Improving reliability of SCB initiators based on Al/Ni multilayer nanofilms

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Abstract. This paper exploits an energetic initiator realized by integrating Al/Ni multilayer nanofilms with semiconductor bridge (SCB). The as-deposited nanofilms have been characterized with varied analytical techniques. Results show that distinct nanofilms are sputter deposited in a layered geometry and give a heat of reaction equal to 1134 J/g. The firing tests of the initiators were accomplished using capacitor discharge unit. Results show that the initiators possess several excellent characteristics such as fast ignition time, low power consumption, high output energy and so on. Therefore, Al/Ni multilayer nanofilms are suitable heat source for improving the reliability of SCB initiators.

1 Introduction

Semiconductor bridge (SCB) is a resistive element, which converts electrical energy into high temperature plasma for the purpose of initiating an explosion of pyrotechnic material in a controlled energetic reaction. It was conceived and patented by Sandia National Laboratories in 80s of last century. SCB possesses excellent properties such as passing requirements for no fire (a 1-A current passed through the bridge for 5 min without function), low ignition energy, fast ignition time and readiness of incorporation with digital logic circuits [1–4]. However, there are still some problems remaining such as not very high reliability, not very good intimate contact between the SCB and the attached reactive materials, and smaller output energy compared with input energy [5–7].

Al/Ni multilayer nanofilms consisting of alternating layers of the Al and Ni films have been observed for two decades [8]. Since the thickness of each layer varies from several nanometers to micrometers, a self-propagating exothermic reaction can be initiated in these thin film systems and produces larger quantity of heat with a small thermal pulse or an electrical stimulus. In the past two decades, they were usually used as a local heat source for soldering and brazing applications [9–12], and several classic review articles have summarized their preparation, characterization and self-propagating reaction waves [13–16]. In addition, Al/Ni multilayer nanofilms possess good exothermic reaction properties which qualify them as a suitable heat source for energetic initiators. For example, Xiaotun Qiu and co-workers have studied the electrical explosion performance of the initiators made with Al/Ni multilayer nanofilms [17–19]. Our team also reported their potential application prospects in energetic initiators. However, the initiators prepared directly with Al/Ni multilayer nanofilms consume relatively longer ignition time and too much electrical energy [20].

A primary object of this study is to provide an energetic initiator realized by integrating Al/Ni multilayer nanofilms with SCB (SCB-Al/Ni). It has both the advantages of SCB and Al/Ni multilayer nanofilms, which may improve the ignition reliability in the case of low electrical energy consumption and fast ignition time.

2 Characterization of Al/Ni multilayer nanofilms

Prior to the preparation of SCB-Al/Ni initiators, free-standing Al/Ni multilayer nanofilms were prepared with magnetron sputtering for characterization, the detailed process flow was depicted in reference [14]. The modulation period is a very important parameter, which has a great influence on stoichiometric reaction. In order to affirm a better modulation period, a series of DSC experiments have been done, and the results show that Al/Ni multilayer nanofilms possess the larger reaction heat when the modulation period is Al (45 nm)/Ni (30 nm). Sirion2000 field emission scanning electron microscopy (FESEM) was used to observe the cross-section of the as-deposited Al/Ni multilayer nanofilms. As shown in Figure 1a, the anticipated layered structure is clearly visible. In the DSC experiments, three exothermic peaks can be identified in the constant-heating-rate curve (Fig. 1b). By integrating the heat flow with respect to time, the heat of reaction was calculated to be 1134 J/g. This result was

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used as input for the analysis of the output energy multiplier of SCB-Al/Ni during the ignition process depicted in Section 4.3. In this paper, the modulation period is empirically determined as 75 nm which includes 45 nm-thick Al film and 30 nm-thick Ni film, and the total thickness is 3\( \mu \text{m} \).

