Effect of Silicone Vapour and Humidity on Contact Reliability of Micro Relay Contacts

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ABSTRACT

Contact resistance characteristics of a micro relay with Au(90wt%)-Ag(10wt%) claded contacts were examined in air containing silicone vapour and in air mixed with silicone vapour and high humidity. Electrical conditions for resistive loads of the contacts were covered with four regions such as bridge region, first micro-arc region, second micro-arc region and arc region. Concentrations of the silicone vapour were selected both 1300 ppm which gives saturation of the vapour, and 7 ppm which is the safety level for the contact reliability. Moreover, effect of humidity on dynamic contact resistance characteristics in the silicone environment was also studied.

As results, a boundary of occurrence of the contact failure in the relationship between voltage and current was found. This boundary was given by a certain electrical power. Number of operations to failure was found inversely proportional to electric power. Under the condition of high humidity, low contact resistance maintained longer operation time than low humidity.

Key Words: Silicone, Micro-relay, Silicone contamination, Contact Failure, Contact resistance, Discharge.

INTRODUCTION

SiO_2 is formed by the reaction of the silicone vapour with O_2 under elevated temperature. Since SiO_2 is a typical insulator, if SiO_2 is formed on the contact surface and is interposed between contacts, contact failure should occur due to degradation of contact resistance character-istics. As silicone contamination of the contact surface, one of direct contaminations is creep of silicone oil to the surface caused by its low surface tension. On the other hand, for indirect contamination, evaporation of silicone and its adsorption on the surface[1-6]. Moreover, residual low molecular weight silicone also evaporates gradually from a silicone compound such as a silicone rubber. However, silicone compounds and silicones have such excellent properties as durability and heat resistance. Therefore, they have been widely applied from electronics to cosmetics.

Molecular weight of silicone is distributed over a wide range depending on its chemical structure. In particular, octamethylcyclotetrasiloxane $[(CH_3)_2SiO_2]_n$, n=4 : D4 has a relative low molecular weight of 296. Therefore, it remains in the atmospheric environment as vapour. On the other hand, vapour pressure of silicone exponentially becomes higher with decrease in molecular weight. The absence of these silicones are desirable for electrical contacts.

For electrical make-break contacts, the thermal energy is supplied by electric discharge at breaking and making a circuit. A build-up of SiO_2 is developed by many repetitions of the discharge at the contact. Feature of the contact failure due to SiO_2 is a sudden increase in contact resistance which is different from the other type of contact failure.

In the present paper, in order to clarify a mechanism of the contact failure of a micro relay due to the silicone vapour, effect of electrical conditions of the contacts on the contact failure was examined under wide range electrical conditions. Safety level of the contact failure under silicone contamination was also examined from a relationship between applied voltage and current. Contaminant products were identified by analysis of X-ray photoelectron spectroscopy (XPS) and electron probe micro analysis (EPMA) [10].

Moreover, Humidity is an important factor which affects contact resistance characteristics in the atmosphere. Therefore, action of the humidity to the effect of the silicone vapour on the contact resistance of the make-break contacts was studied also.

EXPERIMENTAL

1. Experimental environment with silicone vapour

Silicone with a low molecular weight evaporates readily at a low temperature. Octametylcyclotetrasiloxane $[(CH_3)_2SiO]_4$: D_4 evaporates gradually even at room temperature, but its boiling point is 175°C [1].Therefore, in an environment which includes silicone such as D4, the electrical contacts are affected by the vapour at all times.

In regard to the minimum safety level of the silicone vapour, it was reported by the author that under a certain mechanical conditions of contacts, silicone which has a saturation vapour pressure lower than 10ppm (0.13mg/l) is expected no contact failure regardless of its quantity at room temperature [11].

In the present study, as a source of silicon contamination, vapour of D4 was used. Concentrations of the silicone vapour were set at two levels. One of the level was saturated vapour of 1300ppm, on the contrary, the other was minimum level of 7ppm. In order to clarify silicone contamination, the study was carried out in both extremes of silicone concentrations. The saturation of the vapour sets in from 1300ppm at room temperature. Therefore, since 1300ppm is realizable maximum concentration in the atmosphere at room temperature, the condition is the worst for silicone contamination. On the other hand, 7ppm is inferior limit of silicone contamination.

Furthermore, since an important factor in the atmosphere is humidity, effect of the humidity on the contact resistance characteristics of the micro relay under environment with silicone vapour was examined. This examination was carried out at high humidity of 100%RH in a environment containing silicone vapour for each levels of 1300ppm and 7ppm. And these results were compared with ordinary room humidity of 50-60%RH.

In the experiment, the concentration of the silicone vapour in the atmosphere was adjusted by the amount of silicone D4 injected into a hermetically sealed test chamber with a volume of 5 litter which contained normal clean air with a humidity of 50-60%RH at normal pressure. After injection of silicone, the test chamber was permitted to stand for one hour to reach equilibrium vapour pressure. Then the concentration of the vapour was calibrated by gas chromatography.

Furthermore, for examination of the humidity environment, normal clean air was replaced by air with a saturated humidity of 100%RH, and silicone was injected for each concentration.

In these environments, the micro relays were operated until contact failure.

