

AN IN-SITU PREPARED SYNCHRONOUS SELF-COMPENSATED FILM STRAIN GAGE FOR HIGH TEMPERATURE

Shenyong Yang, Congchun Zhang, Hong Wang, and Guifu Ding

National Key Laboratory of Science and Technology on Micro/Nano Fabrication
Department of Microelectronics and Nanoscience, Shanghai Jiao Tong University, Shanghai
200240, PR China

ABSTRACT

The strain of components at high temperature was usually measured by thin film strain gage prepared on the components. However, temperature effect caused by the thermal expansion coefficient mismatch between substrate and strain gage film usually induces the measurement error of metal film strain gage. This paper reports a novel temperature compensation method for in-situ prepared PdCr strain gage. A suspended PdCr film and PdCr film adherent to the substrate with the same layout were deposited, in which a suspended PdCr film was used for the temperature compensation system of PdCr film. The temperature coefficient of resistance (TCR) for the suspended PdCr film and PdCr film adherent to the substrate was measured up to 380°C. Meanwhile, the gage factor K for PdCr film has been calculated for different temperature.

INTRODUCTION

With the operating temperature increase of gas turbines and rocket engines and deep drilling system, the reliable measurement of both dynamic and static strain is critical to the development of gas turbine engines. Engine components are subject to harsh environment such as rigorous mechanical loading conditions, high temperature and high pressure, which put forwards higher requirements for the strain measurement of components. Traditionally, the strain of high-temperature components in service is measured by the wire of foil sensors mounted on the components, which usually induces the large error of measurement. Sensors made of thin films have several advantages over wire or foil sensors. Thin film sensors do not require special machining of the components on which they are mounted, and, with thicknesses less than 10 μ m, they are considerably thinner than wire or foils. Thin film sensors are thus much less disturbing to the operating environment, and have a minimal impact on the physical characteristics of the supporting components [1].

PdCr alloy with excellent structural stability and the desired strain versus temperature characteristics is a leading candidate for the high-temperature film strain gage. NASA has developed static strain gages based on a PdCr (87:13wt.%) alloy in both thin film and wire form, which are capable of operating at temperatures up to 1000°C [2]. However, PdCr alloy has a higher apparent TCR, less resistant to oxidation caused by the internal oxidation of Cr in the alloy at high temperature and a small amount of impurities compared to other alloys [3]. So PdCr film strain gage in-situ prepared on the substrate exists strain error

which can be attributed to the thermal expansion coefficient mismatch between the substrate and film strain gage, and the variation of electrical resistivity with temperature [2-4].

Temperature compensation technique, as a traditional method to decrease strain error from the temperature effect, is widely used in high-temperature metal film strain gage. For example, NASA deposited first the PdCr strain gauge by sputtering the PdCr thin film of about 8 μ m thicknesses, and then patterned using the photolithography technique and chemical etching with FeCl₃. For static thin film strain gage, a platinum (Pt) temperature compensator element is adopted to minimize the effect of temperature on the resistance change of the PdCr. The Pt element of 5 μ m thickness is located around the PdCr gauge grid and connected to the adjacent arm of a Wheatstone-bridge circuit to minimize the temperature effect [5]. Besides, one transverse film strain gage was used as a temperature compensator for film strain gage loaded longitudinally because the two gauges are in the same half bridge and have similar resistance versus temperature characteristics [6].

For in-situ prepared strain film on the substrate, the resistance variation at high temperature is caused not only by the deformation of substrate but also by the thermal expansion coefficient mismatch between substrate and strain film [7], and the variation of electrical resistivity of strain gage film with temperature. In this paper, a suspended PdCr thin film and PdCr thin film adherent to the substrate with the same layout were prepared for the compensation of temperature induced drift in the resistance. This technique can avoid the lateral effect caused by the force which is exerted on the substrate.

