An automated in-situ contact evaluation (ICE) system for MEMS/NEMS electrical contact material evaluation

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An automated in-situ electrical contact evolution (ICE) apparatus is described, the system allows the study of electrical contact performance at low contact force (<2 mN) MEMS/NEMS switching applications. The ICE system is built around a granite metrology frame and combines the controlled switching of surfaces with the ability to measure surface wear. This is achieved using a high precision motion system to move between the switching and the surface measuring positions. The surface is measured using a confocal optical sensor to provide a measurement of 3D surface wear. In this paper we describe an improved ICE system with the ability to measure both static contact force and dynamic force during the switching process. A key requirement of the new system is the ability to measure adhesion forces between opening contacts. In this study a Gold coated hemisphere (radius 1 mm) is used with a Gold Coated (500 nm), multiwalled forest of vertically aligned carbon nanotubes (50 µm), referred to as Au/CNT. The system has been designed to allow a range of contact materials to be tested, providing a unique testing platform that combines the evaluation of switching performance and contact resistance measurement with the ability to monitor surface wear.

Key Words: MEMS, NEMS switching, electrical contact performance, 3D surface wear, contact force.

Introduction

The study of contact resistance and surface wear is critical to the development of Micro and Nano Electro-Mechanical System MEMS/NEMS switching devices for low power (dc, ac and RF) applications, where the contact surfaces have current flowing through the interface, referred to as “hot switching”. MEMS/NEMS fabrication technology has opened the door to switching devices which combine the advantages of mechanical switching, with the miniaturisation associated with nano-fabrication technology. Solid state switching devices (e.g. Transistors, MOSFETS, IGBT’s) have performance limitations related to capacitance and current flow, in and across semiconducting junctions leading to switching losses, heat generation and temperature dependency. The advantages of MEMS switching are: high galvanic isolation when “off”, leading to zero power or signal leakage; and low resistance when “on”, leading to low power loss or heating and low-cost micro-fabrication. Reliability challenges posed by electrical contact fatigue have remained for the more demanding, hot switching condition where there is current flow. The reliability problem is caused by mechanical and electrical stress in the materials used at the electrical contact interface between the switching surfaces resulting in deformation and wear, leading to increased contact resistance or adhesion and device failure. Several material combinations have been proposed for the MEMS/NEMS switching solution [1-3], but to date there have been few commercially available devices, particularly for the more demanding hot switching applications.

In [4] an automated MEMS testing platform was introduced, to allow for the development and analysis of switching surfaces, shown in Fig.1. The automated in-situ contact evaluation (ICE) apparatus was developed to study contact performance for low contact force (<2 mN) switching applications. The system uses a metrology frame to combine the controlled switching of surfaces with the ability to measure the surface changes in-situ. After a defined number of switching cycles in position (a) in Fig.1, the surfaces are separated within the metrology frame and measured at position (b), then relocated to position (a) to a precision of +/-50 nm, as detailed [4]. The system has been used in studies of contact wear for MEMS switching contacts. In [5] an investigation was conducted of surface wear over a defined 1 million cycles, for a range of supply voltage (4 & 8 V) and hot switching current levels (20-50 mA). In [6] the ICE system was used to investigate “cold switching” with 4 billion cycles demonstrated with a dc power supply of 4 V, 6 µA. The surfaces used were the same specification as used in this work. A gold coated (500 nm) hemispherical (1 mm radius) surface in contact with a planar Au coated (500 nm) multi-walled vertically aligned carbon nano-tube surface (50 µm) we define as Au/CNT, [7].

