PASSIVE COMPONENTS FOR HIGH TEMPERATURE OPERATION

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Thin film technology has been well-established as a viable and necessary part of modern microelectronics. Extending the technology of thin films for use at high temperatures has required the development of new materials and processes in order to meet the required electrical specifications at elevated temperatures. By developing thin film components for high temperature applications such as geothermal well-logging, aircraft engine instrumentation, and nuclear reactor monitoring, it will be possible to provide high circuit density and improved reliability.

One of the major objectives in developing thin film materials and processes has been to ensure that they would be fully compatible with standard silicon integrated circuit technology. This would lead to the ability to adapt one or more of the processes into existing processing lines with minimum disturbance. The passive components must also be compatible with hybrid circuit fabrication and, if possible, Integrated Thermionic Circuits.

Research and development work at The University of Arizona has been directed toward resistors, capacitors, and interconnect metalizations. The use of Low Pressure Chemical Vapor Deposition (LPCVD) has been used in material development and component fabrication. This is a major departure from the standard thin film deposition method of sputtering and thermal evaporation. LPCVD by its very nature is a process which allows the passive components to be fabricated at temperatures higher than their highest required operating temperature.

The deposition of thin films by LPCVD is accomplished by reacting one or more gases on the surface of a heated substrate. The major components of an LPDVD reactor are illustrated in Figure 1.

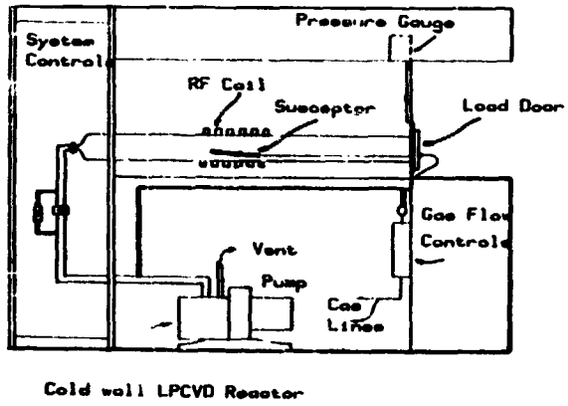

Figure 1. Pictoral representation of the major internal components of the LPCVD reactor.

The substrates to be coated are placed on the graphite susceptor and then loaded into the center of the quartz reaction tube. RF power is applied to the coil on the outside of the reaction tube which in turn is coupled into the graphite susceptor causing it to heat. Temperature of the susceptor is measured with a type-K thermocouple.

The vacuum pump is a special chemical-grade roughing pump designed to withstand the pumping of corrosive gases. Prior to the application of RF power, the atmospheric pressure is reduced to the pressure limit of the pump; the carrier gas is turned on, and the pressure _____set. Pressures of several torr or less are typical, with carrier-flow rates of 0.1 to 2.0 liters/min. Nitrogen, hydrogen and helium are typical carrier gases. These are controlled with mass flow controllers and the pressure is continuously monitored with a capacitive manometer.

Material selection is of primary importance in designing high temperature passive components. All of the materials must have the desired electrical properties, and they must also have compatible mechanical properties including coefficient of expansion, stress, and adherence. Without the required mechanical properties, the components would not survive long enough to test. A group of materials that can be deposited by LPCVD and which also are electrically, chemically, and mechanically well-matched are:

(1) Tungsten
(2) Tungsten-silicon
(3) Silicon nitride

Substrate materials are equally important for the same reasons; the two substrates recommended are:

(1) Oxidized silicon wafers
(2) Sapphire.

The reactions to form the materials are:

$$WF_6 + 3H_2 \rightarrow W + 6HF$$

$$WF_6 + SiH_4 + H_2 \rightarrow W - Si + HF$$

$$3SiH_4 + 4NH_3 \rightarrow Si_3N_4 + 12H_2$$

Not only must the materials be compatible, but so also must the deposition reactions at elevated temperatures so that the deposition of one material does not destroy the previously deposited thin film layers.

Delineation of the materials is accomplished with standard equipment and processes used in silicon IC fabrication. The thin films can be etched by wet chemical etches, or by plasma etching. Negative photoresist has been used since the developers for positive photoresists are basic and therefore tend to etch the tungsten.

Specifications for thin film resistors required stable operation to 500° C. with temperature coefficients of resistance (TCR) less than 50 ppm/°C. over the entire temperature range. The material selected for the resistors was tungsten-silicon deposited by LPCVD. The characteristics of the tungsten-silicon can be adjusted to meet the requirements of high temperature operation, stability, and low TCR.

