

# Preparation and Ignition Properties of Tantalum Nitride Thin-Film Energy Transducers

**Xiaoming Ren**

Shaanxi Institute of Applied Physics and Chemistry

**Kexin Yu**

Shaanxi Institute of Applied Physics and Chemistry

**Ruizhen Xie**

Shaanxi Institute of Applied Physics and Chemistry

**Lan Liu**

Shaanxi Institute of Applied Physics and Chemistry

**Wei Liu**

Shaanxi Institute of Applied Physics and Chemistry

**Junxia Cheng**

Xi'an Technological University

**shenjiang wu (✉ [1225457175@qq.com](mailto:1225457175@qq.com))**

Xi'an Technological University

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## Research Article

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# Abstract

Tantalum nitride (TaN) has excellent electrical properties that can be used as an energy transducer in the ignition field. In this study, TaN film transducers with different bridge parameters were designed and fabricated in an attempt to reduce its energy consumption. The ignition sensitivity of the film transducers was tested using the Langley method. The results revealed that the ignition voltage is the lowest when the thickness of the film is 0.9  $\mu\text{m}$ . If the thickness and length of the bridge film are fixed, the ignition voltage of the transducer first decreases and then increases with the width of the bridge film increases. When the thickness and width of the bridge film are fixed, the ignition voltage of the transducer is first decrease and then increase with the length of the bridge film increases. We also evaluated the ignition mechanism of TaN film transducers. By comparing the performance of TaN, semiconductor bridge (SCB), and nickel–chromium (Ni–Cr) film transducers, the TaN and SCB transducers are proven to have similar ignition performances, which are better than the Ni–Cr transducer. The negative temperature coefficient of TaN and the positive feedback after the initial electrothermal ignition promoted the growth and strengthening of plasma in the bridge film, allowing the medicament to ignite quickly. When the feasibility of the process and the influence of the bridge film parameters on ignition sensitivity are considered, the preferred design parameters of the transducer are a thickness of 0.9  $\mu\text{m}$  and a bridge film size of 0.3 mm $\times$ 0.3 mm. This study shows that TaN can be utilized as a high-performance transducer.

## 1 Introduction

Microelectromechanical system (MEMS) transducers have the characteristics of structural miniaturization, energy exchange information, and sequence integration that are developmentally important to the new generation of pyrotechnics. Microstructure transducers are a core part of MEMS pyrotechnics, and determine their ignition performance, safety, and reliability, all of which affect the combat effectiveness of weapons and ammunition [1-3]. Microstructure transducers are made mainly of metal or semiconductor materials deposited on insulating substrates. Currently, most ignition transducers are made from nickel-chromium (Ni-Cr) and semiconductor bridge (SCB) materials [4-5]. The Ni-Cr bridge film is consistent, reliable, and antistatic, but its temperature coefficient of resistance (TCR) is positive. Therefore, the resistance and ignition voltage increase as temperature increase, so the energy conversion efficiency is not high [6]. In addition, Ni-Cr bridge films dissolve easily in the presence of moisture, which causes the failure of the microstructure energy exchanger [7].

The TCR of the SCB is negative, and the resistance decreases with the increase in temperature, so the SCB requires less ignition energy. The SCB also has the advantage of small ignition time delay, providing safety and compatibility when compared with the traditional integrated circuit process. However, the SCB cannot carry a large amount of power and is affected greatly by the environment, resulting in possible ignition failure. Tantalum nitride (TaN), on the other hand, has excellent electrical properties. It has a high melting point, high hardness, stable chemical and thermal properties, good oxidation resistance, and corrosion resistance, and has some important applications in aerospace, microelectronics, biomedicine, power machinery, and other fields [8-9].

The TCR of TaN is negative and the resistance decreases with the increase in temperature, leading to a low energy conversion of the microstructure transducer. TaN has self-passivating characteristics and oxidizes in air to form a dense Ta<sub>2</sub>O<sub>5</sub> film, with a thickness of approximately 12 nm, which resists erosion from water and gas when working in an unsealed state, ensuring excellent stability and reliability. In addition, TaN has excellent blocking performance, preventing the mutual diffusion between the functional films, which made the working efficiency and service life of the microstructure transducers can be improved [10-11].

This article discussed how a TaN film transducer is designed and prepared, the influence of bridge film parameters (film thickness, size, length, and shape) on the ignition sensitivity of TaN film transducers, and their ignition mechanism. We also provided the basic parameters for the low energy conversion of microstructural transducers.

## 2 Material And Experiment

### 2.1 Design and Preparation

The overall structure of a TaN film transducer consists of a substrate (glass 7740), two intermediate layer [titanium (Ti)], an ignition layer [TaN], and a welding layer [copper (Cu)]. The schematic diagram is shown on the left in Fig. 1. The support carrier of the substrate is glass 7740. The function of the intermediate layer (Ti) is to increase the adhesion between the materials. The ignition layer material is TaN, and the welding layer (Cu) is used to improve conductivity. The shape of the TaN bridge film is rectangular, as shown on the right side in Fig. 1.

