A study of nano-scale electrical discharge characteristics for automotive sensor applications

Hae Woon Choi and Manbae Han
Department of Mechanical and Automotive Engineering,
Keimyung University, 2800 Dalgubeol daero, Daegu, Korea

Abstract
To study the relationship between spark ignition and the gap in the nano-scale region, the electric potential was applied to between a Pt-Ir tip and a gold substrate. The tip was sharpened by electro-chemical etching process in the solution of $CaCl_2$, H_2O and acetone. The radius of tip was measured to be around 200nm and attached to the scanning probe microscope to control the gap between the tip and the substrate. The electric potential of 10V to 80V was applied to initialize the spark. The gaps and the current profile were measured to analyze the characteristics of spark ignition. A spark sustaining time was measured to be between 50ns and 200ns depending on the applied electric potential and the gap between the electrodes. The continuous electric discharge was successfully sustained up to 1 second of spark or arc time. The developed process can be applicable to the micro-scale fabrication of automotive sensors as a similar concept of GTAW.

Key Words : automotive sensor, electric discharge, SPM, nano-gap, micromicro-scale device

1. Introduction

In the automotive engineering, the role of sensors in electronic control unit is getting more important for the safe driving and the reduction of exhaust emissions. Due to the operating condition and the space limitation of the sensors, the sensor design and its fabrication need to be more miniaturized without sacrificing its stability. Recently, a significant progress has been made towards the miniaturization of the sensors in automotives, semiconductors, micro-devices, and biomedical devices using the microelectromechanical systems (MEMS) technology[1]. As those devices becoming functional and complicated, more fundamental studies are needed in such scales. Miniaturization is important not only in that sensors can reduce the size of device assembly, but also it consumes lower energy, provides higher stability and offers more stable dynamic range as well as lower fabrication cost. Such miniaturized devices are now extended to the fabrication of actual micro-scale devices such as power cells, micro-thermophotovoltaic system, and micro-scale combustion engines [2,3,4].

The topics of the electrical discharge in micro-/nano-scale have been explored by many researchers to solve the issues such as spark in a narrow gap or unexpected discharge in micro-devices [5], and the results have provided an insight to researchers for nano-lithography, apertureless focusing, and probe-based machining of structures and devices [6]. However, while demands for miniaturization have increased rapidly, many fundamentals in micro-/nano-scale are not quite developed yet due to its invisibility and characterization scaling issues. One fundamental issue in miniaturization is spark in the very close gap in micro-scale devices where the unit electric potential increases dramatically as the gap is reduced to nano-scale.

In this paper, the mechanism for electric discharge in the nano-scale gap associated with a very sharp tip is presented to understand the electrical discharge characteristics. By analyzing the signals from oscilloscope in the nano-second range and modifying the surface by SEM, one can estimate the characteristics of nano-scale which can be observed electrically and optically.

2. Experiments

2.1 Power source and measurement - A source and measuring unit was integrated and prepared as shown in Fig.1. A scanning probe microscope (SPM) was used to move a very sharp tip toward a gold substrate where another electrode is connected. To control the amount of current flow, a current limit diode was inserted in the line from a power supplier to SPM. An AC current probe responding to the signals with the frequency range of 25kHz ~ 1GHz was used to monitor the transient current flow during electrical discharging. A customized program was coded to control the movement of a sharp tip. The typical steps of experiment procedures are described below.

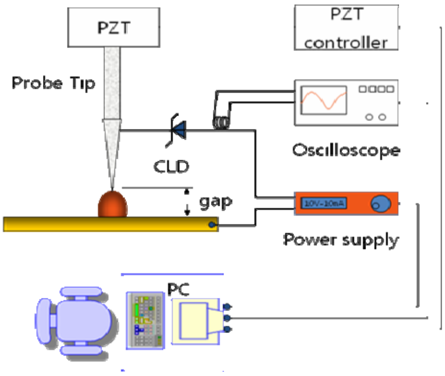

Fig.1 Experimental setup

Step 1. Lower the tip toward the substrate with a 20nm increment
Step 2. Stop the tip when current flows with maximum rate
Step 3. Withdraw the tip with predetermined amount of gap
Step 4. Keep a constant gap and apply electric current with a certain voltage

2.2 Tip etching procedures – To sharpen the tip an electrical etching procedure was developed. The system is composed of an AC power supply, a positioning system, a current transformer, electrodes and beaker which contains the electrolyte solution. The tip was made of 80:20 Platinum/iridium (Pt/Ir) alloy and its diameter was 250nm. The wire was cut and roughly polished with a fine silicon carbide paper, then rinsed with flowing acetone to remove all debris that may affect the bulk etching quality.

