DIFFUSION CHARACTERISTICS OF COPPER-SILICON IN CONNECTION

Mamirov Abduvoxid Muxammadamin o'g'li
Andijan machine-building institute

Abstract

The replacement of Au and Al wires with Cu wires in wire bonding has become an emerging trend in IC packaging nowadays. Although some research works have been carried out for the applications of Cu wire bonding, they are mainly focused on the processing and material issues of Cu wire bonds. However, the Cu in the wire bonds may diffuse into the Si chip and impose reliability threats to the silicon devices. There is no study yet on the Cu-to-Si diffusion in Cu wire bonding. In the present study, Cu-to-Si diffusion in the wire bond is studied in real diode devices. The effect of Cu source supply and Al pad deformation on Cu-to-Si diffusion is investigated with the aid of lab made multilayer structure.

Key words: Interconnection materials, Cu-to-Si diffusion, Au-to-Si diffusion, TiW barrier, thermal annealing, hydrogen peroxide, ion intensity.

Introduction

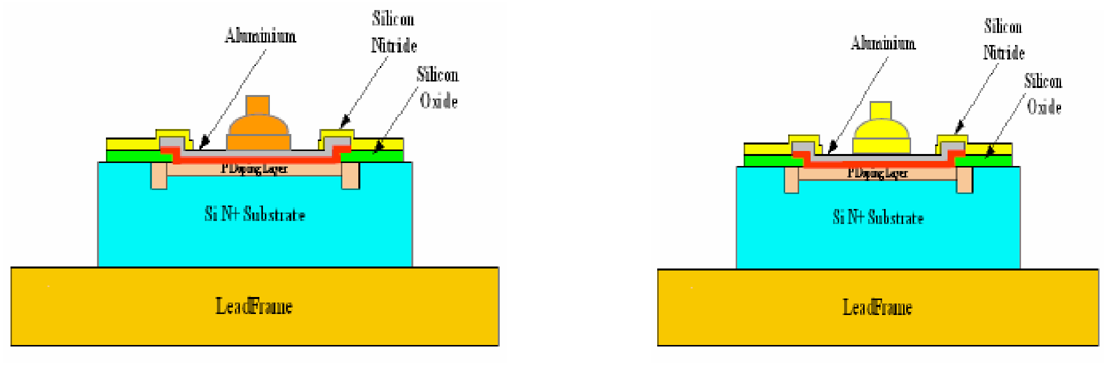
The conventional wire bonding has employed Au and Al wires as interconnection materials for decades. With the requirements for high speed, high power and fine pitch applications, Cu is emerging as the alternative bonding wires to replace Au and Al [1]. In principle, Cu has relatively good electrical, mechanical and thermal properties [2]. However, Cu is known as a fast diffuser in silicon [3, 4]. The diffusivity of Cu in Si is much larger than that of Au and Al [5, 6]. The Cu from the Cu bonding wires may diffuse through the bonding pads to the underlying silicon chip and cause the breakdown of IC devices [7]. Therefore, in order to understand the long term reliability impact of Cu wire bonding, it is necessary to investigate the Cu-to-Si diffusion. In the present investigation, three sets of samples are fabricated for parallel study. One set is ind.-made actual diode devices with wire bonding on aluminum pads. One set is ideal lab-made samples with thin film deposition on silicon substrates. Another set is ind.-lab-made samples with labmade bonding pads and ind.-made bonding wires. The effect of Cu source supply and Al pad deformation on Cu-to-Si diffusion is investigated. Different Cu source supply is provided by the Cu layer with different thickness. Al pad deformation is induced by the thermosonic ball bonding process. To study the effect of barrier layer, a thin film of TiW is deposited between the Al bond pad and the Si substrate to prevent the wire bond materials from diffusing into silicon. The difference between Cu-to-Si diffusion and Au-to-Si diffusion is investigated by Cu and Au wire bonding. The fabricated samples are vacuum-sealed and thermal depth profiles is implemented by D-SIMS (dynamic secondary ion mass spectrometry) for Cu samples and ToFSIMS (time-of-flight secondary ion mass spectrometry) for Au samples.

Experimental Procedures

In order to study the effect of Cu source supply and Al pad deformation on Cu-to-Si diffusion, three sets of samples with different fabrication processes are prepared. One set is the ind.-made actual diode devices with Cu wire thermosonic bonding to Al pad. One set is ind.-lab-made samples with labmade bonding pads and ind.-made bonding wires. Au wire bond samples are also fabricated for comparison purpose. Another set is lab-made samples with multilayer films deposited on Si substrate. Cu film with different thickness is deposited as the different Cu source supply. Because the bonded Cu wires in the ind.-made samples and ind.-lab-made samples are replaced by the deposited Cu film in the lab-made samples, there should be no Al pad layer deformation in the lab-made samples. Furthermore, additional 0.2 μm TiW barrier layer is added between the Al pad and Si substrate for

