12. Photographic reduction from layout drawing to screen pattern is $(200)^{1/2}$ to 1.

ACKNOWLEDGMENTS

The authors wish to thank CTS Microelectronics, Inc, and the Delco Electronics Division of the General Motors Corporation, in particular John P. Colglazier and Arthur M. Hossenlopp, for the donation of equipment; CTS Microelectronics, Inc. for transistor attachment and wire bonding; Motorola, Inc. for donating the transistors; the Electrochemicals Department of E. I. DuPont de Nemours and Company, in particular Dr. L. C. Hoffman, for the donation of the conductor and resistor inks; Veritron West for supplying the headers, and the American Lava Corporation for providing the substrates.

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3. G. W. Neudeck and H. W. Luginbuhl, "Laboratory Experiments in the Fabrication of Thick-Film and Thin-Film Integrated Circuits," IEEE Trans. Education, Vol. E-13, pp. 192–195, November 1970.
4. American Lava Corporation, Laurens, South Carolina, 29360
5. J. Ulano and Company, Inc., 210 E. 86th Street, New York, New York 10028. Available from local art work suppliers.
6. We used 7" X 12" Al frames purchased from CTS Microelectronics P.O. Box 1278, Lafayette, Indiana. Cost was $7.17 in lots of 12.
7. J. Ulano and Company, Inc., 210 E. 86th Street, New York, New York 10028. Blue Poly II Introductory kit for $3.00 contains two 10" X 12" sheets of film together with the necessary chemicals for developing a small supply of Blockout and instructions. Available from local art work suppliers.
8. Additional Blockout can be purchased in one quart lots from local art work suppliers.
9. Electrochemicals Department, E. I. duPont de Nemours and Company, Wilmington, Delaware 19898.
10. Motorola, Inc., Phoenix, Arizona 85036.

A Thick-Film Microcircuit Laboratory

MICHAEL S. P. LUCAS AND WILLIAM H. DAWES

Abstract—A successful, student oriented, minimum supervision, thick-film microcircuit laboratory is described. Key laboratory processes and examples of student projects are illustrated. In the laboratory, emphasis is placed on the use of thick-film technology as a design medium which enables the student to relate theoretical models to real world problems. Laboratory organization is discussed and sources of equipment and supplies noted. A detailed outline of associated lecture topics with references is also given.

INTRODUCTION

A thick-film hybrid circuit is made by screen printing and then firing special pastes to form conductor, resistor, and capacitor elements upon an inert ceramic substrate. Active devices and other special components are attached to the substrate by reflow soldering or bonding. The major steps required to fabricate a thick-film circuit in the laboratory are shown in Figs. 1 through 12; a color slide-tape lecture showing these steps in much greater detail is available from the IEEE headquarters [1].

Thick-film hybrid microcircuits are widely used today by industry to provide electronic functions in such diverse application areas as radio and television receivers, digital computers, and automobiles, with IBM alone producing more than one million hybrid circuits each day [2]. Reasons for this popularity are not hard to find since the contemporary thick-film technology provides a means for the volume manufacture of low-cost, high-yield, high-reliability components and circuits which cannot be matched by any other process.

Thick-film circuits are already in production in most of the industrialized countries of the world and, since the manufacturing processes are relatively simple when compared with silicon technology, it is to be expected that they will achieve widespread use in the emerging nations since these processes can easily be adapted to small-scale production lines.

Surprisingly, few university departments of electrical engineering have recognized the importance of thick-film technology [3]. Yet here is a process which can be used both to provide an inexpensive design medium to complement conventional electronics courses and also to introduce many new ideas to the student that will later help him understand the more complex silicon technology.

