(Strongly coupled) micro-plasma formation during opening of a low current electrical contact

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Abstract: Micro-plasmas occurring during opening of a low current electrical contact are investigated by time-resolved electrical and optical measurements. Successive short duration metal vapor plasma events followed by reformation of the contact are evidenced and studied for different electrical circuit parameters. It is suspected that very dense metal vapor plasmas, which might be strongly coupled, are formed from the explosion of a liquid metal bridge.

Keywords: micro-plasma, electrical contact, dense plasma, metal bridge, transplosion

1. Introduction

Electrical contacts are used in almost every electrical device. Understanding their basics was driven by the need for reliable low voltage interrupters for various applications [1]. Nowadays a renewal of research activity is motivated by the increase of power consumption in these devices in automotives [2] and satellites [3].

Pioneer research demonstrated the presence of a molten metal bridge during opening of low current electrical contacts [4]. Although the formation, stability and shapes of these bridges have been extensively studied, the process of rupture, which finally opens the contact, remains unexplained. Llewellyn Jones [5] observed with high-speed photography that a short duration metal vapor micro-plasma of great brightness could be created from the exploded molten bridge material. He suspected an extremely high plasma density. Metal plasmas are known to be non-ideal under certain conditions [6], in particular close to the liquid-vapor transition [7]. It can therefore be suspected that the metal plasmas created just after the explosion of the liquid bridge can be strongly coupled. This results in drastic changes in plasma properties such as electrical conductivity or optical absorption [7], which might influence the physics of the early phase of contact separation.

In section 2 we first present the experimental set-up and describe the observed micro-plasma activities in the sub-micrometer gap between the wires. The experimental results are presented and discussed in section 3 and summarized in section 4.

2. Experimental

To investigate micro-plasmas during the opening of an electrical contact, two contacting, current-carrying wires are separated under controlled atmosphere by means of a piezoelectric actuator (Fig.1). The distance between the wires was controlled within the nanometre range (10nm step) by a vacuum compatible piezo-actuator (New Focus Picomotor^{TM} Model 8310-V), with a separation speed up to 17μm/s. The whole arrangement was mounted in a UHV vacuum chamber and various gases up to atmospheric pressure have been used.

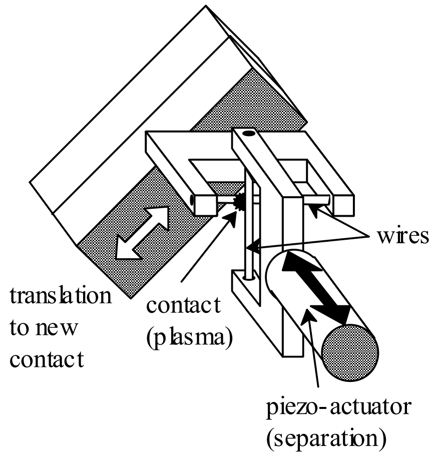

Fig.1 Experimental arrangement for contact opening

The electrical circuit of the experiment is shown in Fig.2. The contact voltage and current have been measured by commercial probes with high frequency bandwidth (LeCroy AP015, DC-50MHz, Bergoz FCT-028 10:1, 1.6GHz, and LeCroy PP006 1:10, 500 MHz). The light emitted from the micro-discharges has been collected by an optical fibre and detected by a fast photomultiplier tube (Hamamatsu H6780 with amplifier C6438-01, DC-50MHz). A gated intensified CCD camera (Princeton Instrument PI-MAX 16bit, >2ns gating, 1024x1024 pixel) mounted on a monochromator (ARC SP275) was used for optical emission spectroscopy of the different arcing events.

Several contact opening experiments were recorded for each condition in order to check the reproducibility of the micro arcing. In particular, for each experiment the contact position on the wires was changed and the wires were carefully cleaned before installation. As wire materials, 0.5mm diam. polished Neyoro, (gold alloy containing platinum, silver, zinc and copper), Paliney (palladium silver-based alloy) and tungsten wires have been used. The wires were inspected *ex situ* by optical microscopy to visualize the damages due to the discharge.

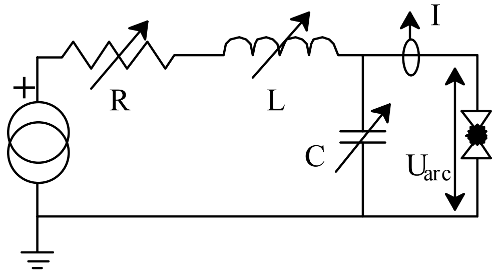

Fig.2 Schematic of the electrical circuit

Fig.3 shows a typical measurement of the voltage, current and photomultiplier signals during the contact opening. Several distinct events (up to more than 10 depending on the conditions) occur before final contact opening. A fast oscilloscope (LeCroy WP950, 1 GHz) operating in the sequence-triggering mode was used to record the successive events. This triggering mode allowed recording the different arcing events with high time resolution, regardless of the comparatively long time between them.

