 Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp415-416

Copper-Ruthenium System Study for Advanced Hybrid BEOL -Interconnects Applications

Nicolas Jourdan, Maxim Korytov, Sven Van Elshocht, Zsolt Tőkei

imec
Kapeldreef 75, 3001 Leuven, Belgium
Phone: +32-16-28-1709 E-mail: nicolas.jourdan@imec.be

Abstract

The Cu-Ru system is studied at blanket level for advanced hybrid BEOL-interconnects applications. It is found that Cu layer can be formed on top of Ru film with sharp interface, without interdiffusion/intermixing and defect-free, even after 420ºC forming gas anneal. In contrast, Ru layer formation on top of Cu film leads to rough surface, large voids in the Cu layer and Cu-diffusion into Ru film. Depending on the Ru deposition process used, the phenomenon occurs at different thermal budget. Among, PVD-Ru, CVD-Ru and ALD-Ru studied in this work, only PVD-Ru on Cu layer was found to be BEOL-interconnect thermal budget (~400ºC) compatible.

1. Introduction

In advanced Integrated Circuits (ICs), the Backend of Line (BEOL) interconnects will require the use of a hybrid metallization scheme in order to meet void-free gap-fill, via/line-resistance and reliability specifications. The hybrid interconnections can consist of the well-known copper (Cu) and one of the most studied barrierless alternative metal, ruthenium (Ru). While Cu is used at upper metal levels, Ru could be used for the most aggressively scaled features (ie. small CD, high aspect ratio). Depending on the application, either Ru needs to land on Cu (eg. Supervia-Ru landing on Mx-Cu) or Cu landing on Ru (eg. Mx+1-Cu on Mx-Ru). Regarding the stack sequence (Cu/Ru vs. Ru/Cu) and the process used, interaction between Cu and Ru can vary greatly. In this work, we investigate the compatibility of Cu-Ru system at blanket level using different Ru deposition processes (PVD, CVD and ALD) in combination with a PVD-Cu/ECD-Cu stack.

2. Experimental

Two types of stacks were deposited on 300 mm Si (100) wafers coated by 100nm of SiO2: 1/ Cu on Ru and 2/ Ru on Cu. 30nm thick Ru layers were formed either by PVD at room temperature using an Ar-plasma, CVD-Ru using an organometallic (OM) precursor with H2 as co-reactant at 250ºC, or ALD-Ru using an OM-precursor with O2 as co-reactant at 325ºC. The 60nm thick Cu film consisted of PVD-Cu-seed and electro-plated Cu (ECD-Cu) stack. Subsequently, the wafers were annealed in forming gas (FG) for 20 minutes in the range of 420ºC to 650ºC. The interaction between Cu and Ru was then studied in detail by TEM, STEM and EDS techniques.

3. Cu on Ru

In the BEOL-interconnection flow, Cu never lands directly on Ru as diffusion barrier such as a thin TaN is required. Nonetheless, we also have studied direct contact of Cu with Ru (-ALD) for fundamental understanding of the Cu-Ru interaction. Additionally, the Cu-layer was capped with PVD-TaN in order to prevent Cu-oxidation and agglomeration during heat treatment. Figure 1 shows cross-sectional TEM images and EDS chemical maps of Cu/Ru stacks (in direct contact), as-deposited [1a], after a 420ºC/20min/FG-anneal [1b] and Cu/TaN/Ru stack (interfacial 3nm-TaN) after a 420ºC/20min/FG-anneal [1c].

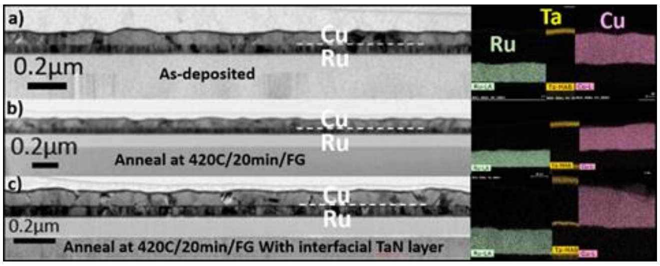

Fig. 1 cross-sectional TEM images and EDS chemical maps of Cu/Ru stacks (in direct contact), as-deposited (a), after a 420ºC/20min/FG-anneal (b) and Cu/TaN/Ru (interfacial 3nm-TaN) after a 420ºC/20min/FG-anneal (c).

