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Application of the Rapid Thermal Process: Sintering the Sputtered Aluminum/Silicon Contact in Silicon Detector Fabrication*

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Abstract

Rapid thermal process (RTP) sintering has been used in p^+ -n junction detector fabrication. For the same thickness of aluminum film and at the same RTP sintering condition, the leakage current of the p^+ -n junction detector with sputtered Al gate showed at least a 50% improvement and no spiking phenomena were observed. RTP sintering in 4% H_2/N_2 ambient passivates the defects introduced by sputtering and the damage caused by the ^{60}Co irradiation.

I. INTRODUCTION

Aluminum and its alloys are widely used for silicon detector metallization because of the ease of deposition, patternability, high conductivity, good adherence, bondability, easy availability and low cost [1].

Numerous techniques of depositing thin aluminum films have been developed by the processing industry, the most important among them being evaporation, chemical vapor deposition and sputtering [2]. For high speed circuit applications, the series resistance between the gate contact and the gate itself must be very low. The common problem is the interdiffusion of Si and Al which is usually termed *spiking*. *Spiking* results in a clear short of the high impedance reverse diode characteristic. Therefore considerable effort has been given to improve the ohmic contact between the aluminum film and the silicon substrate. The use of aluminum metallization sources having an alloy of a few percent silicon, or copper if the contact is to interface with copper electrodes, is a well known solution to the *spiking* or intermetallic migration problem (Kierkendahl effect) [3,4]. The sputtering technique is expected to produce thin aluminum films with the minor constituent, Si, intact in the film, however, the effects of the dense ionization in the sputtering environment on the oxide passivations and oxide-silicon interface for detector configurations must be examined. Deal et al. [5] first described the effects of a low temperature anneal on the SiO_2/Si interface and compared the role of hydrogen from both external (H_2 or N_2H_4) and ambient sources (H_2O). Recently, attention has been directed in device processing toward sintering (a thermal cycle to 450°C in the Al-Si

system) the Al-Si contact using a RTP which has been found to produce a highly reliable Al-Si contact [6-7]. This work reports results of using sputtered and evaporated contacts as well as their RTP sinterings. Comparisons of the leakage current difference and the C-V characteristics between the two types of aluminum contacts before and after sintering were made in this study. The effects of ^{60}Co gamma radiation on the several contacts described were also studied.

II. EXPERIMENTAL

In this work, RTP was used to sinter Al metallization on the implanted p^+ -n junction diode detectors [8] for both evaporated and sputtered Al-Si materials. Silicon materials used here were Wacker n <111> Si wafers with 0.1, 0.165 and 2-4 $k\Omega cm$ resistivity. RTP is performed in two steps to eliminate possible overshooting of the temperature that may cause unexpected problems to the detectors (Fig. 1). In the first step the temperature was raised to 400°C for 40 sec. In the second step the temperature was raised to 450°C for either 20 sec or 2 min on varying samples (Table I). The RTP unit is a PPC (Process Products Corp.) Model PTM-2016-M-2F-FC. The ambient during the RTP is forming gas (4% H_2/N_2).

Fig. 1 Rapid Thermal Process Step

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Table I. Comparisons of the leakage current for evaporated Al and sputtered Al before sintering and after sintering.

Sample No.	Material	Al type	Sintering 4% H ₂ /N ₂	Leakage Current $\bar{I}_L _{100\text{ V}}$		Spiking	$\frac{\Delta I_L}{I_{Lo}}$
				Before Sintering $\bar{I}_{Lo}$	After Sintering $\bar{I}_{Lf}$		
83	FZ n<111> 165 Ωcm	Sputtered	400°C 40 sec 450°C 2 min	53.8 nA	26.0 nA	no	-52%
63	FZ p<100> 2 k Ωcm	Sputtered	400°C 40 sec 450°C 2 min	65.8 nA	30.5 nA	no	-54%
106	FZ n<111> 4 k Ωcm	Sputtered	400°C 40 sec 450°C 2 min	142.4 nA	35.3 nA	no	-75%
107	FZ n<111> 4 k Ωcm	Sputtered	400°C 40 sec 450°C 2 min	146.3 nA	46.7 nA	no	-68%
76	CZ n<111> >100 Ωcm	Sputtered	400°C 40 sec 450°C 20 sec	98.8 nA	26.4 nA	no	-73%
80	FZ n<111> 165 Ωcm	Evaporated	400°C 40 sec 450°C 20 sec	87.0 nA	91.5 nA	no	5%
65	FZ p<100> 2 k Ωcm	Evaporated	400°C 40 sec 450°C 2 min	2.2 μA	51.7 μA	yes	>100%
61	FZ p<111> 5 k Ωcm	Evaporated	400°C 40 sec 450°C 2 min	46.5 nA	70.0 μA	yes	>100%
62	FZ p<111> 5 k Ωcm	Evaporated	400°C 40 sec 450°C 20 sec	57 nA	mAs	yes	>100%
78	CZ n<111> >100 Ωcm	Evaporated	400°C 40 sec 450°C 20 sec	1.3 μA	2.2 μA	yes	69%

