

NICHROME THIN FILM TECHNOLOGY AND ITS APPLICATION

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NiCr thin film resistors are widely used in the current resistor technology. Ranging from discrete resistors up to highest performance hybrid integrated circuits, vacuum deposited NiCr alloys cover extreme areas of application. Depending upon NiCr composition, process parameters, substrate and conductor materials, resistors with extremely low temperature coefficient of resistance (TCR) and high stability, low noise and distortion can be produced. NiCr resistors therefore offer particular advantages for applications with special demand for high stability as well as low TCR-like selected circuits for measuring equipment, data processing, telecommunication. etc.

1. INTRODUCTION

One of the characteristics of the transition metal alloys is their interesting behaviour concerning applications as resistive material:

Comparative high resistivity

Low Temperature Coefficient of Resistance (TCR)

High stability of electrical properties

This behaviour led to wide application of these alloys (sometimes alloyed with Fe, Al, Cu) as resistive material for wire wound resistors.^{1,10}

TABLE I
Resistivity and TCR of bulk NiCr alloys

Composition	Resistivity	TCR
wt-%	μohmcm	ppm/K
Ni(80) Cr(20)	110	+85
Ni(76) Cr(20) Al(2) Fe(2)	133	± 5

The knowledge about the favorable properties of Ni-Cr alloys for electrical applications obviously initiated intense work to deposit them by vacuum techniques in form of thin films, at first surely not fully understanding and appreciating the additional electrical advantages of vacuum deposited thin films, such as higher resistivity and lower TCR.

Discussing the behaviour of thin NiCr films we

should consider:

a) The behaviour of a “real” resistor is determined not only by the performance and reliability of the resistive material itself; rather the properties of the resistors include the influence of the terminations, the interconnections, the substrate, layout design, sealing, environment, etc.

b) The performance of thin film resistors can be influenced positively by suitable vacuum processes, specific vacuum conditions and careful choice of all materials from a metallurgical point of view. NiCr thin film circuits are produced generally by applying the well known thin film process steps:

Vacuum deposition
Photolithographic processing
Stabilisation
Trimming
Assembling
Sealing

Next, we will discuss some selected and characteristic aspects of NiCr technology with respect to production, performance and reliability.

2. NiCr RESISTOR FILMS

2.1. Deposition

Some electrical properties of NiCr films strongly depend on the NiCr ratio (Figures 1, 2). It is well known

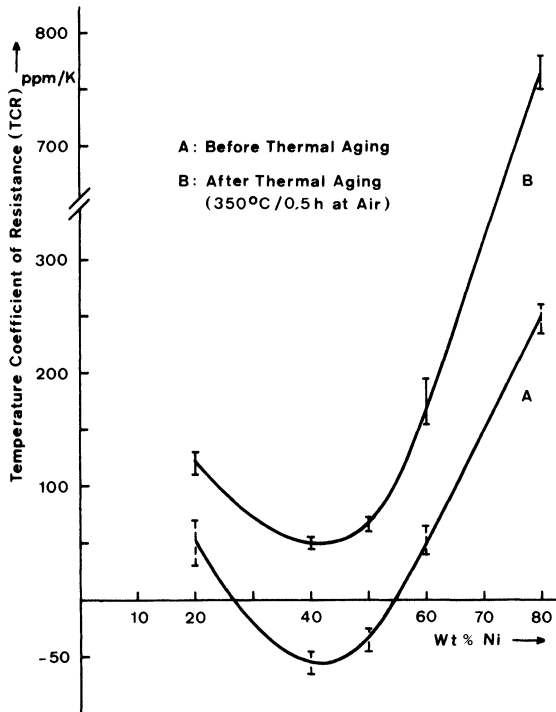


FIGURE 1 Influence of NiCr composition on TCR.

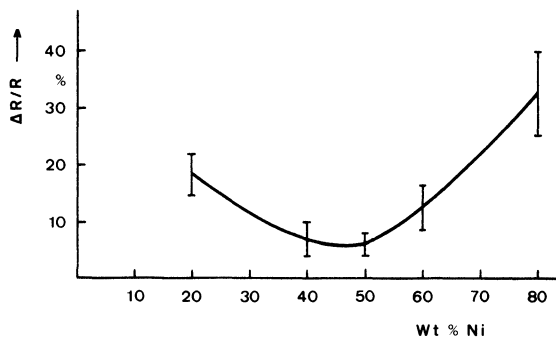
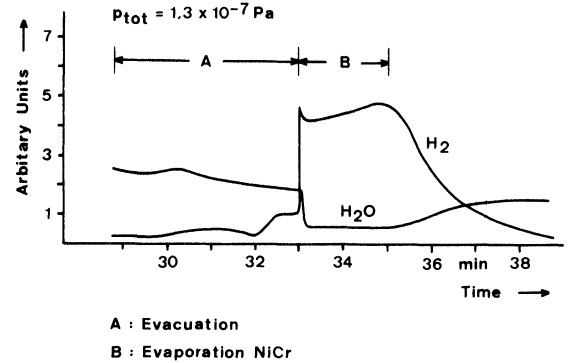


