

Metallization for High Temperature Electronics

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Abstract:

With its wide band gap and large thermal conductivity, silicon carbide can replace silicon as the semiconductor for high temperature and high power electronics. This study investigated metallic capping materials that could withstand elevated temperatures, while maintaining a low sheet resistance. Sputtered gold and ruthenium films were monitored for agglomeration through microscopy and for sheet resistance through the van der Pauw technique. Low resistance, pure gold films demonstrated significant agglomeration upon annealing at 600°C. Pure ruthenium, however, withstood agglomeration through 50 hours of annealing while sustaining an acceptably low sheet resistance. Despite the popularity of gold, a capping layer of 150 nm of ruthenium provides high-quality adhesion and low resistance through continued annealing at 600°C.

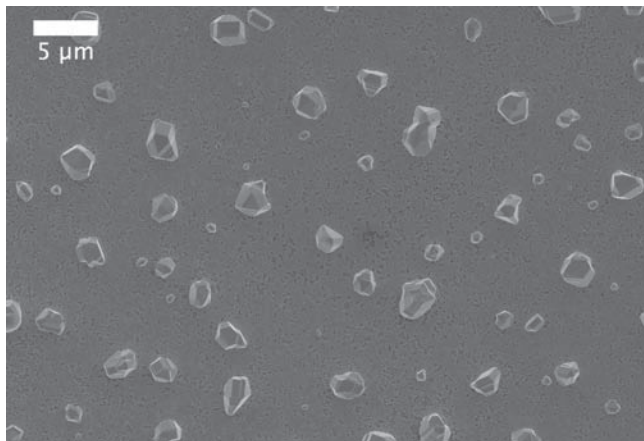


Figure 1: FESEM micrograph of gold agglomeration after annealing.

Introduction:

Wide band gap semiconductors such as silicon carbide can be utilized for high temperature devices. In comparing silicon carbide to silicon electronics, the power to size ratio increases, in addition to an efficiency improvement and a reduction in physical size [1]. With the wide band gap, thermal electrons remain unlikely to surmount the energy barrier and contribute leakage current. In order to realize the full potential of these wide band gap semiconductors, robust metal contact layers must be implemented that can also withstand the high temperatures resulting from significant power operation. As a capping material for electronics, gold has been a popular metal choice due to its low resistivity and limited oxidation. However, gold-based films agglomerated

into mounds as shown in Figure 1 during annealing at 600°C. This research aimed to discern a capping metal or gold alloy with strong adhesion to titanium nitride and low resistance after prolonged annealing in air.

Experimental Procedure:

For economical reasons, silicon pieces were used with a diffusion barrier of grown oxide. A 100 nm titanium layer was sputtered onto the substrate before annealing in nitrogen to produce a titanium nitride thin film. The capping metal film was sputtered onto the titanium nitride contact layer. Various thicknesses of gold, ruthenium, and different co-sputtered gold-ruthenium films were investigated as capping metals. Samples were cycled through annealing in air at 600°C and measuring the sheet resistance. The sheet resistance, or resistance over film thickness, was measured with a four point probe van der Pauw technique. This technique obtained voltages and currents along each pair of the sample's sides to calculate sheet resistance, correcting for shape irregularities [2]. Adhesion was tested with tape. Both an optical microscope and a field emission scanning electron microscope (FESEM) were employed for detecting agglomerations.

Results:

Although possessing a lower sheet resistance upon deposition, the gold films agglomerated rapidly during the annealing process. When the film pulls itself into mounds, the gold minimizes its surface energy. However, the agglomeration increases the sheet resistance and permits oxygen diffusion.

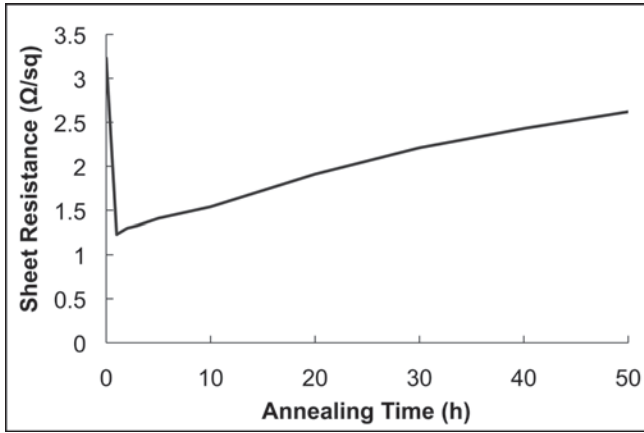


Figure 2: 150 nm ruthenium retained a low sheet resistance after annealing at 600°C in air.