Pure Al was evaporated from a low alkali tungsten filament in a 10^{-7} Torr oil-free, ion-pumped vacuum system. A dc sputtering system was used for sputtered Al contacts. Argon gas pressure was kept at 1.0 m Torr during the sputtering. An aluminum target containing 2% silicon was used to produce an Al-Si alloy contact; it will be shown that co-evolution of Al and Si can be achieved only by the sputtering method. The thickness of the film deposited is about 2500 Å for both evaporation and sputtering.

In order to confirm the incorporation of silicon in the aluminum metallization, samples of the evaporated and sputtered Al films were produced on a clean carbon electron microscope stub and observed in the SEM with a high resolution Si(Li) x-ray detector to measure the deposited Al and Si by their characteristic K x-rays at 1.55 and 1.74 keV, respectively. Figure 2 shows the spectra from the evaporated sample and the sputtered sample. In a difficult measurement, the small Si peak can be seen on the high energy side of the major aluminum peak in the sputtered sample; silicon cannot really be discerned in the evaporated sample. Calibrations indicate that the percentage of Si deposited is $1.2\% \pm 0.2\%$.

MOS capacitors with evaporated Al gates and sputtered Al-Si gates were also fabricated to study the effect of RTP sintering on the oxide damage introduced by sputtering. Several MOS devices have also been prepared for radiation hardening (or softening) experiments using neutron transmutation doped [1,1,1] n-type Wacker silicon with $\rho \geq 5\text{ K}\Omega\text{-cm}$ resistivity. Oxide thicknesses were about 5000 Å. Four mm

diameter circles of Al were evaporated to a thickness of 2500 Å. These MOS structures were divided into two groups: Group A was measured as fabricated and Group B underwent RTP before irradiation by ^{60}Co gamma rays up to 40 k-rad. Each group could then be sintered after irradiation and measured to determine if some oxide hardening (or softening) was introduced by the RTP.

III. RESULTS AND DISCUSSION

Table I shows results of leakage currents of detectors with evaporated and sputtered Al before and after sintering. Leakage currents of detectors with sputtered Al contacts are shown to improve at least 50% after sintering and no spiking phenomena were observed for a wide variety of materials and fabrication runs. Sputtering indeed produced thin Al-Si alloy film. However, the leakage currents of detectors with evaporated Al contacts increased significantly after sintering and observable spiking occurred in some cases. The aluminum metal pellet for the basket in the vacuum evaporator did indeed include 2% Si, however the Si was not co-evaporated with the major component, aluminum. Although evaporated contacts are expected to be considerably less potentially harmful to oxide layer, the spiking occurred at an oxide-Si edge as we have observed in evaporated Al situation. No spiking after sintering was observed in detectors with Al sputtered metallizations even in detectors in which Al step-covers the oxide edges. The step coverage Al contact, in fact, is the

(a) Evaporated

(b) Sputtered

Fig. 2 The energy spectra from the evaporated and sputtered sample.

Fig. 3 C(V) Curve of MOS Capacitor for Sputtered Al Gate

preferable metallization configuration because the contact acts as a field plate to deplete the surface charge and reduce the surface-controlled potential gradient at the junction edge. Therefore, sputtering films provide better step coverage. Using sputtered Al to step-cover the oxide edges, which minimizes the surface leakage current and improves the breakdown voltage, has become a standard metallization step in our detector fabrication process.

