The influence of circuit parameters on Molten Metal Bridge Energy in a MEMS relay testing platform

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Abstract— **A MEMs relay testing platform is described, consisting of an actuation cantilever and switching contacts, where the contact force is determined though the contact resistance measurement of Au coated Multi-walled Carbon Nano-tube (Au/MWCNT) sensor surface. The Au/MWCNT surface is further investigated under a range of DC switching condition to determine the limits of the non-arcing condition, or the minimum arcing voltage and current. The range of circuit conditions is also used to determine the degradation process of the surface in the non-arcing condition through the investigation of the molten metal bridge transient voltages, which have previously been linked to the failure of the surface as switching surface.**

Keywords-.

I. INTRODUCTION

Wear processes on the electrical contact surfaces, used in low voltage (2-12V) switching applications, exemplified by Micro-Electro-Mechanical (MEMS) switching devices or relays; can result in premature device failure, [1]. This becomes evident when the electrical contact surfaces are conventional metallic films. A proposed solution to minimize the electrical contact surface wear is to coat one or both surfaces with a sub-layer of carbon nano-tubes [2].

The process of switching an electrical load, even at the low voltage levels, is referred to as "hot switching" when related to MEMS relays; implying that the electrical load is outside the "dry circuit" condition; when the applied voltage and current have no physical influence on the surface [3]. A typical MEMS relay "hot switching" electrical load of, 1mA-10mA and 4V; although below the minimum arcing voltage associated with most commonly used metallic electrical contact surfaces (~12V); is above the softening and melting voltages for the metallic surfaces [4-6]. This leads to a transfer mechanism between the two surfaces known as "fine transfer", or molten metal bridge phenomena and this was first discussed in the context of the current study in [7]. The material transfer between electrical contacts in MEMS devices is similar to a problem encountered in switching devices used in telecommunication systems in the 1950's and 1960's. The research conducted during that period can be reviewed in [4-6]; however it is important to note that there is one important difference. Although the voltage levels used are comparable, the current levels are higher than those used in MEM relays, and typically of the order of 1A. It is apparent from the studies of "fine transfer" that a primary issue was the influence of the circuit inductance on the transient voltage during opening and closing. Although the steady-state circuit voltage (e.g. 4 V) is below the minimum arcing level (~12 V), the presence of circuit inductance can result in local micro-arcing phenomena, as transient voltages exceed the minimum arcing condition. The mechanism of "fine transfer", without the presence of micro-arcing was shown to be related to the physical properties of the metals used. This can best be described with reference to the ψ, θ theorem [4], where ψ is the electrical potential and θ the temperature in a metallic conductor.

The voltage required to result in the melting temperature and the boiling temperature of Au, commonly used as the metallic contact surface in MEMS; is for melting, 0.43V, and for boiling, 0.88V. Both voltage levels are below the steady state voltage used in MEMS relays. It therefore follows that during each opening and closing operation, the Au surface will result in the formation of a molten bridge, leading to the wear process. The direction of the wear or transfer process is far from trivial, and not fully described; an overview of the thermodynamic and other process is given in [5].

Metallic surfaces used in MEMS relays are often films on Si or other surfaces. If Au is used then the hard (Si) substrate limits the contact area, and even at low force (mN's), the resultant contact pressure can be sufficient to produce cold welding; thus resulting in delamination of the Au films during opening and closing. A proposed solution to both the "fine transfer" and the potential cold welding problems of Au surfaces has been to use a sub-layer of structured carbon nanotubes (CNT's). Recent studies have focused on the application of carbon nanotubes (CNT) as a potential solution to the MEMS electrical contact problem, where a "forest" of vertically aligned, multi-walled carbon nanotubes (MWCNT) sputter coated with a conductive gold layer. This is referred to here as Au/MWCNT. This creates a CNT composite surface, with a high conductivity surface layer and a compliant under layer. In [8], a modified nano-indentation apparatus was used to determine the contact resistance as a function of contact force (1mN) and the data used to model the surfaces in [9]. In [10] the surfaces were tested under a range of current loading conditions and it was shown that the wear process although still dominated by the "fine transfer" process was further complicated at higher currents by apparent delamination of the surfaces, where the fine transfer process resulting from the molten metal bridge (MMB) thins the Au layer and then leads sticking and delamination. In [11] the MMB phenomena has been studied further on the Au/MWCNT surface and the MMB thermal energy used as an indicator of the failure phenomena. It was suggested in [11] that the roughness of the surface would affect the MMB duration. As shown in Fig.1. The idea proposed is that as the surface wears the initial roughness is smoothed by the MMB process from Fig 1a to Fig 1e; and that when the surface is smother i.e with lower roughness that the MMB bridge formation will cover a larger area. This idea has not been proven but it was observed in the same paper that as the contact surfaces wear with number of operations and close to the point of failure that the thermal energy of the MMB increases, suggesting a longer MMB period associated with a larger MMB area. The results are shown in Fig.2, for a Au/MWCNT surface mounted in a MEMS system with very low force (≈ 35μN), and with a 4 V and 50mA supply. The MMB energy is shown to increase from a stable 1.5 μJ to over 13 μJ at the failure point corresponding the increase in contact resistance also shown in Fig.2.