FIGURE 2 Influence of NiCr composition on resistance change during stabilization treatment (350°C, 0.5 h).

that thermal evaporation of NiCr from a finite mass of molten alloy causes a film composition change away from the composition of the source. Besides the film composition changes from run to run. Therefore flash evaporation of NiCr powder or wires¹ or sputtering² are recommended methods to ensure reproducibility. But in order to understand the behaviour of thin NiCr resistor films completely, we have to take into account some phenomena such as incorporated impurities, imperfections, crystal structures, etc. In this connection the following process parameters are of special interest:

FIGURE 3 Partial pressure of H₂O and H₂ before and during evaporation.

Residual atmosphere and deposition rate^{2,3,4,5} (Figure 4).

Substrate temperature during deposition¹²

Film thickness¹¹

Substrate material and surface^{1,12}

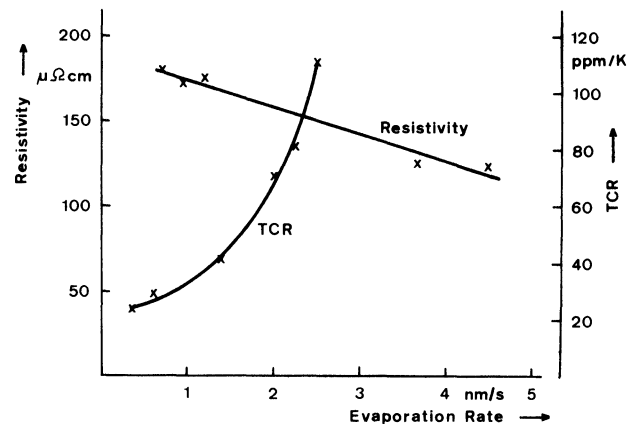


FIGURE 4 Influence of evaporation rate on TCR and resistivity.

Of some major importance is – due to the affinity of Cr for oxygen – the influence of the latter on structure and electrical behaviour (TCR, stability, resistivity). The main source of oxygen and other detectable impurities during deposition are constituents of the residual atmosphere: Oxygen, originated by splitting H₂O-molecules as is shown by mass spectra analysis during deposition (Figure 3). Therefore, a strict control of vacuum and deposition data is absolutely necessary to produce thin film NiCr resistors with closely tolerated and reproducible electrical behaviour.

On the other hand, it is possible to utilize the strong oxygen dependence by reactive sputtering in an Ar/O₂-mixture. By choice of a suitable oxygen partial pressure, followed by a sufficient post deposition heat treatment, stable resistors with low and closely tolerated TCR can be produced² (Figure 5).

Incorporating a third metallic constituent is another way to produce resistors with near zero TCR. Ternary alloys of NiCrSi⁶ and NiCrAu⁷ of suitable composition are reported to provide films with low TCR and high stability too.

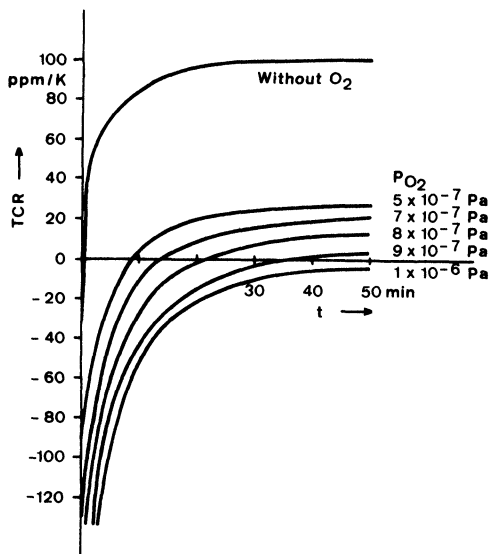


FIGURE 5 Influence of O₂ partial pressure and stabilization time on TCR. Annealing temperature: 350°C.²

2.2. Thermal aging and film structure

Freshly deposited thin films generally contain a great number of structural defects, which considerably determine the electrical behaviour of the film. Being greatly beyond thermodynamic equilibrium, such imperfect films show a tendency of self annealing by minimizing their total energy. Generally, this leads to a remarkable change in resistivity and TCR. Thus, thermal aging during and/or after deposition is necessary to stabilize the film properties.

