

Fabrication and thermal stability characterisation of Ru electrode used for high power contact radio frequency microelectromechanical system switch

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Reported are the fabrication and thermal stability of an Ru electrode, which is used for a high power Ru–Au contact radio frequency microelectromechanical system switch with a microspring contact design. In this reported work, a new process with bilayer lift-off and a strain release layer is developed, thereby acquiring the 3000 Å Ti/Au/Ru electrode with excellent smooth edges for high-power handling capacity and low loss. Furthermore, thermal tests under 400, 500 and 600°C for over 1 h have been performed. Investigation of the surface with scanning electron microscopy and energy dispersive X-ray spectroscopy shows that the electrode has a good thermal stability at 400°C, which is proper for high-power handling. The cold switch DC current handling capacity is advanced from <90 mA per point (failed) to 100 mA per point (still working).

1. Introduction: Radio frequency (RF) components with miniaturised size and low cost are highly demanded for modern communication networks. RF microelectromechanical system (MEMS) switches are good alternatives to the existing solid state switches or electromagnetic relays, on account of their inherent advantages such as linearity, low insertion loss and high isolation [1]. The metal-to-metal contact RF MEMS switch has been studied for over 20 years since its first demonstration by Petersen [2], and its high-power handling ability is vitally important for practical applications.

In the past few years, there have been some researches using different high melting point metals as the contact metal to improve power handling ability. Pt [3], Ru [4], Rh [5] and Ir [6] have been reported as contact materials and their performances have been further investigated via a nanoindenter [5, 6]. These researches show that the Ru–Au and Pt–Au contacts perform better than the Au–Au contact in high current (100 mA) and have at least ten times longer lifetime than the Au–Au contact in a hot switch cycle test. Moreover, the Ru–Au contact softens at about 430°C [5], whereas the Au–Au contact softens at only ~100°C. Besides, the pull off force of the Au–Au contact is much higher than that of the Ru–Au contact, which means that stiction may occur more easily in the Au–Au contact than in the Ru–Au contact.

After comparing with other high melting point metals (as shown in Table 1), Ru may be one of the best choices despite its high stress. When Ru is used as an electrode, its high stress will causes a terrible ‘lift-off fence’ in the conventional lift-off process, which causes the failure of the device. The Ru electrode is used to improve the power handling ability in our novel RF MEMS switch structure with a microspring, as shown in Fig. 1, which has been reported in our previous work [7]. We used sputtering Cu as the sacrifice layer and electroplated Au as the structure layer and coplanar waveguide line. Our previous paper has shown that a better contact can be achieved in the same contact force with this microspring structure [3].

The failure analysis of the power test shows that the rough edge of the Ru electrode is the major cause of the failure, which can be seen through Fig. 2a. Fig. 2a is the scanning electron microscopy (SEM) photo of our switch after the cold switch DC power test, in which the breakdown point mainly takes place at the edge of the electrode but not at the bump in the centre of the electrode. It means that the contact mainly occurs at the rough edge or lift-off

fence of the electrode, which is a kind of point contact, but not at the centre of the electrode with the Au bump, which is a kind of surface contact. The contact with the edge may have a much

Table 1 Physical property of metal suitable for high-power RF MEMS contact

Material	Au	Ru	Pt	Ir	Rh	W
resistivity (bulk material nΩm)	22	71	105	47	43	52.8
Mohs hardness	2.5	6.5	4–4.5	6.5	6.0	7.5
Young's modulus, GPa	79	447	168	528	380	411
soften temperature, °C	~100	~430 [5]	–	–	~360	–
melting point, °C	1064	2334	1768	2466	1964	3422