A MEMS process was used to prepare the TaN film transducer, as follows: substrate ultrasonic cleaning → homogenization → pre-drying → etching → post-drying → Ti film sputtering → TaN film sputtering → stripping → ultrasonic cleaning → blow-drying → homogenization → pre-drying → set engraving → post-drying → exposure → hard mask → blow-drying → Ti film sputtering → Cu film sputtering → stripping → ultrasonic cleaning → blow-drying. The related process parameters are shown in Table 1. Among them, all three films were prepared by magnetron sputtering (model: KS60VR, KENOSISTEC Company, Italy). The common deposition parameters of the TaN, Ti, and Cu films were a background vacuum of  $5 \times 10^{-6}$  Pa, an Ar flow rate of 60 sccm, and a substrate temperature of 70°C. The other deposition parameters were as follows: (1) the target purity of TaN was 99.9%, sputtering power was 200W, sputtering time was 50 min; (2) the target purity of Ti was 99.9%, sputtering power was 100 W, sputtering time was 50s; and (3) the target purity of Cu was 99.95%, sputtering power was 200W, and sputtering time was 40 min. The photoresist used in the stripping process was the RN-246.

Table 1  
Main parameters of the MEMS process

No.	Process	Parameters	No.	Process	Parameters	No.	Process	Parameters
1	Homogenization	3500RPM, 15s	4	Development	3%TMAH, 60s	7	Exposure time	3 × 20s
2	Pre-drying	100°C, 60 s	5	Hard mask	100°C, 20s	8	Etching	NMP, 25 min
3	Post-drying	105°C, 120 s	6	Blow-drying	120s	9	Ultrasonic cleaning	Deionized water, 10min

Note: (1) tetramethylammonium hydroxide (TMAH); (2) N-Methyl pyrrolidone (NMP).

The thickness of the TaN film was changed by adjusting the magnetron sputtering time. The shape of the bridge film was controlled by lithography. This process resulted in the error between the design size of each part of the transducer and the actual measurement size of each part being very small. Therefore, the thickness and size of the TaN films were calculated according to the design values. The actual measurement with the copper wire indicates the resistance of TaN film transducers.

The appearance of a TaN film transducer and the microstructure of its bridge film are shown in Fig. 2. The three-dimensional surface of the TaN film transducer was observed by an Agilent5500 atomic force microscope (AFM; Agilent Technologies, Inc. USA), as shown in Fig. 3. What the root-mean-square-roughness of the TaN film was 3.05nm indicated that the surface of the TaN bridge film was smooth and dense.

## 2.2 Ignition Sensitivity Testing

The ignition sensitivity of TaN film energy transducers with different parameters of bridge films were tested by the Langley method and the GJB5309.9-2004 explosive test method. The instrument resolution was 0.1V, and the test data were assumed to be normally distributed. The test initiation circuit is shown in Fig. 4. Meanwhile, the ignition capacitance was 33  $\mu$ F and the energetic material coated on the bridge film was lead styphnate.

## 2.3 Ignition Energy Testing

According to the formula of electrical energy:  $E(t) = \int_0^t U(t)I(t) dt$ , where the  $U(t)$  is the total thermal energy (J),  $U$  is the charging voltage (V),  $I$  is the current (A), and  $t$  is the charging time (s). As electrical energy is a function of voltage, current, and time, the ignition energy of a TaN film transducer was obtained by integrating power curve. Therefore, this study demonstrated that a comprehensive evaluation of ignition energy can be carried out by using electrical energy [12-14]. The ignition energy test circuit used in this experiment is shown in Fig. 5.

## 3 Results And Discussion

### 3.1 Effects of Different Thickness on Ignition Sensitivity and Energy

When the shape and size of the bridge film (0.1 mm  $\times$  0.1 mm) were fixed, the ignition sensitivity was tested with different bridge film thicknesses of 0.3, 0.6, 0.9, 1.2, and 1.5  $\mu$ m. The results are shown in Table 2. As the thickness of the bridgefilm increased, the resistance of the converter decreased, and the ignition voltage of the converter first decreased and thenincreased. When the thickness of the bridge film was increased to 0.9  $\mu$ m, the ignition voltage was at itsmallest. Since thevacuum sputtering of the film resulted in different degrees of defects, including grain stacking mismatch dislocations, filmpores, impurity intrusion, and reactive gas inclusions,these defects had a direct effect on the resistance, thermal resistance,internal stress, and adhesion strength of the film. Therefore, when the 0.3 $\mu$ m-thick TaN film transducer used in the process of ignition, the current caused a change in the inside composition of the film or the smaller rearrangement of the grain,which madethe ignition voltage be larger.

Table 2  
The ignition sensitivity of TaN film transducers with different thicknesses

No.	Thickness/ $\mu\text{m}$	Number	Resistance/ $\Omega$	Ignition voltage/V	Variance	99% Ignition voltage/V	0.1% Ignition voltage/V
1	0.3	15	36.0	7.1	0.09	7.4	6.9
2	0.6	15	15.8	6.7	0.46	8.1	5.3
3	0.9	15	11.4	5.8	0.35	6.9	4.7
4	1.2	15	9.2	7.3	0.27	8.2	6.5
5	1.5	15	7.4	8.5	0.67	10.6	6.4

### 3.2 Effects of Different Widths on Ignition Sensitivity and Energy

With a thickness of 0.9  $\mu\text{m}$  and a bridge length of 0.1 mm, the ignition sensitivity of TaN film transducers was tested with bridge widths of 0.1, 0.2, 0.3, 0.4, and 0.5 mm. The results are shown in Table 3. The results showed that when the thickness and length of the bridge film were fixed, the resistance all increased as the bridge width increased.