2. Micro relay specimen and electrical switching examination

The micro relay with four twin contacts was used for the present study. Volume of the relay was 3.5 cm^3 covered with plastic case, but the cover was detached at switching test under silicone exposure. Contact specimens were shaped cross bar type of half cylinder with contact load of 8+1g. For the material of the contact, base of Ni(thickness 100μm) was overlayed by Ag (100μm) as intermediate layer, the top overlay on the Ag was Au(90wt%)-Ag(10wt%) with thickness of 5μm.

Specifications of the electrical make-break test conditions were as follows. Frequency of the make-break operation was 1Hz (duty 50%) at temperature of 25°C. Thermal source at the contact for decomposition of silicone is mainly electrical discharge at breaking circuit. Quantity of thermal energy depends on duration time of the discharge. The thermal source is mainly divided into four regions by minimum arc discharge voltage and current characteristic. The electrical conditions subjected by make-break action were mainly divided into four regions depending on a type of discharge, namely, bridge region, first micro-arc discharge region, second micro-arc discharge region, and arc discharge region [7-9]. For Au and its alloy, these regions are divided approximately by lines of 10-15V and 0.38-0.42A as shown in Fig.1.

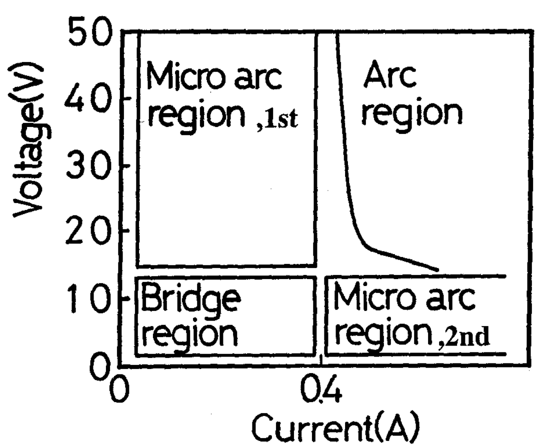


Fig.1 The electrical switching test conditions divided into four discharge regions.

Therefore, in the present study, the electrical test conditions were covered these four regions as voltage range of 0.75-50V DC and current range of 0.01-2A DC with resistive load. In order to avoid complexity at discharge induced by residual inductance in the resistive load, carbon type resistors were used.

To clarify the surface contaminations caused by the build-up of SiO_2 at each time of breaking the resistive circuit, measurements for the relationship between contact resistance and the number of operations are necessary. Therefore, changes in the contact resistance for the number of operations of the relay until contact failure were measured. Eight specimens of the contact were operated under same test conditions at the same time.

3.Measurement of the contact resistance characteristics and analysis of contaminated products on the failed contact surface

The contact resistance was measured by using four terminals potential drop method for each certain number of contact operations. The measuring current for the contact resistance was low current of 1mA - 0.1μA to avoid effect of the current on the formed products.

Next, the failed contact surfaces were observed by an optical microscope taking care of the feature for each discharge regions. Then, products on the surface were analyzed by XPS and EPMA to identify its composition.

RESULTS AND DISCUSSION

1.Effect of silicone vapour on the relationship between contact resistance and the number of operations

Typical example for the measured relationship between contact resistance and the number of operations selected from the electrical conditions of four discharge regions were shown in Fig.2(1-4). The measured relationships are shown comparing with two levels of silicon vapour for 1300ppm and 7ppm.

(a) Bridge region: As an example for this region, change of contact resistance for the number of operations under electrical conditions of 8V and 0.2A is shown in Fig.2(1). In this relationship, measured data of contact resistance are illustrated average value of eight contacts together with maximum and minimum value. As shown in this figure, in the environment of silicone vapour of 1300ppm, sudden increase in contact resistance from $3x10^{-2}\Omega$ to $5x10^{6}\Omega$ occurred at 1300times of operations. On the contrary, for silicone vapour of 7ppm, this increase in the contact resistance appeared at 44000 times and then saturated about 500Ω.

Therefore, from these results, the number of the operations until contact failure in silicone vapour of 7ppm prolonged 34 times as many as for 1300ppm. Moreover, at the region for electrical conditions less than 4V, 0.2A, no contact failure was found regardless of silicone concentration.

In this region, the thermal energy is supplied by very small

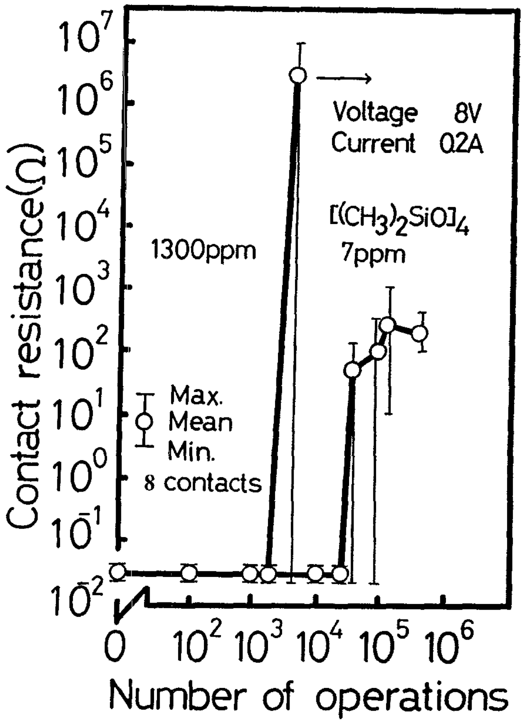


Fig.2(1) Contact resistance characteristics for the number of operations in the bridge region (8V,0.2A).

