United States Patent

Livermore et al.

[15] **3,674,659**

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[54] THIN-FILM RESISTOR ANODIZATION

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[52] **U.S. Cl.** .....**204/56 R,** 204/58, 204/228

[51] **Int. Cl.** **C23b 9/00,** B01k 3/00

[58] **Field of Search** .....204/58, 56 R, 228

[56] **References Cited**

UNITED STATES PATENTS

3,365,379	1/1968	Kaiser	204/56 R
3,341,444	9/1967	La Chapelle	204/56 R
3,148,129	9/1964	Basseches et al	204/56 R

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[57] **ABSTRACT**

A method for adjusting the electrical resistance of thin-film metallic resistors by anodization is disclosed. The method includes the steps of: (1) supplying an electrolyte between a thin-film resistor and a cathode spaced therefrom; (2) applying a measuring voltage across the resistor for a period of time sufficient to determine the resistance of the resistor; (3) removing the measuring voltage, and if the resistance is below a desired value, passing an anodizing direct current between the resistor and the cathode for a time sufficient to anodize a surface of the resistor and thereby increase its resistance, the magnitude of the anodizing current and period of time being selected so as to produce an increase in resistance by an increment proportional to the difference between the desired value and the measured value of the resistance; (4) repeating step (2); and (5) terminating the anodizing of the resistor when the measured electrical resistance reaches a desired value.

1 Claim, 6 Drawing Figures

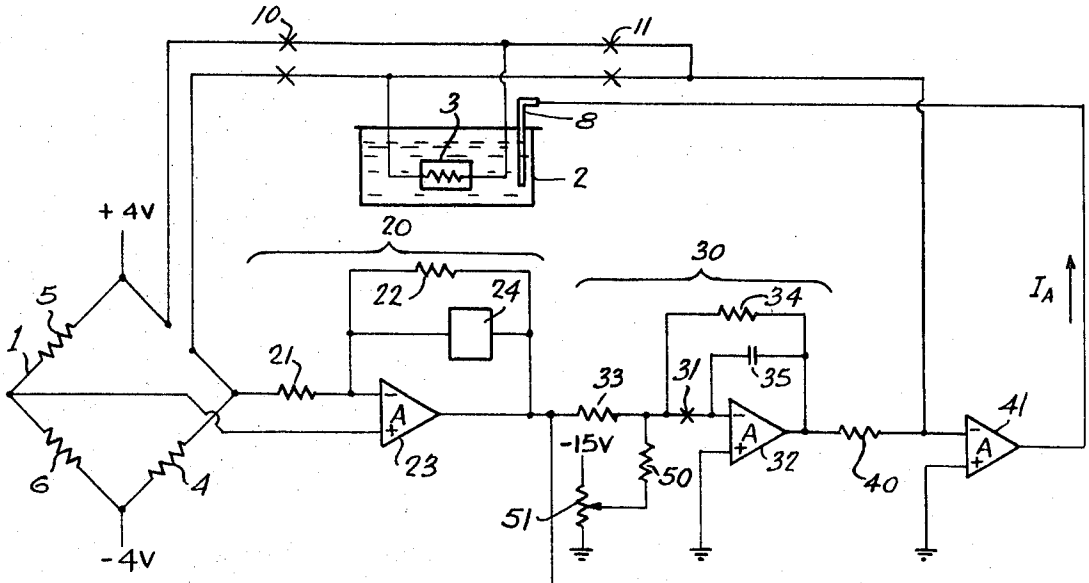


Fig. 1.

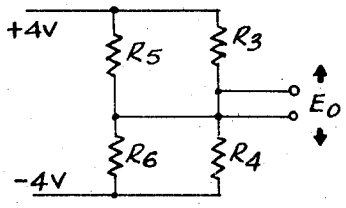


Fig. 2.