The objective of this paper is to investigate the same type of surface under a range of electrical loading conditions, to investigate the influence of the load on both the MMB transient at the opening phase and also to look for the onset of gap breakdown as voltage is increases. For the study we have selected two surfaces of differing surface roughness to investigate further the influence of the roughness on the MMB phenomena.

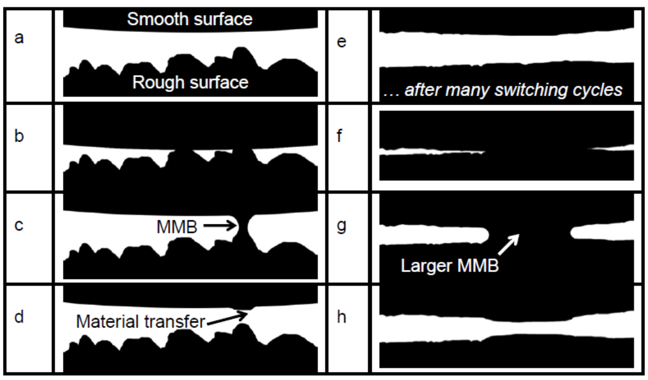

Fig.1 The evolution of MMB as a function of surface wear, [11]

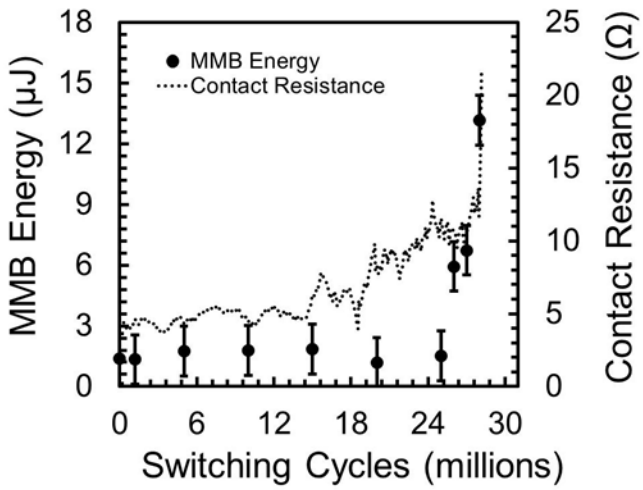

Fig.2 MMB energy and contact resistance versus number of switching cycles. Error bars calculated using standard error, for a Au/MWCNT surface in a MEMs system at 35μN and with a 4 V and 50mA load, [11].

II. Sample Fabrication

A. Sample Fabrication

The fabrication of the Au/MWCNT composite is reported in [10]. A 1.5 nm layer of Al_2O_3 and a catalyst layer of 10 nm Fe are initially sputtered on a silicon wafer. Vertical aligned MWCNTs are grown using thermal chemical vapor deposition (CVD), and ethylene is used as carbon source gas. The growth temperature is 875°C, and the growth time is used to control the height of MWCNT. The last step is sputtering a gold layer onto the nanotubes forest. In this paper, a composite with 500-nm Au sputtered on 50-μm CNT is investigated.

Fig. 3 shows a typical composite surface, with the nanotubes aligned. It is shown that the penetration depth varies from sample to sample; and is 6 μm for the samples presented.

