A comparative assessment of gold plating thickness required for stationary electrical contacts

Sun Ming, Michael Pecht, Marjorie Ann E. Natishan*

CALCE Electronic Products and Systems Consortium, University of Maryland, College Park, MD 20742, USA

Abstract

There is considerable interest in the corrosion control of thin gold plated contact surfaces of consumer electronics products. This originates in the desire to minimize the use of costly gold and other precious metals, like palladium, and their alloys, without sacrificing reliability. When the application is in adverse environments, gold plated contact finishes can enhance the reliability of the electrical contacts. However, the failure mechanisms depend strongly on the operating environment and contact plating and are time dependent processes. Numerous investigations on unloaded gold plated surfaces (unmated and tested at non-operating environmental condition) have been performed to simulate the contact failures induced by corrosion. However, no models have been proposed that account for the effects of loading electrically and mechanically on the corrosion process and selection of gold plating thickness. This article describes the study of loaded electrical contacts with the objective of setting up a comparative model between unloaded and loaded electrical contacts, which will improve the understanding of the influence of contact force and applied voltage on the selection of gold layer thickness and finish material. Contact force will improve the performance of gold finishes in stationary electrical contacts and decrease significantly, the gold plating thickness requirements compared to unloaded situation because of its effect on suppression of surface film growth. Voltage will accelerate the growth of surface film and result in the decrease of contact lifetime. © 1999 Published by Elsevier Science Ltd. All rights reserved.

Keywords: Electrical contacts; Corrosion kinetics; Gold plating; Diffusion; Contact resistance

1. Introduction

Most consumer electronics products are very cost-driven, including personal computer, communications equipment, automobile components, smoke detectors, cameras, and watches. Over the last decade, there has been increasing concern about the use of gold finishes in commercial connector and electrical contact area. There are many electrical contact systems where it is desirable to use contacts with gold metal finishes. However, the costs associated with this practice may be unacceptable. Contacts, connectors, high reliability switches and relays are routinely plated or flashed with gold or gold alloys. This is done to prevent the formation of insulating oxides or tarnish films that would otherwise form on contact surfaces. The films interfere with reliability of the contact under typical low load, dry circuit conditions.

Previous investigations on unloaded or unmated gold plated surfaces showed that the migration of a base metal element from the base metal to the gold plating surface through the defect/or pore would be one of the most common transport phenomena found in the corrosion of electrical contact surface [1–9]. A base metal subjected to an adverse environment can migrate to the gold surface by diffusing either directly through the gold layer or through the pore site. A number of empirical equations or models based on these experimentally observed phenomena have been developed to estimate connector lifetime, contact reliability and such practical applications as connector design, materials selection and plating. However, these studies or experiments did not develop a relationship between the surface film growth on the unloaded contact surface and loaded or mated contact surface. Many questions relevant to contact design, plating and reliability still remains because of the lack of consideration of applied voltage and contact force. Some of these major concerns include whether the required gold layer thickness in operating conditions is the same as that in non-operating conditions and whether the surface film on loaded surfaces or contact spots creeps as fast as that on unloaded surfaces.

The major problem in increasing the reliability of thin gold plated contact in an economical fashion is to develop

---

* Corresponding author. Tel: + (301)-405-5263; fax: + (301)-314-9269.

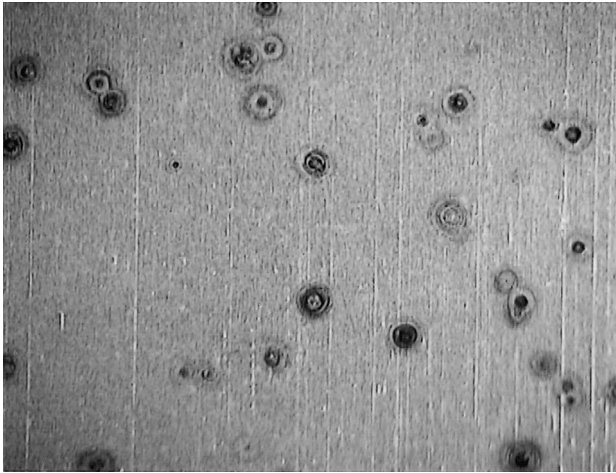*E-mail address*: natishan@calce.umd.edu (A.E. Natishan).

