Fabrication of micro-ignition sequence based on electronics safety and arming unit

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Abstract. This paper describes an ignition circuit consisted of one micro igniter and one electronic security microswitch that could realize the intelligent function of micro-ignition sequence. The micro-ignition sequence, integrated with ignition circuit, chamber, nanothermite and B/KNO$_3$, was fabricated on the same silicon chip by mechanical engraving and classic micro mechanical systems (MEMS) technology including magnetron sputtering and plasma etching steps. In addition, the size of micro-ignition sequence was less than 0.15 cm$^3$. The electronic security microswitch based on energetic film Al/MoO$_3$ can implement the function of circuit switch conversion under 1.5 A during 3 ms. The paper presents the design, fabrication and test of the micro-ignition sequence integrating of electronics safety and arming unit.

1. Introduction

With the vigorous development of microelectronic integrated circuit (IC) technology, the integration of IC technology has been applied to industrial fields and military application. Based on the combination of precision mechanical technology, new material technology, and the original microelectronic technology, microelectronics electromechanical system (MEMS) technology came into being [1-10]. According to different principles of action, MEMS safe arm and fire devices can be divided into two categories: mechanical MEMS safe arm and fire device and electronic safe arm and fire device. The latter can be divided into electromagnetic drive type, electrical gunpowder driven, electrothermal driven, and shape memory alloy driven type according to different modes of action [11-17].

At present, there are few reports at home and abroad about embedding MEMS security agencies in pyrotechnic products. LAAS-CNRS laboratory [18-20] has done a lot of research on MEMS safety insurance devices for many years. In 2005, Carole Rossi first proposed the design of MEMS safety insurance device inside the MEMS detonator and integrated mechanical safe arm and fire part and electronic safe arm and fire part in a MEMS. The MEMS security agency proposed by Carole Rossi can realize the functions of disarming, restoration of insurance and mechanical isolation. The electronic safe arm and fire unit includes three single-use electrical micro switches, and the on-off micro switch is used to arm the initiator. GAP was used to realize to translate the on-off micro switch, however, due to bad contact between the heater and GAP, 10% of on-off microswitch failed. To improve the reliability and shorten disarming delay time, the paper proposed the electronic security microswitch based on the energetic film Al/MoO$_3$ and integrated the electronic security microswitch
with the MEMS micro-ignition sequence. The principle design and fabrication process will be introduced for the micro-ignition sequence based on electronics safety and arming unit. The validation result of arming and disarming operation, together with electrostatic safety test result of electronic security microswitch will be given.

2. Design and architecture of initiator
As shown in figure 1, the micro-ignition sequence based on electronics safety and arming unit consists in an assembly of different layers. The bottom layer of micro-ignition sequence is a silicon chip, on which are integrated a semiconductor bridge to initiate an explosive and an electronic security microswitch to realize electronic safety and arming unit function. The top layer, epoxy resin plate, is the chamber integrating nanothermite and B/KNO$_3$ charge. To distinguish the semiconductor bridge contacted with nanothermite charge and the semiconductor bridge of electronic security microswitch, we call them Main-SCB and Arming-SCB, respectively.

Figure 1. Schematic view of micro-ignition sequence based on electronics safety and arming unit: 1 chamber layer, 2 Ignition circuit layer.

2.1. Design and preparation of electronics safety and arming unit
Electronic security microswitch (figure 2) was designed to realize electronic safety and arming unit function of the ignition sequence.

The requirements for electronic security microswitch used in micro-ignition sequence are as follows:
- The electronic security microswitch can complete the circuit state conversion reliably and quickly.
- Stable storage performance is important for electronic security microswitch.

Considering the design requirements and simplicity of manufacture processes of MEMS [21], the energetic film Al/MoO$_3$ was chosen to be the key part of the electronic security microswitch.