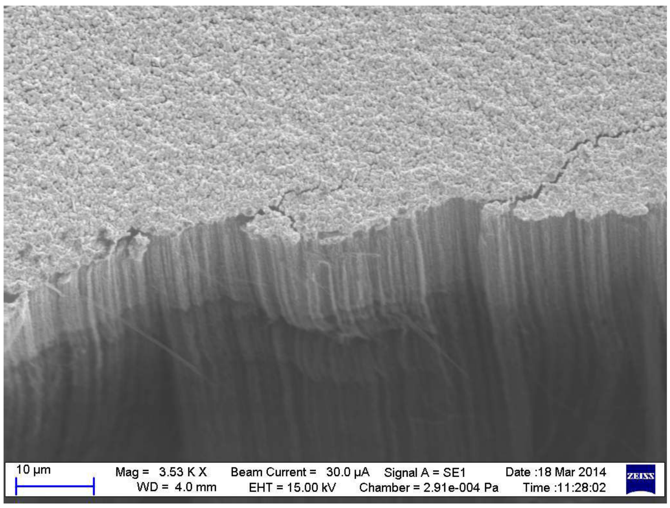

Fig. 3. SEM image of a nominal 500 nm gold coated on 50 μm CNT surface (angle of incidence of 55°), showing the penetration of gold into MWCNT. The surface is cut using a sharp slider to see the cross section of the surface.

B. Surface characterization

Two surfaces have been sued for the investigation, a rough surface and a relatively smooth surface. A TaiCaan XYRIS 4000WL 3D optical profiler was used to evaluate texture the composite surface. This measurement method is used as it offers the capability to evaluate the entire composite surface while retaining a high vertical measurement resolution (10nm). Fig. 4 shows the smooth surface over a 0.2mm x 0.2mm measurement region. The peak to valley measurement for the cross section highlighted is 1.651µm. Fig. 5 shows the rough surface over a measurement of the same area 0.2mm x 0.2mm, where the cross section shows a peak to valley of 31.425 µm.

