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THIN-FILM MICROCIRCUITS ON FLEXIBLE SUBSTRATES

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The feasibility of fabricating flexible thin-film circuits while planar, and then folding or rolling the circuits to conform to packaging constraints was investigated. This approach would significantly increase microcircuit packing density and offer a new dimension to the thin-film circuit engineer.

The flexible substrate used was the polyimide film, Kapton; identical circuits were also fabricated on borosilicate glass substrates for comparison. The conductor-resistor arrays used a new material system (copper/Kanthal)

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20. ABSTRACT (Cont'd)

offering low cost, low temperature coefficient resistors, and a simple fabrication process. The flexible thin-film resistors were found to show very small resistor value changes when flexed (average about 0.[illegible]% for 1-cm radius of curvature), and resistor temperature coefficients comparable to those on glass substrates. This work suggests that flexible thin-film substrates may help solve complex thin-film microcircuit packaging problems.

CONTENTS

I. INTRODUCTION

Thin-film microcircuits have typically been fabricated on smooth, solid substrates, such as glass or quartz. The solid substrate offers the advantage of rigidity for mechanical support and ease of handling. However, as higher density microcircuits are engineered, ever yielding to the pressure to reduce the circuit volume, the notion of a circuit which can be folded or rolled into a smaller package becomes attractive. The flexible substrate offers this possibility. One might envision, for example, a thin-film flexible substrate microcircuit fabricated in a planar array, for example 1 x 4 in., and then rolled for ultimate packaging in a cylinder of perhaps 1/2-in. diameter. This was done by Zimmerman and Hicks*, whose pioneering work helped establish the feasibility of this concept.

In this paper a flexible substrate thin-film microcircuit technique is developed using a low cost resistor and conductor process [1]. Identical circuits were fabricated on glass and flexible substrates so that performance comparisons could be made between the two approaches.

II. MATERIALS

Substrate selection was an important phase of this work. A good substrate should be smooth, flat, and nonporous. Any substrate roughness will result in nonuniformities in the deposited films; lack of flatness degrades pattern definition during through-mask deposition and/or photoresist operations.

The thermal coefficient of expansion (TCE) of the substrate should be similar to that of the deposited film to minimize stress introduced by temperature changes. The substrate must withstand the temperatures imposed by subsequent processing, and be inert to chemicals used during that processing.

The flexible substrate material selected was Kapton (registered trademark of Dupont), a flexible polyimide film available in a variety of thicknesses; a thickness of 1 mil was used for this work. Polyimide materials have been used before as hybrid microcircuit substrates, motherboards, and structures for system packaging [2, 3, and 4]. For many applications it has been shown that these materials can be directly substituted for more conventional substrate materials. Conventional processing can be used with the exception that the rise in substrate temperature during film deposition must be limited to less than 100°C

*Zimmerman and Hicks, unpublished work at Johns Hopkins University, Applied Physics Laboratory, Silver Spring, Maryland.

and preferably to 50°C [4]. Size and weight are reduced, packing density is increased, and there is a cost reduction as well.

It has been shown that polyimides exhibit high peel strengths for thin-film metallization, excellent resistance to solder processing temperatures as high as 260°C, resistance to processing chemicals and solvents, dimensional stability after etching and baking, good electrical properties, and survival under repeated hand rework cycles. Polyimide films tend to absorb more moisture than conventional substrate materials but this can be overcome by an oven bake at the appropriate time [4]. As previously mentioned, conventional solid substrates were also used as a control group against which to measure the performance of the flexible circuits. Pyrex glass was chosen for this purpose because it has a long history of use as a thin-film substrate and thus provides an acceptable standard. Table 1 compares some of the properties of Pyrex and of Kapton.

The resistor film was deposited by thermally evaporating Kanthal Al wire. Kanthal Al is an alloy consisting mainly of iron (70%), chromium (22%), and aluminum (5.5%) manufactured by Kanthal Corporation, Bethel, Connecticut. Although generally used as heating elements in furnaces and ovens, it has previously been used to produce low thermal coefficient of resistance (TCR) thin-film resistors by Dhere, et al [5] and Watts**. Besides its low TCR, they discovered that it was easy to work with, compatible with conductor films, and adherent to substrates. In addition, it allowed long filament source life.

