Friction and Elongation of Al Electrodes due to Micro-Sliding between the Inner Mo Electrode and the Al Electrodes in High-Power Devices

Jin Onuki¹, Toshiaki Morita², Mitsuo Satou² and Tsutomu Yatsuo²

¹Department of Electronics and Information Technology, Akita Prefectural University, Honjo 015-0055, Japan
²Hitachi Research Laboratory, Hitachi Ltd., Hitachi 319-1293, Japan

The high friction coefficients between the inner Mo electrode and the cathode Al electrodes in large-area, high-power devices causes Al to stick to Mo or causes short circuiting due to the large elongation of the Al electrodes. Equipment which can reproduce these friction behaviors has developed. The friction coefficients and the Al elongation were evaluated for various combination systems. It was found that friction coefficients and Al elongation were much smaller for Mo/Cd || Al and Mo || Mo foil || Al systems than those for the conventional Mo || Al system. The reliability of large-area, high power devices using Mo foil was satisfactory.

(Received May 17, 2002; Accepted July 23, 2002)

Keywords: friction coefficient, molybdenum inner electrode, aluminium electrodes, elongation of aluminium electrode, copper outer electrode, mounting force, thermal fatigue test

1. Introduction

High-power, large-area devices play an important role in heavy-duty electrical applications, such as motor drives and power supply systems.¹,² The device consists of Si, Al electrodes on both cathode and anode sides, a W internal electrode bonded to the Al electrode of anode side, a Mo internal electrode plate set on the cathode Al electrodes, and the outer Cu electrodes. The internal electrodes protect the Si portion against thermal and mechanical stress. Cu electrodes are used for heat dissipation.³ Contact resistance between the cathode Al electrodes and the Mo plate must be low and uniform over the whole contact area for the device to have both high power and reliability.⁴ However, making uniform contact becomes more difficult as the device increases capacity and size, because oxidation, contamination, and irregularities on the surfaces of both the Al electrodes and the Mo plate prevent metallurgical contact, resulting in large contact resistance.

Thus a large mounting force is required to keep uniform contact between the Al electrodes and the Mo plates. Figure 1 shows the relationship between the mounting force and on-state voltage of a 100 mm diameter high power device. It is clear that the on-state voltage decreases substantially with a mounting force up to 28 MPa, above which it decreases slowly.

The large mounting force described in Fig. 1 generates a large thermo-mechanical stress during heating and cooling cycles in the operation of the devices.⁵ This stress and the relative thermal expansion mismatch among Al, Mo, and Cu electrodes generate large Al deformation and Si cracking. This may be due to the fact that friction coefficient between Al and Mo is very high and hence Mo and Al stick to each other.⁶

The first part of this paper describes the development of a micro-sliding apparatus to reproduce Al deformation. Then, the surface roughness of Mo, plated materials on Mo on friction coefficient and Al elongation have been investigated to find the most suitable combination systems. Finally, a long term reliability test was performed using the most suitable electrode system as confirmation.

2. Experimental Procedure

A schematic illustration of the equipment for measuring the friction coefficient is shown in Fig. 2. A 10 mm diameter Mo cylindrical specimen is attached to a fixture with a rigid body. Alternately, a 6 mm diameter Fe cylindrical specimen on the top of which the same diameter 600µm thick Si is bonded, is fixed to the movable fixtures of the rigid body on the load cell. The 6 mm diameter Si was fabricated from a 100 mm
diameter Si power device, on which more than 3000, about 150 \mu m wide, 4 mm long, and 20 \mu m thick Al electrodes are patterned.

Load cells for measuring both the vertical and lateral loads are fixed below the bottom and to the right side of the movable fixture. After a uniform load of 28–100 MPa is applied to the Al electrodes, lateral micro sliding with 60 \mu m moving distance was done 0–1500 times in a N\textsubscript{2} atmosphere. The N\textsubscript{2} was introduced after the closed chamber was evacuated, just like the real sealed packages. The 60 \mu m moving distance was defined as the value of the moving distance of a Mo internal electrode in a large-area, high power device during operation. The friction coefficient, \mu, is defined below.

\[ \mu = \frac{L_{la}}{L_{v}} \]  
(1)

Where \( L_v \) is the vertical load, and \( L_{la} \) is the lateral load needed to move the lower fixture by 60 \mu m.

