Low Energy Sputter Deposition and Properties of NiCr Thin Film Resistors for GaAs Integrated Circuits

Jinhong Yang, Paul Miller, Fabian Radulescu, Ron Herring,
Kamal Avala, Debra Maxwell, Li Liu, and Richard Morton
TriQuint Semiconductor, 2300 N.E. Brookwood Parkway, Hillllsboro, OR 97124
Email: jyang@tqs.com; Tel: (503)-615-9244

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Abstract

This paper presents a comprehensive study of NiCr thin film resistors developed using a Trikon Sigma sputtering system on 150 mm wafers. The effects of sputtering process parameters and substrate conditions on resistivity and temperature coefficient of resistance (TCR) are discussed. A low energy deposition process with low power and high pressure has been developed to avoid NiCr thin film resistor edge oxidation and achieve high sheet resistance uniformity and low TCR.

INTRODUCTION

NiCr resistors are widely used in a variety of circuit designs due to their low thermal coefficient of resistance (TCR). The sheet resistance is typically about 50 Ohm/sq and the TCR is about +80 to -250 × 10^{-6}/°C[1,2,3]. NiCr thin film resistors are usually manufactured by evaporation or sputtering. NiCr resistance is very sensitive to deposition parameters, preclean, and substrate conditions. In-wafer and wafer-to-wafer uniformity and NiCr reactivity have been the biggest manufacturing challenge for both types of processes.

METHOD AND MATERIALS

For evaporated NiCr, it is hard to control film composition. In this work, the NiCr film was deposited on PECVD silicon nitride or silicon dioxide using a Trikon Sigma DC magnetron sputtering deposition system. The deposition was performed from a NiCr target (332 mm in diameter) in an Ar atmosphere. The substrate is located horizontally below the target and the sputtering is carried out vertically in the chamber. The target-to-substrate distance was 45 mm. The base pressure for each wafer was below $1x10^{-7}$ Torr. The gas flow rate was adjusted by a mass flow controller.

Two methods can be used for patterning NiCr resistors: lift-off or etch. It is difficult to etch NiCr. A NiCr lift-off process has been used in the TriQuint Oregon fab. The disadvantage of a lift-off process is that the sheet resistance cannot be directly measured after sputtering. Process control was the biggest hurdle. Also, low energy deposition needs to be used to prevent photoresist profile change.

NiCr sheet resistance was measured using a standard Van Der Pauw structure (TFRVDP). TCR was measured on a 2 µm X 20 µm resistor (TFR2x20), as shown in Figure 1. Film thickness was determined using TEM. Field emission Auger analysis was used to determine the contamination in NiCr resistors.

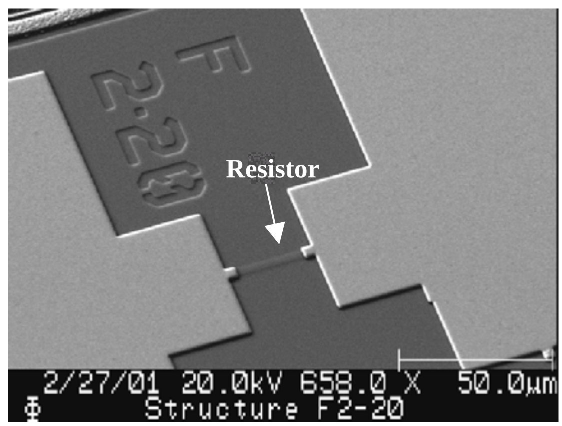

Figure 1. TriQuint 2µm X 20 µm resistor.

RESULTS AND DISCUSSION

NiCr Resistor Edge Oxidation

A low-pressure (4.5 mT) sputtering process was initially used for NiCr deposition. However, the resistance of the narrow resistors (TFR2x20) (Figure 1) was very high compared with the TFRVDP value. Resistor size was not the issue.

Field emission Auger survey scans along the width of TFR2x20 were used to determine the contamination level. Data were acquired on selected areas after ion etching to depths of 100 Å (SiO_2 equivalent depth). Field emission Auger analysis is inherently surface sensitive having a depth of investigation that is typically in the range of 10 to 30 Å. The lateral resolution is less than 150 Å.

