Defence Science Journal, Vol. 67, No. 6, November 2017, pp. 664-667, DOI : 10.14429/dsj.67.11119

Compact Planar One-Shot Circular Spark Gap Switch

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ABSTRACT

The fabrication and characterisation of micro spark gap switch for single shot firing applications are given in detailed . A circular switch with triggering electrode is realised on alumina substrate and can be integratable easily with the electronics for ignition applications. Circular switch is realised on 25 mil alumina substrate within substrate diameter of 10 mm. The switch measurement shows having repeatable performance of pulse peak current of around 2000 A and less than 100 ns rise time. This article details the design, development including fabrication aspects of spark switch with trigger capabilities along with characterisation of switch on alumina substrates.

Keywords: Spark gap switch; Alumina substrate; Triggering electrode; Exploding foil intiator

1. INTRODUCTION

Switches can be of many types such as electromechanical, vacuum, solid state or gas based. Pulsed power applications need large current switches such as insulated gate bipolar transistor (IGBT), thyristors, thyratrons, mercury vapour switches and spark gap switches for generating large peak currents. The main advantages associated with the spark gap switches are: operation at relatively higher voltages, high speed and ability to withstand extreme shock, temperature and vibration. They are having wide operating range and can operate from vacuum to high pressure[1]. Spark gap switches with fixed or rotating electrodes exist and switch with fixed electrodes can be further classified as self-triggered and forced triggered switches. Spark gap switch with triggering electrode provides the precision timing activation of in-flight functions for motor ignition and missile stage separation. Topologies for triggered switch can be divided into planar or coaxial type[2]. Planar topology is preferred for single shot applications having space constraints[3]. Further, it can be realised using existing standard fabrication techniques for microelectronic devices resulting in added advantage of less turnaround time and cost effectiveness. The construction of triggered planar spark gap switch is ceramic-to-metal layer consisting of two main printed arc electrodes and a thin strip acting as a triggered electrode. The present article details the fabrication and testing aspects of the switch.

The main aspects of the realised spark gap switches are monolithic construction, one-shot capability, intregratable with stripline geometry, actuation with low voltage trigger pulse, reproducibility and reliability. This article demonstrates planar spark gap switch which was realised along with exploding foil initiator (EFI) on gold metallised alumina substrate using double sided lithography technique. Planar switch was developed on one side while the EFI on the opposite side so as to make the system compact along with reducing parasitic inductance and resistance. This one-shot switch can be easily integrated with driving electronics because of planar configuration and is based on the approach suggested by Shen[4], *et al.* but in present case fabrication process is modified and carried out on both sides of alumina substrate to realize compact structure. The system inductance and resistance are greatly reduced because of the geometry and extremely fast rise time of current pulse is obtained. This article details the methodology of realisation of the switch architecture in circular shape which is implemented using double side lithography process and connected through filled via with proper alignment.

2. SWITCH DESIGN

The main characteristics of the trigger switch for pulsed operations are: trigger voltage, operating voltage, peak current and pulse rise time[5]. The main assembly of the switch consists of two main electrodes and a small strip working as a triggered electrode . The two main electrodes diameter is about 4000 μm and the gap distance between them is 800 μm. The triggering electrode with a width of 140 μm is located inside one of the main electrode and the gap is kept around 30 μm as shown in Fig. 1**.** The main parameters of the spark gap switch are

- Turn on voltage
- Static breakdown voltage
- Pulse peak current
- Pulse rise time

Sharp rise time, low trigger voltage, and peak current are

Received : 28 January 2017, Revised : 04 April 2017
Accepted : 24 April 2017, Online published : 06 November 2017

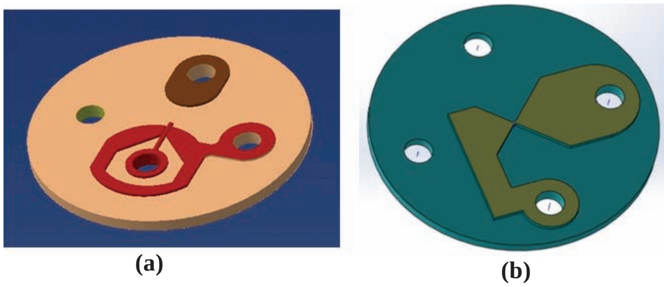


Figure 1. Assembly of the switch, (a) top and (b) bottom.

the main design criteria of the switch. Sharp rise time can be achieved by keeping inductance minimal which is attained by keeping track lengths as short as possible and developing EFI on the other side. Operating voltage requirement is decided by the circuit parameters for load current. Inter electrode distance (δ) is chosen so that the operating voltage can be applied to the device at normal atmospheric pressure without the need for having sophisticated mechanism for maintaining pressure. The breakdown voltage (V) of air in the uniform field can be given as

$$V = 6.72\sqrt{pd} + 24.36\,pd \qquad (1)$$

where d is the distance of the gas gap and p is the gas pressure[4]. Metalised film thickness above substrate impacts the hold on voltage and enhanced film roughness leads to decrease in hold on voltage. Further layer thickness also impacts the peak current for sharp rise time requirements. In the present design Cr/Cu/Au layer is chosen as metal layers with overall thickness of 5 μm. Deposition parameters of the metal layer are optimised to reduce the surface roughness.