Table 3  
Test results of fire sensitivity of transducer elements with different bridge width

No.	Size/mm	Number	Resistance/ $\Omega$	Average Ignition voltage/V	Variance	99% Ignition voltage/V	0.1% Ignition voltage/V	Ignition energy/mJ
1	0.1 × 0.1	15	11.4	5.8	0.35	6.9	4.7	0.55
2	0.1 × 0.2	15	14.7	7.8	0.25	8.6	7.1	0.77
3	0.1 × 0.3	15	17.5	8.8	0.14	9.2	8.3	0.83
4	0.1 × 0.4	15	22.5	9.7	0.14	10.1	9.2	0.98
5	0.1 × 0.5	15	23.3	11.0	0.15	11.5	10.6	1.45

### 3.3 Effects of Different Lengths on Ignition Sensitivity and Energy

With a thickness of 0.9  $\mu\text{m}$  and a width of 0.1 mm, the ignition sensitivity of TaN film transducers was tested with the bridge lengths of 0.1, 0.2, 0.3, 0.4, and 0.5 mm. The results are shown in Table 4. The results demonstrated that when the thickness and the width of the bridge area were fixed and the bridge length was increased, the resistance decreased, but the ignition voltage and the ignition energy both increased.

Table 4  
Test results of ignition sensitivity of TaN film transducers with different bridge lengths

No.	Length/mm	Number	Resistance/ $\Omega$	Average Ignition voltage/V	Variance	99% Ignition voltage/V	0.1% Ignition voltage/V	Ignition energy/mJ
1	0.1	15	11.4	5.8	0.35	6.9	4.7	0.55
2	0.2	15	9.4	6.7	0.13	7.1	6.3	0.71
3	0.3	15	8.8	9.0	0.58	10.8	7.2	1.00
4	0.4	15	8.4	9.7	0.84	12.3	7.2	1.10
5	0.5	15	6.8	9.8	0.26	10.6	9.0	1.20

### 3.4 Effects of the type of shape on Ignition Sensitivity and Energy

The shape of TaN bridge film with thickness of 0.9  $\mu\text{m}$  and size of 0.1 mm  $\times$  0.1 mm when  $\theta = 30^\circ$ , is shown in Fig. 6. The test results of ignition sensitivity of this structure are shown in Table 5. The results showed that the average ignition voltage of the bridge film was 4.8V. However, in Fig. 2, the rectangle shape of the TaN film shown had a minimum average ignition voltage of 5.8V and a maximum average ignition voltage of 11V. These results indicate that the bridge film shape has an obvious influence on the converter thermal power pressure.

Table 5  
Ignition sensitivity of the TaN film transducer in Fig. 6 when  $\theta = 30^\circ$

No.	Number	Resistance/ $\Omega$	Average ignition voltage/V	Variance	99% Ignition voltage/V	0.1% Ignition voltage/V
1	15	12.4	4.8	0.15	5.3	4.4

### 3.5 IV Testing

In general, the action mode of a transducer is divided into electro-thermal conversion and electro-induced plasma-explosion [15]. Nano-energetic materials, such as metal foil, metal wire, and nanoscale alternating multilayers, undergo an electrical explosion under the action of a large pulse current, producing plasma that generates shock waves and optical radiation into the surrounding medium [16]. IV testing of TaN, SCB, and Ni-Cr bridge films was completed by setting the voltage to 8 V and the capacitance to 33  $\mu\text{F}$ . The results of these tests are shown in Fig. 7. Under these conditions, the three kinds of bridge films demonstrated an electro-thermal conversion action process. Additional IV testing on the three bridge films was completed by setting the voltage to 16 V, and the results are shown in Fig. 8. As demonstrated in Fig. 8(a) and Fig. 8(b), the voltage and current of the two transducers rise by transition when the TaN and SCB discharge at the beginning of the capacitor. The voltage and current lines decrease again after 5 and 10  $\mu\text{s}$ , respectively, followed by a horizontal constant (original value). These results demonstrate that during this process, the bridge region rapidly fused and gasified into luminescent plasma, and that the action process of both is electro-induced plasma explosion [17-19]. Fig. 8(c) shows that the initial voltage and current appear to transition during the combustion of the Ni-Cr bridge film, then become a continuous and

stable decline curve, and finally trend to a constant value (original value). This result shows that the Ni–Cr bridge area does not fuse and that it uses an electric heat transfer process during the power-up excitation process.

## 3.6 Ignition of Lead Styphnate

IV and ignition testing of TaN film transducers containing lead styphnate were also completed. The voltages were set to 8 and 16 V, respectively. The test results are shown in Fig. 9, which show that lead styphnate was ignited successfully in both cases. The voltage–current curve of the TaN films can rise rapidly at low voltage, as shown in Fig. 9(a). At about 20  $\mu\text{s}$ , the current rises to the maximum value, and then begins to decrease slowly. During this process, the TaN film transducer converts electrical energy into thermal energy, and when the heat rises to a certain level (at approximately 120  $\mu\text{s}$ ) leads styphnate ignition. The bridge film is not broken until the current and voltage reach 400  $\mu\text{s}$ , where it trends to the constant value (initial value). According to Fig. 9(b), the TaN film transducers are vaporized rapidly under the excitation of 16 V, where a strong glow is emitted by the action of the electrical field, forming a plasma discharge of thousands of degrees. This fluid, at high temperature and high pressure, diffuses rapidly into the charge, causing the lead styphnate to heat upto ignition temperature. The total ignition time is short, and the response speed is fast.

