

APPLICATION NOTES

RESISTOR TECHNOLOGY ASSESSED AT MICROWAVE FREQUENCIES

Major resistor systems for microwave devices are examined, and their relative advantages and disadvantages are discussed.

Virtually all electronic systems require resistors and resistive products. When specifying resistive devices, it is helpful to have a basic understanding of resistor materials, technology, and manufacturing processes in selecting the appropriate device. The following discussion presents this type of information.

The resistance (R) is defined for a film as:

$$R = \frac{\rho L}{A} \text{ or } R = \frac{\rho L}{Wt}$$

where L, W, and t are the length, width, and thickness of the electrical conductor; ρ or resistivity is a property of the basic material. If one considers the film to be of uniform thickness, is it possible to simplify this to:

$$R = P_s \left(\frac{L}{W} \right)$$

and R then becomes a simple geometric function of the length and width or number of squares of film and P_s or sheet resistivity.¹

The resistivity is a function primarily of imperfections and crystalline lattice motion and is $\rho = 1/ne\mu$ where n is the number of electrons available for conduction, e is the charge of an electron and is defined as mobility or the ratio of drift velocity (v) to electric field strength (E) or:

$$\mu = \frac{E}{nev}$$

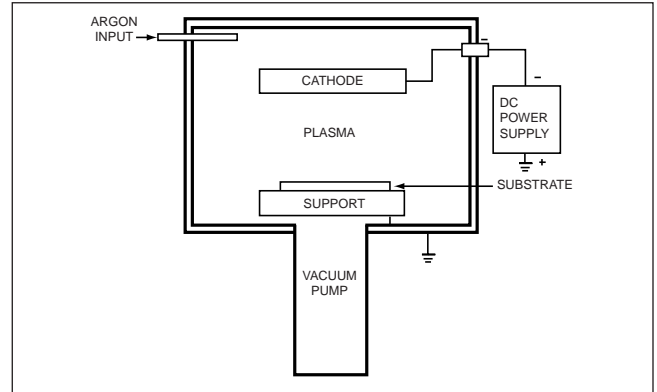
Thus, resistivity is determined by the number of available electrons and the perfection of the conducting lattice. No property of solid materials has such a wide range of values as resistivity. The best insulators have resistivities that can be 10^{25} times greater than conductors.

Films used for microwave resistors are all metallic or metallic-bonded materials which supply an abundance of free electrons. These may actually be considered as loose clouds at ordinary temperatures. Microwave resistors use relatively low-value resistivity films and, at frequencies below the microwave/RF range, these films act as pure resistance.

As frequency increases, however, they become reactive and the RF properties are affected. If one considers film on a smooth substrate, with no imperfections and having metallic conductivity, then these are purely geometric devices and the frequency response is primarily a function of the pattern configuration.² When put into a cavity or circuit, the substrate characteristics and hardware characteristics will, of course strongly affect RF properties.

MICROWAVE FREQUENCIES

High-frequency resistors generally available at microwave frequencies consist of a film on a substrate (which supports the film) and a very low-resistivity termination to connect the resistor to the circuitry. This termination must usually be solderable.



In this basic sputtering configuration, the cathode is negative. The positively charged gas ions will be attached to the cathode and will literally bombard it, dislodging material in atomic form from the cathode.

Carbon film resistors. Carbon film was one of the earliest materials employed for microwave resistors. This film is used primarily for coaxial element devices, because it is difficult to process into flat stripline and microstrip. The carbon film is in the graphitic crystalline structure. Although not a metal, the nature of electronic conductivity in graphite does approach that of metallic conduction.

The film is prepared by high-temperature pyrolysis. Heating methane or propane gas in the absence of oxygen causes a complicated series of reactions that eventually result in graphite. The overall reaction is $CH_4 \rightarrow C + H_2$. The film is quite pure when compared to evaporated films, is robust and reacts well to high-power pulsing. In situ, masking is not feasible because of the high temperatures involved in the process.

