

SPECIFICATION

Method and device for testing electrical conductors

The invention relates to testing of electrical conductors.

Electrical conductor elements such as gold, aluminum, or suitably doped silicon stripes deposited on a substrate are commonly used in integrated circuit devices to electrically connect active and passive circuit components. Such elements typically have a thickness on the order of a fraction of a micrometer and a width on the order of a few micrometers and, consequently, can be inspected visually only by means of magnifying equipment such as a microscope. Moreover, visual inspection is too time-consuming to be practical in the context of large scale industrial production of integrated circuitry.

While gross defects such as discontinuities in conductor stripes become manifest immediately upon functional testing of a circuit, other defects may go undetected initially but may yet result in premature failure of a device in use. To identify such potentially short lived conductor elements, a so-called third harmonic method has been proposed for testing conductor stripes. This method is based on the observation that conductor stripes which are prone to fail, e.g., due to nonuniformity of width, thickness, composition, or adhesion to the substrate, typically exhibit nonlinearity of resistance as a function of current. According to the third harmonic method a fundamental sinusoidal signal is applied to a linear AC-coupled network across whose output terminals the conductor element to be tested is placed. By measuring the amplitude of the third harmonic component of the output signal a measure for the nonlinearity of resistance of the circuit element is obtained. Successful application of this method is described in "The Nonlinearity of Fixed Resistors" by P.L. Kirby, *Electronic Engineering*, November, 1965, pages 722-726, and in "Harmonic Testing Pinpoints Passive Component Flaws" by Vilhelm Peterson and Per-Olof Harris, *Electronics*, July 11, 1966, pages 93-100. However, due to the need for a signal generator which produces a signal of extremely low harmonic contents, test equipment implementing the third harmonic method tends to be complicated and poorly suited for use in the large scale testing of integrated circuitry.

By measuring the resulting average output voltage a measure of nonlinearity of resistance of the conductor element is then obtained. This test for nonlinearity may be applied simultaneously to a plurality of conductor elements such as thin film conductor stripes on an integrated circuit chip and provides for an estimate of the reliability of such conductor stripes.

In accordance with the invention there is provided a method of testing an electrical conductor by determining nonlinearity of electrical resistance of the conductor as a function of current

flowing in the conductor, comprising applying a wave signal to the conductor such that either the average of the current in the conductor or the average of the voltage drop across the conductor is zero and such as to produce a voltage across the conductor or a current in the conductor respectively, for which the average depends on the said nonlinearity, and measuring the average of the produced voltage or current.

A current wave of zero average value may be applied to the conductor via an A.C. coupling network.

An embodiment of the invention will now be described, by way of example, with reference to the attached drawings in which:

Figure 1 is a diagram of an exemplary circuit which can be used for determination of nonlinearity of resistance by a method, in accordance with the invention;

Figure 2 is a diagram of an alternative exemplary circuit which can be used for determination of nonlinearity of resistance by a method, in accordance with the invention;

Figure 3 is a graphical representation of test results;

Figure 4 shows a test station for testing microcircuitry; and

Figure 5 is another alternative exemplary circuit which can be used for determining nonlinearity of resistance by a method in accordance with the invention.

Figure 1 shows current generator 11 and a linear AC-coupling network 15 which consists of blocking capacitor 12. Averaging voltmeter 13 measures the average voltage across conductor element 14 which is being tested for nonlinearity of resistance by the disclosed method. Generator 11, network 15, and voltmeter 13 are shown inside enclosure 16.

Figure 2 shows current generator 21 a linear AC-coupling network 25 consisting of transformer 22. Averaging voltmeter 23 measures the average voltage across conductor element 24 which is being tested for nonlinearity of resistance by the disclosed method. Generator 21, network 25, and voltmeter 23 are shown inside enclosure 26.

The A.C. coupling network ensures that the average current in the conductor being tested is zero.

Figure 3 shows current as a function of time in a stepped stress high current test of a number of aluminium conductors. Points marked and labelled indicate failure of the circuit element, the numerical value of the label being the voltage measured by voltmeter 13 of Figure 1. It can be seen that high measured voltage is directly related to early failure of the circuit element.

Figure 4 shows electrically insulating rim 31 of a test station for microcircuitry. Probes 32 are attached to rim 31 and electrically connected to test circuitry which is not shown. The tips of probes are aligned with and pressed against contact pads located along the edges of device 33 being tested.