3 Design and preparation of SCB-Al/Ni

The fabrication processing of SCB is a simple CMOS procedure. More than 2000 SCB patterns can be defined on a 4-in.-diam wafer, and the wafers are then diced into individual chips. In this experiment, heavily \( n \)-type doped polysilicon wafer was applied to make SCB chip, and only two computer generated masks are required in this simple process. The first defines the “double-V” shaped bridge, and the second determines the shape of the Ti/Au lands. Considering no fire safety and electrostatic safety, the resistance of SCB was designed as 1.3 \( \pm 0.1 \Omega \). The bridge has two V-type angles (90°) and the size is 380 \( \mu \text{m} \) (width) \( \times 80 \mu \text{m} \) (length) \( \times 2.5 \mu \text{m} \) (thickness). The prepared SCB chip is shown in Figure 2a. SCB is designed to operate using large current pulse to vaporize the bridge producing plasma and small mechanical stress waves. The generated plasma and stress wave directly impact the Al/Ni multilayer nanofilms to initiate it. However, Al/Ni multilayer nanofilms are very difficult to etch, and therefore the SCB-Al/Ni chip was prepared using a combination of photolithography, sputtering and lift-off techniques on a SCB wafer. Prior to deposition, the SCB wafer was pre-cleaned using acetone, and then a thick photoresist was coated and patterned. Then, Al/Ni multilayer nanofilms were deposited onto the wafer surface only where the photoresist was previously removed, whose
size is 1 mm (length) × 1 mm (width) × 3 μm (thickness). Finally, the photosresist was removed by sonication in acetone, thereby causing lift-off of the films from the unwanted areas. The prepared SCB-Al/Ni chip is shown in Figure 2b, whose resistance is the same as SCB.

For electrical initiation experiments, the chips were mounted into the channel of ceramic plug with non-conductive epoxy resin. The external diameter of ceramic plug is 6 mm and the height is 4.5 mm. Then, the Ti/Au lands of SCB chip and electrical leads of ceramic plug were connected together with gold wires whose diameter was 30 μm and length was 2 mm by ultrasonic bonding technology. The top view of packaged SCB-Al/Ni is shown in Figure 2c.

4 SCB-Al/Ni electromechanical characterization

Ignition power, ignition delay, output energy and electrical explosion temperature play a crucial role for the practical applications of SCB-Al/Ni. These parameters were achieved by using a capacitor firing circuit equipped with Multioscillograph (LeCory 44Xs-A) recording the electrical features simultaneously. A high-speed camera (HG-100 K) was used to observe the initiators as electrical power was applied. It was set to record at 50 000 frames per second. Microscope photographs were also taken of the ignition element before and after testing to observe any permanent physical effects. Additionally, the explosion temperature of the SCB-Al/Ni was determined by spectral temperature diagnosis system.

4.1 Open-air electrical explosion testing

For a fixed set of apparatus, a specific structure of initiator corresponds to an optimized charging voltage. When the capacitor is charged to a lower voltage, the initiator cannot obtain sufficient energy to explode thoroughly. However, the efficiency of the circuit will be decreased with less energy and smaller output energy. Therefore, the capacitor 47 μF and 30 V were used according to previous work. The interval between adjoining pictures is 20 μs. For SCB-Al/Ni, plasma is seen at ~20 μs (frame: 2), and then combustion glow gets brighter. At ~80 μs (frame: 5), the combustion glow builds up to full combustion. As shown in Figure 4b, the area marked with yellow arrows is the edge of ceramic plug, not a plasma plume. For SCB, the plasma at ~20 μs has the same characteristic shape as that of SCB-Al/Ni. After that, the plasma becomes weaker because of no films on SCB. It is notable that the plasma is almost extinguished for SCB at ~60 μs, on the contrary, the plasma plume can still be seen for SCB-Al/Ni at ~60 μs and seems to be more intense. For SCB-Al/Ni, it seems that the SCB bursts first, and then the films are ignited. In addition, Al/Ni multilayer nanofilms could enhance the plasma temperature and its duration of SCB.

An optical micrograph of the combustion products from a fired SCB-Al/Ni is shown in Figure 5. There are black products left on the SCB, particularly at the pads where self-propagating exothermic reaction takes place. The most interesting feature in this photograph, however,
is the absence of products above the burst point. At the burst point, the film was penetrated by the Si plasma at the moment SCB burst. The absence of product suggests that the electrical explosion temperature was sufficient to evaporate some of the product in this region, and was high enough to initiate Al/Ni multilayer nanofilms, but not completely evaporate it. XRD traces of the as-deposited Al/Ni multilayer nanofilms compared with the reaction products are shown in Figure 6. Before the reaction, all major peaks corresponded to Al and Ni. While after the reaction, all major peaks corresponded to the ordered AlNi compound. Thus, the AlNi compound was expected to be the dominant reaction product of the film during the ignition process. It can be definitely concluded that an Al/Ni thermite reaction occurred during the electrical explosion, otherwise the rapidly vaporized Si plasma would just penetrate the Al/Ni multilayer nanofilms above with no unusual phenomena observed.