Copper was chosen as the conductor material because it is inexpensive, readily available, can provide very low sheet resistances, and is solderable. A disadvantage of copper is that it corrodes easily unless protected by a layer of passivating material. This problem was overcome by treating the circuit with a gold electroless plating solution, Atomex (registered trademark of Engelhard Industries). The adherence of copper to substrates is generally poor. However, when deposited on top of a resistive layer deposited from Kanthal, the adherence was found to be quite good. A complete description of this copper-Kanthal thin-film conductor/resistor technology has been previously published [1] including advantages and disadvantages of this system.

III. MICROCIRCUIT LAYOUT AND FABRICATION

The material system just described could be used in either an additive (through-mask) process or a subtractive one. The second

**C. Watts, Private Communication.

requires depositing the films over the entire substrate and then selectively etching the desired pattern; this type of procedure was used in this work.

The thin-film test circuit (Figure 1) was designed on the microelectronic computer aided design system at Auburn University. This thin-film circuit requires two mask levels; one defining the conductor and resistor area, the second only the resistors. The first mask is a negative in that the first etch removes metal from all areas except the conductor and resistor areas. The second mask is a positive in that the resistor areas are defined and a selective etch exposes the resistors by etching the copper film from over them. The glass mask masters were made by using a Gyrex 1005 Pattern Generator System in the Auburn Microelectronics Laboratory (Figure 2).

The circuit layout contains 28 resistors, two integrated circuit (IC) chip bonding pads, and several isolated conductors of different widths. Resistors 1 through 8 all have the same width but different lengths; Resistors 9 through 13 have the same aspect ratio but different areas; and Resistors 15 through 23 have the same length but varying widths. These resistors will serve as a test array for evaluating thin-film resistors and conductors fabricated by the techniques to be described.

Resistors 24 through 28 are for use in a band gap reference circuit which can be implemented by attachment of a silicon transistor array (e.g., RCA CA3083) to one of the bonding pads. Resistor 14 can be used to detect any anomalies associated with a meandering topology resistor. The conductor array of varying line widths is used to assess the probability of metallization opens and the minimum line width easily reproducible. The process sequence followed for the fabrication of the thin-film microcircuits on glass substrates is described in Reference [1].

The flexible Kapton substrate requires a means of mechanical support to keep the substrate planar during processing. Various Teflon clamps and holders were devised for this purpose; however, one of the most effective techniques was simply to mount the Kapton on a borosilicate glass square by epoxy placed on the corners. After processing, the flexible circuit could then be cut free from its underlying glass support. Figure 3 presents a completed circuit gripped by tweezers on one edge and folded back over itself.

IV. CHARACTERIZATION AND MEASUREMENT

A. Physical Characterization

Two glass substrate samples and two Kapton substrate samples were selected for evaluation from the same evaporation run to eliminate run differences in comparing glass to flexible substrate circuits.

Optical microscopic evaluation revealed that while the samples on glass looked smooth, the ones on Kapton appeared to have a more grainy surface. This is confirmed in the scanning electron microscope photos discussed later. This is probably due to the smoother surface finish of the glass. If a piece of Kapton that has no deposited film is examined, it appears that the surface has many fine scratches; the presence of these scratches undoubtedly contributes to the nonuniformity of these films.

All samples exhibited adequate adhesion, both Kanthal to substrate, and copper to Kanthal. The standard Scotch tape test [6] was performed on all circuits; none of the films shows any lifting. The excellent adhesion of the copper-Kanthal metallization system, combined with its associated simple two-step evaporation process, provided promising results for this thin-film scheme.

Examing the circuits with a scanning electron microscope, AMR Model 1000, revealed the copper films on glass substrates showed a smooth surface except for some small blister-like nonuniformities, thought to be particulate "spatter." The resistive film on glass under scanning electron beam microscope (SEM) analysis showed a very uniform and smooth surface structure. Energy Dispersive Analysis of X-rays (EDAX) analysis of the Kanthal resistor films was performed using an EDAX Model 707A interfaced with the previously mentioned SEM. The results indicated the deposited Kanthal film contained large proportions of chromium, iron, and aluminum, as expected.