Fig. 1. Example of pore corrosion in a gold plated contact. [0.381 micrometer (15 microinches) of gold over 1.37 micrometer (50 microinches) of nickel on a phosphor bronze].

methods for making thin gold plate impervious to environmental corrosion. Gold plate thickness depends not only on the environmental corrosion process, but also on the mechanical wear of the contact area. A related problem involves extending the wear life of gold contacts, as the corrosion susceptibility of thin gold plate is caused by both its as-plated porosity and to gold removal during thermally and mechanically induced motion. The present article introduces a new approach for the determination of the gold layer thickness required in the operating environment of high contact force and low voltage. Further questions such as wear life of the contact owing to gold removal during thermally induced motion that often occurs between the contact interfaces when subjected to operating environment with low contact force is beyond the scope of this work.

2. Gold plate thickness

Most gold plated or flashed contacts are made from copper alloys, with beryllium copper and phosphor bronze being the most common. Copper is used for its low cost, high electrical conductivity, and low stress relaxation properties. The most significant drawback to the use of copper is that it is very reactive to atmospheric environments. Insulating oxides form almost immediately on copper surfaces exposed to the atmosphere and can cause intermittent or circuits open. To prevent the formation of these oxides, a thin layer of gold is plated or flashed on to the contact surface. Gold plating dramatically reduces the tendency of a contact surface to fail caused by corrosion, but do not eliminate the corrosion failure mechanism. Many parameters including plating process, wear, normal force and usage environmental interact to affect the severity of the corrosion process.

2.1. Corrosion types

The main types of corrosion that affect separable electrical contacts are dry corrosion, characterized as oxide formation, moist corrosion, specifically known as creep corrosion, and fretting corrosion induced by the micromotion in the electrical contact interface. Pore corrosion is of special interest to gold plated or flashed electrical contact.

2.1.1. Dry corrosion

Dry corrosion takes place with the presence of an oxidizing gas such as oxygen or sulfur. It does not require the presence of a liquid electrolyte, hence the term ''dry corrosion''. As copper oxides are both ionic and electronic conductors, the oxide layer serves as the electrolyte. The oxide layer also forms the electrode where oxygen is reduced and the diffusion layer through which the ions and electrons must migrate. The more metal rich oxides exist at the metal interface, while the more oxygen rich oxides exist at the atmospheric interface. In copper a surface cross section would reveal the following layers: Cu, CuO, CuO_2, O_2. The film generated by dry corrosion on copper is porous and the thickness is not self-limiting but it is electrically insulating. In addition to the noble metal plating on the contact surface, nickel underplates are often employed as diffusion barriers. The nickel plate forms a two-way barrier against corrosion. Copper diffuses through nickel approximately 1 000 times slower than through gold, so the migration of copper to the contact surface is drastically slowed. Nickel exposed at the base of the pores in the gold plating forms a self-limiting film that does not grow out of the pore defect and cover the gold surface.

2.1.2. Moist corrosion

Moist corrosions require the presence of moisture supplied by the humidity in the air. A thin layer of moisture from the ambient relative humidity combines with gaseous corrodants to form an electrolyte. Either a galvanic cell or differential cell is created with the metals of the electrical contact forming the anode and cathode, while monolayers of water contaminated with such impurities as chlorine and sulfur forming the electrolyte.

