

A micro initiator realized by reactive Ni/Al nanolaminates

Xiaotun Qiu · Rui Tang · Ranran Liu ·
Hai Huang · Shengmin Guo · Hongyu Yu

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Abstract This study described a micro initiator realized by reactive Ni/Al nanolaminates. A self-propagating reaction can be triggered in the Ni/Al film by applying a DC voltage of 1.5 V. This exothermic reaction can raise the temperature of the film (10 μm in thickness) surface to as high as 622 K. The measured ignition power to start the self-propagating reaction in the film was 3 mW with an ignition delay of around 0.63 s. The small ignition energy required and the large energy output make the Ni/Al film superior to the current resistive heater based initiators. Numerical simulation results demonstrated that different temperatures can be achieved by simply alternating the film thickness and the localization of high temperature exposure was realized to avoid unintentional fire of adjacent initiators. These findings were confirmed by the experiment using thermal indicators.

1 Introduction

Micro initiators can be found in numerous civilian and military applications such as triggering the inflation of

airbags in automobiles [1], micropropulsion systems for microsatellites [2], and safe-and-arm devices used in missiles, rockets, and many other ordnance systems [3]. Traditionally, a bridgewire was used to ignite the subsequent reactions. However, this kind of initiator suffers from weak contact between the wires and the reactive materials. Meanwhile, they are not suitable for batch fabrication and high level of integration due to the relatively large size. Nowadays, initiators usually employ micro resistive heaters, such as polysilicon heaters [4] to initiate the explosives. However, an input voltage as high as 30 V is required. They also possess such disadvantages as low reliability and smaller output energy compared with input energy. Alternatively, a nano initiator has been developed by integrating Al/CuO based nanoenergetic materials with a thin film microheater [5]. However, the introduction of CuO nanowires complicates the fabrication process.

Reactive Ni/Al nanolaminates contain thousands of nanoscale Al and Ni bilayers. With a small thermal pulse, they can react exothermically and generate a self-propagating reaction. Self-propagating reactions in these films are driven by a reduction in chemical bond energy. This local reduction of chemical bond energy produces a large quantity of heat that is conducted down the film and facilitates more atomic mixing and compound formation. Such exothermic reactions in reactive Ni/Al films have been used as local heat sources to melt solders or brazes and thus bond components in a variety of applications, such as bonding stainless steel, aluminum, titanium, metallic glass, silicon wafers and parylene [6–14]. With localized heating, temperature sensitive components such as micro-electronic devices can be joined without thermal damage.

In this study, a micro initiator based on reactive Ni/Al nanolaminates was investigated. The properties of the Ni/Al films were characterized using X-ray diffraction (XRD)

X. Qiu
Qualcomm, San Diego, CA 92121, USA

R. Tang (✉) · H. Huang · H. Yu
School of Electrical, Computer and Energy Engineering,
Arizona State University, Tempe, AZ 85287, USA
e-mail: rtang4@asu.edu

R. Liu · S. Guo
Department of Mechanical Engineering, Louisiana State
University, Baton Rouge, LA 70803, USA

H. Yu
School of Earth and Space Exploration,
Arizona State University, Tempe, AZ 85287, USA

and differential scanning calorimetry (DSC). The ignition power to start the self-propagating reaction in the film and the ignition delay of the initiator were determined. Temperature distribution on the device during ignition was simulated by a numerical method and confirmed using thermal indicators.

2 Experimental

The schematic structure of the micro initiator is shown in Fig. 1. Ni/Al nanolaminates (Ni/Al atom ratio is 1:1) were deposited layer by layer using magnetron sputtering and patterned by wet chemical etching (nitric acid and hydrochloric acid). The total thickness of the Ni/Al films used here was 10 μm with a bilayer thickness of 40 nm (Ni: 16 nm; Al: 24 nm). The crystallographic phases of the as-deposited Ni/Al film and the reaction products were investigated by a Rigaku MiniFlex XRD using Cu $K\alpha$ radiation. The heat of reaction was measured by a Perkin Elmer differential scanning calorimeter (DSC7). In each DSC run, about 10 mg freestanding films were heated from 323 to 998 K at a rate of 40 K/min in flowing N_2 . A base line was obtained by repeating the heating cycle, which was then subtracted from the heat flow in the first run. By integrating the net heat flow with respect to time, the heat of reaction was obtained.