EXPERIMENTAL

To compensate the temperature effect of PdCr thin film at high temperature, the suspended PdCr thin film proposed in our study was also prepared on the substrate surface just with some fulcrums by utilizing a general micro fabrication technique (Figure 1). Quartz glass was used as the high temperature substrate due to its electrically insulating, low thermal expansion coefficient (5.3-5.8ppm/°C) and high thermal stability at elevated temperatures. Besides, Quartz glass can operate for a long time at 1100°C, and the highest temperature can reach 1450°C. Different from the reported lift-off technology [8], we adopted general micro fabrication technology for the deposition of PdCr film and suspended PdCr film in order to obtain two thin films with almost identical initial resistance. First, a 50nm thick Cr adhesion layer and a 150nm thick Cu seed layer were deposited on the

quartz glass substrate by magnetron sputtering. The substrate was spin coated with 7 μ m of positive photoresist. Following spin coating, the positive photoresist layer was baked at 90°C for 30min and then exposed using a UV light source lithography system [9]. The pattern can be developed by using the alkali aqueous solution as the developer. Following development of the photoresist, the photoresist template was ready for metal electroplating. Electroplating was performed using a two electrode configuration. Following metal deposition, the photoresist was stripped in a bath of sodium hydroxide solution (5%) at room temperature and rinsed in acetone, alcohol and deionized water successively. After removal of the photoresist, the 10 μ m thickness of PI spin coated on the quartz glass substrate and then was baked at 130°C for 60min. Following baking the PI, the photoresist was spin coated on the PI and exposed with a UV light source lithography system, then the photoresist and PI was developed in alkali aqueous solution. Afterward, the thin film was sputtered with a magnetron sputtering machine in argon at a pressure of 5×10^{-4} Pa at an DC power of 300W using a 99.99% pure Palladium chrome (Pd-Cr 87:13wt.%) target. After sputtering, 5 μ m thickness of PI was ground using abrasive paper, and then the rest of PI was totally removed with sodium hydroxide solution (5%), the thin film was patterned. Finally, electroplated Cu and seed layer Cu were removed by ammonium hydroxide (NH₃•H₂O) and hydrogen peroxide (H₂O₂). Then the seed layer Cr was dissolved away by KMnO₄ solution and the sample was rinsed with alcohol, acetone and Freon. And then the suspended PdCr thin film and PdCr thin film were obtained.

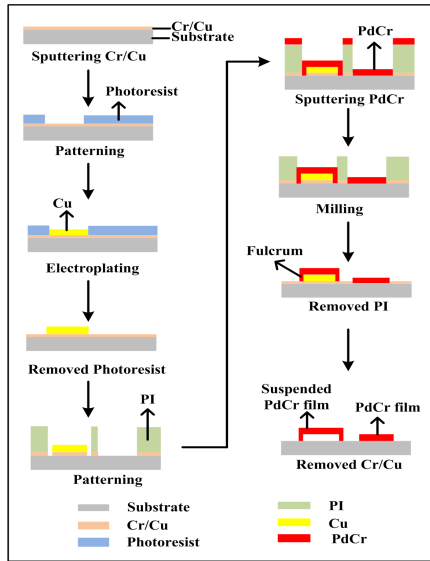


Figure 1: General micro fabrication technology for PdCr film and suspended PdCr film.

The thicknesses of the films were measured by a mechanical stylus profilometer. The TCR of the films was determined by heating the films in an oven and measuring the temperature and the resistance simultaneously by Kelvin Four-terminal sensing resistance method [10].

RESULTS AND DISCUSSION

The schematic diagram of suspended PdCr thin film(S-Film) as temperature compensator was illustrated in Figure 2[11]. The original position of a PdCr thin film (Film) and substrate is shown at point A (Figure 2a). When an instrumented test article is subject to a uniform temperature change of the substrate from an initial reference temperature ΔT , substrate and thin film will attempt to expand or contract by an amount corresponding to their coefficients of thermal expansion. Assuming the thermal expansion coefficient of substrate is lower than that of thin film, that is, $\beta_g > \beta_s$ (β_g is the thermal expansion coefficient of thin film; β_s is the thermal expansion coefficient of substrate). Figure 2b shows the resulting thermal expansion of the thin film and substrate if both are heated and allowed to expand freely in the positive x direction. In this case, the substrate expands to point B, and the thin film expands to point C. Because of the thermal expansion coefficient mismatch between substrate and PdCr thin film, the substrate will force PdCr thin film to conform to its expanded position at point B (Figure 2c), making PdCr thin film generate shrinking strain and corresponding resistance variation ΔR_g . The final resistance variation of PdCr thin film is at ΔR_f (Figure 2d).