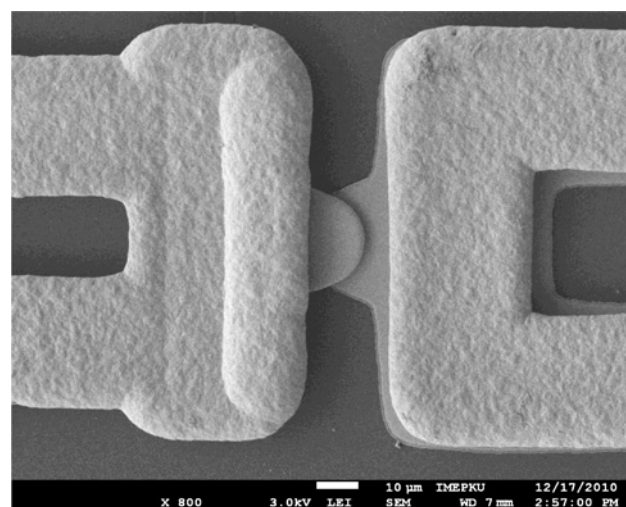


Figure 1 SEM photo of our novel structure RF MEMS switch with a microspring

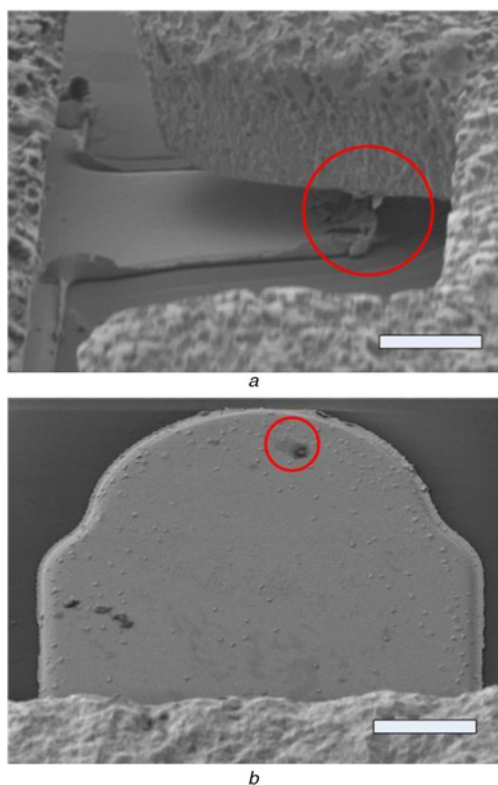


Figure 2 SEM photos

a Failure switch during a cold switch DC power test, which shows that the breakdown point occurs at the rough edge
b Promoted smooth-edged Ti/Au/Ru multi-metal-layer electrode of our switch after the hot switch DC power test, while the breakdown point occurs at the centre of the electrode

smaller contact area compared with the contact with the Au bump. Moreover, the contact with the edge is quite unstable and ruins the stability of the device. Thus, the rough edge of the Ru electrode is the main cause of the failure. To solve this problem, we promote the bilayer lift-off process and add a strain release layer to obtain a smooth edge. Fig. 2*b* shows the promoted smooth-edged Ti/Au/Ru multi-metal-layer electrode of our switch after the hot switch DC power test, whereas the breakdown point occurs at the centre of the electrode where the bump contacts.

2. Experiments

2.1. Fabrication: The conventional bilayer lift-off process often uses some special polymer, such as LOL2000, as a cushion layer to create an undercut beneath the photoresist. Here, we use Cu or Al as a cushion layer under the PR (photoresist) to achieve an undercut, while the process becomes more stable compared with using LOL2000. Fig. 3 shows the process of the promoted bilayer lift-off process. First, a 5000 Å Cu or Al is sputtered on the glass substrate (B33) as shown in Fig. 3*a*. Here, we only use the glass substrate as a demo, whereas in the application any substrate can be used, such as high resistance silicon, SiC, Al₂O₃ and quartz which have been widely used in high power and RF devices. Then, the PR is spin-coated and patterned on the Cu or Al layer. After that the Cu is etched using HAc:H₂O₂:DI water = 1:1:20, the undercut below the PR is formed as shown in Fig. 3*b*. The undercut is about 1 μm wide, which can be seen in Fig. 3*a*, Fig. 3*a* is the cross-section of the bilayer system before the lift-off process. Then, a 3000 Å-thick Ti/Au/Ru (200 Å/2000 Å/800 Å) is sputtered (Fig. 3*c*), followed by a lift-off process (Fig. 3*d*). The sputtered Ti/Au/Ru is 3000 Å thick, thinner than the cushion layer, so there is a 200 nm gap between the sputtered

