

# Mechanism of Contact Enhancing Chemicals for Electrical Interconnection

Guilian Gao and Dongkai Shangguan

**Abstract**—Contact enhancing chemicals, the magic fluids which vanquish intermittent contacts, have been in existence for many years. However, their use has been very limited due to the lack of understanding of their conduction mechanism. In this paper, electrochemical experiments were conducted to reveal the mechanism of conduction through the contact enhancing chemicals. The results have invalidated claims by several manufacturers of contact enhancing chemicals that conduction takes place by means of “tunneling.” It has been demonstrated that these novel chemicals function through a rather common conduction mechanism, by serving as an electrolyte for metal dissolution, ionic transport, and metal deposition. Metallurgical examinations have provided direct evidence of the existence of metallic dendrites between mating elements that have been treated with the chemicals, and confirmed the electrochemical reaction mechanism for contact enhancement.

**Index Terms**—Conduction mechanism, connector, contact enhancing chemicals, dendrite formation, dendritic growth, electric contact, electrochemical testing, heal, intermittent failure, ionic conduction, metal dissolution, metallic bridge, recovery, re-deposition, wire crimp.

## I. INTRODUCTION

**M**ECHANICAL contacts, such as sockets, connectors and wire crimps, are an integral part of the electrical interconnect system. Despite the rapid advance in the quality of many high technology electronic components, many mechanical contacts still remain relatively unreliable and may become a major cause of product failures due to intermittent contact. Elevated temperatures, airborne contaminants, vibration, corrosive gases and oxidizing environments all contribute to the degradation of connection performance [1], [2], and this is particularly severe in an automotive environment. It is estimated that 1800–2000 wire crimps are used in an average vehicle; Failures due to intermittent contact of the wire crimp has been the cause of concern for many years.

The conventional approach to protect the connection from degradation includes the use of lubricants, mineral oils, and sealer waxes [3], [4]. However, these chemicals tend to evaporate, degrade or polymerize over time, leaving an insulating film on the surface. Other chemicals which improve the performance of mechanical contact surfaces have been in existence for

years [5]. In contrast to the conventional oils and grease which can only be applied to new and clean surfaces, the contact enhancing chemicals can even work to “heal” connections which have degraded over time.

However, despite the successful application of these contact enhancing chemicals in mitigating intermittent contact problems in the field, the mechanism of conduction remained a mystery. Some manufacturers claimed that the conduction took place through “electron tunneling.” In physics, electron tunneling is a phenomenon that happens within the width of 1 nm [6]. The tunneling current is very sensitive to the width of the barrier, and decays sharply when the width exceeds 1 nm. For many mechanical connections, a gap of several microns between the mating metal surfaces is commonly encountered. Claims that the contact enhancing chemicals promote “electron tunneling” through a barrier several microns wide have added even more confusion to the subject.

In this paper, laboratory experiments using an inter-digitated test pattern were designed to first investigate whether these chemicals conduct through the “tunneling” mechanism claimed by several manufacturers or any other novel conduction mechanism operative in barriers of several microns wide. The experimental results do not support the “tunneling” mechanism. Instead, it has revealed a mechanism of metal dissolution, ionic conduction and metal re-deposition through electrochemical reactions.

In addition, wire crimps which failed due to very high contact resistance were treated with the contact enhancing chemical; Afterwards, these wire crimps were cross sectioned for metallurgical examination. The metallurgical examinations confirm the existence of a metallic bridge in the form of “dendrites” between the mating elements (wires and barrel of the crimp), which is formed through the electrochemical reaction and serves to ‘heal’ the electrical contact between the mating surfaces.

## II. EXPERIMENTAL PROCEDURES

A commercial contact enhancing chemical was used for the study. It was claimed by the manufacturer that the chemical functions through a novel conduction mechanism called “long range quantum tunneling” through which electrons tunnel through a space of several microns.

Chemical characterization has revealed that the material is a glycol ether polymer. One distinct characteristic of such a material is that it is very hygroscopic and absorbs moisture readily from the air. Since water is a very good ionic conductor, the absorbed moisture can make the material function as an electrolyte. It was therefore postulated in this study that the chemical probably conducts electricity through ionic conduction.

Manuscript received October 22, 1999; revised September 28, 1999. This work was presented at the Joint International Meeting of the Electrochemical Society and the Electrochemical Society of Japan, Honolulu, HI, October 17–22, 1999. This work was recommended for publication by Associate Editor M. Braunovic upon evaluation of the reviewers’ comments.

G. Gao is with Ford Research Laboratory, Ford Motor Company, Dearborn, MI 48121 USA.

D. Shangguan is with Visteon Automotive Systems, Ford Motor Company, Dearborn, MI 48121 USA.

Publisher Item Identifier S 1521-3331(00)07283-4.