Based on the above analysis, the process for igniting the Al/Ni multilayer nanofilms is as follows: the electrical energy causes the bridge region to heat up rapidly until it bursts. The burst could ignite a self-propagating exothermic reaction of Al/Ni multilayer nanofilms, which consists of two parts, one is on SCB bridge region, and the other is on SCB pads. The films on bridge region are heated directly, as well as impact action, so that the combustion reaction is more violent, and the products are ejected away. At the same time, self-propagating exothermic reaction of the films on pads occurs. The combustion wave speed is about 5 m/s according to references [9–14], and the length of films on each pad is 0.5 mm, so the combustion delay is about 100 μs, which is similar to that of electrical explosion. Therefore, the combustion reaction of Al/Ni multilayer nanofilms completes in a very short time, so the reaction heat may be added in the output energy of SCB-Al/Ni as described in Section 4.3.
4.3 Output energy multiplier of SCB-Al/Ni

For one SCB-Al/Ni, assuming the density of Al film and Ni film is similar to that of the bulk, the heat released by Al/Ni multilayer nanofilms could be roughly derived with mathematical calculations. The general equations are:

\[ Q = q_{DSC} \times m_{Al/Ni}, \]
\[ m_{Al/Ni} = m_{Al} + m_{Ni}, \]
\[ m_{Al} = \rho_{Al} \times V_{Al}, \]
\[ m_{Ni} = \rho_{Ni} \times V_{Ni}, \]

where \( Q \) is the released heat of Al/Ni multilayer nanofilms, \( q_{DSC} \) is 1134 J/g obtained with DSC experiment, \( m_{Al/Ni} \) is the mass of Al/Ni multilayer nanofilms, \( m_{Al} \) is the mass of Al film, \( m_{Ni} \) is the mass of Ni film, \( V_{Al} \) is the volume of Al film, \( V_{Ni} \) is the volume of Ni film, \( \rho_{Al} = 2.7 \text{ g/cm}^3 \), \( \rho_{Ni} = 8.9 \text{ g/cm}^3 \). The size of Al/Ni multilayer nanofilms deposited onto SCB is 1 mm (length) \times 1 mm (width) \times 3 \mu m (thickness), the modulation period is Al (45 nm)/Ni (30nm), therefore, it could be calculated that \( V_{Al} \) and \( V_{Ni} \) are \( 1.8 \times 10^{-6} \text{ cm}^3 \) and \( 1.2 \times 10^{-6} \text{ cm}^3 \), respectively. Therefore, calculation of \( Q \) is 17.6 mJ. The average value for input energy of SCB-Al/Ni is 2.6 mJ. Considering the principle of energy conservation, the total output energy is 20.2 mJ, which is nearly 10 times higher than that of the SCB.

4.4 Electrical explosion temperature and its duration of SCB-Al/Ni

The electrical explosion temperature and its duration of SCB and SCB-Al/Ni were characterized, respectively, with spectral temperature measurement system originally built by Junde Wang and co-workers [21]. Its temporal resolution is 0.1 \( \mu s \), so the time evolution of the plasma temperature is obtained by a given shot. The fundamental principle has been described in detail in previous articles [22–24]. The comparison as a function of time for SCB and SCB-Al/Ni both loaded with 47 \( \mu F \) and 30 V is shown in Figure 7. For SCB, the temperature increases initially
with the time and then varies from 5000 K to 4000 K for approximately 140 μs. For SCB-Al/Ni, the temperature immediately reaches about 7000 K, and then varies from 8000 K to 4000 K for approximately 140 μs. It could be deduced that the exothermic reaction of Al/Ni multilayer nanofilms occurs, resulting in a further extension of the electrical explosion.

5 Conclusions

The SCB-Al/Ni initiator was successfully realized by integrating Al/Ni multilayer nanofilms with SCB. Electromechanical characterizations show that Al/Ni multilayer nanofilms have an important role in improving the ignition reliability of SCB. With 47 μF discharged in 30 V, a self-propagating reaction was triggered in Al/Ni multilayer nanofilms generating localized high temperature and ejected products. The small ignition energy required (2.6 mJ) and the large energy output (20.2 mJ) with an ignition delay of around 17 μs made the SCB-Al/Ni superior to the current resistive heater-based initiators. Therefore, SCB-Al/Ni is supposed to have a variety of potential applications in both civilian and military areas. In the future, a great attention will be paid on the research of initiating pyrotechnics and explosives.

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