Since there are no practical etchants for carbon, machining techniques are the only way to pattern carbon resistors. Some of the various limitations of carbon resistors are:

- The high-reaction temperatures necessitate high-temperature materials such as stable ceramic.
- The graphite does not chemically wet or react with a ceramic surface but must be mechanically "locked" to it. To do this, the substrate must be roughened. A typical ceramic substrate will have a fired finish of 30/40 microinch RMS, and then be etched to several times that value. Since heavy, low-resistance carbon film is only four microinches thick on this rough substrate, this film is no longer a "two-dimensional" device. Carbon resistors do not generally perform well at very high frequencies.

Nickel chrome alloys (nichrome, etc.). Commercial nichrome is 80 percent nickel and 20 percent chromium. This material is frequently evaporated from tungsten heaters. Variations in composition of up to 50 percent chromium are available. These materials are generally deposited by vacuum evaporation or sputtering.

KEY: Inches [Millimeters] .XX ±.03 .XXX ±.010 [X ±0.8 .XX ±0.25]

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The vacuum evaporation process is usually done at a pressure of 10 to 10^{-5} Torr. Some basic parameters of the vacuum evaporation process are shown below and provide background for several significant conclusions (Table 1).

Table 1—Vacuum Evaporation Process

Pressure Torr	Atmo- sphere	Number of gas molecules cm ³ (air) 250	Mean free path	Collisions with surface molecules/ sec./cm ²	Time for a monolayer of gas to form (sec.)
760	1	2.5×10^{19}	6×10^{-6} cm	2.9×10^{23}	3×10^{-9}
1×10^{-3}	1.3×10^{-6}	3.2×10^{19}	5 cm	3.8×10^{17}	2.3×10^{-9}
1×10^{-5}	1.3×10^{-6}	3.2×10^{11}	5 m	3.8×10^{15}	0.23

These parameters indicate that when evaporation is typically done at 1×10^{-5} Torr, there is only one gas molecule left out of every 100 million molecules in the starting air atmosphere. However, even this low concentration is enough to significantly affect the films because of the number of surface collisions.

Energy in the form of heat is applied to the nickel-chromium alloy. When the temperature is high enough to raise the vapor pressure to about 10^{-2} Torr (1400/1500°C for nickel chrome), enough atoms leave the material so that “evaporation” occurs. The metals leave with an energy level of 1400°C or 0.2 electron Volts. The evaporation process can be visualized as the metal leaving the heated area, and traveling in a straight line (mean free path = 5 meters) to land on a suitably placed substrate.

An explanation of vapor pressure is that atoms are always leaving the surface of a liquid or solid. The number of atoms that leave depends on the particular substance and its temperature. This number increases rapidly with temperature rise. Chromium, for example, has a vapor pressure of 10^{-63} Torr at room temperature. At 1300°C, its vapor pressure is 10^{-2} (0.01) Torr and it will evaporate fairly readily. When the alloy is heated to the necessary temperature, chromium will evaporate about 7 1/2 times more rapidly than nickel. The first film formed is rich in chromium (55 to 60 percent). This has the advantage of increasing adhesion since chromium and gaseous atoms which are also hitting the substrate react and increase bonding strength.

After deposition and removal from the vacuum system, the films are given an air heat treatment to stabilize them. The resulting film is a sandwich structure with a highly oxidized film close to the substrate. | As the film gets thicker, it is more metallic. The top surface is oxidized due to oxygen diffusion during a post-evaporation heat treatment for stabilization.

There are many stable terminations for nickel chromium. Among them are fired precious metal cermets, fired molybdenum coatings, evaporated or plated metal, and others.

These films are extremely stable when properly deposited, terminated, and heat stabilized. Their high-frequency performance depends primarily on patterning and is typical of the fine performance to be expected of thin-film geometry on smooth substrates. The films are, however, subject to electrolysis in high-humidity conditions. This effect is more pronounced for DC conditions but there are still electrolytic effects for high-frequency AC conditions.

Nickel-chromium resistors may be adjusted by computer-controlled laser, sand machining, or by mechanical adjustment methods. All of these methods alter the resistor geometry and, therefore, have some effect on frequency characteristics. However, it is indeed possible to get microwave device parts which work well at 26.5 GHz using these adjustment techniques.