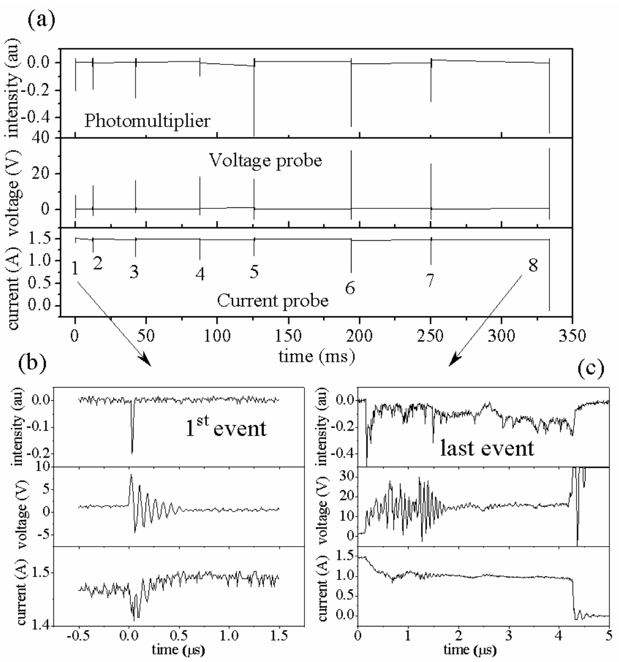

Fig.3 (a) Raw data from the photomultiplier, voltage and current probes (R=30Ω, I=1.5A, 17 µm/s opening speed); detail of the first (b) and last (c) events.

The arc interruption is followed by exponentially-damped oscillations driven by the energy stored in the external electrical circuit. For very small wire separation the electrical contact is not interrupted but the current recovers until a new event occurs. Before arcing, which is accompanied by light emission, a liquid metal bridge between the separating wires is formed. The following explosion or vaporization of the bridge leads to the micro-discharge. During such an event, the current delivered from the power supply decreases rapidly in a first phase (Fig.3b). This period finishes suddenly and the current recovers exponentially to its starting value. During this recovery no light is emitted indicating the absence of any plasma. The plasma melts sufficient material so that a liquid bridge can be re-formed, establishing full electrical contact again. However, if the separation of the wires is too large the final contact opening follows the arc interruption (Fig.3c). During a typical contact opening experiment, as reported here, the final contact opening gap has a separation of about 5-6 µm, occurring about 0.4 s after starting the wire movement. The distance of separation where contact interruption occurs depends on the wire material, gas pressure and on the external electrical circuit.

3. Results and discussion

3.1 Experimental results

The dependence on the number of events, the event duration, the appearance time of the event after the start of wire movement and the arc current are investigated as a function of the key elements in the electrical circuit such as resistance, inductance, and capacitance.

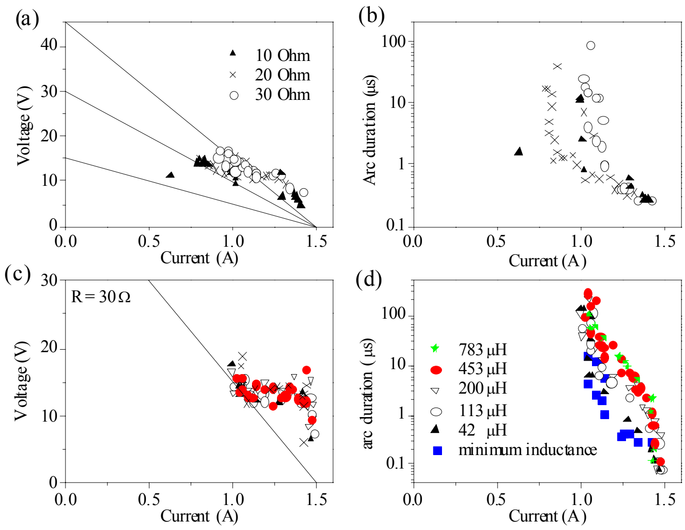

Fig.4 Voltage-current characteristics with the corresponding load lines (a, c) and arc duration vs. current (b, d) for various resistances and inductances. (Neyoro, 1.5 A).

The voltage-current characteristics as well as the arc duration vs. current show roughly the same dependence for all the resistances (Fig. 4a and b) and inductances (Fig. 4c and d) used. For the first events the mean arc voltage is above the load line and further approaches it for later events.