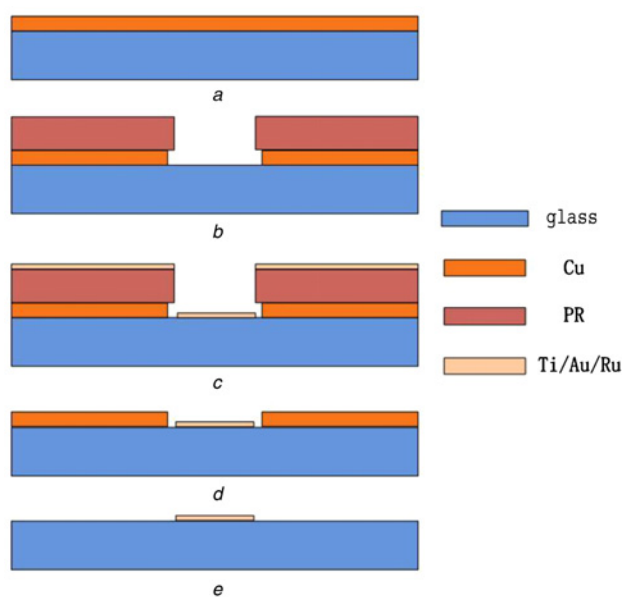


Figure 3 Fabrication process of the bilayer lift off for Ti/Au/Ru

Ti/Au/Ru multi-metal layer and the PR, as shown in Fig. 3*b*. After removing the cushion layer metal Cu or Al in etchant with ultrasonic treatment, the multi-metal-layer Ti/Au/Ru electrode with a smooth edge is achieved, as shown in Fig. 4*d*.

Figs. 4*a–d* show, respectively, the contrast of the Ti/Ru (200 Å/2800 Å) lift-off electrode with LOL2000 as cushion layer; the Ti/Au/Ru (200 Å/2000 Å/800 Å) lift-off electrode with Al as cushion layer; Ti/Ru (200 Å/2800 Å) lift-off electrode with Cu as cushion layer; Ti/Au/Ru (200 Å/2000 Å/800 Å) lift-off electrode with Cu as cushion and Au as the strain release layer. When using LOL2000 and Al as the cushion layer, the lift-off fence is very serious. On the contrary, when using Cu as the cushion layer, the lift-off fence is obviously minimised. That is, the Ti adhesion layer has good adhesion to Al and LOL2000 but not to

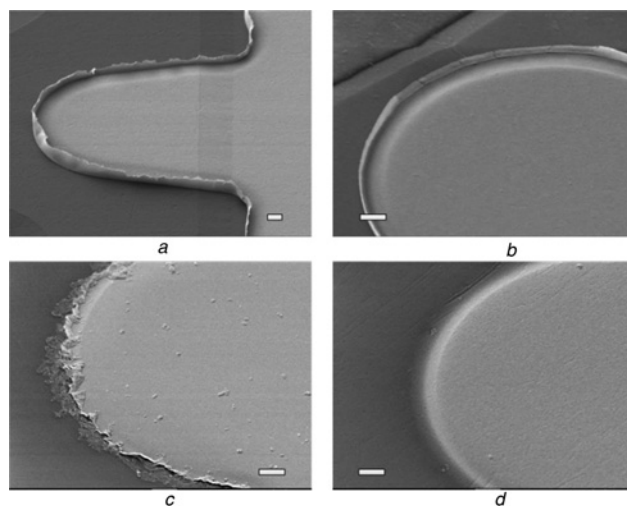


Figure 4 Comparison of surfaces

a Ti/Ru (200 Å/2800 Å) bilayer lift-off process with LOL2000 as the cushion layer
b Ti/Au/Ru (200 Å/2000 Å/800 Å) bilayer lift-off process with Al as the cushion layer
c Ti/Ru (200 Å/2800 Å) bilayer lift-off process with Cu as the cushion layer
d Ti/Au/Ru (200 Å/2000 Å/800 Å) bilayer lift-off process with Cu as the cushion layer

the Cu. The Ti–Al bond strength is relatively strong compared with either Al–Al or Ti–Ti. Hence, Ti has good adhesion with Al and Al alloys but is not working well on Cu [8]. Therefore the 200 Å Ti adhesion layer can form a continuous film on the Al cushion layer, whereas that does not happen on Cu, which can be seen in Fig. 5.

