

Radio Frequency Performance of Electroplated Finishes

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Summary

It is often found that silver-plating a copper conductor increases the radio frequency losses instead of reducing them as expected. The main causes of this apparent anomaly are found to be:

- (a) the conductivity of an electroplated metal is normally lower than that of the pure, cast and wrought metal;
- (b) the way that the current is distributed between the layers in a bi-metallic conductor;
- (c) the use of unsuitable intermediate layers beneath the silver, and
- (d) the use of a thick medium conductivity protective layer to prevent the silver tarnishing.

From a consideration of these various problems, it is shown that the most satisfactory low-loss finish can be produced by first plating with a high conductivity copper plate, and then following this with a very thin layer of low conductivity material to provide corrosion protection.

1. Introduction

Silver is frequently specified as an electroplated finish for conductors carrying r.f. currents for two reasons:

- (i) Pure silver, which has a relative conductivity of 105% I.A.C.S.†, is usually thought to be the best conductor.‡
- (ii) The tarnish film which forms on the surface of silver is often erroneously thought to have a low contact resistance.

Unfortunately, it is almost impossible to produce an electroplated silver finish which has as high a conductivity as pure silver.¹⁻⁴ At best the conductivity of the deposit will be about the same as that of pure copper and it is often much less. This effect is not confined to silver and the conductivity of most electroplated metals is less than that of the pure wrought metal. It will be shown later

in the paper that, instead of being a problem, this reduction in conductivity of electroplated metals can be used to produce a low-loss finish.

Two of the most interesting points to come out of the investigations are:

- (i) a thin plating of either very high conductivity or of very low conductivity over copper will have negligible effects on the overall radio frequency resistance, and
- (ii) a plating having about half the conductivity of the copper base will cause the greatest increase in overall resistance.

Further investigation has shown that the conductivity of much of the commercial silver plating is about half of that of pure copper and therefore this type of silver

†I.A.C.S.: the International Annealed Copper Standard. An annealed copper wire, density 8.89 g/cm³, 1 metre long, weighing 1 gram and having a resistance of 0.15328 ohm has a conductivity of 100 percent I.A.C.S., all measurements being made at 20°C. This corresponds to a resistivity of 1.7241 micro-ohm centimetre and a conductivity of 5.8001×10^7 mhos/metre.

‡This is not strictly true: Values of conductivity up to 106.2% I.A.C.S. have been recorded for samples of specially purified copper, see, for instance, Gregory, P., Banga, A. J. and Bird, T. L., "The Electrical Conductivity of Copper", *Metallurgia*, Vol. 71, No. 427, May 1965, p. 207.

1. Fischer, J. and Weimer, D. E., "Precious Metal Plating", Robert Draper Ltd., Teddington (1964), p. 65.
2. Keil, A., "Leitfaehigkeitmessungen an galvanisch erzeugten Metallfolien", ("Conductivity of Electroplated Metal Foils"), *Metalloberflaeche A*, Vol. 9, No. 6, June 1955, p. 81.
3. Raub, E., "Eigenschaften und Zustand galvanisch abgeschiedener Metalle mit höherem Gehalt an nichtmetallischen Fremdstoffen", ("Properties and Characteristics of Electrodeposits with High Non-metallic Contents"), *Z. Metallkunde*, Vol. 39, No. 2, February 1948, p. 33.
4. Raub, E. and Mueller, K., "Fundamentals of Metal Deposition", Elsevier Publishing Co., Amsterdam (1967). (Note: this book contains a most comprehensive bibliography with over 300 references, many of them dealing with the effects of additional agents on the properties of electro-deposits.)

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plating is unsuitable for use for radio frequency applications.

Commercial plating processes are mostly aimed at producing a fully bright deposit which will require no subsequent buffing. To this end, most plating solutions contain proprietary brightening or grain-refining agents. These are either organic or metallic compounds which are absorbed by and/or co-deposited with the metal. The result is a very significant change in the physical properties of the electroplated finish⁵ and, in particular, a reduction in the electrical conductivity.

The decrease in conductivity is well documented in plating literature but does not appear to be well known amongst electronic engineers. This is surprising because of the number of papers published in the last fifteen years that describe the increased losses caused by silver plating.⁶⁻⁸ In turn, the significance of the lower conductivity has been missed by the electroplaters. A typical comment, from an electroplating text book on silver plating, is "However, the higher electrical resistance is rarely of any significance in practice".

2. Skin Effect

Skin effect, the crowding of the current to the outer surface, makes the a.c. resistance of a conductor higher than its d.c. resistance. In a solid homogeneous conductor carrying an alternating current, the current density decreases roughly exponentially from the surface. In a conductor having a thin covering of another metal this no longer happens and there is a step in the current density at the boundary of the two metals such that $J_1 \sigma_1$ equals $J_2 \sigma_2$.^{*} The effect is illustrated in figs. 1 and 2. At high frequencies the internal reactance and the a.c. resistance are equal in a solid conductor but because of the redistribution of the current this is not always the case in the composite conductor.

The effect of an outer layer of different metal on the resistance and the reactance of a conductor was investigated by Whinnery⁹ and more recently by Astbury.¹⁰ The exact formulae derived by Astbury have been used to calculate the resistance, reactance and current distribution in a large number of composite conductors at radio frequencies and the results are shown in figs. 3 to 7.

5. Brenner, A., "Electrodeposition of Alloys", Vol. 1, Academic Press, London and New York (1963), p. 254.
6. Von Baeyer, H. C., "The Effect of Silver Plating on Attenuation at Microwave Frequencies", *The Microwave J.*, Vol. 3, No. 4, April 1960, p. 47 (includes a list of some twenty papers on this problem).
7. Lending, R. D., "New Criteria for Microwave Component Surfaces", Vol. 11, I.R.E. National Electronics Conference, Chicago, 1955, p. 391.
8. Krusenstjern, A., Keil, A. and Wellner, P., "Elektrische Leitfaehigkeit galvanisch erzeugter Silberschichten", ("Electrical Conductivity of Silver Plating"), *Metalloberflaeche*, Vol. 20, No. 1, January 1966, p. 10.
9. Whinnery, J. R., "Skin Effect Formulas", *Electronics*, Vol. 15, No. 2, February 1942, p. 44.
10. Astbury, N. F., "Alternating-Current Properties of a Copper Conductor Clad in a Magnetic Sheath", *Proc I.E.E.*, Vol. 110, No. 11, November 1963, p. 2055.

^{*}See appendix for definitions of symbols.

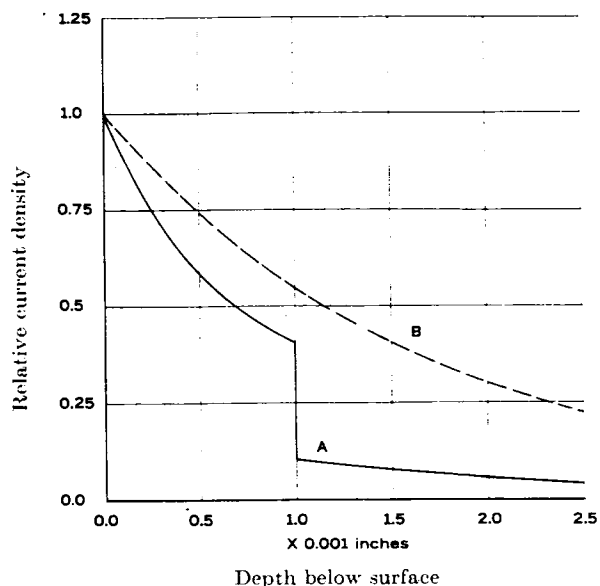


Figure 1.—Distribution of current in a circular rod at 10 MHz.
Curve A. 0.25 in dia. brass rod (conductivity 25% I.A.C.S.)
plated with 0.001 in of metal of conductivity 100% I.A.C.S.
Curve B. 0.252 in dia. copper rod (conductivity 100% I.A.C.S.)

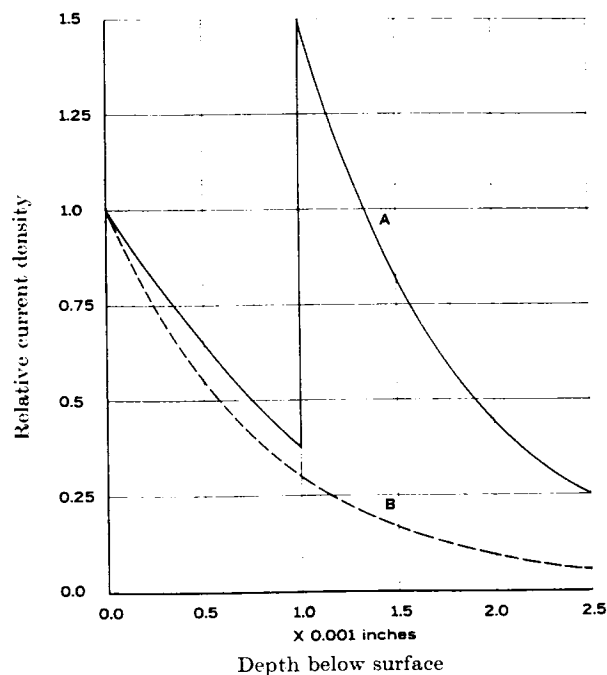


Figure 2.—Distribution of current in a circular rod at 10 MHz.
Curve A. 0.25 in dia. copper rod (conductivity 100% I.A.C.S.)
plated with 0.001 in of metal of conductivity 25% I.A.C.S.
Curve B. 0.252 in dia. brass rod (conductivity 25% I.A.C.S.)