The Kapton substrate circuits under SEM analysis showed a surface finish quite different than that of the glass samples. Figure 4 is a 5000X photo of a copper film on Kapton; the film surface exhibits numerous irregularities. This is also evident in the SEM photograph of the Kanthal film on Kapton (Figure 5). The fact that these irregularities were not seen on films made during the same deposition on glass substrates indicates that the irregularities are most likely on the Kapton surface.

B. Electrical Characterization

The sheet resistance as measured by the resistance monitor for Run 11 was 192 ohms/square. Sheet resistance values for the circuits done on glass were generally lower than the value measured at the time of deposition on all runs. One hypothesis is that the several substrate heating operations during processing allow some annealing and corresponding resistance reduction.

Sheet resistance values for the circuits done on Kapton were generally higher than the value measured at deposition. There are several possible reasons for this. The surface irregularities shown in Figures 4 and 5 undoubtedly have the effect of increasing sheet resistance. Also, because the sticking coefficients for glass and Kapton are different, and because the resistance monitor was glass, the sheet resistance of the films on Kapton might have been higher to begin with. Another possible problem is stress put on the films during nitrogen blow-off by high speed vibration of the flexible Kapton. Thermal stress induced by heat treatments in processing are probably not the cause; Table 1 shows the TCEs of glass and Kapton are quite similar. Resistance measurements in these tests were made by probing directly across the resistor contacts to eliminate the effects of interconnection resistance.

The two glass substrate circuits that were evaluated from Run 11 are designaged as 11GA and 11GB; the two Kapton substrate circuits are designated 11KA and 11KB. Table 2 summarizes the sheet resistance data obtained from these circuits. Aside from the higher sheet resistance of the films on Kapton (already discussed), there is an order of magnitude greater standard deviation of sheet resistance on the circuits fabricated on Kapton.

The SEM photos show that the Kapton had a surface with a large number of randomly distributed surface irregularities. Thus, the variation of resistance for a particular resistor would depend on its position relative to these substrate imperfections, leading to a high standard deviation. Further work is recommended with the goal of obtaining polyimide film substrates showing a smoother surface topology. Whether this can be accomplished with improved handling techniques on commercially available films or whether special polyimide substrate fabrication is required remains to be seen.

Flexing, of course, is possible only with the Kapton substrates. Only certain resistors are situated such that their values can be easily monitored during flexing. All the resistors used for this test had contact pads which were accessible on the left border of the circuit. The Kapton was flexed to a radius of curvature of 1 cm. As the resistors were flexed, some small change was noted in each resistor value. The Appendix shows that the percentage of change in resistor value resulting from flexing is independent of resistor length.

Table 3 summarizes the resistance data measured during substrate flexing. The resistance change is generally averaging approximately 0.2% with a maximum observed change on one resistor of 0.6%. The standard deviations of percentage change for Circuits 11KA and 11KB are 0.194% and 0.241%, respectively.

To determine how much, if any, of this decrease was due to flexing in the interconnection lines, isolated conductor paths at the top of the circuits were tested in the same manner. When this was done, there was no measurable change in resistance. It follows that all the resistance changes measured in the previous flexing tests are essentially independent of changes in interconnection resistance.

The results from the flexing tests show that it is possible to fabricate a thin-film resistor/conductor network in a planar configuration on a flexible substrate, and then subsequently fold or bend the circuit to increase the packaging density greatly while maintaining nearly constant resistor values.

The TCRs on Sample 11GA (glass substrate) ranged from 41.6 to 58.3 ppm/°C, with an average of 48.2 ppm/°C and a standard deviation of 5.8 ppm/°C. On glass sample 11GB, the TCRs ranged from 38.1 to 66.6 ppm/°C, with an average of 47.6 ppm/°C and a standard deviation of 7.8 ppm/°C. The TCRs for the resistors on Sample 11KA (Kapton substrate) ranged from 72.5 to 151.4 ppm/°C, with an average of 96.5 ppm/°C and a standard deviation of 23.6 ppm/°C. These measurements were performed in air environment. Because of the severe oxidizing problem of the copper at the high stabilization temperature, it was decided that the measurement on the other Kapton sample (11KB) would be performed under a stream of dry nitrogen. (These circuits had not yet had their conductor surfaces treated with the electroless gold plating solution.) The inert environment made a substantial difference as the TCRs were found to be between 30.4 and 71.8 ppm/°C, with an average of 46.2 ppm/°C and a standard deviation of 12.5 ppm/°C. These values are consistent with those measured on the glass substrates. For this reason, it is believed that the poorer values recorded for 11KA were a consequence of the problem of making probe contact through the oxide.