Test boards with inter-digitated metallic test patterns were used for the study (Fig. 1). Two types of samples were used. One type of sample (pattern *A*) consists of aluminum conductors on an oxidized silicon substrate. The spacing between the metal conductors for pattern *A* is  $2\ \mu\text{m}$ . In order to examine any conduction mechanism other than metal dissolution and electromigration, metal dissolution must be minimized to prevent formation of dendrites. Aluminum was chosen for the study because it forms a protective oxide in the air which greatly reduces the rate of metal dissolution. The other type of sample (pattern *B*) consists of copper conductors on an oxidized silicon substrate. The spacing between the metal conductors for pattern *B* is  $50\ \mu\text{m}$ . Copper was chosen for this study because it is the metal used in most connectors and wires.

The test patterns were manufactured through sputter deposition of the respective metals followed by selective etching to produce the desired spacing. During the test, the gap between the two metallic conductors was filled with the material under testing, effectively forming a metal/liquid/metal electrochemical cell.

A Keithley 617 electrometer, combined with a Keithley low current scan card, was used to provide a voltage bias ( $\Delta E$ ) to the test pattern and to measure the corresponding leakage current ( $I$ ). Two test procedures were conducted. For the first test procedure, the test started from  $\Delta E = 0\ \text{V}$  between the two conductor lines and increased to  $\Delta E = 20\ \text{V}$  at the end of the test.  $1\ \text{V}$  increment and  $5\ \text{min}$  intervals were used from  $0$  to  $10\ \text{V}$ ;  $2\ \text{V}$  increment and  $5\ \text{min}$  intervals were used from  $10$  to  $20\ \text{V}$ . The current measurement was taken  $5\ \text{min}$  after each voltage change. For the second test procedure, a constant voltage of  $20\ \text{V}$  was applied to the two conductor lines, and the current from the test pattern was measured as a function of time for  $1\ \text{h}$ .

Tests were conducted at the ambient condition (roughly  $23\ ^\circ\text{C}$ ,  $50\%$  relative humidity, or RH) unless stated otherwise. In one experiment, the test pattern was heated to  $40\ ^\circ\text{C}$  using a hot stage. In another instance, the experiment was conducted at  $40\ ^\circ\text{C}$  and  $60\%$  RH inside a temperature/humidity chamber.

Wire crimps were also tested as a confirmation of the results obtained using the inter-digitated test patterns. The height of the wire crimp is  $1.65\ \text{mm}$ . As in most regular wire crimps, the wires and the barrel are made of Cu, and the barrel of the wire crimp is coated with Sn.

In this test, wire crimps, which have failed due to high contact resistance in excess of  $10\ 000\ \Omega$ , were treated with the contact enhancing chemical and subjected to a voltage bias of  $12\ \text{V}$ . During the test, the wire side was the positive side and the barrel side was the negative side. As a result of the test, the contact resistance decreased significantly and the wire crimp interconnection became functional again.

After the test, metallographic mounts were made for the wire crimps, and cross sections were prepared. Observations were made using light microscopy as well as scanning electron microscopy (SEM) in both the secondary electron image (SEI) mode and the backscattered-electron image (BEI) mode. Energy dispersive spectroscopy (EDS) was used to identify elements present in areas of interest, and wavelength dispersive spectroscopy (WDS) microprobe

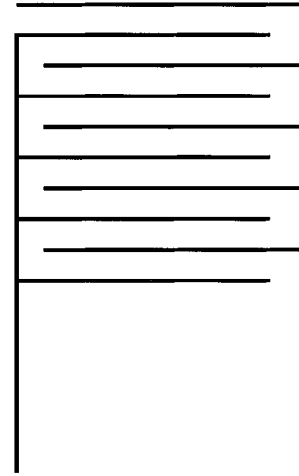


Fig. 1. Schematic diagram of the test patterns used for this study.

elemental mapping was performed on those areas to identify the elemental distribution.

### III. EXPERIMENTAL RESULTS

#### A. Electrochemical Test

The first experiment was conducted to study the effect of the spacing between the metal conductors and the bias voltage on the conductivity of the contact enhancing chemical. As shown in Fig. 2, for test pattern *A*, when  $\Delta E$  was increased from  $1$  to  $20\ \text{V}$ , current increased gradually, changing from  $0.1\ \mu\text{A}$  at  $\Delta E = 1\ \text{V}$  to  $13.3\ \mu\text{A}$  at  $\Delta E = 20\ \text{V}$ ; a sharper increase was observed when  $\Delta E$  was under  $8\ \text{V}$ . The same phenomenon was observed on test pattern *B*; However, the magnitude of change on test pattern *B* was greater, with current increasing from  $6.7\ \text{nA}$  at  $\Delta E = 1\ \text{V}$  to  $12.5\ \mu\text{A}$  at  $\Delta E = 20\ \text{V}$ .