Tungsten-silicon is grown from the reaction of tungsten hexafluoride, silicone, and hydrogen:

$$WF_6 + SiH_4 + H_2 \rightarrow W - Si + HF + H_2$$

The ratio of tungsten to silicon can be varied. The TCR can be made both positive or negative depending on

the process parameters used. Figure 2 is a resistance vs. temperature curve for a W-Si resistor. Typical resistivity of the tungsten-silicon used for the resistors is 2,500 μΩ.cm. Sheet resistors range from 50 to 1000 Ω/□ and TCR values from -50 to 50 ppm/°C. The process is compatible with silicon IC fabrication and thin film capacitor processes.

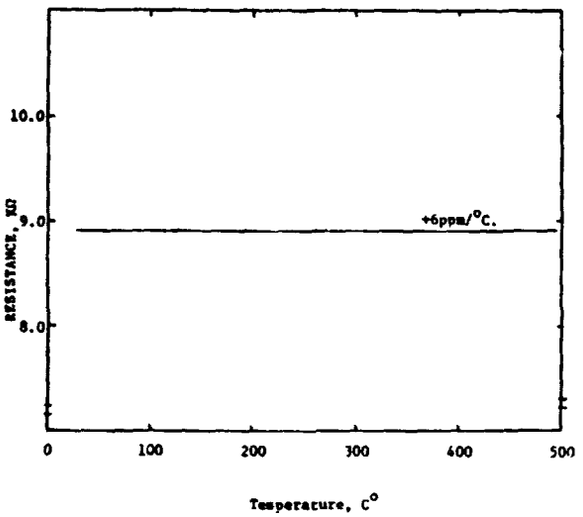

Figure 2: Resistance versus temperature curve for a W-Si thin film resistor TCR = +6 ppm/°C.

The thin film capacitors are designed to operate from room temperature to 350° C. and to fill the need for high temperature capacitor with capacitance up to 0.1 μF. Work voltage is specified at two points:

(1) 50 WVDC at 25° C,

(2) 20 WVDC at 350° C.

With a 20-volt bias applied across a capacitor at 350° C., the DC resistance must be greater than 1×10^7 Ω.

Dissipation factor is required to be less than 0.010 at 1 KHz. over the above temperature range.

Capacitors are parallel plate structures using oxidized silicon wafers as substrates; however, sapphire could be used. A cross-section is illustrated in Figure 3.

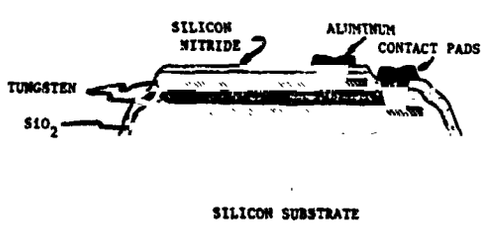

Figure 3: Cross-section of thin film capacitor. Tungsten is used for the parallel plate electrodes, and silicon nitride is used for the dielectric layer and the passivation. All materials with the exception of the aluminum bonding pads are deposited by LPCVD.

The electrodes are tungsten and the dielectric layer and passivation are silicon nitride. Bonding pads are thermally evaporated aluminum.

With LPCVD deposition of the layers, pinhole problems in the nitride have not been encountered, and it has therefore been possible to fabricate capacitors with several square centimeters area. Typical capacitance is 0.02 μF/cm.^{2}; areas as large as 4 cm. have been used.

The relative dielectric constant of the silicon nitride is 8.6 and the dissipation factor due solely to the silicon nitride is 0.0002. For large value capacitors, the series resistance term becomes the dominant factor in increasing the dissipation factor. The total dissipation factor is generally less than 0.003 at 350° C. and 2.0 KHz.

In order to meet the DC resistance requirements, it is necessary that the silicon nitride have very low conductivity. The conductivity is a function of both the temperature and the applied electric field so both must be considered when designing a capacitor. Capacitors which were fabricated exhibited a temperature coefficient of capacitance of approximately +70 ppm/°C.; a typical capacitance-temperature relationship is shown in Figure 4.

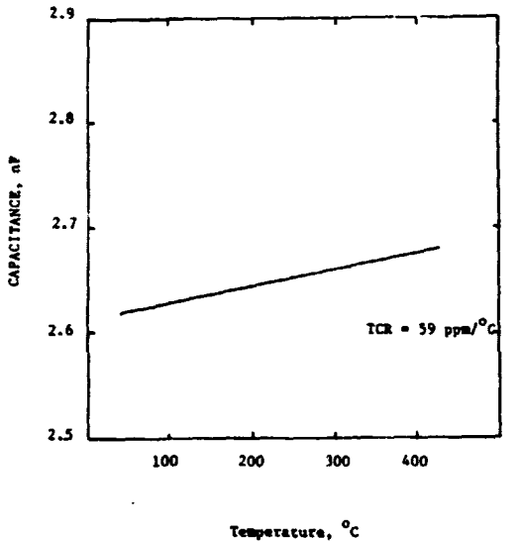

Figure 4: Capacitance as a function of temperature for a thin film capacitor.