3. SWITCH WORKING

The spark gap is considered closed when the potential difference between the electrodes is reduced and circuit becomes current limited[6]. Switch is excited with the application of the high electric field between trigger electrode and adjacent electrode as shown in Fig. 2.

This results in breakdown of air gap and availability of charge carriers between the two electrodes and also adjacent electrode and opposite electrode as shown in the Fig. 2(b). Presence of charges between the adjacent electrode and opposite electrodes increases the electric field which further results in breakdown of air gap between them and hence closure of switch. The breakdown of the spark gap initiates electron avalanche due to ion density. Propagation velocity of

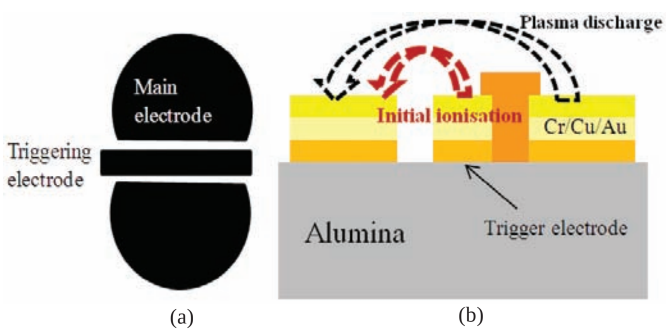


Figure 2. Planar spark switch topology (a) top view (b) cross section view.

the electron avalanche is proportional to the applied electric field so gap closure is dominated by the applied electric field. The electron density $N(t)$ grows from its initial value N_0 with the applied electric field

$$N(t) = N_0 \exp^{\int \alpha(v)v.dt} \qquad (2)$$

υ is the velocity of the electron, t is the time and $\alpha(v)$ is the electron ionisation rate coefficient. After the post breakdown, voltage is inhibited to rise due to the inductance of the spark channel itself. The rise time of electromagnetic pulse through a spark gap filled with an insulating media of permittivity ε and permeability μ can be approximated as

$$t_r \sim \delta\sqrt{\varepsilon\mu} \qquad (3)$$

where δ is an inter-electrode gap[7]. Initially the electric field strength in the switch is smaller than the breakdown electric field strength and with the turn-on voltage the triggering gap breaks down due to high electric field strength. The potential inside becomes same and afterwards main gap breaks down resulting in large current pulse.

4. FABRICATION ASPECTS

The prime criterion for the switch realisation is the selection of insulation material and in present case alumina substrate is chosen due to its high resistivity in the range of MΩ-cm. Main challenge in fabricating the spark switch on alumina is drilling and metallisation of holes ensuring top and bottom continuity. Further double sided lithography technique along with proper alignment is carried out for ensuring compactness. The proposed micro switch is realised on alumina substrate (Fig. 3) having the dimensions 1”×1”× 0.025”.

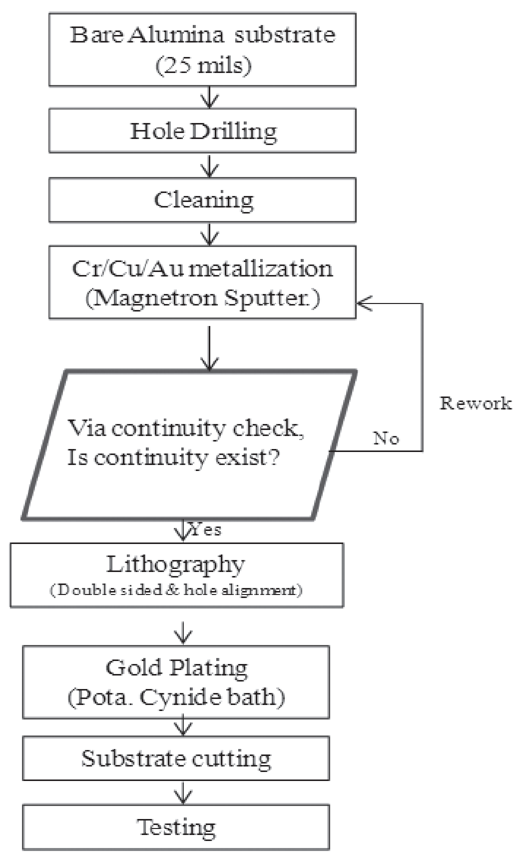


Figure 3. Flow chart of the switch realisation.