In another experiment, the effects of temperature and humidity on the conductive behavior of the chemical were studied by imposing a  $20\ \text{V}$  bias on test pattern *B* and measuring current as a function of time. After  $1\ \text{h}$  under a  $20\ \text{V}$  bias, the test patterns were removed and examined using an optical microscope.

As shown in Fig. 3, at ambient condition, current increased from  $16.7\ \mu\text{A}$  to  $182\ \mu\text{A}$  in  $1\ \text{h}$ . When the temperature was increased to  $40\ ^\circ\text{C}$  in the open air environment, current decreased from  $11.8\ \mu\text{A}$  to  $1.74\ \mu\text{A}$  in  $1\ \text{h}$ . However, when the humidity was increased to  $60\%$  RH at  $40\ ^\circ\text{C}$ , in contrast to the decrease observed in the open air environment, current increased by  $2.5$  orders of magnitude in  $30\ \text{min}$ ; Afterwards, current showed considerable fluctuation.

#### B. Metallurgical Examination

Fig. 4 gives the optical examination results of test pattern *B* after  $1\ \text{h}$  under  $20\ \text{V}$  bias at  $40\ ^\circ\text{C}$  and  $60\%$  RH, as mentioned above. It can be seen that the copper on the anode was largely depleted. Copper dendrites were formed on the cathode. Some filaments bridged the  $50\ \mu\text{m}$  spacing between the two conductors. Formation of dendrites was also observed on samples tested at room temperature, although the extent of metal depletion was not as severe.

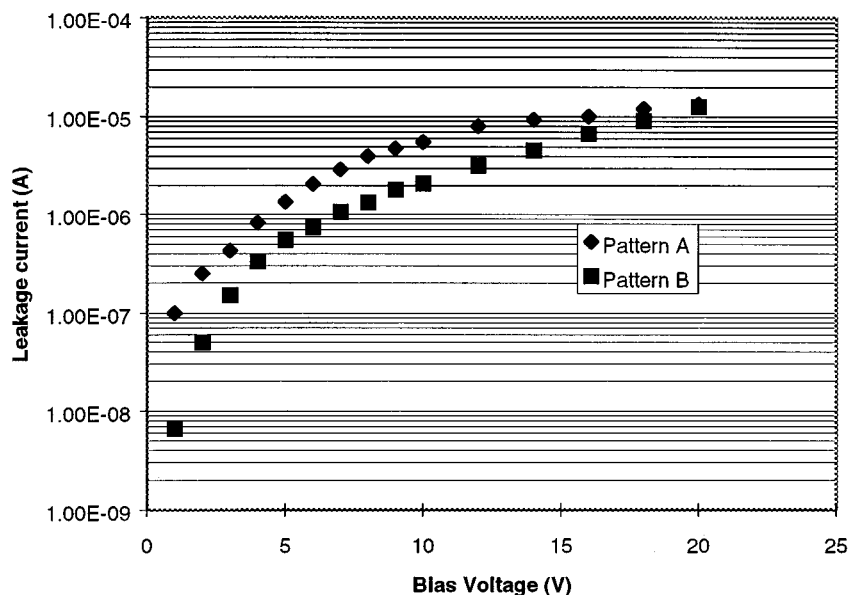


Fig. 2. Leakage current as a function of bias voltage ( $\Delta E$ ) for pattern A ( $2 \mu\text{m}$  spacing) and pattern B ( $50 \mu\text{m}$  spacing) at the ambient condition ( $23^\circ\text{C}$ ).