Consider the case of a copper wire plated with a metal of lower conductivity. Typical curves are shown in fig. 3. As might be expected, the resistance initially increases as the plating thickness is increased, although only slowly at first. It then rises rapidly to a maximum value and then decreases as the diameter, and hence the cross-sectional area, is increased. Therefore with a thick layer of plating the properties are similar to those of a

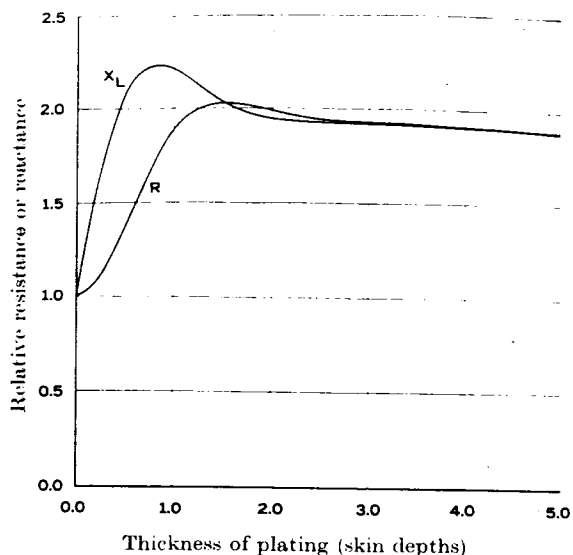


Figure 3.—A.C. resistance (R) and reactance (X_L), at 10 MHz, of a 0.25 in dia. copper rod (conductivity 100% I.A.C.S.) plated with a metal of conductivity 25% I.A.C.S.

solid conductor of the plating metal. The resistance of the composite conductor reaches a maximum value when the thickness of the plating is approximately one and one half times the skin depth† for the plated metal. The reverse happens when the outer layer is a better conductor and in this case the resistance drops to a minimum value when the layer is about one and one half times the skin depth in thickness as shown in fig. 4.

The shape of the curve is important and it is informative to study a family of these curves. As stated earlier, the

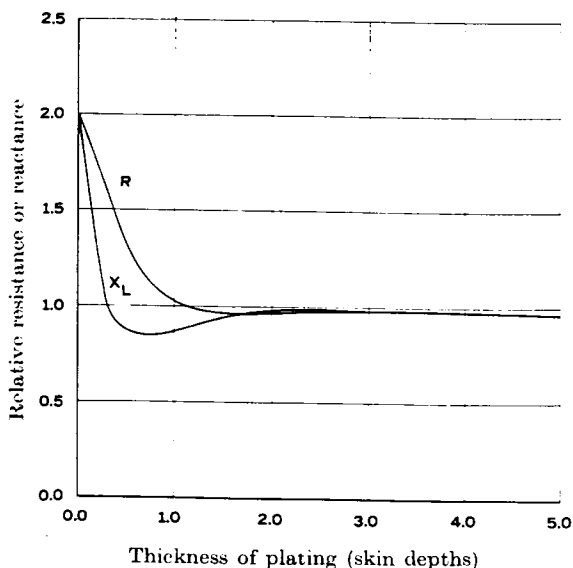


Figure 4.—A.C. resistance (R) and reactance (X_L), at 10 MHz, of a 0.25 in dia. brass rod (conductivity = 25% I.A.C.S.) plated with a metal of conductivity 100% I.A.C.S.

†The skin depth is defined for a plane solid of infinite depth as that depth where the current density has fallen to 1/e (about 37%) of the value at the surface. It is also the thickness of a plane conductor having a d.c. resistance equal to the a.c. resistance of the plane conductor of infinite depth and the same width.

curve rises only slowly at the start and in fact the lower the conductivity of the plating the lower the initial slope of the curve. This means that for a thin layer of plating, the lower the conductivity of the plating material the lower will be the resistance of the composite conductor. This effect is shown in fig. 5 and perhaps even more clearly in fig. 6. In general, the curve for each plating metal is the same shape but with the maximum moved progressively to the right and upwards as the conductivity of the plating decreases.

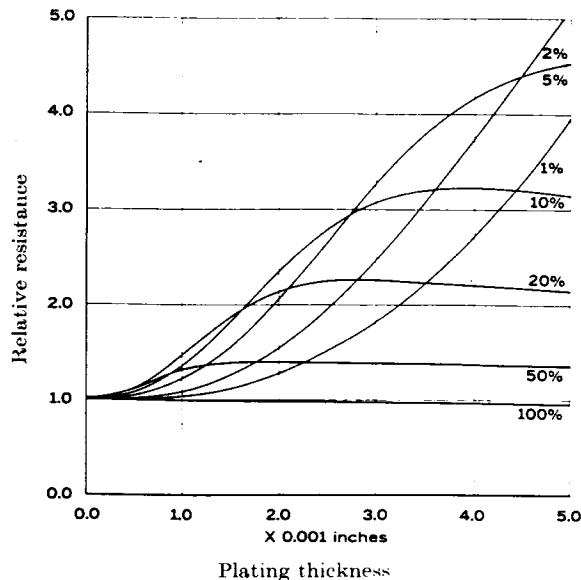


Figure 5.—A.C. resistance, at 10 MHz, of a 0.25 in dia. copper rod (conductivity 100% I.A.C.S.) plated with metals of various conductivities and unity permeability.

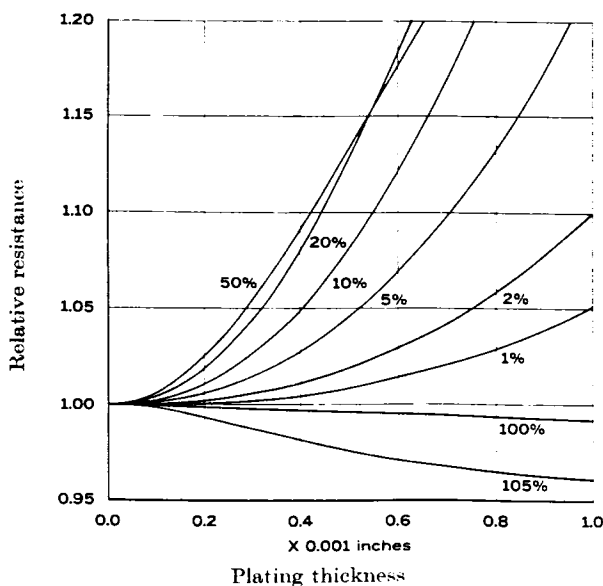


Figure 6.—A.C. resistance, at 10 MHz, of a 0.25 in dia. copper rod (conductivity 100% I.A.C.S.) plated with metals of various conductivities, and unity permeability (enlarged section of fig. 5).

Plating with a ferro-magnetic material such as nickel, which is often used as an underlay for chromium or silver,^{1, 11} will cause very high losses. The skin depth decreases with an increase in both the conductivity and permeability, while the a.c. resistance decreases with increasing conductivity and increases with increasing permeability, as shown in fig. 7.

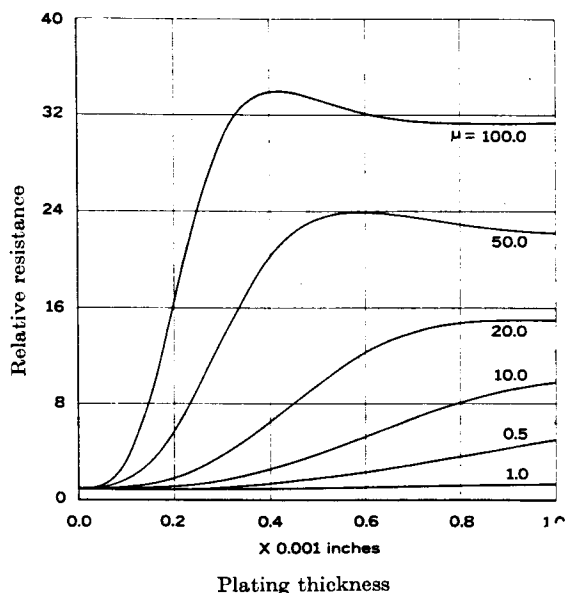


Figure 7.—A.C. resistance, at 10 MHz, of a 0.25 in dia. copper rod (100% I.A.C.S.) plated with metals of various permeabilities, and a conductivity of 10% I.A.C.S.

In a practical case, the tank coil of a 10 MHz high-powered transmitter was fabricated from a length of 3 inch o.d., 1/8 inch wall copper tube. This operated normally at 65°C but when an identical coil, which had been nickel plated, was substituted, the operating temperature rose to 350°C. This is approximately the Curie ‡ temperature for nickel so that the impedance would decrease until a stable operating condition was reached.

3. Conductivity of Electroplated Metals

There is remarkably little published information of the conductivity of electro-deposited metals and very often the information omits one of the three following important points :

- (i) the method used to prepare the samples ;
- (ii) the method used to carry out the measurements ;
- (iii) the frequencies at which the measurements were made.

Lamb and Valentine¹² of the National Bureau of

11. A.S. K161 and CK 12: 1966. "Electroplated Coatings of Silver for General Engineering Purposes", Stand. Ass. Aust.

12. Lamb, V. A. and Valentine, D. R., "Physical and Mechanical Properties of Electrodeposited Copper", I. Literature Survey, A.E.S. Research Project No. 21, *Plating*, Vol. 52, No. 12, December 1965, p. 1289.

‡Curie temperature—this is the temperature at which the relative permeability drops to 1.0 and the metal ceases to be ferro-magnetic. As a result, the skin depth will increase and the a.c. resistance will drop.

Standards in a literature survey of some 165 papers on electroplated copper reported that "Data on effects of plating variables on electrical resistivity of electro-deposited copper are nearly non-existent".

Zentner, Brenner and Jennings¹³ of the National Bureau of Standards, from their own work and from a search of some 200 papers, have listed resistivities of electro-deposited nickel ranging from 7.41 to 35.93 μΩ cm. Keil^{2, 8} has reported values of 1.8 to 3.0 μΩ cm for silver. Raub^{3, 4} gives a range from 1.59 to 1300 μΩ cm for silver and from 1.7 to 1350 μΩ cm for copper electro-deposits.