Grundmann et al. [20] found that plasma can be formed only when a delay in discharge is formed, which time of the ignition can be realized. Fig. 9(b) shows that two voltage peaks are generated when the TaN film transducer ignites, which are located near the times of 4 and 15  $\mu\text{s}$ . When the current flows through the bridge area, the discharge luminescence is first generated along the bridge edge with the largest potential gradient. As the impedance of TaN is a negative temperature coefficient, the resistance value decreases with the increase in temperature, forming a positive feedback in the increased temperature. The decrease of resistance and the increase

of current lead to the rapid temperature increase that ultimately reaches the TaN melting point. It will produce a melt and gasification process that drives continuously to the center of the bridge, and eventually produces a strong ionized vapor layer on the surface of the bridge film. The resistance of TaN for an ion state is larger than its resistance to melting and gasification. Thus, a large partial voltage is obtained, and a second voltage spike is formed. At this moment, the current enters this region and heats enough to form a delay in discharge. The TaN film transducer goes through four stages: heating, melting, vaporizing, and plasma generation. The negative temperature coefficient of TaN and the positive feedback produced after the initial electro-thermal ignition that promotes the growth and strengthening of the plasma in the bridge area. Finally, it caused the medicament to ignite quickly.

## 4 Conclusions

TaN is a new energy-exchange material that is corrosion resistant, suitable for harsh environments, and has a simple manufacturing process. (1) When the size and shape of the bridge area are fixed, the resistance increases with the increase thickness of the bridge film, and the thermal power pressure first decreases then increases. To realize the low energy conversion of TaN film transducers, the optimal thickness of the transducer was approximately 0.9  $\mu\text{m}$  that based the factors of a MEMS preparation process, film adhesion, and ignition energy. (2) When the thickness and length of the bridge film are fixed, the resistance, ignition voltage of the transducer, and ignition energy all increase with the width increases. The low energy conversion of TaN film transducers is realized by reducing the size or changing the shape of the bridge film. (3) Through IV testing of TaN, SCB, and Ni–Cr film transducers, TaN film transducers were found to successfully ignite lead styphnate at voltages of 8V and 16V. When the charging voltage is 8V, an electro-thermal conversion phenomenon is demonstrated. When the charging voltage

is 16V, an electro-induced plasma explosion phenomenon is appeared. The firing performance of TaN film transducers can reach the same level as mature SCB film transducers, but they have better performances than metal bridge film transducers. Therefore, TaN can be utilized successfully in high-performance transducers.

## Declarations

### Acknowledgments

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### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

### Conflicts of Interest:

The authors declare no conflict of interest.