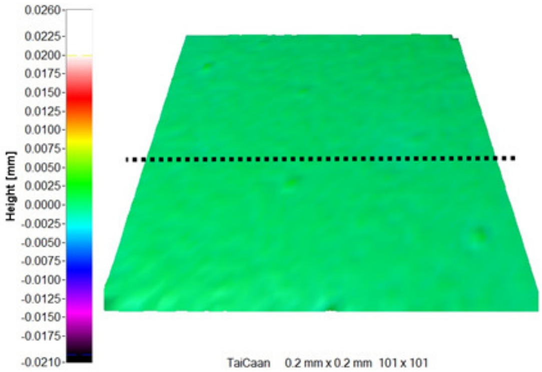

Fig. 4 Peak to Valley on 2D Cross Section (along dotted line) 1.651um

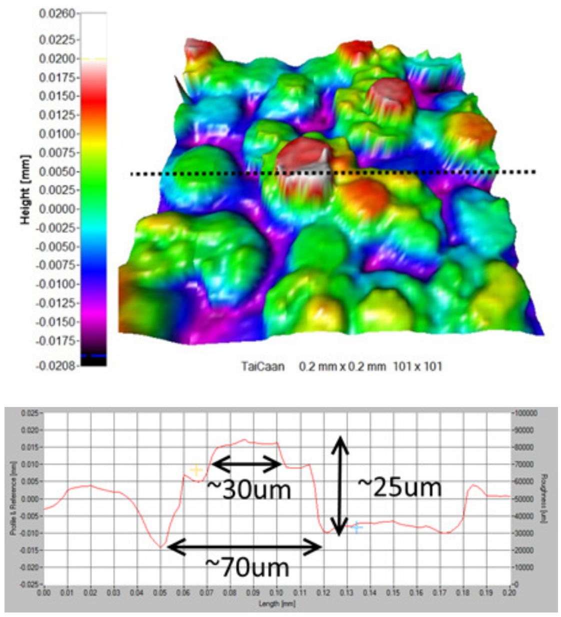

Fig. 5 Peak to Valley on 2D Cross Section (along dotted line) 31.425um

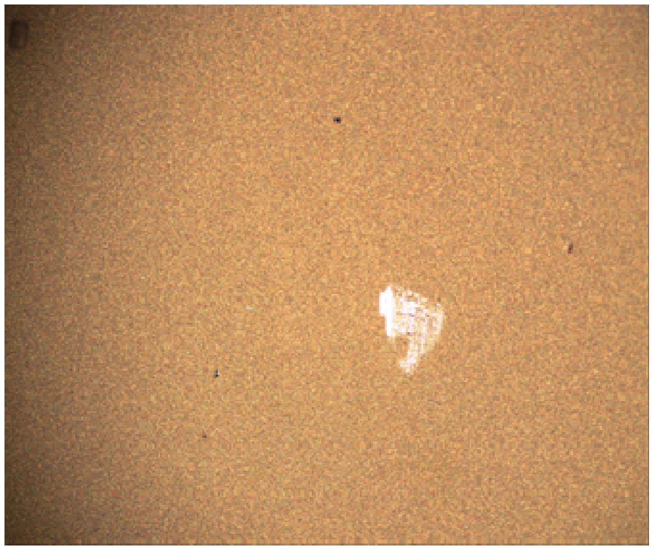

Fig 6. An image of surface in the Fig.4 over an area of 3mm x3mm

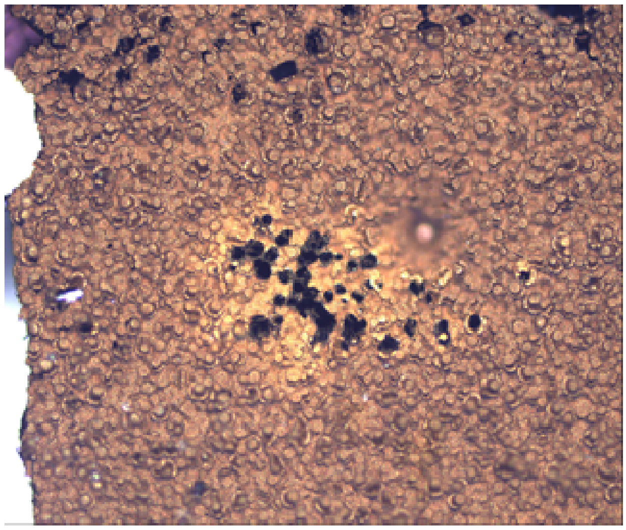

Fig.7 An image of surface in the Fig.5 over an area of 3mm x3mm

The rough surface shown in Fig's 5 and 7 consists of flattened peaks ~30um in diameter at the tip and ~30um in height. The composites were characterised for their variation in surface amplitude using a measured evaluation area of 1mm x 1mm and 201 x 201 data points (every 5um). The variation in amplitude was quantified statistically using the areal arithmetic mean absolute roughness parameter (Sa). A 0.25mm Gaussian filter was applied to the data to remove the influence of long wavelength surface features on the Sa parameter that do not influence the contact dynamics. The Areal surface roughness of the rough sample is Sa = 7.822um with a 0.25mm Gaussian filter, 1mm x 1mm, 201 x 201 measurements. The Area surface roughness of the smooth surface Sa = 0.231 with a 0.25mm Gaussian filter, 1mm x 1mm, 201 x 201 measurements.

C. *Experimenatl Method*

The experimental apparatus is the same as described in [10], and a schematic of the testing system is shown in Fig. 8. The setup is mounted on an anti-vibration workstation in an environmental controlled room with average humidity at 60.6% (variance of ±10%) and average temperature at 20 ºC (variance ±1 ºC). To simulate the repeated switching behaviour of MEMS switches, the Au/MWCNT composite was attached to a PZT cantilever which was actuated by a function generator. The contact force was 1 mN, and the load voltage was 4 V for all variation in current experiments presented. The experiments were performed with load current values of 10, 20, 50, 100 and 200 mA. To investigate the influence of the voltage on the MMB the current was held at 50 mA and the voltage varied from 4, 6, 8, 10, and 12 V. In all cases the surface is switched for 50 "Hot switching cycles", for a particular load condition. The point of contact is then moved and the test repeated at a new location on the surface for a new load condition. The voltage and current transients are stored and then evaluated for the thermal energy of the MMB for each switching operation, [11].

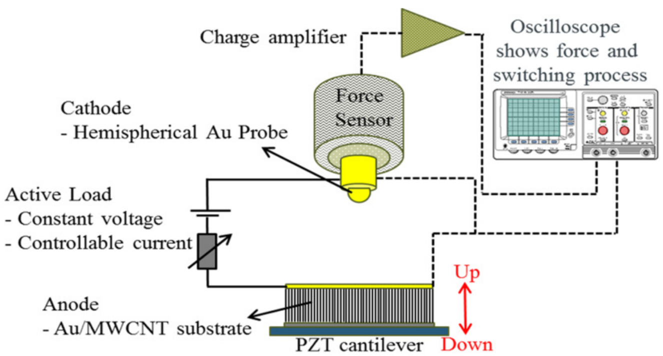

Fig 8. Schematic of the test apparatus used for the hot switching tests.