After finishing rough polishing, the bulk etching process was performed by using the mixture of solutions, $CaCl_2$, H_2O and acetone. The optimum dilution of solution was developed and the best result was found at 52g of dry $CaCl_2$, 200ml of distilled water and 200ml acetone which was expected to control the hydrogen bubbles. Approximately 40ml of acetone was vaporized. The tip of the Pt/Ir wire was dipped vertically into the solution, 1mm along with a graphite counter electrode at the other end. A potential of 20 AC RMS was applied at 60Hz between the electrodes. The voltage was continuously applied until the current reached below 30mA. When the current dropped below 30mA, it was turned off to avoid the destruction of the sharp tip.

Fine Etching: For the better sharpness of the tip, the micro-polishing process had been conducted. The tip had been re-polished throughout the 2mm loop made of a copper coated steel wire. The solution, then, had been mixed with approximately 52g of dry $CaCl_2$, 200ml H_2O, and 200ml HCl by volume. A potential of 2VACrms was applied between the tip and the loop electrodes. The tip was finally cleaned via ultrasonic cleaning and rinsed in the flowing acetone. Expecting a better result, the tip had been slowly raised out of the solution when the current reads at 100mA. The typical range of a tip radius was varied between 100nm and 500nm, and the change of the current flow on the current meter was one way to estimate the tip sharpness. The gradual drop of the current to 30mA from 100mA could make the tips sharper than the sudden drop of current.

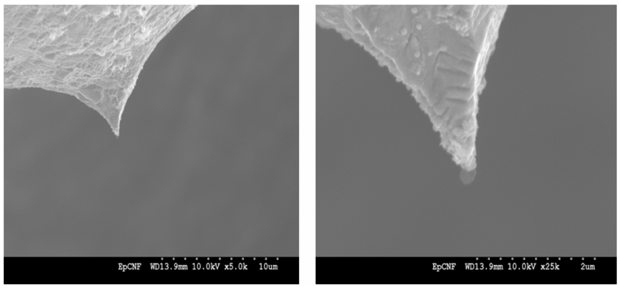

Fig.2 Etched tip

A general shape of the tip after etching is shown in Fig. 2. The sharpness varied between 100nm and 200nm depending on the dilution of the solution and the variation of the etching time. The sharpened tip can be partly visible by a diffractive backlight from SPM station as shown in Fig. 3.

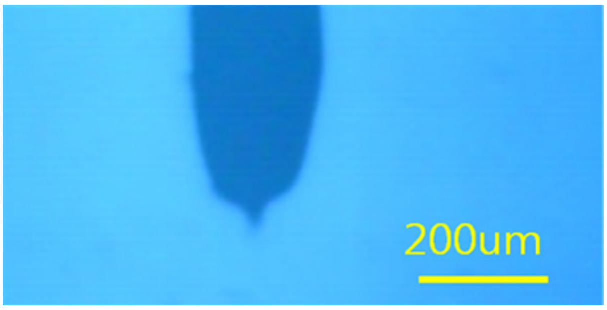

Fig.3 Mounted tip shape by a diffractive light

3. Results and discussion

To characterize the electrical discharge in the nano-scale gaps, a variable voltage was applied to between an electric tip and a substrate. The detailed experiment sets and results are described in Table 1, where three distinct regions were evident. The first set "⊗" is a region where no spark occurred under the given conditions. It is believed that the electric potential is not sufficient enough to initialize the spark. In the second set with a symbol "⊕", marginal sparks were observed in the experiments. In this region, spark is not always guaranteed, but the spark occurred stochastically rather than deterministically. The main reason of unstable spark is believed to be caused by unstable experimental conditions induced by applied voltage, and the gap size. In the third region "▣", spark was always guaranteed in the experiment.

