

Sputtered aluminum-nitride for integration in IC processes

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Abstract—In the semiconductor industry many efforts are made to reduce the minimum feature size, increase the speed and lower the power consumption. To achieve this not only the steps of the standard silicon processes are continuously developed but there is also research going on to introduce new materials into the process flow, which can substitute the materials already in use, because of their better properties, for example in case of conductors better electrical conductivity, or in case of dielectrics larger dielectrical constant or larger heat conductivity (high κ dielectrics).

In this latter group, dielectrics with a high thermal conductivity are among others diamond, beryllia (BeO) and aluminum nitride (AlN). This work focuses on the integration of aluminum-nitride into IC processes.

Keywords— high κ dielectrics; aluminum-nitride

I. INTRODUCTION

The semiconductor industry is strongly pushing the feature size, speed and power consumption towards their limits. To achieve the needs of all three fields trade-offs must be made within the current processes, there should be a paradigm change carried out. Such change can be the introduction of new materials into the processes, to substitute the previously used ones with a similar material, but with better properties.

One field of interest of the material substitution is the so-called high κ dielectrics: insulating materials, which are at the same time good heat conductors, or at least relatively good heat conductors compared to the standardly used silicon-dioxide with the heat conductivity of around 1 W/mK or silicon-nitride with the heat conductivity of around 2.2 W/mK [1].

Among the high κ dielectrics the most applicable is diamond, beryllia and aluminum-nitride. They have a heat conductivity of 1600 W/mK, 180-300 W/mK and

70-200 W/mK, respectively [2]. These heat conductivity values are for bulk materials and for thin films used in the semiconductors these values can hardly be achieved: the actual crystalline structure – which strongly depends on the growth conditions and post-processing steps – has a great influence not only on the magnitude of the heat conductivity, but also can cause large differences between the lateral the vertical directions.

This paper focuses on the integration of aluminum-nitride in IC processes. AlN has numerous advantages from the process-point of view:

- it is not contaminating, and not poisonous (like e.g. beryllia), therefore no separate treatment or additional cleaning steps or other safety precautions are needed

- it can be sputtered easily using an aluminum target in nitrogen atmosphere, instead of the standard Al/Si(1%) target, which is mainly for metallization contacting the silicon. In our lab the aluminum-nitride deposition is performed with a pure Al target. The sputter rate is the same as the Al/Si(1%); this also enhances the heat conductivity because of the absence of the much more worse heat conductor silicon-nitride

- it does not require special chemicals for processing. Standard dry and wet etching can be performed and tuned later measuring the etch rates and the selectivities to other materials and also investigating the possibilities of endpoint-detection

- the deposition of the aluminium-nitride can take place in a wide temperature range: from room temperature (20 °C) up to 400 °C, which enables deposition even after process steps, which do not allow further high-temperature processing, and in that way also the stress issues can be investigated and tuned.

Several experiments have been carried out to determine the applicability in IC processes: stress measurements to see the thermal treatments needed after

deposition to avoid stress-induced failures such as cracks in the devices; charge-to-breakdown measurements to appoint the electrical isolation and the minimal thickness needed; etching experiments to calculate the etch-rates during wet and dry etching, the selectivity between AlN and other materials, and the possibilities of endpoint-detection.

II. STRESS MEASUREMENTS

A. Gluing experiment

To determine the treatments needed after deposition of aluminum-nitride to reduce the stress a gluing experiment was carried out. There were four wafers with the same structure, so bare silicon wafer, 100 nm thermally grown oxide and 1 μm AlN deposited at room temperature in the Sigma Trikon Technologies Inc. sputtercoater on the top of it. On the first wafer 0.2 μm alumina (Al_2O_3) was deposited, the second was put into oxygen plasma to oxidize the top. On the third wafer a standard alloying step was carried out at 400 $^\circ\text{C}$ for 20 minutes in nitrogen/hydrogen atmosphere, causing an outgassing. And the fourth wafer was used as a reference. After the post deposition treatments the wafers were flipped and glued with a standard SOA process on an AF-45 glass wafer, and the bulk silicon was etched away [3]. Fig. 1 shows the pictures made by a microscope over the surfaces through the glass wafer.

