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Argon plasma treatment on Cu surface for Cu bonding in 3D integration and their characteristics

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ABSTRACT

3D integration enhances RC delay mitigation, improves inter-die bandwidth, and has routing advantages for the next generation integrated circuit technology. To realize the advantages of 3D integration, metallic bonding between different dies or wafers is necessary. So, Cu-to-Cu metallic bonding is, without doubt, a key process needed for 3D integration. In this study, Ar plasma treatment on the Cu surface for Cu thermo-compression bonding temperature less than 400 °C was investigated. Ar plasma treatment on the Cu thin film was performed using a conventional DC sputtering technique. The effect of Cu surface modified by Ar plasma was studied for Cu-to-Cu bonding. Also, the influence of Ar plasma treatment on the Cu surface was evaluated structurally and electrically.

1. Introduction

3D integration technology enhances RC delay mitigation, improves inter-die bandwidth, and has routing advantages, in addition to reducing form factors and manufacturing costs. The RC delay reduction from 3D integration has been reported in detail elsewhere [1–3]. According to List et al. [3], 3D integration reduces the global interconnect RC delay problem between 30% and 75%. The RC delay of semi-global and global interconnects in 3D integration has become a key factor in controlling the device performance. To fabricate the 3D integration system, one of the required processes is bonding between different dies or wafers. Among various bonding methods Cu-to-Cu metallic bonding is a key process that needs to be developed, especially for its high density and performance. Many studies on the Cu-to-Cu bonding process have been reported so far [4–8,22]. The advantages of Cu as a bonding material are its mainstream CMOS material, low resistivity, high thermal conductivity, good resistance to electromigration (EM), and no brittle intermetallic compound (IMC) formation. However, one limitation of Cu-to-Cu bonding is its relatively high bonding temperature above 400 °C to achieve a good diffusion bonded interface. This high temperature bonding process is not suitable for conventional integrated circuit (IC) fabrication. Recently, to lower the Cu-to-Cu bonding temperature, room temperature surface activated bonding (SAB) was reported for wafer level 3D integration. The SAB method utilizes plasma irradiation of bonding surface to remove all contaminations prior to Cu-to-Cu bonding [9,10]. However, SAB requires nano-scaled surface roughness and needs a well-controlled atomic level interaction, which is not suitable for high volume manufacturing. Another bonding method called self-assembled monolayer (SAM) bonding technique was studied with a temporary layer to remove contaminations and prevent Cu oxidation while lowering the bonding temperature to 300–350 °C [11]. The main challenge of SAM is currently to decompose temporary coating material without outgassing prior to bonding. Among the few Cu-to-Cu bonding techniques, thermo-compression bonding is suitable for high volume manufacturing if the bonding temperature is reduced to less than 350 °C. One objective in this study is to investigate a potentiality of Cu-to-Cu thermo-compression bonding at lower than 350 °C using surface plasma treatment prior to bonding process for 3D integration.

Plasma treatment for surface modifications has been used in various applications to produce new functionalities generated on the surfaces of metals, glasses or polymers. The metal surfaces

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modified by plasma have many applications in the field of automobiles, printed circuit board manufacturing, and electromagnetic interference shielding materials [12]. Metal surface modification by plasma on polycrystalline Cu has created a lot of interest to form ordered nanostructures [13–15]. The nanostructure formation by plasma treatment has been investigated intensively [16], but the majority of studies focused on patterning the surfaces of bulk materials and few studies have been reported on thin metal films [13,15]. The microstructure such as the distribution of grains and grain orientation in polycrystalline thin films generally affects the properties, performance, and reliability of thin films [17].

In this study, the effects of Ar plasma on the Cu surface and the effect of Cu surface modified by plasma on Cu-to-Cu bonding were studied. The surface modification of Cu thin film was performed using a conventional DC sputtering technique, which is a very simple and highly cost-efficient method to generate surface modification of Cu thin film. The surface characteristics of Cu thin film modified by plasma were analyzed structurally and electrically. The effects of plasma treatment conditions (pressure, power, and plasma treatment time) on each response such as grain size, roughness, contact angle, and sheet resistance of the Cu surface were investigated. Also, the feasibility of low temperature Cu-to-Cu bonding process was studied for 3D integration.