Metallisation of Cr/Au layer (0.03/1 μm) is carried out using evaporation and pattern (15.5 mm ×5 mm) is realised with single sided lithography having middle line width of 140 um and gap of 30 μm on both sides. The overall size of the realised structure is 20 mm x 20 mm as shown in Fig. 4 along with the close view of triggering electrode.

To reduce the overall size, the modified structure is realised using double sided lithography technique along with the top and bottom hole alignment as shown in Fig. 5.

Cr/Cu metallisation using magnetron sputtering with the thickness of Cr (0.02 μm - 0.03 μm) and Cu (2.0 μm - 3.0 μm) is carried out. Further gold metallisation and electroplating is done along with the double sided lithography technique with proper alignment to achieve the desired patterns within the diameter of 10 mm. Front and back view of the realised structure is shown in Fig. 6 and further continuity tests is carried out to validate the process.

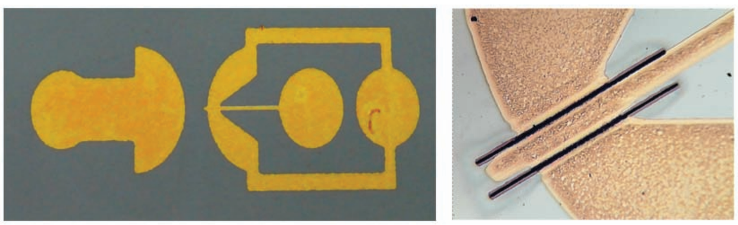


Figure 4. Realised structure using single mask.

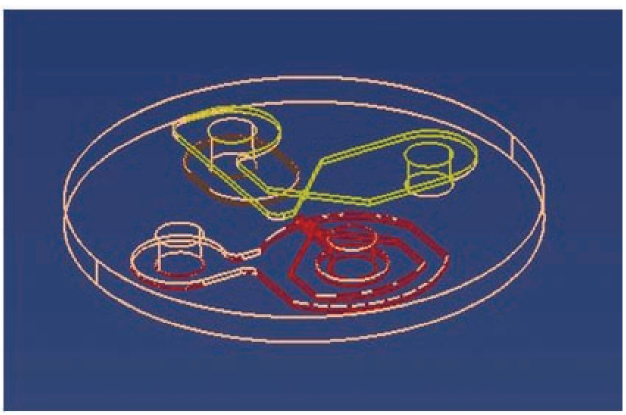


Figure 5. Overview of the assembly (top and bottom alignment).

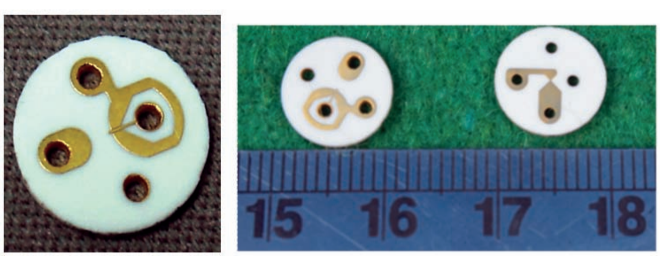


Figure 6. Realised switch structure.

5. EXPERIMENTAL RESULTS

Triggering of switch can be carried out by external voltage triggering pulse and the corresponding discharge circuit is as shown in Fig. 7.

Realised structure is measured for the pulse rise time and breakdown voltage. The breakdown voltage measured between the trigger electrode and adjacent electrode is 400 V (pulse) and

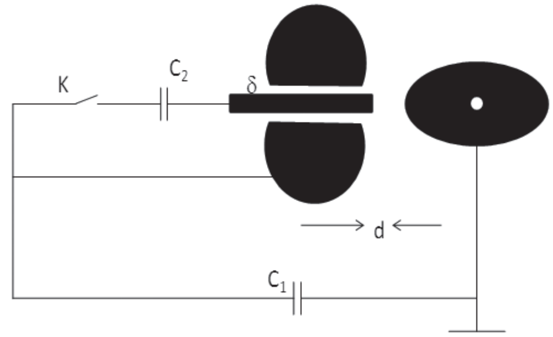
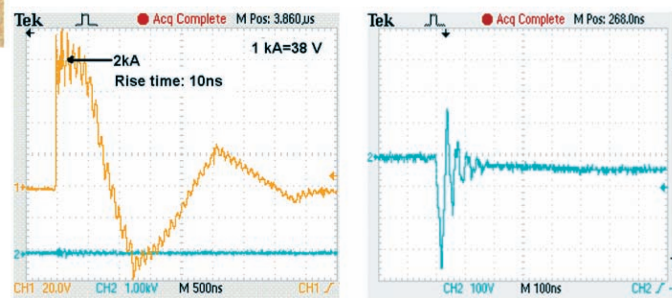


Figure 7. Switch discharge circuit.

the static breakdown voltage between the adjacent electrode and opposite electrode is measured around 2.8 kV.