An aluminium line is placed on top of the energetic film Al/MoO$_3$ deposited on the Arming-SCB on a silicon-based substrate. The Arming-SCB is a polysilicon resistance of 14 Ω with a polysilicon resistivity of 3.8 Ω/square. In addition, In order to avoid the Arming-SCB short-circuited by aluminium line, the energetic film Al/MoO$_3$ is insulated from both aluminium line and Arming-SCB by depositing metallic oxide (MoO$_3$) at the junction.

The area and shape of energetic film Al/MoO$_3$ can be changed by altering the mask size of Magnetron sputtering. To ensure an ideal reliability of the energetic film Al/MoO$_3$ operation, here, Al/MoO$_3$ membrane, the area of which has been fixed at 2 mm $\times$ 2 mm, has a shape of square and a thickness of 3 μm.

When the electronic security microswitch operates, the Arming-SCB rapidly heats up to the decomposition temperature of the energetic film Al/MoO$_3$, and then it reacts quickly to produce high temperature combustion products that breaks the aluminium line which deposited on top of the energetic film Al/MoO$_3$. 
2.2. Assembly of ignition circuit

Ignition circuit is designed on the silicon-based substrate, which is the bottom layer of the micro-ignition sequence and has a size of 9.5 mm × 8.7 mm × 0.5 mm. As illustrated in figure 3, the architecture of the ignition circuit consists in an assembly of the Main-SCB and electronic security microswitch.

Figure 4 shows the construction of the ignition circuit. The pads of the Main-SCB of micro-ignition sequence are connected to the electrical grounds so that the micro-ignition sequence can be stored in a safe mode before receiving the disarming instruction. At this stage, if the operator sends an order to ignite the Main-SCB, the Main-SCB can be protected by the aluminium line. After receiving the disarming instruction, the energetic film Al/MoO$_3$ is ignited by the Arming-SCB to cut the electrical short-circuit to electrical ground. Then, the Main-SCB is in a waiting state to ignite the nanothermite.
2.3. Packaging of MEMS-based electrical safety micro initiator

The top layer, epoxy resin plate, has the total thickness of 1 mm. The chamber in the epoxy resin plate is composed of two concentric chamber mechanical engraving. The small chamber below for nanothermite charge has a diameter of 1 mm and a thickness of 0.5 mm, and the large chamber above for B/KNO₃ pellet has a diameter of 1.5 mm and a thickness of 0.5 mm. As seen in figure 5, the centers of both chambers are on the same axis so that B/KNO₃ pellet can be placed upon the nanothermite charge. The chamber position is directly above the Main-SCB.

![Figure 5. Photograph of micro-ignition sequence after assembly.](image)

3. Characterizations

3.1. Validation of electronic safety part operation

3.1.1. Characteristic of energetic film Al/MoO₃. The energetic film Al/MoO₃ were deposited alternatively on the Arming-SCB by magnetron sputtering. First, a MoO₃ layer (300 nm) was deposited onto Arming-SCB by sputtering to act as electrical insulating layer. Subsequently, Al/MoO₃ multilayer nanofilms were deposited with the same process. Each bilayer is 20 nm and 30 nm thick for Al and MoO₃, respectively. The top layer of the energetic film Al/MoO₃ is also MoO₃ to ensure the energetic film insulate from the aluminium line. The total thickness is kept at 3 μm with 60 bilayers deposited as shown in figure 6. The cross-sectional SEM images of the energetic film Al/MoO₃ shows that the Al and MoO₃ layers are free from cracks and have distinct boundary lines, which verifies the consistency and stability of the magnetron sputtering process.

The stoichiometric Al: MoO₃ ratio is 2:1 from the following balanced reaction:

\[ 2\text{Al}+\text{MoO}_3 = \text{Al}_2\text{O}_3 + \text{Mo} \]

The densities of Al (2.70 g/cm³) and MoO₃ (4.692 g/cm³) are considered as the density of the Al films and MoO₃ films, respectively. The thickness ratios of Al and MoO₃ reflect the volume ratios of single Al films and MoO₃ films because the Al films and MoO₃ films have the same deposition areas. The thickness value in Al/MoO₃ RMF is 20 nm/30 nm, with corresponding stoichiometric ratios of Al: MoO₃ of 2:1. The energetic film Al/MoO₃ with stoichiometric ratios of Al: MoO₃ of 2:1 has a self-propagating combustion process after being ignited by a semiconductor bridge [22].