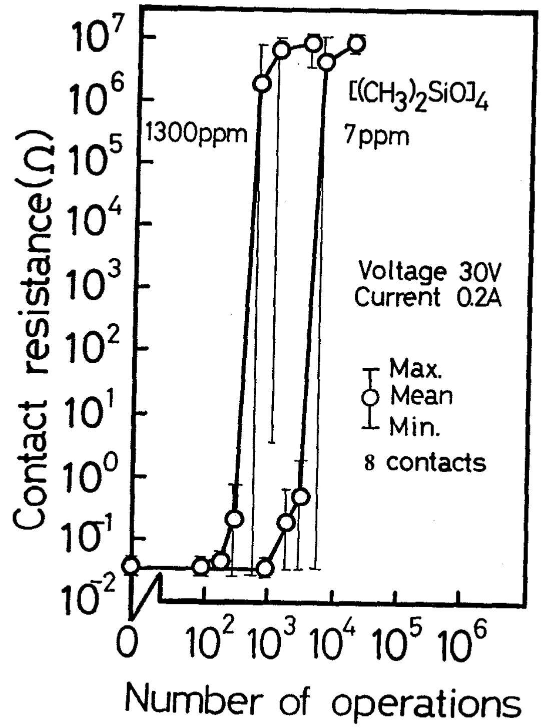


Fig.2(2) Contact resistance characteristics for the number of operations in the first micro-arc region (30V,0.2A).

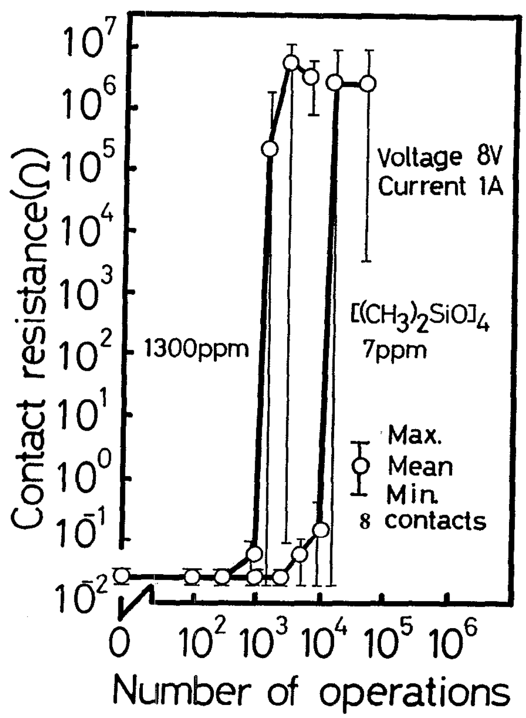


Fig.2(3) Contact resistance characteristics for the second micro-arc region (8V,1A).

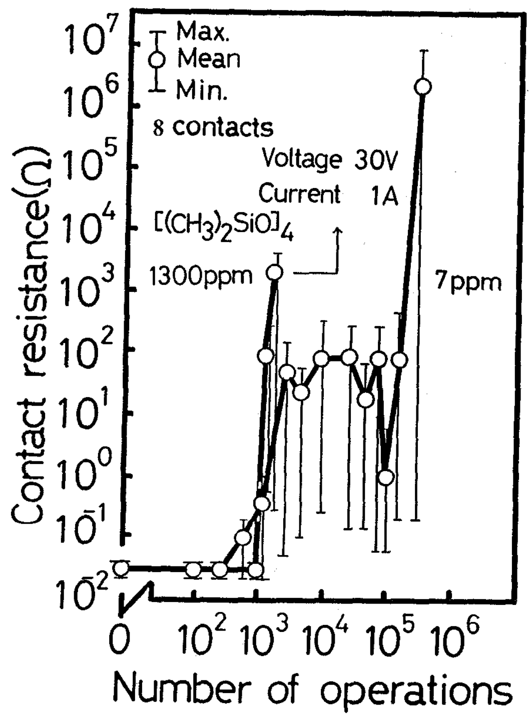


Fig.2(4) Contact resistance characteristics for the arc discharge region (30V,1A) metal molten bridge between opening contacts and metal vapour caused by rupturing of the bridge. Therefore, since thermal energy is lower than the other discharge region, silicone vapour does not decompose actively. Formation of build-up SiO_2 should not be developed rapidly

(b) First micro-arc discharge region: Typical characteristic for electrical condition of 30V-0.2A chosen from this region was shown in Fig.2(2). As seen from this figure, it is a feature of this region that contact resistance gradually increased from 30mΩ to 1.0Ω, and then suddenly increased to $10^6\Omega$ and saturated about $10^7\Omega$. This sharp change in contact resistance was 400 operations for 1300ppm, and 4500 operations for 7ppm. Duration of low level contact resistance in 7ppm is also longer than in 1300ppm.

