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Light Effect in Semiconductor Bridge Plasma Ignition

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Abstract: Heat is considered to play an important role in Semiconductor Bridge (SCB) plasma ignition. Nevertheless, in this paper a non-heat effect is reported for SCB ignition of primary explosives. An initial comparison showed that there is no reasonable correlation between the ease of plasma ignition and the 5-s explosion temperature. Meanwhile the addition of Pb_3O_4 was found to make lead styphnate (LS) more active to SCB plasma ignition whereas the heat decomposition of this mixture was not accelerated. In terms of the phenomena mentioned above and the response of primary explosives to SCB plasma, we propose an effect of light in SCB plasma ignition. The free radical concentration change indicates that light enhances the activity of primary explosives in SCB plasma ignition. Regarding the mixture of LS and Pb_3O_4, the additive itself does not make LS sensitive to the SCB plasma. However, the supplement makes LS active under light exposure. As a result, the effect of light on SCB plasma ignition was confirmed by the experiments conducted in this study. This paper provides a new understanding of SCB plasma ignition from the viewpoint of explosives, which is of importance for the design of SCBs.

Keywords: SCB plasma ignition, non-heat effect, light effect, free radicals

1 Introduction

Semiconductor bridge (SCB) is a type of silicon-based electronic device that performs the function of an explosive initiator by generating a silicon plasma when an appropriate electrical input is applied. SCBs have been used widely in the field of energetic materials due to their rapid response, repeatability and safety [1, 2]. The development of SCBs is regarded as the most important milestone in the revolution and development of igniter devices [3]. Much research has been

reported regarding the SCB plasma ignition mechanism, in which heating effects are predominant: for example, the micro-convective heating model [4], the heat transfer simulation [5] and the temperature distribution analysis of the silicon bridge [6]. Each of these studies concentrated on the SCB itself and assumed that ignition is produced by the heat generated by the SCB plasma. However, the effect of other types of energy in the SCB plasma have also been discussed in the literature [7-9]. Shock energy is thought to be of little importance because the expansion rate of gas products is much lower than the sound speed [7]. Meanwhile, SCB plasma emission is thought to be involved in the process of ignition, but has not been evaluated in any detail [8]. In other cases of plasma ignition, heat is also considered to be the primary cause of ignition, based on experimental data [10] and numerical simulations [11]. However, the influence of plasma radiation [12], plasma pressure [13] and plasma flow-field distribution [14] are addressed in other systems. Thus, other forms of plasma energy besides heat must be considered.

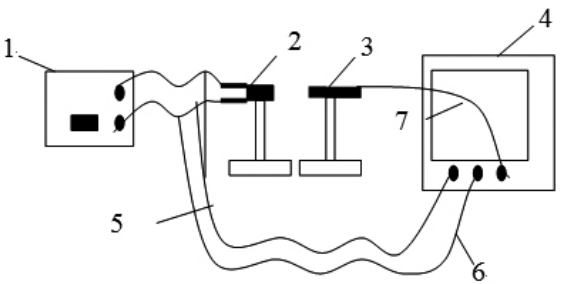
In our SCB plasma ignition experiments, we focus on the characteristics of primary explosives because they respond to plasma directly [15]. Five primary explosives were utilized in our study of SCB plasma ignition and compared in order to understand the dynamics of plasma ignition. We noticed that there are some special phenomena in SCB plasma ignition. Among the five primary explosives, the one that can be ignited by SCB plasma with the lowest ignition voltage was found to respond to heat very slowly. On the other hand, the explosive that can be triggered by heat very quickly was found to be detonated by SCB plasma with a higher voltage. The heating effect of the plasma could not explain these results. In addition to the research that was conducted to analyze the surface chemical activity of the propellants after exposure to plasma [16], the coherent connection between primary explosives and the plasma emission spectra is emphasized in this paper. As a result, a light effect of the SCB plasma is proposed and confirmed. The results reported in this paper provide a new understanding of SCB ignition from the viewpoint of the explosive which is vital for the design of SCBs and their applications.