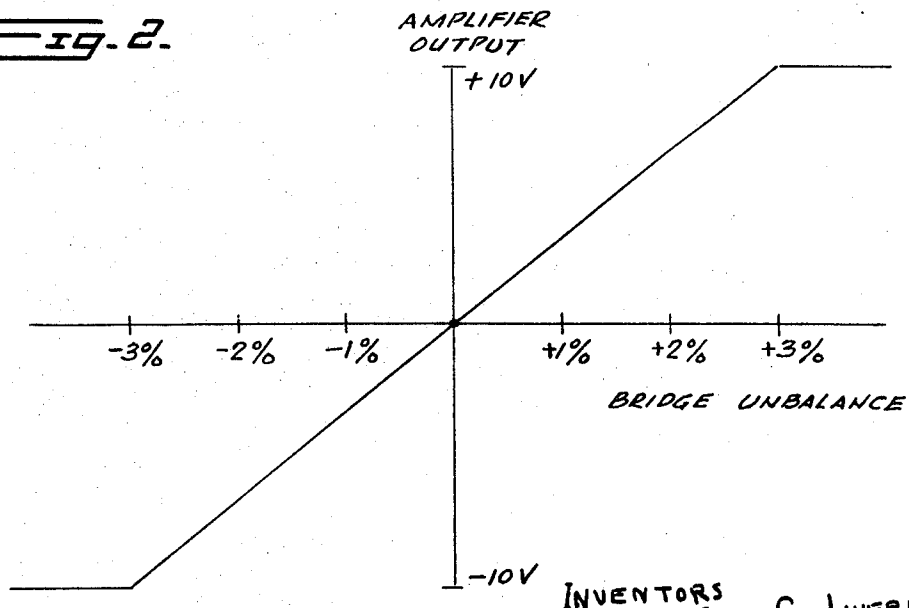


Fig. 3.

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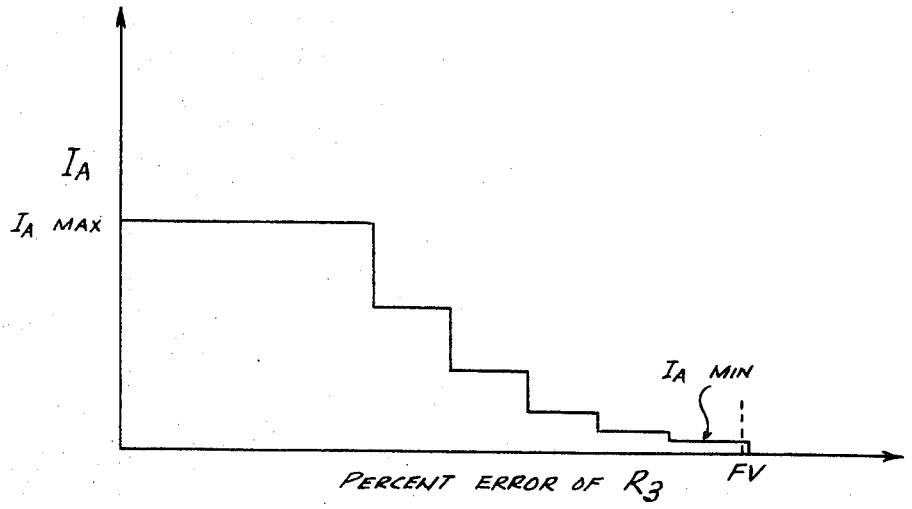


Fig. 4.

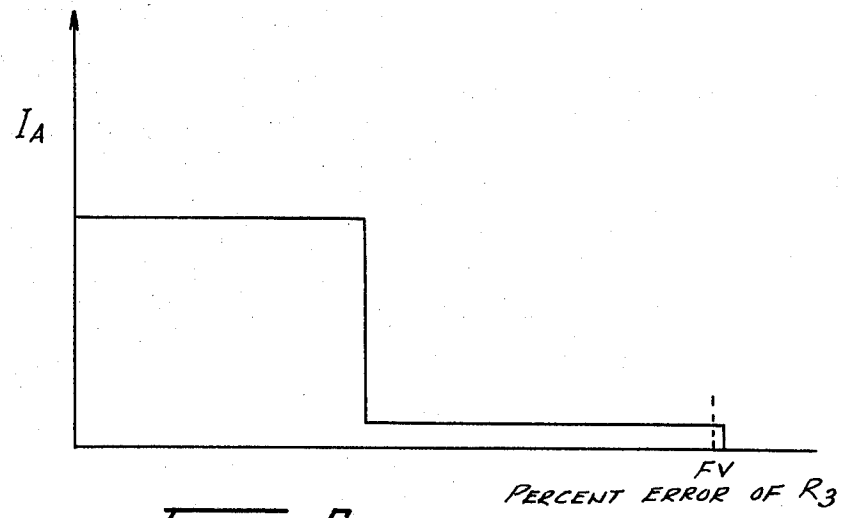


Fig. 5.
(PRIOR ART)