III. RESULTS AND DISCUSSION

A. *Smooth Au/MWCNT surface.*

Fig's 9 and 10 shows the influence of the load current on the MMB energy over 50 switching cycles for the smooth surface described in Fig's 4 and 6, for the variation of the load current. Fig 9 is for all current values while Fig 10, focuses on the lower current values which are not clearly shown in Fig. 9. The first point to observe is that for 50 mA the MMB energies are lower here than in [11], with a typical average value of 100 nJ in Fig.10 compared to 1500 nJ as shown in Fig.2, [11]. The surface in [11] although not identical has a similar roughness value to the surface used here. The key difference between the two results is that a different test apparatus was used. In [11] the tests were performed on MEMS beam with a contact force of 35 µN compared to the PZT beam used here with a higher force of 1000 µN or 1 mN. It is conceivable that the lower contact force results in a lower opening velocity and thus extending the time period of the MMB, and increasing the MMB energy. This would need to be investigated further.

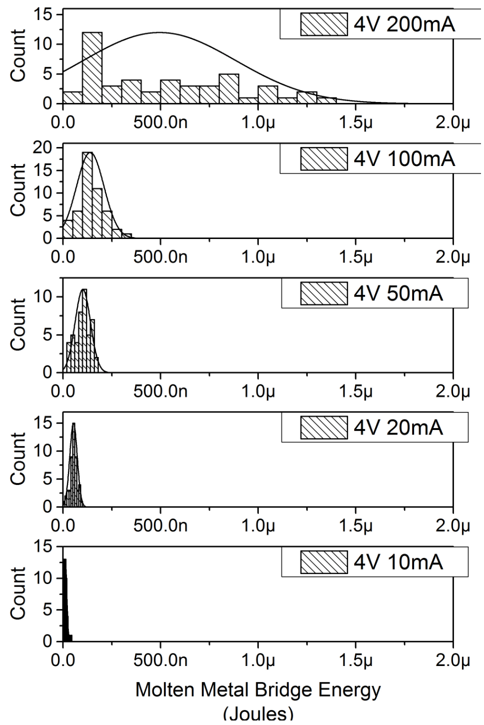

Fig.9 MMB Energy for smooth Au/MWCNT surface, for 4V, and varying load current

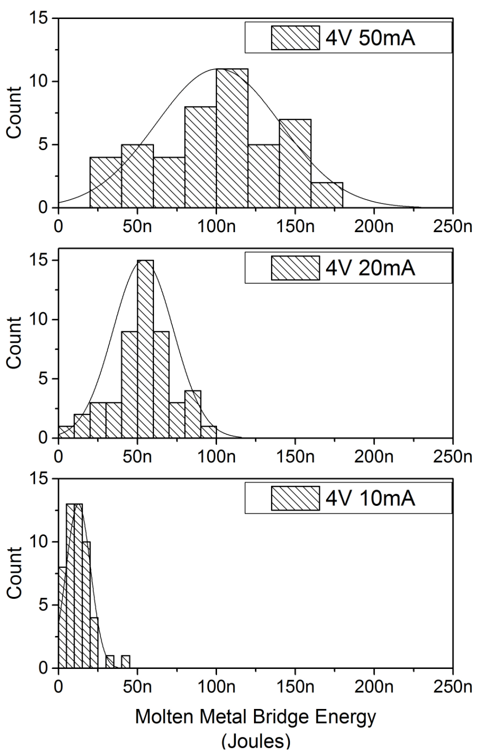

Fig.10 MMB Energy for the Rough Au/MWCNT surface, for 4V, and varying load current.

The MMB energy data in Fig. 9 shows the variability of the MMB process, with Gaussian curves modelling the variability. The higher the current the higher the energy as expected but also the higher the variability. Fig. 10 shows the same characteristics for the three lower load current values. The data in Fig.11 shows the influence of load voltage, and as expected there is no apparent tend with the supply voltage.

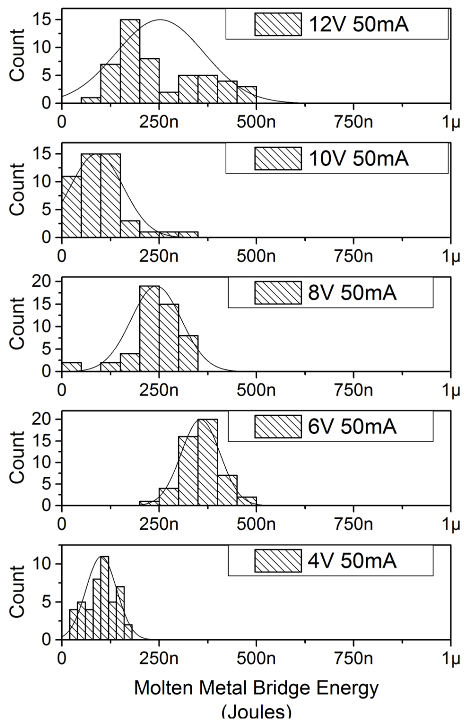

Fig.11 MMB Energy for Smooth Au/MWCNT surface, for 50 mA, and varying load voltage.