![Figure 6. SEM image of energetic film Al/MoO₃ cross-section.](image)
3.1.2. **Validation of electronic arming operation.** To investigate the characteristics of micro-ignition sequence based on electronics safety and arming unit, constant current firing circuit test system was adopted to apply the current across the semiconductor bridges, as shown in figure 7. In the experiment, the disarming and ignition process was recorded using a high-speed camera (HG-100 K) that captured 5000 frames per second. An oscilloscope was used to record voltage and current synchronously. At the same time, optical signal and ignition time of electronic security microswitch can be noted with optical fiber. Besides, Oscilloscope and stereomicroscope were taken to make the electrical and optical checking of electronic safety and arming function.

![Figure 7. Schematic diagram of the experimental setup.](image)

Before receiving the disarming instruction, a constant current of 1 A for 1 ms is applied to the pads at both ends of the Main-SCB to validate the short-circuit protection function of aluminium line. The curves of voltage and current are shown in figure 8. The voltage at both ends of the pads of the Main-SCB maintains in the value of 2.5 V, and it remains unchanged. After the constant current excitation, the resistance at both ends of the Main-SCB remains the same with that before the constant current excitation, indicating that the aluminium line has a short-circuit protection effect on the Main-SCB and realizes the core function of the electronics safety and arming unit. In addition, figure 9 shows a microscope view of the Main-SCB after the constant current excitation. The appearance of Main-SCB remains intact before and after constant current excitation, which also validates the electronic arming operation.

![Figure 8. Voltage-current curves of the pads at both ends of the Main-SCB.](image)
3.1.3. Validation of electronic disarming operation. The Arming-SCB is used to ignite the energetic film $\text{Al/MoO}_3$. When receiving the disarming instruction, constant current of 1.5 A for 3 ms was applied to the Arming-SCB. Subsequently, the Arming-SCB ignited the energetic film $\text{Al/MoO}_3$, and the firing of energetic film $\text{Al/MoO}_3$ resulted in the broken of aluminium line, which means the Main-SCB electrical short-circuit to electrical ground is cut.

The voltage-current curve of the Arming-SCB at 1.5 A constant current for 3 ms and the optical signal of the energetic film $\text{Al/MoO}_3$ are shown in figure 10. It can be seen from figure 11 that the energetic film can be successfully ignited at the constant current of 1.5 A for 3 ms. In addition, we define the time from energizing the Arming-SCB to the ignition of the energetic film $\text{Al/MoO}_3$ as delay time in disarming. The moment when the optical signal starts to rise is the moment when the energetic film $\text{Al/MoO}_3$ is ignited. The delay time in disarming in figure 10 is quite short, which shows that the electronic disarming operation is realized almost at the same time that the Arming-SCB receives a constant current excitation of 1.5 A. A microscope view of electronic security microswitch was shown in figure 11, we can see the aluminium line deposited on the energetic film $\text{Al/MoO}_3$ was completely blown off, and the resistance measurement of the Main-SCB was performed after electronic disarming operation. The resistance value at pads of both ends of the Main-SCB is 13.8 $\Omega$, which is the actual value of the Main-SCB. The Main-SCB enters the working state with the completion of the electronic disarming operation.

![Figure 9](image1.png)

**Figure 9.** Microscope view of the Main-SCB before and after the constant current excitation.

![Figure 10](image2.png)

**Figure 10.** Curves of current, voltage, and optical signal varied with time under Constant current of 1.5 A.
3.2. *Igniter performance after electronic disarming operation*

An electrical power presses (model: ZP-500S1), with an applied pressure of 7.2 kgf, was used to press the powdered B/KNO₃ into a 1.5 mm diameter, 0.28 mm height cylindrical grain as shown in figure 12. The electronic press was also used to apply a high pressure to charge the nanothermite in a chamber with a diameter of 1 mm and a depth of 0.5 mm. And, the B/KNO₃ pellet is placed on the upper chamber of a diameter of 1.5 mm and a depth of 0.5 mm.