As anticipated, voltage coefficients of resistance (VCRs) for these thin-film circuits were negligible. Resistors 6 and 10 on Samples 11GA and 11KB were measured at applied voltages of 2 to 20 V with no discernable VCR. As a solution for the problem of copper oxidation, circuits were treated in an electroless plating solution (previously described). This solution works on basis of ion exchange and leaves the surface of the copper interconnections covered with a layer of gold to inhibit corrosion. A glass substrate sample so treated was heated for 5 min at 200°C in air with negligible oxidation of the metallization.

V. CONCLUSIONS

This research has investigated the use of a polyimide film such as Kapton as a flexible substrate for thin-film microcircuits using the previously described technology. The circuits deposited on Kapton are somewhat inferior to those on glass in terms of uniformity and TCR; however, the irregular surface of the Kapton and the problems encountered with mounting have at least contributed to these shortcomings. It was very encouraging that the flexing caused very little change in resistance values. The data show that the average resistance deviation for a circuit flexed to a radius of curvature of 1 cm is approximately 0.2%. This suggests that circuits can be fabricated while planar using this type of technology and folded to conform to packing requirements, with greatly increased packing density.

Additionally, a new thin-film conductor/resistor material system (copper/Kanthal) was employed which provides low materials costs, compatibility with certain selective etches to accomplish a subtractive process, conductor resistivity lower than gold, resistor TCRs easily less than 50 ppm/°C, and a simple fabrication process.

TABLE 1. COMPARISON OF PROPERTIES OF KAPTON AND PYREX

Property	Kapton	Pyrex
Thermal Coefficient of Expansion - /°C	2.0×10^{-5}	3.25×10^{-5}
Thermal Conductivity cal-cm/(cm^2-sec°C)	0.00037 to 0.00045	0.0021 to 0.0030
Dielectric Constant	3.0 to 3.5	4.0 to 6.0
Specific Gravity	1.42	2.32
Flexible	Yes	No

TABLE 2. SUMMARY OF SHEET RESISTANCE DATA

	Circuit 11GA	Circuit 11GB	Circuit 11KA	Circuit 11KB
Average Sheet Resistance (Ω/□)	174.5	174.7	282.8	286.7
No. of Resistors Measured on Circuit	22	17	21	22
Standard Deviation (Ω/□)	8.2	6.6	90.2	96.2

TABLE 3. EFFECT OF FLEXING TO 1-cm RADIUS ON RESISTOR VALUES

Circuit	No. of Resistors Measured	Average Percentage of Change	Standard Deviation
11KA	9	-0.23%	0.194%
11KB	9	-0.26%	0.241%