Although many other workers have measured the conductivity of plated metals, they have done so in an effort to determine whether or not impurities are present in the deposit. Those results that have been reported show very wide variations. There have been a number of other conductivity measurements made at u.h.f. but these generally have been relative conductivity of different finishes rather than absolute measurements.

The range of conductivities of electroplated metals, together with the conductivity of the pure bulk metal is shown in table 1. This is the only information on mea-

Table 1
Range of conductivities of electro-deposited metals

Metal	Conductivity of pure metal		Conductivity of plated deposit	
	MΩ/m	% I.A.C.S.	MΩ/m	% I.A.C.S.
Copper	58	100	0.07-58	0.13-100
Chromium	7.9	13.6	1.6 -7.7	2.8-13.3
Gold	43	74	6 -43	10.0-74
Nickel	14	24	2.8 -13.5	4.8-23
Rhodium	23	34	5 -5.6	8.0-9.0
Silver	62.5	105	0.07-55	0.13-95

Table 2
Skin depths in various electroplated metals for the conductivities shown

Plating metal	D.C. conductivity (% I.A.C.S.)	Skin depth at		
		1 MHz	100 MHz	1 GHz
Copper	100	0.0025	0.00025	0.00008
Gold	50	0.0044	0.0004	0.00013
Nickel*	20	0.00025 (μ = 500)	0.000025 (μ = 40)	0.000008 (μ = 10)
Silver	50	0.0044	0.0004	0.00013

*Values of permeability of electro-deposited nickel are not available for these frequencies. These are the values for nickel wire as quoted by Allanson, J. T., "The Permeability of Ferromagnetic Materials at Frequencies between 10⁵ and 10¹⁰ c/s", *J.I.E.E.*, Vol. 92, Part III, No. 20, December 1945, p. 247.

13. Zentner, V., Brenner, A. and Jennings, C. W., "Physical Properties of Electrodeposited Metals", *Plating*, Vol. 39, No. 8, August 1952, p. 865 and p. 933 (Corrections: No. 10, November 1952, p. 1229). Reprinted as A.E.S. Research Report Serial No. 20.

sured values of conductivity which has been located from both an extensive literature survey and correspondence with various plating authorities. Most of the values of resistivity given in published properties of electro-deposits are the value for the pure cast and wrought metal. In general, no mention is made of the increased resistance of an electro-deposited metal.

4. Methods of Measurement of Conductivity

The conductivity of an electro-deposit may be measured by first physically or chemically stripping it from the base metal and then carrying out d.c. or a.c. measurements. The stripping must be carried out carefully to avoid work-hardening the sample as this may affect its physical properties. The layer may only be separated provided it is crack-free and reasonably free from stress. Many deposits will disintegrate when an attempt is made to separate them from the base metal.

Keil² has used an eddy current thickness gauge to compare the conductivity of various detached samples with pure silver foils of various thicknesses.

Beck and Dawson¹⁴ measured the resistance of a sample of plated wire used as the centre conductor of an open-ended coaxial line. They measured the loaded "Q" of this coaxial line resonator, corrected this to obtain the unloaded "Q" of the centre wire (sample) and hence determined its effective conductivity.

Shigebumi¹⁵ used the plated sample as one end of a coaxial resonator and deduced the relative conductivity of various samples from the changes in "Q" of the cavity.

One of the most promising methods is that described by Karbowskiak¹⁶ who deduces the surface impedance of the inside surface of a cavity from resonant conditions of the cavity operating simultaneously in H_{01} and E_{11} modes. The method has the advantage that the cavity bandwidth is a measure of the surface resistance, R_s , while the surface reactance, X_s , is deduced from the separation between H_{01} and E_{11} responses. As the values of R_s and X_s are equal when the plated layer is thick enough to behave as if the cavity was made from a single metal, the method gives a good guide to the thickness required.

However, there is still no readily available instrument which will allow rapid measurement of a finish that has been used on a particular component. The only real test available at present is to measure the resultant loss when the component is placed in circuit.

5. Reasons for Variation in Conductivity

Various workers have shown that the conductivity of the deposited metal also depends on:

14. Beck, A. C. and Dawson, R. W., "Conductivity Measurements at Microwave Frequencies", *Proc. I.R.E.*, Vol. 38, No. 10, October 1950, p. 1181.
15. Shigebumi, S., "Surface Loss of Silver Plated Metal Plates at 9,000 MHz and Its Correlation with Surface Roughness", *Proc. I.R.E.*, Vol. 42, No. 12, December 1954, p. 1810 (Correspondence).
16. Karbowskiak, A. E., "An Instrument for the Measurement of Surface Impedance at Microwave Frequencies", *Proc. I.E.E.*, Vol. 105, Part B, No. 20, March 1958, p. 195.

- (i) the composition of the plating bath;
- (ii) the temperature of the plating bath;
- (iii) the current density in the bath, at the plated surface;
- (iv) the surface preparation of the base metal; and
- (v) the thickness of the plated layer.

As shown in table 3, Raub^{3, 4, 17} has measured a very wide range of conductivities for both silver and copper plated from various baths. He has also shown that although the conductivity of the deposit may be increased

Table 3

Effect of addition agents on the conductivity³ of silver and copper electro-deposits: the silver was deposited from a cyanide bath and the copper from a sulphate bath

Addition agent	Impurity in electro-deposit (% weight)	Specific resistance ($\mu\Omega/\text{cm}$)		Conductivity (% I.A.C.S.)	
		Silver	Copper	Silver	Copper
None		1.59	1.7	108	100
Glycocoll	0.1	—	1.7	—	100
	0.2	1.9	—	91	—
	0.19	—	1.8	—	96
Metaphosphoric acid or metaphosphate	0.2	—	17.0	—	10
	0.87	300	—	0.58	—
	2.3	—	1350	—	0.13
	2.65	960	—	0.18	—
Citric acid or citrate	0.67	—	95.5	—	1.8
	2.6	—	290	—	0.59
	3.5	1300	—	0.13	—
Tartaric acid or tartrate	0.7	62.6	—	2.8	—
	1.2	270	—	0.63	—

by subsequent annealing, the final value is still much lower than the pure metal.^{3, 18, 19}

The variation in conductivity is not confined to electro-deposits and it is also a good reason why the grade of material to be used as a base metal should be very carefully specified and then checked during manufacture. The conductivity of any metal is reduced by adding small quantities of other elements, either as alloys or as a mixture.^{20, 21} As an example, the effect of the inclusion of other elements on the conductivity of copper is shown in fig. 8.*

17. Raub, E. and Mueller, K., "Fundamentals of Metal Deposition", Elsevier Publishing Co., Amsterdam (1967), p. 170.
18. *Ibid.*, p. 182.
19. Raub, E. and Sautter, F., "Der Aufbau galvanischer Leiterungsniederschlaege XII, Die Kupfer-Zinn-Legierungen", ("The Structure of Electro-deposited Alloys—XII—The Copper-tin Alloys"), *Metalloberflaeche*, Vol. 11, No. 8, August 1957, p. 249.
20. Rose, R. M., Shepard, L. A. and Wulff, J., "The Structure and Properties of Materials", Vol. IV, "Electronic Properties", John Wiley, N.Y. (1966), p. 82.
21. Mott, N. F. and Jones, H., "The Theory of the Properties of Metals and Alloys", S456—Dover Publications, N.Y. (1958), p. 240.

*Reproduced by courtesy of "Copper and Brass Information Centre" from "Copper Cables" C.D.A. Publication No. 56.

Benson²² gives one example of a waveguide having an unexpectedly high attenuation. On investigation, it was found that it had been fabricated from arsenical copper having a conductivity of 36% I.A.C.S.

6. Use of Silver Plating to Reduce Losses

Pure silver has a d.c. conductivity only 5% higher than that of pure copper and at radio frequencies where the relative conductivity is proportional to the square root

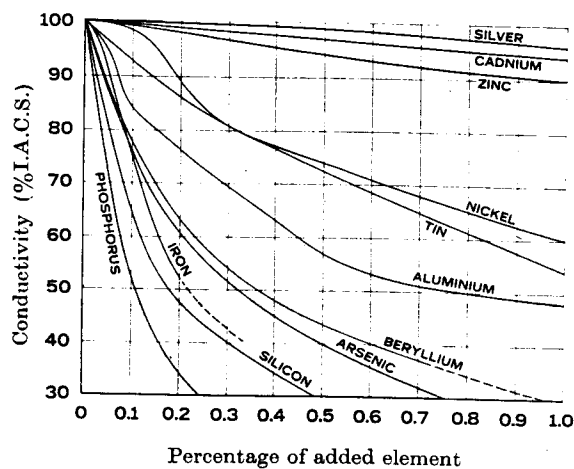


Figure 8.—The effect of added elements on the electrical conductivity of copper.

of the d.c. values, it is only 2.5% higher. This improvement is insignificant in terms of the "Q" factor. In view of this and the difficulty in producing high conductivity silver plating, why has silver plating been specified for electronic components for many years?

Most commercially available copper tube contains 0.015% to 0.08% phosphorus as a de-oxidising agent,²³ so that its conductivity may range from 60% to 90% I.A.C.S. It was more than likely, in the early days of radio, that silver plating a coil would increase its "Q" because: (a) the available copper tubing had a higher impurity content, and hence resistance, and (b) the silver plating processes available at the time produced a very pure silver deposit of high conductivity.

