Study on film resistivity of Energy Conversion Components for MEMS Initiating Explosive Device

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Abstract: Resistivity of Plane-film Energy Conversion Components is a key parameter to influence its resistance and explosive performance, and also it has important relations with the preparation of thin film technology, scale, structure and etc. In order to improve the design of Energy Conversion Components for MEMS Initiating Explosive Device, and reduce the design deviation of Energy Conversion Components in microscale, guarantee the design resistance and ignition performance of MEMS Initiating Explosive Device, this paper theoretically analyzed the influence factors of film resistivity in microscale, through the preparation of Al film and Ni-Cr film at different thickness with micro/nano, then obtain the film resistivity parameter of the typical metal under different thickness, and reveals the effect rule of the scale to the resistivity in microscale, at the same time we obtain the corresponding inflection point data.

Key Words: MEMS energy conversion component; Scale effect; resistivity

1 Introduction
MEMS initiating explosive device which base on the MEMS technology or compatible with MEMS process, it has some size characteristics: the structure of energy conversion components and the scale of energy materials in micro, the scale of core device in the sub-millimeter level, and the scale of system in millimeter level. This kind of initiating explosive device is integrated with information control, safe and actuator and detonating unit, bring it has the characteristics of information, small and multi-function, and it’s a key basic technology of informatization, smart ammunition¹-³. Energy conversion components as the core device in the MEMS initiating explosive device, which realize the energy conversion function, energy conversion components generally are the surface resistance that
made of metal thin film material, its realize the heat transfer to energy material and also further amplify the energy.

Lower ignition energy and the high energy conversion efficiency are the main characteristics of ideal energy conversion components of MEMS initiating explosive device, and it’s mainly affected by resistance and bridge structure of energy conversion components\(^4\). Therefore, we must pay more attention to the ignition resistance and bridge structure when design MEMS energy conversion components.

At present, the research mainly focused on the influence of substrate\(^5\) and bridge structure\(^7\) on energy conversion components performance, but the influence research of ignition resistance is less\(^10\), and it’s a matter with material and its micro structure scale. Thus, this paper theoretical analyzed the influence factors of thin film energy conversion components, prepared the different material and different thickness metal film by magnetron sputtering technology, through analyzed their morphology and electrical parameters, we obtained the basic data and test results, and verified the micro-nano scale effect rule of the resistivity, which would provide important support to optimal design and preparation of MEMS energy conversion components.

2 Theoretical analysis

Material resistivity is a physical quantity that characterization of material resistance properties, which is the electrical properties of the material itself. The product of bulk resistivity of metal materials and the mean free path of a electron, and this has no relationship with geometric dimensions of materials. With the development of micro/nano technology, geometric dimensions or microstructure scale of metal materials in the energy conversion components of initiating explosive device decreased gradually from the macro scale to micron, sub-micron or even nanometer level. And the resistivity at the room temperature tends to show obvious size effect, namely when the structure of the metal materials reaches sub-micron or nanometer, its resistivity increased dramatically. If we still use the bulk resistivity of metal materials for the design of MEMS energy conversion components, it would lead to large deviation between design resistance and test resistance, which would affect the design resistance accuracy of the MEMS energy conversion components.

According to the metal material resistivity calculation theory, Fuch-Sondheimer(F-S)\(^11\), Mayadas-Shatzke(M-S)\(^13\) model gives a detailed explanation. Among them, the calculation formula is given by the F-S theory, which mainly combined with the statistical distribution of the mean free path (λ),

\[
\frac{\rho_a}{\rho_{FS}} = \frac{k}{\varphi_P(k)}
\]

\[
\frac{1}{\varphi_P(k)} = \frac{1}{k} + \frac{3}{2k^2} (1-P) \int_1^\infty \left( \frac{1}{t^3} - \frac{1}{t^5} \right) \frac{1-e^{-kt}}{1-Pe^{-kt}} dt
\]

Where \( k = t/\lambda_0 \), and \( \lambda_0 \) is the mean free path, and \( t \) is the thickness of metal film, and \( \rho_0 \) is the bulk resistivity, and \( P \) is thin film surface reflect electronic score, and its value between 0 and 1, and \( P=0 \) for the diffuse the situation, and \( P=1 \) for all of specular reflection.

Another calculation formula is given by the M-S theory, which mainly combined with materials internal microstructure parameters, especially grain boundary in the process of film deposition and the average grain size of the difference, then put forward with the reflection coefficient \( R \) to show the
effect of grain boundaries on the resistivity, namely

$$\frac{\rho_0}{\rho_{MS}} = \left[1 - \frac{2}{3} \alpha + 3 \alpha^2 - 3 \alpha^2 \ln \left(1 + \frac{1}{\alpha}\right)\right]^{-1}$$

(3)

$$\alpha = \frac{\lambda_0}{D} \left(\frac{R}{1-R}\right)$$

(4)

Where $\lambda_0$ is the mean free path as defined above, and $D$ is the average grain size, and $R$ is the reflection coefficient of grain boundary, and its value between 0 and 1, and $R=0$ for completely mirror reflection and $R=1$ for the diffuse the situation. For the block metal, $R_{Al} = 0.17$.