Figure 5 shows voltage generator 51 and AC-coupled linear network 55 consisting of transformer 52. Conductor element 54, which is being tested for nonlinearity of resistance by the disclosed method,

is connected to a network consisting of capacitors 56 and 57, operational amplifier 58, and variable feedback resistor 59. Voltage measured by voltmeter 53 is proportional to the average current flowing in conductor element 54 which average current, is a measure of nonlinearity of resistance of element 54.

The method aims at determining reliability of conductor elements by means of a determination of nonlinearity of resistance, i.e., of deviation from

Ohm's law of a linear relationship between voltage applied to and current flowing in the conductor element. Such deviation typically amounts to a change in resistance as a result of an increase in voltage or current and may be expressed quantitatively by the parameter λ in the formula

$$R_l = R_0 (1 + \lambda I^2)$$

which approximately represents the functional relationship between current I , nominal resistance R_0 , and resistance R_l of a conductor element. It can be shown that this functional relationship is compatible with a physical explanation of nonlinearity of resistance due to Joule heating of the conductor element.

The operation of the method may be conveniently described by reference to Figure 1. It can be shown that if generator 11 produces a rectangular current waveform of peak to peak magnitude I and duty cycle F , the voltage V measured by averaging voltmeter 13 is expressed by the formula,

$$V = \lambda R_0 I^2 F(1-F) (1-2F)$$

from which the direct relationship between voltage V and nonlinearity λ is apparent. It is also apparent that if a duty cycle of $F=0.5$ is utilized, then $V=0$ independent of the value of the parameter λ . Consequently, a waveform having duty cycle of 50 percent is ineffective for the purpose of nonlinearity testing. On the other hand, it has been determined that duty cycles $F_1=0.21$ and $F_2=0.79$ produce a maximized value V_m of the average voltage V . Consequently, duty cycles of approximately 20 percent or approximately 80 percent are particularly advantageous to fully exploit the capabilities of a voltmeter having limited sensitivity. More generally, a duty cycle in the range of from ten percent to 40 percent or in the range of from 60 percent to 90 percent is suitable for sufficiently accurate determination of nonlinearity.

Relationships between average voltage V and nonlinearity λ , similar to those stated above, hold for waveforms other than rectangular waveforms. Furthermore, networks other than network 15 of Figure 1 may be beneficially employed for the purpose of the invention. In particular, as shown in Figure 2, transformer 22 may be used instead of the blocking capacitor 12 of Figure 1. What is required, in general, is that the network 15 be linear and AC-coupled.

The concept of duality, makes it apparent that if the voltage applied across the conductor to be tested were constrained to have a zero average value, the average value of the resulting current would be a measure of the nonlinearity of the resistance. Apparatus implementing this dual method is depicted in Figure 5 where average current is shown being measured by means of an operational amplifier. The transformer 52 constrains the voltage

applied across the resistor 54 to be tested to have a non-zero time average. The current in the resistor 54 is represented by a voltage proportional thereto, at the output of the operational amplifier 58.

70 Example

Forty-five aluminum conductors deposited on a magnetic bubble device were tested by the disclosed method. The conductors had a thickness of 0.5 micrometer and had varying width of not less than 3 micrometers. A

Hewlett Packard HP8007 pulse generator was used which produces rectangular pulses up to 10 volts out of a 50 ohm source impedance. A pulse repetition rate of 20 kHz was chosen and the voltage appearing across the test conductors was filtered with a ten ms. RC filter and measured with a digital voltmeter having 10 microvolt sensitivity. The 45 conductors produced values V_m in the range of from 0.1 to 1.0 mV, the majority producing values in the range of from 0.1 to 0.2 mV. Conditions under which conductors failed are depicted in Figure 3 which shows how the lifetime of conductors is correlated to the measured voltage.

CLAIMS

1. A method of testing an electrical conductor by determining nonlinearity of electrical resistance of the conductor as a function of current flowing in the conductor, comprising applying a wave signal to the conductor such that either the average of the current in the conductor or the average of the voltage drop across the conductor is zero and such as to produce a voltage across the conductor or a current in the conductor respectively, for which the average depends on the said nonlinearity, and measuring the average of the produced voltage or current.
2. A process as claimed in claim 1, wherein a current wave of zero average value is applied to the conductor via a linear A.C. coupling network.
3. A method as claimed in claim 2, in which said network consists of a blocking capacitor.
4. A method as claimed in claim 2 in which said network consists of a transformer.
5. A method as claimed in any preceding claim in which said electrical wave signal comprises a train of rectangular pulses.
6. A method as claimed in claim 5, in which the duty cycle of said pulse train is in the range of from ten percent to 40 percent or in the range of from 60 percent to 90 percent.
7. A device for testing an electrical conductor element by determining nonlinearity of electrical resistance of said element as a function of current flowing in said element, said device comprising an electrical wave generator connected to the input terminals of an AC-coupled linear electrical network, means for electrically connecting said electrical conductor element to the output terminals of said network and an averaging voltmeter or current meter connected for measuring the current or voltage output of said AC-coupled network.
8. A device as claimed in claim 7, in which said electrical network consists of a blocking capacitor.
9. A device as claimed in claim 7, in which said electrical network consists of a transformer.
10. A device as claimed in any of claims 7 to 9, in which said electrical wave generator produces a train of

