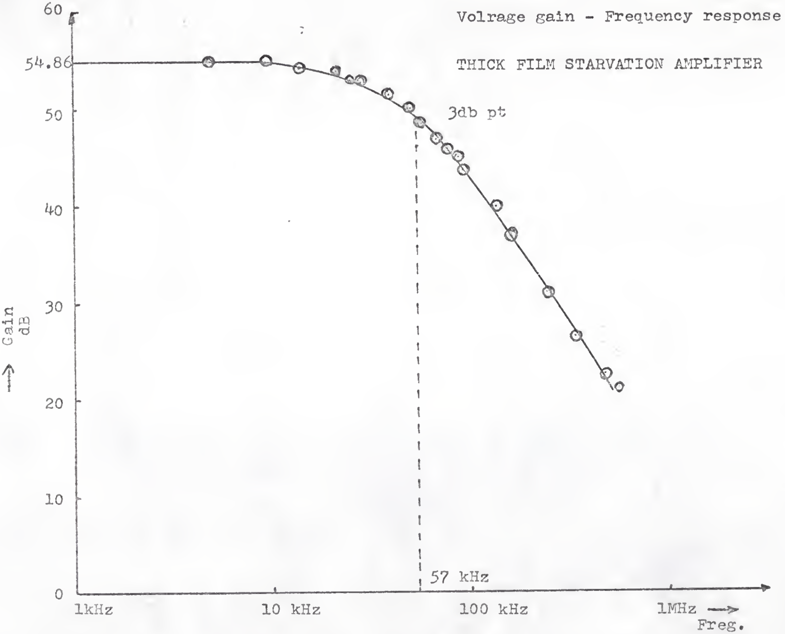

Volrage gain - Frequency response
THICK FILM STARVATION AMPLIFIER
3db pt
60
54.86
50
40
30
20
10
0
Gain
dB
57 kHz
1kHz
10 kHz
100 kHz
1MHz
Freg.

Fig. 21.

shown in fig. 21, also roughly matches with that of the conventional amplifier.

CHAPTER V

CONCLUSIONS AND SUGGESTIONS

It may be concluded that although sophisticated circuits, such as the starvation amplifier, can be successfully made with the present set-up, the reproducibility and the yield of the set-up are very low. These factors cannot be improved upon too much even if a person acquires great skill.

It may be said that if two things, viz., the snap-off distance and the temperature profile of the furnace, are made independent of human error the above factors can be improved considerably. To get a better profile probably the best thing is to make an arrangement wherein a continuous stainless steel belt can be moved in the furnace at a predetermined rate. This rate should also be made adjustable, e.g. by varying the voltage to the motor driving the belt or by some clutch arrangement. Obviously, the optimum rate can only be found out by trial and error. To make the snap-off distance free of human error, the best way is to purchase a laboratory size, manually operated squeegee machine which is available for about $ 500.

The values of the capacitors and inductors can be considerably improved by using dielectric and inductive pastes. The effect of direct and rotating magnetic field on the resistivity of resistors and conductors is worth investigating. Probably the effect of screening direction can be compensated for by airdrying the inks in a proper magnetic field.

More complicated circuits can be printed in parts on two or more substrates and the substrates may then be cascaded (see fig. 22)

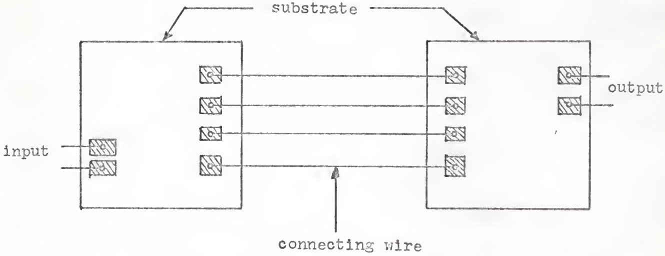


Fig. 22. Cascading substrates

Another interesting area for further work is in multilayer techniques. As mentioned in chapter II, multilayer units are available with buried conducting risers and patterns. More circuits can be printed and fired on the top and the bottom layers of these units.

The simplicity and inexpensiveness of the thick film process has been demonstrated. The only limit to its flexibility is perhaps the human imagination. If the reader now realizes the importance and the bright future of the thick films, the purpose of this thesis will be served.

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ACKNOWLEDGEMENTS

The author is indebted to Dr. Michael S. P. Lucas, who suggested the topic and offered invaluable guidance and stimulating encouragement throughout the preparation of this thesis.

FABRICATION OF THICK FILM CIRCUITS

by

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B.E., University of Bombay, Bombay, India, 1965

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

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Manhattan, Kansas

1969

ABSTRACT

The term "Thick Films", which is frequently found in current papers dealing with electronics, refers to a particular type of hybrid integrated circuit generally made by a development of the graphic arts process. The thick film system is one of the most economic methods of producing integrated circuits. Its simplicity and flexibility make it a wide choice over other processes which are often more sophisticated.

The entire thick film manufacturing process is discussed in some detail and related to recent developments in materials, equipment and manufacturing technology.

A simple laboratory set-up is described which demonstrates the inherent simplicity of the thick film technology. This set-up was used to fabricate fundamental components such as resistors, inductors, capacitors and conductors. The properties of these components were studied on a comparative basis by relating the performance of a micropower amplifier fabricated by thick film techniques to identical circuits made by both conventional and thin film methods.