As Figure 6 (A) shows, NiCr films annealed in high vacuum, show a remarkable increase of TCR and a decrease of resistivity. It is assumed that this change is due to grain-size growth and decrease of grain-boundary area.

In presence of oxygen (Figure 6 (B)), the increase of TCR is diminished due to formation of an oxide phase

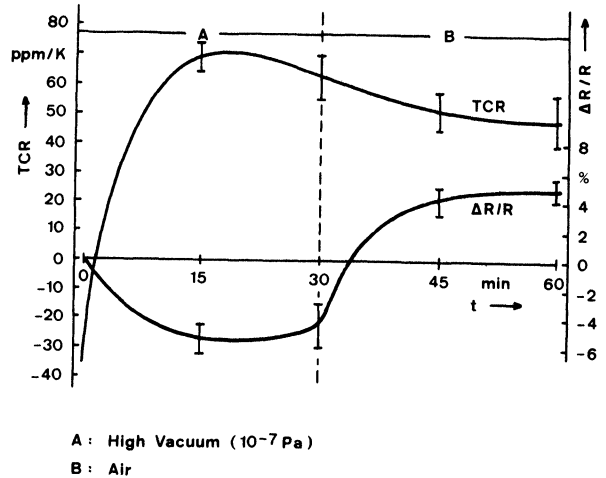


FIGURE 6 Change of TCR and resistivity during heat treatment. Temperature: 350°C.

(Cr₂O₃) with negative TCR. Figure 1 shows the composition influence on TCR change during heat treatment. There is a considerable increase of TCR for Ni rich films, due to precipitation and oxidation of Cr during annealing.⁴

The structure of thin NiCr film depends considerably upon the deposition conditions. The equilibrium phase diagram of bulk NiCr shows a large immiscibility gap between two solid solutions (Figure 7):

bcc α -Cr with incorporated Ni

fcc γ -Ni with incorporated Cr

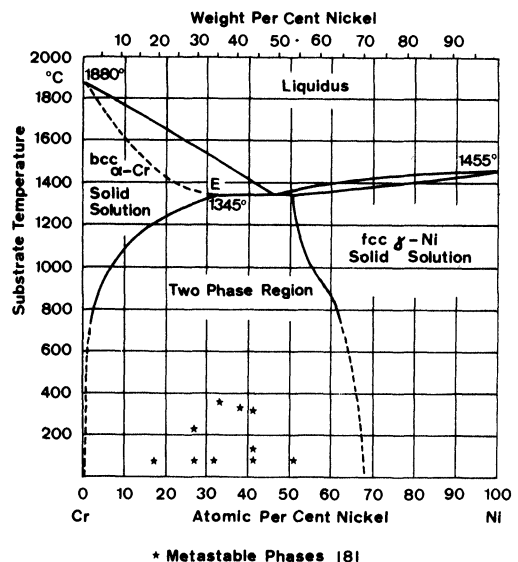


FIGURE 7 Phase diagram of bulk NiCr.

This wide immiscibility, the relatively deep eutectic and the capability of NiCr to form metallic compounds are reported to favour the appearance of metastable phases.^{8,9} In Figure 7 star-shaped marks show the compositions and substrate temperatures at which metastable phases have been detected. It should be mentioned, that their formation is limited to very particular conditions (substrate type and temperature, deposition rate, film thickness, pressure, etc); therefore, in practice, in many cases they don't occur. But if they are present in the film, their considerable influence on resistivity and stability has to be taken into account. As deposited NiCr films show, depending upon the substrate temperature during deposition, an amorphous, highly distorted or fine-grained structure can result. By heat treatment at air, grain-size growth and oxidation is enforced.¹³ Thereby, film stability increases by anticipation of otherwise spontaneously occurring processes. The best stabilization conditions may be determined empirically by measuring stability versus time and temperature of heat treatment.¹⁴

2.3. Substrates

The electrical properties and the stability of NiCr resistor films are considerably influenced by physical and chemical interactions between film and substrate surface.^{5,16,18} Thus, the yield of production greatly depends upon the uniformity and reproducibility of substrate properties, such as surface roughness (Figures 8, 9), texture, flatness, chemical composition, etc. Any choice of substrate material for a particular application is determined by such quite different aspects as power dissipation, required stability, TCR, costs, etc. Thus, in thin film technology alternative materials are used:

- Borosilicate glasses
- Polycrystalline alumina, glazed or as fired
- Silicon wafers
- Polyimide¹⁷

Advantages and disadvantages of the above materials are discussed shortly:

Borosilicate glasses: High uniformity and reproducibility of resistance, (Figure 9), low TCR, high resistor stability, low thermal conductivity, low mechanical strength, fairly low costs.

