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Research on Damage Mechanism of SCB Initiators under RF

***Abstract**. In order to elucidate the response characteristic of semiconductor bridge(SCB) initiators under radio frequency(RF), RF measurement system was used to test the RF sensitivity of SCBs, after that the energy stored in a 22μF was used to activate the SCB. It is inferred from the results of Bruceton-method firing experiment that RF energy does not damage the SCB chip, but can lead to the accidental ignition of SCB initiators or change the color of normal lead styphnate(NLS). RF can also passivate SCB significantly and the all-fire voltage increases from 6.71V to 7.72V. The experimental data of X-ray photoelectron spectroscopy(XPS) analysis, directly indicated that heat generated by RF changes the valence of Pb in NLS from +2 to +4. The decomposition of NLS is responsible for the loss in sensitivity of SCBs. The research results provide a theoretical guidance for the electromagnetic compatibility(EMC) design of SCB initiators.*

***Streszczenie.** W artykule opisano badanie oddziaływania sygnałów częstotliwości radiowej (ang. Radio Frequency) na zapalniki zbudowane z mostka półprzewodnikowego. Przedstawiono omówienie teoretyczne oraz wyniki badań eksperymentalnych. (**Mechanizm uszkodzenia mostkowego zapalnika półprzewodnikowego pod wpływem fal radiowych**)*

Keywords: initiator, SCB, RF, NLS, XPS, EMC
Słowa kluczowe: Zapalnik, SCB, RF, NLS, XPS, EMC

Introduction

SCB is an energy-exchange device used in explosive devices. SCB initiator comprises SCB and the primary explosive which is a kind of sensitive energetic material. It attracted people's attention in the mid-1980s [1]. Generally, it is desired that SCB provides highly reliability ignition while requiring less energy input. By passing an electrical current, the polysilicon bridge of SCB module is heated to generate high temperature. After that, the temperature causes the vaporization of polysilicon film and obtains plasma. Subsequently, the primary explosive around SCB chip is ignited by the thermal plasma in a few microseconds to cause the explosion of explosive chargé [2-3]. Compared with the conventional hot-wire unit, under adiabatic firing conditions, where the firing energy is delivered to the SCB on a timescale which is either shorter than, or roughly equivalent to, one thermal time of the lumped SCB-primary explosive system, SCB has the smaller volume (one thirtieth of that of hot-wire), lower critical firing energy (no more than 3mJ), higher reliability and shorter function time (less than 20μs), larger no-fire current [4-5]. It is a good choice to replace the hot-wire unit.

Feng Qingmei[6] and other people have researched the damage mechanism of hot-wire units under RF. They state that RF can be coupled into initiators by two pins and induced current flows through. For the heating effect of electrical current, high temperature is maintained to heat primary explosive by conduction. While the temperature reaches a certain value, the bridge wire initiators are ignited unexpectedly or the performance of explosive changes to result in the failure of initiators. The safety and reliability of initiators will be affected by RF energy [7]. Although the SCB initiators are safer than the hot-wire, the ubiquitous electromagnetic energy in environment still may damage SCBs which fall into the EED category [8-9].

At present, the damage mechanism of SCB initiators under RF has not been systematically defined, nor the difference of RF response characteristic between SCB initiators and hot-wire. It is investigated in this article by comparing the measured data from the SCB with the related standards. The result provides the guidance for choosing the suitable RF protection technologies.

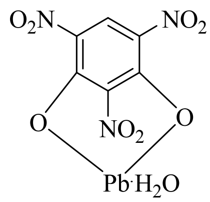
1 Sample Preparation

1.1 SCB Electrode Plug

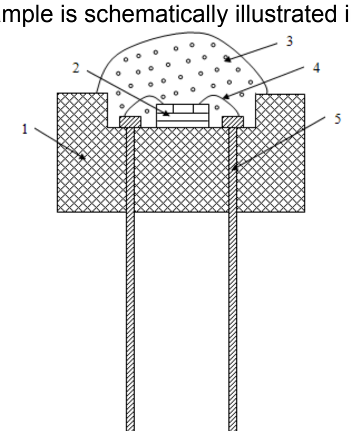
SCB chip is the most important acting component of SCB initiator which is an n-type device. Phosphorus was diffused to polysilicon and the dopant concentration was about 1020/cm3. The low firing-energy SCB was used in this study whose chip size was 28μm(length) × 100μm(width) × 2μm(thickness) and the resistance was 1.4±0.1Ω. The SCB module (1mm thick) was stuck into the channel of ceramic plug, which had 6mm external diameter and 4.5mm height, with non-conductive epoxy resin. Then, the Al lands of SCB chip and electrical leads were connected together with gold wires whose diameter was 30μm and length was 2 mm by ultrasonic bonding technology.