However, even on using the promoted bilayer lift-off process with Cu as the cushion layer, the one with Au as a strain release layer (Fig. 4c) has a very smooth edge, whereas the one without Au as a strain release layer (Fig. 4d) still has a rough edge. We once use 150 Å Cr to replace Ti as the adhesion layer to achieve the promoted Cr/Au/Ru (150 Å/1800 Å/1000 Å), but the result is worse than Ti. We believe that the internal stress of the Cr adhesion layer that is higher than that of the Ti layer may cause the worse result. The Ru layer, which has a strong tension, may warp at the edge, as shown in Fig. 4c. To solve this problem, we add a strain release layer to release the stress of both the Ti and the Ru layer, and after that the warping is eliminated. Here, the metal for the strain release layer should be of low Young's modulus, low Mohs hardness and, most importantly, can undertake high temperature. Then, gold is the excellent choice for this job. Hence, we add 2000 Å Au as a strain release layer beneath the 800 Å Ru layer. It is proved to be effective, as shown in Fig. 4d.

2.2. Thermal stability: Obviously, the thermal stability of the Ti/Au/Ru electrode is not as good as the Ti/Ru electrode. To make sure that the Ti/Au/Ru multi-metal-layer electrode can be used for

high-power handling, we tested the thermal stability of the Ti/Au/Ru (200 Å/2000 Å/800 Å) electrode at 400, 500 and 600°C in the atmosphere. The SEM photos in Fig. 5 show the surface of the Ti/Au/Ru electrode after the thermal test at 400°C (Fig. 6b), 500°C (Fig. 6c) and 600°C (Fig. 6d) for over 1 h. The thermal treatment time with 1 h is long enough for metal diffusion.

The SEM photos in Fig. 6 show the surfaces of the Ti/Au/Ru electrode after the thermal test at 400°C (Fig. 6b), 500°C (Fig. 6c) and 600°C (Fig. 6d) for over 1 h. We can see that the surface of the sample at 600°C has been destroyed, as shown in Fig. 4d. In Fig. 4c, there are some surface protuberances. We believe that at 500°C, the Au layer penetrates the Ru layer above it and diffuses to the surface forming the protuberance in Fig. 4c. The energy dispersive X-ray spectroscopy (EDX) of that area (Fig. 6e) shows that there is 15.79At% of Au on the surface, which supports our conclusion, and some other researches [8, 9] also indicate that the Au layer will diffuse into the Ru layer obviously above 500°C. In their researches, the Ru layer is used as a diffusion barrier between the top Au and the bottom Ti adhesion layer. Their experiments show that the Ru layer is an effective diffusion barrier for the Au layer below 500°C.