As fired thin film alumina (99.5%): High thermal conductivity, high mechanical strength, lower uniformity (Figure 9), reproducibility and stability (Figure 10) of resistor parameters, fairly high costs.

Glazed alumina: Properties and costs between glass and as fired alumina, reduced mechanical strength due to the glaze.

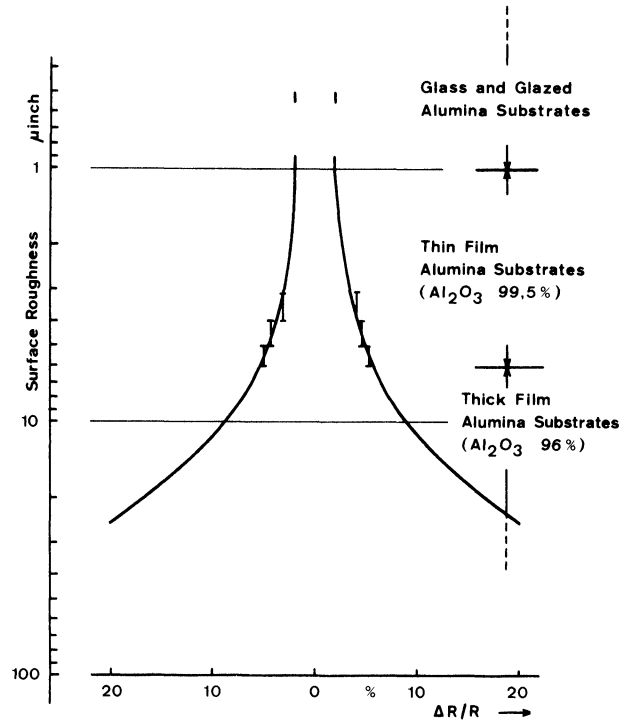


FIGURE 8 Influence of surface roughness on resistor spread. One substrate for each substrate type. (73 resistors).

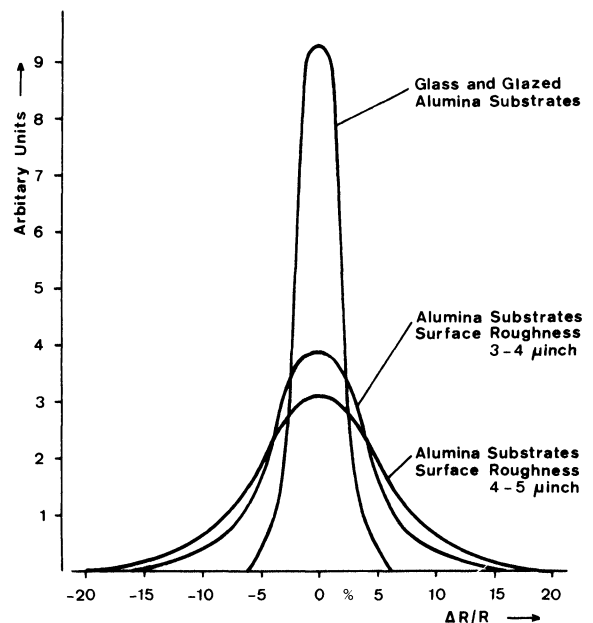


FIGURE 9 Influence of surface roughness on resistor uniformity and reproducibility across 50 substrates (3650 resistors) for each substrate type.

Oxidized silicon wafers: High performance material, but also high costs.