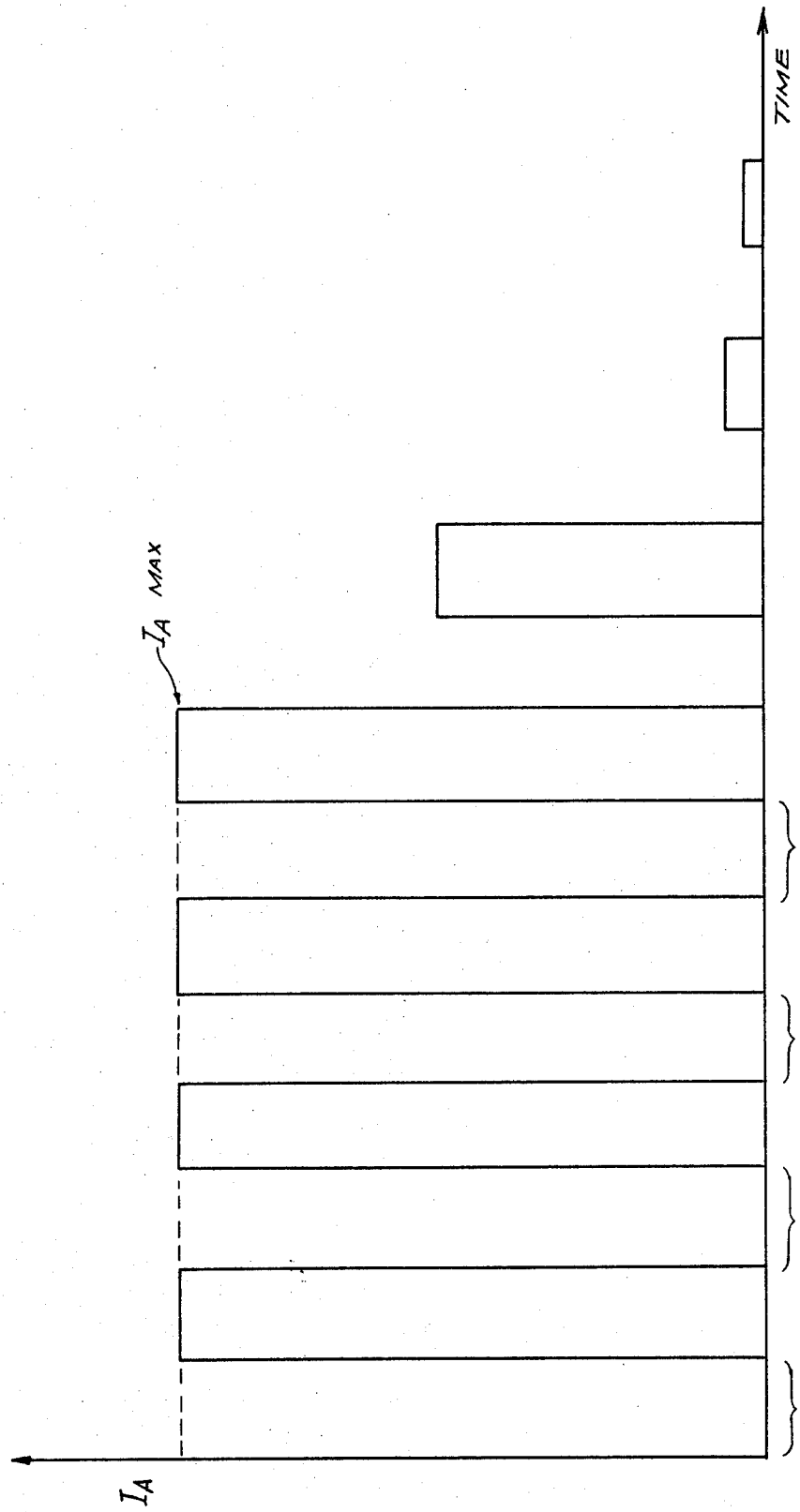


FIG. 6.

THIN-FILM RESISTOR ANODIZATION

This invention is concerned with control of the electric current used to anodize thin-film metallic resistors, and is particularly applicable to adjustment of the resistance value of thin-film tantalum resistors utilized in hybrid microcircuits.

The increasing use and refinement of such hybrid microcircuit devices has created a requirement for precise thin-film metallic resistors which can be fabricated relatively easily, and which can be accurately and simply adjusted to a required resistance value. One way to manufacture such thin-film resistors is by depositing a thin film of a refractory metal, such as tantalum, on a dielectric substrate. By using masking and etching steps which are well known in the art, resistors having the desired dimensions are produced; the resistivity and dimensions of the resistor determing its resistance value. Because of difficulties encountered in accurately controlling the exact dimensions and material properties of the thin-film resistors so-produced (particularly due to their extreme thinness and fine tolerances), it has been found desirable to deposit the metal film in a thicker layer than required; the resultant resistor then has a value less than that ultimately desired. Thereafter, the deposited metal film can be electrolytically anodized to convert a portion of the film thickness to its oxide form, a dielectric, thereby reducing the cross-sectional area of the resistor and concomitantly increasing its resistance. The oxide formed on the surface of the metal layer by the anodizing step also acts as a protective insulating coating which stabilizes the resistor value.

The anodization of the metal film is continued until the resistance of the particular resistor has increased to the desired value. One of the difficulties encountered in thin-film resistor anodization is termination of the anodization step when the resistor has reached exactly the resistance value desired. If the process is terminated too soon the resistor will be below the desired value, and if anodization is carried on too long the resistance will be greater than required. Termination of the anodization process within the required accuracy tolerance requires some method of monitoring the resistance value as the anodization proceeds. Measurement of the increasing resistance is complicated by the flow of anodizing current through the resistance, and so the production of thin-film resistors within the required percentage error has proved difficult and time-consuming.