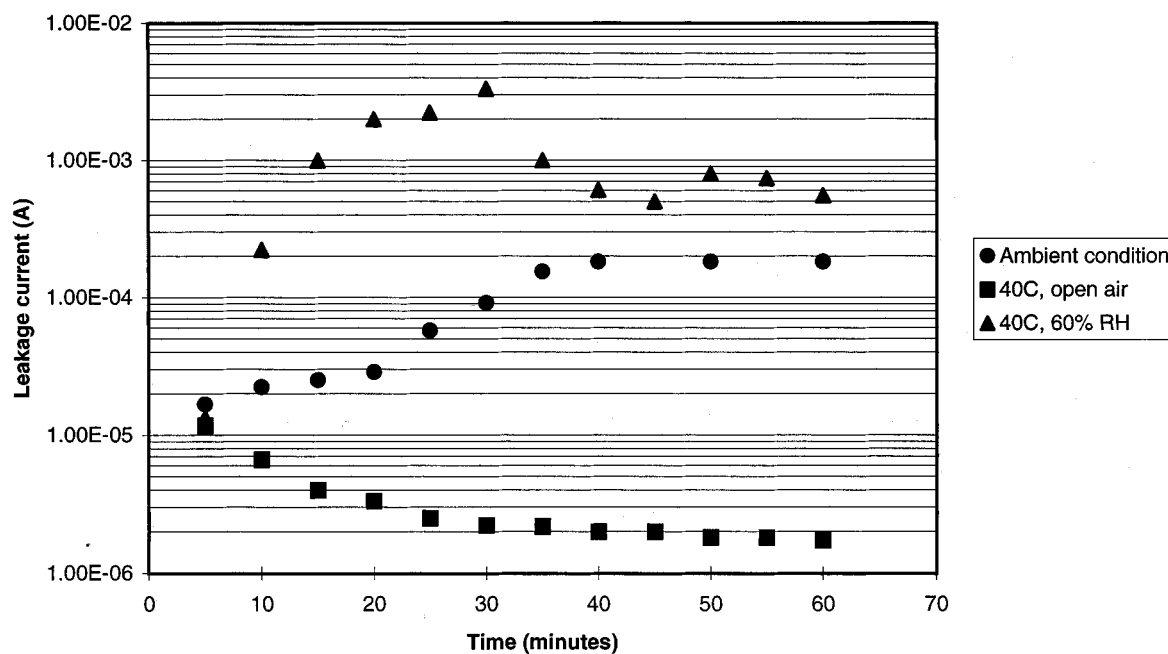


Fig. 3. Leakage current measured on pattern B at  $\Delta E = 20 \text{ V}$  as a function of time.

Fig. 5 shows the optical microscopy photograph of the cross section of the wire crimp after the test as described previously. Structures of a dendritic morphology can be seen in the spaces between the wires and the barrel. No such dendrites can be seen (Fig. 6) in samples which are otherwise identical to the sample in Fig. 5, except that they were not treated with the chemical.

SEM analysis was performed in order to identify the metallic nature of the “dendrites” in Fig. 5. Fig. 7 shows the SEI picture of the cross section shown in Fig. 5, as well as close-ups of the dendrites which have been formed between the wire and the barrel, at higher magnifications. The WDS microprobe elemental mapping for Cu is also shown, indicating that the dendrite is made of Cu.

## IV. DISCUSSION

### A. Electrochemical Reactions

If a novel conduction mechanism such as “long range quantum tunneling” is operative over a spacing of several microns, then current measured on test pattern A ( $2 \mu\text{m}$  spacing) should be much higher than that measured on test pattern B ( $50 \mu\text{m}$  spacing), since the spacing for the test patterns exceeds the barrier width claimed by the manufacturer for the “long range quantum tunneling” mechanism. However, the results in Fig. 2 indicate that this is not the case. The trends of current change observed on the two test patterns are very similar when  $\Delta E$  was increased from 1 to 20 V, indicating that the conduction

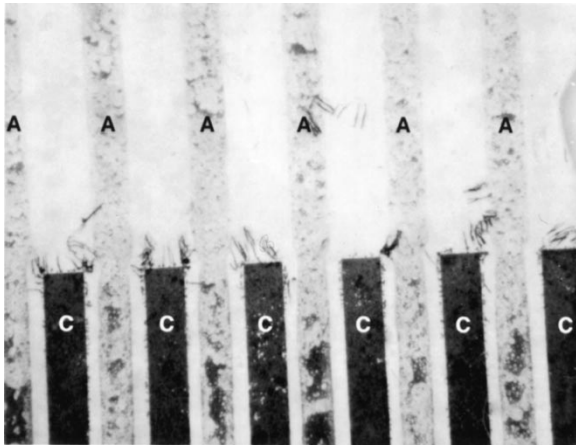


Fig. 4. Optical examination results of test pattern B after 1 h at 40 °C, 60% RH and under 20 V bias, showing depletion of copper from the anode (lines marked as A) and formation of dendrites on the cathode (lines marked as C).

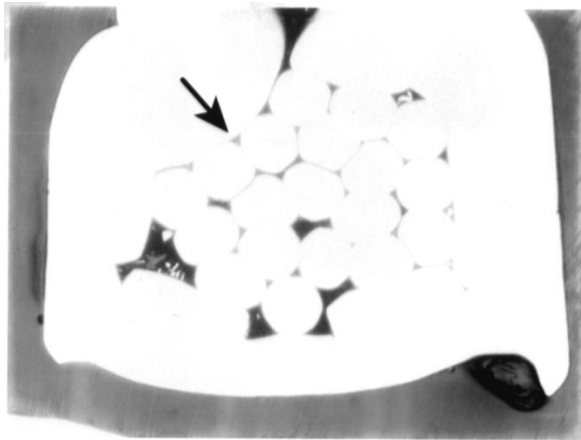


Fig. 5. Optical microscopy photograph of the cross section of a wire crimp which was treated with the contact enhancing chemical. (50X)