If the electrical contact designer selectively gold plates only the intended contact area, the contact may be susceptible to creep corrosion. This phenomenon occurs when sulfide drive tarnish films to form on exposed copper and migrate across the gold plated surfaces, electrically insulating them. In additions, pore on the gold plating surface is a source of the creep corrosion. Discontinuities in the gold are called pores. Copper exposed at the base of the pores in the gold plating forms the corrosion products that grow out of the pore and creep over the gold surface. An electrical contact surface affected by pore corrosion develops discrete ''mounds'' of corrosion on an otherwise uncorroded surface. For pore corrosion to occur, the presence of both

discontinuities in the plated surface and a corrosive environment is required.

A corroded pore on a gold plated surface with 0.381 micrometer (15 microinches) of gold over 1.27 micrometer (50 microinches) of nickel on a phosphor bronze substrate exposed to a corrosive environment is shown in Fig. 1. Note the bloom at the center of the pore and the surrounding ''haloes'' of corrosion.

Pore corrosion can also cause a mechanical disrupting in the plating. As the corrosive products formed at the base of the pore are less dense than base copper, they have a larger volume. As the new corrosive products form, they can exert a force on the plating layers to break them apart. This disruption exposes more of the corrosion-prone underplate and intensifies the corrosion problem.

In practice it is not always possible to differentiate sharply between these two types of atmospheric corrosion, because, depending on the corrosion conditions, gradual transition from one form to another is possible. So, for instance, structures initially corroded in air by the dry corrosion mechanism can begin to corrode by the moist mechanism as a result of increase in moisture or formation of hygroscopic corrosion products.

2.1.3. Fretting corrosion

Fretting corrosion of electrical contacts is becoming more of a concern in electronics because of the increasing number of low power connections in electronic packaging. Thermal cycling as well as ordinary micro-vibration provide the driving mechanism for the micromotion required to induce fretting corrosion with the resulting decrease in the reliability of the electrical system.

In fretting, two contacts are brought together with a given contact normal force and then moved with respect to each other cyclically. This motion is typically 10–100 microns in amplitude at a frequency dependent on the driving mechanism. The degree of fretting corrosion is highly dependent on environmental condition, frequency, normal force, contact materials, and presence of lubricants. However, the increased resistance associated with fretting corrosion is only one part of the problem. The occurrence of electrical intermittences associated with the fretting process is also an issue, as they can degrade digital circuit signals.

Gold plating technology has been widely used to decrease the fretting corrosion in the electrical contacts. However, formation of an insulating surface film and further fretting corrosion in the gold plated contacts as a result of the gold plate damage and diffusion of substrate metal through gold is still one of the major concerns in producing reliable electrical contacts with low contact force application.

2.2. Plating thickness determination

As a result of interest in minimizing the thickness of gold plating on electrical contacts owing to cost reduction and materials conservation, it is worthwhile to determine whether contact resistance stability is related to corrosion and plating thickness. As mentioned before, current thickness determination is based on the testing data received from unloaded surfaces. So it is necessary to consider what happen in the corrosion process through the pore and surface film creep on the contact surface when gold plated or flashed contact is subjected to mechanical and electrical loading. Obviously, these changes are very critical to the determination of required gold thickness and contact lifetime.

As analyzed earlier, there is a strong similarity in both moist and dry corrosion processes in that there must be a diffusion process for the elements of environmental gases and copper to move through the corrosion products to continue the corrosion processes. As salt films or oxides on copper have ionic crystal structures that, as a rule, possess ionic and to some extent electronic conductivity, we may expect film diffusion to consist not only of movement of copper atoms but also of copper ions and free electrons. For noble metal plated copper, the principal direction of diffusion is that of base copper ions or atoms through the film to the outside and to a smaller degree the diffusion of oxidizing agent(s) in the opposite direction [9]. Except considering the very first moment of the copper corrosion process, the process is retarded not by the speed of the chemical reaction but by the speed of diffusion because the diffusion particle penetrating the film does not accumulate, but immediately enters into the reaction [9].