One of the earlier disclosed methods of trimming thin-film metallic resistors to a desired value is described in U.S. Pat. No. 3, 148,129, Basseches et al., issued Sept. 8, 1964. In that patent the resistance value of the resistor is continuously measured during the anodization step and the process is terminated once the desired value has been reached. The flow of current effecting anodization of the resistor varies as the anodizing proceeds, and this current must be considered in determining the actual value of the resistor's resistance. This complicates accurate anodization of thin-film resistors, and the tolerances obtainable by this method have proved inadequate for precise applications. U.S. Pat. No. 3,254,014, Daddona, issued May 31, 1966, describes a method of altering the resistance of a thin-film resistor to a desired value which requires maintaining a constant anodization current and monitoring the voltage necessary to maintain that constant current as the oxide coating builds up. When the desired voltage, calculated beforehand, is reached, the anodization is discontinued. This method of adjusting thin-film resistors has not found wide acceptance, again in view of its lack of accuracy because the bulk properties, anodization efficiency, growth kinetics, etc., often vary with depth. Another approach to control of the anodization of thin-film metallic resistors is described in U.S. Pat. No. 3,365,379, Kaiser, issued Jan. 23, 1968. This patent discloses the use of an AC bridge for controlling the anodizing current and the resistance measurement.

U.S. Pat. No. 3,341,444, La Chapelle, issued Sept. 12, 1967, discloses an improved way of determining accurately when a resistor has reached the required value and anodization should cease. The resistor is alternately anodized and then its resistance measured; when the desired resistance value is obtained, anodization is terminated. Since this method does not provide constant monitoring but rather the sequence test-anodize-test-anodize-test, as the desired resistance value is approached difficulties are encountered in determining the magnitude of the incremental anodization steps which should be used and which will keep the number of steps to a minimum but which will not overshoot the required final value. It is time-consuming and uneconomic to keep stopping the anodization and testing the resistor value many times in order to approach the desired value carefully and achieve the necessary precision.

A further problem associated with incremental testing and anodization is outlined in U.S. Pat. No. 3,341,445, Gerhard, issued Sept. 12, 1967. The switching of the resistor contacts back and forth between the anodize circuit and the test circuit results in transient switching currents which can and do interfere with the accuracy of the resistance measurements. Another phenomonen which can cause erroneous results when alternately anodizing and then testing is the presence of parasitic capacitance between the resistor and electrolyte, with the anodized layer acting as the dielectric. This situation together with the presence of switching transients has made it desirable to include a stabilizing period between the anodizing and measuring steps. Such a procedure is described in Canadian Pat. No. 791,350 (Carroll), issued July 30, 1968. The inclusion of a stabilizing period between anodizing and testing of the resistor has further lengthened and complicated the incremental steps necessary to approach slowly and to reach accurately the required resistance value of the resistor, without overshooting.

In methods of anodizing such as those described in U.S. Pat. No. 3,341,444 and Canadian Pat. No. 791,350, the rate at which anodization takes place remains constant. Such use of a single rate of anodization is very time-consuming if small increments are used such that a high degree of accuracy can be achieved.

It is an advantage to be able to reduce to a minimum the number of times it is necessary to stop and measure the resistance of the resistor being anodized. Accordingly, it has been proposed to utilize apparatus capable of two different rates of anodization. Initially, when the resistor is farthest from its desired value, large increments of anodization are utilized, and then when closely approaching the required value, the increments are reduced to a magnitude such that the target value of resistance can be reached within precise error limits.

Such a procedure, using two different anodization rates, can be utilized, for example, with a resistor which is about 86 percent of its required value and which must be anodized to within 0.1 percent of the desired value. Typically in such a situation, the resistor is anodized in 2 percent increments until it is less than 2.5 percent below the required level, and at this point the anodizing rate is changed to 0.1 percent per step. In this example, approximately six steps at the high rate and 20 increments at the low rate would be required. It is difficult to avoid such a lengthy procedure since if 0.1 percent accuracy is required the smaller rate cannot be of any greater increment, and if a larger initial rate is chosen then the anodization apparatus must be switched to the lower rate a greater percentage distance away from the final desired level, thus necessitating a greater number of increments at the lower rate.

It is an object of this invention to provide a method for the anodization of thin-film metallic resistors which reduces the time required to bring the value of a thin-film resistor to a desired level, while maintaining a very high degree of accuracy of the end product.

In the practice of this invention, instead of working with one or two fixed increments of anodization, it is carried out in increments proportional to the percentage error between the actual resistance value and the desired ultimate value. It has been found that this method substantially decreases the

number of steps required to trim a resistor to its final value, and so the time and effort necessary to manufacture thin-film metallic resistors in hybrid microcircuits also is reduced. Variation in the current and/or time period, used to anodize a resistor so that each increment is proportional to the percentage offset of the resistance from the desired final value, has proved to be an efficient and less expensive way of producing precise thin-film metallic resistor components.