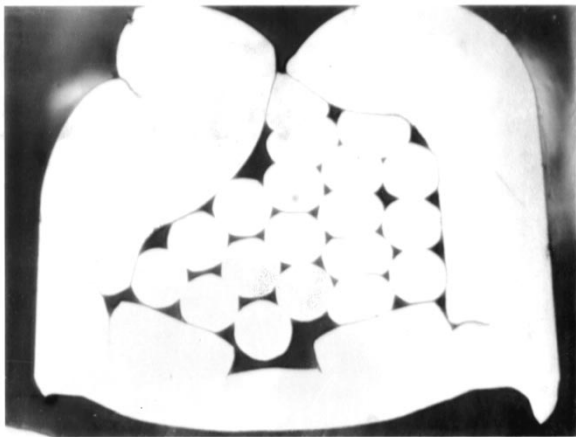


Fig. 6. Optical microscopy photograph of the cross section of a wire crimp which was not treated with the contact enhancing chemical (50X).

mechanism operative on the two test patterns are the same. Despite the 25 times difference in the spacing of test patterns A and B, the currents under  $\Delta E = 20$  V were very similar for the two test patterns.

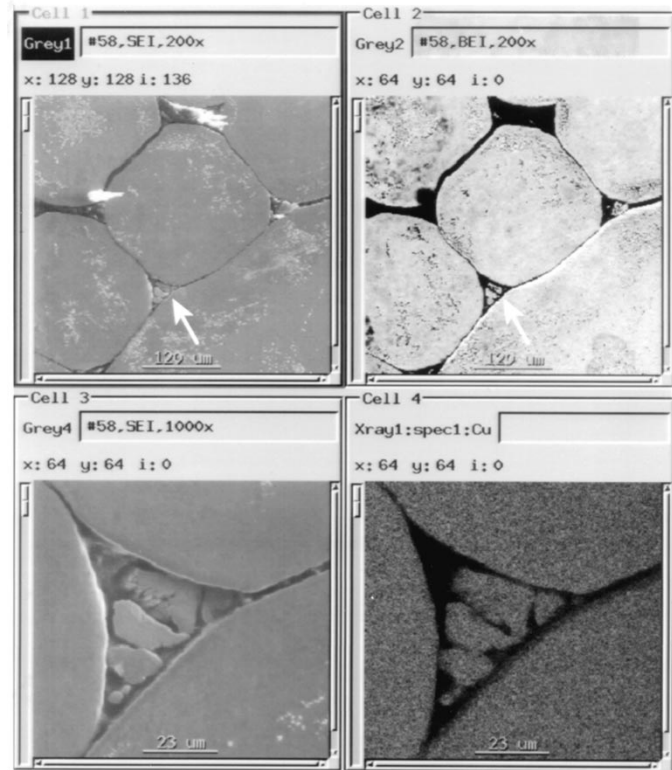


Fig. 7. SEI and BEI pictures and WDS microprobe elemental mapping for Cu for the area indicated by the arrow in Fig. 5. Cell 1: SEI (200X); Cell 2: BEI (200X); Cell 3: SEI (1000X) for the area indicated by the arrow in Cells 1 and 2; Cell 4: Cu map for the area shown in Cell 3.

The more logical explanation is that it is an electrochemical process that is taking place in the presence of an electrolyte and a voltage bias. The gradual change of current with  $\Delta E$  in Fig. 2 can be explained by several electrochemical processes taking place simultaneously in the electrochemical cell.

As illustrated in Fig. 8, when a bias voltage ( $\Delta E$ ) is imposed on to the electrochemical cell, the following electrochemical processes take place.

At the high voltage end (the anode), metal dissolution takes place



The overpotential for the metal dissolution ( $\eta_a$ ) can be expressed as

$$\eta_a = a_a + b_a \log I \quad (2)$$

where  $I$  is the current,  $a_a$  and  $b_a$  are the anodic Tafel constants [7].

The dissolved metal ions then migrate through the electrolyte to the low voltage end (the cathode), where they are deposited out



Other reactions which take place at the cathode are oxygen reduction and hydrogen evolution



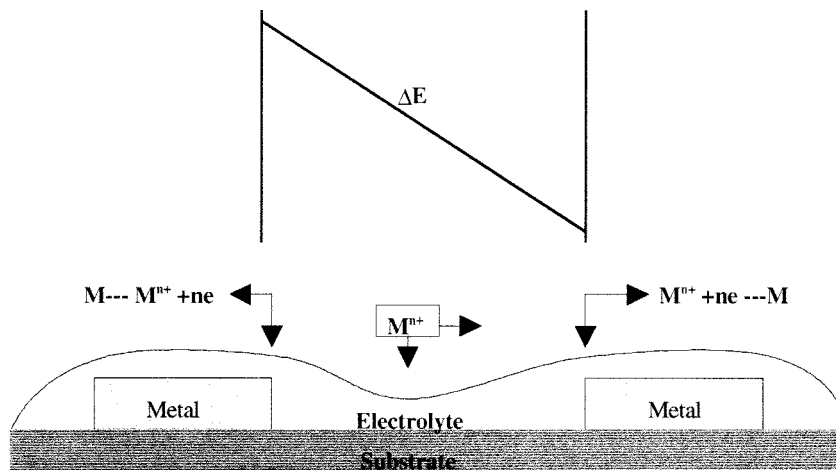


Fig. 8. Schematic illustration of the metal migration process that happens on the inter-digitated test pattern shown in Fig. 1 with the presence of an electrolyte and a voltage bias.