As a result of this characteristic of the diffusion process, the growth of corrosion products is dominated by diffusion coefficients of copper and gases in corrosion film as well as concentrations of copper and gaseous atoms in the corrosion film. With diffusion of copper atoms or ions outward through the corrosion product layer, the zone of corrosion product growth will be evidenced at the exterior surface. On the contrary, with diffusion of atoms of oxidizing agent (oxygen, for example) inward through the film, the zone of corrosion product growth will occur at the interface between the copper and the copper corrosion product.

Tompkins and Sun et al. found the corrosion film growth through the pore of the gold layer followed a parabolic law [2,10]. Further, Sun et al. studied the creep phenomena of corrosion film on gold plated contact surface and found that the creep of surface film also obeys a parabolic law. We will now focus our attention on what effects mechanical contact force and electrical voltage drop have on the film growth and creep and then set up the relationship between film growth on unloaded surface and loaded surface.

Film growth through a pore in the gold layer can be calculated by using Eq. (1), which is based on the mechanism of copper diffusion through the pores of gold layer [2,10],

$$Z_p = 2\gamma\sqrt{Dt}, \tag{1}$$

where Z_p is the film growth distance at a pore, lifetime t and

γ is a function of copper concentration at the interfaces. D is a copper diffusion coefficient in copper corrosive products and has a general expression,

$$D = D_0 e^{-Q_a/RT_a}, \tag{2}$$

with D_0 a constant having dimensions of cm^2/s, T_a absolute temperature at the pore, R universal gas constant, and the activation energy (Q_a) having dimensions of J/mol.K. In this model all diffusion paths, dislocation, grain boundaries, interfaces, free surfaces and lattices of corrosion products are included in one diffusion coefficient to simplify the models expression for practical applications.

In general, the above equation can be used to estimate film growth at pores. However, with regard to the activation energy, Q_a, is a very important variable in the contact area. In order to calculate and analyze the actual diffusion activation energy in materials with known porosity and roughness characteristics, more discussion must be devoted to the effects of mechanical contact force on this activation energy.

An atom can jump from its lattice position into a neighboring vacant site, thereby leaving a vacant site behind. Another atom (or the same one) can jump into this vacant site in turn, shifting the vacancy to a third (or back to the first) position. If we consider the simplest case of self-diffusion, where only one atomic species is present, the vacancy migrates through the lattice. In the presence of a concentration or a potential gradient, the average drift of many vacancies after a sufficiently long time will result in the required net transport of mass.

The probability of an atom jumping, and in particular, the difference in jumping probability of different atoms, depends on the vacancy concentration, on the diffusion driving force (or gradient of the chemical potential) and on the height of the free-energy barrier between two neighboring atom positions before and after the jump. The height of the barrier will depend on the type of crystal, the nature of the migrating atom, the diffusion mechanism, the interatomic forces, etc. The energy to overcome the barrier must be provided by thermal vibrations. This is one of the reasons why atomic diffusion requires an energy of activation, the other reason being that the equilibrium concentration of defects also depends on the temperature.

Diffusion of atoms or ions through a lattice, along grain boundary, or a surface, is equivalent to a transport of vacancies in the opposite direction. Following the reasoning used by Nabarro [11], based on the mechanism of vacancy diffusion, an energy U_v is required to form a vacancy in a stress free region. If an area of each atom (α^2) is exposed to a stress σ, then the work done by the stress on removing the atom is $\sigma\alpha^3$, and the effective energy of formation has become $U_v - \sigma\alpha^3$. σ is positive in a tensile region and negative in a compressive region. The diffusion activation energy, Q_a, necessary for atoms to diffuse in the tensile region is smaller than that in the compressive region.