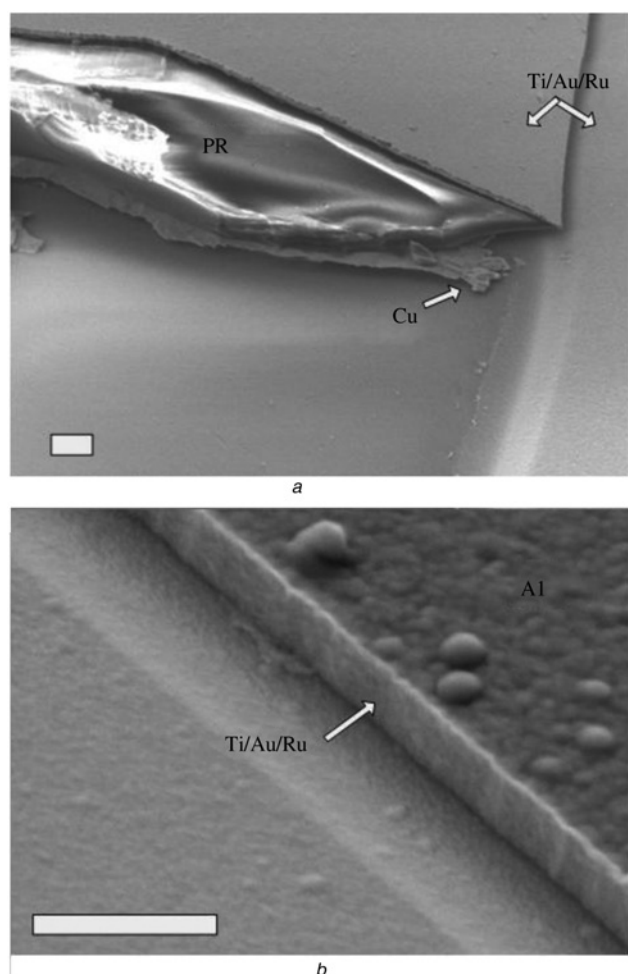


Figure 5 SEM photo after sputtering Ti/Au/Ru (200 Å/2000 Å/800 Å) in the bilayer lift-off process with Cu and Al as cushion layers
a Cu as cushion layer
b Al as cushion layer

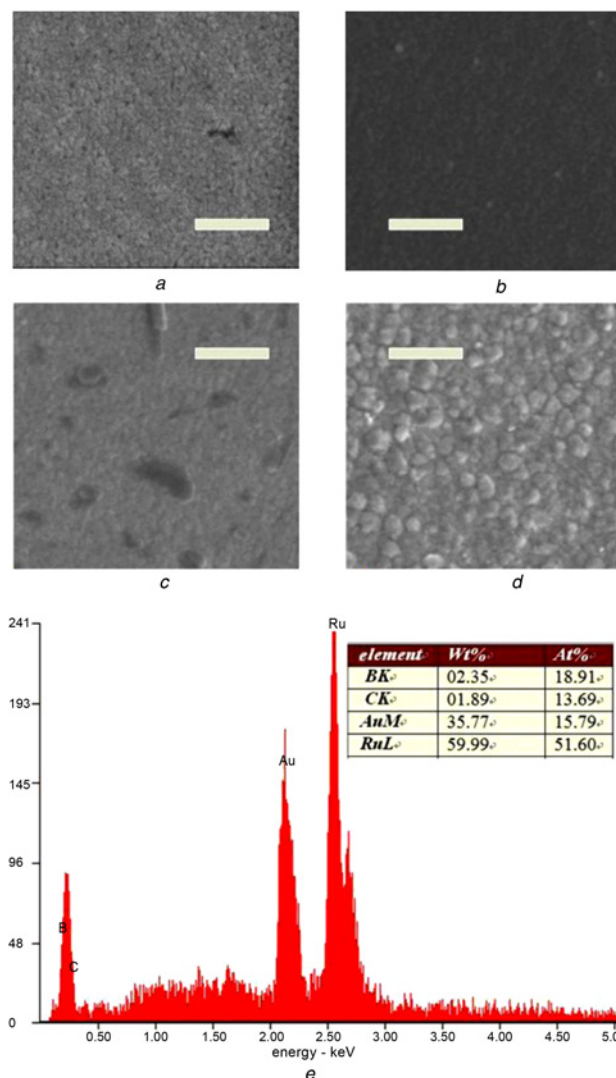


Figure 6 SEM photos of the electrode
a Before thermal test
b 400°C
c 500°C
d 600°C
e EDX of the sample after 500°C treatment, which shows that Au beneath the Ru diffuses to the surface after 500°C for over 1 h

On comparing the SEM photo of the original sample (Fig. 6a) and that under 400°C (Fig. 6b), we find that there is nearly no change on the surface. Therefore we believe that this Ti/Au/Ru electrode with an excellent smooth edge has a good thermal stability at 400°C. Considering that the Ru–Au contact softens at about 430°C [5], this contact cannot always work at or above 400°C, so that the RF MEMS switch has enough lifetime. Thus, the Ti/Au/Ru electrode with an excellent smooth edge has well enough thermal stability for high-power RF MEMS switch use.