A SiO_2 layer was used under the Ni/Al film to provide thermal insulation from the silicon substrate. A 1.5 V DC voltage source was employed to initiate the self-propagating reaction. The electrical circuit included the voltage source and the film as a resistor. The voltage across the film was recorded by a NI USB-6289 Data Acquisition Card through a Labview program. The data were used to

Table 1 Thermophysical parameters for the reactive Ni/Al film, silicon and silicon dioxide used in the simulation

	Thermal conductivity (W/mK)	Heat capacity (J/kgK)	Density (kg/m^3)
Silicon	149	707	2,330
SiO_2	1.38	703	2,634
Film (as-deposited)	160	830	5,500
Film (reacted)	25	610	5,860

calculate the ignition power to start the self-propagating reaction in the film and determine the ignition delay.

Numerical simulation was conducted to predict the temperature distribution on the initiator during ignition using commercial finite element analysis software, Fluent [15]. The numerical model was based on a simplified description of the self-propagating reaction and the thermal transport occurring in the initiator. The model assumed one-dimensional motion of the reaction front, which was described using experimentally determined heats of reaction and reaction velocities of the films [6]. More details of the numerical model can be found in our previous papers [12, 16]. The simulation started when the reactive film was ignited. The physical properties of different materials used in the simulation are listed in Table 1. Thermal indicators (temperature indicating minilabel and temperature indicating liquid) were applied to the initiator to monitor the peak temperatures experienced at different locations on the device. The outcomes were compared with the simulation results.

3 Results and discussion

Ten micrometer thick reactive Ni/Al nanolaminates with a bilayer thickness of 40 nm were used in this study as the initiator. For Ni/Al films, the reaction velocity decreased with increasing bilayer thickness. The heat of reaction increased as bilayer thickness increased, due to intermixing occurred during deposition [6]. In order to achieve a balance between high reaction velocity and high reaction heat, the bilayer thickness of the films was set at 40 nm.

X-ray diffraction traces of the as-deposited reactive Ni/Al films and the reaction products are shown in Fig. 2a. Before the reaction, all major peaks corresponded to Al and Ni. While after the reaction, all major peaks corresponded to the ordered B2 AlNi compound. Thus, the B2 AlNi compound was expected to be the dominant reaction product of the film during the ignition process [12]. In the

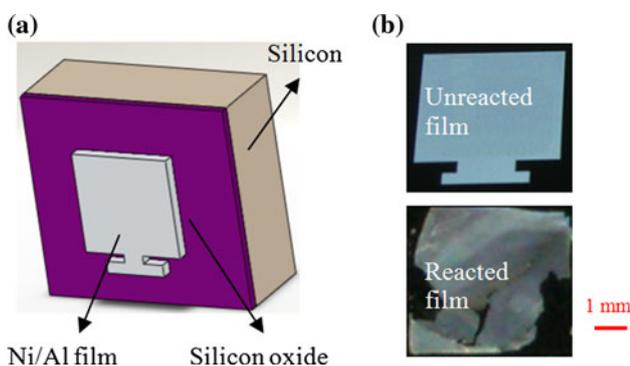


Fig. 1 **a** The schematic structure of the micro initiator; **b** the photographs of the Ni/Al film before and after ignition. The film was bright and shiny before reaction. It turned out to be cracked after reaction due to the contraction from density change and cooling from high reaction temperatures