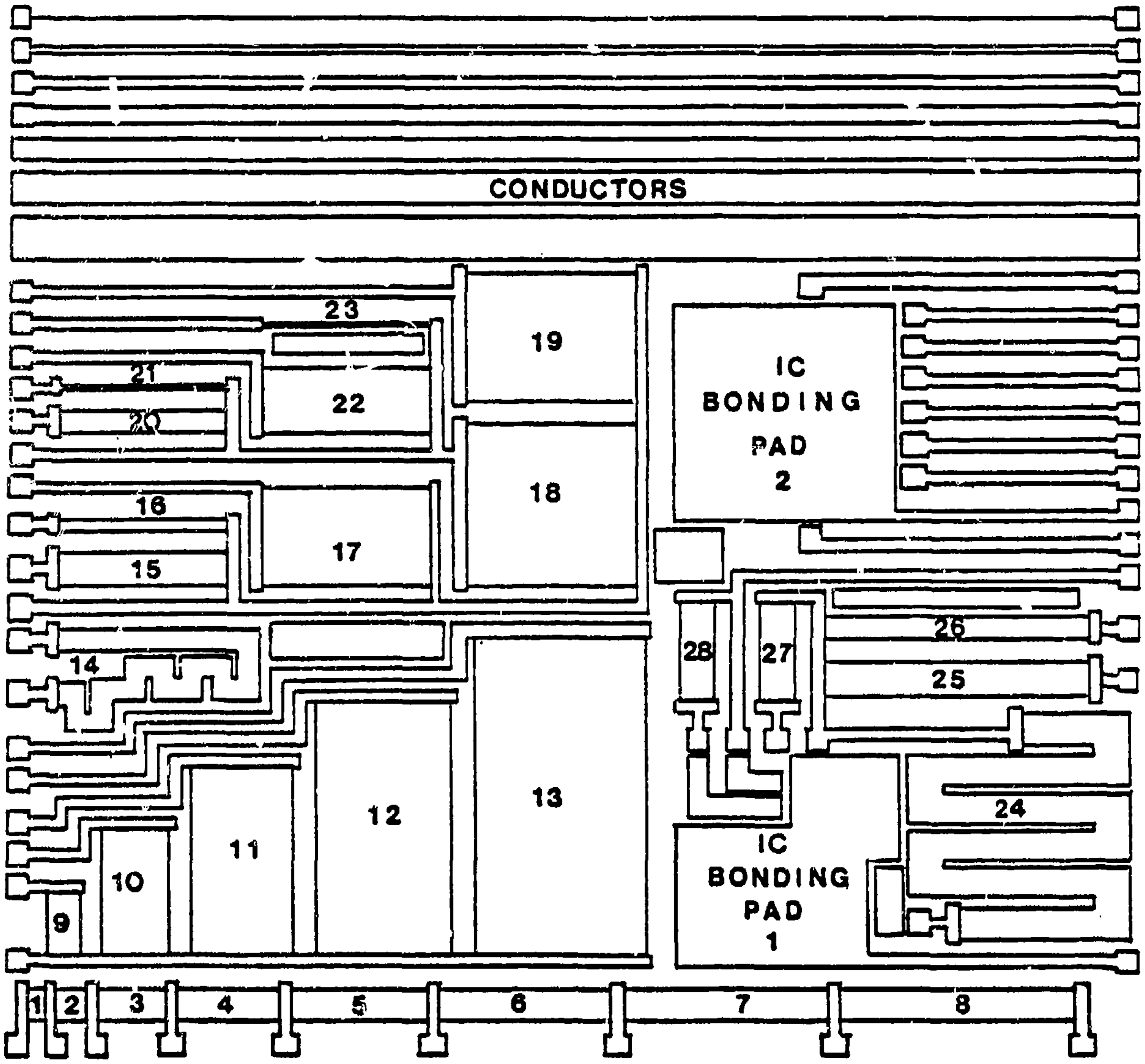
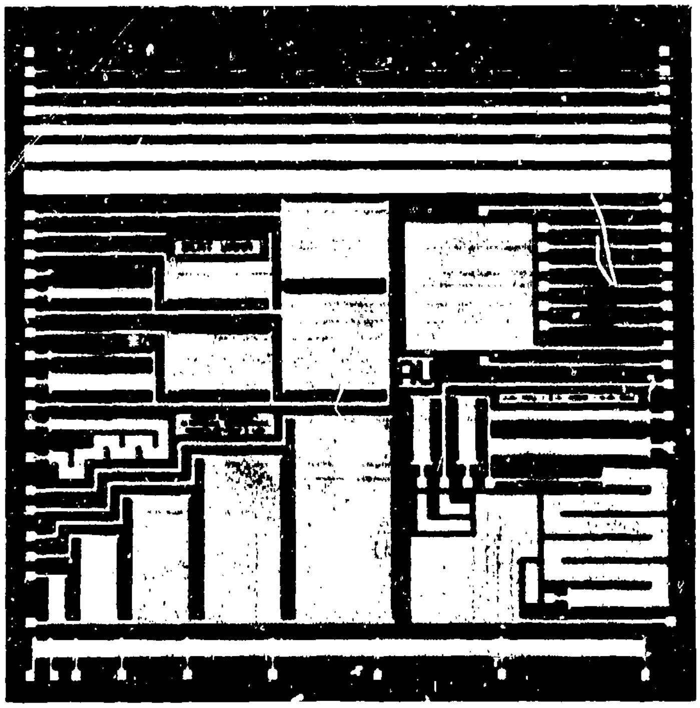


Figure 1. Thin-film microcircuit layout.



(a) CONDUCTOR–RESISTOR PATTERN

(b) RESISTOR PATTERN

Figure 2. Exposure masks.