2 Experimental

The experiments consisted of SCB ignition experiments and sensitivity tests of SCB-loaded explosives. SCB plasma spectral measurements were reported by us in detail in [17]. A diagram of the SCB ignition experiments is shown in Figure 1. The ignition experiments consisted of making a current flow through

an SCB made of silicon. The silicon first melted and then vaporized, resulting in the generation of high temperature plasma. After the plasma was generated, the explosive ignited. During this process, the voltage and current were monitored using appropriate probes. The light produced by the explosion was collected by an optical fiber connected to a photodiode, which converted the detected light signal into a voltage signal that was recorded using an oscilloscope [2]. The SCB ignition sensitivity tests were conducted according to the D-optimal method so that the all-fire voltage of the SCBs could be computed allowing the responses of different explosive to be compared.

The SCB used in this research was a rectangular block with two V-shaped notches, typically 100 mm long by 380 mm wide by 2 mm thick. The resistance of the SCB was 1.0 ±0.1 Ω. The primary explosive with average size about 50 mm was loaded with the SCB under a pressure of 1200 kg/m^2. Five primary explosives were chosen to study: lead styphnate (LS), lead azide (LA), nickel hydrazine azide (NHA), nickel hydrazine nitrate (NHN), and tetrazene.



1 − electrical source, 2 − SCB, 3 − photoelectric conversion, 4 − oscilloscope, 5 − voltage probe, 6 − current probe, 7 − light probe

Figure 1. Schematic diagram of SCB ignition

3 Results and Discussion

3.1 SCB plasma ignition

The SCB was charged using a voltage of 60 V and a capacitance of 47 μF. The signals were recorded simultaneously, as shown in Figure 2. It can be seen that there are two peaks in the voltage-time curve. The first peak is attributed to the melting of the silicon film [2]. The phase transition in silicon leads to a broken circuit, thereby causing the resistance to increase sharply. When the liquid silicon evaporates, ionization and discharge follows, making a second peak appear in the voltage curve. The appearance of the second peak is regarded as indicating

the generation of plasma. The measured current also reaches a maximum at the moment of plasma generation which then lasts for some time afterwards. After plasma generation, the light signal emerges, indicating that the LS reacts. Explosion occurs after a delay of 30 μs. At the exact moment of light emergence, the SCB plasma ignition is completed.

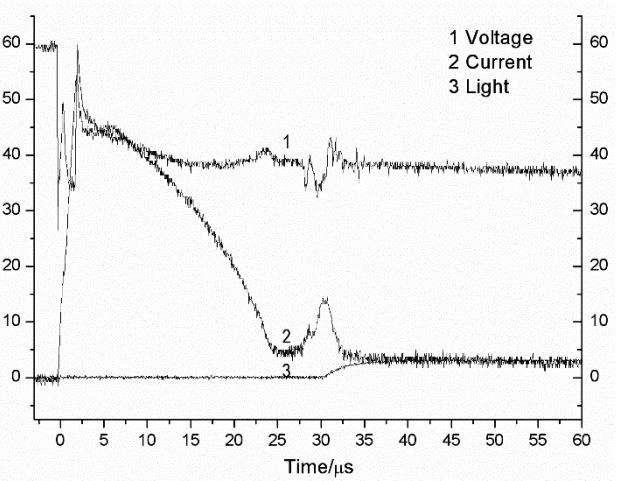


Figure 2. Discharge voltage-current curves of SCB-LS (60 V, 47 μF)

To evaluate the response of explosives to SCB ignition quantitatively, sensitivity experiments were conducted according to the D-optimal method allowing the 50 per cent-fire-voltage to be obtained. Subsequently the all-fire voltages (*i.e.* 99.9% fire voltage) were computed and shown in Table 1.

Table 1. Characteristics of the different primary explosives

	50% Fire voltage [a,c] [V]	99.9% Fire voltage [a,c] [V]	0.1% Fire voltage [a,c] [V]	Standard deviation	Function time of SCB ignition [b] [μs]	5-s Explosion temperature [°C]
Tetrazene	15.74	19.46	12.02	1.24	56	160
NHN	37.93	47.95	27.91	3.34	2000	256
NHA	8.75	10.73	6.97	0.66	22	190
LA	21.54	34.35	8.73	4.27	8	310
LS	8.25	10.23	6.27	0.66	38	282
LS + Pb_3O_4	8.15	10.16	6.14	0.67	41	287

[a] charge capacity is 47 μF; [b] charge capacity is 47 μF and voltage is 60 V; [c] the confidence level of data with D-optimal method is 95%