In this study the ICE system is further developed to allow the simultaneous measurement of the both the static and dynamic contact force. The new system also includes an improved measurement of the surface wear. The integration of the force measurement follows a study [8] where a force sensor was integrated into a prototype switching system and used to identify force transients during the switch process. In [8] it was shown that there were two types of opening force transient, shown in Fig.2, the first (upper) is associated with a molten metal bridge process (MMB) [9], with a fluctuating force during the MMB, followed by a peak transient force as the contacts open, identified in the figure as 15 µN. The MMB process is shown with an increasing contact potential (voltage), over the 500 ns time frame, form 0.5 to approximately 0.8 Volts, before

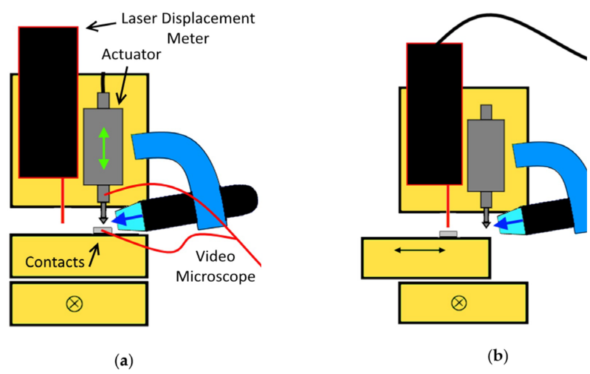

Fig. 1. A schematic of the In-situ Contact Evolution (ICE) Apparatus during a) switch cycling and b) measurement of the contact surface.

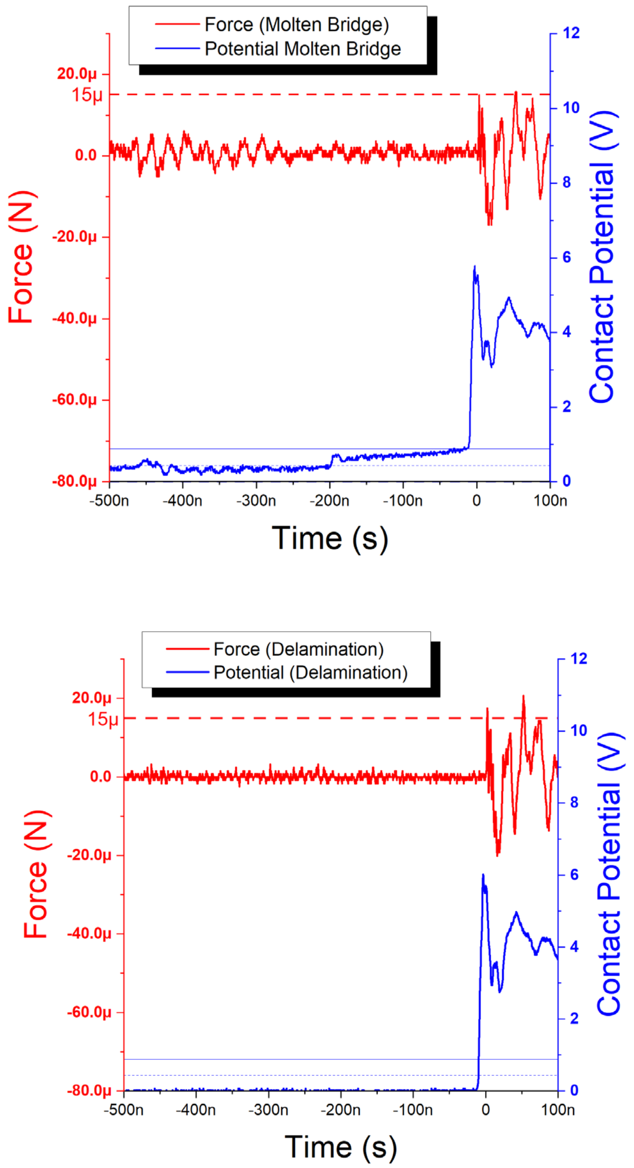

Fig.2 Transient force during the Molten Metal Bridge process (upper) and during the delamination/adhesion process (lower)

