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Cleaning effect on surface activated aluminum to aluminum wafer bonding

Sebastian Schulze[a], Thomas Voß[a], Patrick Krüger[a], Rasuole Lukose[a], Philipp Kulse[a], Matthias Wietstruck[a]
[a]IHP – Leibniz Institut für innovative Mikroelektronik, Im Technologiepark 25, 15230 Frankfurt (Oder), Germany
schulze@ihp-microelectronics.com

Abstract

This work presents a surface activated aluminum to aluminum (Al-Al) wafer bonding process and the effect of different cleaning chemistries used after dry etching on the later bonding quality. Different cleaning procedures based on ammonium fluoride (NH_4F) and a hydroxylamine (NH_2OH) were investigated. The bonding quality was evaluated using C-mode scanning acoustic microscopy (C-SAM) and the results were correlated to the surface properties of the aluminum investigated with atomic force microscopy (AFM), scanning electron microscopy (SEM) and X-ray photoelectron spectroscopy (XPS). We show that the best bonding quality is obtained using a 20 min NH_2OH-based clean. It efficiently removes etch residues without significantly affecting the surface properties of aluminum.

1 Introduction

Al-Al wafer level bonding is a very promising technique for 3D heterogeneous integration. However, a major drawback is the fast oxidation of the Al surface in air. The stable oxide layer acts as a barrier and inhibits the diffusion of Al atoms across the bonding interface [1]. This can be avoided by using a ComBond high vacuum system. Here, the aluminum surface is treated with an Ar plasma, which first removes the oxide and then the wafers are bonded in a high vacuum atmosphere to prevent reoxidation. Still, the bonding result depends heavily on the condition of the aluminum surface. This study investigates the effects of different cleaning methods on the aluminum surface and the subsequent bonding result. The roughness and contamination of the aluminum surface were measured using atomic force microscopy (AFM) and X-ray photoelectron spectroscopy (XPS), respectively. We then correlated these measurements directly with the bonding quality, which was investigated using C-mode scanning acoustic microscopy (C-SAM).

2 Experimental

2.1 Wafer fabrication and cleaning

The top and bottom wafers for Al-Al bonding were prepared as described below. The top wafer contained a non-patterned 1000 nm Al layer (99.5% Al, 0.5% Cu), which was sputtered on a 25nm Ti/ 55nm TiN barrier on top of 600nm SiO_2. The bottom wafer contained the same layer sequence. But the Al layer and the Ti/TiN barrier were additionally patterned using reactive ion etching. The remaining resist was stripped and subsequently the bottom wafer was exposed to different wet cleaning. We investigated NOE cleaning, ACT®935 cleaning of varying lengths, and compared the results with uncleaned wafers. NOE cleaning uses a mixture of ammonium fluoride (NH_4F) and ethylene glycol ($C_2H_6O_2$). It is performed at a temperature of 35 °C for 2:20 min. ACT®935 cleaning uses a mixture of hydroxylamine (NH_2OH) and isopropanol (C_3H_8O). Cleaning is performed at 80°C, and we investigated two different durations: 20 and 40 minutes.

2.2 Surface activated wafer bonding

The surface activated bonding process was carried out in an EVG® ComBond® system using a high vacuum handling cluster with several modules. First, both wafers were transferred to the ComBond® activation module, where a dry etch process removes the oxide and potential contaminants on the Al bonding pads. The pretreatment was performed in an Ar plasma for 3:30 min with a beam current of 100 mA and a voltage of 200 V. The wafers were tilted 15° and rotated with 70 rpm. Without breaking the vacuum to avoid a reoxidation, the wafers were handled to the vacuum alignment module, where the flipped top wafer and the bottom wafer were brought into contact. The wafer stack was then transferred to the bonding chamber where the thermocompression bonding was performed for 1h at 300°C with a force of 60kN.