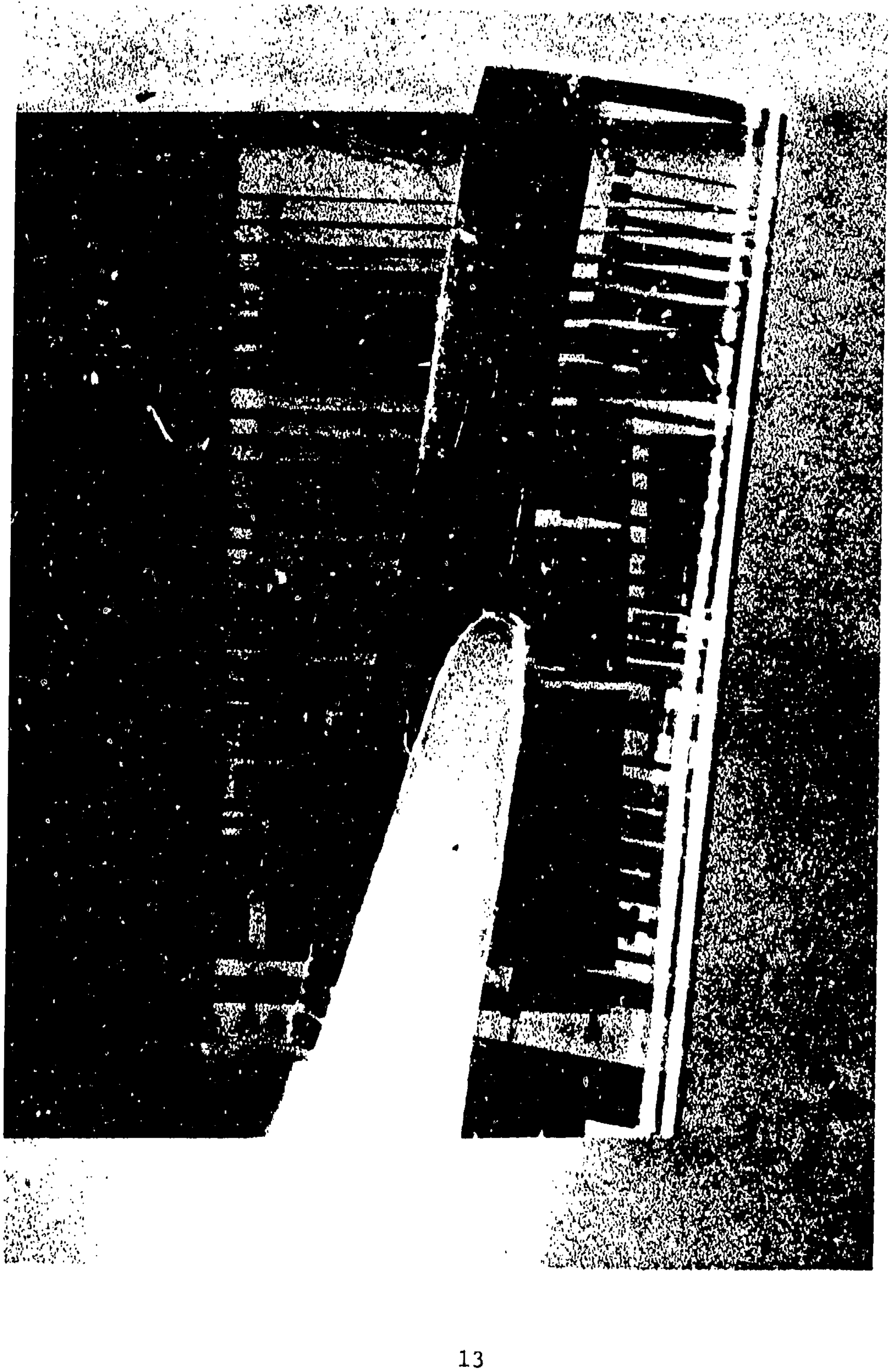


Figure 3. Thin-film circuit on flexible substrate (flexed).