the contact opens to the open circuit voltage of 4 V. It is noted that there is a delay of approximately 20 ns between the opening of the contacts and the associated force transient. This delay is a consequence of the time taken for the vibration transient to propagate at the speed of sound to the force sensor. The lower graph in Fig 2, shows the force transient following an adhesion event. The contact potential (voltage) remains constant and stable until the contacts open, 20 ns before the force transient. There are no fluctuations in force prior to opening and at the opening event the magnitude of the force transient exceeds that measured during the MMB event, shown here to be approximately 18 µN. Gold on gold surfaces are prone to adhesion and this condition normally represents a failure in a MEMS/NEMS device, unless there is sufficenet restoring force to overcome the adhesion. In the ICE system the applied force from the nano-positioner is sufficient to force the contact open and, in the process, causes surface delamination and a peak transient force higher than the MMB process. The average peak transient force for the former sampled over 100 consecutive samples is 18.6 µN and 21.6 µN for the latter, [8].

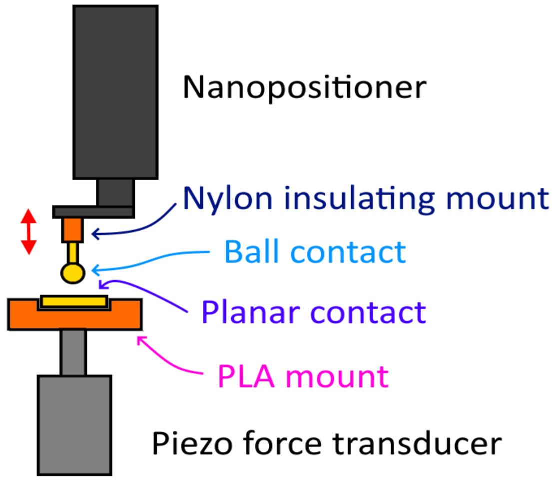

Fig 3. Modified ICE (In-situ Contact Evolution) system with force measurement

Integration of force sensing into the ICE system

In the former ICE system, [5,6] the contact force was inferred from a calibration of the force, contact resistance relationship for the material under investigation. In the new ICE system shown in Fig.3 the force is measured directly using a piezoelectric force transducer, Kistler Model 9207 with 115 pC/N sensitivity. The force transducer is linked to a charge amplifier (Kistler Type 5007 -3db frequency response 2.3 GHz), the force sensitivity is ~ 1 µN. The electrical contact surface under investigation is supported in the 3D printed PLA mount, mounted directly to the force transducer. The system allows for the direct measurement of adhesion force, the transient forces during switching and the static contact force. The static force is measured indirectly by extending the piezo-driver stage referred to as the nano-positioner in Fig. 3 (Thorlabs, Newton, NJ, USA), pushing the upper ball contact into the lower planar contact. The actuator position is linked to the contact force as the nano-positioner has exceptionally high modulus (blocking force of 1,000 N at 60 V). To detect the static force the contacts are closed to a set position, then rapidly retracted to the fully

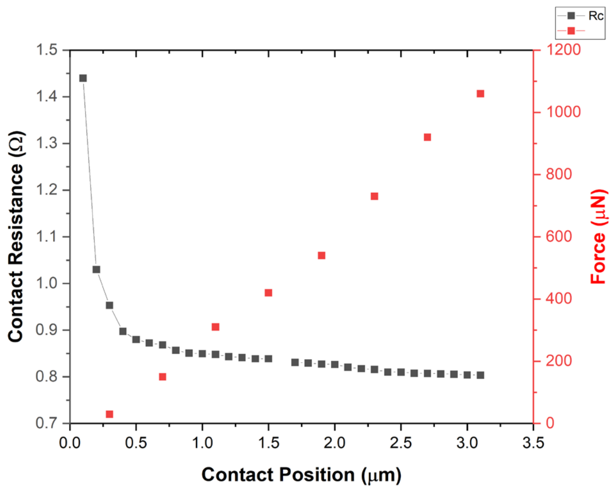

Fig 4. Calibration of static force with the nano-positioner displacement, and the corresponding contact resistance for the Au coated ball with the lower Au/CNT surface.