3 Results

Fig. 1 shows the C-SAM mappings of the bonded wafers using different cleaning methods. In case no cleaning was applied after the resist stripping the C-SAM image reveals several weakly bonded areas (bright areas in fig. 1a). The use of a NOE clean significantly reduces the unbonded regions, though it does not eliminate them entirely (fig. 1b). The best result was obtained with a 20-minute ACT clean (fig. 1c). The few remaining defects in the center of the wafer originate from particles. The two unbonded areas directly at the edge of the wafer are due to the construction of the bottom heater in the bonding chamber. This can be avoided by rotating the wafer by 90 degrees after half of the bonding time. Increasing the ACT®935 process time to 40 minutes does not improve the bonding quality any further (fig. 1c). On the contrary, the C-SAM image reveals larger areas of defects, located in a ring structure close to the wafer edge.
We believe that the large amount of unbonded area for the wafers without additional cleaning is due to residues left

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after the dry etching process, which are visible in the AFM image (fig. 2a). According to the F1s and Al2p XPS spectra shown in fig. 3, these residues are highly oxidized and may contain small amounts of fluorine. During the NOE clean the ammonium fluoride dissolves the native aluminum oxide layer [2] and removes the residues after dry etching process. The AFM measurement (fig. 2b) shows that the average surface roughness (R_a) has increased slightly to 5.1 nm, while the maximum peak-to-valley height (R_z) remains relatively high at 45.8 nm. The SEM image (fig. 2d) of the wafer processed in NOE shows small pits probably created during the cleaning process, leading to a high R_z value and bonding defects. The Al2p XPS spectra in fig. 3b shows a decrease in the intensity of the peak attributed to aluminum oxides. Additionally, a high F1s intensity was detected at a binding energy of 686.4 eV (fig. 3a), which can be assigned to an AlF_3H_2O compound on the surface [3]. After a 20-minute ACT®935 cleaning, the XPS spectra indicate a reduced fluorine concentration and a stronger oxidation of the Al surface. Apparently, this stronger oxidation has no negative impact on the subsequent bonding as the oxide layer is removed during the Ar sputter clean in the high vacuum bonder. The AFM measurement (fig. 2c) shows an average surface roughness (R_a) of 4.6 nm and the lowest R_z value (34.2 nm) compared to the other cleaning variants, which might explain the better bonding quality. A longer ACT clean of 40 min leads to a R_a of 4.1 nm and increases R_z to 51.6 nm (fig. 2d). This might be the reason for the decreased bonding quality.

In summary, we showed that the clean after resist stripping strongly affects the later bonding quality. The best bonding results were obtained after ACT®935 cleaning for 20 minutes, which effectively removes the residues without evident effect on the surface properties of the aluminum.

3.1 Images

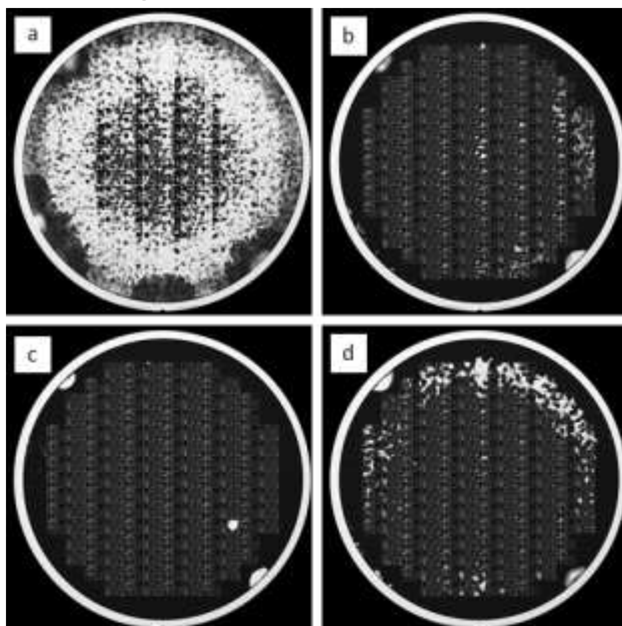

Figure 1 C-SAM images of Al-Al bonded wafers with different cleanings after dry etching: a) no cleaning, b) NOE c) ACT®935 20 min, d) ACT®935 40 min.