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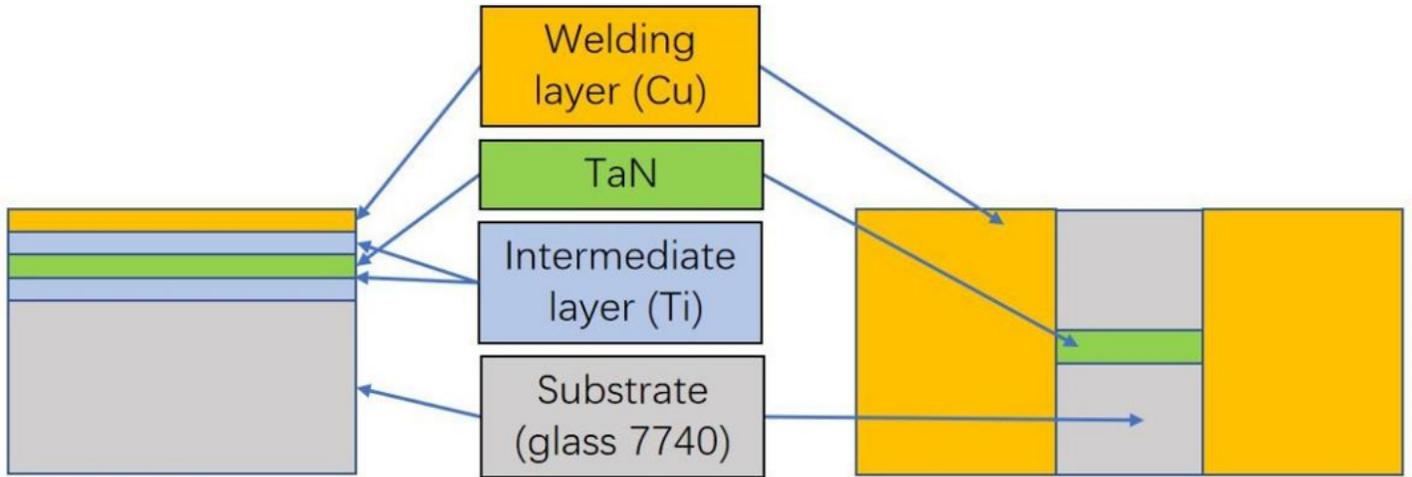
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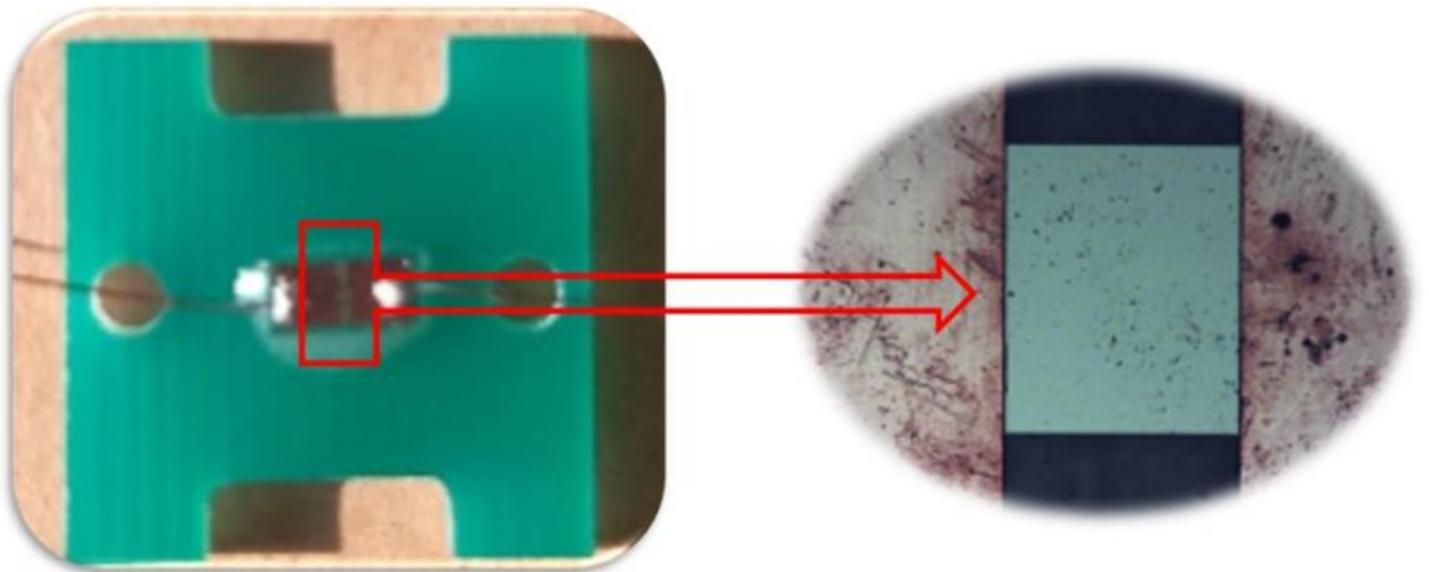
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## Figures



**Figure 1**

Structural diagram of a TaN film transducer (left: section structure; right: surface structure)