A thick-film laboratory has now been in operation for the past three years at Kansas State University as part of the Integrated Circuits Engineering course; this is an elective that is available to undergraduate seniors and first-year graduate students. The course is designed to give an overview of contemporary integrated electronics plus some hands-on experi-

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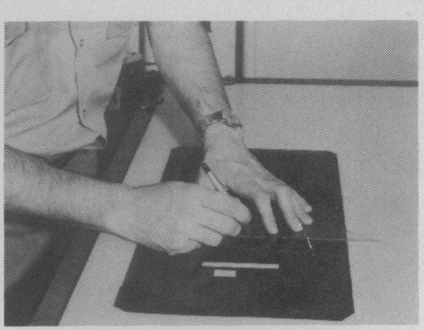

Fig. 1. Cutting Rubylith with Ulano swivel knife

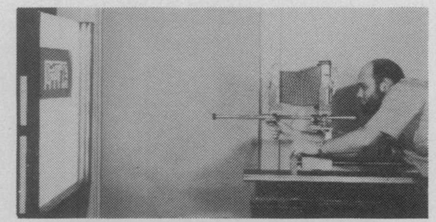

Fig. 2. Photoreduction system using Calumet press camera

ence in the design and fabrication of thick-film or thin-film circuits. Normally, the course consists of thirty scheduled lectures, movies, and slide-tape presentations plus thirty hours of laboratory work each semester. Our major purpose in the present paper is to describe the parts of the Integrated Circuits Engineering course which are related to thick films.

This paper is expressly written for those instructors who have previously steered clear of any kind of integrated circuit laboratory because of the high cost involved. We believe that an adequate thick-film laboratory can now be offered at the same cost as any other laboratory if our technique is followed.

TEACHING PHILOSOPHY

The preoccupation of the typical engineering educator with mathematical analysis to the almost complete exclusion of other intellectual activities has tended to reduce student participation in engineering design to a very low level. We feel that, in addition to analysis, a university curriculum should provide some detailed knowledge of current engineering practice in at least one specialized area. This knowledge should include some engineering design work at a reasonably advanced level. The engineering design work should make use of as many analytical techniques as possible so that the student is forced to relate his theoretical models to real world problems.

Potentially, the electrical engineering student is in an extremely fortunate position with respect to his peers in other branches of engineering when the ease with which he may undertake quite complex design projects is considered. In the normal university laboratory it is almost impossible for the civil engineer to build a bridge or the nuclear engineer to build a nuclear reactor as a personal project, yet is is comparatively easy for the electrical engineer to build a control system, mini-computer or bio-medical telemetry system using state-of-the-art components.

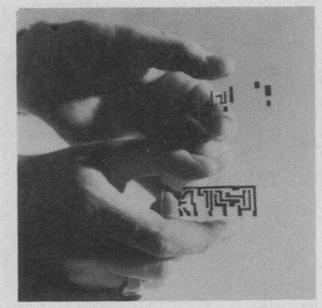

Fig. 3. Photoreduced negatives using 5:1 reduction on Kodalith Ortho Type 3 Film

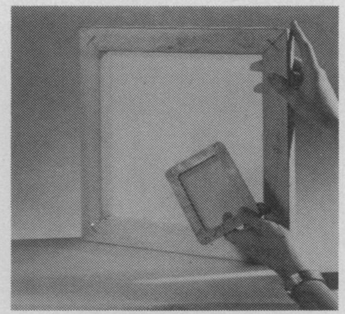

Fig. 4. Printing screens, a comparison of aluminum & wood frames

In a recent article entitled; "Teaching an Engineering Sixth Sense," Hill [4] comments that design instruction requires:

1. Total involvement on the part of the student.
2. The instructor's role as a coach who never supplies answers to questions.
3. Student frustration when dealing with design process.
4. Self-evaluation by the student. Often oral critiques will achieve this. An optimum attitude would be that the student designs for the satisfaction he gets out of it.

We find that the above requirements form a good general framework for our thick-film laboratory projects.

COURSE ORGANIZATION

The scheduled lecture periods are used for introduction of new concepts, presentation of factual information, discussion of design problems, and course administration. Whenever possible, engineers are brought in from industry to talk about their current assignments. After hearing so much about the challenges that exist in industry many seniors are worried about their ability to meet them; they are reassured when they hear young engineers, with two or three years in industry, explain the type of work that they do and the problems that they encounter.

