Reduced Metal Spits in E-beam Metal Evaporation via Improved Crucible Liner-Hearth Power Dissipation

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Abstract

In integrated circuit manufacturing, 'Metal spits' is one of the most common metal defects seen in electron beam (e-beam) metal evaporation that leads to compromised visual and electrical yields. Additionally, presence of one such metal defect in a big-area capacitor can disqualify the entire die at the final visual inspection. In this paper, we discuss the importance of regulating the heat dissipation between the gold (Au) crucible liner and the copper (Cu) hearth along with the metal deposition rate, in order to achieve extremely low-level of spits that demand by modern shrinking circuit architectures to achieve reasonable product yields.

INTRODUCTION

Metal spits is a very common defect seen in e-beam metal evaporation in integrated circuit manufacturing, causing tarnished visual and electrical yields[1,2]. These particle defects are often visible on the large metal pads, for example large-area capacitors, which happens to be one of the major die killing defects. Metal spits are generated from inadvertently ejected metal liquid droplets from the molten metal source during the deposition due to non-uniform power (heat) distribution across the melt pool in the crucible. These liquid droplets solidify as particles or nodules in the deposited film, which could significantly affect production yields as they can lead to device malfunction through the breakdown of layered structures[1,2,3,4].

It has been very well understood that Au spits is mainly dependent on source material quality and e-beam evaporation process conditions. Material purity and cleanliness are the two major components belong to material quality[5], out of which cleanliness (carbon content in Au) has been the cynosure among many researchers to understand where this carbon is coming from, what it does in processing and how to prevent from accumulating carbon in the metal source in processing. It has further been studied that trapped carbon in the bulk of Au slugs from carbon-containing lubricant based Au slug fabrication is transformed into a thin carbon film that floats over the top of Au melt pool during deposition[3,4]. This thin carbon film scatters e-beam and reduces the effective area of Au melt for evaporation, resulting an increase in deposition power to compensate for the reduced evaporation area under deposition rate-controlled conditions. The increased deposition power density substantially increases the level of spitting while promoting photoresist patterns to be cross linked, which is a potential risk for metal stringer formation[3]. As high carbon level in the Au source has the same effect as increased power density, process parameters that have an effect on the heat input and heat loss (heat dissipation) between the Au melt source in the crucible liner and Cu hearth have a direct impact on level of spitting. Power input, efficacy of heat transfer, crucible liner material, e-beam sweep pattern, ramp profiles and deposition rates are leading process parameters that have a direct correlation with the degree of deposition power density.

In this paper, we discuss the significance of regulating the heat dissipation between the crucible liner and the Cu hearth and deposition rate in order to achieve extremely low-level of Au and Pt spits. We also reveal that tendency of Au being over flown due to low sticking coefficient and tantalum (Ta) addition to regulate the carbon in the Au melt source cause Au melt to wick out of the crucible liner, resulting a thick layer of metal/carbon/Ta buildup on the side wall of the crucible liner. This excessive material buildup on the liner sidewall subsequently interrupts the optimal heat dissipation during the deposition, resulting non-uniform heat distribution across the Au melt source. When the resultant higher deposition power density exceeds a certain threshold value, Au spitting will commence.

RESULTS AND DISCUSSION

Figure 1a shows an optical microscopic image of a so-called capacitor defect, which was not seen at the gate level but after first nitride and metal one (M1) depositions. As shown in figure 1c, Focused Ion Beam (FIB) and elemental analysis (EDAX) revealed that these capacitor defects were Au and Pt spits. FIB cross sectional analysis further revealed that these spits were originated at the gate metal deposition via electron-beam evaporation. They were not captured at the gate level visual inspection, because the particle size is at the same order as that of diffraction limit of light. It should also be noted that particle defects illustrated in figure 1b are not spits but cluster of particles generated from a random scratch. One of the key signatures of Au/Pt spit is its perfectly defined spherical geometry in contrast to random particles depicted in figure 1b.