For all three samples, no voids, sharp interfaces are observed (figure 1). Furthermore, neither diffusion nor material intermixing were detected as demonstrated by corresponding EDS chemical profiles (figure 2).

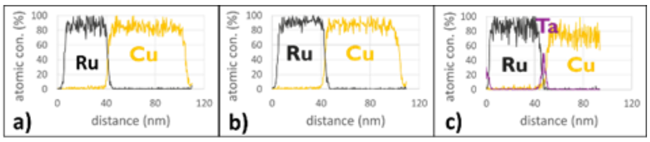

Fig. 2 EDS chemical profiles of Cu/Ru stacks (in direct contact), as-deposited (a), after a 420ºC/20min/FG-anneal (b) and Cu/TaN/Ru (interfacial 3nm-TaN) after a 420ºC/20min/FG-anneal (c).

All these observations demonstrate that Cu and Ru are intrinsically compatible and are immiscible, consistent with the bulk diagram phase of the system. As a result, Cu interconnections can be fabricated on top of Ru lower levels in a hybrid BEOL interconnections scheme.

4. Ru on Cu

Figure 3 shows cross-sectional TEM images and EDS chemical maps of as-deposited PVD, CVD, and ALD Ru films on Cu films. In the case of PVD-Ru (fig. 3a), smooth surface, sharp interface and no voids were observed. Furthermore, as demonstrated by the corresponding EDS chemical profile, neither material diffusion nor intermixing was observed (fig.4a). As regards CVD-Ru, Ru-hillocks on the surface are observed without any voids detected in the stack (fig.3b). However, considerable diffusion of Cu into the Ru-layer was detected (fig.4b). Finally, in the case of ALD Ru, the surface was very rough and large voids locally present were visible inside the Cu layer (Fig. 3c), in addition to strong Cu diffusion up to the Ru surface (Fig. 4c).

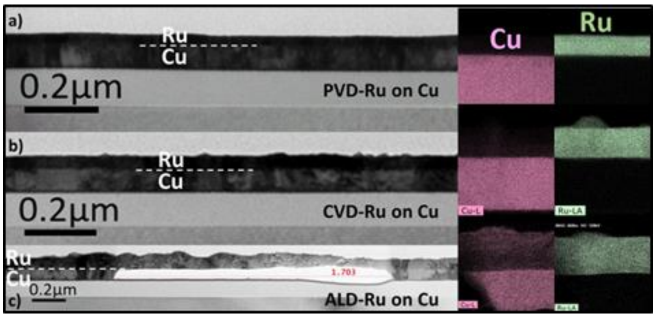

Fig. 3 cross-sectional TEM images and EDS chemical maps of Ru/Cu stacks as deposited. PVD-Ru/Cu (a), CVD-Ru/Cu (b) and ALD-Ru/Cu (c).

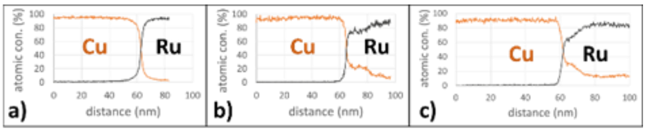

Fig. 4 EDS chemical profiles of Ru/Cu stacks as deposited. PVD-Ru/Cu (a), CVD-Ru/Cu (b) and ALD-Ru/Cu (c).

In figure 5, the same stacks are shown after a 20 minute FG anneal at 420ºC. The integrity of the PVD-Ru-based stack is preserved upon anneal (figs. 5a, 6a).