The processing needed to form high temperature capacitors with areas up to 4.0 cm.^{2} and capacitance values to 0.1 μF has been developed to the point where it can be transferred to commercial production. Table I shows the salient features of the process.

By extending the use of the LPCVD tungsten, interconnects between passive components can be formed. If the tungsten is deposited directly over the surface of a silicon wafer that has been processed to the point where it is ready for the metallization, tungsten can be substituted for the normal aluminum interconnect metallization.

Aluminum as an interconnect metal on silicon integrated circuits has a number of problems when high current densities and high operating temperatures are present. Under these conditions, electromigration

of the aluminum can occur, causing the physical transport of silicon out of the contact regions of the silicon.

TABLE I

HIGH TEMPERATURE CAPACITOR MANUFACTURING PROCESS

1. LPCVD TUNGSTEN - 2,000 A.
2. PHOTOLITHOGRAPHY - BOTTOM ELECTRODE
3. LPCVD - Si_3N_4 (3500 A) FOLLOWED BY LPCVD TUNGSTEN (2000 A, TOP ELECTRODE)
4. PHOTOLITHOGRAPHY - TOP ELECTRODE
5. LPCVD - Si_3N_4 (1,000 A, PASSIVATION) AND LPCVD TUNGSTEN (2,000 A, USED AS ETCH MASK)
6. PHOTOLITHOGRAPHY - CONTACT WINDOWS IN TUNGSTEN ETCH MASK.
7. ETCH Si_3N_4
8. PHOTOLITHOGRAPHY - REMOVE ETCH MASK
9. ALUMINUM CONTACT EVAPORATION
10. PHOTOLITHOGRAPHY - ALUMINUM CONTACTS.
11. TEST.

Failure of the interconnect then occurs; the failure rate is accelerated as the temperature is increased. Failure can also occur because of poor step coverage of the aluminum used in silicon IC. Tapered regions in the interconnects often form in the bottom of the steps during the deposition process.

Tungsten was investigated as a possible material for use with high temperature silicon IC to avoid the problem of premature failure of the metallization at elevated temperatures.

The contact regions between the tungsten interconnect and the silicon must form ohmic contacts. This was investigated as a function of silicon doping, process parameters in the tungsten deposition and temperature. Ohmic contacts were formed in both n- and p- type silicon for phosphorus doping levels of 4 x 10^{18} cm.$^{-3}$ to 5 x 10^{20} cm.$^{-3}$ and boron levels of 2 x 10^{17} cm.$^{-3}$ to 1.0 x 10^{20} cm.$^{-3}$. The ohmic characteristic of the contact is seen in the linear I-V relationship for a 10 μm x 10 μm contact shown in Figure 5.

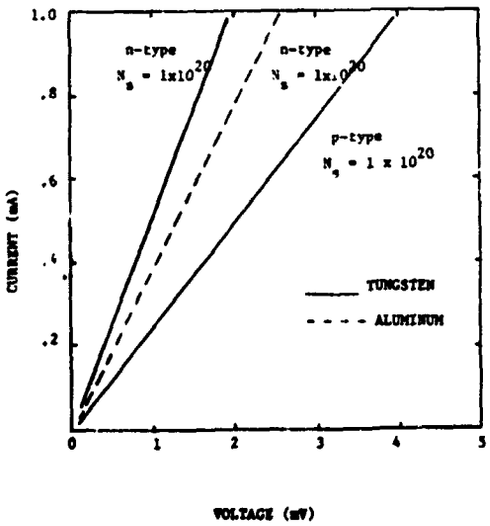

Figure 5: I-V curves for ohmic contacts to n- and p-type silicon. The solid line represents tungsten metallization, and for the comparison, the dashed line is for an aluminum/silicon contact to n-type material.

Tests for electromigration were made using two metallization strips; each strip was 10 μm wide and 0.5 μm thick. They were designed so that the current could be injected into or brought out of the tungsten through a silicon contact or through the tungsten alone. One strip was designed to traverse .5 μm of oxide strips. The contact resistance between the silicon and tungsten could also be monitored separately.

No evidence of electromigration was seen in the tungsten at current densities of 4 x 10^6 A/cm.^{2} for 72 hours. Tests were run at substrate temperature from 25° C. to 300° C. The actual temperature of the interconnect was somewhat higher due to the power dissipated by the test current.

Critical current densities (current density at point of interconnect failure) were 4.5 x 10^6 A/cm.^{2} for Si_3N_4 passivated tungsten, and 5.7 x 10^6 A/cm.^{2} for hydrogen-annealed tungsten.

SEM microphotographs of the tungsten over oxide steps indicated excellent step coverage. No failures due to exceeding the critical current densities occurred in the step regions.

Schottky diodes were also formed between the tungsten and the silicon wafer; however, they were leaky. It is now felt that the leakage current was the result of improper diode design rather than an inherent problem in forming good Schottky diodes between silicon and LPCVD tungsten.

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