The arc duration varies over 3-4 decades from below 100ns for the first events up to 100µs for the last events. The longest durations are found when the interrupting arc takes place.

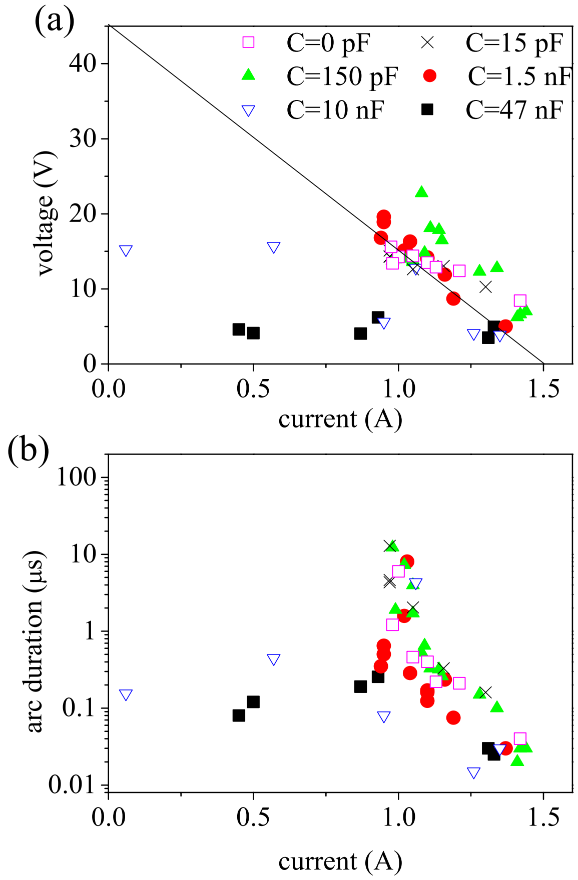

Fig.5 Effect of a capacitance on the voltage-current characteristics (a) and on the arc duration vs. current (b).

A different behaviour is observed if a capacitance is added to the circuit. For low capacitance the voltage-current characteristic is similar to the above. However, for larger capacitance an important deviation is found (Fig. 5a and b). The discharge voltage remains small and nearly independent of the current which decreases to very low values. The arc duration considerably decreases below 100ns and for large capacitances of a few nF the arc duration remains roughly constant even for very low currents. Furthermore we observed a strong reduction of the number of arc events and a substantial decrease in time between the different events as in [4].

When the gas pressure was varied from ultra high vacuum (10^{-7} mbar) up to atmospheric pressure, no large difference is observed in the voltage-current characteristics and the arc duration vs. current, compared to the previously discussed results. However, the time distribution of the successive arcs after the first event is considerably extended for pressures larger than about 10-100 mbar (Fig. 6). In addition heavy damage on the wires were observed for the higher gas pressures, which could even lead to a complete melting. For the larger gaps investigated (a few µm), the well-known gas discharges are possible only for pressures higher than 10-100 mbar, where the electron-neutral mean free path drops below the gap size. However at smaller gaps, only metal vapour arcing occurs regardless the pressure. This is in agreement with Slade [8] who investigated electrical breakdown in small gaps.

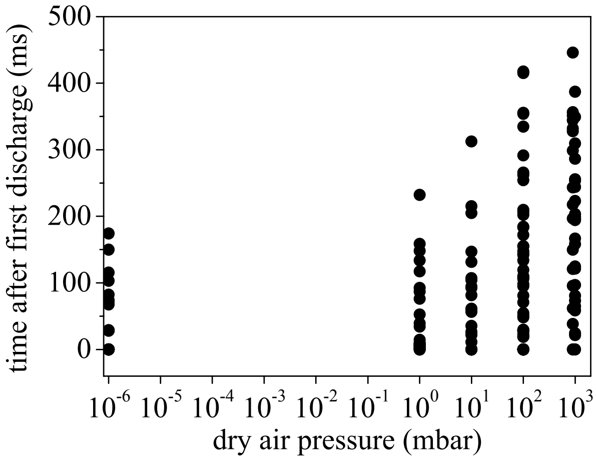

Fig.6 Time distribution of the successive discharges for different ambient air pressures.

A strong dependence on the contact material could be observed. In particular tungsten wires showed a number of events greatly reduced compared to Neyoro and Paliney. In addition, the time between the individual events decreased drastically. This effect is very similar to the one observed by adding a parallel capacitance to the opening contact (Fig.5).