Data of flatband voltage changes of MOS capacitors with evaporated and sputtered Al gates before and after sintering is shown in Table II. The flatband voltage of a MOS capacitor with sputtered Al gate is found to be larger than the one with an evaporated Al gate before rapid thermal sintering. Sputtering clearly creates more positive charges in the oxide layer due to the damage caused by energetic ion bombardment. After rapid thermal sintering, however, both the flatband voltage shift ΔV_{FB} and the stretchout δV_{FB} of the MOS capacitor with sputtered Al gates became comparable to those with evaporated Al gates, as shown in Figs. 3 and 4. Table III shows the data of flatband voltage changes of MOS capacitors with evaporated Al gates before and after radiation and the effect of RTP treatment. A large flatband shift (ΔV_{FB}) has been found for all capacitors in Group A and B except capacitor B4. This indicates that a large amount of positive charge was created in the oxide layer after irradiation. In the B4 case (irradiated with no bias), some positive charge may have been neutralized after irradiation into neutral traps. However, after RTP sintering, the flatband voltages became comparable with those prior to irradiation for capacitors in both groups. The same improvement was found for the stretchout of the C-V characteristic after RTP sintering indicating the annealing out of interface states. Rapid thermal sintering process, with its hydrogen rich high temperature ambient, proves to passivate the interface states at the Si/SiO₂ interface and remove positive charge in the oxide layer introduced by both sputtering and ⁶⁰Co irradiation. Since the surface leakage current (via, i.e., the junction edges) is proportional to the surface states N_{it} : $I_s = en_i (\sigma v_{th} N_{it})$, a decrease of I_s after sintering is expected and this may be the cause of the observed overall leakage current decrease after sintering for detectors with sputtered Al contacts.

In conclusion, we found that the rapid thermal sintering process in a 4% H₂/N₂ ambient passivates the defects introduced by sputtering and the damage caused by the ⁶⁰Co irradiation in the oxide layer. No spiking was observed for detectors with sputtered Al contact after RTP sintering. The sputtered film maintains a composition close to the source material and provides better step coverage. Thus Al-Si alloy is transferred as the metallization, spiking is largely eliminated as expected and good quality junction detectors are produced. RTP combined with sputtering technique fulfills the requirements of Al-Si contact: produces a low series resistance, gives a very bondable contact land and because of its short time duration does not influence other dopant species in the device. Sputtering and rapid thermal sintering have been accepted as the standard means of metallization in our detector processing.

Table II. Comparison of the flatband voltage and the stretchout between evaporated Al and sputtered Al.

Material 5000 Å	ΔV_{FB} (before sintering)		ΔV_{FB} (after sintering)		δV_{FB} (before sintering)		δV_{FB} (after sintering)	
	Evaporated Al	Sputtered Al	Evaporated Al	Sputtered Al	Evaporated Al	Sputtered Al	Evaporated Al	Sputtered Al
n <111> 2-4 kΩcm	-6.4 V	-27.4 V	-3.9 V	-3.6 V	0.48 V	3.60 V	0.24 V	0.27 V
n <111> 10 Ωcm	-3.7 V	-10.4 V	—	-3.4 V	0.80 V	4.40 V	—	0.40 V
p <100> 2 kΩcm	-12.0 V	-26 V	-8.2	-1.23 V	0.90 V	13.00 V	3.00 V	0.36 V

Table III. Comparison of Flatband Voltage for Radiated MOS Capacitors Before and After Sintering

Sample No.	Bias	ΔV_{FB} (before radiation)		δV_{FB} (before radiation)		ΔV_{FB} (after radiation) (40 K-rad)		δV_{FB} (after radiation) (40 K-rad)	
		No Sintering	Sintering	No Sintering	Sintering	Before Sintering	After Sintering	Before Sintering	After Sintering
A1	+	-4.9 V	—	0.3 V	—	-12.8 V	-3.7 V	6.1 V	0.7 V
A2	-	-5.5 V	—	0.3 V	—	-7.8 V	-3.9 V	2.1 V	0.6 V
A3	0	-4.9 V	—	0.3 V	—	-8.5 V	-3.7 V	1.9 V	0.8 V
A4	0	-5.0 V	—	0.3 V	—	-8.7 V	-3.7 V	2.1 V	0.6 V
A5	+	-6.7 V	—	0.4 V	—	-12.6 V	-7.5 V	5.9 V	0.4 V
A6	-	-5.6 V	—	0.4 V	—	-9.4 V	-3.5 V	2.1 V	0.7 V
B1	+	-9.7 V	-10.4 V	0.3 V	1.1 V	-15.2 V	-6.6 V	5.9 V	0.6 V
B2	+	-3.8 V	-4.1 V	0.3 V	6.2 V	-12.6 V	-3.2 V	6.5 V	0.7 V
B3	-/0	-5.3 V	-6.1 V	0.3 V	0.5 V	—	-4.3 V	—	0.2 V
B4	0	-6.0 V	-6.9 V	0.3 V	0.6 V	-2.7 V	-5.1 V	1.8 V	0.2 V

Fig. 4 C(V) Curve of MOS Capacitor for Evaporated Al Gate

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