A 4 \mu m thickness of soft metals, such as Ag and Cd, were plated on the Mo cylindrical specimen to lower the friction coefficient.\textsuperscript{6, 7} A surface roughness Ra of the Mo specimen on \mu was also done based on the previously reported theory.\textsuperscript{6, 7} Alternately, the effect of a 100 \mu m thick Mo foil inserted between the Mo and Al electrodes on \mu was also investigated, because \mu between Mo and Mo is lower than that between Mo and Al.\textsuperscript{8}

\mu and the elongation of the Al electrodes were measured for various combinations between Mo roughness, plated materials and Mo foil as a function of micro sliding cycles.

3. Results and Discussion

3.1 The validity of micro sliding tests

Figure 3 shows SEM images of the surfaces of Al electrodes before (a) and after (b) thermal fatigue tests of 20 k cycles. Temperature fluctuation during the thermal fatigue test, \( \Delta T_j \) was 50 K. By comparing (b) with (a), it can be seen that the Al electrodes extend from the original position by about 160 \mu m. This is very serious, because the vertical distance between one Al electrode to another electrode is about 300 \mu m.

Figure 4 shows SEM images of Al electrodes after micro sliding test for 150 cycles under the following conditions. Load: 28 MPa, distance: 60 \mu m, N\textsubscript{2} atmosphere. (b) is a magnification of (a). The Al electrodes are extended from their original positions because of the micro sliding tests, whereas Al electrodes are lost during the usual friction test. Hence we are able to evaluate the friction coefficient by this new equipment.

3.2 Evaluation of the friction coefficient

Figure 5 shows the friction coefficient, \mu as a function of the number of micro-slidings between Mo with a Ra of 0.5 \mu m and of 0.01 \mu m and Al electrodes. The friction coefficient, \mu in both cases, increases with the number of micro-sliding cycles. \mu for Mo (Ra: 0.5 \mu m) Al is higher than those for Mo (Ra: 0.01 \mu m) Al up to 150 cycles. However, \mu takes almost the same value-about 0.75-after 500 cycles in both cases. Here 500 cycles corresponds to 10 k cycles of a thermal fatigue test of a 150 mm diameter power device with \( \Delta T_j \) of 50 K. This value of 0.75 is somewhat higher than that for bulk Mo and bulk Al obtained by usual friction test in air.\textsuperscript{8}

This may be due to the fact that our experiment was done in \textsubscript{N}2 for Mo || evaporated Al system.\textsuperscript{9}

Next, we have investigated the influence of soft metals, such as Ag and Cd, on the friction coefficient between the Mo and Al electrodes. Because soft metals provide a low shear surface when the thickness is several \mu m as reported in a previous paper.\textsuperscript{9}

The friction coefficient, \mu between 4 \mu m thick Ag film plated on Mo and Al electrode is plotted as a function of number of micro-sliding cycles in Fig. 6. \mu increases with the number of cycles up to 300 cycles, above which it takes the constant value of 0.6. This value is lower than that for the combination between Mo and Al electrode.

Figure 7 shows friction coefficient, \mu between 4 \mu m thick Cd film plated on Mo and Al electrodes as a function of the number of micro-sliding cycles. It was found that \mu takes the almost constant value of 0.25–0.3 independent of the number of cycles. The reason why the Mo/Cd || Al system exhibits lower \mu than that for Mo/Ag || Al system is that Cd with its hexagonal crystal structure is softer than Ag and has a lower work hardening exponent than Ag which has a cubic crystal structure.\textsuperscript{6}

Then, we investigated the influence of Mo foil inserted between the Mo and Al electrodes on the friction coefficient. Because, the friction coefficient between Mo and Mo is lower than that between Mo and Al. In addition to this, adhesion coefficient between Mo and Mo is very low.\textsuperscript{9} Figure 8 shows \mu for Mo || Mo || Al and Mo || Mo/Ag || Al systems as a function of the number of micro-sliding cycles. It was found that \mu for both systems had very similar values of about 0.4, which is very close to \mu between Mo and Mo in air.\textsuperscript{8} These results show that micro-sliding occurs between Mo and Mo foil only, because friction coefficients between Mo and Al, Mo/Ag and Al are about 0.75, 0.6, respectively as shown in Figs. 5 and 6. Furthermore, this result implies that Mo || Mo foil || Al systems have very similar properties.
system does not cause Al stick to Mo even if Al sticks to Mo foil and hence does not result in a Si crack.