This explains why silver plating occasionally reduces the losses in a coil wound from copper tubing and why the practice of silver plating electronic components has grown up over the years. The position has changed in the intervening years, and present-day electrical grade copper has a conductivity of 101.6% I.A.C.S.,²⁴ while the bright silver plates which are in common use have a much lower conductivity than pure silver.^{1-4, 7}

With the currently-used plating processes it should be possible to obtain better r.f. performance by plating a layer of high-conductivity copper instead of by using silver plating.

7. Structure of an Electro-deposited Metal Layer

The structure of an electro-deposited metal layer is usually very different from that of the pure wrought metal.²⁵ The metal may be deposited in bands or layers. The crystals may grow epitaxially from the base metal or have a random orientation. The crystal structure may be so fine as to be invisible under the best optical microscopes and the deposit appears to be amorphous; many bright deposits are of this type. The deposit may have internal stresses, which may be either compressive or tensile, ranging from zero to some hundred tons per square inch. These stresses may be high enough to cause distortion of the plated article or cracking of the electroplated layer. This latter is a particular problem in the case of thicker deposits of rhodium and most deposits of chromium.

The structure is very greatly affected by the composition of the plating bath, the temperature of the bath and the current density used for plating. It may be changed by subsequent heat treatment. The different structures that result from these variations will have widely different physical properties. In fact, the plater can vary the conditions to obtain a desired result, usually high brightness, good corrosion resistance or hardness.

Various materials are added to the plating bath, usually as brightening or hardening agents and some of these will co-deposit with the metal as impurities. They may form mixtures or true alloys,⁵ they may be deposited as insulating films in the grain boundaries or they may be deposited in the crystal lattice with resultant distortion of the lattice.^{26, 27} Impurities may also be deposited from accidental contamination of the plating bath. Each of these changes to the structure will reduce the conductivity of the deposit compared with that of the pure metal.

It is also common practice to deposit either alloys or mixtures of metals to obtain special properties not available from the pure metals. In some cases there is only a small percentage of the second metal present; in other cases, such as tin-nickel²⁸ alloy, the metals are present in an equi-atomic ratio. Most gold deposits contain a high percentage of alloying elements to obtain the desired hardness or colour.^{29, 30}

22. Benson, F. A., "Waveguide Attenuation and its Correlation with Surface Roughness", *Proc. I.E.E.*, Part III, Vol. 100, No. 64, March 1953, p. 85.

23. BS.1172: 1952, "Phosphorus De-oxidised Non-arsenical Copper", *Brit. Stand. Inst.*

24. Eldridge, E. A., "Electrical Properties of Copper and High Copper Alloys", *Copper Development Association Inc.*, N.Y., Application Data Sheet 108/6.

25. Raub, E. and Mueller, K., "Fundamentals of Metal Deposition", Elsevier Publishing Co., Amsterdam (1967), Chapter 4.

26. Fischer, J. and Weimer, D. E., "Precious Metal Plating", Robert Draper Ltd., Teddington (1964), p. 57.

27. Raub, E. and Mueller, K., "Fundamentals of Metal Deposition", Elsevier Publishing Co., Amsterdam (1967), p. 102 and p. 169.

28. B.S. 3597: 1963, "Electroplated Coatings of 65/35 Tin-Nickel Alloy", (with amendment PD5576, July 1965), *Brit. Stand. Inst.*

29. Brenner, A., "Electrodeposition of Alloys", Vol. II, Academic Press, N.Y. and London (1963), p. 523.

30. Foulke, D. G., "Plating on Precious Metals". *Plating*, Vol. 51, No. 7, July 1964, p. 685.

8. Structure of Electroplated Finish

An electroplated finish is often not a single layer. The article to be plated may be fabricated from several metals and may have joints which have been soft-soldered, silver-soldered or welded. To render the surface homogeneous, the plater must first specially prepare the heterogeneous surface to ensure that each metal is satisfactorily conditioned to receive a metal deposit. The article may then be given a "strike" coating of, for example, copper from a cyanide solution, to ensure that good adhesion of the subsequent coatings is achieved ("strike" coatings are applied to render the surface homogeneous and to avoid the formation of immersion deposits when a part is immersed in the plating solution and before electrical contact is established).

Composite coatings may also be required to provide adequate corrosion or wear resistance, to level a surface, to control inter-diffusion between metal layers or to prevent epitaxial crystal growth.

Prior to silver plating, mercury "quicking" of a copper surface was once used instead of a silver strike. This forms a thin layer of copper amalgam which avoids immersion coatings of silver when the part is placed in the silver bath. This practice may cause serious problems during the service life of the part and it should be avoided.³¹

As an example of specification plating, consider the silver plating of steel for electrical purposes.* After cleaning and other preparation, the metal is given a copper "strike" followed by a further plate of copper in a different bath or a coating of brass and/or nickel. This will be followed by a silver "strike" after which the main silver coating is plated on the article.

It is most important to realise that the purity or structure of the silver deposit is not laid down in many standards and specifications and if normal commercial coatings are requested, composite coatings may be supplied which will not perform as well as pure silver at radio frequencies.

9. Corrosion Protection

The silver deposit is readily attacked by sulphides present in the atmosphere, with an increase in the contact resistance and severe discolouration.^{32, 33} In a typical case the contact resistance of two silver-plated wires rose from 6 milliohms to 200 milliohms after two hours' exposure to hydrogen sulphide.³³

31. Fischer, J. and Weimer, D. E., "Precious Metal Plating", Robert Draper Ltd., Teddington (1964), p. 30.

32. Antler, M., "New Developments in the Surface Science of Electrical Contacts", *Plating*, Vol. 53, No. 12, December 1966, p. 1431.

33. Keil, A., Krusenstjern, A. and Veil, G., "Einfluss von Deckschichten auf den Übergangswiderstand Zwischen galvanisch versilberten kontaktstücken" ("The Influence of Overplating on the Contact Resistance of Silver Contacts"), *Metall: Zeitschrift für Technik, Industrie und Handel*, Vol. 20, No. 6, June 1966, p. 592.

*DEF (Aust.) 167 requires silver 2/3 for general use for good electrical properties and specifies BS.2816 Ag 5S (equivalent to AS K161—Ag 5S). The total thickness of underlays required by Ag 5S is 0.0005 inches, followed by 0.0005 inches of silver.

It is becoming increasingly common to specify a further protective layer, the commonest being gold or rhodium. Neither of these is entirely satisfactory. A gold flash (10 micro-inches) is often used although many workers have shown that the deposits are not pore-free³³⁻³⁵ and that at least 200 micro-inches of gold are necessary to provide adequate protection. Antler³² has shown that unless the gold completely covers the silver, sulphide films will start on the silver surface and creep over the gold layer. Rhodium is frequently used, as, like gold, it forms no oxide film. Its main application is to sliding contact surfaces, where 0.0002 to 0.001 inches are used, although a thickness of only 15 to 20 micro-inches is normally specified for electronic applications. Rhodium deposits are very hard. Care must be taken in the design of the contacts to prevent excessive pressure deforming the base metal and fracturing the rhodium deposits. This would expose sharp cutting edges which would rapidly destroy both the rhodium and the undercoat.^{36, 37}

Duva³⁸ recommends against the use of normal rhodium plating because of the porous nature of the deposits but suggests the use of low-stress rhodium deposits. Fischer³⁶ and Mills³⁷ recommend the use of hard gold deposits in preference to rhodium.

If copper is used instead of silver, some form of corrosion protection will still be required. This may be either a very thin layer of low conductivity metal or a low loss dielectric. Polystyrene and similar plastics have been suggested but many of these absorb moisture from the air which will cause corrosion of the copper. Several workers have recommended clear lacquers which have been found to give good results. With the rapid changes in paint formulations these days it would be wise to investigate currently available finishes rather than rely on earlier recommendations.

10. Reasons for Variation in R.F. Resistance

The r.f. resistance will be affected by

- (i) the lower conductivity of the electro-deposit;
- (ii) the use of a number of layers in the deposits;
- (iii) the properties of the base metal; and
- (iv) the surface finish.

Consider the previous case of a silver plated steel surface. The various layer thicknesses are shown in fig. 9.

34. Noonan, H. J., "Electrographic Determination of Porosity in Gold Electrodeposits", *Plating*, Vol. 53, No. 4, April 1966, p. 461.

35. Harding, W. B., "The Tarnish Resistance of Gold Plating over Silver", *Plating*, Vol. 47, No. 10, October 1960, p. 1141.

36. Fischer, J. and Weimer, D. E., "Precious Metal Plating", Robert Draper Ltd., Teddington (1964), p. 192.

37. Mills, R. A., "Electrodeposited Contact Metals", *Electroplating and Metal Finishing*, Vol. 20, No. 3, March 1967, p. 70.

38. Duva, R., "Metal Finishing—Guidebook and Directory", (32nd. Edition), Metals and Plastics Publications Inc., N.J. (1964), p. 282.

Rather than calculate the actual current distribution, consider the skin depth in each metal separately, neglecting the steel. At 1 MHz, the silver plate is only 20 percent of the skin depth, so that most of the current will flow in the nickel under-layer (skin depth: 250 micro-inches) and cause high losses. At 100 MHz the silver layer is slightly more than one skin depth thick but the thickness of the gold layer is now about half a skin depth. At 1 GHz, the gold layer is greater than one skin depth, so that it carries most of the current.