Figure 8 shows the plot between time and amplitude clearly showing that peak current of ~ 2000 amp with a rise time of < 100 ns is obtained with the triggering of the voltage. This clearly demonstrate the validity of the methodology adopted of achieving high current with compact topology utilising double side lithography operations.



(a) (b)

Figure 8. Measured rise time and amplitude of (a) current pulse and (b) trigger voltage.

6. DISCUSSIONS

The developed switch is having small size, low profile and fabricated on the standard alumina substrate using double sided lithography and electroplating process. Multiple switches are tested and repeatable performance of the devices is observed. Depending upon the desired load current characteristics spark gap length can be varied to alter the operating voltage. The demonstrated one-shot compact topology on alumina substrate is cheaper alternative compared with the existing topologies including EFI and can be easily realised with standard IC techniques. Same methodology can be easily adopted on silicon substrate for further integration of electronics. Developed micro switch is robust, reliable and having potential to be used in as ignition device with the proposed methodology resulting in the size reduction of more than 30 per cent.

REFERENCES

1. Seriburi, Pahnit; Kercher, Dan & Allen, Mark G. An experimental study of micro-fabricated spark gaps: Wear and erosion characteristics. *J. Micromech. Microeng.*, 2001, **11**(3), 165-174.
doi: 10.1088/0960-1317/11/3/302

2. Winands, G.J.J.; Liu, Z.; Pemen, A.J.M.; Heesch, E.J.M. van & Yan, K. Long lifetime, triggered, spark-gap switch for repetitive pulsed power applications. *Rev. Sci. Instruments*, 2005, **76**(8), 085107-(1-6). doi: 10.1063/1.2008047
3. Baginski, T.A. A high voltage single shot switch implemented with a MOSFET current source and an avalanche diode. *IEEE Trans. Ind. Electron.*, 1997, **44**(2), 1-6. doi: 10.1109/41.564154
4. Shen, H.; Yang, Z.; Ding, G.; Zhou, Z. & Zhao, X. A planar spark gap switch with a triggereing electrode. *Micro Nano Sys.,* 2011, **3**(4), 354-359. doi: 10.2174/1876402911103040354
5. Baginski, Thomas A. & Thomas, Keith A. A robust one-shot switch for high-power pulse applications. *IEEE Trans. Power Electron.*, 2009, **24**(1), 253-259. doi: 10.1109/TPEL.2008.2005411
6. Yan, K.; Heesh, E.J.M.; Nair, S.A. & Pemer, A.J.M. A triggered spark gap switch for high- repetition rate high-voltage pulse generation. *J. Electrostat.*, 2003, **57**(1), 29-33. doi: 10.1016/S0304-3886(02)00093-1
7. Lehr, J.M.; Baun C.E. & Prather, W.D. Fundamental physical consideration for ultra fast spark gap switching. Switching Notes from Philips Laboratory, 1997. doi: 10.1109/uwbsp.1998.818934

ACKNOWLEDGEMENTS

Authors are grateful to the support provided by colleagues at DOS/ISRO/TBRL. Special thanks to Mr R.B. Upadhaya, SAC, Mr Ayan Karamakar and the industry partner. We are also indebted to the encouragement and support provided by the respective Deputy Directors and Directors.

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In the current study, he provided the concept and driving force in executing this concept.

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In the current study, test set-up and switch testing carried out by him.

Mr M.R. Patel obtained MSc in Chemistry. Presently working as 'SE' at Thin Film and Substrate Processing Division, Electronics Service Support Area, Space Applications. He has vast experiences in metal finishing and corrosion protection for ground and space use, thin film deposition for electronics applications for space and ground use, laser application for material processing and printed circuit board fabrications work.
In the current study, he developed process and carried out fabrication.

Mr A.V. Nirmal obtained his BE (Mechanical Engineering) from Kerala University, in 1984. Presently working as Group Director, Systems Engineering Group, ISRO Satellite Centre. He is credited with production and delivering of sub-systems of IRS and Geosat missions. He was involved in the design and development of various mechanical systems for both launch vehicle and satellites and establishment of test facilities.
In the current study, he provides constant encouragement and motivation.