No quizzes or examinations are given directly over the material treated in the lecture periods—all grades are based on the laboratory projects. The assumption is made that in order to complete a satisfactory laboratory project the student will have to acquire a certain amount of "hard" information; some of this he will obtain from the lectures, but the rest he will have to dig out for himself. We encourage the student to

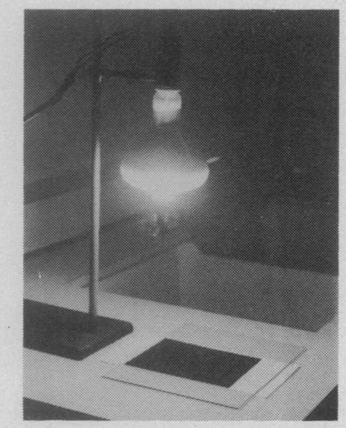

Fig. 5. Exposing Blue Poly film with sunlamp

Fig. 6. Washing out Blue Poly after exposure

develop the ability to learn by his own reasources. Students are urged to use the reference materials which are available in both the departmental and university libraries. Certain manufacturer's data sheets and specifications are shelved in the laboratory.

As might be expected, no suitable textbook has yet been found for this course. In the lectures a liberal use is made of handouts which may range from offprints from the *IEEE Spectrum*, *Electronics* and other similar journals to ad hoc papers on such topics as Beam-Lead Devices, Liquid Crystals, or merely how to trim a thick-film Twin-*T* network. The net result of this use of current literature is that the student becomes aware of the value of professional publications and a technical reference library. As a result of this exposure many join the IEEE Student Branch in order to obtain personal subscriptions to the various publications that they have often found helpful on the course.

OUTLINE OF LECTURES ON THICK FILMS

As previously noted, no suitable single text has been found for this course; the most nearly siutable is *Thick-Film Microelectronics* by Morton L. Topfer [2]. Our experience has been that the most viable course is obtained when the lectures are based on current papers and the various relevant texts are used for supplementary reading. The major topics that should be considered in the lectures are listed below with the appropriate references.

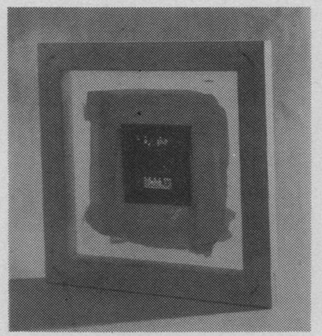

Fig. 7. Completed screen ready for printing

Fig. 8. Inexpensive manual printing system

A comparison of thick-film, thin-film, and silicon integrated circuits [2, 4, 5, 6, 7, 8, 9, 10, 11].

Circuit layout, design and photographic processes [2, 12, 13, 14, 15, 16].

Substrates and substrate materials [2, 10, 17, 18].

Paste manufacture and properties [2, 19].

Screen preparation and printing [1, 13, 20, 21, 22, 23, 24].

Firing parameters [25, 26].

Resistor structure and conduction processes [27, 28, 29, 30, 31, 32].

Resistor trimming techniques [33, 34].

Active and passive components, assembly and bonding [2, 10, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50].

Packaging and testing [10, 36].

Economic considerations [47].

LABORATORY ORGANIZATION

This is an open laboratory with no fixed hours of attendance and no direct supervision although help is available if requested. The student works when he feels like working, not at a time assigned by a computer. However, various deadlines are established throughout the semester to make sure that much of the work is completed prior to the semester's end. General housekeeping duties are performed by student assistants.

Students are given the minimum formal instruction in the thick-film processes. We expect them to be frustrated at first