To validate the availability of the micro-ignition sequence after electronic disarming operation, optical fiber was placed right above B/KNO₃ pellet charged in the chamber so that the optical signal of B/KNO₃ firing process can be recorded with voltage-current curves of Main-SCB synchronically. The high-speed camera was triggered synchronously by a constant current power supply. Figure 13 is the high-speed photographic record of a micro-ignition sequence firing at a constant current of 1A for 1ms after electronic disarming operation. The Main-SCB ignites the nanothermite charge, and it can be seen from figure 14 that nanothermite charge starts to ignite and lasts to 0.4 ms. During 0.4 ms-0.6 ms, the upper B/KNO₃ charge was ignited by the nanothermite, and the firing process of B/KNO₃ charge lasted about 3 ms. The oscilloscope was used to record the voltage-current curve of the Main-SCB at 1A constant current for 1ms and the optical signal of the B/KNO₃ charge firing as shown in figure 14. We can see from figure 14 that the optical signal of B/KNO₃ firing generated at the 500 μs moment after the current signal appeared, which is consistent with the phenomenon in high-speed photography that B/KNO₃ starts to fire during 0.4 ms-0.6 ms. The moment of the strongest optical signal on the oscilloscope corresponds to the moment when the flame is highest in the high-speed photograph.
Figure 13. High-speed photographic record of the micro-ignition sequence firing at a constant current of 1 A for 1 ms after electronic disarming operation.

Figure 14. Curves of current, voltage, and optical signal varied with time under Constant current of 1 A.

3.3. Electronic sensitivity of igniter
In order to test the electrostatic safety of the electronic security microswitch equivalently, we prepare energetic film Al/MoO$_3$ compositied on the Arming-SCB as a whole to perform an electrostatic sensitivity test on it. Three samples are shown in figure 15. The parameters of energetic film Al/MoO$_3$ and the Arming-SCB are as follows:

- The average resistance value of the Arming-SCB is 14.0 $\Omega$.
- The thickness of the energetic film Al/MoO$_3$ is 3 $\mu$m.

Figure 15. Photograph of energetic film Al/MoO$_3$ compositied on the Arming-SCB.
Figure 16. Photograph of the experimental setup for electrostatic sensitivity test.

The electrostatic sensitivity test is performed on the energetic film Al/MoO$_3$ composited on Arming-SCB by the up and down method with electric spark tester (JGY-50III). Figure 16 gives the photograph of the experimental setup for electrostatic sensitivity test. The capacitance of the capacitor is 500 pF and the connected resistance in the discharge circuit is 5000 Ω.

According to the regulations of GJB/Z 377A-94, a non-group test was performed. In the electrostatic sensitivity test, Arming-SCB composite energetic film Al/MoO$_3$ igniter has a discharge voltage at 50% of 14.78 kV, a discharge voltage at 0.1% of 9.5 kV, and a discharge voltage at 99.9% of 20.06 kV.

4. Conclusion
In combination with the development requirements of the new generation of smart and smart weapon ammunition technology, the electronic security microswitch was designed on silicon substrate to realize the electronic safety and arming unit function of the ignition sequence. Mechanical engraving and classic micro mechanical systems (MEMS) technology including magnetron sputtering and plasma etching steps are used to prepare the micro-ignition sequence based on electronics safety and arming unit. Constant current of 1.5 A for 3 ms applied on Arming-SCB can ignite the energetic film Al/MoO$_3$ and realize the disarming function. The energetic film Al/MoO$_3$ is in close contact with the Arming-SCB and the aluminum line that improve the reliability of the electrical disarming operation. The electrostatic safety of the electronic security microswitch has been tested. The discharge voltage at 50% of Arming-SCB composite energetic film Al/MoO$_3$ is 14.78 kV.

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