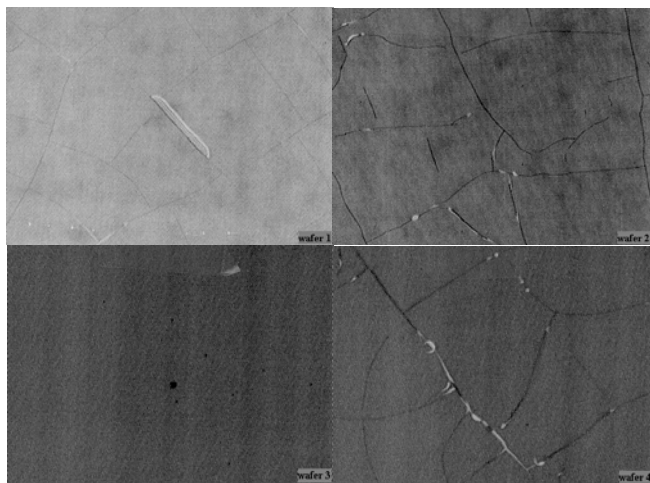


Fig. 1. This figure shows the surfaces of the wafers 1, 2, 3 and 4 after the gluing step.

As it can be seen, only the third wafer had a perfect surface, that means, that the stress in the aluminum-nitride was mainly caused by the insufficient outgassing of the AlN layer. This can be solved by applying a thermal after-treatment after deposition.

B. Stress and refraction index measurement

To receive exact measurement results the change in the stress caused by an additional heat step was measured in the Flexus stress meter. Also the refraction index was measured before and after the heat treatment, to be able to make conclusions regarding the possible change in the crystalline structure of the aluminum-nitride.

Two wafers with the same structure, a bare silicon wafer with 30 nm thermally grown oxide and 0.8 μm aluminum-nitride layer deposited at 50 $^\circ\text{C}$. The first wafer was heated up to 400 $^\circ\text{C}$ with a ramp of 10 $^\circ\text{C}/\text{min}$, annealed for one hour, then cooled down to room temperature. The second wafer was heated up to 900 $^\circ\text{C}$ with a ramp of 10 $^\circ\text{C}/\text{min}$, annealed for one hour, then cooled down to room temperature. The changes in the stress on the first and the second wafer can be observed in Fig. 2(a) and Fig. 2(b), respectively.

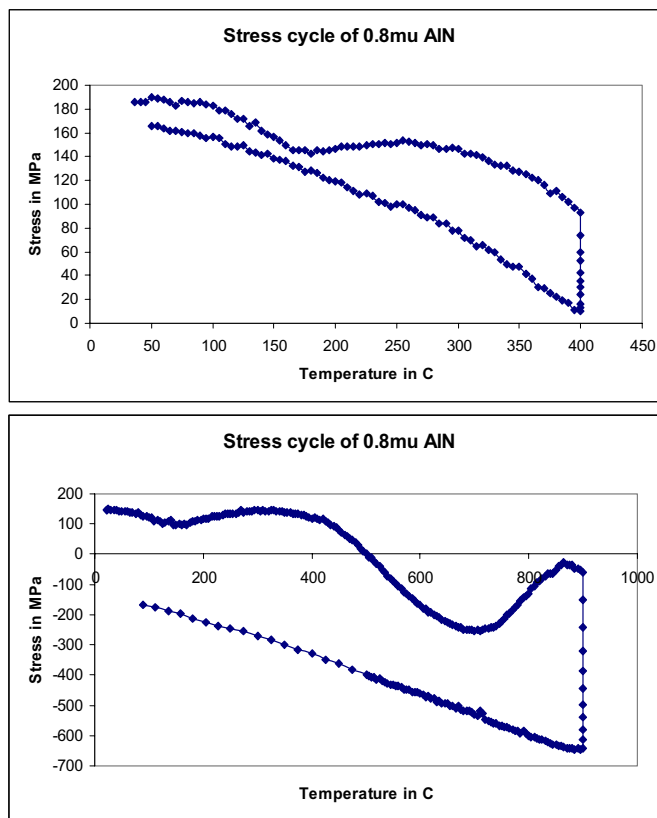


Fig. 2. The (a) and (b) figures show the stress versus the temperature during the heating-up, annealing and cooling-down of wafer 1 and wafer 2, respectively.