**Figure 2**

The TaN film transducer and its film bridge

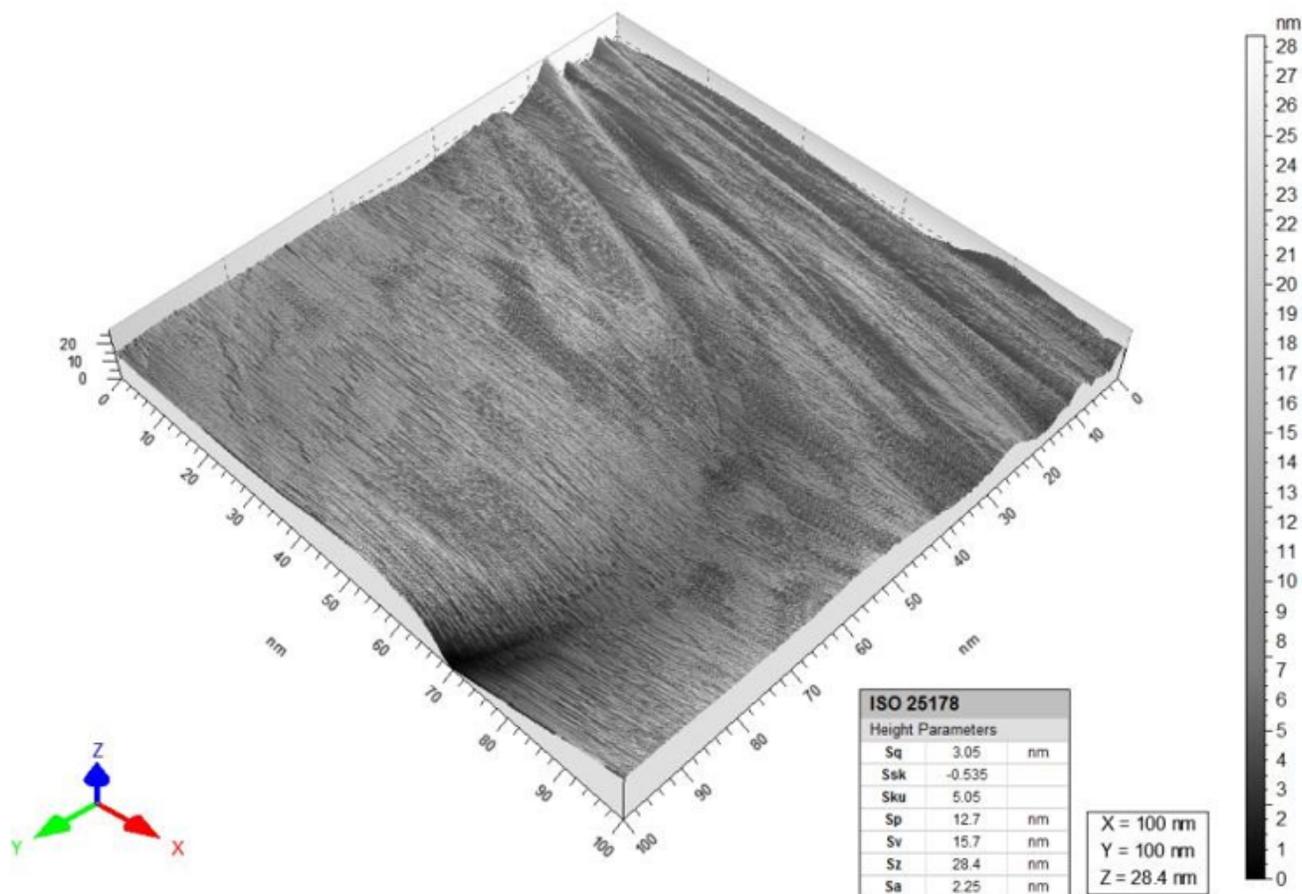


Figure 3

The AFM photograph of a TaN thin film

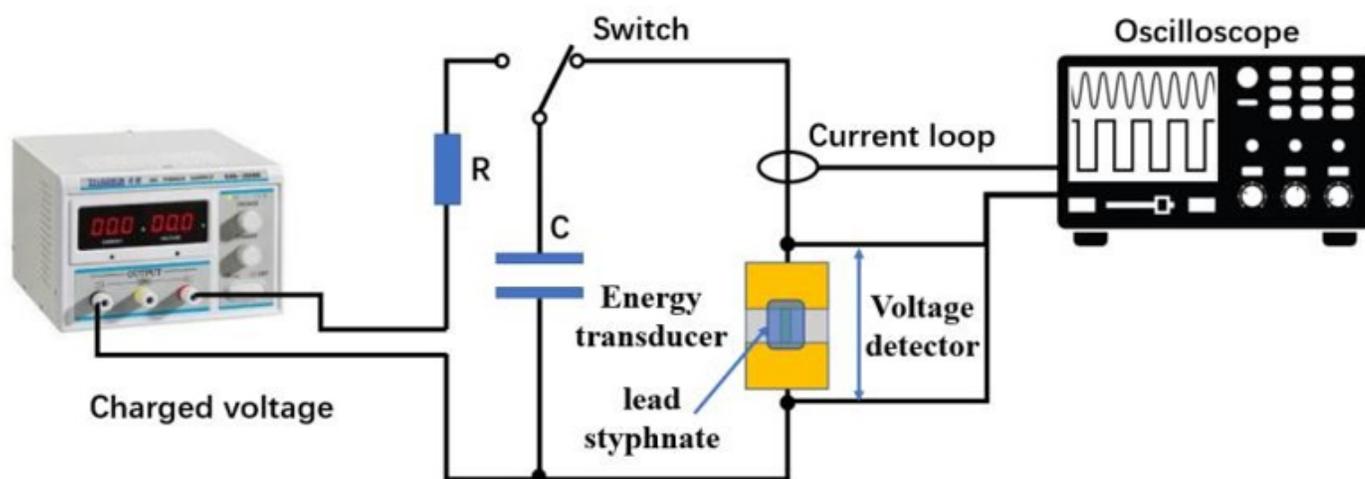


Figure 4

The ignition sensitivity testing circuit of a TaN film transducer

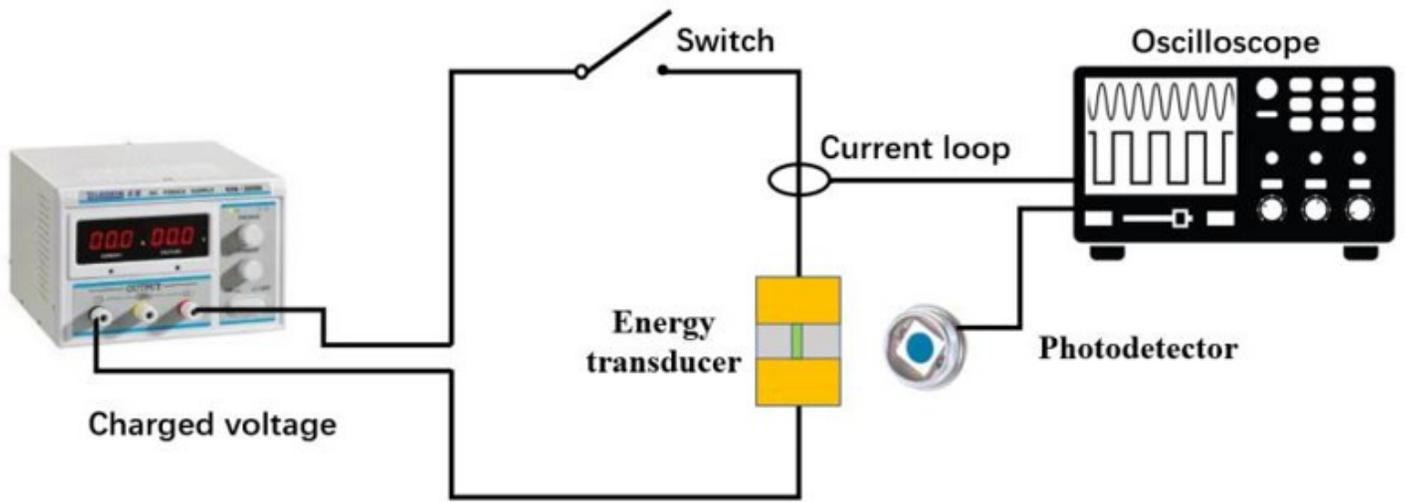