Due to the absence of metal ions in the contact enhancing chemicals, concentration polarization is likely to be significant. Therefore, the overpotential for the cathodic reaction ( $\eta_c$ ) can be expressed as [7]

$$\eta_c = a_c + b_c \log I - d \log(1 - I/I_L) \quad (6)$$

where

- $a_c$  and  $b_c$  cathodic Tafel constants;
- $d$  diffusion constant;
- $I_L$  limiting current density for the diffusion process through the electrolyte.

Because of the very limited amount of charge carriers available in the electrolyte, as evidenced by the very low current measured under the applied bias voltage, the ohmic resistance of the cell ( $R_w$ ) is also expected to be significant. Taking into consideration all the reactions and processes, the relationship between  $\Delta E$  and current can be expressed as [8]

$$\Delta E = \eta_a + \eta_c + IR_w. \quad (7)$$

Combining (2), (6), and (7) gives

$$\Delta E = a + b \log I - d \log(1 - I/I_L) + IR_w \quad (8)$$

where  $a$  and  $b$  are the Tafel constants which vary with the metal and the nature of the electrolyte.

Although the relationship shown in Equation (8) is rather complex since  $R_w$  and  $I_L$  change with time due to the influence of the reaction products formed at both electrodes, it can be used to explain the experimental data qualitatively.

The difference in current for pattern A and pattern B can be explained by the difference in the metal used for the conductor and the conductor spacing. The first two terms in Equation (8) are related to the corrosion and electrochemical properties of the metal. For pattern A, aluminum is a very passive metal. It forms

a dense and passive oxide in the presence of oxygen and moisture, which renders the ionization process in Equation (1) very difficult [9]. For the small amount of ions that did form in the electrolyte, since aluminum is a very reactive metal, the energy required to deposit out the ions is also considerably high. However, for pattern B, copper is not as passive as aluminum, thus the ionization process in Equation (1) takes place more readily [9]. Since the equilibrium potential for  $\text{Cu}/\text{Cu}^{2+}$  is 2 V higher than that for  $\text{Al}/\text{Al}^{3+}$ , the deposition process in Equation (3) also takes considerably less energy for copper [9]. Such differences in the reactivity and passivity of the two metals can explain why even at the beginning of the test, current measured on pattern A is only 15 times of that measured on pattern B, despite the fact that the difference in the spacing for the two patterns is as much as 25 times.

With the increase in  $\Delta E$ , more metal ions enter into the electrolyte, resulting in a gradual increase in the electrolyte conductivity (i.e., a decrease in  $R_w$ ) and the limiting diffusion current  $I_L$ , which explains the nonlinear relationship between  $I$  and  $\Delta E$  as shown in Fig. 2. As discussed earlier, since ionization of copper happens at a much higher rate, the increase in  $I_L$  and the decrease in  $R_w$  also happen at a much higher rate. This explains the gradual narrowing of the difference in current measured on the two test patterns.

If the conduction mechanism by electrochemical reactions as mentioned above is true, the absorbed moisture should play a key role in supporting the electrochemical reactions because it provides the free moving charge carriers  $\text{H}^+$  and  $\text{OH}^-$ . Results shown in Fig. 3 prove that the moisture level in the air indeed has a major effect on the conductivity of the chemical. At the ambient condition, current under  $\Delta E = 20$  V on pattern B increased gradually with time, due to the change in the electrolyte conductivity as discussed above. When test pattern B was placed on a hot stage at 40 °C in the open air environment, the relative humidity around the sample dropped to a much lower value, since the moisture content at 23 °C and 50% RH is only equivalent to 19% RH at 40 °C, and the decrease in RH adversely impacted moisture absorption. Consequently, current decreased by almost 1 order of magnitude from the start to

the end of the experiment. At the end of the 1 h measurement, current measured at 40 °C is nearly two orders of magnitude lower than that measured at the ambient condition. However, when the test was conducted in a humidity chamber set at 40 °C and 60% RH, moisture absorption was expected to increase due to the higher temperature and humidity. As expected, current measured also showed a much more rapid increase with time, and current measured at the end of the 1 h test is also higher than that measured at the ambient condition.