In accordance with the practice of this invention, the method for adjusting the resistance value of a thin-film metallic resistor by anodization includes the steps of: (1) supplying an electrolyte between the resistor and a cathode spaced therefrom, (2) applying a measuring voltage across said resistor for a period of time sufficient to determine the electrical resistance of said resistor, (3) removing the measuring voltage and if the measured electrical resistance of said resistance is below a desired value, passing an anodizing electric current between the resistor and the cathode for a period of time sufficient to anodize a surface of said resistor and thereby increase the resistance value thereof, the magnitude of the anodizing current and the period of time being selected so as to produce an increase in resistance by an increment which is directly proportional to the difference between the desired value and the measured value of the electrical resistance of said resistor, (4) repeating step (2), and (5) terminating the anodizing when the measured electrical resistance reaches a desired value.

The amount of anodization which takes place depends upon both the magnitude of the anodizing current and the period of time for which it passes through the electrolytic cell. A reduction in either current, time, or both will reduce the degree of anodization and the increase in resistance achieved by each anodizing increment.

The anodizing current has been found a relatively easy factor to vary in reducing the size of the anodizing increments, with the duration of each increment remaining constant. Although theoretically it might be desirable to have the anodizing current always fractionally proportional to the percentage offset, in actual practice it has been found preferable to place maximum and minimum limits on the magnitude of the anodizing current. The maximum anodizing current which should be utilized is a function of the resistor geometry, the capacitance of the electrolytic cell, growth kinetics, and other material properties of the metal film. It is definitely advisable not to exceed a certain current saturation density in the electrolytic cell in which anodization is taking place, since it is important that the oxide produced on the metal film be a dense strong material which is tightly adherent to the metal resistor.

In practice, therefore, anodization proceeds in increments at an optimum current until the resistor is a specific percent below the target value, and at that time the increments of anodization are adjusted downward to be proportional to the percentage error between the resistor value and the required final value. This is done by reducing the anodization current magnitude (or alternatively the time period) utilized for the anodization increment. The ratio of the fractional proportionality may be varied so that it is possible to define a rate-of-approach of the resistor toward its required ultimate value.

An optimum anodization current is established at the beginning of anodization from the parameters for each resistor and the characteristics of the anodizing circuit; the use of a maximum limit protects the device and ensures that anodization takes place at the optimum rate until the resistance value of the resistor approaches close enough that another anodization increment would overshoot the target value. Once the resistance is within that limit, the current and/or duration of the next anodization increment is reduced so that it is proportional to the error between the present value and the target value.

It also has been found that the anodization current should be subject to a minimum level; below a particular value (again dependent upon the lumped capacitance of the cell plus strays and the resistor parameters) anodization proceeds at a very inefficient or almost non-existent rate. When closely approaching the final value of resistance it is desirable in some instances not to reduce the current almost to zero, but rather to maintain a minimum current strength.

With the procedure of the present invention the sequence of operations necessary to achieve the final resistance value is much shorter, as exemplified by comparing it with the number of steps required by the example of anodization given earlier. In this case the resistance of the resistor is first measured to ensure that it is below the desired target value, and a maximum current density is selected for the particular resistor being anodized. Assume (as in the previous example) that the maximum rate of anodization will be utilized until the offset is less than 2.5 percent away from final value and that in this circuit less than 2.5 percent maximum increment is produced by an anodize control voltage of 10 volts. The resistor is alternately tested and anodized in approximately 2 percent increments until the percentage error from target value is less than 2.5 percent. Once the percentage error becomes less than 2.5 percent, the anodize control voltage of the anodizing circuit is set to a value which is a fraction of 10 volts (proportional to the percent error) which is based upon the equation:

$$\frac{\text{percent error}}{2.5\%} \times 10 \text{ volts}$$

Using this procedure, the resistor can be anodized to within the same or closer tolerance as in the preceding situation with approximately six steps at maximum anodization current (giving about 2 percent increments) and just three steps (as opposed to 20) at the proportional rate. Thus anodization, in the example used, can be completed in about 35 percent of the time required by the old method.

The invention now will be described in more detail by reference to the accompanying drawings which illustrate one manner in which this invention may be put into practice. The particular examples which are illustrated and described have been included to facilitate understanding of the invention, and are not to be construed as limiting the scope thereof.

In the drawings:

FIG. **1** is a schematic diagram of an anodization control circuit according to the practice of this invention;

FIG. **2** is a simplified diagram showing a portion of the circuit of FIG. **1**;

FIG. **3** is a graph of the output of a particular point in the circuit of FIG. **1**;

FIG. **4** is a graph of anodization current plotted against resistor value for a particular example using the circuit of FIG. **1**;

FIG. **5** is a graph of a prior art result for the same example as FIG. **4**; and

FIG. **6** is a plot of anodization current with time for a particular example using the circuit of FIG. **1**.