A much thicker layer of silver is required at low frequencies, about 0.004 inches at 1 MHz, and a high conductivity silver plate ($\geq 90\%$ I.A.C.S.) must be used, if a

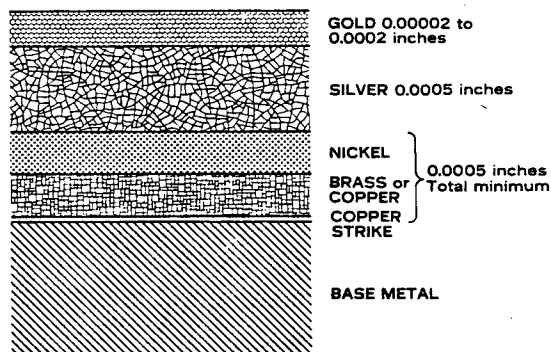


Figure 9.—Cross-section of a typical silver plated finish on steel, with a gold tarnish-prevention layer. The silver and undercoats are as specified in BS.2816 Ag 5S.

low-loss coating is required. At ultra-high frequencies, there seems little point in using a layer of silver, as, with the above thickness, the current will nearly all flow in the final layer of gold.

The problem is basically this: if silver is used, then a very thick layer of gold is required for corrosion resistance and, apart from the cost, the thick layer of gold cancels out any conductivity advantage gained from a layer of silver.

10.1 Effect of Surface Finish

Many workers* have investigated the effect of the surface finish on conductivity at radio frequencies. This is a particular problem at frequencies above 1 GHz, where the imperfections may be several skin depths deep.

Several reasons have been given for the decrease in conductivity below the bulk values, including:

- (a) the Beilby layer³⁹: the outer layer of a metal that has been deformed by machining has a lower d.c. conductivity than the bulk metal;

*See references 6, 7, 14, 15, 22 and 39 to 41.

39. Chambers, R. G. and Pippard, A. B., "The Effect of Method of Preparation on the High-Frequency Surface Resistance of Metals", Properties of Metallic Surfaces, Institute of Metals, 1953.

- (b) the porous nature of the electrodeposits: a number of early workers attempted to plate the inside surface of waveguides by using only external anodes in the plating bath. The layer formed on the inside surface was either an immersion coating or deposited under such adverse plating conditions that it was very rough and porous. This problem can only be overcome by using correctly sized and placed internal anodes and by circulating the plating solution through the parts to be plated.

- (c) the hill and dale effect: the current path is no longer a straight line but follows the surface with an increase in the a.c. resistance and reactance. This last problem has been investigated fully by Benson^{40, 41} who recommends chemical or electrolytic polishing to produce a smooth surface and lower losses.

11. Choice of a Suitable Finish System

One metal may be coated with another by electroplating, electroless plating, metal spraying, vacuum deposition or hot dipping. The method chosen will depend on the application. A base metal will be coated with one or more layers of other metals to:

- (a) improve the appearance;
- (b) improve the corrosion-resisting properties;
- (c) improve the conductivity;
- (d) improve the solderability or weldability;
- (e) improve the shelf life before assembly;
- (f) improve the reliability of electrical contacts or sliding or plug-in connections;
- (g) improve the wear resistance at sliding surfaces.

Particular care must be taken in specifying not only the finish to be used but also the pre-treatment of the material and the methods of fabrication to be employed. For instance, many electroplated finishes will not take successfully over a soft-soldered joint. The electroplater will overcome this problem by using an undercoat which will take over the solder but which may be entirely unsuitable for electronic applications. Where there is a choice of undercoats the required type should be clearly specified.

To minimise plating problems and the cost of the plated component, many difficulties can be avoided at the design stage by discussions with a consultant familiar with electroplating.

40. Allison, J. and Benson, F. A., "Surface Roughness and Attenuation of Precision-Drawn, Chemically Polished, Electroplated, and Electroformed Waveguides", Proc. I.E.E., Vol. 102, Part B, No. 2, March 1955, p. 251.

41. Benson, F. A., "Rectangular-Waveguide Attenuation at Millimetric Wavelengths", Proc. I.E.E., Vol. 110, No. 6, June 1963, p. 1008.

In most cases the plating process used is not under the control of the designer. Work is normally taken to a jobbing shop and will get the normal commercial decorative finish. Few firms are set up to handle the specialised requirements of the electronics group. Where the application is critical, it may be better to avoid a plated finish entirely or, failing this, to select one which will have the least possible effect on the overall results. Where high conductivity and low losses are important, it is recommended that the base metal be electrical grade copper or, failing this, that the base metal be plated with a high conductivity copper plate to a thickness of at least one and one half skin depths at the operating frequency. The copper should then be protected from corrosion by the thinnest acceptable layer of a plating having a very low conductivity.

11.1 Suggested Low-Conductivity Deposits

1. *Tin-Nickel*. This is an electro-deposited alloy having the composition 65% tin and 35% nickel.^{28, 42-46} Price⁴⁷ has measured a resistivity of 140 $\mu\Omega$ cm (1.2% I.A.C.S.) for a detached sample but it is not known whether this value changes after heat-treatment. The alloy has excellent corrosion resistance, is self-lubricating and is non-magnetic.⁴⁸

2. *Copper-Tin-Zinc*. There are a number of ternary alloys which may be plated readily. One of these, containing 55% copper, 30% tin and 15% zinc, is stated to have very good radio frequency properties^{49, 50} and is used for special low-loss components. No published value of conductivity is available but, being an alloy, the material is likely to have low conductivity. The particular alloy should be carefully chosen. Brenner⁵¹ gives a value of 35% I.A.C.S. for another Cu-Sn-Zn alloy but this would be unsuitable and would cause high losses, as shown in figs. 3 and 5.

3. *Gold Alloys*. A number of the hard gold deposits

have high resistance⁵²⁻⁵⁴ and may prove suitable where cost is not important. Rochat⁵⁵ reports that a gold-copper alloy had resistivities ranging from 150 to 250 $\mu\Omega$ cm (0.7% to 1.1% I.A.C.S.). This decreased to 20 $\mu\Omega$ cm (8.5% I.A.C.S.) after annealing.

4. *Tin*. Tin has high corrosion resistance and may be applied by electroplating or hot dip tinning. No information is available on the conductivity of either deposit but electroplated tin is likely to have a higher resistance.

5. *Chromium*. In commercial practice, chromium is normally plated over nickel. However, most commercial nickel deposits are magnetic and so are unsuitable for use at radio frequencies. Chromium may be deposited directly on copper⁵⁶ but a thick layer should not be used on sliding contacts. The soft copper does not provide sufficient mechanical support for the chromium which cracks and exposes sharp cutting edges in the same way as does rhodium. The resistivity of chromium electro-deposits has been measured at 65 $\mu\Omega$ cm (2.5% I.A.C.S.).⁵⁷⁻⁵⁹ This may be reduced by subsequent annealing to between 13 and 35 $\mu\Omega$ cm⁵⁰ (5% to 13% I.A.C.S.).

6. *Nickel-Phosphorus*. Nickel may be deposited with a wide range of phosphorous content, generally by electroless plating. The phosphorus increases the resistivity markedly, normal electroplated nickel has a resistivity of 8 $\mu\Omega$ cm (21% I.A.C.S.) and this is increased to 75 $\mu\Omega$ cm (2.2% I.A.C.S.) with 7% phosphorus and to 120 $\mu\Omega$ cm (1.4% I.A.C.S.) with 13% phosphorus.^{60, 61} Brenner⁶⁰ states that nickel deposits containing more than 8% phosphorus are non-magnetic. The deposit is bright and has very good corrosion resistance.

7. *Cobalt-Phosphorus*. Brenner⁶² also suggests cobalt-

42. Angles, R. M., "Tin-Nickel Alloy Plating", The International Nickel Company (Mond) Limited, Publication 2740, 1964.
43. "Electroplated Tin-Nickel Alloy", Tin Research Institute Publication No. 235, (Revised Edition, 1962).
44. Couch, R. W. and Bikales, R. G., "Plating of Printed Circuits with Pyrophosphate Copper and Tin-Nickel", 48th. Annual Convention, Tech. Proc. Amer. Electroplaters Soc., 1961, p. 176.
45. Fairweather, A., Lazenby, F. and Parker, A. E., "Long-Life Low-Voltage Contacts", *Proc. I.E.E.*, Vol. 109, Part B, Sup. No. 22, 1966, p. 567.
46. Brenner, A., "Electrodeposition of Alloys", Vol. II, Academic Press, N.Y. and London (1963), p. 315.
47. Price, J. W. (Private communication, December 12, 1966).
48. Bigg, P. H. and Burch, F. H., "Further Tests on Stability of Analytical Weights in Chemical Laboratories", *Brit. J. App. Physics*, Vol. 5, No. 11, November 1954, p. 383.
49. Pinner, R., "Copper and Copper Alloy Plating", Copper Development Association, London, Publication No. 62, (Second Edition), 1964.
50. Mohler, J. B., "Copper-Tin-Zinc Plating", *Metal Finishing*, Vol. 53, No. 10, October 1955, p. 47.
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52. Brenner, A., "Electrodeposition of Alloys", Vol. II, Academic Press, N.Y. and London (1963), p. 523.
53. Foulke, D. G., "The Effect of Addition Agents on the Structure and Physical Properties of Gold Electrodeposits", *Plating*, Vol. 50, No. 1, January 1963, p. 39.
54. Foulke, D. G., "Quality Control in Precious Metal Plating", *Metal Finishing*, Vol. 63, No. 7, July 1965, p. 42.
55. Rochat, "The Effect of Thermal Treatment upon Certain Electrodeposited Alloys", *Bull. ann. Soc. Suisse de Chronométrie, Lab. Suisse Recherches Horlogeres*, No. 4, 1957, p. 45.
56. Cam, D., "Practical Experience with Chromium Without Nickel Undercoats", *Plating*, Vol. 40, No. 1, January 1953, p. 47.
57. Brenner, A., "Electrodeposition of Alloys", Vol. I, Academic Press, N.Y. and London (1963), p. 257.
58. Morisset, P., Oswald, J. W., Draper, C. R. and Pinner, R., "Chromium Plating", Robert Draper Ltd., Teddington (1954), p. 216.
59. Brenner, A., Birkhead, P. and Jennings, C. W., "Physical Properties of Electrodeposited Chromium", 34th. Ann. Proc. Am. Elec. Soc., 1947, p. 32.
60. Brenner, A., "Electrodeposition of Alloys", Vol. II, Academic Press, N.Y. and London (1963), p. 477.
61. Keil, A. and Berger, B., "Die elektrische Leitfähigkeit von chemisch erzeugten Nickelschichten", ("The Electrical Conductivity of Chemically-applied Nickel Coatings"), *Metall-oberflaeche*, Vol. 10, No. 12, December 1956, p. 356.
62. Brenner, A. (Private communication, December 8, 1966).

phosphorus which is a bright deposit. No information is available on its conductivity but it is expected to be low at high phosphorus content. No information has been found on the percentage of phosphorus needed to make the alloy non-magnetic.⁶³

8. *Rhodium*. Rhodium has been used for many years as a protective coating for silver. As mentioned in section 9 it is subject to cracking and may not give adequate corrosion protection. Keil² has measured conductivities of 8% to 9% I.A.C.S. for low stress deposits. Rhodium does not form an oxide film on the surface and hence would be suitable for sliding contact surfaces if the corrosion problems could be overcome by developing a suitable deposit.