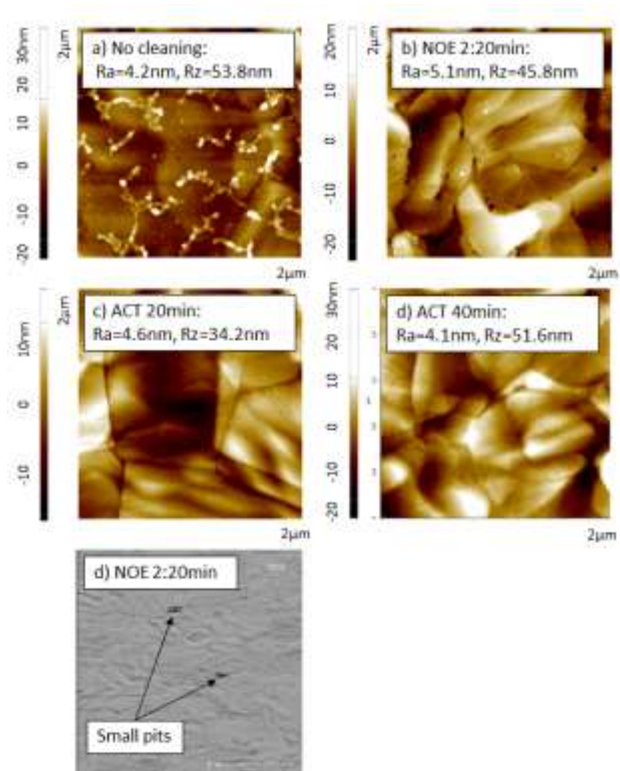

Figure 2 AFM images of wafers with different cleanings after dry etching: a) no cleaning, b) NOE c) ACT®935 20 min, d) ACT®935 40 min, d) SEM image of NOE cleaned wafer.

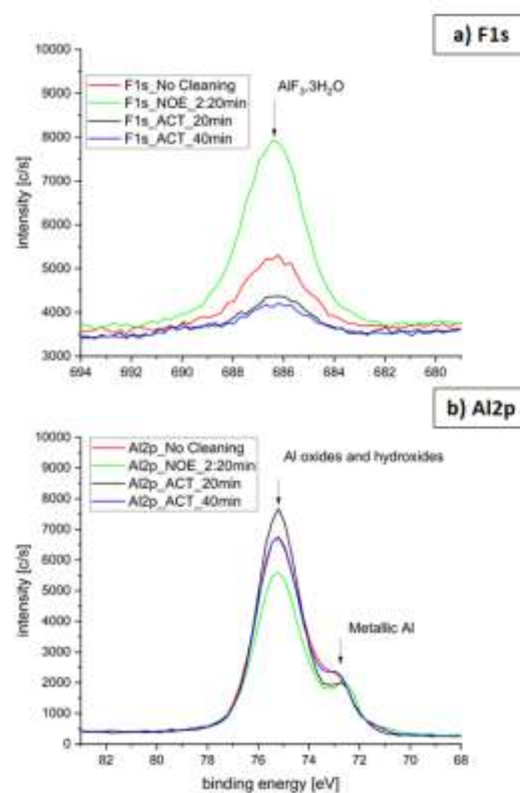

Figure 3 F1s (a) and Al2p (b) XPS spectra of wafers with different cleanings after dry etching.

4 Literature

[1] A.P. Hinterreiter, B. Rebhan, C. Flötgen, V. Dragoi and K. Hingerl, “Surface pretreated low-temperature aluminum–aluminum wafer bonding”. Microsyst Technol vol. 24, pp. 773–777, 2018

[2] M.K. Carter, R. Small, M. Cernat and B. Hansen, “Effects of Amine Fluoride Cleaning Chemistry on Metallic Aluminum Integrated Circuit Films: I. Experimental Measurements and Chemical Modeling.” Journal of the Electrochemical Society, 150(2), B52, 2003

[3] A. Limcharoen, C. Pakpum, and P. Limsuwan. "An X-ray photoelectron spectroscopy investigation of redeposition from fluorine-based plasma etch on magnetic recording slider head substrate." Procedia Engineering 32, pp. 1043-1049, 2012