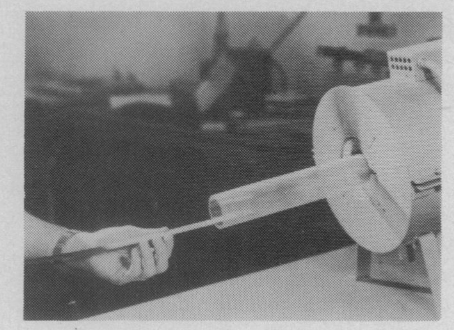

Fig. 9. Firing thick circuits in obsolete diffusion furnace

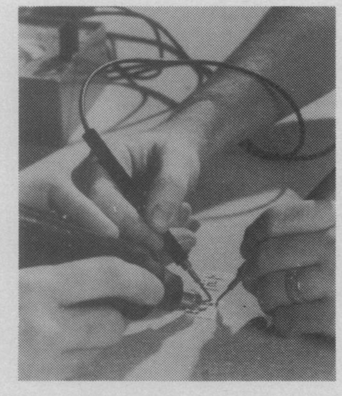

Fig. 10. Trimming resistors with Dremel Moto Tool

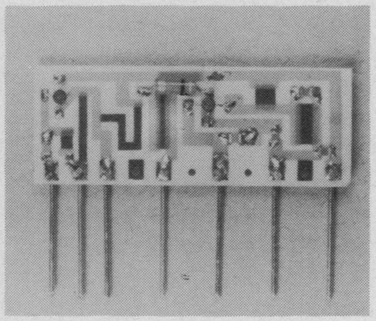

Fig. 11. Completed circuit showing attached components

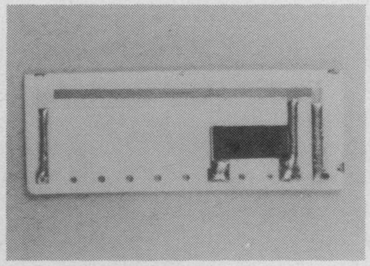

Fig. 12. Distributed *RC* notch filter

until they adapt to a new situation. Formal instruction consists of a slide-tape presentation plus an orientation tour of the laboratory to indicate the position of the vital pieces of equipment and supplies. Handouts are available in the laboratory for each of the important processes. Such a system is self-regulating; when the student masters all of the necessary steps he obtains a working circuit with the desired characteristics. If the circuit does not work the first time he goes back around the loop; some students will spend a total of ten hours in the laboratory while others will spend more than one hundred, but in the end they all emerge with working circuits. For many students this is the first occasion on which they have had the satisfaction of designing and building something on their own without outside supervision—this is an exciting experience.

Log books are maintained by the students for the important items of equipment. These ensure that they have a continuous record of the important process parameters and that each person can learn from the mistakes or successes of others. In addition the log books quickly indicate when a particular machine or process is not functioning correctly. Student project reports are kept in a central file which is available to all students, not just those of a particular fraternity. Each semester the new class is able to build upon the experience of the prior group and consequently the laboratory continues to develop. When an improved process is developed a new technical instruction is written to replace the old handout.

A selection of the best projects is displayed in a special showcase. This ensures that each new group of students has some definite standards for which to aim. The poor examples are used for classroom design discussions and frequently the whole class is required to redesign a particular project. Incidentally, these displays attract a remarkable amount of attention from other, more junior, students since they provide concrete evidence of what to expect if they elect to take the Integrated Circuits Engineering course. Many of the displays are also used in other classes as teaching aids.

LABORATORY EQUIPMENT

First, it is essential that the laboratory itself should have an adequate number of sinks for processing the printing screens. The immediate sink area should be shielded from strong ultraviolet light. Where new sinks are required we have found that the inexpensive plastic laundry sinks as sold by Sears are quite adequate. The UV light may be excluded by placing yellow Kodagraph sheeting over the windows and fluorescent light tubes.

For normal thick film work a precision drawing machine is not essential and the printed circuit taping methods described by Jacobsen [13] are quite satisfactory. The method illustrated in Fig. 1 is probably the most inexpensive. Our photoreduction system, shown in Fig. 2, consists of a Calumet press camera, with a Schneider Repro-Claron, 8¼″, f9 lens, mounted on an old lathe bed. The light box, upon which the artwork master is placed for photoreduction, was made by a student.

Three years ago, when the course first started, we used industrial printing screens with aluminum frames and stainless steel mesh but these proved to be easily damaged and much to too expensive. We now use the screens shown in Fig. 4, which are made in the laboratory from cheap wooden frames and polyester mesh to give a much cheaper and more practical system. Sources for these and other laboratory supplies and approximate costs are given in the Appendices. One method of stretching the polyester mesh over the wooden frame is shown in the Advance catalog. We now use grooved frames in which the fabric is stretched by driving a cord into the groove.

We have tried a number of different ways of transferring circuit patterns onto the printing screen but the Ulano Blue Poly 2 has proved to be the most satisfactory for our purposes. Introductory kits of this material are available from Advance. A Sears Sunlamp is used for exposing the Blue Poly film but any projector lamp with a high UV light content will work.

The inexpensive manual printing frame shown in Fig. 8 is quite adequate as long as provision is made for holding the substrate in place during printing—a vacuum hold-down can be made with an ordinary household vacuum cleaner. Squeegees of various types can be obtained from Advance or other sources.