Tantalum resistors. Tantalum can only be evaporated in special equipment, as it is a refractory or high-melting metal. In fact, its vapor pressure reaches 10^{-2} Torr at 3000°C, which is its melting point. Tantalum films are therefore usually formed by a sputtering process.

Sputtering is a vacuum process very different from the evaporation process previously described. To sputter in a chamber, it is first necessary to pump down to low vacuum (at KDI, we pump to below 10^{-6} Torr). After this pumpdown, the chamber is backfilled by the introduction of gas while still pumping. Typically, the gas will be 99.999 percent pure Argon. The pressure is then controlled at 1 or 2×10^{-3} Torr. A voltage is applied, high enough to cause the gas to ionize and conduct current. This low-pressure electrical phenomenon is generally called a glow discharge, and the mass of ionized gas is called a plasma.

A simple sputtering configuration is shown in the figure, where the cathode is negative. The applied voltage will range from several hundred to several thousand Volts. The charged (positive) gas ions will be attracted to the cathode and will literally bombard it. This will dislodge material in atomic form from the cathode. Substrates can be placed to intercept the dislodged atoms, therefore becoming coated.

In the evaporation process, evaporated atoms were raised to a high internal-energy level by thermal means and their energy levels were measured as temperature (degrees centigrade). For the sputtering process, the atomic energy levels are measured in electron Volts. An electron Volt is the quantity of energy that a particle of unit electric charge acquires, when passing through a potential difference of one Volt—this is a great deal of energy.

The following parameters illustrate energy levels in the sputtering process:

- eV (electron Volt) $\cong 12.00^\circ\text{C}$.
- Metal atoms are typically bonded with energies of 2 to 10 eV.
- Absorbed gaseous layers have binding energies of 0.5 eV.
- In the sputtering process, particles bombarding the cathode will have energy levels greater than 100 eV.
- The sputtered atoms (charged or otherwise) land on the substrate with an energy level of 10 to 40 eV (compared to evaporation energy levels of 0.2 to 0.3 eV).

Because of these characteristics, the foregoing explains the advantages (and disadvantages) of the following attributes inherent in devices manufactured by the sputtering process:

- Adhesion can be very strong with sputtering, because of high-energy particles forcing into the substrate, and because the substrate can be “degassed” by high-energy reverse sputtering.
- Alloys can be sputtered with uniform composition because it is a mechanical and not a thermal process.
- The process goes around corners and goes into very small holes because it is not a “line-of-sight” process.
- Control of film thickness is simply current multiplied by time duration of sputtering and can be quite accurate.

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- Substrates can be back-sputtered and cleaned while in the vacuum chamber. A film may then be deposited on the clean surface without opening the vacuum system.
- Control of the crystalline structure of deposited film can be achieved by adjusting the sputter rate.
- Since sputtering is done in the 10^{-3} Torr range, the sputtered films are generally not as pure as evaporated films; there tends to be more occluded gas in the film. Most haphazard contaminants are removed by pumping the system to a low pressure (10^{-6} Torr) and then back-filling with a sputtering gas.
- Because of the pressures and many vapor collisions, sputtering works well when depositing chemically reacted materials. By introducing nitrogen into the backfilled gas, we can sputter tantalum nitride (Ta_2N) which is the most stable tantalum resistor phase. This is a means of using the gas contamination to advantage.
- A disadvantage of sputtering is that the rates of film deposition are slower than for evaporation. However, since there is a very large amount of material in the cathodes, the deposition can be continued for long periods of time and very heavy films (very low-resistance values) can be obtained.
- Equipment costs for a sputtering system are much higher than for evaporation systems.

TANTALUM-NITRIDE MICROWAVE RESISTORS

In the KDI process, tantalum is sputtered in a nitrogen atmosphere. The nitrogen pressure is carefully controlled so that the film is Ta_2N , which (as was already stated) is the most stable tantalum resistance film. The process (briefly) is:

- Sputter Ta_2N .
- Sputter NiV without opening the system.
- Plate pure gold.
- Mask and etch the gold leaving only the desired terminals and the tantalum-nitride film.
- Mask and etch the tantalum nitride leaving only the resistor area.
- Clean and heat-treat the wafer.
- Anodize or laser trim to values.
- Dice wafer.
- Final test.