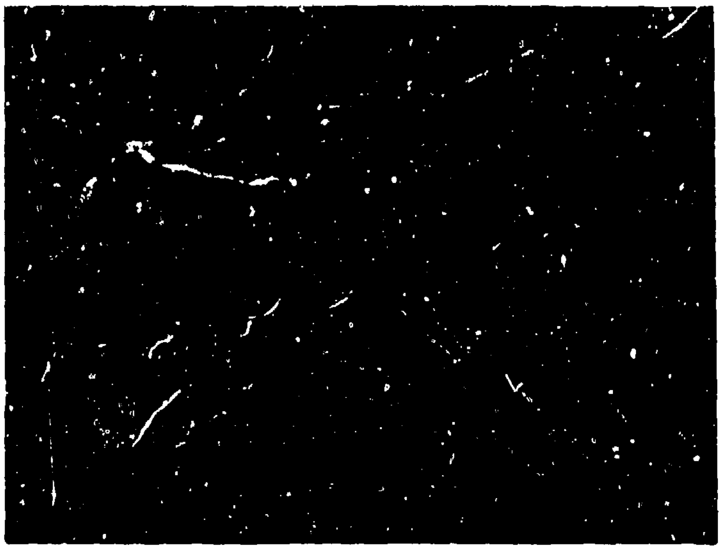


Figure 4. SEM photo of copper film on Kapton (5000X).

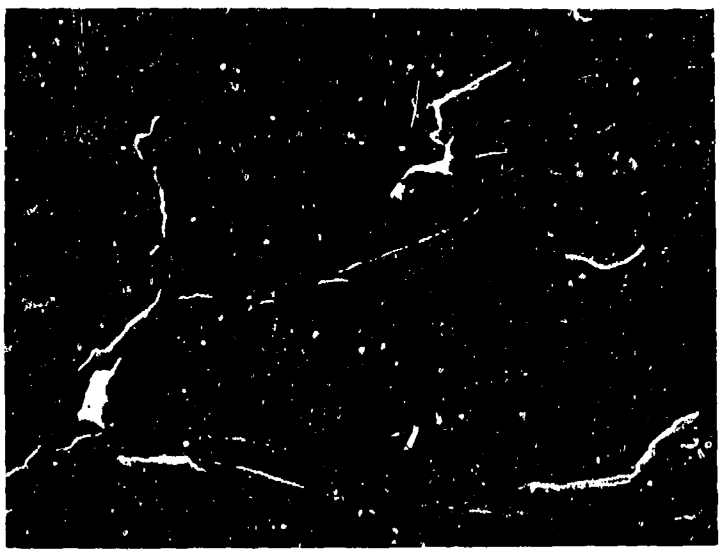


Figure 5. SEM photo of Kanthal film on Kapton (5000X).

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Appendix. EFFECT OF RESISTOR LENGTH ON PERCENTAGE RESISTANCE CHANGE OF FLEXED THIN-FILM RESISTORS

It was previously stated that the percentage of change in resistance of thin-film resistors due to flexing is independent of the resistor length. The following is a proof of that statement.

Assume two resistors are made with the same sheet resistance. Resistor R_A has width w and length L_A. Resistor R_B has width w and length L_B. Let $L_B = xL_A$ and thus $R_B = xR_A$. Both resistors can be said to be composed of series increments of value R_n such that

$$R_A = nR_n \qquad \text{(A-1)}$$

and

$$R_B = xnR_n \quad . \qquad \text{(A-2)}$$

When an incremental R_n is flexed uniformly end to end its value becomes R_{nf} and

$$R_{nf} = yR_n \qquad \text{(A-3)}$$

where y is a constant dependent upon the radius of curvature of the flexing.

If R_A and R_B are oriented the same way and are flexed end to end in an equal and uniform radius of curvature, the series R_n's will all change a like amount such that

$$R_{Af} = nyR_n \qquad \text{(A-4)}$$

and

$$R_{Bf} = xnyR_n \qquad \text{(A-5)}$$

where R_{Af} and R_{Bf} are the flexed values of R_A and R_B, respectively. The ratio of the flexed value of the two resistors to the original value gives

$$R_{Af}/R_A = nyR_n/nR_n = y \tag{A-6}$$

and

$$R_{Bf}/R_B = xnyR_n/xnR_n = y \quad . \tag{A-7}$$

It follows from this that the percentage change in resistance due to flexing depends on the radius of curvature and not on the length of the resistor being flexed.

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