(c) Second micro-arc discharge region: As shown in Fig.2(3) which is a typical example of this region, electrical condition is 8V-1A, sudden increase in contact resistance was 1100 operations for 1300ppm, and 11000 operations for 7ppm. This characteristic is very similar to the first micro-arc discharge region. In this region, duration of low level contact resistance in 7ppm is 10 times as many as in 1300ppm.

(d) Arc discharge region: Typical example for electrical discharge of 30V-1A (30W) chosen from the arc discharge region is shown in Fig.2.(4). The increase in contact resistance occurred at 1200 operations for 1300ppm, and at almost same operations for 7ppm. In 7ppm condition, increase in contact resistance cease about 10-100Ω and saturate. This is clearly different from the other regions. The cause of this saturation due to 7ppm should be induced by sputtering of ionized environmental gas. In the 7ppm vapour, since produced SiO_2 small in amount, the products are easily removed by the sputtering. Thus, the contact resistance hold a certain medium level due to the balance of growth of build-up SiO_2 caused by arc discharge and removal of them caused by sputtering.

From these results in the four regions, difference between contact resistance characteristics for silicone vapour concentration are clearly recognized. Duration of low level contact resistance until contact failure at 7ppm was much prolonged than at 1300ppm. Difference in the duration between at 1300ppm and 7ppm was the longest in the bridge region and was not recognized in the arc region. Intermediate duration appeared in the two micro-arc regions. This difference in the duration can be considered as depending on a amounts of the thermal energy supplied by the regions. and on low vapour level of 7ppm.

Even at minimum level of 7ppm, contact failure occurred. As the reason of this fact, since amount of the build-up of SiO_2 in the initial stage of contact operations is very small and easily removed mechanically by make-break and slide actions, the contact resistance shows low level. However, when the build-up of SiO_2 proceeds, as it can not be removed mechanically by make-break action, sudden increase in the contact resistance may appear. Therefore, occurrence of the increase in the contact resistance should be dependent on balance of mechanical removal of closing contact and the build-up of SiO_2.

Moreover, the mechanical contact load influences mechanical removal of the build-up SiO_2, and duty cycle of the make-break contacts of the micro-relay also influences adsorption rate of the vapour to the surface [12]. Therefore, the minimum safety level of the silicone vapour may be changed depending on the mechanical conditions of the contacts. Therefore. for the test conditions in the present study, the contact failure should occur at the minimum level of 7ppm.

2.Occurrence of the contact failure and electrical conditions

The number of operations until contact failure changed depending on the regions of discharge. Accordingly, in order to find electrical switching conditions in which contact failure does not occur, the number of operations until contact failure was plotted in the coordinates of voltage and current as shown in Fig.3. A certain relationship is found in this Fig.3. From this relationship, in the low level region of voltage-current, no contact failure is found. Namely, this region is restricted lower level of the bridge region, first and second micro-arc region.

In Fig.3, measured data is also indicated with contact failure rate of eight contacts specimen and the number of operations to the contact failure. Occurrence of the boundary for the contact failure is clearly recognized in Fig.3 for both silicone vapour of 1300ppm and 7ppm. This boundary line indicates electrical power around 1.6W regardless of the concentration of silicone vapour. The boundary line can be recognized as limitation of occurrence for the discharge, since contact failure was not found for the region less than approximate 1W. The boundary line is same for both 1300ppm and 7ppm, but the number of operation until contact failure for 7ppm is larger than for 1300ppm.

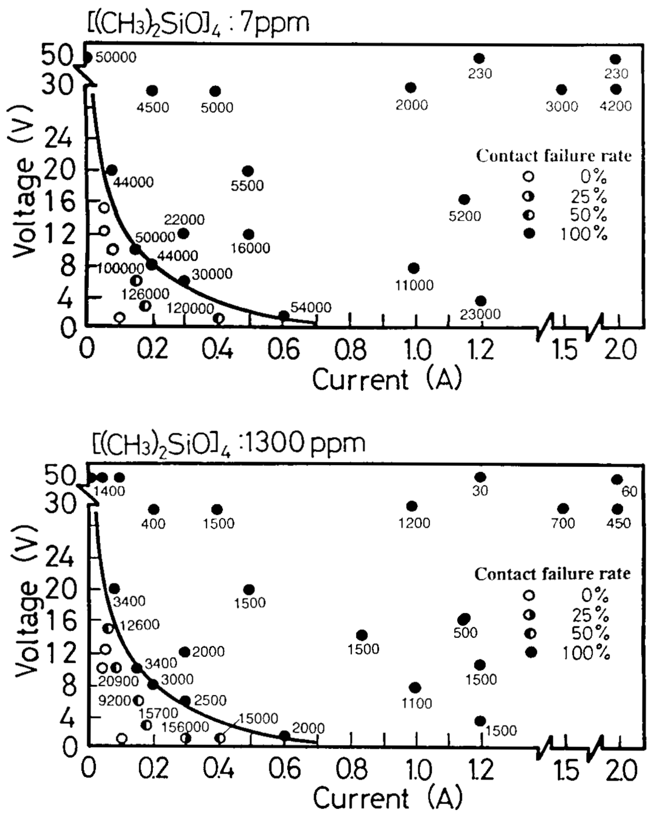


Fig.3 The boundary line of contact failure in the relationship between voltage and current. (The number of operations until contact failures are shown numerically, contact failure rates are also shown in percentage.)