It was found that oxygen penetrated into the NiCr line at least 0.4 microns from the edge, as shown in Figure 2. Ni and Cr atoms are probably highly energetic due to the low process pressure and the close target-to-substrate spacing. These atoms probably knocked off some oxygen atoms from the photoresist sidewall and incorporated oxygen into the NiCr film. The detected oxygen did not come from the natural surface oxidation because there was no oxygen at the middle width of the TFR2x20 line. The sputtering etch prior to Auger line scan was deep enough to remove the surface oxide. NiCr edge oxidation could increase the resistance of narrow resistors significantly. To lower the energy of Ni and Cr atoms, high pressure, low deposition power and low deposition temperature could be used. There is not too much room to vary process temperature. To keep consistent lift-off photo resist profile, wafers were loaded on an electrostatic chuck (ESC) during deposition, which will maintain a stable temperature of 30°C.

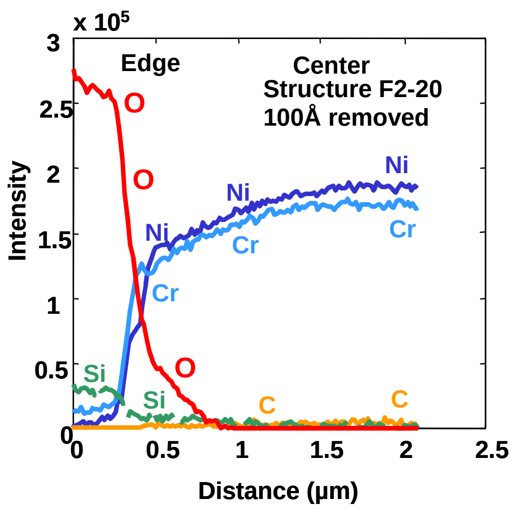

Figure 2. Auger Analysis indicated that the NiCr edge had higher oxygen content.

Deposition pressure effects were investigated, as shown in Figure 3. NiCr was deposited on Si dioxide using a low power level. In Figure 3, the y axis represents both the NiCr sheet resistance (TFRVDP) and one tenth of the resistance value for the narrow resistor (TFR2x20). As the pressure increases, the difference between TFRVDP and (TFR2x20)/10 becomes smaller. High-pressure processing brings more gas atoms into the chamber. Applying a certain power, each atom will get less energy at a higher pressure and become less reactive with photoresist. A 13 mT process brought the resistance value of the narrow resistor (TFR 2x20) in line with the NiCr sheet resistance (TFRVDP).

Deposition Power

Like the other thin film resistor processes[4], low-power sputtering regimes need to be used to get a low deposition rate and ensure good film thickness control. Also, because NiCr targets have a high electrical resistance, we wanted to avoid overheating the targets and the resultant change in the target composition that high-power regimes can cause. HALO (High Accuracy at Low Output) mode with an Advanced Energy MDXII power supply is used for NiCr production.

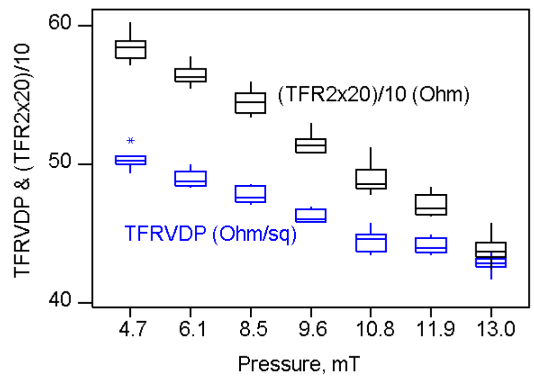

Figure 3. Quartile plot of NiCr deposition pressure effect on the difference between NiCr sheet resistance (TFRVDP) and one tenth of the narrow resistor resistance (TFR2x20).

It has been found that the power level could significantly change the in-wafer uniformity. Figure 4 is an example of the power effect on NiCr uniformity when the substrate is Si nitride. 65 sites were measured on each wafer. The standard deviation of NiCr sheet resistance across wafer was less than 0.2 Ohm/sq at 0.35 kW.

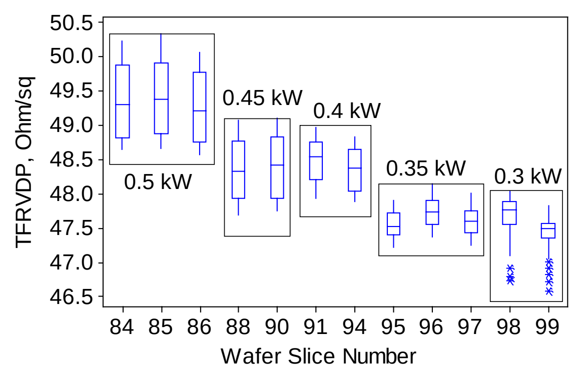

Figure 4. Effect of NiCr target power on NiCr uniformity.