FIG. **1** is a diagram of an anodizing circuit embodying the principles of the present invention. The several circuit components are shown schematically connected to form an anodizing control circuit. The circuit includes as major constituents thereof a Wheatstone bridge **1**, an electrolytic cell **2**, and the resistor **3** to be anodized. The Wheatstone bridge includes in three arms thereof resistors **4**, **5**, and **6**, while the fourth arm of the bridge is connected via relay **10** to the resistor **3** whose value it is desired to adjust.

Outlining briefly the operation of the anodizing circuit, the first step in the trimming of thin-film resistor **3** is to connect resistor **3** to the Wheatstone bridge **1** by closing relay **10**. Measuring the output of bridge **1** compares the resistance value of resistor **3** to a standard resistor **4** in one arm of the bridge circuit. If the resistor is found to have a value less than that of the standard resistor, the circuit will be switched to anodize sequence by opening relay **10** and closing relay **11**. The resistor is anodized with a constant current for a fixed period of time, and at the completion of the anodizing cycle the circuit returns to the measuring mode. This sequence is repeated until during a measuring cycle the resistor **3** being anodized is

found to have a value equal to or greater than that of the standard resistor. The circuit preferably is equipped with means for indicating that anodization is complete, and this can be accomplished by feeding signals to the system control circuitry. In the embodiment illustrated these control signals are generated in amplifier **61**, and passed to the system control logic which can be used to determine the end of the anodize-measure sequence for each resistor.

The Wheatstone measuring bridge **1** has resistors **5** and **6** of known and standardized resistance value (typically 10K ohms) forming one side of the bridge; standard resistor **4** (whose value may be altered depending upon the target value of resistor **3**) and the resistor **3** undergoing anodization comprise the other side of the Wheatstone bridge. The bridge is supplied with a direct current potential of ±4 volts, as shown.

The Wheatstone bridge **1** is connected to a detector-amplifier **20** comprising resistors **21** and **22**, amplifier **23**, and a ±10 volt clamp circuit **24**. The amplifier **23** is connected between the midpoints of the two bridge arms as shown. At the balance or null point, the output from the bridge to the detector-amplifier **20** will be 0 volts since $R_5=R_6$ and R_3 will equal R_4. The amplifier **23** is connected to have a gain defined by resistors **21** and **22** and a maximum output voltage swing of ± 10 volts defined by the 10-volt clamping circuit **24** across feedback resistor **22**. Typically, in the circuit illustrated, the resistors **21** and **22** have values of 600K ohms and 100M ohms, respectively. The amplifier gain of detector component **20** is defined by the ratio

$$\text{GAIN} = R_{22}/R_{21}$$

which in this case

$$= 10^8/(600 \times 10^3)$$

$$= 166.$$

Since the maximum output from the detector-amplifier **20** is ±10 volts, the maximum input for a linear output

$$= 10/166 = 60 \text{ mV}.$$

With reference to FIG. **2**, which is a simplified diagram showing the Wheatstone bridge balance and output E_o, then:

$$E_o = \frac{V_1 + V_2(1+\alpha)}{(2+\alpha)}$$

where

$$\alpha = \frac{R_4 - R_3}{R_4}$$

If R_3 = 99 percent of R_4, then the bridge unbalance is −1 percent,
and

$$\alpha = 0.01$$

then

$$E_o = 4(0.01)/(2.01)$$
$$= 20 \text{ mV}.$$

FIG. **3** is a plot of the output of detector-amplifier **20** against the percent of bridge unbalance as derived from the above equations. As can be seen from FIG. **3**, for resistance values of the resistor **3** (which is being anodized) that are less than 97 percent of the value of standard resistor **4**, the output of the detector-amplifier component **20** will be limited to −10 volts.

Returning to FIG. **1**, the portion of the circuit indicated by reference number **30** constitutes a sample and hold amplifier. During the measuring sequence relay **31** at the input to amplifier **32** closes and the component **30** will act as a normal inverting amplifier with its gain defined by resistors **33** and **34**. In the circuit illustrated the two resistors each have a resistance value of 10K ohms, and the amplifier gain:

$$= -R_{34}/R_{33} = -10\text{K}/10\text{K} = -1.$$

The input to the sample and hold component **30** is fed from the output of detector-amplifier **20**, and the voltage at the output of **30** is equal in amplitude and 180° out of phase with the output of **20**. At the end of the measure sequence relay **31** opens but the anodize control voltage at the output of component **30** is maintained by the charge on capacitor **35**, which in the circuit shown is a 0.01 μf capacitor.

If during the measuring sequence the anodized resistor **3** is found to have a resistance value less than standard resistor **4**, then the circuit advances to the anodize mode. Relay **10** opens and relay **11** closes. The resistor **3** which is being anodized is now connected to the summing input of amplifier **41**. This amplifier provides the constant current anodize supply to the cathode **8** of electrolytic cell **2**, through the resistor to be anodized, **3**, (forming the anode), and to the summing input of amplifier **41**.