Figure 9 shows the friction coefficient, $\mu$, for Mo $\parallel$ Mo foil $\parallel$ Al system as a function of load. This experiment was done in order to confirm the load quantity that can be applied to the package system for the reduction of the on-state voltage in large-area, high-power devices. $\mu$ was found to be decreased with load. This means that Mo foil slides smoothly below a Mo internal electrode even if the load becomes so high that contact resistance between the Mo inner electrode and the Al electrodes is sufficiently reduced.

Hereafter, we would like to discuss the elongation of the Al electrodes during the micro-sliding cycles.

### 3.3 Relationship between the friction coefficient and elongation of Al electrodes

As discussed in the previous section, the elongation of the Al electrodes causes the devices to short circuit when it exceeds over 300 $\mu$m. Lowering the friction coefficient may reduce this elongation. Hence, we have investigated the maximum elongation of the systems discussed above as a function of the micro-sliding cycles.

Figure 10 shows the results. It is clear that the gradient of $\mu$ against the number of cycles for the systems increases in the following order: Mo/Cd $\parallel$ Al ($\mu$: 0.25), Mo $\parallel$ Mo foil $\parallel$ Al ($\mu$: 0.4), Mo $\parallel$ Al ($\mu$: 0.75). For the Mo $\parallel$ Al system, the elongation of Al will exceed over 400 $\mu$m within 1000 cycles, which correspond to 20000 cycles of a thermal fatigue test. Alternately, for the Mo/Cd $\parallel$ Al and Mo $\parallel$ Mo foil $\parallel$ Al systems, the elongation of Al electrodes is less than 50 $\mu$m, even when the number of micro-sliding reaches 1500 cycles, which corresponds to 30000 cycles of a thermal fatigue test.

### 3.4 Investigation of voltage drop and reliability of the devices

Thermal fatigue tests were done for Mo foil inserted into 150 mm diameter large-area, high-power devices up to 30000 cycles. $\Delta T_j$ was fixed as 50 K. The mounting force was also fixed at 28 MPa. No degradation was found after the thermal fatigue test.

Further more, we have already reported that the voltage drop between Mo inner electrode and cathode Al electrodes (hereafter abbreviated as Mo/Al voltage drop) amounts to 25% of the total voltage drop in 50 mm diameter power devices. In addition, we have also confirmed that Mo/Al voltage drop can be reduced by 20% through the insertion of Mo foil between the two.

From the above results, it is concluded that Mo foil inserted between Mo inner electrode and cathode Al electrodes can reduce the voltage drop and enhance the reliability of the power devices.
4. Conclusion

(1) The equipment to reproduce the friction behavior between a Mo inner electrode and Al electrodes in a thermal fatigue test of large-area, high-power devices, has been developed.

(2) The friction coefficients between the Mo inner electrode and the Al electrodes varied substantially with the coating materials on Mo or with the insertion of Mo foil. The friction coefficients for Mo || Al, Mo/Ag || Al, Mo/Cd || Al, Mo || Mo foil || Al, and Mo || Mo/Ag || Al are 0.75, 0.6, 0.25–0.3, 0.4, and 0.4, respectively.

(3) The elongation of Al electrodes decreases as the friction coefficient is reduced. In the case of systems with the low friction coefficients, i.e., less than 0.4, the elongation was confirmed not to exceed the vertical distance between one Al electrode and another.

(4) A thermal fatigue test shows the high-reliability of Mo foil inserted into 150 mm diameter large-area, high-power device.

Acknowledgements

The authors express their sincere thanks to Dr. Y. Aono, Dr. N. Monma of Hitachi Research Laboratory, HRL and...
Fig. 7 Friction coefficient for the Mo/Cd∥Al system as a function of the number of micro-slidings.

Fig. 8 Friction coefficient for the Mo∥Mo foil∥Al and the Mo∥Mo foil∥Al system as a function of the number of micro-slidings.

Fig. 9 Friction coefficient for the Mo∥Mo foil∥Al system as a function of the load.

Fig. 10 Elongation of Al electrodes as a function of the number of micro-sliding cycles.

Mr. S. Sakurada of Hitachi Works for their encouragements.

REFERENCES