above three sets of samples to prevent Cu-to-Si diffusion. Fig. 1 is the diagrams of ind.-made Cu and Au samples with TiW barrier layer. The diameter of Cu and Au wire is 23 μm and the Al pad layer thickness is 1.4 μm. Fig. 2 is the diagrams ofn ind.-lab-made Cu and Au samples with TiW barrier layer. Fig.3 is the diagrams of lab-made Cu samples with TiW barrier layer. Different Cu layer thickness of 0.4 μm and 10 μm are prepared to study the effect of Cu source difference to Cu-to-Si diffusion. The diagrams of the samples without TiW barrier layer are not shown here. The above prepared samples are then thermal annealed at 300oC for 1.5 hrs, 3.0 hrs and 4.5 hrs for short term aging and 175^{o}C for 200 hrs, 300 hrs and 400 hrs for long term aging. Glass sealing of the samples is carried out with vacuum of 3.0×10^{-2} mbar before thermal annealing to prevent sample oxidation.

The annealed samples are then etched by aqua regia (3HCl:HNO3) to remove the wire bonds, Al pads for indmade and indlamade samples and Cu film, Al pads for labmade samples. TiW barrier layer is dissolved by hydrogen peroxide (H_2O_2) for samples with TiW. The Si substrate is then exposed for the subsequent Cu-to-Si diffusion testing. SIMS depth profiling is implemented to analyze Cu and Au diffusion in Si substrate. D-SIMS measurements are performed for Cu profiling using a Cameca IMS 4F spectrometer with oxygen source. ToF-SIMS measurements are performed for Au profiling using a Physical Electronics PHI 7200 spectrometer with Cs source.



(a) (b)

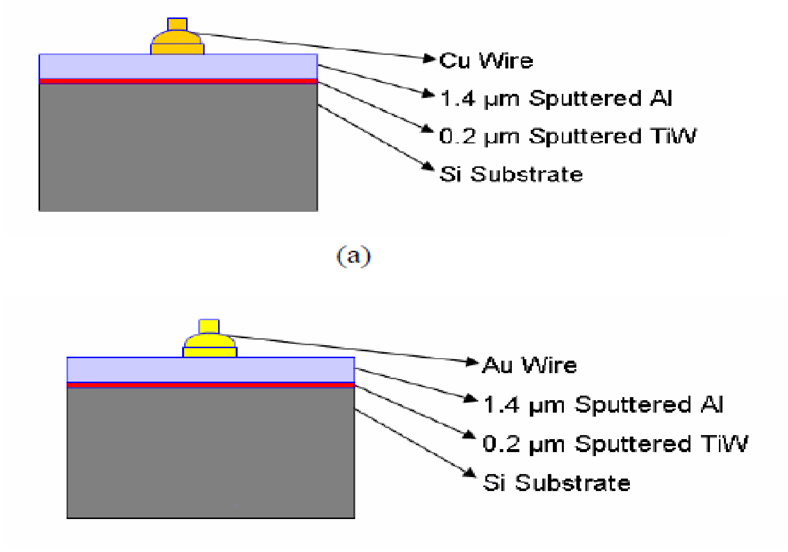
Figure 1. Ind.made Sample (a) Cu Wire Bond Sample with TiW, (b) Au Wire Bond Sample with TiW

Results and Discussion

Effect of Cu Source Supply on Cu-to-Si Diffusion

To study the effect of Cu source supply, Cu layers with different thickness were sputtered in the lab-made samples as shown in Fig. 3 [8, 9]. The samples without TiW barrier layer are adopted. After thermal annealing and removal of the metal bonds and layers, SIMS depth profiling is performed., the Cu diffusion profiles in Si at different annealing conditions are plotted in the same chart for comparison purpose. The origin of x-axis represents the Si surface and the inner part represents the Si bulk. During SIMS analyzing, there is surface effect region as indicated by the dashed black line within the depth of about 20 nm. Because there usually is native oxide and C contamination present on the sample surface, and also there is a stabilization process for the SIMS primary species in the sample to reach equilibrium, the acquired SIMS signal within this region will consist of the surface effect [10]. We will not compare and explain the SIMS profiles at the surface part.