The differences between tantalum-nitride and nickel-chrome films are:

- Temperature coefficient of resistance NiCr. ± 100 PPM/ $^{\circ}C$ is standard. It can be as low as ± 5 PPM/ $^{\circ}C$ if required. Ta_2N : 0 to -150 PPM/ $^{\circ}C$ is obtained, most parts are in the range of -75 to -125 PPM/ $^{\circ}C$.
- Stability. Long-term stability is substantially equal for both films.
- High-temperature capability. The NiCr should not be heated above $200^{\circ}C$.
- Humidity. NiCr is subject to humidity corrosion and must be protected where this is a factor.
- Ta_2N is not corroded by humidity, as it is quite chemically inert. Also, the surface has been oxidized.
- Film adherence. Both NiCr and Ta_2N adhere well to glass and ceramics. However, at KDI, the NiCr is evaporated and the Ta_2N is sputtered. It is the high-energy sputtering which accounts for the excellent adhesion of the Ta_2N . The KDI process adheres to beryllium-oxide ceramics as strongly as fired moly-manganese.

THICK-FILM (CERMET) RESISTORS

These films are quite different from the previously discussed resistor films. They are composite systems consisting of a "stringy" electrically conductive network in a glass insulating phase. They are called "thick films" since their dimensions are on the order of thousandths of an inch (0.001 inch) thick while the "thin films" are on the order of millionths of an inch.

These resistors are made from a paste consisting of finely ground discrete particles of glass, a crystalline conducting phase, and an organic or liquid binder. This is spread on a substrate to get a uniform film. Generally, a screen-printing process is used. This has the advantage of spreading the wet film evenly and into the desired pattern in the same operations.

The film is dried to remove volatile solvents, then fired at temperatures ranging from $800^{\circ}C$ to $1000^{\circ}C$. The temperature is gradually raised and the organic binder is burned off as volatile gases. As the temperature is increased, it is known that the conductive particles agglomerate into networks, and the glass particles sinter into a solid mass. There is also some conductive material dissolved into the glass.

The process has many variables which must be carefully controlled:

- The conductor material (generally, ruthenium oxide).
- The chemical composition of the glass.
- The size of the particles of glass and conductor.
- The rate of temperature rise in the firing furnace.
- The peak furnace temperature and the length of time the resistor is held at peak.
- The substrate used.

When properly screened and fired, the resultant resistor will have a low TCR. It will be robust since it is a relatively massive film of inert materials and is quite stable. Trimming is done by computer-controlled laser machining or abrasive sand blasting.

The resistors may have a variety of terminations depending on the application. These may be pre-fired, post-fired, or even a non-fired low-temperature organic-based conductor such as silver epoxy. The characteristics of the resistors are:

- Fairly insensitive to humidity.
- Stable with time.
- Robust and capable of high power and voltage ratings.
- Generally less expensive than thin film since there are fewer production operations. This is true even though material costs are high.
- Poor adhesion to smooth surfaces such as 99.5 percent alumina and pure beryllia.

We have indicated the major resistor systems used for microwave devices. Carbon film resistors are relatively stable, and good for power-pulse operations, but are frequency-limited and virtually limited to coaxial-element systems.

Nichrome resistors have excellent long-term stability and have the lowest temperature coefficient of resistance. They can be used up to very high frequencies, and in stripline and microstrip configurations.

Tantalum nitride can also be used for microstrip and stripline. They are better than nichrome for pulse and difficult environmental applications. They are often more costly than nichrome resistors or attenuators.

Fired thick-film resistors are robust and good for power and pulse applications. They can also be used for most possible configurations.

References

1. Maissel and Glang. *Handbook of Thin Film Technology*, McGraw Hill, 1970, pp. 13-14.
2. R. W. Berry, P.M. Hall and M.T. Harris. *Thin Film Technology*, Van Nostrand Reinhold, 1968, p. 336.

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