As anodization proceeds, the voltage being dropped across the oxide being formed on the resistor is increasing in order to maintain the anodizing current constant during that increment; the magnitude of I_A being determined by the anodize control voltage. The control voltage is held constant for the duration of each increment by sample and hold amplifier **30**. The constant current anodize supply must increase its voltage output over the duration of each increment in order to maintain I_A constant, and this function is performed by amplifier **41**. Amplifier **41** supplies a constant current output as long as it is being fed a constant anodize control voltage; the amplifier transforms an input voltage level into an output current level. The value of the constant anodization current is determined by the output anodize control voltage from the sample and hold amplifier **30** and the size of variable resistor **40** which is input to the anodize supply.

In this particular circuit, for values of R_3 that are more than 3 percent below R_4, as shown in FIG. **3** the anodize current will be at its maximum:

$$I_A \text{ MAX} = 10/R_{40}$$

For values of R_3 that are less than 3% different from R_4, then I_A will be:

$$I_A = \frac{10}{R_{40}} \times \frac{\text{Percent error}}{3\%}$$

Maximum values of I_A are defined by controlling variable resistor **40**. The maximum current is adjusted having regard to the geometry and dimensions of the resistor being anodized so as to not damage it. A typical I_A MAX is of the order of 2.5 milliamps.

I_A MAX preferably is set to a value that will cause a change of approximately 3 percent in resistor **3** for each anodizing increment. Therefore, if R_3 has a value of 98 percent of reference resistor **4**, then I_A will be reduced to:

$$I_A = \frac{10}{R_{40}} \times \frac{\text{Percent error}}{3\%}$$
$$= I_A \text{ max} \times \frac{2\%}{3\%}$$
$$= 67\% \; I_A \text{ max}$$

Therefore, on the anodizing step which follows, resistor **3** will be changed by:

$$\Delta R_3 = 3 \times 2\%/3\%$$

$$= 2\%.$$

As can be seen from the above, the anodizing current decreases proportionally as the error between R_3 and R_4 decreases. In order that the anodizing current does not fall below a certain minimum level (as discussed previously), a standing voltage input is supplied to the sample and hold amplifier **30** through resistor **50**. Variable resistor **51** can be adjusted to vary the magnitude of the standing input control voltage, and in this particular example resistance **51** has been adjusted to give a minimum anodizing current I_A MIN which is approximately 1.5 percent of I_A MAX. The values of R_{50} and R_{51} are 100K ohms and 10K ohms, respectively.

The minimum anodization current, in addition to being preferred from a standpoint of efficient anodization, also can be adjusted having regard to the degree of accuracy which is necessary to achieve in the final resistance value of the resistor. If, for example, the tolerance of the target value is 0.05 percent error (which is a reasonable requirement in thin-film metallic resistors), then it is much quicker and simpler to approach the final value with a minimum increment which will produce a change Δ R of not much less than 0.05 percent. Variation of resistor **51** permits adjustment of the minimum anodization current I_A MIN to keep it from getting so small as to make the approach to final value unnecessarily time-consuming.

The adjustment of thin-film metallic resistors usually takes place after the hybrid microcircuit device has been fabricated; this being the reverse of normal procedure wherein a resistor would be tested and adjusted and then placed in the circuit. The thin film of metal (typically tantalum) is built up on an insulating substrate and usually has gold plated leads on the ends thereof. The resistor is anodized by clamping the substrate in position, placing the head of the anodization apparatus over the substrate in such a manner as to seal against the edges of the resistor, and introducing the electrolytic solution between the head and the resistor. The ends of the resistor are connected such that the resistor becomes the anode, and the head includes a cathode. The schematic diagram of the anodization cell as shown in FIG. **1** has been utilized to simplify that circuit diagram and also since the actual anodization apparatus used in the manufacture of thin-film resistors is well known. The anodization cell functions in a conventional manner utilizing a customary electrolyte such as dilute aqueous nitric acid, acetic acid, boric acid, or citric acid.

FIG. **4** is a plot of the anodizing current I_A against the increasing resistance value R_3 of the resistor being anodized (expressed as a percentage error of the desired final value FV). FIG. **5** graphically depicts the prior art procedure discussed previously which utilized only two rates of anodization current, and which did not vary the anodization increments proportionally to the percent error from final value.

FIG. **6** is a graph of anodizing current I_A against time. The gaps between increments of anodizing current represent the cycles during which the circuit is permitted to stabilize and the resistance of the thin-film resistor is measured. Methods of providing a period of stabilization before measurement are described in detail in the prior art referred to earlier in this specification, and will not be discussed in detail herein.