12. Action Required

There is a pressing need for further action in the following areas :

- (a) Education of electronic engineers :
 - (i) in the basic properties of electro-deposits, and
 - (ii) to select and specify a finish system as carefully as any other component.
- (b) Education of electroplaters in the problems of the electronic industry, so that the correct finish system will be adhered to.
- (c) Determination of the requirements of a finish for electronic applications.
- (d) Revision of current standards and specifications for electroplating to include a section on the electrical requirements of the deposit or, alternatively, to prepare separate standards for the electronic industry.
- (e) Development of suitable finishes to meet the electronic industry's requirements.
- (f) Development of simple methods and equipment to allow easy checks on the r.f. performance of a finish system, at the frequency at which it is to be used.

13. Conclusion

It has been shown that there are two separate problems :

- (i) the conductivity of electroplated metals is generally lower than that of the pure cast and wrought metal ;
- (ii) the current distribution in a composite conductor, and hence its impedance, depends not only on the conductivity of the sheath but also on that of the core.

The finish system used for a conductor carrying r.f. currents must be chosen very carefully if losses are to be kept to a minimum. The use of unsuitable under-lays or over-lays or the wrong plating procedure may give completely unexpected results.

For general use, it is recommended that the most suitable low-loss finish is obtained by using a layer of high conductivity copper plating at least two skin depths in thickness, at the operating frequency, then protecting this against corrosion by a very thin layer of low conductivity plating or a layer of low-loss lacquer.

A number of further practical problems remain to be solved jointly by the electronic and electroplating industries.

Acknowledgment

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Appendix

List of Symbols*

- a Radius of core (metres).
- b Radius of outside of sheath (metres).
- i Current in composite conductor (amps).
- i_c Current in core.
- i_s Current in sheath.
- j $\sqrt{-1}$.
- J_0 Current density at the surface of the sheath (amp/metre²).
- J_1 Current density at radius r in core (amp/metre²).
- J_2 Current density at radius r in sheath (amp/metre²).
- L Effective internal inductance of the composite conductor (henry/metre).
- m_1 $(\omega \mu_0 \mu_1 \sigma_1)^\dagger$.
- m_2 $(\omega \mu_0 \mu_2 \sigma_2)^\dagger$.
- q $(\sigma_1 \mu_2 / \sigma_2 \mu_1)^\dagger = \sigma_1 m_2 / \sigma_2 m_1$.
- r Radius of core or sheath at which current density is to be calculated.
- R Effective resistance of the composite conductor (ohm/metre).
- X_L ($= \omega L$) Effective internal reactance of the composite conductor (ohm/metre).
- Z ($= R + j X_L$) Impedance of the composite conductor (ohm/metre).
- μ_0 Permeability of free space ($4\pi \times 10^{-7}$ henry/metre).
- μ_1 Relative permeability of material of the core.
- μ_2 Relative permeability of material of the sheath.
- σ_1 Conductivity of material of the core (mho/metre).

*The notation A, B, c, d, e, etc., follows that used by Astbury, except that the formulae have been modified to use Kelvin Functions of zero order throughout, to simplify the numerical evaluation.

63. Zentner, V., "Electrodeposited and Electroless Magnetic Alloys for Computers", *Plating*, Vol. 52, No. 9, September 1965, p. 868.

σ_2 Conductivity of material of the sheath (mho/metre).

ω $2\pi \times$ frequency.

$A = cv - qft$.

$B = qfd - eg$.

where $c = \text{ber}(m_1 a) + j \text{bei}(m_1 a)$

$d = \text{ber}(m_2 a) + j \text{bei}(m_2 a)$

$e = \text{ber}(m_2 b) + j \text{bei}(m_2 b)$

$f = \text{ber}'(m_1 a) + j \text{bei}'(m_1 a)$

$g = \text{ber}'(m_2 a) + j \text{bei}'(m_2 a)$

$h = \text{ber}'(m_2 b) + j \text{bei}'(m_2 b)$

$t = \text{ker}(m_1 a) + j \text{kei}(m_1 a)$

$u = \text{ker}(m_2 a) + j \text{kei}(m_2 a)$

$v = \text{ker}'(m_1 a) + j \text{kei}'(m_1 a)$

$w = \text{ker}'(m_2 a) + j \text{kei}'(m_2 a)$

$I_0(m_1 r \sqrt{j}) = \text{ber}(m_1 r) + j \text{bei}(m_1 r)$

$I_0(m_2 r \sqrt{j}) = \text{ber}(m_2 r) + j \text{bei}(m_2 r)$

$K_0(m_2 r \sqrt{j}) = \text{ker}(m_2 r) + j \text{kei}(m_2 r)$.

Here, $\text{ber}(mr)$, $\text{bei}(mr)$, $\text{ker}(mr)$ and $\text{kei}(mr)$ are Kelvin Functions⁶⁴ and correspond to the real and imaginary parts of $I_0(mr \sqrt{j})$ and $K_0(mr \sqrt{j})$, the modified Bessel functions of the first and second kind with complex argument.

In carrying out the calculations for the resistance and reactance of, and the current distribution in, a conductor coated with a uniform layer of another metal, the following assumptions have been made.

- (i) The conductivity of the metal is high enough so that displacement currents may be neglected. This will be the case for all normal metals or deposits.
- (ii) The conductivity is uniform throughout each metal, that is, there are no discontinuities or severe temperature gradients.
- (iii) If either the core or sheath metal is ferromagnetic, then the permeability is constant throughout a cycle. This is obviously unlikely but the calculations will at least indicate the range of the effects in a magnetic conductor.
- (iv) There is a sharp boundary between the core and the sheath, that is, one has not diffused into the other and also, there is ohmic contact at the boundary.
- (v) The temperature is not so low that anomalous skin effect occurs.
- (vi) The frequency is not so high that the roughness in the surface finish becomes important.*
- (vii) The calculations are carried out for a long, straight, isolated cylindrical conductor.

64. McLachlan, N. W., "Bessel Functions for Engineers", (2nd. Edition), Oxford University Press, London (1961), p. 137.

*It is considered that the effects that are described in this paper hold at all frequencies. The limit is imposed because of the difficulties encountered in trying to calculate the effect with a current that is not flowing in a straight line but flowing around surface irregularities that are of the order of one skin depth or more in size. This surface roughness often accounts for the increase in apparent resistivity of a single metal conductor.

The above restrictions are somewhat artificial but the results of the calculations may be used as a guide in the practical case.

Formulae

For a conductor of a single metal

Current density, J_r , at any radius, r

$$J_r = J_0 \frac{\text{ber}(mr) + j \text{bei}(mr)}{\text{ber}(ma) + j \text{bei}(ma)} \quad (1)$$

Impedance of the conductor

$$Z = R + j \omega L = \frac{m \sqrt{j}}{2 a \sigma} \frac{\text{ber}(ma) + j \text{bei}(ma)}{\text{ber}'(ma) + j \text{bei}'(ma)} \quad (2)$$

For the composite conductor

Current density, J_2 , at any radius, r , in the sheath

$$J_2 = \frac{J_0}{Ae + Bu} \cdot [A I_0(m_2 r \sqrt{j}) + B K_0(m_2 r \sqrt{j})] \quad (3)$$

Current density, J_1 , at any radius, r , in the core

$$J_1 = \frac{J_0}{Ae + Bu} \cdot \frac{\sigma_1}{\sigma_2} \cdot (dv + gt) \cdot I_0(mr \sqrt{j}) \quad (4)$$

Impedance of the composite conductor

$$Z = R + j \omega L = - \frac{j m_2}{2 \pi b \sigma_2} \frac{Ae + Bu}{Ah + Bw} \quad (5)$$

Total current flowing in the sheath

$$i_s = \frac{2\pi}{m_2 j} \cdot \frac{J_0}{Ae + Bu} \cdot [A(hb - ga) + B(wb - va)] \quad (6)$$

Total current flowing in the core

$$i_c = \frac{2\pi}{m_2 j} \cdot \frac{a J_0}{Ae + Bu} \cdot (Ag + Bv) \quad (7)$$

Total current flowing in the composite conductor

$$i = i_s + i_c = \frac{2\pi J_0 b}{m_2 j} \cdot \frac{Ah + Bw}{Ae + Bu} \quad (8)$$

The formulae for the composite conductor are those derived by Astbury.¹⁰ The formulae for the solid conductor are the standard formulae quoted in many text books. They may also be derived from those of the composite conductor by letting $a = b$, $m_1 = m_2$. Similar formulae for a hollow tube (of one metal) may also be derived by letting $\sigma_1 = 0$.