Polyimide: A recent development, cheap in mass production by continuous band processing. Nevertheless considerable high resistor performance.¹⁷

3. TERMINATIONS AND CONDUCTOR MATERIALS

A “real” thin film resistor consists of three parts: the resistor film, the conductor and an interfacial film between both. Technological shortcomings concerning these films and/or insufficient layout design may impair the high performance of the resistive material by increasing TCR and current noise, and decreasing the long term stability.¹⁹ To insure an adequate bond to the resistive film, usually a chemically active material (e.g. Ti, Cr) is deposited between resistor and conductor film. By combining metallurgically unsuitable materials, a remarkable increase of interfacial resistance may occur due to interdiffusion, forming intermetallic compounds with high resistivity. Further, conductor films, evaporated at higher angles of incidence, may show a porous structure, thus supporting electrocorrosion or oxidation of the adhesion layer.²⁰ The adhesion strength of such conductors may decrease and a higher current noise can occur.

Besides metallurgical processes at the resistor/conductor interface, similar processes on top of the conductor have to be considered. Depending upon the assigned assembling techniques (bonding, soldering), demands for high frequency stability (e.g. MIC's) and cost efficiency, different metallizations for different applications are usual. Thus, in NiCr thin film technology a wide spectrum of materials and combinations of materials can be found for conductor application, e.g.: Al,²¹ Cu,¹⁷ Au,¹⁶ PdAu,²² NiAu.¹⁴

4. NiCr RESISTOR PROPERTIES AND RELIABILITY

The main advantage of NiCr thin film resistors is their high stability in combination with very low TCR, an indispensable requirement for circuits with demand for extremely high stability of electrical function. Table II shows typical data of NiCr resistors in hybrid integrated circuits:

Resistor stability is usually evaluated by accelerated life tests at elevated temperatures with or without additional electrical load. Within limited temperature

TABLE II
Properties and reliability of NiCr resistors

	Units	Range
Sheet resistance	ohm/sq	30–300
Resistance	ohm	10–10 M
Tolerance	%	±0.01 ^a
TCR	ppm/K	0 ± 10–50
Tracking of TCR	ppm/K	1–3
Stability $\Delta R/R^b$	‰	0.5 ^c –2 ^d
Tracking of $\Delta R/R^b$	‰	0.2–0.4
Current noise index A	dB	–40 ^e
Distortion index A ₃	dB	120 ^f –150 ^{df}

^aLaser trimmed

^bStorage at 125°C, 0.5 h

^cAlkali free glass

^d99.5% Alumina (as fired)

^eA = 20 log E_1/U , Measurement method DIN 44049

^fA₃ = 20 log U_1/E_3 , Measurement method DIN 44049

range the resistance drift $\Delta R/R$ is proportional to $t^{1/n}$ with n between 2²⁵ and 4, depending upon processing and film structure²⁶ (Figure 10). Concerning the temperature dependence, a linear relationship exists between log $\Delta R/R$ and $1/T$, being typical for thermal activated processes. This can be used to predict long term stability at the operation temperature: We found by thermal analysis and extrapolation a resistance drift of NiCr films on as fired alumina (Figure 10) less than 1% after 15 years operation at 70°C.

In practice, long term stability may be deteriorated by superimposed additional processes like ion-migration, chemical or electrochemical corrosion. The former process may occur due to choice of unsuitable (e.g. sodium rich) substrate material.²⁴ The

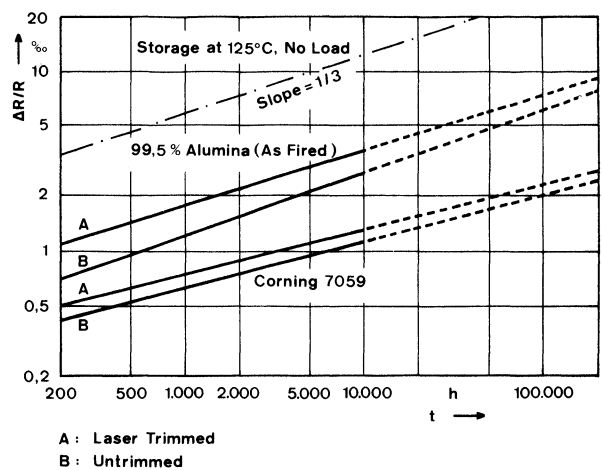


FIGURE 10 Resistor stability for different substrate materials. $\Delta R/R = t^{1/3}$

latter is related to the sensitivity of Ni- and Cr- oxides (or the resistor/conductor interface) to electrochemical attack in presence of condensed moisture, possibly participating residual chemicals from etchants or gasses of industrial environment.²¹ Therefore, the carefully rinsed circuits generally have to be sealed with coatings either on silicone basis, or silicon monoxide, -dioxide, -nitride, borosilicate glass, etc.^{21,23,24,27} Circuits operating frequently below dew point conditions should be mounted into hermetically sealed packages, and the residual vapor content has to be low enough to safely prevent moisture condensation at the lowest possible storage- or operation temperature.