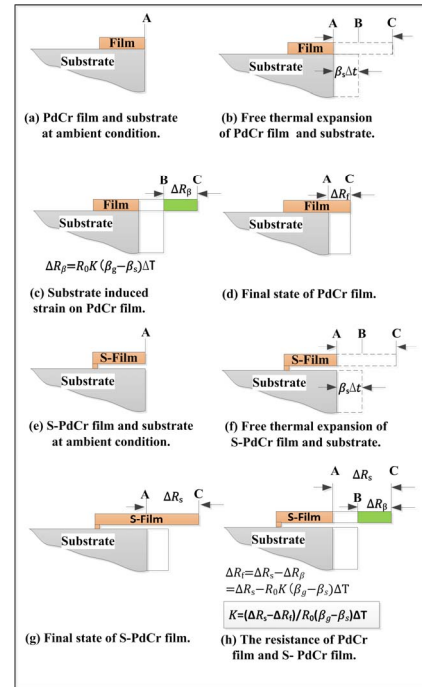


Figure 2: The schematic diagram of suspended PdCr thin film(S-Film) as temperature compensator. β_g : thermal expansion coefficient of PdCr Film; β_s : thermal expansion coefficient of the substrate; $\beta_g > \beta_s$; K : gage factor of the PdCr film; ΔT : the temperature variation; ΔR_s : resistance variation of the S-Film; ΔR_g : resistance variation of the film due to temperature effect; ΔR_f : resistance variation of Film.

Figure 2e shows the original position of a suspended PdCr thin film and substrate at point A. when both heated, the

suspended PdCr thin film and substrate will expand freely, as shown in Figure 2f. So the final position of free thermal expansion of the suspended PdCr thin film was shown in Figure 2g. The strain caused by substrate expansion and externally applied forces cannot induce the deformation of the suspended PdCr films regardless of the tiny effect of fulcrums, indicating that the resistance variation of suspended PdCr thin film ΔR_s just resulted from the temperature effect of suspended PdCr thin film itself. On this basis, gage factor K in different temperatures can be calculated according to the relation of resistance variation between the suspended PdCr thin film and PdCr thin film, as schematically shown in Figure 2h. Finally, PdCr thin film and suspended PdCr thin film were connected to Wheatstone bridge to achieve the compensation of temperature effect.

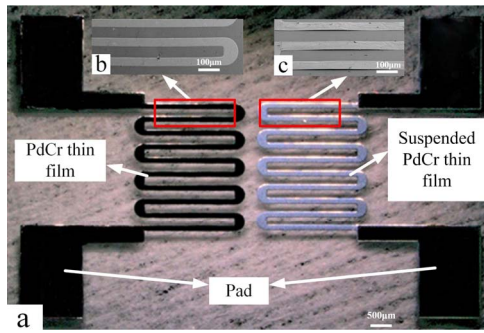


Figure 3: View of suspended PdCr thin film and PdCr thin film. a, the white is suspended PdCr film, the black is PdCr film; b is SEM of PdCr film; c is SEM of suspended PdCr thin film.

Figure 3 shows the morphology of suspended PdCr thin film and PdCr thin film deposited on the quartz glass substrate. In order to minimize the effect of temperature gradient of quartz glass substrate, the relative position of the two thin films should be as close as possible. From the optical micrograph (Figure 3a) it can be seen the suspended PdCr thin film and PdCr thin film were different. PdCr thin film adherent to substrate is black due to lightproof caused by its close touch with the quartz glass substrate. On the contrary, suspended PdCr film is bright because both top and bottom surface are light-reflecting. Besides, figure 3b and c show the SEM images of the magnified PdCr thin film and suspended PdCr thin film. PdCr thin film (Figure 3b) is closely attached to the quartz glass substrate. However, the middle of the suspended PdCr thin film (Figure 3c) is warped; suggesting that the suspended PdCr thin film can be obtained by our method.