These formulae were used to calculate a series of curves for the current density and impedance of a range of conductors having sheaths of different conductivities and thicknesses. Some of these results are shown in figs. 1 to 6. All calculations and the plotting of curves were carried out on a CDC-160A computer. Numerical evaluation of the Kelvin Functions was carried out from the Chebyshev^{65, 66} polynomial approximations

65. McCracken, D. D. and Dorn, W. S., "Numerical Methods and Fortran Programming", Wiley, N.Y. (1964).

66. Clenshaw, C. W., "Mathematical Tables", Vol. 5, Chebyshev Series for Mathematical Functions, H.M.S.O., London (1962).

given in the N.B.S. Handbook.⁶⁷ The approximations in the handbook change from the series expansion to the asymptotic form for arguments greater than 8.0.

The functions of the first kind increase in value, while the functions of the second kind decrease, for increasing values of the argument. Now the expansions for the functions of the second kind contain a term which is the difference between two functions of the first kind. This leads to very low accuracy unless double precision arithmetic is used for the evaluation. It was found that a simpler approach was to vary the cross-over points as follows:

$$\text{ber}(z) + j \text{bei}(z) \quad z \geq 8.0$$

$$\text{ber}'(z) + j \text{bei}'(z) \quad z \geq 9.5$$

$$\text{ker}(z) + j \text{kei}(z) \quad z \geq 4.0$$

$$\text{ker}'(z) + j \text{kei}'(z) \quad z \geq 4.5.$$

The use of the Chebyshev polynomial approximations, rather than the more usually quoted high frequency approximations, allow considerably better accuracy in the calculations.

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78. Blum, W. A., "Properties of Electrodeposited Nickel and What Influences Them", *Material and Methods*, Vol. 37, No. 4, April 1953, p. 101.
79. Brenner, A. and Garcia-Rivera, J., "An Electronic Thickness Gauge", *Plating*, Vol. 40, No. 11, November 1953, p. 1238.
80. Gray, A. C., "Modern Electroplating", John Wiley and Sons, N.Y. (1953).
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Discussion

Mr. B. H. S. Day (Non-member)*

I would like to comment on the tensile cracking and structure of electro-deposits. It is normal to deposit both chromium and rhodium with tensile (contractile) internal stresses which are beyond the ultimate tensile strength of these metals and therefore they crack as you said. However, good commercial practice could allow relatively crack-free deposits of chromium and rhodium up to 0.0005 inches thick without special stress reducing additives. These thicknesses are generally well beyond those used on the electronic equipment you were discussing. As a general rule chromium and rhodium coatings for most electronic equipment would not be thicker than about 0.00003 inches and 0.0002 inches respectively (over nickel plating) but the British rhodium specification (DTD 931) does allow thicker coatings for corrosion resistance and of course hard chromium can be very thick too if required.

There is at least one commercial chromium plating

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process which must be mentioned, as it deliberately aims at producing a large number of micro-cracks in thin coatings to develop a very large number of anodic corrosion sites in the nickel undercoat. This reduces the corrosion rate at each site because of smaller cathode areas around sites and in some environments the life of components may be extended considerably. However, this type of deposit is not commonly used in Australia for electronic equipment. There is also a somewhat similar commercial nickel plating process in which a fine suspension of insoluble matter is included in the plating solution and some particles deposit with the nickel producing an attractive satin finish which has phenomenal corrosion resistance. Again you will not find this process used frequently on electronic equipment.

Modern electroplating practice aims at producing coatings which are attractive, bright and corrosion resistant without requiring polishing or further treatment (for example, subsequent layers of plating). Special properties such as ductility, hardness, wear resistance, electrical conductivity, solderability, contact resistance, internal stress and chemical purity are usually incidental and special arrangements must be made for them. To achieve brightness, levelling and throwing power, electroplating baths have become quite complex formulations with additives to produce or affect polarisation and crystal growth. As a rule these additives or their breakdown products are ultimately included in electro-deposits with noticeable effects on the structure of crystals of the metal. A fully bright deposit usually is almost amorphous with a banded type of structure. Metallic brighteners such as antimony in silver, are often plated out with the major metal and become included in the crystal structure. They cause crystal strain and dislocations and thereby the grain refinement needed for bright deposits. Organic addition agents are usually polar compounds and tend to be segregated along grain boundaries. A large number of such organic compounds contain sulphur groups and it has been noticed that as a general rule such brighteners in silver baths only slightly reduce conductivity of silver deposits. Antimony on the other hand appears to reduce conductivity. The higher resistance of antimony in silver deposits might be explained by a big increase in dislocations and possibly a much larger grain boundary surface area due to extremely small (practically amorphous) grain sizes. Stress reducing additives in plating baths tend to fill in at vacancies in deposits or prevent vacancies from forming in the crystal lattices. Therefore they may have either a beneficial or harmful effect on electrical conductivity and each such additive will have to be considered according to the mechanisms of its stress reducing action.

To help in this discussion, I have prepared test pieces from a few random plating baths in South Australia. Conductivity measurements, which are presented in the accompanying table, show a very wide divergence of conductivities in similar metals. In the light of your paper, many of these deposits would be poor from a r.f. point of view and it is clear that much more research is

needed in this field to enable electroplaters to serve electronic engineers effectively.

Many thanks for allowing me to attend your meeting ; it was most interesting and I hope something worthwhile will develop from it.

Measured Values of Conductivity of Electroplated Metals

Sample	Thick-ness inches	Resist-ance of test piece (ohms)	Conductivity		
			M Ω /m	% of wrought metal	% I.A.C.S.
Silver					
Proprietary organic type bright bath					
No. 1	0.0013	0.0050	54	87	93
No. 2	0.0011	0.0056	57	92	98
No. 3	0.0020	0.0090	16	26	27
Periodic reverse without addition agents	0.0010	0.0059	59	95	102
Copper					
Proprietary bright acid bath					
No. 1	0.0009	0.0186	21	36	36
No. 2	0.0012	0.0068	43	74	74
Acid sulphate without additives					
20 A/ft ²	0.0009	0.0098	40	69	69
50 A/ft ²	0.0009	0.0077	51	88	88
Rochelle salt-cyanide bath					
No. 1	0.0019	0.0048	42	72	72
No. 2	0.0018	0.0051	38	66	66
Gold pure cyanide without additives	0.0012	0.0101	29	64	50
Cadmium bright cyanide plus Turkey red oil and nickel sulphate	0.0010	0.0321	11	73	19
Tin alkaline solution 10 A/ft ²	0.0011	0.1605	2	22	3.5
Nickel Watts bath without additives	0.0009	0.0388	13	93	22
Organic bright bath	0.0011	0.0438	7	50	12

Direct measurement with precision d.c. bridge, on samples electro-formed and peeled from stainless steel strips, 9 inches long and 2 inches wide. All test pieces 4 inches long by 0.450 inches wide.

*Mr. R. D. Slade (Non-member)**

I would like to add a few comments from one more familiar with the electroplating side than the electronic. Mr. Fowler has described a situation from which it appears obvious that a closer understanding is required of the needs of the electronic engineer on the one hand and the products of the electroplater on the other. In actual fact, the situation could probably be even worse than Mr. Fowler has indicated, as modern advances in electroplating technology have led to the development of brighter, harder deposits. A particular example of this is the series of new gold alloys briefly mentioned. Whilst I cannot quote figures for electrical conductivity, I do know that some of these deposits are extremely hard

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and, because of this state of high internal stress, I would expect them to exhibit relatively poor electrical conductivity. The same considerations would apply to rhodium, which is frequently used to protect silver in electronic apparatus.

Mr. P. Tracy (Associate Member)†

Mr. Fowler has asked for methods of measuring the conductivity of electroplated conductors and I would like to suggest two methods I used several years ago to compare a small number of samples. The work was not connected with a comprehensive study of plating as such but merely to check or improve a component for a particular purpose and the results should be used only as a basis for further investigation.

Broadly, the tests carried out were :

- (1) Reflect the impedance of a test ring into a coil by placing the ring inside the coil and measure the resultant impedance on a Q meter.
- (2) Wind a coil closely over a solid sample and measure the impedance of the coil, again using a Q meter.

Another method was used by a fellow worker to compare samples of plated aluminium with copper. The samples were in the form of shorting rings which fitted outside a high-Q coil.

The actual object of the first two tests was to provide plated coatings on r.f. transformer cores to yield the lowest leakage impedance. In the first case, the major impedance measured is that of the coil, the "primary leakage" and resistance in the transformer equivalent circuit, and the "secondary" resistance, the wanted element, tends to be swamped. In the second test, this also applies but there is the added error arising from lack of repeatability of the winding geometry.

As I recall, the first test used a coil about $\frac{3}{4}$ inch inside diameter wound from about 20G enamelled copper wire and about $\frac{1}{4}$ inch long. The rings used were about $\frac{5}{8}$ inch o.d. with wall thickness about $\frac{1}{8}$ inch and approximately $\frac{3}{16}$ inch long. Two such rings are used, one plated with the desired coating over copper or other cores and the other made of solid electrical grade copper of the same outside dimensions. Plating thicknesses were usually between 0.005 inch and 0.010 inch. The platings used were always of the "high conductivity" group and tests on poor conductors were not included.

The rings are placed, in turn, inside the coil on the Q meter and Q readings, at the same frequency, are taken. The coil was at all times insulated from the rings by a small air gap. At one time, the gradual degradation of a sample plated from 0.001 inch to 0.010 inch with silver was noted but, as you have pointed out, to stop and re-start a plating process in this fashion is asking for trouble.

In the second test, a test sample effectively about $\frac{3}{8}$ inch square by 1 inch long was wound with 20 turns of fine gauge nylon covered Litz wire (close wound near the centre) and a copper replica was wound with a similar coil.