Magnetron Offsets

Magnetron positions were optimized to achieve maximum efficiency and in-wafer uniformity. Discharge current (I) increases rapidly with target voltage (V) at any pressure; it is usually plotted as log (I) vs. V, and produces straight lines that can be curve fitted into an empirical equation:

$$I = k\, V^n,$$

where k is a constant and the exponent (n) is a measure of the magnetron efficiency[5]. If the magnetic field decreases, so will the value of n. The magnetron operation can therefore be checked easily from a log (I)-V plot. n should be greater than 9 for a good magnetron setting[5]. At TriQuint process pressure (13 mT), n was 9.08 for our NiCr module:

$$I = 4.9E\text{-}24 * V^{9.08}, \qquad R = 0.999.$$

Flow Rate

The flow rate of the Ar process gas is used to adjust sheet resistance when deposition time cannot provide more precise control. It has been found that a 1 sccm flow rate decrease will increase NiCr sheet resistance 0.3 Ohm/sq, as shown in Figure 5. A good mass flow controller is needed for a good NiCr deposition system!

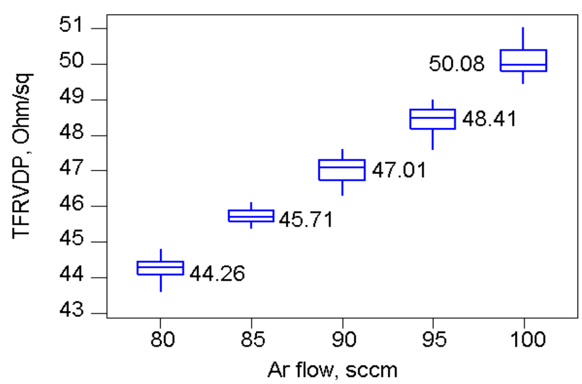

Figure 5. Effect of Ar flow rate on NiCr sheet resistance.

Dielectric Substrate Effect

NiCr sheet resistance highly depends on substrate type and surface conditions. The sheet resistance of NiCr deposited on Si dioxide is usually 4-5 Ohm/sq higher than the sheet resistance of NiCr deposited on Si nitride.

Light wet etching or plasma etching can be used for preclean prior to NiCr deposition. All the etching processes can change surface chemical states and surface roughness of Si dioxide and Si nitride. Dilute buffered HF oxide wet etch preclean was seen to lower NiCr sheet resistance 2 Ohm/sq, while an Ar plasma preclean lowers NiCr sheet resistance 4.5 Ohm/sq.

Si dioxide process variations can significant affect NiCr sheet resistance. Figure 6 (a) shows a NiCr film on Si dioxide deposited right after the PECVD tool showerhead change. When the PECVD tool had appropriate conditioning after chamber maintenance, NiCr columns and voids are less distinct, as shown in Figure 6 (b). The columns will disappear when NiCr film becomes fully dense. The sheet resistance of the NiCr film in Figure 6 (a) was 1.7 Ohm/sqr higher than that of in Figure 6 (b). A NiCr sheet resistance measurement became one of the qualifying procedures for Si nitride and dioxide deposition tools after maintenance work.

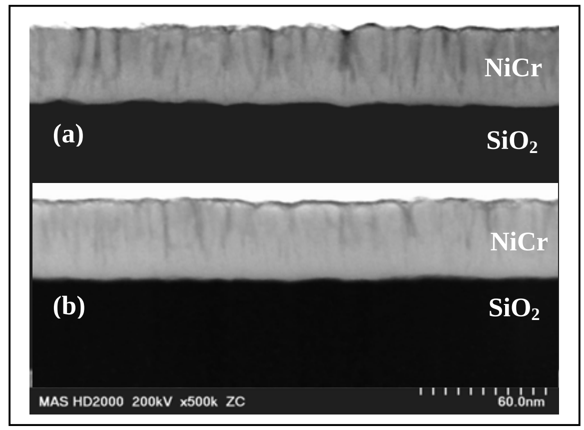

Figure 6. NiCr film on SiO_2 dielectric. (a) SiO_2 film was processed right after chamber showerhead change. (b) SiO_2 film was processed after normal conditioning.

The SiO_2 process pressure also will slightly change SiO_2 film density and surface condition. Figure 7 presents the NiCr sheet resistance difference for two SiO_2 process pressures. The average surface roughness calculated based on AFM images shows only 1 Å difference for these two depositions.