All the above theory, show that the resistivity of metal film is higher than the corresponding bulk materials, the main reason is the role of film surface and grain boundary scattering. Metal film showed obvious scale effect when they reach micron/nanometer lever: the smaller film thickness, as its average grain size decrease, the film resistivity greatly increase. When metal film thickness is less than a certain critical size (usually within 100 nm), the increase of resistivity is mainly due to the interface and grain boundary scattering at the same time; and when metal film thickness is greater than a certain critical size, the interface for free electron scattering effect is abate and the increase of resistivity is mainly due to the grain boundary scattering.

The range of thin thickness for energy conversion components of MEMS initiating explosive device is usually in 0.2~2.0μm, so in this paper we focus on the effects of grain boundaries on the film resistivity. The effect of grain boundaries on the resistivity is mainly the increase of membrane residual tensile stress, and membrane residual tensile stress is closely related to the 111 orientation\cite{14}. For the surface energy, the close surface’s (111) is lowest; for the strain energy, 111 orientation of grain in the strain energy density is the largest. That’s to say, with the increase of the residual tensile stress, the membrane (111) orientation was enhanced. At this point, the strain energy of thin film can gather more, and it caused grain deformation, which increased the distortion degree of grain boundary. Hence, the increase of film resistivity can be characterized by grain boundary distortion (111 orientation).

3 The experiment and test

We use 76mm*25mm*1mm glass as base layer in the process of preparing metal film, and use polyimide tape to keep out in the middle of the glass before sputter deposition. Then, we remove the tape after sample preparation to keep the sample step. Last, we test the thickness and electrical of the sample. We ignored the substrate impact on the resistivity of metal film with the same substrate.

Using DISCOVERY635 magnetron sputtering machine that made by Denton companies in the United States for film preparation, and using Al target (purity 99.99%). According to the early stage on the process, we determine the best sputtering process of Al that is 0.5A/20SCCM, and thickness range from 0.2μm to 2.0μm with 0.2μm gradient. Also, we do the same research for metal material such Cr, W, Ni-Cr, which are the most frequently used material for energy conversion components.

3.1 characterization of surface topography

Frist of all, using the SEM for grain size and uniformity test of the different thickness Al films, and partial results obtained are shown in Figure 1. Through the comparative analysis shows that within the
scope of the research method to the scale, with the film thickness smaller, the grain size to be smaller, and the film surface smoother.

![Image 1](image1.png)

**Figure 1.** Test result of SEM of Al film

Then, using the AFM for surface roughness test of the different thickness Al films, and partial results obtained are shown in Figure 2. And the Al surface roughness \( (R_q) \) is 15.2nm and 33.5nm, which show that thin film surface consistency control is better.

![Image 2](image2.png)

**Figure 2.** Test result of AFM of Al film

Last, using X-ray diffraction analysis the Al thin film, and its diffraction pattern shown in Figure 3. Compared with standard atlas of Al, the results show that Al mainly tetragonal crystal system exists in the film, and Al\(_2\)O\(_3\) was not detected, and it may exist in less amorphous or polycrystalline state. Al (111) orientation in the film are significantly higher than the strength of the standard atlas of Al (111) orientation, namely strain energy accumulation is more in the film, and increasing the grain boundary distortion degree to lead to increase grain boundary scattering of electrons, which made the film resistivity increases exceedingly.
3.2 electrical performance analysis

Upon completion of the metal film grain size, surface roughness and XRD diffraction spectrum analysis, using the steps apparatus to measure the thickness for the different thickness of Al film, and taking three times the average of the measurement for thin film thickness. Then, using the four point probe to measure the square resistance for the different thickness of Al film, and the results as shown in Figure 4, which is the square resistance and resistivity parameter under different thickness of Al films.

Figure 4 is the square resistance and resistivity test curve under different thickness of Al films. The figure shows that the square resistance ($R_s$) and the change trend of resistivity ($\rho$) is consistent, namely decreasing as the film thickness increase, and gradually become metal Al volume resistivity (2.75µΩ·cm). When the thickness is less than 300nm, the films resistivity begin to steep, and up to 7.89µΩ·cm in 200nm with an increase of nearly 200%. Then, we had the Boltzmann fitting for the test of Al film resistivity data, and obtained the relation equation between the film resistivity ($\rho$) of Al film and film thickness (t) in a specific scale range (0.2~2.0µm), and fitting degree $R^2$ is 0.99188. The fitting curve is shown in Figure 5.
\[ \rho = A_2 + (A_1 - A_2) \ast (1 + e^{-\frac{t-t_0}{dt}})^{-1} \]  

(5)

Where is \( A_1 = 2647.97615, A_2 = 3.47471, t_0 = -0.01142, \ dt = 0.03295. \)

![Figure 5. Resistivity fitting curve of Al film with different thickness](image1)

Similarly, we do the same work for the different thickness of the Cr, W, and Ni - Cr film, and the data obtained as shown in Figure 6, Figure 7, Figure 8.