### B. Contact Enhancement

Optical examination of the pattern tested at 40 °C and 60% RH shows that the copper in the conductor is largely depleted from the anode (Fig. 4), and metallic dendrites were formed on the cathode. Some of the dendrites almost bridged the gap between the two electrodes. The result shown in Fig. 4 also explains the current fluctuation shown in Fig. 3. current started to decrease as copper was depleted from the anode. However, when metallic dendrites bridged the space between the two electrodes, conduction through metal took place, resulting in a higher current. If the higher current burned off the dendrites, current would again decrease.

The metallurgical examination of the wire crimps which have been treated with the contact enhancing chemical also reveals the existence of dendrites between the mating members, as described previously. In a regular crimp, the failure mechanism due to intermittent contact is primarily due to an increase in the contact resistance because of separation between the contact surfaces and the build-up of an oxide layer in between. Once this happens, in the presence of an electrical field, an electrical potential comes into existence between the contacting surfaces (i.e., the wires and the barrel), with the wire side being the positive side and the barrel side being the negative side in the experiment under discussion here. Subsequently, for wire crimps that have been treated with the chemical, in the presence of an electrolyte (i.e., the contact enhancing chemical), an electrochemical reaction takes place between the anode (i.e., the wire in this case) and the cathode (i.e., the barrel). As discussed previously, metals (Cu) in the anode (the wire) become ionized and migrate toward the cathode (the barrel), and get deposited there. This is evidenced by the fact that the metallic structure between the wires and the barrel is made up of Cu from the wire material, instead of Sn which coats the barrel surface.

As a result of the electrochemical reaction, metallic dendrites are formed. The growth of the dendrite provides a “bridge” between the mating elements (the wires and the barrel), thus providing a “healing” mechanism for contact enhancement. The formation of the dendrites is the concrete evidence that the conduction mechanism of the contact enhancing material is electrochemical reaction and ionic conduction.

Compared with oils and greases that are traditionally used on mechanical interfaces for electrical connection, the contact enhancing materials that have limited ionic conductivity and promote dendritic growth have several advantages. As illustrated in Fig. 9, on a microscopic scale, the surface in contact is rather jagged, and metal to metal contact only happens at the high points. As a result, the current densities at these contact points

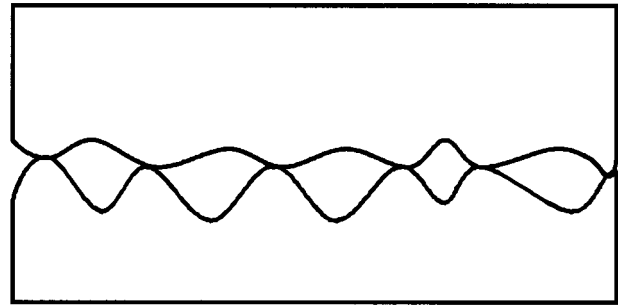


Fig. 9. Schematic illustration of the microscopic view of mating metal surfaces for electrical connection.

are very high. The high current density at these points can result in localized heating and oxide film build-up, and the oxide film at these points in turn gives rise to high resistance. In addition, physical gaps can also develop between the mating surfaces due to vibration, thermomechanical loading, etc., thereby inducing high contact resistance. The high resistance ultimately leads to the failure of the connection.

A contact enhancing material with some ionic conductivity improves the electrical connection by several means. First, the ionic conduction lowers the current density at the contact points, effectively increasing the surface area for electrical passage by many times. The dissolution of metal and oxygen [Equations (1) and (4)] into the liquid phase in turn greatly enhances electrical conductivity due to a dramatic increase in the amount of charge carriers. Secondly, the ionization process at the anode prevents oxide build-up. Thirdly, the metallic dendrites formed as a result of ionic migration serve as metallic bridges between the mating surfaces, effectively eliminating any physical gaps.

It must be cautioned that the enhancement in conductivity comes at the expense of metal corrosion. Corrosion has been a known failure mechanism for contact surfaces. The contact enhancing chemical may enhance conductivity in the short term, but may lead to degradation of long-term reliability by inducing corrosion failure. A previous field and laboratory study [4] has shown that a commercial contact enhancer similar to the subject of current study caused more corrosion than most conventional lubricants.

In addition, the chemical causes significant decrease in not only the resistance between the mating surfaces of a contact system, but also the insulation resistance between the pins that operate at different voltages. That may lead to failure due to high leakage current or even shorting. Therefore use of such material on connectors with tight spacing between pins, such as edge card connectors for high density electronic circuit boards, can be very dangerous.

## V. CONCLUSION

This study has shown that the conduction mechanism behind novel contact enhancing chemicals for electrical connection is electrochemical in nature. The chemical has limited ionic conductivity, and serves as an electrolyte for dissolution of metals at the high voltage end, transportation of metals through the physical gaps, and re-deposition of metals at the low voltage end. As

a result of the electrochemical reaction, dendrites are formed between the mating elements, thereby providing contact enhancement. Metallurgical examinations have directly revealed the existence of a dendritic bridge between the mating elements in the presence of the contact enhancing chemical, and confirmed the electrochemical reaction mechanism for contact enhancement.