is connected to a network consisting of capacitors 56 and 57, operational amplifier 58, and variable feedback resistor 59. Voltage measured by voltmeter 53 is proportional to the average current flowing in conductor element 54 which average current, is a measure of nonlinearity of resistance of element 54.

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Ohm's law of a linear relationship between voltage applied to and current flowing in the conductor element. Such deviation typically amounts to a change in resistance as a result of an increase in voltage or current and may be expressed quantitatively by the parameter λ in the formula

$$R_l = R_0 (1 + \lambda I^2)$$

which approximately represents the functional relationship between current I , nominal resistance R_0 , and resistance R_l of a conductor element. It can be shown that this functional relationship is compatible with a physical explanation of nonlinearity of resistance due to Joule heating of the conductor element.

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$$V = \lambda R_0 I^3 F(1-F) (1-2F)$$

from which the direct relationship between voltage V and nonlinearity λ is apparent. It is also apparent that if a duty cycle of $F=0.5$ is utilized, then $V=0$ independent of the value of the parameter λ . Consequently, a waveform having duty cycle of 50 percent is ineffective for the purpose of nonlinearity testing. On the other hand, it has been determined that duty cycles $F_1=0.21$ and $F_2=0.79$ produce a maximized value V_m of the average voltage V . Consequently, duty cycles of approximately 20 percent or approximately 80 percent are particularly advantageous to fully exploit the capabilities of a voltmeter having limited sensitivity. More generally, a duty cycle in the range of from ten percent to 40 percent or in the range of from 60 percent to 90 percent is suitable for sufficiently accurate determination of nonlinearity.

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Furthermore, networks other than network 15 of Figure 1 may be beneficially employed for the purpose of the invention. In particular, as shown in Figure 2, transformer 22 may be used instead of the blocking capacitor 12 of Figure 1. What is required, in general, is that the network 15 be linear and AC-coupled.

The concept of duality, makes it apparent that if the voltage applied across the conductor to be tested were constrained to have a zero average value, the average value of the resulting current would be a measure of the nonlinearity of the resistance. Apparatus implementing this dual method is depicted in Figure 5 where average current is shown being measured by means of an operational amplifier. The transformer 52 constrains the voltage

applied across the resistor 54 to be tested to have a non-zero time average. The current in the resistor 54 is represented by a voltage proportional thereto, at the output of the operational amplifier 58.

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2. A process as claimed in claim 1, wherein a current wave of zero average value is applied to the conductor via a linear A.C. coupling network.

3. A method as claimed in claim 2, in which said network consists of a blocking capacitor.

4. A method as claimed in claim 2 in which said network consists of a transformer.

5. A method as claimed in any preceding claim in which said electrical wave signal comprises a train of rectangular pulses.

6. A method as claimed in claim 5, in which the duty cycle of said pulse train is in the range of from ten percent to 40 percent or in the range of from 60 percent to 90 percent.

7. A device for testing an electrical conductor element by determining nonlinearity of electrical resistance of said element as a function of current flowing in said element, said device comprising an electrical wave generator connected to the input terminals of an AC-coupled linear electrical network, means for electrically connecting said electrical conductor element to the output terminals of said network and an averaging voltmeter or current meter connected for measuring the current or voltage output of said AC-coupled network.

8. A device as claimed in claim 7, in which said electrical network consists of a blocking capacitor.

9. A device as claimed in claim 7, in which said electrical network consists of a transformer.

10. A device as claimed in any of claims 7 to 9, in which said electrical wave generator produces a train of

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rectangular pulses.

11. A device as claimed in claim 10, in which said electrical wave generator has a duty cycle in the range of from ten percent to 40 percent or in the range of from 60 percent to 90 percent.

12. A method of testing an electrical conductor substantially as hereinbefore described with reference to the accompanying drawings.

13. A device for testing an electrical conductor substantially as hereinbefore described with reference to Figure 1 or 2 of the accompanying drawings.

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