1.2 Explosive Coating

NLS whose chemical name is lead-2,4,6-trinitroresorcinate styphnate is normal lead styphnate for short. It is a brown-yellow benzene-ring prismatic crystal and has the molecule of crystal water[10]. Its formula is $C_6H(NO_2)_3O_2Pb{\cdot}H_2O$ and the relative molecular mass is 468.3. The chemical structural formula of NLS is



NLS was poured and mixed into the slurry which was formed by NC(nitrocellulose) and ethyl acetate. The concentration of NC in the slurry was 45%, which was coated above the bridge, and the nitrogen percentage composition of the NC was 12.8%. Then the plug was dried at 60° for two hours in the water oven. A typical experimental sample is schematically illustrated in Figure 1.



1-ceramic plug, 2-SCB chip, 3-LTNR, 4-bonding wire, 5-pin
Fig. 1 Schematic Diagram of SCB initiator

2 Experiment

2.1 RF Sensitivity Test

The RF sensitivity of SCB initiators were measured to obtain the no-fire and all-fire RF power, after which the RFI phenomenon in physical environment was estimated.

According to GJB 5309.13-2004[11], we selected Langley method to test the RF sensitivity of SCBs. Experimental conditions: frequency was 400MHz (in this frequency, the coupling coefficient between the test systems is highest and the output of RF energy is maximum[6]); ambient temperature was 25□; relative humidity was no more than 45%; RF energy was input through two pins. The output power of RF source was adjustable and current duration was 10 seconds. The diagram of test system was shown in Figure 2.

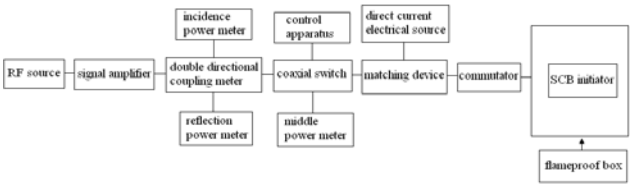


Fig. 2 Schematic diagram of RF sensitivity test system

TL16G-TP1 four parallel coaxial deployment was used on the SCB initiator to achieve the impedance matching at 400MHz, namely the ratio of absorbed to reflected power on double directional coupling meter was 100:1 which was better than the satisfactory match level (100:5) abroad. The firing results of samples were listed in Table 1.

Table 1 The results of RF sensitivity test

Model number	Power/W	State of sample	Model number	Power/W	State of sample
S12	7.75	0	S25	8.1	1
S13	8.62	0	S26	7.62	0
S16	9.06	1	S27	7.86	0
S18	8.84	1	S28	8.17	1
S19	8.3	1	S29	8.02	1
S20	7.15	0	S30	7.82	1
S21	7.72	0	S31	6.91	0
S22	8.28	0	S32	7.36	0
S23	8.67	1	S33	7.69	1
S24	8.48	1	S34	7.52	0

Note: "1" for fire, "0" for no-fire.

The igniton power in the device was calculated from the experimental data in Table 1. P_{50} which is for the mean RF ignition power of SCB initiators is 8.01W and the standard deviation is ±0.56W. Therefore the safe power $P_{0.1}$ which is regarded as the no-fire percentile is 6.28W, 5% ignition power P_5 is 7.09W and all-fire power $P_{99.9}$ is 9.74W.

2.2 RF Injection at the Certain Power Condition

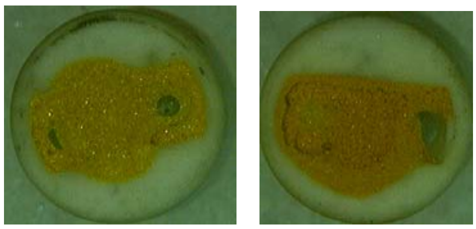
RF energy was injected into the SCB electrode plugs uncoated primary explosive and SCB initiators at the same experimental system and condition. Table 2 showed that SCB electrode plugs were not ignited at 9.74W, while SCB initiators were all fired under the same condition. Before and after RF injection, the bridge area of SCB electrode plug was photographed and the appearances of bridge film did not have any changement. The resistance of electrode plug was listed in Table 3.