The all-fire voltage means that the explosive could be ignited definitely using this voltage. A low all-fire voltage indicates the igniter could work with a smaller input energy. So this voltage value is usually used as a quantitative sign to rank the sensitivity of explosives. In our experiments lead styphnate was the most sensitive explosive to SCB ignition while its all-fire voltage was 10.73 V as shown in Table 1. At the same time, the function times of the various explosives studied to SCB ignition were recorded and listed in Table 1. The shorter the function time, the faster the explosive is ignited by an SCB. Thus the function time also could reflect differences in explosive response. However, the all-fire voltage ranking of the five explosives was not the same as the ranking based on the function time, which indicates the complex nature of SCB ignition mechanisms. The reason for the discrepancy is because the all-fire voltage indicates the threshold of explosive reaction to SCB ignition whereas the function time shows the reaction speed. Conventionally the all-fire voltage is regarded as the criterion for evaluating explosive sensitivity. Thus we compare the all-fire voltages in our research on SCB ignition of explosives. So on the basis of all-fire voltage, the sensitivity of explosives to SCB plasma can be listed as: NHN < LA < tetrazene < NHA < LS.

3.2 Non-heat effect in SCB plasma ignition

As mentioned in the Introduction, many researchers consider that heat, *via* heat-transfer or heat-convection, to be the main energy source of SCB plasma ignition [3]. However, two unusual phenomena were found in our study, which prove that there exist effects in SCB plasma ignition that are not due to heat. The first is that there is no relation between the ease of plasma ignition and the heat sensitivity of explosives. The second is that certain additives make the explosives more sensitive to SCB ignition while not triggering the reaction earlier or accelerating the reaction when conventional heating is applied.

Concerning the first phenomenon, it is reasonable to deduce that for a given explosive, the higher the 5-s explosion temperature is, the more difficult SCB ignition is on the basis that the primary explosive is triggered to explode *via* the SCB plasma heat. The 5-s explosion temperature is defined as the temperature a primary explosive must be heated to in order to ensure explosion within in 5 seconds [18]. Different primary explosives have different 5-s temperatures. As a result, the 5-s explosion temperature is generally regarded as the criterion for evaluating the heat sensitivity of primary explosives [18].

To verify the above statements that explosives with low 5-s explosion temperature can be characterized by ease of plasma ignition, five primary explosives were chosen for study: LS, LA, NHA, NHN and tetrazene. Their

5-s explosion temperatures are as follows: tetrazene 160 °C, NHA 190 °C, NHN 256 °C, LS 282 °C and LA 310 °C [18]. The 5-s explosion temperatures of these explosives are thus ranked: tetrazene < NHA < NHN < LS < LA. These explosives were studied in SCB plasma ignition experiments, as presented in the previous section. For a primary explosive, the all-fire voltage for SCB plasma ignition is used as the criterion to evaluate the ease of plasma ignition [15]. Thus these explosives can be compared using the all-fire voltage for SCB plasma ignition. The all-fire voltages for SCB plasma ignition were LS 10.23 V, NHA 10.73 V, tetrazene 19.46 V, NHN 27.91 V, and LA 34.35 V. So the ease with which these explosives can be ignited using the SCB plasma technique is: LS > NHA > tetrazene > NHN > LA.

Among these five primary explosives, LS is ignited by SCB plasma at an all-fire voltage of 10.23 V, whereas its 5-s explosion temperature is the second highest. Tetrazene is characterized by the lowest 5-s explosion temperature; however, it is middle ranking with respect to ease of plasma ignition. Thus, no coherent relation exists between the ease of plasma ignition and the 5-s explosion temperature. In other words, the variety of responses of explosives to SCB plasma could not be explained only by the effect of heat. This result pointed towards forms of energy in addition to heat being important in SCB plasma ignition.

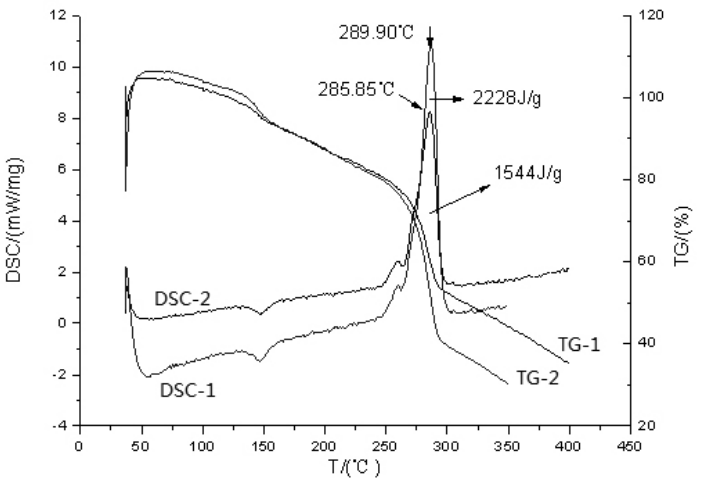


Figure 3. TG and DSC of LS (1) and LS with Pb_3O_4 (2)