2.3. DC power handling test: Here, the cold switch DC power handling test of the switch with the promoted multi-metal-layer electrode has been conducted. In the cold switch test, when the switches are closed, a 0.5 s period pulse with an amplitude of 100 mA passes through and then the switches are opened up. The process was repeated 60 times, and the switch still works. Moreover, after a 40 s 100 mA DC current passes through (simulating the CW–continuous wave) the switch still works. Hence, the preliminary results show that our switches with the promoted multi-metal-layer electrode have at least 100 mA per point DC power handling capacity. In comparison, the switches using Al as the cushion layer and Ti/Ru lift-off electrode have only at most 90 mA per point DC current handling capacity.

3. Conclusion: In the present Letter, we use a promoted bilayer lift-off process and gold as the strain release layer to achieve a multi-metal-layer Ti/Au/Ru electrode with an excellent smooth edge. Also, the thermal test shows that its thermal stability is good enough for the high-power RF MEMS switch use. Moreover, the promoted multi-metal-layer electrode with a smooth edge improves the yield dramatically. The cold switch DC power handling capacity is improved from <90 mA per point (failed) to 100 mA per point at least (still working).

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5 References

- [1] Rebeiz G.M., Muldavin J.B.: ‘RF MEMS switches and switch circuits’, *IEEE Microw. Mag.*, 2001, **2**, pp. 59–71
- [2] Petersen K.E.: ‘Micromechanical membrane switch on silicon’, *IBM J. Res. Dev.*, 1979, **23**, pp. 376–385
- [3] Liu B., Lv Z.Q., He X.J., Liu M., Hao Y., Li Z.H.: ‘Improving performance of the metal-to-metal contact RF MEMS switch with a Pt–Au microspring contact design’, *J. Micromech. Microeng.*, 2011, **21**, p. 065038
- [4] Ke F., Miao J., Oberhammer J.: ‘A ruthenium-based multimetal-contact RF MEMS switch with a corrugated diaphragm’, *J. MEMS*, 2008, **17**, (6), pp. 1447–1459
- [5] Broue A., Dhennin J., Charvet P.-L., *ET AL.*: ‘Multi-physical characterization of micro-contact materials for MEMS switches’. Proc. 56th IEEE Holm Conf. Electrical Contacts, Charleston, SC, USA, 2010
- [6] Choi D.-J., Park J.-H., Lee H.-C., *ET AL.*: ‘Contact materials and reliability for high power RF-MEMS switches’. Proc. IEEE 20th Int. Conf. Micro Electro Mechanical Systems (MEMS), Hyogo, Japan, 2007, pp. 231–234
- [7] Liu B., Lv Z.Q., He X.J., Hao Y., Li Z.H.: ‘Novel multicontact radio frequency microelectromechanical system switch in high-power-handling applications’, *J. Micro/Nanolith. MEMS MOEMS*, 2011, **10**, (1), p. 011505
- [8] Rossnagel S., Powell R., Ulman A.: ‘PVD for microelectronics: sputter desposition applied to semiconductor manufacturing’ (Academic Press, 1998, 1st edn), pp. 230–232
- [9] Reddy V., Rao P.K., Ramesh C.K.: ‘Annealing effects on structural and electrical properties of Ru/Au on n-GaN Schottky contacts’, *Mater. Sci. Eng. B*, 2007, **137**, pp. 200–204
- [10] Malina V., Vogel K., Ressel P., Barnard W., Knauer A.: ‘Comparison of Ti/Pt/Au and Ti/Ru/Au contact systems to p-type InGaP’, *Semicond. Sci. Technol.*, 1997, **12**, p. 1298