Fig. 2(a), the graph of the stress cycle of the first wafer up to 400 $^\circ\text{C}$ and back to room temperature doesn't show too much difference between the beginning and end values of the stress. The refraction index at 450 nm rises from 2.00 to 2.10, which means that some densifying takes place during the thermocycle,

but by the refraction index it can be told that the crystalline structure does not change, it stays crystalline [4]. Outgassing takes place above 150 °C. The stress at 400 °C is still going down, because the temperature of the wafer is probably behind the temperature of the thermocouple in the stress meter.

During heating the second wafer up to 900 °C in Fig. 2(b) the aluminum-nitride layer changes, because the stress level is not the same anymore. Also the optical properties are changed: the refraction index at 450 nm drops from 2.00 to 1.80. The reason for this drop could be the recrystallization of the AlN layer, by the refraction index the crystalline structure changed from crystalline to amorphous [4]. But looking at the Fig. 3(a) and Fig. 3(b), there is not much difference between the crystalline structure of the two wafers, only the surface got smoother at higher temperature.

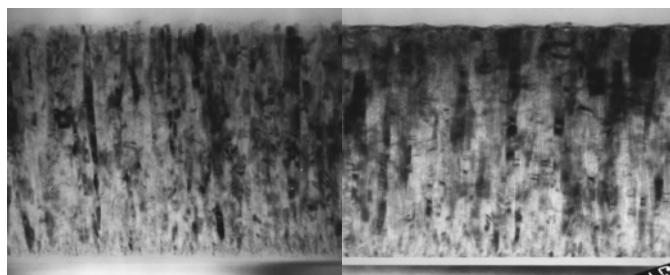


Fig. 3. The (a) and (b) figures show the cross section of the first and the second wafers, respectively, after the thermo cycle.

III. CHARGE-TO-BREAKDOWN MEASUREMENTS

Also the electrical isolation of the aluminum-nitride was tested with performing charge-to-breakdown measurements [5].

A. Minimum thickness for electrical isolation

One experiment was about appointing the minimum thickness of the aluminum-oxide needed for good electrical isolation. There were five wafers with MINOX structures with different thicknesses of aluminum-nitride, from 0.3 μm to 1 μm.

Wafer no	$t_{\text{deposition}}$	AlN thickness [μm]	Qbd > 10C/cm ²
1	31'24"	1	25
2	25'07"	0.8	24
3	18'50"	0.6	1
4	12'34"	0.4	0
5	9'25"	0.3	0

Fig. 4. Results of charge-to-breakdown measurements with varying thickness of the aluminum-nitride.

The vertical structure of the wafers was: silicon wafer with 100 nm of thermal oxide grown on it, 1 μm Al/Si(1%), AlN and 675 nm Al/Si(1%) deposited consequently. To get rid of the stress issues, right after depositing the aluminum-nitride an alloying step was carried out to cause an outgassing.

By the results on Fig. 4 if the aluminum-nitride layer becomes thinner than 0.8 μm, the breakdown will occur too early.

B. Influence of the deposition temperatures

Another set of experiments was carried out to determine the influence of the deposition temperature on the electrical isolation. There the same structure, so silicon wafers with 100 nm of thermally grown oxide, 1 μm Al/Si(1%), 1 μm AlN, and 1 μm Al/Si(1%) on the top. In each experiment the deposition temperatures of the aluminum-nitride and also the deposition temperature of the aluminum was varied.

		pure AlN		
		20 °C	150 °C	300 °C
Al/Si (1%)	50 °C	insulating	all leaky	all leaky
	350 °C	all leaky	all leaky	all leaky

Fig. 5. Results of charge-to-breakdown measurements varying the deposition temperatures of the aluminum-nitride and aluminum in the test structure.