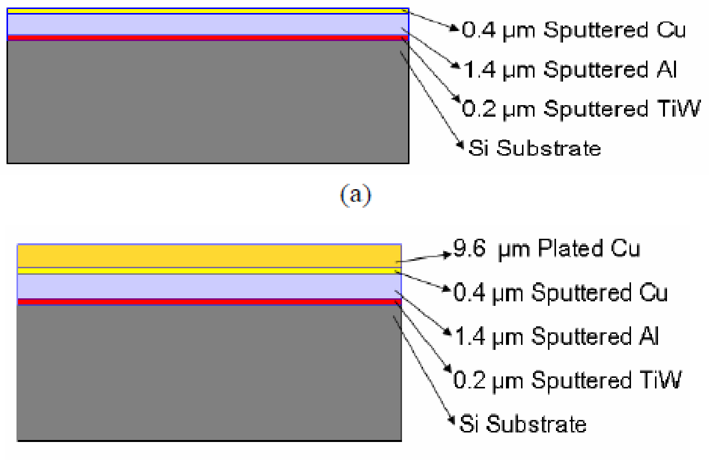
For D-SIMS analysis, the original SIMS Cu profiles with secondary ion intensity (c/s) of y-axis are converted to the real Cu concentration in Si represented by atom density (atoms/cm^3). This conversion is based on the calibration of the SIMS instrument with ion implanted Cu standard. As seen from the Cu SIMS profiles, Cu concentration decrease at the beginning and then reach a certain stable level with fluctuation of Cu SIMS signal where it is beyond the SIMS detection limit of around 5×10^{16} atoms/cm^3. The Cu diffusion depth in the SIMS depth profiles is defined as the depth where the Cu profile firstly meet the base line which is drawn from the mean value of the stabilization part of the Cu SIMS profile. As seen in the SIMS plots, the base line for each Cu profile has been drawn to determine the Cu diffusion depth. There is a small variance of base line levels for different samples and it is due to the SIMS sensitivity difference to different samples. The vertical colored dashed lines are drawn to indicate the Cu diffusion depth for different thermal annealed samples.



(a)

(b)

Figure 2. Ind.-Lab-made Sample with Deposited Multilayer (a) Cu Wire Bond Sample with TiW, (b) Au Wire Bond Sample with TiW



(a)

(b)

Figure 3. Lab-made Sample with Deposited Multilayer(a) Thin Cu Layer Sample with TiW,
(b) Thick Cu Layer Sample with TiW

For room temperature (RT) samples without thermal annealing), there is a surface peak in the Cu profiles which falls in the surface effect region. The samples without deposited Cu layer or bonded Cu studs have also been analyzed by SIMS and the results show the similar Cu surface peak in the Cu profiles. Because the surface effects can cause a surface peak for many species, if the intersection of Cu profile with base line falls in the surface effect region, it will be regarded no diffusion of Cu in Si.

Effect of Al Pad Deformation on Cu-to-Si Diffusion

The multilayer metal films are deposited by sputtering for the lab-made samples, it is assumed there is no Al layer deformation for the lab-made samples. However, for the ind.-made samples and ind.-lab-made samples, the Cu wires are thermosonic bonded to the Al pad. During the wire bonding process, the applied bonding pressure and the ultrasonic vibration will induce non-uniform deformation of the Al pad layer.

Cu diffuses greater in ind.made samples and ind.-lab-made samples compared with the lab-made samples.[11-14] This indicates the Al pad deformation will promote the Cu-to-Si diffusion. The thinner area of the deformed Al pad layer will serve as the fast diffusion path for Cu diffusion, which has shorten the time for Cu to diffuse through the Al layer to reach Si. However, this is not the case for the lab-made Cu samples with uniform Al layer. The base lines of the Cu diffusion profiles in are not shown for the concision. The diffusion depth versus annealing time for different Cu samples is plotted in and the slope and annealing time for Cu diffuses to Si are listed in. It is shown that there is similar Cu diffusion rate for different Cu samples. However, longer time is consumed for Cu to reach Si for the lab-made Cu samples compared with the ind.-made and ind.-lab-made Cu samples. This verifies the effect of Al pad deformation to Cu-to-Si diffusion[15-18]. The main difference between the ind.made and ind.-lab-made samples is the quality of Al pad layer. The Al layer of ind.lab.made samples is harder than the ind.made samples, which will lead to smaller Al pad deformation and hence less Cu-to-Si diffusion.

Conclusions

In this paper, Cu-to-Si diffusion in the wire bond is studied. The effect of Cu source supply and Al pad deformation on Cu-to-Si diffusion is investigated. The TiW barrier layer is added to study the barrier layer effect. Au wire bond samples are also adopted for parallel comparison with

Cu wire bond samples. The following phenomena have been observed from the experimental results.

1) The amount of Cu supply may affect the diffusion rate. In this study, more Cu-to-Si diffusion is found for thicker Cu layer samples.

2) The smearing of Al pad may promote the diffusion of Cu into Si. With the Al pad deformation, fast diffusion path is provided for Cu diffusion and lead to more Cu-to-Si diffusion.

3) The Cu-to-Si diffusion is much faster than the Au-to-Si diffusion both for the samples with TiW and without TiW.

4) With the TiW barrier layer addition, Cu-to-Si and Au-to- Si diffusion have been effectively suppressed.

This should be ascribed to the different Al pad deformation and different Al layer quality. With the optimization of Cu bonding process and appropriate selection of pad layer structure, the devices with Cu wire bonding should behave better performance and reliability than,Au wire bonding.

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