For the sake of convenience, instead of the activation energy, Q_a, the effective energy of formation, $Q_a - \sigma\alpha^3$, will be used [11]. Then the Eq. (2) becomes

$$Z_p = 2\gamma\sqrt{D_0 t e^{-(Q_a - \sigma\alpha^3)/RT_a}} = 2\gamma\sqrt{Dt}e^{(\sigma\alpha^3)/2RT_a}. \tag{3}$$

Eq. (3) shows that film growth at pore depends not only on the temperature, concentration of environmental gases and diffusion coefficient, but also on the contact stress in the contact area, σ. This suggests that the contact force, serving as a compressive force at a contact area, might play an important role in preventing ingress of insulating film onto the contact area because the compressive force can suppress the diffusion of copper to the gold surface.

Similar to the corrosion situation at pores, surface film ingress onto contact areas also follows the same form as Eq. (3),

$$A = 2\gamma\sqrt{D_0 e^{-Q_a - \sigma\alpha^3/RT_a}t} \tag{4}$$

and

$$A = 2\gamma\sqrt{Dt}e^{\sigma\alpha^3/2RT_a},$$

where A is the ingress distance of surface film in the contact area and

$$T_a = \sqrt{T_0^2 + \frac{U^2}{4L}}, \tag{5}$$

where U is the contact voltage, L is the Lorentz constant, and T_0 is the absolute temperature in the non-contact area [12].

Eq. (5) illustrates the power loss in the contact area that was changed into thermal energy resulting in the increase of temperature in the contact area. The increase of temperature in the contact area accelerates the diffusion process and results in faster ingress of surface film onto the contact area. Eqs. (3) and (4) imply that gold plating thickness might be reduced in the electrical contacts with high contact force and low voltage drop.

3. Discussion

From the foregoing discussion, it is obvious that mechanical contact force and applied voltage have a considerable influence on the film growth and gold thickness requirement. To illustrate the magnitude of the affect of the above two parameters on the gold thickness requirement, let us now compare the gold thickness requirement in two situations, unloaded, and loaded with a contact force and voltage.

From Eq. (3), the film growth through a pore gives Eq. (6) for Z_1 unloaded and Z_2 loaded,

$$Z_1 = 2\gamma\sqrt{Dt} \tag{6}$$

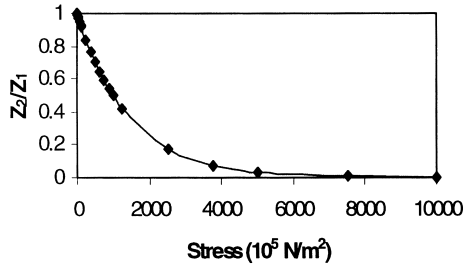$$Z_2 = 2\gamma\sqrt{Dt}e^{\sigma\alpha^3/2RT_a},$$

Fig. 2. Stress effect on the film growth through the pore at $T_a = 333$ K.

where Z_1 and Z_2 are the film growth distances for unloaded and loaded respectively. The following relationship then holds,

$$\frac{Z_2}{Z_1} = e^{\sigma\alpha^3/2RT_a}, \tag{7}$$

where σ is negative for compression stress.

From Eq. (4), the ingress of film gives Eq. (8) for A_1 unloaded and A_2 loaded,

$$A_1 = 2\gamma\sqrt{D_0 e^{-Q_a/RT_0}} \tag{8}$$

$$A_2 = 2\gamma\sqrt{D_0 e^{-Q_a-\sigma\alpha^3/RT_a}}, $$

where T_0 is the temperature on the unloaded surface, such as the temperature of testing coupon, while T_a is the temperature at the contact area in the loaded situation such as a connector in the operating environment. Obviously, the following relationship holds,

$$\frac{A_2}{A_1} = e^{-\frac{Q_a-\sigma\alpha^3}{2RT_a}+\frac{Q_a}{2RT_0}}. \tag{9}$$

Analytic solutions corresponding to Eqs. (7) and (9) are given in Figs. 2 and 3.