The results in Fig. 5 show that only the wafer worked, where both the aluminum and the aluminum-nitride were deposited on a low temperature. If the deposition temperature of the AlN is higher, the stress between the aluminum and aluminum-nitride layer can create aluminum hillocks, and that's why the MINOX test structures break down immediately. If the aluminum is deposited on higher (in our case of 350 °C) temperature, it has a more rough surface, which also makes the formation of the hillocks easier.

C. Suppressing hillocks with TiN

To extend the maximum deposition temperature of the aluminum-nitride the formation of hillocks has to be inhibited. With deposition of titan-nitride on the top of the bottom aluminum layer this problem can be solved. Four wafers with the same structure were used for this experiment, so silicon wafer with 100 nm thermal oxide grown on it, 0.5 μm Al/Si(1%) and 100 nm TiN, 0.8 μm AlN and 675 nm Al/Si(1%). The deposition temperature of the two aluminum layers and the TiN layer was 50 °C. The deposition temperature of the AlN and the heater pulse power of the target was varied: 300 °C or 400 °C, and 2 kW or 4 kW, respectively (Fig. 6).

Deposition temperature	Target heating pulse power	
	2 kW	4 kW
300 °C	insulating	all leaky
400 °C	all leaky	all leaky

Fig. 6. Results of charge-to-breakdown measurements varying the deposition temperature and the heater pulse power.

The upper temperature limit by deposition of AlN for resulting an insulating AlN layer is 300 °C using a TiN hillock-prevention layer. At that deposition temperature a maximum 2 kW heating pulse can be applied.

IV. ETCH RATES

Also the etch rate of the aluminum-nitride with wet and dry etching methods was tested. The wet etching methods were the previously standardly used ones, such as 0.55% HF, BHF 1:7 and Al₂O₃ etch solutions, the latter contains CrO₃ and H₃PO₄. The dry etching was performed in the Omega Trikon Technologies Inc. plasma etcher, with a mixture of gases Cl₂ and Br₂ with a flow rate of 30 sccm and 40 sccm, respectively. The results can be seen in Fig. 7.

Etchant	Etch rates [nm/min]			
	AlN@25C	thermal SiO ₂	TEOS SiO ₂	Si ₃ N ₄
0.55% HF	5.6	2.75	18	~0
BHF 1:7	13.5	80	360	0.82
Al ₂ O ₃ etch	60	0	0	4.18
Cl ₂ /Br ₂ dry	188	65	65	-

Fig. 7. The etch rates of the aluminum-nitride and the most commonly used masking and structural materials in standardly used dry and wet etching processes.

Among the wet etching methods the Al₂O₃-etchant solution has the highest etch rate and also the selectivity is excellent. Although the selectivity of the currently shown Cl₂/Br₂ dry etching method is not that good as the Al₂O₃-etchants, if there's a need for going down with the dimensions under 2 μm, dry etching has to be used. Not only the underetching in the wet etching process limits the minimum size achievable with the wet etching, but also the adhesion of the resist to the aluminum-nitride is not so good which causes an additional extra overetching during wet etching. It has to be mentioned that to use the AlN to form structures with the desired minimum size either a better uniformity of the AlN layer has to be achieved or an etching process with much better selectivity has to be found.

V. CONCLUSION

In general the several advantages of the aluminum-nitride – from the process, safety and material properties point of view – make it a low cost solution for integration as a high κ material in silicon IC processes. The pure AlN layers deposited at lower temperatures (20-50 °C) are already applicable with a minimum thickness of 0.8 μm for the sufficient electrical isolation, and with an additional outgassing step for lowering the stress inside the material. For depositions at higher temperatures the upper limit is 300 °C applying a hillock-prevention titan-nitride layer. Although a standard wet etch solution has been already found with an excellent selectivity, to be able to go down with the minimum size either the uniformity of the AlN layer has to be improved, or an etching plasma composition has to be found with much higher selectivity.

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