		Applied Voltage (V)						
		5	10	20	30	50	60	80
Gap (nm)	50	⊗	⊗	▣	▣			
	75	⊗	⊗	▣	▣	▣		
	100	⊗	⊗	⊕	▣	▣		
	200	⊗	⊗	⊕	▣	▣	▣	
	300		⊗	⊕	⊕	▣	▣	▣
	500		⊗	⊕	⊕	⊕	▣	▣
	600					⊕	▣	▣
	1000						⊗	⊗

Table 1 Experiment sets (⊗: No spark ⊕: Marginal spark, ▣: Guaranteed spark)

To monitor the electrical discharge in spark, the electric current flow was measured by a current transformer with the maximum sample rate of 1.5GHz. As shown in Fig. 4 – 7, the initial spark current was not controlled by a current limiting diode and flowed as high as 3mA. Considering the maximum current of 100mA applied by a power supply, the initial peak current could be higher than the value shown in the figures. However, the maximum current was not able to be measured due to the resolution limit of current transformer.

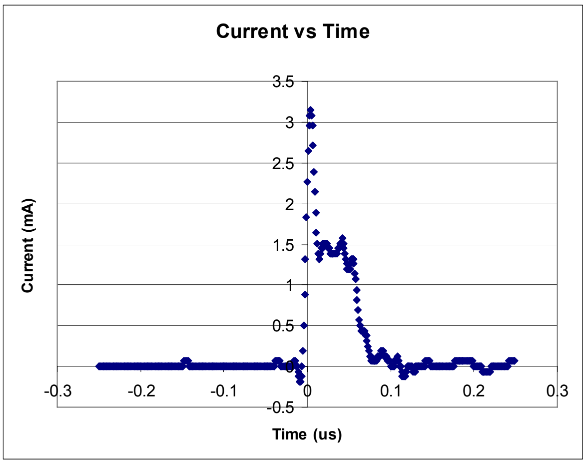

Fig.4 Transient current profile (V=20V, Gap 100nm)

Another phenomenon is the duration of spark (or spark sustaining time) which was measured to be between 50ns to 100ns. One can indirectly calculate the total heat input by integrating the product of current and applied voltage in the given profile as Eq. (1). The Eq. 1 provides a rough estimate of total electrical discharge between the electrodes without considering the efficiency of the circuit.

$$E = \int_{t0}^{t1} I \cdot V dt \qquad (1)$$

With different voltages and different gaps, the same experiments were conducted as shown in Fig. 5 The initial peak current is similar to the condition of 20V and 100nm gap, but the current profile during spark was somewhat shorter than that of 20V and 100nm gap. It is believed that the gap is too wide and there might not be enough current flow to sustain the current profile.

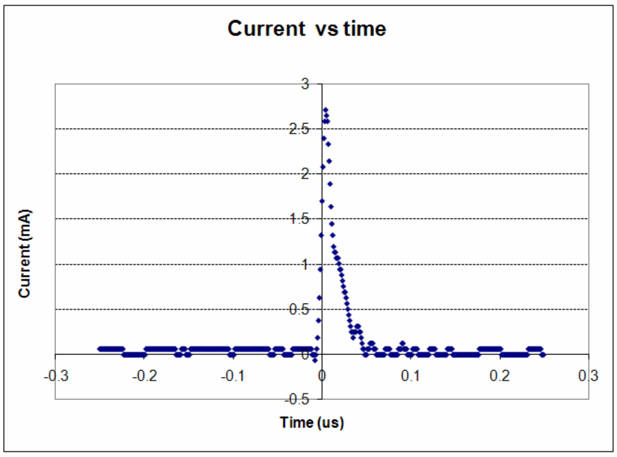

Fig.5 Transient current profile (V=30V, Gap=200nm)

The experiment was extended to 50V condition which is more violent and chaotic for spark. As described in Fig. 6, the initial peak current was measured to be 3.5mA similar to the prior experiments such as 20V and 100nm gap or 30V and 200nm gap, but the spark sustaining time was measured to be a little bit longer than those two experiments.