open position. The dynamic response of the piezo-force transducer, as shown in Fig. 2, is used to determine the peak force at opening and this is used to define the static contact force. The force range is up to a maximum of 2 mN. Fig.4 shows the nano-positioner displacement with the measured static contact force using the method described, for the contact materials under investigation. The relationship between the applied force and the nano-positioner displacement is linear, and the relatively low elastic modulus of the Au/CNT surface reflected in a 3µm displacement of the nano-positioner; as the much harder hemispherical surface sinks into the softer Au/CNT surface. The corresponding contact force is approximately 1 mN. The corresponding contact resistance is shown in Fig.4 measured using an established 4-wire methodology [4]. The force contact resistance relationship can be used to measure the effective resistivity of the two contact surfaces, [11].

Surface morphology evaluation.

In a further development the laser displacement meter (confocal) used in the former ICE system, shown in Fig.1 has been replaced with a confocal white light sensor. The new system has two advantages, firstly the smaller sensor can be positioned closer to the switching position reducing re-positioning errors and secondly improving the accuracy of the surface wear evaluation. The laser confocal sensor has been shown to overestimate the surface position when there is a discontinuity such as a shape edge on the surface, and this leads to an over estimation of surface roughness. Fig 5 shows a reference au/CNT surface measurement after 1 million switching cycles, with 20 mA, 4 V, dc. The surface has been cycled with a novel ball contact surface, selected to minimise surface adhesion. The un-damaged portion of the surface, in the top left segment, highlighted as the square in Fig.5, (0.2 x 0.2 mm) has a surface roughness of Sq = 0.485, after a 80 µm gaussian surface filter has been applied. This result is consistent with previous published values of a similar Au/CNT surface, [10]. Fig 5. Shows the circular wear region in the lower central region

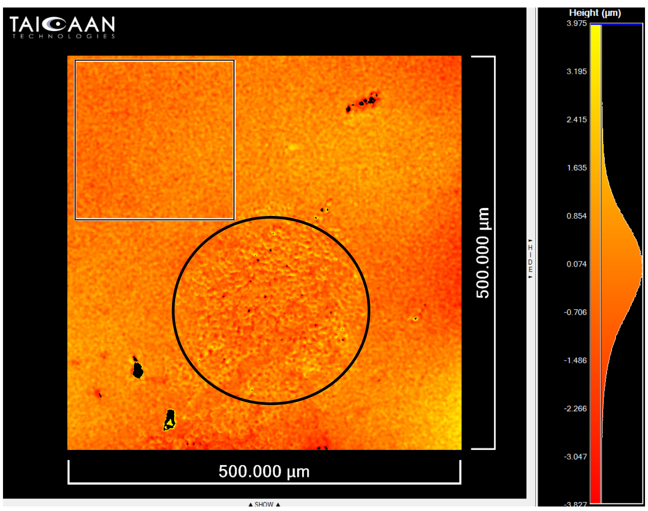

Fig.5 Surface wear of Au/CNT surface measured after 1 million switching cycles, 20 mA 4V dc, using the ICE (mark 2) with WL sensor. Data is 1001 x 1001 over 0.5 x 0.5 mm. Dark area are dust particles.

(highlighted) where the surface has been made rougher by the action of the switching process.

Conclusions

The ICE system first described in [4] has been developed to include the measurement of both static contact force and the dynamic force during the electrical contact opening event. The former is critical to the force, contact resistance relationship while the latter is essential for the detection of adhesion. An adhesion event during MES/NEMS switching is normally a failure event as the contact surfaces cannot easily be re-opened. The ICE system using a directly driven nano-positioner is able to overcome the adhesion and as consequence we are able to measure the adhesion force directly. The system shows that there is a clear fluctuating force prior to the opening event when the contacts are switched under normal conditions with a molten metal bridge occurring between the opening contacts.

The ICE system has also been modified for an improved measurement of the 3D surface, with a confocal white light sensor used to scan the worn surface.

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