From memory, the inductance as well as the Q varied in this test and since I did not at the time need the equivalent series impedances and since I cannot recall the figures with the necessary accuracy, I cannot offer any conclusions on the merits of this test. In the particular application, a completely plated toroid of ferrite material was compared to a solid copper toroid and the short circuit impedance of the coil was the only figure of interest to me. I did, however, note here that a particular copper plating, bright copper as used for plating plastics, gave the closest approximation to solid copper.

Many thanks for your work in this field as it must, in time, do much to improve the confidence of all engineers in their designs and I look forward to seeing whether your paper can draw out some more interesting methods.

*Mr. L. H. Esmore (Associate Member)**

As a member of the electroplating fraternity as well as a member of this Institution, I must admit that the paper just presented is disturbing though not unexpected. We have known for many years that bright electro-deposits are not pure metals.

Bright coatings are generally produced by adding certain substances to the plating solution called "brighteners" by the trade. These may be organic substances which are co-deposited by absorption on the surface, with interference to normal columnar crystal growth or they may be inorganic and plated with the metal as an alloy. Substances of the first type include glue and various organic compounds containing sulphur. Cobalt in nickel baths and the various alloy plating solutions give bright deposits. Most of these substances are incorporated in patented proprietary processes and the chemical and physical properties of the electro-deposits may be difficult to establish and may vary from time to time.

It is not unexpected that Mr. Fowler finds that some of these coatings have lower conductivity than pure metals and I agree that it is high time that efforts were made to establish which coatings and processes are suitable for radio frequency applications with the accent on performance rather than appearance.

While the plater depends on patented processes, the suppliers should know the effects of their formulations and be able to specify which are suitable for our purposes.

For bright silver deposits, it appears that bright systems based on sulphur and selenium may be acceptable whereas those based on antimony and arsenic may not be.

It may be that baths which deposit pure metals of high conductivity can be used with periodic reverse current to yield bright finishes. With this technique, the current is reversed to a prescribed cycle so that plating and electro-chemical dissolution of the coating occurs. Alternatively, either chemical or electrolytic polishing may be employed.

It would seem that engineers do not appreciate other characteristics of the electro-deposition process. The

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uniformity of an electro-deposit must not be assumed and if it is required, it must be specified so that suitable arrangements of auxiliary anodes can be devised. The engineer must learn to specify his requirements and I would draw attention to specifications, many of which have been prepared by Committee CH/8 of the Standards Association of Australia. No doubt this committee would welcome comment on their draft and final specifications from engineers who ultimately depend on them so that their requirements can be properly considered.

I am most interested in the concept of a thin highly-resistive coating instead of the highly conductive coating. There should be some interesting new possibilities if this concept is proven to be sound and if we can produce coatings with sufficient corrosion resistance. Chromium directly plated on to copper could be considered and the use of lubricants may offset poor corrosion resistance of some systems. The nickel phosphide coatings commonly called "electroless" nickel are deposited very uniformly and are generally non-magnetic. Decorative rhodium plating is frequently used for jewellery but, if this process does not produce a satisfactory deposit for electrical use, some of the other "low stress" rhodium baths should be considered. Again it is a matter of specifying the type of finish more carefully.

The lecture should be very seriously considered by both electronic engineers who use the plated components and the electroplater who produces them because a thorough appreciation of the many problems from both aspects is essential. By mutual co-operation, I am sure that much can be done to improve the present situation and to develop newer and better systems.

The Author in Reply

Mr. Day has made a number of interesting comments. I had not intended to infer that all chromium and rhodium deposits are cracked but to point out that such deposits do exist. It is unlikely that they would be used in a plating shop specialising in electronic components but work is often taken to a jobbing shop for plating. Unless the customer knows enough about the plating process he needs, he may end up with a product that looks attractive and has good corrosion resistance but completely wrong electrical properties.

The point I am making is that electronic engineers must learn more about the properties of the electroplated finishes and take as much care in the selection of a plating as in the choice of any other component.

It is equally important for the electroplating industry to develop finishes with suitable electrical properties. The table of measured conductivities is very interesting and the wide range of measured values highlights the need to check very carefully the plating process used.

Mr. Slade has raised another interesting point. Both gold and rhodium are frequently recommended as a final layer because of their relatively good conductivity. It would seem more than likely however, that they are proving satisfactory because of the low conductivity of the deposits.

Mr. Tracy has suggested two methods which are worth investigating for measurements from medium to very

high frequencies. Of the two variations of the first method, I think I would prefer to use the test sample inside the coil. In this case the current will be concentrated on the outer circumference of the sample. When the sample is placed around the coil, the current will be concentrated on the inner circumference. The inner circumference is likely to have uneven plating thickness where it has made contact with the supporting wire during plating and this could produce misleading results.

Mr. Esmore's comments highlight the problems of insufficient exchange of information between various disciplines. Electroplaters are well aware of the difference in properties between an electroplated and a bulk metal, yet I was taught that electro-deposits were pure metals. On the other hand, electronic engineers have never really looked clearly at the problems of obtaining a satisfactory finish. They cannot altogether be blamed for this, much of the electroplating manufacturers' literature still refers to gold and silver as high conductivity metals. I would like to see electroplaters' suppliers include measured values of resistivity in their data sheets just as they now publish values of the other physical properties of the deposits.

I hope that many more people take notice of the work of the S.A.A., or equivalent bodies in other countries, and make sure that their interests are adequately covered in both the existing and proposed standards, even where these seem to be outside their immediate field of interest.

I would like to thank all the speakers for taking part in the discussion and for the interesting information they have provided. I hope that the two industries will look at the problems together and develop a better understanding of each others needs.

Written Contribution

*Mr. S. W. Conning (Member)**

The information in the paper should be of considerable value to design engineers in the r.f. field. The point about the adverse effect of brightening agents on the conductivity of plated silver is important and it would be useful if there was some indication in the paper of the best processes to use. Has the author considered the use of the periodic reverse technique as recommended by Lending? I should also like to draw the author's attention to "Microwave Transmission Circuits" by Ragan†. Section 3.6 deals with the effect of electroplated finishes on the conductivity of materials at microwave frequency and the results parallel those of the author. The effect of surface roughness in microwave frequencies is very important and I would like to see suitable reference made to this in the paper. The author mentions the problems of discolouration and increased contact resistance of silver due to hydrogen sulphide attack. While these may not be important in some applications there will also be a change in the conductivity. Has the author made a study of this and also of the effectiveness of protective flashes?

*S.T.C., Sydney.

†Ragan, G. L. (Editor), "Microwave Transmission Circuits", Vol. 9, M.I.T. Radiation Lab. Series, McGraw-Hill (1948).

The Author in Reply

I would like to thank Mr. Conning for his comments and information. With regard to the best processes to use I am not in a position to make a recommendation. Although I have been trying for several years to obtain this information from both the plating industry and the electronic industry I have not yet been successful. The periodic reverse plating process was brought to my attention by Mr. Esmore in his discussion at the meeting and I have investigated it a little further since. Electroplating with this process is considerably more expensive than other methods because of the repeated cycle of deposition and removal of metal to give a smooth polished finish. For this reason it is not in wide-spread use in this country and in fact I have found considerable difficulty in locating platers who are equipped to handle the process. In view of the recent work which Mr. Day presented during the discussion it would appear that more economical processes are available for regular use. However, the periodic reverse process appears promising for small custom jobs where a very high standard of finish is required.

I found the material by Walker in section 3 of Microwave Transmission Circuits to be very interesting.* It seems that my calculations have duplicated those of

*Walker, R. M., "Materials and Construction Techniques", Chapter 3 of "Microwave Transmission Circuits", *op. cit.*

Walker as shown in his fig. 3.3. In his discussion on the use of palladium as a flash plating for the protection of silver, he has come to the same conclusion as myself, that a thin layer of low conductivity material will have little effect on the overall conductivity at radio frequencies.

My own work was confined to medium and high frequencies and as a result I had not made as extensive a search as I should through the microwave literature. I wish now that I had come across this reference earlier as it would have saved me considerable work. Thank you for bringing this particular reference to my attention.

Again because my work had been confined to the lower frequencies I had not considered the effect of surface roughness in any detail. I agree with you that the surface roughness is important and have included a section on this in the paper for publication.

I have not made a detailed study of the effects of corrosion products on the conductivity. I have read many papers on the effectiveness of protective finishes and in general it would seem that these finishes will not provide corrosion protection unless they are sufficiently thick to be free of pores. The problem then arises that when the coating is sufficiently thick to provide protection it forms a significant part of the conductor and will influence the overall conductivity. This is an important problem and I would like to see much more work being carried out in this area.

CONTRIBUTORS

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Alan M. Fowler was born at Camberwell, Victoria, and educated at Scotch College, Melbourne. He joined the Postmaster-General's Department as a Technician-in-Training and was selected as a Cadet Engineer in 1948. On the completion of his Cadetship, he was appointed to the Victorian Radio Section. He has held the position of Divisional Engineer since 1955, and has been responsible for the design, installation, and operation of broadcast studios and transmitters for the National Broadcasting Service, and for the operation of Radio Australia transmitting facilities.



He transferred to the P.M.G. Research Laboratories in 1967 initially in Radio Systems, and currently in Pulse Systems, where he is responsible for the investigation and development of digital transmission systems. Mr. Fowler is a Member of the Institution of Radio and Electronics Engineers Australia, and Member of The Institution of Engineers, Australia.

Murray H. Stevenson was educated at the Sydney Technical High School after which he was associated with the establishment and technical operation of Radio Station 2UE in 1924. He was appointed chief engineer of 2UE in 1936 and held this position until he transferred to television station ATN following the introduction of television in 1955, which position he still holds.



Mr. Stevenson is a Past President and a Fellow of the Institution. He has served on the Council for a number of years and is the Honorary Editor of the Institution's publications.