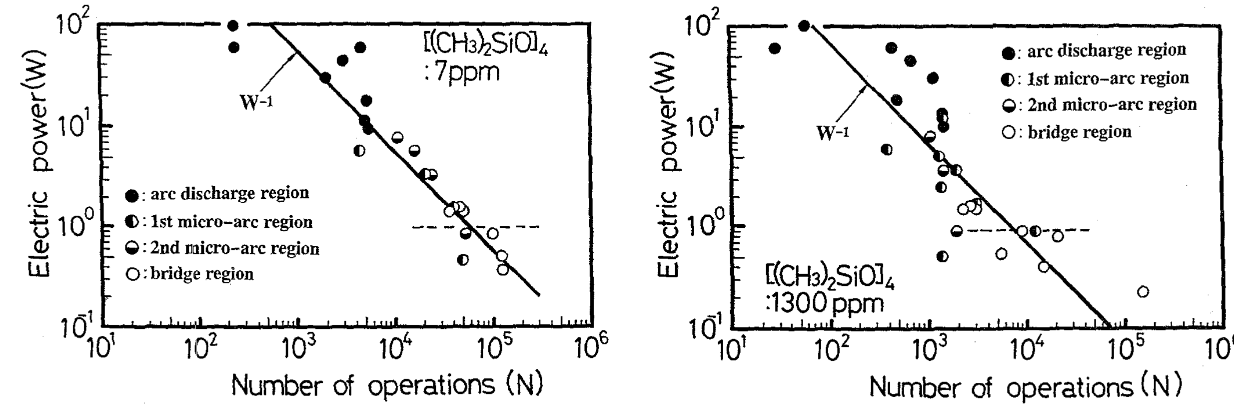


Fig.4 Relationship between the number of operations and electric power at the occurrence of the contact failure.

From above results, it can be deduced that the electrical power of the boundary line of 1.6W is a limitation to decompose the silicone vapour and to form build-up SiO_2. As the temperature of the decomposition is same for both 1300ppm and 7ppm, the boundary line takes also same level. However, difference between 1300ppm and 7ppm can be considered as difference of the amount of build-up products.

3. Relationship between the number of operations until contact failure and electrical power of switching

From view-point of occurrence of the contact failure, relationship between the number of operation until contact failure and electrical power switched by the contact specimen was rearranged by using measured data. This relationship is shown in Fig.4. From Fig.4, it was found that the number of operations is inversely proportional to electric power. In other word, this relationship indicates a gradient of -1. As the electric power increases, thermal energy to decompose silicone vapour increases. Therefore, the number of operations until contact failure decreases.

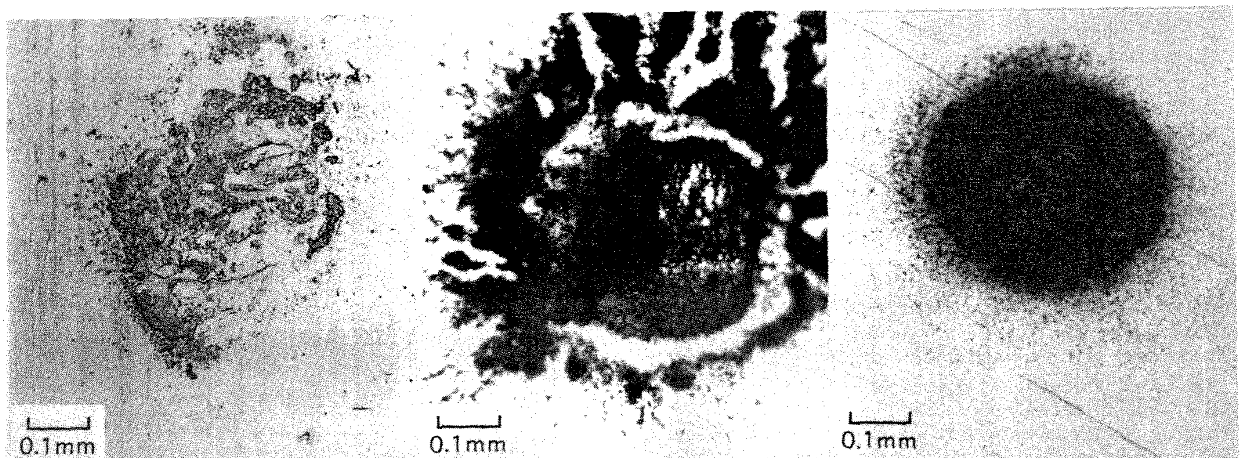
This result shows that electrical power concerning temperature is important to produce build up SiO_2.