The above diagrams show that film growth in a loaded electrical contact is much slower than that in an unloaded surface because contact compression force has made it more difficult for atoms or ions to diffuse into the contact area. Therefore, we may expect that the thickness requirement for gold layers in the loaded electrical contact with contact force is lower than that in unloaded surfaces as unmated connectors, as determined by testing coupons that are
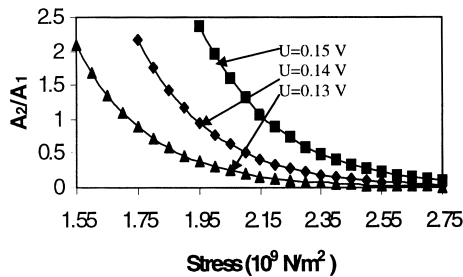

Fig. 3. Influences of stress and voltage on film ingress distance at contact area.

widely used in experiment and quality control. As the contact force increases the requirement of gold layer thickness drops according to Eqs. (7) and (9).

Sun et al. studied loaded gold plated contact surfaces and have demonstrated that the lifetime of a gold plated contact is not only a function of gold layer thickness, environmental temperature and environmental gas concentration, but also a function of normal force, and contact voltage drop [13]. Lifetime of gold plated or flashed electrical contact could be given by (10)

$$\frac{R(t)}{R(t=0)} = \frac{1}{1 - \xi e^{-\frac{Q_a-\sigma\alpha^3}{2RT_a}} t^{1/2}}, \tag{10}$$

where

$$\xi = \frac{2\gamma\sqrt{D_0}}{A_0}$$

and

$$T_a = \sqrt{T_0^2 + \frac{U^2}{4L}},$$

where A_0 is initial diameter of contact spot. The influence of the contact stress on the lifetime resistance of electrical contact is shown in Fig. 4.

When an electrical contact spot is subjected to stationary $10^9 \sim 10^{10}$ N/m^2 contact stress which corresponds approximately to 100 g contact normal force [14,15] and a low contact voltage drop, the film ingress into the spot is very slow, which is shown in Fig. 4. The above analysis and discussion also suggests that there might be a possibility of using thinner gold layers in the electrical contacts in order to decrease the gold consumption.

Although a detailed mechanism responsible for the fretting corrosion is beyond the scope of this work, some plausible explanations about concerns regarding plated electrical contact can be offered by the earlier analytical results. There is a significant difference in the fretting film source between the gold plated contacts and non-gold plated or flashed contacts, such as a tin-lead plated contact. In the gold plated contact the surface film at the contact area is supplied by the substrate metal surface film migrating through a pore in the gold layer and then growing onto contact area, while in the non-gold plated contacts the film is supplied locally and continuously by the plating material itself, such as tin oxide film.

The fretting source at the contact spot consists of the surface film, supplied by the film ingress from outside into the spot, and the film breakdown, induced by the micromotion in the contact interface. There are two benefits drawn from high contact force design. First, high contact force can suppress the diffusion of base metal into the contact area, in other words, suppress the film supply. Second, high contact force can also increase the contact mechanical stability, by
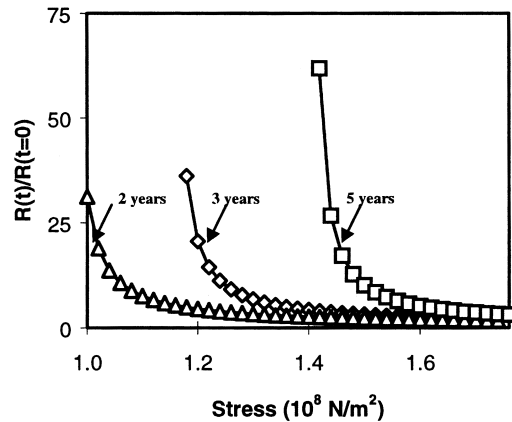
Fig. 4. Effects of contact stresses on lifetime resistances of electrical contacts under $U = 140$ mV.

reducing the micromotion and wear in the contact interface and therefore, result in the decrease in fretting corrosion.