![Figure 6. Square resistance and resistivity of Cr film with different thickness](image2)

Figure 6 is the square resistance, resistivity test curve and fitting curve under different thickness of Cr film. The figure shows that the square resistance \( R_s \) and the change trend of resistivity \( \rho \) is consistent, namely decreasing as the film thickness increase, and gradually become metal Cr volume resistivity \( (12.9 \, \mu\Omega \cdot \text{cm}) \). Because Cr film data collection point is relatively small, and fitting \( R^2 \) based on the Boltzmann fitting is poorer, so choosing the Allometric function to fitting for Cr film resistivity, and fitting degree \( R^2 \) is 0.99328. Fitting equation is

\[ \rho = a \ast t^b \]  

(6)

Where is \( a = 10.33677, b = -1.45296. \)
Figure 7. Square resistance and resistivity of W film with different thickness

Figure 7 is the square resistance, resistivity test curve and fitting curve under different thickness of W film. The figure shows that the square resistance \(R_s\) and the change trend of resistivity \(\rho\) is consistent, namely decreasing as the film thickness increase, and gradually become metal Cr volume resistivity \(5.5 \, \mu\Omega\cdot\text{cm}\). Choosing the Allometric function to fitting for Cr film resistivity, and fitting degree \(R^2\) is 0.99644. Fitting equation is

\[
\rho = a * t^b
\]

Where is \(a=35.14768\), \(b=-0.98384\).

Figure 8. Square resistance and resistivity of W film with different thickness

Figure 8 is the square resistance, resistivity test curve and fitting curve under different thickness of Ni-Cr film. The figure shows that the square resistance \(R_s\) and the change trend of resistivity \(\rho\) is consistent, namely decreasing as the film thickness increase, and gradually become metal Ni-Cr volume resistivity \(90 \, \mu\Omega\cdot\text{cm}\). Choosing the Allometric function to fitting for Ni-Cr film resistivity, and fitting degree \(R^2\) is 0.99013. Fitting equation is

\[
\rho = a * t^b
\]

Where is \(a=118.83507\), \(b=-0.76887\).

From the above results, we known that the metal film thickness less than 1\(\mu\text{m}\), and the film resistivity as rapidly increases with the decrease of the thickness, when the thickness of the metal film
is greater than 1 μm, the film resistivity tends gradually metal volume resistivity. When the metal started to deposit, the metal existed as main island shaped structure, and at this point, the conductive mechanism of thermionic emission tunnel movement, so the film resistivity is greater than volume resistivity. With the increase of film thickness, metal film slowly by island structure into a mesh structure, and at this point, the electrons through the conductive path and form seepage conductive, which increases greatly the conductivity of the metal film, so the resistivity decreases sharply as the film thickness increases. When the metal form a continuous film, it’s mainly presents the nature of the metal, and the film resistivity gradually tends to the metal volume resistivity with the increase of film thickness. The main reason is that with the increase of film thickness, film grain increase, which decrease the grain boundary electron scattering, thus the resistivity reduce. The film resistivity will always be greater than the metal volume resistivity, because the film structure than the block of metal structure is loose, and has many defects or containing impurities.

Base on the study results, we design and manufacture MEMS energy conversion components shown in Figure 9, which with plane-film structure and use the Ni-Cr material. The resistance value shown in Tab.1, its deviation less than 0.35 Ω, and indicate that we can accurately control the MEMS energy conversion components resistance value design.

![Figure 9. Samples of energy conversion components](image)

| Structure     | V-50 | V-100 | F-150 | S-100 | L-1  | Snake-1 |
|---------------|------|-------|-------|-------|------|---------|
| Design resistance/Ω | 6.5  | 5.5   | 5     | 9     | 8.5  | 31      |
| Test resistance Average/Ω | 6.63 | 5.6   | 5.28  | 9.22  | 8.68 | 31.32   |
| Deviation     | 0.13 | 0.1   | 0.28  | 0.22  | 0.18 | 0.32    |
| Variance      | 0.296 | 0.293 | 0.255 | 0.331 | 0.071 | 0.343 |

4 Conclusion and perspectives
The film resistivity of energy conversion components of MEMS initiating explosive device is the key parameter to influence the resistance performance and combustion, and it has important relationship with the preparation of thin film technology, and scale, and material and etc. The paper theoretical analyzed influence factors of metal film resistivity, and tested grain size and the electrical performance for Al, Cr, W and Ni-Cr under the micro-scale, and obtained the scale effect of partial metal film.

Metal film resistivity is higher than the corresponding bulk materials, and the main reason is that a
combined action of thin film surface and grain boundary scattering. When the thickness of Al is less
than 300nm, the films resistivity begin to steep, and up to 7.89μΩ·cm in 200nm. When the thickness
of Cr, W and Ni-Cr is less than 1μm, the increase trend of film resistivity is more apparent with the
decrease of film thickness. With the further decrease of the material microstructural scale and
geometrical dimensions, it’s a major challenge for the basic theory of initiating explosive device ender
microscale, and it needs to think a lot about film resistivity scale effect.

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