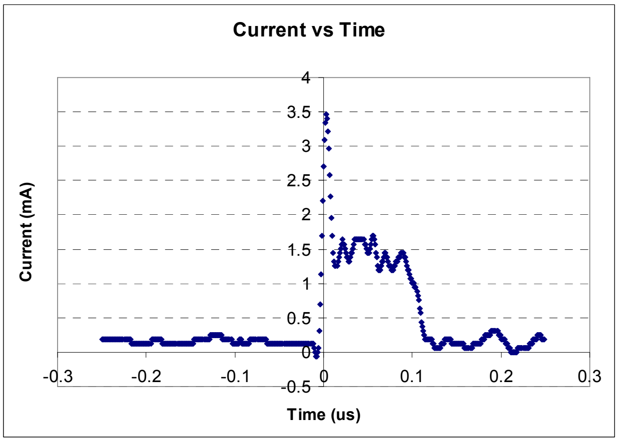

Fig.6 Transient current profile (V=50V, Gap=300nm)

As shown in Fig. 7, the spark sustaining time increased to 200ns with the 60V and 400nm gap condition. However, the initial peak current was still measured to be around 3.5mA similar to the prior three experiments. It is still premature to conclude the relationship between the spark sustaining time and other experimental parameters such as resistors, diodes, and capacitors in the circuit The spark sustaining time, however, increases as the applied electric potential increases.

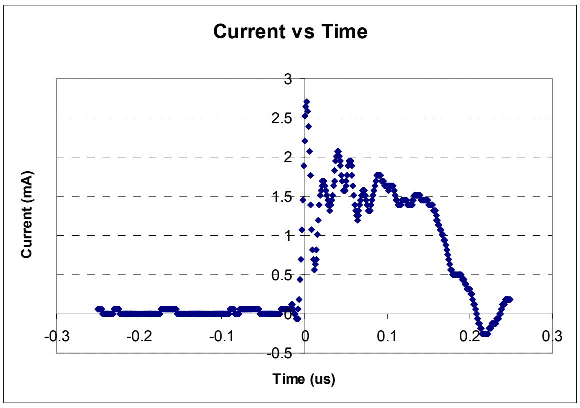

Fig.7 Transient current profile (V=60V, Gap=600nm)

Based on the previous experimental results, a continuous discharge experiment was carried out with the condition of the applied voltage of 80V and the gap around 500nm as shown in Fig. 8. At this condition spark is always guaranteed. The measured spark time was as long as 1 second, which was observed by an optical monitoring system, camera.

One issue during the experiment was that the gap was kept adjusted. It is believed that there are two major physical parameters to determine the spark dischare process. The first one is plasma density which increases the electric conductivity and can decrease the required gap between a tip and substrate. The second is the degree of the tip erosion caused by the high temperature plasma radiation. The tip or the substrate might be gradually damaged or melt, which widens the gap between two electrodes.

Fig.8 Continuous discharge for micro-welding

4. Conclusions

In this paper, the characteristics of the electrical discharge were studied between two electrodes. A sharpened tip and a substrate were placed in the nano-scale gap, and the electric potential was applied to between two electrodes. The current profile during spark showed that the spark sustaining time was between 50ns and 200ns depending on the discharging conditions. The current limiting diode was unable to control the initial current flow in the spark; however, it could control the current profile during the spark sustaining time. The spark gap was controllable by adjusting the electric potential between two electrodes. From the experiments, it was also possible to discharge the electric current up to 1second of time. Therefore, the developed process can be applicable to the micro-scale fabrication for automotive sensors, medical devices as a similar concept of GTAW.

Acknowledgements

This work was supported by the Ministry of Knowledge Economy(MKE) and Korea Institute for Advancement of Technology(KIAT) through the Center for Mechatronics Parts(CAMP) at Keimyung University. Authors also thank to LMMPC lab advised by Prof. Dave Farson at the Ohio State University for their experiment equipment support.

References

1. A. Gorecka-Drzazga: Vacuum, 83(200), 1419
2. J. Li, S. Chou, Z. Li, and W. Yang: Combustion and Flame, 156 (2009), 1587
3. Y. H. Jeong, B. H. Yoo, H. U. Lee, B. K. Min, D. W. Cho, and S. J. Lee: J. of Mat. Proc. Tech., 209 (2009), 5399
4. J. Li, S. K. Chou, G. Huang, W. Yang, and Z. W. Li: Exp. Thermal and Fluid, 33 (2009), 764
5. D. Farson, H. Choi, and S. Rokhlin: Nanotechnology, 17 (2006), 132
6. D. Allen, P. Shore, R. Evans, C. Fanara, W. O'Brien, S. Marson, and W. O'Neill: Manuf. Tech., (2009), 16