Table 2 The firing situation of samples after RF injection

State of experimental samples	Power/W	amount of samples	amount of firing samples
SCB electrode plugs	9.74	10	0
SCB initiators	9.74	10	10
SCB initiators	8.01	23	13
SCB initiators	7.09	30	2

CDU(capacitor discharge unit) uses the electronic switch that has small impedance and loss. The ESR(equivalent series resistance) of the capacitor is 28mΩ±2mΩ munder 25□ and 100kHz. Parasitic circuit resistance is less than 50mΩ. SCB electrode plugs after RF experiment can also normally fire and generate plasma from Table 3. Comparing with the samples that were not passed RF energy, the function time of electrode plugs decreased by 0.06μs and firing energy reduced by 0.013mJ at 22μF capacitance and 9V voltage. For the two ignition characteristic parameters both changed no more than 5%, and the variation value of resistance was only 0.004Ω which is less than 5% of the SCB resistance, it is concluded that there was no significant changement after 9.74W RF injection. This indicates that not that RF damages the SCB bridge film, but that results in the variation of primary explosive.

At 7.09W, 2 samples were ignited. The color of remaining no-fire samples did not change significantly. 13 samples of 23 experimental samples were ignited at 8.01W, and the color of the no-fire explosive, as shown in Figure 3 that provided qualitative evidence to the hypothesis of chemical change to the NLS, was obviously different from the one without RF injection. The color that resulted from the high temperature generated by RF, outside the ceramic plug, was changed from the original bright-yellow to dark-red, which coincides with the conclusion above-mentioned.



(a) before RF injection (b) after RF injection

Fig. 3 Color comparison charts of explosive before and after RF injection

Table3 Resistance and ignition characteristic of SCB electrode plugs before and after RF injection

State of experimental samples	Average resistance/Ω	standard deviation/Ω	Average function time/μs	standard deviation/μs	Average firing energy /mJ	standard deviation/ mJ
SCB electrode plug without RF injection	1.398	0.043	5.55	0.21	0.395	0.034
SCB electrode plug after 9.74W RF injection	1.402	0.094	5.49	0.31	0.382	0.034

2.3 Capacitor Discharge Firing Experiment

28 no-fire samples at 7.09W in Table 2 were measured in Bruceton-method capacitor discharge firing experiment. The step-size was 0.2V to obtain 6 voltage levels. Compared with control samples, the ignition characteristic of these samples was investigated. After the impingement of the rapid electrical pulse discharged from 22μF tantalum capacitor, experimental results were listed in Table 4.

The average ignition voltage and $U_{99.9}$ of SCBs after RFI increased by 0.52V and 1.01V, respectively. The oscilloscope monitored the voltage-time and current-time curves of SCB during the discharge of CDU. Some bridges had vaporized to generate plasma, which resulted from the phenomenon that the typical behavior of two peaks in the voltage-time curve was gathered in the measurement process, but the primary explosive above these chips was not ignited. Experimental record was considered as no-fire. This evidences that NLS has been passivated by RF and it leads to the dud or failure of SCB initiators.

Table 4 Ignition voltage contrast between the control samples and samples after RF experiment

State of experimental samples	U_{50}/V	standard deviation	$U_{99.9}$/V
Control samples without RF injection	5.90	0.27	6.71
SCB samples after 7.09W RF injection	6.42	0.43	7.72

2.4 Chemical Composition Analysis of NLS

It seems that RF can damage the primary explosive NLS to lead to the changement of its ignition characteristic. Also, it can be seen from the chemical structure of NLS that the damage point may only be the abjunction of crystal water or the decomposition of NLS. To ascertain the chemical composition of explosive after RF experiment, the corresponding comparative analysis of LNTR was taken.

2.4.1 Vacuum oven dehydration

Adjust the vacuum degree of the oven and set the temperature upto 140℃. SCB initiators were put into the oven drying for 8 hours. By the gravimetric measurement, the weight reduction was 3.80%, while crystal water content in NLS is 3.84%. Because the thermal stability of NLS is so good that NLS will not decompose but loss the crystal water[10]. Then, the dehydrated samples were activated at 22μF by selecting Bruceton method.