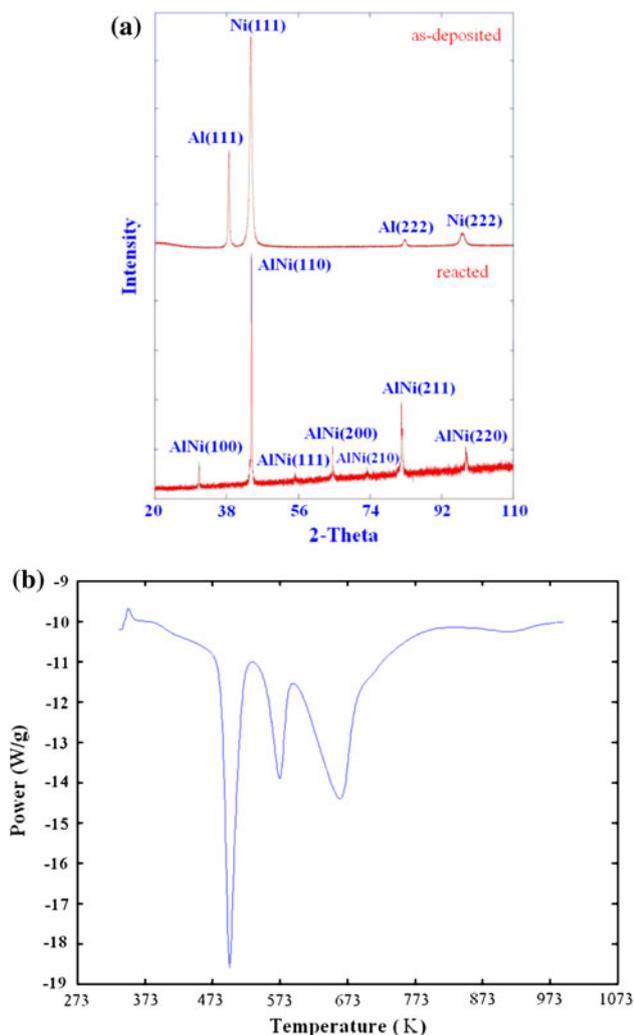


Fig. 2 **a** XRD patterns for Ni/Al reactive films (both as-deposited and reacted); **b** DSC curve of Ni/Al reactive film. The heat of reaction was -57.9 kJ/mol

DSC experiment of the reactive Ni/Al films, three exothermic peaks can be identified in the constant-heating-rate curve, as shown in Fig. 2b. By integrating the heat flow with respect to time, the heat of reaction was calculated to be -57.9 kJ/mol [12]. This result was used as input for the numerical study of the temperature distribution on the initiator during the ignition process.

Figure 3a shows the voltage variation with time during the initiation of the Ni/Al film. A 1.5 V DC voltage was applied to the film (0.085 s). The voltage drop across the film was 0.03 V due to its small resistance (0.3Ω). At 0.715 s, the voltage began to increase (Fig. 3b). Therefore, the ignition delay was around 0.63 s and the ignition power to start the self-propagating reaction in the film was 3 mW. In stage I (Fig. 3b), intermixing occurred between Al and Ni, which released heat and increased the film resistance