The choice of conductor, resistor, and dielectric pastes depends upon the amount of money available. However, care should be taken not to purchase one of the more toxic paste systems nor one that requires firing in an inert atmosphere. A list of paste suppliers is given in Appendix I.

After printing, each pattern must be thoroughly dried; a cheap electric grill or toaster of the horizontal type works well here. The films can be fired in any furnace which is capable of being set at any temperature up to 1,100°C. The furnace shown in Fig. 9 is a very old diffusion furnace in which the tube is slightly inclined to maintain an atmosphere of clean air within the tube.

Resistor trimming, shown in Fig. 10, is easily performed with a Dremel Moto Tool or with an old dental drill. A diamond tipped drill works best.

Dip soldering may be performed in a Pyrex petri dish placed on an electric hotplate. The temperature of the bath should be between 230°C–250°C and checked with a thermocouple. An anti-oxidant (peanut oil works well) should be used on the bath surface. Dipping time is from 3 to 10 seconds.

THICK-FILM LABORATORY GRADING SYSTEM

Work required of the students in the thick-film laboratory is best illustrated by the edited example of an actual course handout given below. This handout describes the grading system, gives the due dates for various items of work and briefly describes the work required. The handout reads as follows:

1. Print and fire the thick-film conductor pattern for mounting flip-chip transistors. Attach at least two flip chips. Mount in centrifuge and accelerate until at least one flip chip flies off. Write your name on the back of the substrate together with the RPM at which the circuit failed. Hand in substrate on October 14. Percentage of Grade: 15%

2. Hand in a typewritten, one-page proposal broadly outlining your laboratory project. List the following items:
   - (a) major processes required,
   - (b) special processes that you might require,
   - (c) special components,
   - (d) special or unusual test equipment,
   - (e) unresolved problems or problem areas.

Hand in proposal on October 14. Percentage of Grade: 15%.

3. Demonstrate a working breadboard circuit by November 18. Percentage of Grade: 10%

4. Complete a neat and attractive display card 11" X 14" showing your circuit diagram together with an example of a finished working circuit. This circuit will be tested to determine part of your grade. Percentage of Grade: 30%. Hand in by December 2.

5. Final Report. Hand in by December 9 for 30% of grade. This must be typewritten, not more than twelve pages long, and contain your master drawings plus photoreduced negatives together with an example of a fired circuit without attached components. Include a set of operating instructions for your circuit. Make certain that your report does not contain any spelling mistakes.

LABORATORY PROJECTS

As far as possible each student is free to choose his own project within the limitations of time, laboratory facilities, and personal ability. Each semester a handout is prepared setting project guidelines and containing suggestions for those students who are not sure what they want to do. An edited version of one such handout entitled "Laboratory Projects—Fall 1971" is given below.

1. At this stage you should be able to print and fire conductor patterns and have some idea of the difficulties of dip soldering and mounting Flip-Chip transistors.

2. Your next step will be to choose a suitable major project. (Note the timetable on the paper describing the course grading system) Note also that the course requirements are quite flexible and that as far as possible you will be encouraged to work on something which interests you.

3. Steps in Major Project

   For most people the following steps will be required:
   1. Selection of a suitable circuit plus redesign work.
   2. Wiring and testing circuit breadboard.
   3. Preparation of rough layout (5X final circuit).
   4. Cutting or taping masters.
   5. Photoreduction of masters. (This will be done for you.)
   6. Preparation of silk screen.
   7. Printing circuit.
   8. Firing circuit.
   9. Dip solder and attach leads.
   10. Trim resistors.
   11. Attach active elements and capacitors.
   12. Test in centrifuge.
   13. Encapsulate
   14. Final functional test.

4. Available Components for Thick-Film Circuits

Inks

Electroscience	100 kΩ/square	100 g
Unknown (DuPont?)	5 kΩ/square	200 g
DuPont	40.6 kΩ/square	1 oz
Alloys Unlimited	Insulator	2 oz

Capacitors

Ceramic chip capacitors: 0.03 mF, 0.02 mF, 0.003 mF, 0.002 mF, 8,200 pF and 200 pF.