5. APPLICATIONS

NiCr alloys, deposited by vacuum methods, are widely used in the current resistor technology. NiCr films cover extreme areas of application reaching from discrete resistors to highest performance integrated resistor networks.^{28,29}

In detail, we find large volume production of discrete NiCr film resistors at adequate quality and low cost for main requirements, on the other hand high quality resistors with low TCR, high stability and low tolerance of TCR and resistance.

In the hybrids field NiCr thin film resistors offer specific advantages by the combination of very low TCR with high stability, low noise and distortion⁵ (Figure 11). Thus, NiCr thin film technology is the

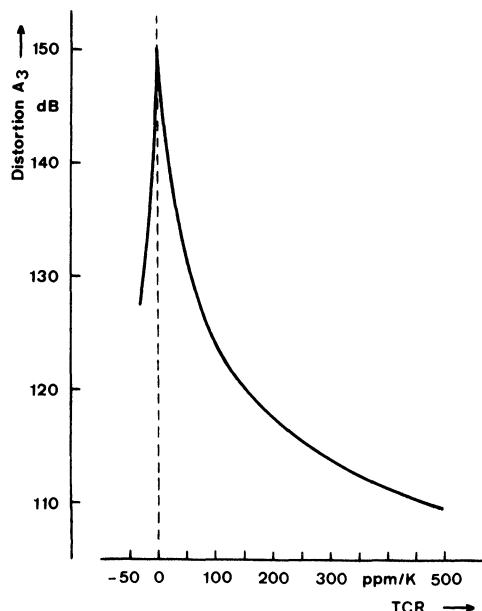


FIGURE 11 TCR vs. distortion index A_3 .

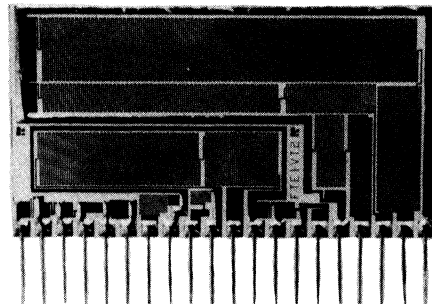


FIGURE 12 Voltage divider for X-Y-plotter.

choice technology for resistors and hybrids for measuring equipment, for data processing and for special applications in the telecommunication field with demand for high stability of electrical function.

Typical applications therefore may be voltage dividers (Figure 12) or instrumentation amplifiers for measuring equipment, R-2R-ladder networks (Figure 13) and reference circuits for A/D and D/A converters,^{30,31} submerged repeaters or attenuation networks for long-range communication,²⁵ or to some extent active filters for telecommunication.³¹

Concerning the latter, highly stable filters can be built up by combining NiCr resistors of zero TCR with NPO chip capacitors;^{31,2} and this, for small production runs,

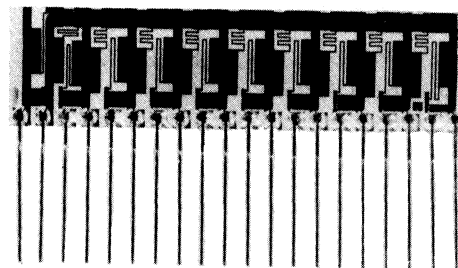


FIGURE 13 R-2R-ladder for D/A converter.

at adequate costs. But an analysis of costs also shows that at increasing production rates integrated R-C thin film technologies become increasingly economical. This is due to the fact that the cost per capacitor chip decreases very slowly with increasing quantities. On the other hand, integrated components start with high cost at small volume production, but decrease rapidly as the additional investment is spread across a large production. Further cost reduction is caused by less effort in assembling, due to the reduced number of components to be mounted. Thus, for filters, oscillators or similar applications integrated thin film (and increasingly thick film) hybrid technologies are preferred. Among these, tantalum-based thin film technologies are of importance, due to the excellent suitability of tantalum for both resistor – and thin film capacitor fabrication.³² In the past, we therefore developed parallel to NiCr an integrated hybrid R-C technology with TaAl resistors and TaAl-Oxid/SiO₂ dielectric for capacitors to cover the above applications.³³

To round up the picture, it should be mentioned that NiCr is used for some other applications, for example radiation hardened circuits,³⁴ fusible links in PROM's,²¹ resistance standards (e.g. 1000 M with TCR of less than 3 ppm/K!)³⁵ and recently thermal printheads.²³

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