4. Surface observation and identification of products on the contact surface

(1) Microscopic observation of the contact surface

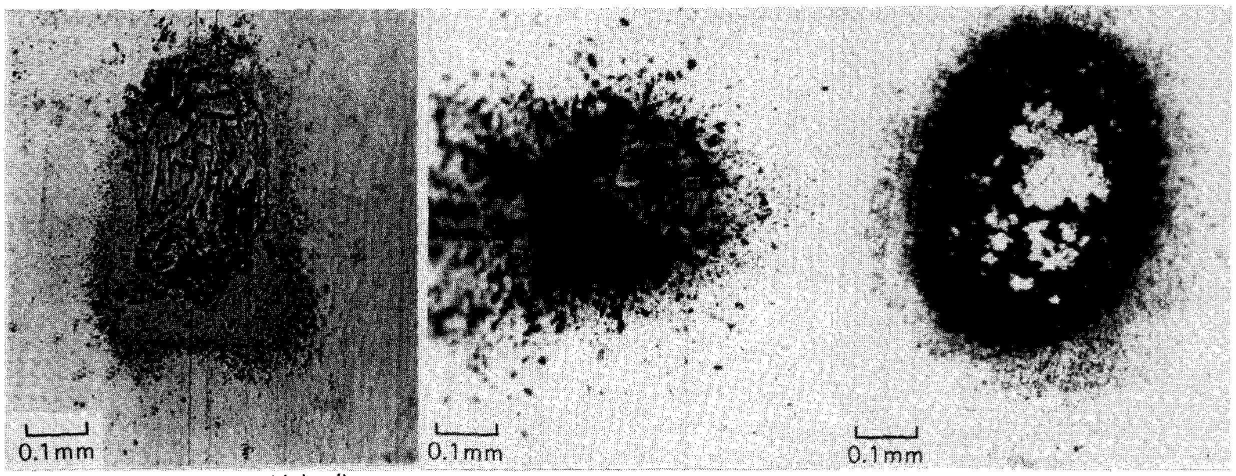
At the first stage of this study, four regions depending on the type of discharge were considered as electrical conditions. However, since the boundary line of the contact failure was found as discussed in the previous section, microscopic observation of the contact surface and identification of the products on the contact surface are discussed around the boundary line. Typical example of optical micrograph for the contact surface after switching operation test under 1300ppm silicone vapour at three levels of electrical power are shown in Fig.5(1-3). These three levels of electric power are corresponding to the boundary line, lower level and higher level than the line. Obvious difference in contact traces was not found for both anode and cathode.

The microscopic characteristic of contact traces for low level power(0.1Ax0.25V=0.025W) indicates only deformed traces without discoloration as shown in Fig.5.1. In this case, the contact failure was not detected. The result of the observation well agreed with contact resistance characteristics. From these facts, the thermal energy which affects tempera-



(1)silicone:1300ppm,0.1A-0.25V circuit below the boundary line (cathode)
(2)silicone:1300ppm,0.2A-8V circuit on the boundary line (anode)
(3)silicone:1300ppm,0.5A-20V circuit above the boundary line (anode)

Fig.5 Optical micrograph of contact traces after the test.



(1)silicone:7ppm,0.06A–15V circuit below the boundary line (cathode)
(2)silicone:7ppm,0.2A–8V circuit on the boundary line (anode)
(3)silicone:7ppm,0.5A–20V circuit above the boundary line (cathode)

Fig.6 Optical microgaraph of contact traces after test.

ture in this power region can be considered as not enough to decompose the silicone vapour.

However, the micro graph of the contact traces just on the boundary line (0.2Ax8V=1.6W) indicates brown colored built-up contamination products scattered around the traces as shown in Fig.5.2. In this case, the number of operations until contact failure was 3000 times. From the micro graph of scattered products around the periphery of the contact area, the spray of molten metal at breaking the bridge may be affected to form the contaminant products.

Moreover, for higher level of electric power (0.5Ax20V=10W) than the boundary line, the surface state of the contact traces shows circular black build-up products as shown in Fig.5.3. This black contaminant can be seen the build-up of SiO_2. In this case, the contact failure occurred at operation of 1500 times.

With respect to the concentration of silicone vapour of 7ppm, the micro graph of the contact traces are shown in Fig.6(1-3). The surface contaminations caused by three different electric power conditions are similar to the case of 1300ppm.

(2) Analysis of the contaminant product

In order to identify the products of the contamination on the contact traces, the products were analyzed by using XPS and EPMA. In the results of XPS analysis, SiO_2 was detected for higher electrical conditions of the contact circuit than the boundary line. However, formation of SiO_2 was not found for the electrical conditions lower than the boundary line. Typical example of the spectrum of the binding energy of photoelectrons of atoms for the contacts of 8V-0.2A (1.6W) circuits under 7ppm shown in Fig.7. This spectrum shows peaks of O_{1s}, Ag_{3d}, C_{1s}, Si_{2p}, and Au_{4f}. The binding energy of low level peak of Si_{2p} can be recognized as 102.3(eV). This value agreed with a value of SiO_2. As seen from Fig.6, level of Si_{2p} peak is lower than the others. Because detecting area of the photoelectron is larger than the contact traces. In other words, SiO_2 is restricted to the contact traces.