Active Devices

Motorola NPN transistors MMT 3903, PNP transistors MMT 3905

Delco PNP "Flip Chips"

Western Electric 49A Dual Transistors

Miscellaneous diode chips

Special Items

Special components can be obtained given sufficient notice. If you require a special item for a personal project go ahead and order it yourself. You can keep your finished project as long as you leave a sample on the display card for the Department.

5. Drawing Supplies

If you have a very intricate circuit requiring great precision use Rubylith material on the Micromarker. Otherwise, use the PARA-TONE Para-Paque strip-away paper or ZIP-A-LINE chart tape which may be purchased in the Union Bookstore.

6. Suggestions for Useful Projects

1. Design and build an Analog-to-Digital Converter for Electrocardiograms.

2. Design and build improved thick-film FM telemetry transmitter. (Circuit built last semester)

3. Design and build simple strain telemetry system which eventually might be mounted inside a concrete beam and sampled annually for 50 years!

4. Further develop and improve the prototype humidity gauge designed last year.

5. Manufacture and test a number of distributed constant notch filters using the thick-film process.

6. Manufacture, test, and mount 25 of the ELECTRONIC BUILDING BLOCK CIRCUITS (EBBC's) designed and built by various students last semester.

7. Convert existing V_{mg} Meter made from discrete components into a thick-film assembly. Note this device is a small analog computer.

8. Design and build a simple anemometer using an AM microtransmitter mounted on one of the rotating arms as the signal source.

9. Design a variable threshold Schmitt Trigger to interface with TTL.

10. There is a need for someone to go through the past student projects in detail and pick out the best. These should then be reviewed and if necessary redesigned to conform with current thick film laboratory practice. The circuit descriptions should then be written in a standard format so that the circuits can form part of a laboratory catalog of circuits. These circuits would then be added to semester by semester. *This is the type of project which should suit the student who hopes to become an engineering manager!* (20% Bonus points for this project.)

7. Specifications for EBBC's

We still have a need for more building block circuits. These EBBC's are basic circuits which can be mutually interconnected to form small systems and would form the basis for experiments in other laboratories, e.g. Engineering Concepts.

A partial list of EBBC's is given below:

Schmitt Trigger,

Sine Wave Oscillator (10 kHz, external adjust),

Astable Multivibrator (Externally variable frequency),

Voltage Controlled Sine Wave Oscillator (10 kHz center frequency),

Unijunction Relaxation Oscillator,

Voltage Controlled Astable,

Balanced Modulator using FET's.

Assume that all of the above circuits will have to work from a 9 volt unregulated DC supply and if possible they should be designed to be compatible with RTL (Resistor Transistor Logic). All circuits should be student proof.

8. Laboratory Rules

A. Always work in pairs.

B. Clean up your own mess.

RESULTS AND CONCLUSIONS

The results of the course are perhaps best demonstrated by the examples of student projects shown in Figs. 12 through 16; these circuits reflect state-of-the-art circuits for the Fall 1971 class. The next development will be to encourage the general use of flip-chip, and die-bonded transistors. Transistors are already being made by more advanced students working in the associated semiconductor laboratory.

Another important psychological result of the course is that the students feel much more confident about tackling the problems that will face them in industry. They have learned something of industry's problems from their contact with the visiting engineers; and they have mastered a series of processes sufficiently well to obtain a product!

It is also interesting to note that although attendance is not required in the lectures and there are no examinations or quizzes attendance is extremely good. Feedback from College of Engineering course evaluations indicates that the Integrated Circuits Engineering course is highly rated by the students and they feel that it contributes greatly to their professional development.

From time to time the suggestion is made that the unstructured laboratory should be structured with a series of standard experiments—this suggestion is always viewed with dismay by the students. We must conclude from this reaction that students do appreciate the opportunity to become involved, that they do design work because they enjoy doing it,

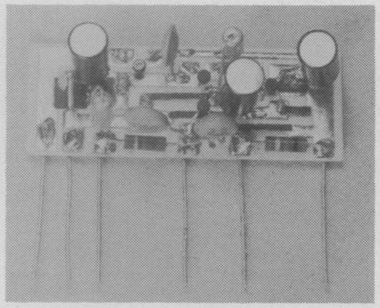
Fig. 13. Thick-film preamplifier for a radiation detector