The oxidation mechanism of PdCr thin film is very complex when exposed to various heat treatments [12]. PdCr started oxidizing at around 400°C and formed CrO_2 on the surface which decomposed and vaporized at around 450°C. The impurities (vacancies, grain boundaries, diffused species, etc.) found in the PdCr thin film may also enhance the oxidation rate [3]. In order to avoid the oxidation of PdCr thin film, the measurement temperature is no more than 400°C. In

our study, no external force exerted on the substrate when heating the substrate in order to study the effect of thermal expansion coefficient mismatch on the resistance of thin film.

Figure 4 shows the resistance variation of the two films with increasing temperature. With the increase of temperature, the resistance of suspended PdCr thin film (ΔR_s) and PdCr thin film (ΔR_f) linearly increase. But the increment of ΔR_s is larger than that of ΔR_f because the suspended PdCr thin film produce larger expansion due to no constraint from the quartz glass substrate compared with the PdCr thin film. Thus, TCR of suspended PdCr film (+200~+396 ppm/°C) is higher than that of PdCr film (+200~+304 ppm/°C) at temperature ranging from 25°C to 380°C. In addition, the TCR of suspended PdCr film increase rapidly with the increase of temperature compared with that of PdCr film because the mismatch of coefficient of linear thermal expansion has the more significant effect on the PdCr film.

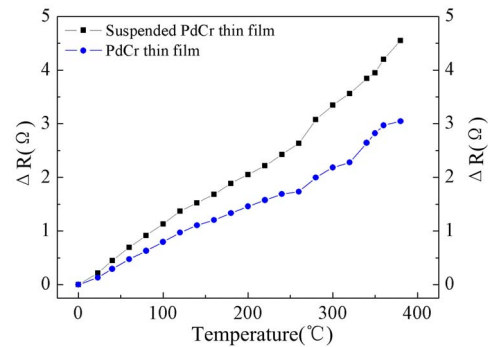


Figure 4: The resistance variation of suspended PdCr thin film and PdCr thin film with the variation of temperature.

The gage factor of PdCr thin film and suspended PdCr thin film can be calculated according to equation (1):

$$K = (\Delta R_s - \Delta R_f) / R_0 (\beta_g - \beta_s) \Delta T \quad (1)$$

Where ΔR_s and ΔR_f are the resistance variation of suspended PdCr thin film and PdCr thin film, respectively. R_0 is the initial resistance of the two thin films. β_g and β_s are the thermal expansion coefficients of PdCr thin film (13.8 ppm/°C at room temperature [2]) and the quartz glass substrate (5.3-5.8 ppm/°C at room temperature), respectively. ΔT is the temperature variation.

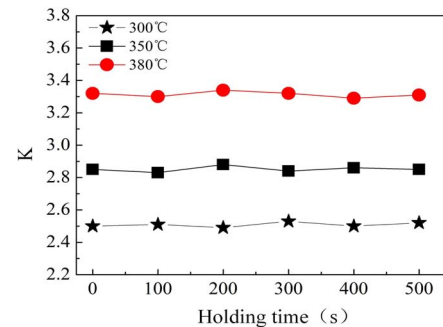


Figure 5: The variation of gage factor (K) at different temperature.

Figure 5 shows the gage factor of suspended PdCr thin film and PdCr thin film at different temperature. It can be found that gage factor increases with the increase of temperature, which is different from that reported in other references where gage factor of PdCr alloy decreases slightly or is a constant [13]. Temperature significantly influences the thermal expansion coefficient of metal, especially PdCr alloy. However, the gage factor in our study was calculated by the thermal expansion coefficient at room temperature because few references reported the thermal expansion coefficient of PdCr alloy at different temperature. However, the gage factor is stable with the increase of holding time at a fixed temperature, suggesting that the drift of the resistance PdCr thin film is tiny at a fixed temperature.