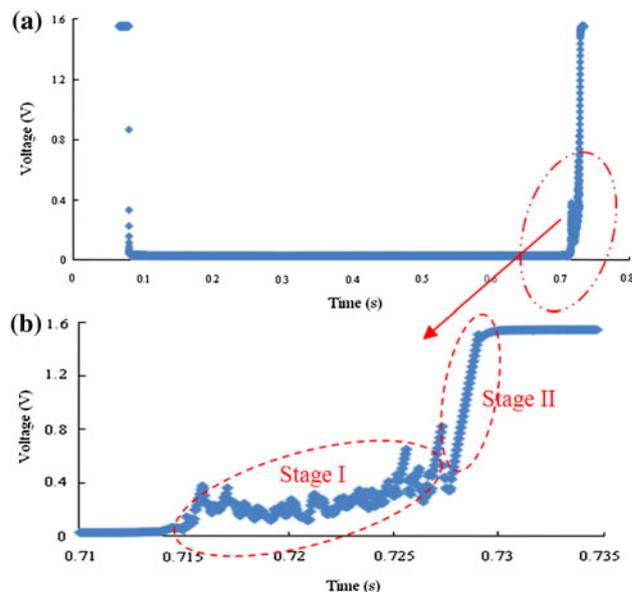


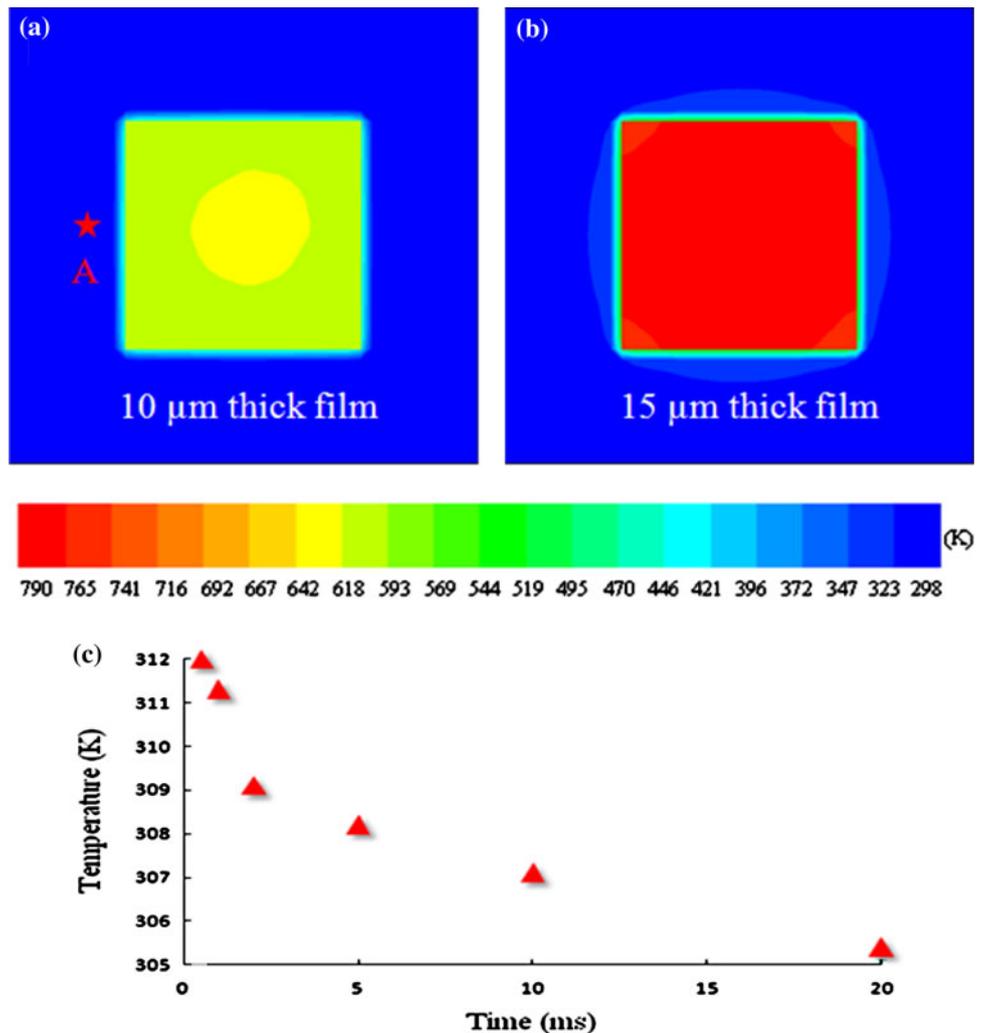
Fig. 3 **a** The voltage variation with time during the ignition of the Ni/Al film. A 1.5 V DC voltage was applied to the film (0.085 s). The voltage drop across the film was 0.03 V; **b** At 0.715 s, the voltage began to increase. In stage I, intermixing occurred between Al and Ni, which released heat and increased the film resistance gradually. As the heat accumulated, a self-propagating reaction was triggered, resulting in a sudden increase of the film resistance due to the generation of cracked AlNi. Thus, in stage II the voltage across the film reached the open circuit voltage of 1.5 V in 2 ms

gradually. As the heat accumulated, a self-propagating reaction was triggered, resulting in a sudden increase of the film resistance due to the generation of cracked AlNi (Fig. 1b). Thus, in stage II the voltage across the film reached the open circuit voltage of 1.5 V in two milliseconds.

Figure 4a and b illustrate the simulation results of the temperature distribution of the initiator surface 0.5 ms after the ignition of the self-propagating reaction (when the initiator experienced the highest temperature). High temperature (622 K) can be achieved with 10 μm thick film, while for 15 μm thick one, it can reach 790 K. Thus, the reactive film provided a simple way to control the working temperature of the initiator by alternating the film thickness. Another advantage was the localized heating nature of the Ni/Al film. Figure 4c shows the temperature evolution after the ignition of the self-propagating reaction at a position 100 μm away from the initiator (point A in Fig. 4a). The highest temperature was only 312 K. Therefore, unintentional fire of adjacent initiators can be prevented and dense initiator array can be realized for such applications as in digital microthrusters.