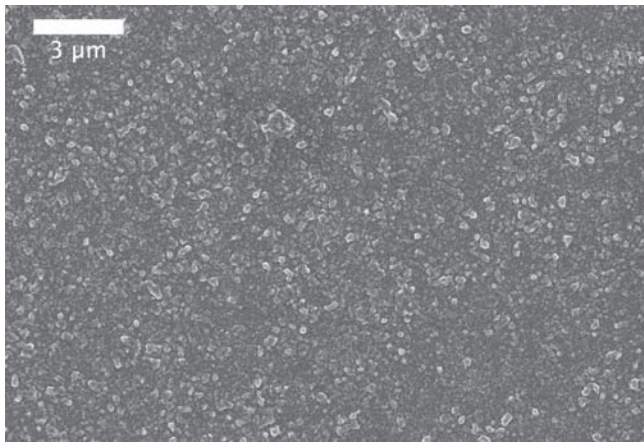


Figure 3: FESEM micrograph of the ruthenium surface after prolonged annealing.

Possibly caused by stress in the films, the agglomeration in gold films had a fractal appearance similar to that reported by Gadkari et al. [3]. Pure ruthenium demonstrated an initial drop in sheet resistance before rising slowly with prolonged annealing, as shown in Figure 2. The sheet resistance remained very low at 2.6 Ω/square, even after 50h of annealing. The ruthenium film was agglomeration-free at 44h, as shown in Figure 3. Co-sputtered alloys of ruthenium and gold showed an early onset of agglomeration and increased sheet resistance.

High-quality adhesion in a sample was valued for material compatibility in the device. Whereas the gold-based films had weak adhesion, ruthenium films showed strong adhesion to the titanium nitride layer. When layered, gold and ruthenium adhered considerably to each other as well.

With annealing time, the gold-based films darkened towards a brass color. Ruthenium experienced various color changes through the annealing process. Initially a shiny silver color, ruthenium passed from orange to red to purple by three hours of annealing. The purple hue continued deepening. After 20h of annealing, however, a dark blue color was prevalent. The color change may be constructive light interference of a surface oxide. The oxide composition likely would be ruthenium oxide or ruthenium-titanium oxide. Auger electron spectroscopy revealed only ruthenium and oxygen present at the surface. Notably, Rard and others mentioned that ruthenium (IV) oxide, RuO₂, was a dark blue color [4]. Further, RuO₂ has been noted as a conductive oxide, which would help retain the low sheet resistance [4].

Conclusions and Future Work:

Although gold initially had a lower sheet resistance, ruthenium maintained a lower sheet resistance throughout annealing compared to the gold-based films. Ruthenium also possessed better adhesion than gold to titanium nitride. A metal capping layer of 150 nm ruthenium has been recommended from this study for further inquiry. Ruthenium being less expensive than gold, the thin 150 nm requirement creates a financially viable solution. Future work will investigate the specific composition of the oxide and further evaluate ruthenium as a possible metallization layer for silicon carbide devices.

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References:

- [1] Neudeck, P.G.; "Silicon Carbide Electronic Devices"; Encyclopedia of Materials: Science and Technology, Vol. 9, 8508-8519 (2001).
- [2] Schroder, D. K.; Semiconductor Material and Device Characterization, 3rd Ed., 2-20 (2006).
- [3] Gadkari, P. R., A. P. Warren, R. M. Todi, R. V. Petrova, K. R. Coffey; "Comparison of the agglomeration behavior of thin metallic films on SiO₂"; J. Vac. Sci. Technol. A, Vol. 23(4), 1152-1161 (2005).
- [4] Rard, J. A.; "Chemistry and Thermodynamics of Ruthenium and Some of Its Inorganic Compounds and Aqueous Species"; Chemical Reviews, Vol. 85(1), 18-20 (1985).