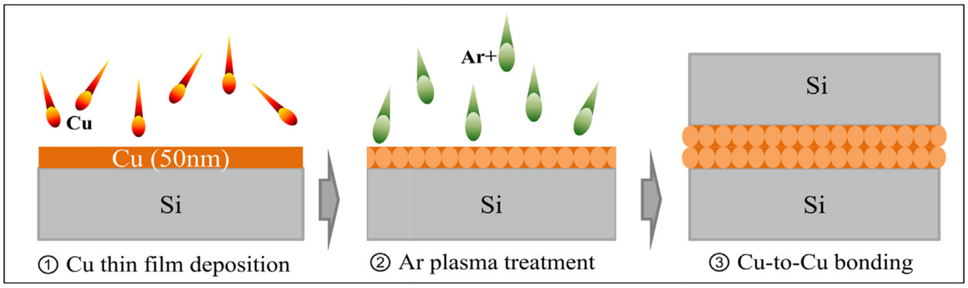
2. Experimental procedure

Ar plasma treatment on the Cu surface prior to Cu-to-Cu bonding was evaluated in this study. The brief process flow of sample preparation is schematically illustrated in Fig. 1(a). The sputtered Cu thin film was deposited on a 150 mm Si wafer, and the sputtering conditions for Cu deposition are shown in Table 1. After depositing the Cu thin film, the Si wafer was cut into many samples 2 cm × 2 cm in size. These samples were exposed to various Ar plasma conditions, which was done by a conventional DC sputtering technique. The plasma chamber configuration is shown in Fig. 1(b). The Ar plasma conditions are tabulated in Table 2. The Ar plasma power was varied from 50 W to 150 W, the pressure was varied from 0.67 Pa to 3.33 Pa, and lastly the plasma treatment time was varied from 60 s to 300 s. The Cu-to-Cu thermo-compression bonding was performed at 300 °C under 2 MPa for 1 h right after the Ar plasma treatment. Cu-to-Cu bonding interfaces were analyzed by FIB (focused ion beam, FEI Nova 600 NanoLab) and SAM (scanning acoustic microscope (HITACHI FineSAT FS200III) measurements. SAM that operates in a reflection mode was used to examine the Cu-to-Cu bonding interface.

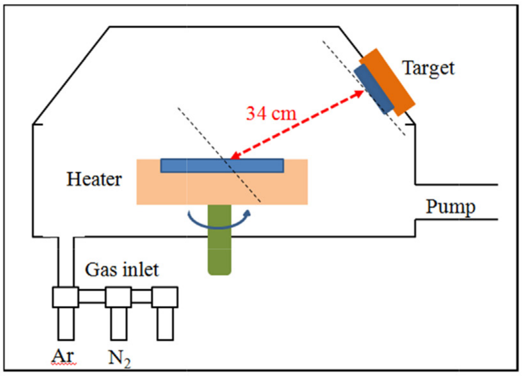
Table 1
Cu thin film deposition conditions by DC sputtering.

Deposition conditions	Value
Ar flow	80 sccm
Pressure	5 mTorr
DC power	2.5 kW
TS distance	34 cm
Substrate rotation speed	40 rpm
Deposition rate	18.5 Å/s

This experiment was performed based on the design of experiment (DOE) using a full factorial method. The DOE plan was set up with three factors (pressure, rf power, and plasma treatment time) that may alter the Cu surface, and consequently, the Cu bonding quality. The DOE setup conditions are tabulated in Table 2. The grain size, roughness, contact angle, and sheet resistance of Cu surface were measured as the responses for DOE outputs. The order of influencing factors on each response was mainly analyzed. The influencing factors may be either a single factor or confounding factors of two or more. The grain size was estimated through XRD (X-ray diffraction, Rigaku Dmax2500/PC) measurements. The XRD used a Cu Kα source in the rotating anode system with an 18 kW generator. In addition, the chemical analysis of XPS (X-ray photoelectron spectrometer, Thermo Fisher K-Alpha) measurements was done using a hemispherical analyzer (high resolution of 0.45 eV)



(a) Schematics of process flow



(b) Sputtering chamber used for Cu deposition and plasma treatment

Fig. 1. (a) Schematics of process flow and (b) sputtering chamber used for plasma treatment.