To verify the effect non-heat energy on SCB plasma ignition, we concentrated on the characteristics of primary explosives, especially LS, which was found to react to the SCB plasma quickly and could be ignited at the lowest voltage.

The peculiarity of LS should be emphasized and illuminated. Meanwhile, if the ignition voltage for LS changed specifically, the characteristics of this sample would provide extra information for the understanding of SCB plasma ignition mechanisms. Subsequently, Pb_3O_4 was selected as an additive on the basis that it is a mixture of Pb^{4+} and Pb^{2+} ions and electron transfer may cause the generation of free radicals. Most explosives undergo chain-reactions involving free radicals. So the existence of free radicals in an additive may be available for the reaction. Thus Pb_3O_4 was utilized to reduce the ignition voltage for LS.

After 5% Pb_3O_4 was added to the LS powder, the all-fire voltage of the mixture was found to be lower than that for the original LS (Table 1). The two samples were analyzed using TG and DSC to compare the heat decomposition (Figure 3).

In Figure 3 the peak temperature of sample 2 (*i.e.*, LS with additives) is 289.9 °C, while that of sample 1 (pure LS) is 285.85 °C. The explosion heats of sample 1 and sample 2 are 1554 J/g and 2228 J/g, respectively. These results indicate that the additives enhance both the reaction heat and the temperature. The TG curves in Figure 3 show that there are two apparent weight loss steps, which respond to two main reactions: one at a temperature of 50 °C and the second at 150 °C. A comparison of the TG curves of the two samples shows that they are very similar in the initial and the second reaction temperature and even in the decomposition rate. Therefore, the TG and DSC curves prove that the use of additives is helpful for LS explosion in terms of reaction completeness and in increasing the reaction heat and temperature. However, the additives do not cause the reaction itself to occur earlier or later. Combining the TG and DSC curves with the plasma ignition results can make sense in that the additives lower the ignition voltage without changing the primary explosive decomposition rate. In other words, the SCB plasma ignition of LS is not sensitized through accelerating the heat decomposition. Thus, these experiments provide extra evidence for non-heat effects in SCB plasma ignition.

3.3 Effect of light on SCB plasma ignition

We previously reported that there were intense emission spectra in the SCB plasma in the wavelength range 390-430 nm, as shown in Figure 4 [17]. Meanwhile the experiments reported in sections 3.1 and 3.2 proved that there was an effect on SCB plasma ignition of sources of energy other than heat. So we connected these specific spectra with LS ignition experiments. The following experiments were designed so that LS was exposed to light in the wavelength range from 200 nm to 400 nm and the activity of chemical reaction was recorded simultaneously.

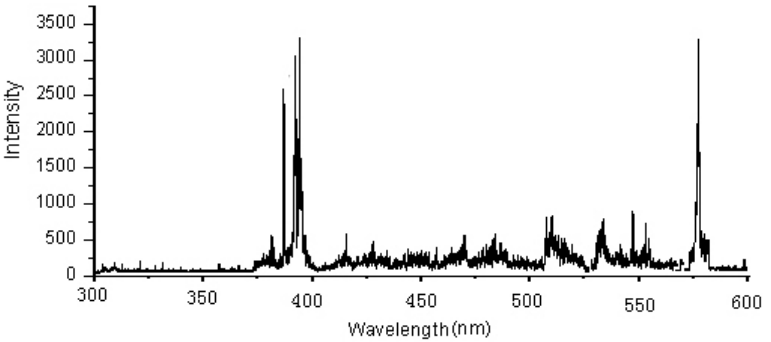
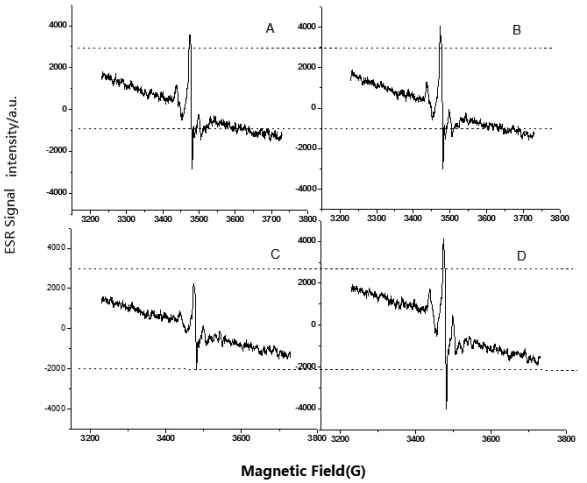