Figure 5

The diagram of an ignition energy test circuit

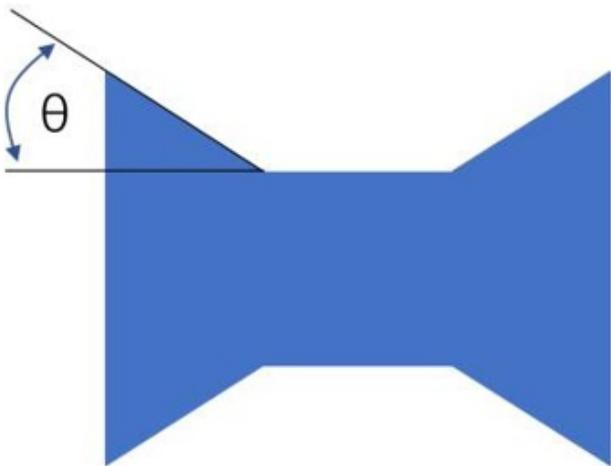
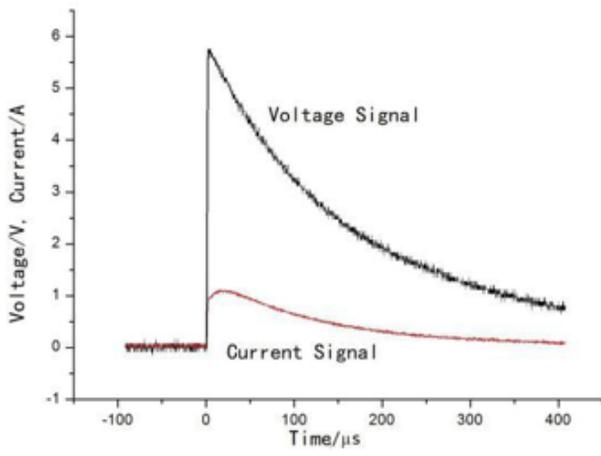
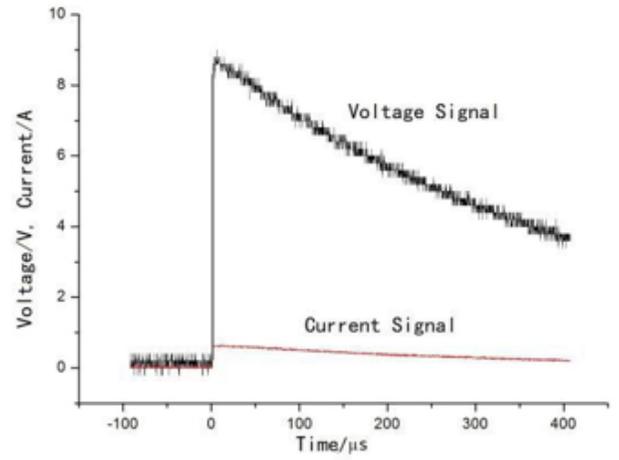


Figure 6

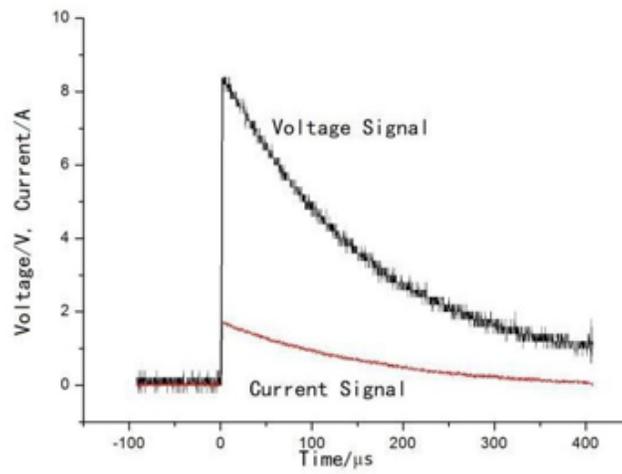
Diagram of the bridge shape and the actual sample



(a)