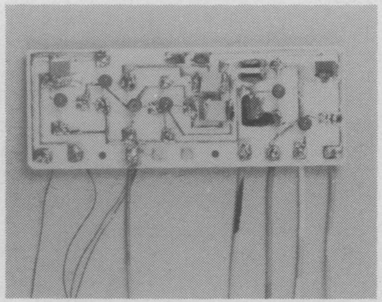
Fig. 14. Strain telemetry circuit

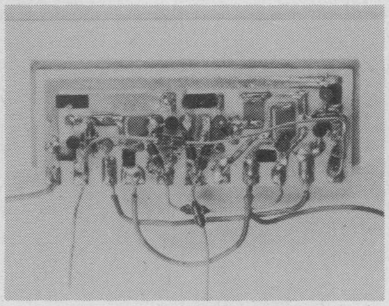
Fig. 15. Voltage controlled oscillator—not an ideal circuit for thick film

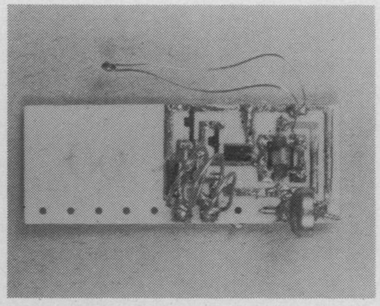
Fig. 16. An FM temperature transmitter

and that they will accept frustration as part of the design process.

APPENDIX I
SOURCES OF SUPPLY FOR EQUIPMENT AND MATERIALS*

1. Conductor, Resistor, Dielectric Pastes

E. I. Du Pont de Nemours & Company
Electrochemicals Department
Electronic Products Division
Wilmington, Delaware 19898

Electro-Science Laboratories, Inc.
1133 Arch Street
Philadelphia, Pennsylvania 19107

Methode Development Co.
7447 West Wilson Avenue
Chicago, Illinois 60656

Electro Materials Corporation of America
605 Center Avenue
Mamaroneck, New York 10543

2. Substrates

American Lava Corporation
Laurens, South Carolina 29360

Coors Porcelain Co.
Golden, Colorado

3. Capacitors

American Lava Corporation
Laurens, South Carolina 29360

Vitramon, Inc.
Box 544
Bridgeport, Connecticut 06601

4. Screen Printing Materials

Advance Process Supply
400 North Noble Street
Chicago, Illinois 60622

Joseph Podgor Company, Inc.
P. O. Box 1714
Philadelphia, Pennsylvania 19105

APPENDIX II
TYPICAL COSTS FOR EQUIPMENT, MATERIALS, AND COMPONENTS

Equipment*

1. Photoreduction System: Calumet Camera and Lens	$300.00
Light Box—Student Made	25.00
2. Furnace—An old diffusion furnace is ideal for initial work—Surplus From Industry	–
3. Manual Printing Frame	20.00
4. Sun Lamp, Holder and Stand	25.00
5. Horizontal Toaster (To Dry Prints)	15.00
6. Dremel Moto Tool (To Trim Resistors)	50.00
	$435.00

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*Note, this list is not exhaustive and is merely given to provide a starting point for the newcomer to the field.

*Information concerning surplus hybrid equipment available for donation to universities may be obtained from: The International Society for Hybrid Microelectronics, 1410 Higgins Road, Park Ridge, Illinois.

Materials

Quantities shown for a class of 24 students. Left hand column shows typical quantities for initial purchase. Right hand column cost per student per semester.

1. Rubylith 5DM 40″ X 150″	$ 23.50	$ .60
2. Kodalith Type 3, 4″ X 5″ Ortho Film (2 Boxes of 50)	10.44	.42
3. Blue Poly 2 Film 40″ X 150″	18.50	.15
4. Photographic Chemicals	50.00	1.00
5. Printing Frames (12″ X 12″ ID) (30 Frames)	50.40	1.00
6. Polyester Screen Fabric (180-M, 220M) 9 yards	72.00	2.00
7. Substrates 96% alumina, 250 1″ X 1″	50.00	2.00
8. Conductor Paste 5 Troy Ounces	250.00	.50
9. Resistor Paste 10 Troy Ounces	250.00	.50
10. Capacitor Kit–Kemet 280 10 pF → 50 μF	99.00	.60
	$873.84	$8.77

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