Table 5 Ignition voltage contrast before and after the vacuum oven dehydration

State of experimental samples	U_{50}/V	standard deviation	$U_{99.9}$/V
SCB initiators without oven dehydration	5. 90	0.27	6.71
SCB initiators after oven dehydration	5.98	0.21	6.61

Comparing with the control samples, as shown in Table 5, the change values of U_{50} and $U_{99.9}$ were both no more than 0.1V which is relatively small to 5.9V and 6.71V. Thus, it indicates that the presence or absence of crystal water does not affect the firing performance of NLS. Therefore, it is concluded tha the abjunction of water molecule is not the real reason of NLS changes to be deterred by RF effect.

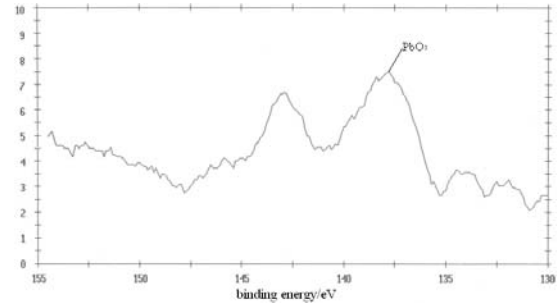
2.4.2 XPS valence analysis

PHI5300 XPS produced by PERKIN-ELMER Company was used to test the valence of Pb. X-ray source was Al target and the anode voltage was 15kV. Pass energy was 71.55eV and the power was 240W. The vacuum degree of instrumental analysis room was adjusted between 10-8Pa and 10-9Pa. Analysis model was fixed by passing energy.

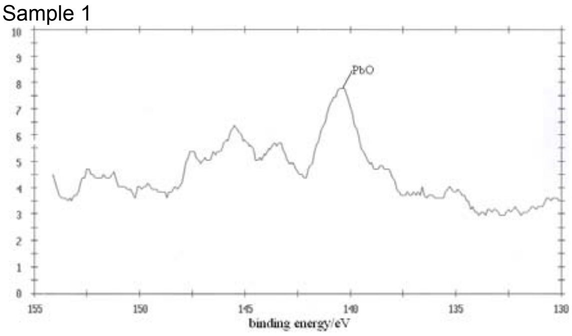
The explosive was scraped down from the no-fire SCB initiators at 8.01W in Table 2. It was made into the test sample recorded as No. 1, whose length was 10mm, thickness was 1mm and width was 3mm. Then the control sample No. 2 without RF injection was prepared. The two samples were analysisd in XPS respectively and the binding energy characteristic peaks of Pb in NLS was obtained. Figure 4 shows energy spectrum curves of two samples.

From Figure 3(a), the characteristic peak of Pb in NLS after RF injection is 137.9eV, while the characteristic peak of Pb in Figure 3(b) is 140.4eV. We check the handbook of XPS and find that the characteristic peak of Pb of No. 1 sample corresponds with PbO_2, while No.2 sample coincides with PbO.

Experimental results show that the valence of Pb in NLS changes from +2 to +4 after the impingement of RF. Thus it is obvious that the NLS is broken down under the effect of the heat generated by RF, which is higher than 235℃—the decomposition temperature of NLS[10], and its performance changes.



(a) Sample 1



(b) Sample 2

Figure 3 XPS analysis spectrums of Pb in NLS

3 Conclusions

In order to understand the RF damage mechanism of SCB initiators, the RF sensitivity and firing performance of electrode plugs were calculated and compared with the initiators. The temperature generated by RF energy is not high enough to damage the polysilicon bridge film whose boiling point is up to 2600℃, but it makes the primary explosive deterred and increases the ignition voltage of SCB initiators that results from the data of firing experiment. This is easily seen by comparing the U_{50} and $U_{99.9}$ of samples after vacuum oven dehydration with those of the control samples that the abjunction of crystal water is not the reason of RF passivates NLS. The XPS analysis method is introduced to obtain the characteristic peaks of Pb in NLS. It is obvious from the spectral lines that the valence of Pb changes from +2 to +4. It is concluded that RF generates high temperature and leads to the decomposition of NLS. Ultimately, the thermal effect results in the dud of explosive or reduces the reliability of SCB initiators.

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