B. The Rougher Au/MWCNT surface.

Fig's 12 and 13 shows the influence of the load current on the MMB energy over 50 switching cycles for the rougher surface described in Fig's 5 and 7, for the variation of the load current. Fig 12 is for all current values while Fig 13, focuses on the lower current values which are not clearly shown in Fig. 12. Again the MMB energy for the 50 mA are lower here (280 nJ compared with 1500 nJ) than in [11], but actually higher than for the smother surface in Fig 10. This result contradicts the suggest process in Fig.1, as is the key observation in this work. According to Fig.1 the rougher surface would be expected to have a lower MMB. This result is important as it now suggests that the increase in MMB energy over the lifetime of the device is not linked to the surface roughness changes.

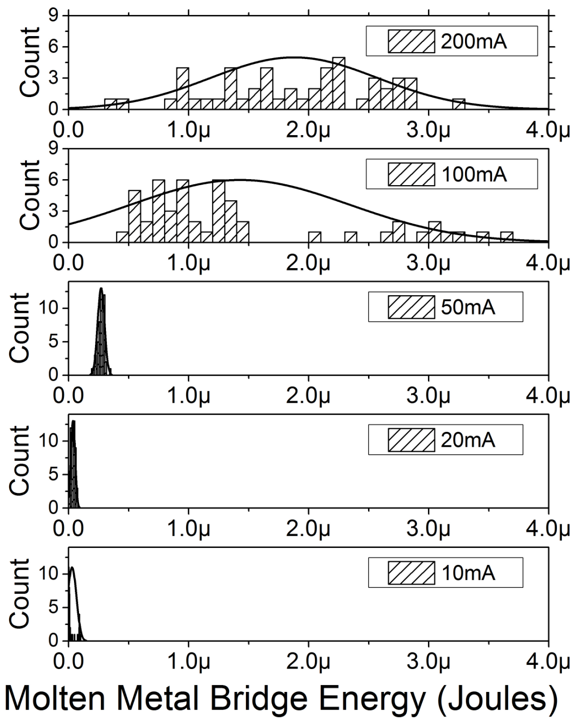

Fig.12 MMB Energy for Rough Au/MWCNT surface, for 4V, and varying load current.

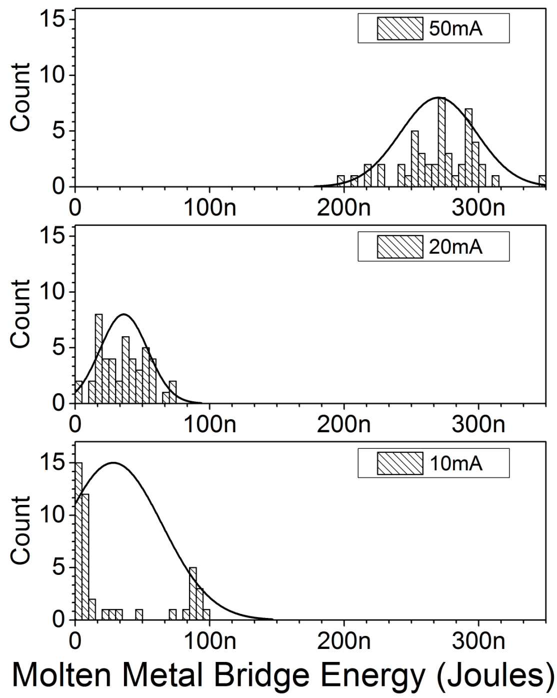

Fig.13 MMB Energy for the Rough Au/MWCNT surface, for 4V, and varying load current.

IV. CONCLUSIONS

The objective of the paper was to investigate the Au/MWNCT surface used for MEMS switching conditions, under a range of electrical loading conditions, to investigate the influence of the load on the MMB transient at the opening phase under “hot switching” conditions; and to test the hypothesis that the MMB energy was linked to the roughness of the surfaces. The results have shown that the MMB energy appears to be links to the surface roughness but in the opposite sense than expected. It is shown here that the MMB energy is linked closely to the load current and increases with the increase in surface roughness.

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