4. Conclusions

In this article we have studied some of the main factors responsible for the reliable performance of thin gold plated electrical contacts. The mechanisms of electrical contact failures caused by surface film growth have been studied to understand the influences of contact force and voltage drop on the determination of gold layer thickness in the electrical contacts. The present investigation has also set up the comparative models between the loaded and unloaded contact surfaces, which provide an approach to compare the thickness requirement of gold layer for a reliable electrical contact with that attained from an experiment or testing on the free surface exposure (unloaded).

1. The results show that contact force will suppress the surface film growth either through a pore in a gold layer or ingress at the contact area, which contributes to the resistance stability of electrical contacts and decreases of fretting corrosion, therefore, increase the reliability of electrical contacts.
2. The results also show that voltage will accelerate film growth and result in the lifetime decrease of gold plated electrical contacts, however, when electrical contacts are subjected to low voltage and high contact force applications, the lifetime of the electrical contact will be dominated mainly by contact force.
3. The relationship between loaded and unloaded contact surfaces derived in this article shows that there is a possibility to use a thinner gold layer instead of the current gold plating thickness in the high contact force and low voltage application.
4. Thin gold plated electrical contacts with high contact force and low voltage design can play a role in reducing a fretting corrosion before the gold has worn away.

References

[1] R.J. Geckle, R.S. Mroczkowski, Corrosion of precious metal plated copper alloys due to mixed flowing gas exposure, Proceedings of the 37th IEEE Holm Conference on Electrical Contacts, 1990, pp. 193–202.
[2] H.G. Tompkins, M.R. Pinnel, Low-temperature diffusion of copper through gold, Journal of Applied Physics 47 (9) (1976) 3804–3812.
[3] J.L. Chao, R.R. Gore, Evaluation of a mixed flowing gas test, Proceedings of the 37th IEEE Holm Conference on Electrical Contacts, 1991, pp. 216–228.
[4] W.H. Abbott, The development and performance characteristics of mixed flowing gas test environments, Proceedings of the 33rd IEEE Holm Conference on Electrical Contacts, 1987.
[5] Antler, Field studies of contact materials: contact resistance behavior of some base and noble metals, IEEE Transactions on Components, Hybrids and Manufacturing Technology, Vol. CHEMT-5, 1982, pp. 301–7.
[6] W.H. Abbott, The corrosion of porous gold platings in field and laboratory environments, Proceeding of 13th International Conference on Electrical Contacts, Lausanne, 1986, p. 343.
[7] Magne Runde, Mass transport in stationary contact points, IEEE Transaction on Components, Hybrids and Manufacturing Technology CHMT-10 (1) (1987) 89–99.
[8] V. Tierney, The nature and rate of creep of copper sulfide tarnish film over gold, J. Electrochem. Soc.: Solid-State Science and Technology, 1981, pp. 1321–1326.
[9] Tomashov, Theory of Corrosion and Protection of Metals, Macmillan, New York, 1966.
[10] M. Sun, S. Javadpour, R.I. Martens, M. Pecht, Kinetic modeling of corrosion film on unloaded precious metal plated contacts, Proceeding of 30th Connector and Interconnection Technology Symposium, 1997, pp. 227–244.
[11] H.G. Van Bueren, Imperfections in Crystals, 2nd ed., North-Holland, Amsterdam, 1961.
[12] R. Holm, Electrical Contact, 4th ed., Springer, New York, 1967.
[13] M. Sun, M. Pecht, R. Martens, Lifetime resistance in stationary contact spot of porous precious metal plated electrical contacts, submitted to IEEE Transactions on Components, Packaging and Manufacturing Technology Part A, 1998.
[14] S. Roland, A. Timsit, Possible degeneration mechanism in stationary electrical contacts, IEEE Transactions on Components, Hybrids and Manufacturing Technology 13 (1) (1990) 65–68.
[15] M.D. Bryant, Jin Moulin, Time-wise increases in contact resistance due to surface roughness and corrosion, IEEE Transactions on Components, Hybrids and Manufacturing Technology 14 (1) (1991) 79–89.