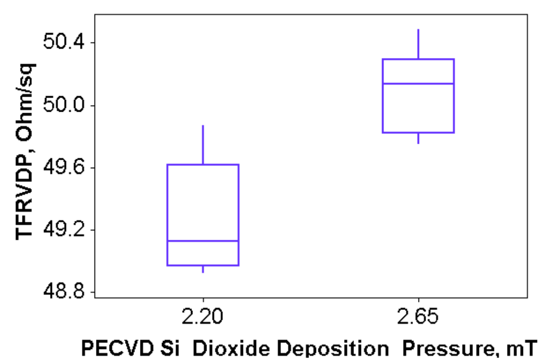

Figure 7. Effect of Si dioxide deposition pressures on NiCr sheet resistance. Eight wafers were processed at each deposition pressure.

Resistor Stability

The temperature coefficient of resistance (TCR) was measured over a temperature range from 20 to 125 °C. In the resistance vs. temperature curve the resistivity decreases linearly with an increase in temperature (negative slope). Linearity of the curve means a constant TCR value. Dielectric type and deposition power had little effect on TCR, as seen in Table I.

Resistor stability during subsequent processing was also a big concern. NiCr was passivated using Si nitride after liftoff. Sheet resistance was measured after liftoff, a 368 °C anneal, and wafer final passivation. After anneal, sheet resistance dropped 0.5 Ohm/sq and became thermally stabilized. When wafers finished in the fab, the NiCr sheet resistance was not significantly different than the as-annealed film, as seen in Table II.

NiCr film reliability was also tested after 7 days, 275 °C oven bake and 96 hours autoclave (121°C with a 100% relative humidity). NiCr sheet resistance shifted 0.25 Ohm/sq after 7 days bake, while NiCr sheet resistance had no change after 96 hours autoclave test.

TABLE I.
NiCr TEMPERATURE COEFFICIENT OF RESISTANCE (TCR)

Dielectric	Deposition Power, kW	TCR, ppm / °C
Si Nitride	0.30	-27.0
	0.35	-27.1
	0.40	-23.9
	0.45	-25.8
	0.50	-27.1
Si Dioxide	0.50	-22.8
	0.50	-21.2

TABLE II.
NICR SHEET RESISTANCE STABILITY

Wafer No.	Ar flow rate (sccm)	Sheet Resistance, Ohm/sq		
		After Liftoff	After 368°C Anneal	After Fab
1	94	50.3	49.6	49.7
2	96	51.1	50.5	50.5
3	98	51.4	51.1	51.3
4	100	51.4	51.0	51.2

Uniformity

After further refinement resulting from running thousands of wafers through the system, the magnetic field applied to the targets, the power level, and substrate conditions have been optimized. NiCr in-wafer uniformity and wafer to wafer uniformity reach 1 % one sigma. Figure 8 demonstrates the NiCr sheet resistance distribution over 1200 product wafers.

CONCLUSIONS

Low energy sputtering deposition and integration can be well controlled to produce high precision resistors with good uniformity and low cycle times. After fully understanding the effects of NiCr deposition, substrate, and other related processes, one only needs a four-point probe sheet resistance measurement to monitor production deposition rate twice a day to ensure that both in-wafer and run-to-run sheet resistance uniformities reach 1% 1σ.

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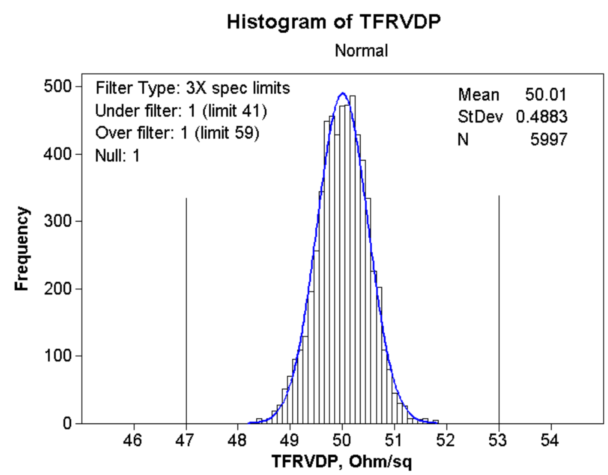

Figure 8. Histogram of NiCr TFRVDP data over 1200 product wafers.

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ACRONYMS

TCR: Temperature Coefficient of Resistance
TFR: Thin Film Resistor