Temperature indicating minilabels were placed next to the initiator before it was ignited (Fig. 5a). If the

Fig. 4 Simulation results: **a** and **b** The temperature distribution of the initiator surface 0.5 ms after the ignition of the self-propagating reaction (when the initiator experienced the highest temperature). High temperature (622 K) can be achieved with 10 μm thick film, while for 15 μm thick one, it can reach 790 K. **c** The temperature evolution after the ignition of the self-propagating reaction at a position 100 μm away from the initiator (point A). The highest temperature was only 312 K



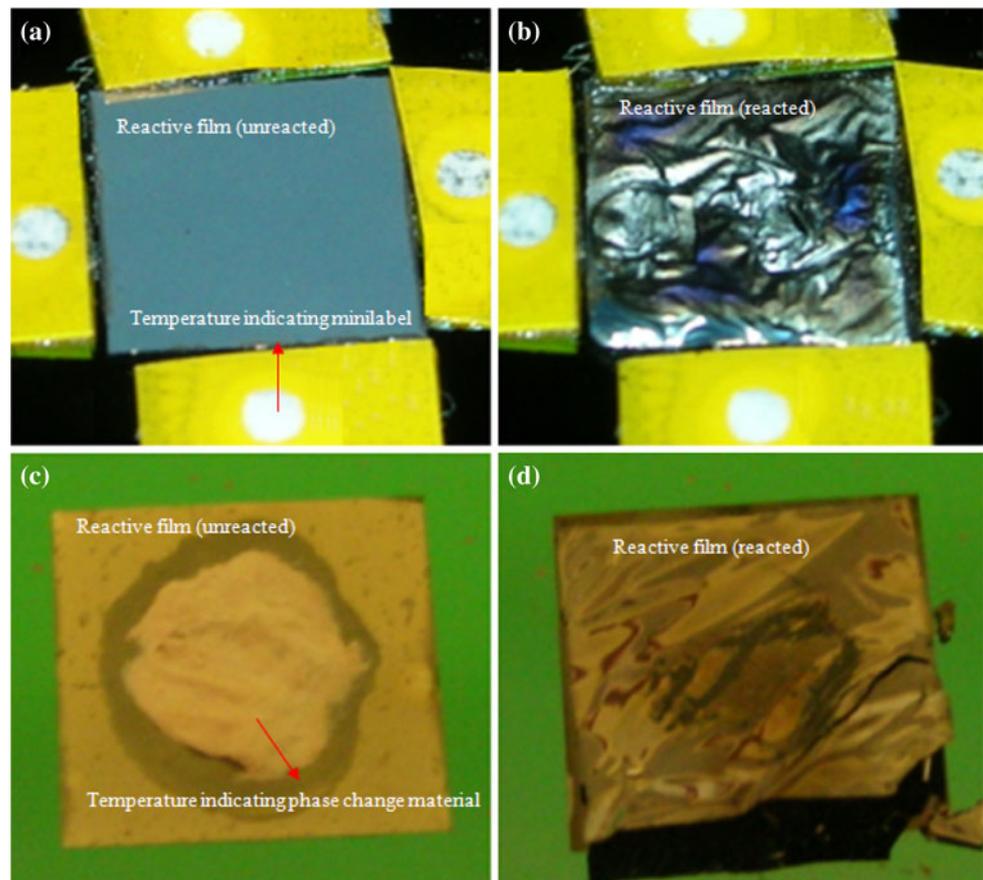
temperature exceeded 313 K, the color of the label can change from white to black. Figure 5b illustrates the status of the labels after ignition. No appreciable changes were identified. Therefore, the localized heating nature of the Ni/Al film obtained from the simulation results was confirmed. Temperature indicating liquid was used to evaluate the temperature of the initiator surface during the ignition process. When the initiator surface reached 616 K, the indicator can transform from solid to liquid and evaporate. Figure 5d shows the experiment results. After ignition, there was no solid material left on the initiator surface, which demonstrated the surface temperature of the initiator exceeded 616 K (a temperature high enough to ignite most common explosive materials). These results proved the

feasibility of employing reactive Ni/Al nanolaminates as potential micro initiators.

4 Conclusions

A micro initiator was successfully realized by reactive Ni/Al nanolaminates. With a DC voltage of 1.5 V, a self-propagating reaction was triggered in the Ni/Al film. The ignition power to start the self-propagating reaction in the film was 3 mW with an ignition delay of around 0.63 s. Simulation results showed that the initiator temperature can be altered easily by changing the Ni/Al film thickness. Localized high temperature can be generated on the initiator, which was confirmed by both the experiment and

Fig. 5 Experiment results: **a** and **b** The color of the temperature indicating minilabels did not change during the ignition process of the initiator, which confirmed the localized heating nature of the Ni/Al film. **c** and **d** The surface temperature of the initiator exceeded 616 K during the ignition process demonstrated by the temperature indicating liquid. The different appearance of the films was due to different background lighting conditions during the photo shoot



numerical modeling results. The micro initiator is supposed to have a variety of potential applications in both civilian and military areas.

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