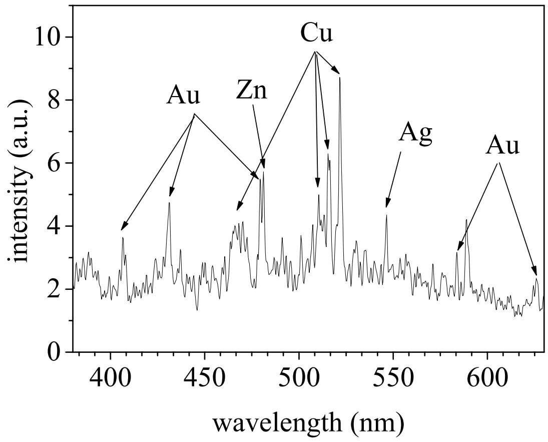

Fig.7 Optical emission spectrum averaged over several arcing events (30Ω, 1.5A, Neyoro)

Optical emission spectroscopy has been performed to investigate the plasma composition during contact opening. The light intensity is integrated over several arc events of one experiment. A typical spectrum is presented in Fig. 7 and shows that the plasma emission consists essentially of lines from the metal atoms originating from the wire. This also clearly demonstrates that the dominant discharge events are metal vapour plasmas even when operating in dry air at atmospheric pressure.

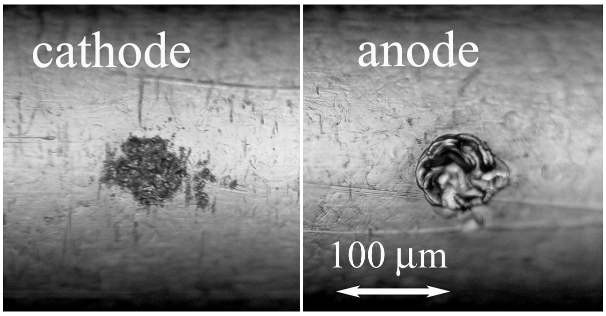

Fig.8 Micrographs of the craters on the electrodes (30Ω, 1.5A, 8 events during 0.37s, interruption at 6.3µm)

Ex-situ inspection of the wires by optical microscopy revealed several overlapping craters (Fig.8) coming from distinct arc events, which confirms that the arcs consist of metal plasmas from the eroded wires. The anode shows more melting probably from the bridge formation, whereas the cathode shows more erosion due to evaporation attributed to cathode spots.

3.2 Discussion

Just before the arcing event a voltage of about 1-1.5V is built up across the contact (Fig.3b). At this stage a molten bridge [4, 9] between the wires is already formed and the contact voltage is already higher than the melting voltage of the material [1]. In some cases, low intensity light could be detected from the incandescent bridge which is similar to the liquid wire in exploding wire experiments [10] where the metal can strongly superheat. Then sudden boiling happens and a "transplosion" [11] occurs, in which the metal expands explosively due to the high pressure gradient. As a result the electrical conductivity changes quickly by several orders of magnitude down to about 10^4-10^5 $(\Omega\ m)^{-1}$, estimated from the calculated instantaneous resistance (5 - 10 Ω) and assuming a 10µm diameter, 1µm long plasma volume. This value is very near to the calculation of the electrical conductivity of very dense metal plasmas [12, 13]. The resulting vapour has still a very high density and the discharge might only be initiated by pressure ionisation, thanks to lowering of the ionisation energy level due to the extremely high density. Therefore the first part of the discharge pulse is supposed to be a non-ideal plasma originating from the liquid-gas transition. Moreover, the voltage is just below the minimum arc voltage necessary for classical ionization. Very similar observations and interpretation are given already in the early work of Holm [4]. If the contact gap is larger then a few micrometers the mean free path of the electrons at the end of the plasma pulse is shorter then the gap dimension. In this case, a stable self-sustained discharge can be established. Such a transition is seen in Fig. 3c. At first the spiky light emission and the oscillation on the voltage trace indicate the presence of individual plasma pulses which then evolve to a more continuous light and a constant voltage typical of classical metal vapour arcs [14].

4. Summary

Formation of dense metal plasma is observed from electrical contact separation at low current and very small gap. The electrical and optical emission properties of such plasmas have been investigated for various ambient pressures and electrical circuit parameters. It is suggested that a liquid metal bridge formation is followed directly by a transition to a supercritical fluid which undergoes a "transplosion". This leads to strongly coupled plasmas which evolve, by expansion, into non-equilibrium metal vapour discharges. Further work is underway to show the non-ideality of the dense plasmas in the early phase.

Acknowledgements

This work was initiated by ESTEC (Contract No. 18700/04/NL/Sfe). The authors would like to thank P.A. Mäusli and G. Feusier from RUAG Aerospace and G. Migliorero from ESTEC for support and comments during the project.

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