Therefore, to determine more precise, contaminated contact area was analyzed by EPMA. Typical example of the

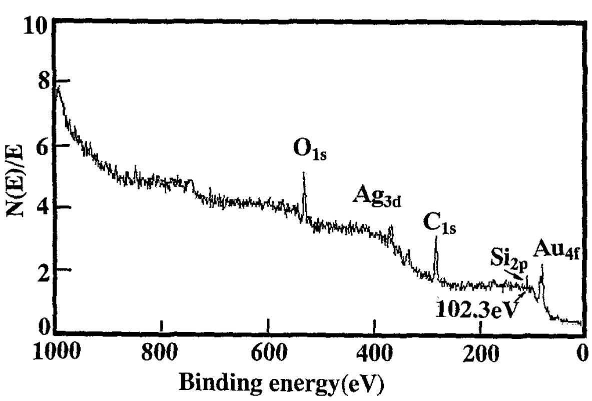


Fig.7 Spectrum of binding energy for the failed contact surface.(silicone:7ppm, 0.2A–8V circuit on the boundary line)

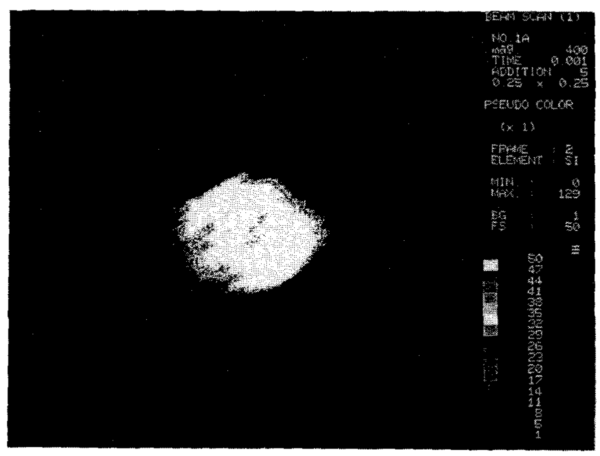


Fig.8 Si on the contact surface analyzed by EPMA.(silicone: 7ppm, 0.2A–8V circuit on the boundary line)

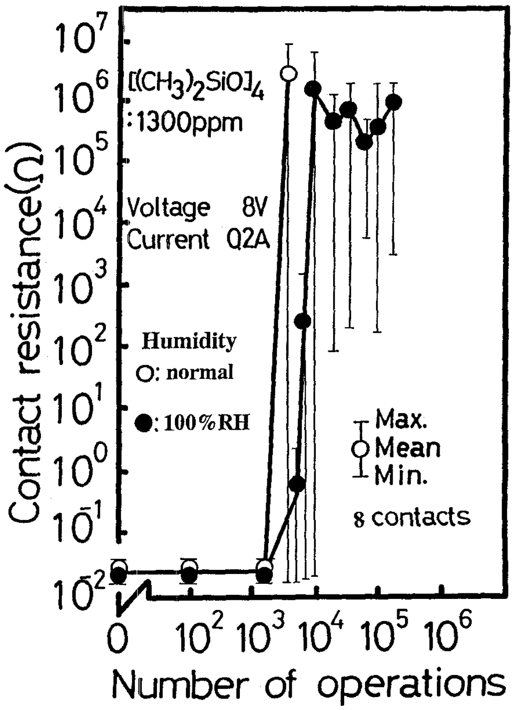


Fig.9(1) Contact resistance characteristics under high humidity with silicone 1300ppm. Bridge region: 0.2A-8V.

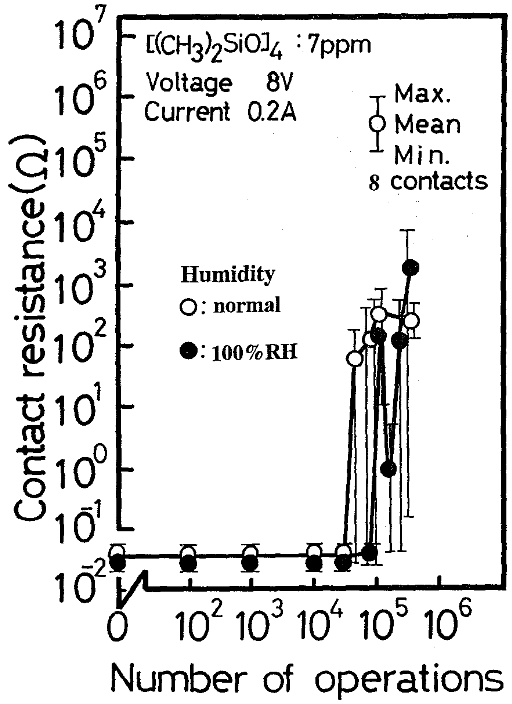


Fig.9(2) Contact resistance characteristics under high humidity with silicone 7ppm, Bridge region: 0.2A-8V.