For the purpose of providing an example, assume that a resistor to be anodized to a final value, upon initial measurement is 86 percent of the target value, i.e., it is 14 percent below the desired resistance level. Also assume that the maximum anodization current (I_A MAX) and the time period has been chosen such that each anodizing increment produces an increase of 3 percent in the resistance of the resistor which is being anodized, expressed as a percent based on the required final value being 100 percent. As shown in FIG. **6**, four increments of 3 percent each bring the resistance value of the resistor to 89 percent, 92 percent 95 percent and then to 98 percent of full value, respectively. In this example, the anodize control voltage necessary to produce I_A MAX is 10 volts, and the offset necessary to produce maximum anodization current is 3.5 percent from target value. On the fifth testing cycle the resistor is found to be 98 percent of full value. This is 2 percent away from the desired level. The maximum anodizing current was produced with 10 volts at 3.5 percent offset. At 2 percent error the anodization current will be reduced to:

$= (2\%/3.5\%) \times 10$ volts

$= 5.7$ volts

$= 57\%$ of I_A MAX, as shown.

Now, 100 percent of I_A MAX produced a 3 percent increase in resistor resistance. Therefore, the next increment in resistance (the fifth) will result in a $3\% \times 0.57 = 1.7\%$ increase in resistance. This brings the resistor to $98 + 1.7 = 99.7\%$ of the desired value. The next measurement shows a 0.3 percent error in the resistor. The permitted tolerance in the final value is likely to be of the order of 0.05 percent and the circuit will not cease to anodize until the resistance value of the resistor being adjusted is equal to or greater than that of the standard resistor to which it is being equated. The next anodize cycle will produce a current of:

$$(0.03/3.5) \times 10 = 0.86 \text{ volts}$$

$$8.6\% \; I_A \text{ MAX.}$$

This will result in an increase of $3\% \times 0.086 = 0.26\%$ in the resistance value of resistor during the next anodize cycle. This procedure is repeated until the resistor is adjusted to the required value.

As mentioned previously, it is preferable to design the circuit so as to maintain a value of I_A MIN which prevents the anodizing current from dropping to an inefficient density and also minimizes the number of final increments required when the resistor is approaching very close to the final value. The error limits permitted in the final product also make it desirable to maintain a minimum value of anodizing current since, for example, if the permitted error in the final value of the resistor is 0.1 percent, then a minimum increment which is much smaller than 0.1 percent is unnecessary.

As noted in the preceding example, the maximum increment in resistance to be gained from an anodization cycle was 3 percent, and therefore the circuit was designed to produce I_A max only at offsets at least greater than 3 percent, in this case equal to or greater than 3.5 percent. This prevents overshooting the required final value and ensures that the final increments will approach the desired level in small steps.

In actual practice, it has also been found preferable to set the comparison resistor very slightly below the desired final value since the circuit does not cease anodization increments until the resistor being anodized reaches a value equal to or greater than that of the standard resistor. By using a standard resistor for comparison which has slightly less resistance (say 0.05 percent) than that required, the percentage error in the resistors being manufactured is less on the average.

In some instances, for example, in fabricating an oscillator, it is not necessary to adjust a resistor to a specific value, but rather it is sufficient and quicker to adjust the resistor so that the circuit has the desired response characteristics; the resistor can have any value within a certain range, and it is not important what that particular value is as long as the circuit functions correctly and provides the desired frequency. In that particular situation, the resistor can be trimmed to a desired system response value, rather than a particular level of resistance.

The circuit and procedure which have been described are essentially analogue in function; although the anodization proceeds in increments, the anodization current is continuously variable in response to an analogue value. It is possible to convert the value obtained during the measuring cycle into digital form such that a digital computer could be utilized to program the anodization of the thin-film metallic resistor.

Although the example used of a metal which is particularly desirable for the fabrication of thin-film resistors has been tantalum, it will be obvious that the techniques of the present invention are applicable to the adjustment of thin-film resistors made from other substances. Metals other than tantalum are being utilized in the making of thin-film resistors, for example aluminum, titanium, zirconium, and indeed alloys such as tantalum-aluminum alloys hold promise for the future fabrication of thin-film resistors whose resistance value can be adjusted by anodization techniques.

We claim:

1. A method for adjusting the electrical resistance value of a thin-film resistor by anodization in an anodizing circuit comprising the steps of;

a. supplying an electrolyte between the resistor and a cathode of said anodizing circuit spaced therefrom;

b. connecting said resistor in one arm of a resistance measuring bridge;

c. sampling and holding an error voltage developed across diagonal corners of said bridge;

d. disconnecting said resistor from said bridge and connecting it to said anodizing circuit;

e. applying a constant anodizing current to said anodizing circuit for a selected period of time, said current being directly responsive to the magnitude of said error voltage while not above a maximum nor below a minimum value;

f. repeating steps (b), (c), (d), and (e) until said error voltage reaches a preselected value.

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