The experimental results do not support any kind of unusual conduction mechanism such as "long range tunneling" as claimed by some manufacturers of contact enhancing chemicals.

Chemicals that enhance electrical connection through ionic conduction outperform conventional oils, greases and sealer waxes, because it can effectively increase the surface area for electrical conduction, prevent oxide build-up, and bridge the physical gap through the formation of metallic dendrites between the contacting members.

Great caution should be exercised when considering such chemicals for any contact system. Its use on the contact surfaces of wire crimps may have some merits provided the extent of electrochemical reaction does not induced corrosion failure. Use of such chemicals should be avoided for connection systems that have tightly spaced pins operating at different voltages since the material degrades the insulation resistance between the pins.

#### ACKNOWLEDGMENT

The authors like to thank J. Southworth, Ford Motor Company for helpful discussions and assistance.

#### REFERENCES

- [1] M. Antler, "Survey of contact fretting in electrical connectors," *IEEE Trans. Comp., Hybrids, Manufact. Technol.*, vol. CHMT-8, pp. 87-104, Jan. 1985.
- [2] G. Kulwanoski, M. Gaynes, A. Smith, and B. Darrow, "Electrical contact failure mechanisms relevant to electronic packages," in *Proc. 37th IEEE Holm Conf. Electrical Contacts*, 1991, pp. 184-192.
- [3] W. H. Abbott and J. H. Whitley, "The lubrication and environmental protection of alternatives to gold for electronic connectors," in *Application Note P-230-80*. Harrisburg, PA: Amp, Inc., 1980.
- [4] W. H. Abbott, "Field and laboratory studies of corrosion inhibiting lubricants for gold-plated connectors," in *Proc. 42nd IEEE Holm Conf. Electrical Contacts*, 1996, pp. 414-428.
- [5] S. H. Leibeon, "Contact-enhancing chemicals: Fluids vanquish intermittent contacts," *EDN*, vol. 36, no. 6, pp. 59-64, 1991.
- [6] K. Krane, *Modern Physics*, 2nd ed. New York: Wiley, 1996, pp. 164-168.

- [7] D. Jones, *Principles and Prevention of Corrosion*, 2nd ed. Upper Saddle River, NJ: Prentice-Hall, 1996, pp. 80-86.
- [8] L. L. Shreir, R. A. Jarman, and G. T. Burstein, *Corrosion*, 3rd ed. Oxford, U.K.: Butterworth-Heinemann, Ltd., 1994, vol. 1, pp. 1:88-1:92.
- [9] M. Pourbaix, *Atlas of Electrochemical Equilibria in Aqueous Solutions*. Houston, TX: NACE, 1974, pp. 168-172 and 384-392.



**Guilian Gao** received the B.Sc. degree in materials science and engineering from Beijing University of Aeronautics and Astronautics, Beijing, China in 1984, the M.Sc. degree in corrosion and protection from the University of Manchester, Manchester, U.K. in 1986, and the Ph.D. degree in materials science and metallurgy from the University of Cambridge, Cambridge, U.K., in 1990.

She is currently a Senior Technical Specialist at the Ford Research Laboratory, Ford Motor Company, Dearborn, MI. She has ten years of research and industrial experience in reliability evaluation and prediction for electronics and electrical interconnects, materials, and manufacturing technology development for electronics, aqueous corrosion, molten salt corrosion, automotive corrosion and prevention, especially galvanic corrosion and prevention of aluminum and magnesium alloys. She has over 20 publications and five U.S. patents. She currently serves on the Board of Review of *Metallurgical and Materials Transactions*.

Dr. Gao is the Vice Chair of the Automotive Corrosion Subcommittee of the NACE International.



**Dongkai Shangguan** received the B.Sc. degree in mechanical engineering from Tsinghua University, China, and the Ph.D. degree in materials from the University of Oxford, Oxford, U.K.

He was a Post-Doctoral Visiting Fellow at the University of Cambridge and then as a Post-Doctoral Research Fellow at The University of Alabama, Tuscaloosa. He joined the Ford Motor Company, Dearborn, MI, in 1991, and is currently a Senior Technical Specialist in the Visteon Automotive Systems Department. He is currently working on electronics packaging and manufacturing technology, interconnect technology and reliability, metal corrosion and protection, and other metallurgy and materials issues related to automotive components. He is the author of the book *Cellular Growth of Crystals* and has over 40 publications in the field of metallurgy and materials science. He has ten U.S. patents issued and a number of U.S. and international patents pending. He currently serves on the Board of Review for *Metallurgical and Materials Transactions*.

Dr. Shangguan received the SME "Outstanding Young Manufacturing Engineer Award" in 1998 and has been listed in *American Men and Women of Science: A Biographical Directory of Today's Leaders in Physical, Biological, and Related Sciences*.