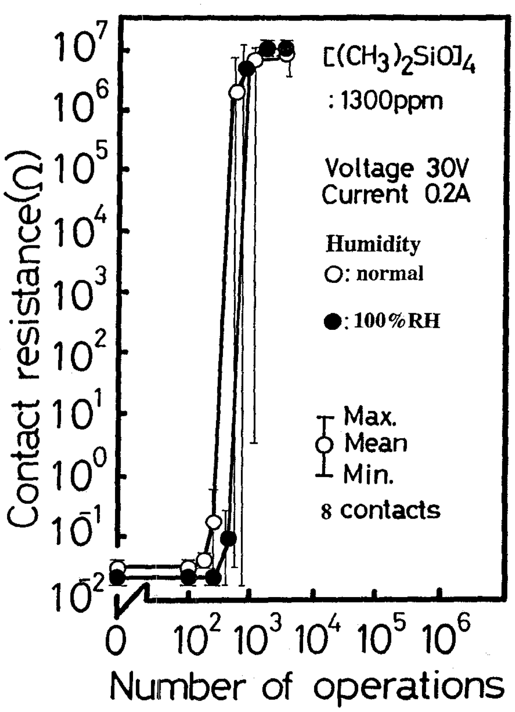


Fig.9(3) Contact resistance characteristics under high humidity with silicone 1300ppm, First micro-arc region: 0.2A-30V.

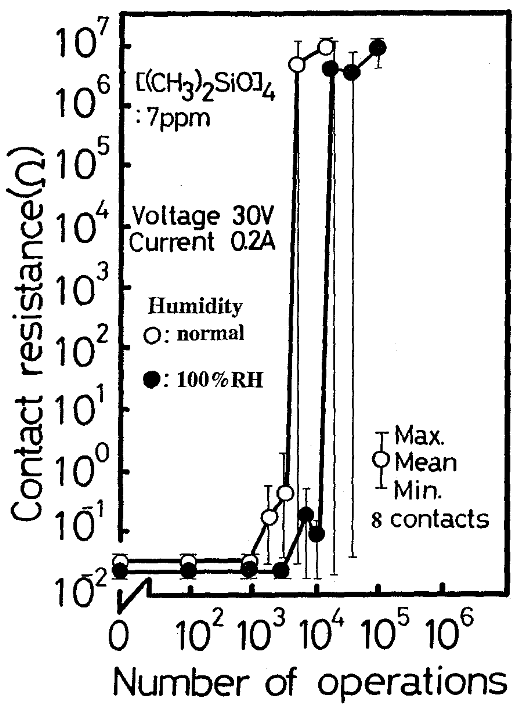


Fig.9(4) Contact resistance characteristics under high humidity with silicone 7ppm, First micro-arc region: 0.2A-30V.

results of the analysis for the contacts of 8V-0.2A (1.6W) circuit under silicone vapour of 7ppm indicates existence Si atom as shown in Fig.8. Similar result was obtained also higher electrical conditions. However, for the circuit condition of lower electric power than the boundary line, Si atom existed slightly.

Results of these observation and analysis of the contact traces were well agreed with the contact resistance characteristics as above discussed. Namely, main cause of contact failure results in the build-up SiO_2.

5. Effect of humidity on the contact resistance characteristic under operation

The relationships between contact resistance and the number of operations under high humidity for both 1300ppm and 7ppm silicone vapour are shown in Fig.9(1) and Fig.9(2) respectively comparing with normal humidity. From Fig.9(1) and Fig.9(2), effect of the humidity can be seen. Namely, the action of the humidity prolonged the number of operations until contact failure.

This fact was also obtained for the first micro-arc discharge region as shown in Fig.9(3) and Fig.9(4) for both 1300ppm and 7ppm respectively. The number of operations for the sudden increase in the contact resistance in the highly saturated humidity is higher than that of the normal atmosphere humidity.

However, for the second micro-arc discharge region and arc discharge region, the action of the humidity was not measured. One cause of the effect of the high humidity on the contact resistance characteristics can be considered as separation of build-up SiO_2 from the surface and disassembling condensed SiO_2 particles. However, in the strong arc region such as the arc discharge, the humidity effect may have disappeared by evaporation of adsorbed H_2O molecules from the contact surface.

CONCLUSIONS

Effect of the concentration of the silicone vapour on the contact life of the micro relay was confirmed at maximum 1300ppm and minimum 7ppm. As for the silicone vapour of 7 ppm, the number of operation of the contacts was prolonged for all electrical conditions. However, even at minimum 7 ppm contact failure occurred. It was found that minimum safe level of the silicone vapour is changed by the mechanical conditions of the contacts. This cause results in a balance between the condition of the mechanical removal action of contacts and occurrence of the build-up products.

On the silicone contamination, electrical conditions concerned with decomposition temperature of silicone affected greatly on the contact life rather than the concentration of the silicone vapour. Electrical boundary line of approximate 1.6W in the coordinate of voltage and current for the contact failure was found for both 7ppm and 1300ppm. For lower level of electrical conditions than the line, the contact failure was not detected. However, the contact failure was detected for the conditions higher than the line. Moreover, the number of the operations was found to be inversely proportional to the electrical power related to the decomposition of the silicone vapour. This cause was clarified from the discussion of the supplied thermal energy and decomposition of the vapour.

The contaminant products on the failed contact traces were identified by XPS and EPMA as SiO_2. However, on non failed surfaces only Si atoms were detected.

Effect of the high humidity on prolongation of the contact life was found in the low level electrical conditions. This should be caused by decomposition of the condensed SiO_2 particles. However, for high electrical conditions such as arc discharge region, this effect was not found. This reason can be seen due to evaporation of adsorbed H_2O on the contact surface.

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