Figure 4. The emission spectra of SCB plasma

ESR (electron spin resonance) is a technique that has been widely used for the study of radicals formed in solid materials. The presence of radicals is a useful indicator for the very beginning of chemical reactions, especially for explosives, because chain reactions are typically initiated by free radicals. As a result, in this research the ESR spectrum of LS was deliberately chosen for observation. For comparison, a sample of LS with the addition of 5% Pb_3O_4 was also studied under the same conditions, as illustrated in Figure 5.



A: LS before light exposure; B: LS after light (200-400 nm) exposure; C: LS with Pb_3O_4 before light exposure; D: LS with Pb_3O_4 after light (200-400 nm)

Figure 5. Free radicals of LS observed by ESR spectra

An intense peak can be identified as O−N−O free radicals in the four images, as shown in Figure 5. The contrast is highlighted by the peak differences before and after light exposure for both samples. Figure 5b shows the initial sample after exposure to light in the range of 200 nm to 400 nm; its ESR spectrum peak was found to be definitely augmented. In Figure 5c, the sample is LS with the additive; in this case, the peak was found to be reduced, which emphasizes the fact that the additive itself does not promote peak increase. On the contrary, an ESR spectrum peak for LS with the additive decreased because of the dilution of LS. However, the ESR spectral peak of the sample with the additive increased greatly after light exposure, as shown in Figure 5d, to a level even larger than that of the initial sample (shown in Figure 5b).

The larger the peak is, the more free radicals are present, and thus the more active is the reaction. Therefore, amplification of the peak indicates that the reaction becomes easier to initiate. This is especially true for primary explosives. In fact, primary explosives undergo a chain reaction once the reaction is initiated. As a result, the augmented peak in Figure 5b indicates that LS is sensitized and apt to react after exposure to light in a specific wavelength range. A comparison of Figures 5a and Figure 5c indicates that the additive itself does not increase the number of free radicals and even dilutes their original concentration. At the same time, it can be inferred that LS is activated by the light from SCB plasma emission making it easier for reaction to occur, as demonstrated by comparing Figures 5a and Figure 5b.

Further evidence of the light effect in SCB plasma ignition can be seen by comparing Figures 5c and Figure 5d. As demonstrated, LS with the addition of 5% Pb_3O_4 could be ignited using a voltage of 18 V, which is even lower than that for LS itself. Although it is thus proved that the additive enables complete reaction, the additive itself does not accelerate the reaction or favor the generation of free radicals. The reason for the activation of LS by the additive lies in its enhancement of free radical generation when exposed to light radiation, as shown in Figure 5c and Figure 5d.

In summary, light at certain wavelengths plays an important role in SCB plasma ignition of LS. LS becomes activated by light. Moreover, additives can promote the reaction of LS due to the light enhancing the generation of free radicals. It can be concluded that this mixture could produce more free radicals after exposure to light at specific wavelengths, which leads to a more sensitive reaction that can be initiated at a lower ignition voltage.

4 Conclusions

SCB plasma ignition was investigated by studying the characteristics of primary explosives. The effect of energy other than heat in SCB plasma ignition is proposed because of the observation that the ease of plasma ignition and the 5-s explosion temperature do not correlate for a certain explosive. This proposal was confirmed by an experiment involving the use of additives that make the explosive more sensitive to SCB plasma ignition. Furthermore, the primary explosive and the SCB plasma emission spectra were found to be related, and effect of light in the SCB plasma was presented. The ESR spectra indicated that light enhances the activity of primary explosives in SCB plasma ignition. Thus the light effect in SCB plasma ignition is verified.

Acknowledgments
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