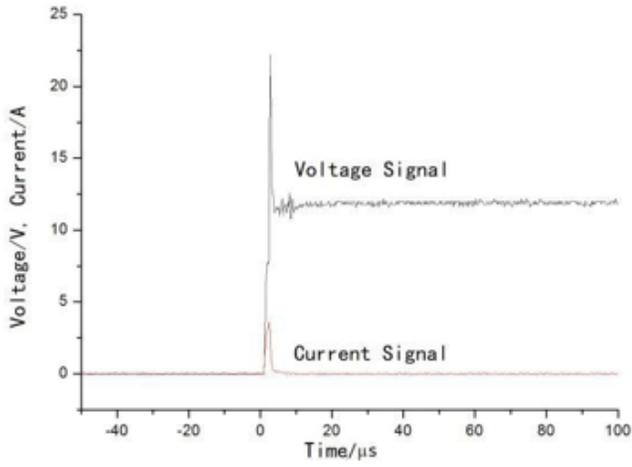
(b)



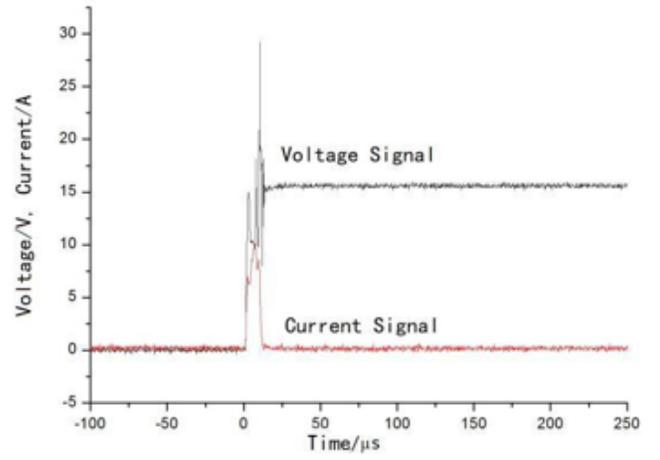
(c)

Figure 7

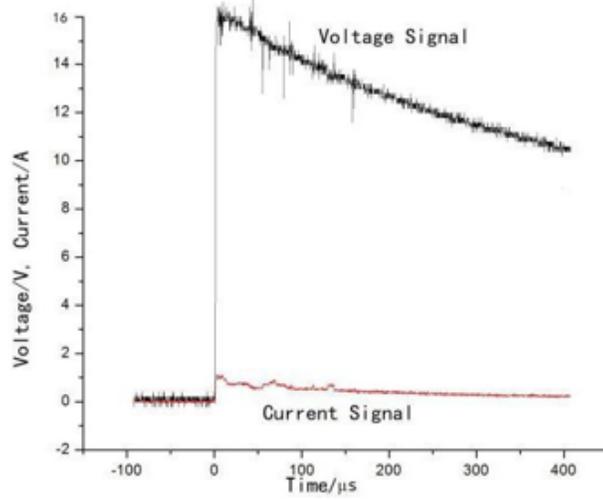
IV testing of different kinds of transducers with a voltage of 8V: (a) TaN; (b) SCB; and (c) Ni-Cr



(a)



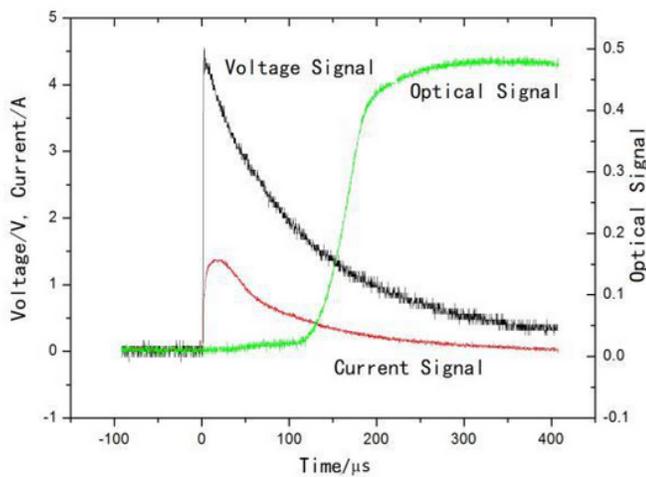
(b)



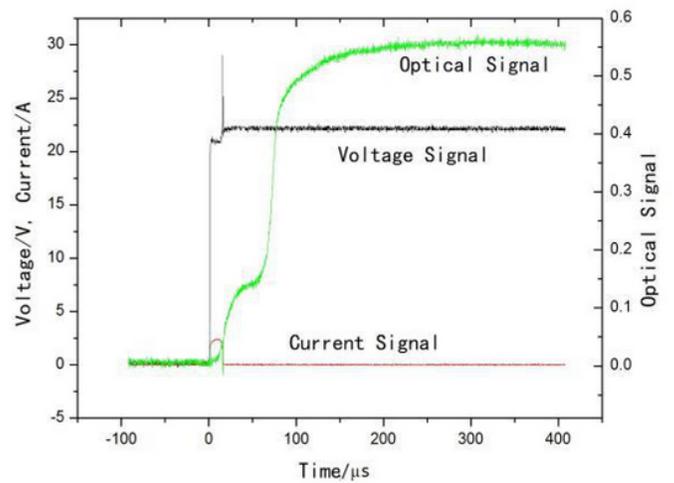
(c)

Figure 8

IV testing of different kinds of transducers with a voltage of 16V: (a) TaN; (b) SCB; and (c) Ni-Cr



(a)



(b)

## Figure 9

Lead styphnate ignited by TaN film transducers with different voltages: (a) 8 V and (b) 16