CONCLUSION

In this paper, a suspended PdCr film and PdCr film adherent to the substrate with the same layout was prepared by utilizing a general micro fabrication process. The resistance variation of suspended PdCr film and PdCr film was measured in hot plate up to 380°C by Kelvin Four-terminal sensing. The resistance variation of suspended PdCr film is higher than that of PdCr film due to no constraint of the substrate. Thus, TCR of suspended PdCr film (+200~+396 ppm/°C) is higher than that of PdCr film (+200~+304 ppm/°C) at temperature ranging from 25°C to 380°C. In addition, gage factor of thin film increases slightly with the increase of temperature because the thermal expansion coefficient of both substrate and thin film varies with the temperature. In addition, K can keep stable with the increase of holding time at a fixed temperature, suggesting that using the suspended PdCr film as a temperature compensator is viable. It can be found that the suspended PdCr film can effectively compensate the temperature effect of PdCr film.

ACKNOWLEDGEMENTS

This work is sponsored by the cooperative project GO0030002 between Aviation Industry Corporation of China, and Shanghai Jiao Tong University.

REFERENCES

- [1] John D. Wrbanek, Gustave C. Fralick, José M. Gonzalez, "Developing Multilayer Thin Film Strain Sensors with High Thermal Stability", *42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Sacramento, California, July 9-12, 2006.
- [2] C.O. Hulls, R.S. Bailey, F.D. Lemkey, "High temperature static strain gage alloy development program", *NASA Report No. CR-174833*, 1985.
- [3] J. Lei, W. Williams, "PdCr Based Static Strain High Temperature Gage" *AIAA Second International Aerospace Planes Conference*, Orlando, FL, October 29-31, 1990.
- [4] Soeren Fricke, Alois Friedberger, Gerhard Mueller, Helmut Seidel and Ulrich Schmid, "Strain gauge factor

and TCR of sputter deposited Pt thin films up to 850°C", *IEEE SENSORS 2008 Conference*, Lecce, Italy, Oct. 26-29, 2008, pp:1532-1535.

- [5] J.F. Lei, D.R. Englund and C. Croom, "The temperature compensation technique for a PdCr resistance strain gauge", *Proc. SEM Fall Conf. Structural Testing Technology at High Temperature*, Dayton, OH, USA, 1991, pp. 190-196.
- [6] P. Kayser, J. C. Godefroy, L. Leca, "High-temperature thin-film strain gauges", *Sensors and Actuators A*, 37-38, pp.328-332, 1993.
- [7] S. Fricke, A. Friedberger, H. Seidel, U. Schmid, "A robust pressure sensor for harsh environmental applications", *Sensors and Actuators A*, 184, pp.16-21, 2012.
- [8] S.E. Dyer, O.J. Gregory, J.D. Cooke, "Improved passivating Cr₂O₃ scales for thin film high temperature PdCr strain gages", *Thin Solid Films*, 312, pp:331-340, 1998.
- [9] Blaha C.A., "Photolithographic Fine Patterning of Difficult-To-Etch Metals," *NASA Tech Briefs LEW-17079*, March, 2002.
- [10] F. M. Smits, "Measurement of sheet resistivities with the four-point probe", *The bell system technical journal*, pp: 711-718, 1958.
- [11] W. Lance Richards, "A new correction technique for strain-gage measurements acquired in transient temperature environments", *NASA technical paper*, March 1996.
- [12] Darwin L. Boyd, Mary V. Zeller, Thermogravimetric Study of Oxidation of a PdCr Alloy Used for High Temperature Sensors, *NASA Technical Memorandum 106473*, March, 1994.
- [13] C.O. Hules, R.S. Bailey, H.P. Grant, W.L. Anderson, J.S. Przbvyszewski, High temperature static strain gage development. *NASA Lewis Research Center Contract NAS3-23722*, August, 1991.

CONTACT

*Congchun Zhang, tel:+86-021-34206687; zhcc@sjtu.edu.cn
 *Guifu Ding, tel: +86-021-34206686; gfding@sjtu.edu.cn