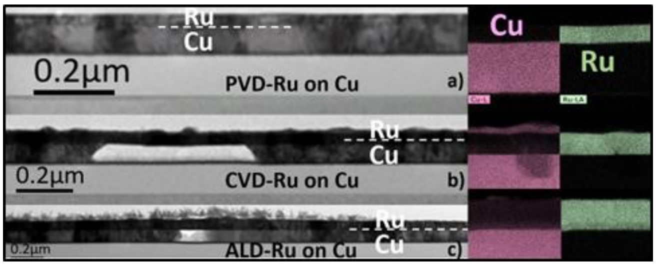

Fig. 5 cross-sectional TEM images and EDS chemical maps of Ru/Cu stacks after 420ºC/20min./FG-anneal. PVD-Ru/Cu (a), CVD-Ru/Cu (b) and ALD-Ru/Cu (c).

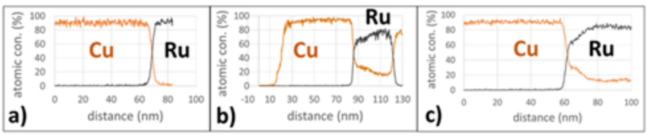

Fig. 6 EDS chemical profiles of Ru/Cu stacks after 420ºC/20min./FG-anneal. PVD-Ru/Cu (a), CVD-Ru/Cu (b) and ALD-Ru/Cu (c).

The ALD-Ru-based stack behaves poorly (figs. 5c, 6c) as in the as-deposited case. Finally, the CVD-Ru-based stack loses its integrity, exhibits large Cu diffusion up to the surface and very large extended voids inside the Cu layer (figs. 5b, 6b). The integrity of the PVD-Ru-based stack was checked at higher temperatures. Figures 7a and 7b show the cross-sectional TEM images of PVD-Ru-based stacks after 20 minutes anneal under forming gas at 520ºC and 650ºC, respectively.

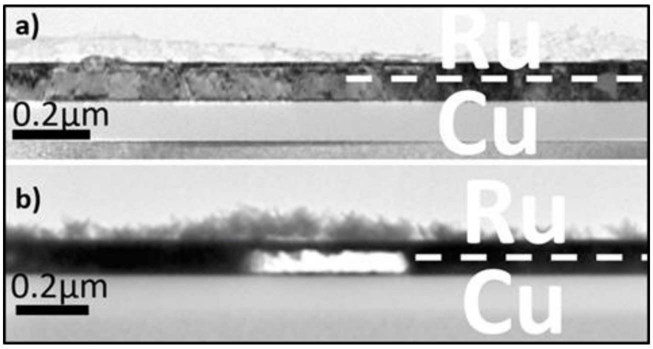

Fig. 7 cross-sectional TEM images of PVD-Ru/Cu stacks after 520ºC/20min/FG-anneal (a) and 650ºC/20min/FG-anneal (b).

As can be clearly seen, the PVD-Ru-based stack shows loss of integrity at 520ºC and complete failure (ie. rough surface, extended voids in the Cu-layer) at 650ºC. As the Cu-Ru system does not have intrinsic incompatibility, as shown in the previous section, the stack integrity failure observed here can only be attributed to the interaction of the Ru deposition process with Cu. Currently, further investigations are ongoing to understand the detailed failure mechanisms. Moreover, the result of this work is in a very good agreement with literature [1] and indicates that the Cu does not only diffuse through bulk-Ru but also through defective sites in the Ru film, leading to localized large voids within the Cu layer. Finally, for a hybrid BEOL-interconnects application, where the thermal budget is limited to about 400ºC, only PVD-Ru is compatible over Cu layer.

5. Conclusions

The Cu-Ru materials interaction is studied at blanket level for advanced hybrid BEOL-interconnects applications. It is found that Cu layers can be formed on Ru without interdiffusion/intermixing, defect-free and with sharp interfaces, even after a 420ºC FGA anneal, applicable to BEOL-interconnections. In contrast, formation of a Ru layer on top of Cu was found to be challenging leading to a very rough surface, large voids in the Cu layer and Cu-diffusion into the Ru layer. However, depending on the Ru deposition process used, the phenomena occurred at different thermal budget. Amongst, PVD-Ru, CVD-Ru and ALD-Ru studied in this work, only PVD-Ru on Cu layer was found to be compatible with a BEOL-interconnect thermal budget of about 400ºC.

References

[1] W. Wei et al. Appl. Phys. Lett. 90, 111906 _2007.