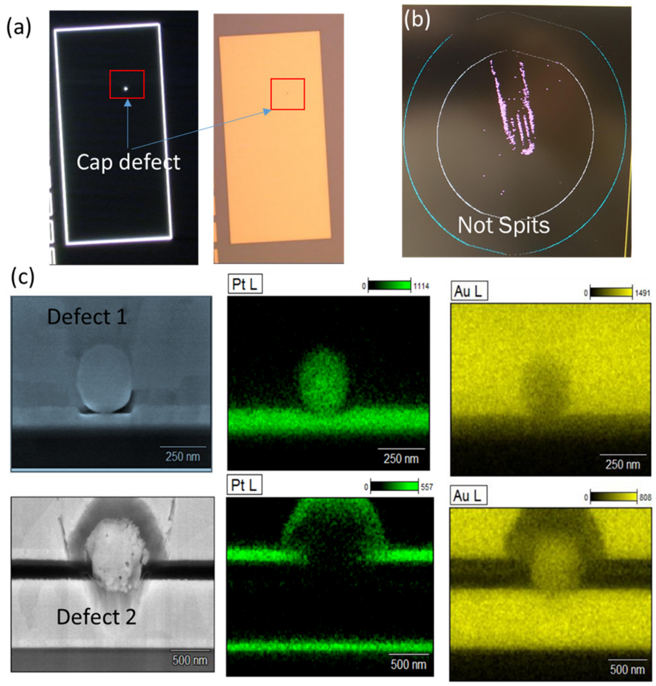

Fig 1. Optical and elemental analysis of particle defects generated during e-beam metal evaporation. (a) Dark and bright field optical images of a capacitor defect. (b) Optical image of a silicon wafer with random non-spit particles. (c) FIB and EDAX analysis of two capacitor defects.

Spitting during Au evaporation is the unintended escape of liquid droplets from the melt pool, which solidify as nodules or particles in the deposited film. These spit particles can significantly affect production yield as they can lead to device malfunction through the breakdown of complex layered metal stacks. Degree of Au spitting is a function of both process conditions and material quality. Material quality is twofold: purity of the Au slugs to make sure volatile elements with higher vapor pressures compared to Au are kept to a minimum and their cleanliness. Cleanliness mainly refers to organic surface residues, which is preliminary carbon. Further, carbon causes an increase in deposition power for a deposition rate-controlled evaporation to compensate for the reduced evaporation area[3,4,5,6]. Likelihood of spitting substantially increases with the elevated deposition power density.

Figure 2 illustrates the SEM/EDAX analysis of 1000 A Au film evaporated from 5N Au slugs, both as received and post in house chemical cleaning, in addition to Au films evaporated from Evapro IV Au slugs. Evapro IV Au slugs produced the Au films with minimal carbon content, which also didn't require in house chemical cleaning prior to use, which reduced the process cycle time. Evapro Au slugs were used in this study to make Au molten source. Under process conditions, any process parameter that has an effect on the heat input and/or heat loss of the deposition system (i.e. heat transfer between Au crucible liner and Cu hearth) has an impact on Au spitting.

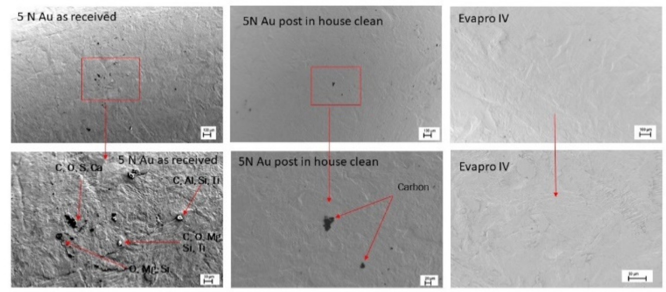

Fig 2. SEM and EDAX analysis of e-beam deposited Au thin films evaporated from both 5N and Evapro Au slugs.

In this study, we probe the impact of heat dissipation between the crucible liner and Cu hearth and deposition rates on level of spitting, for both Au and Pt e-beam evaporation.

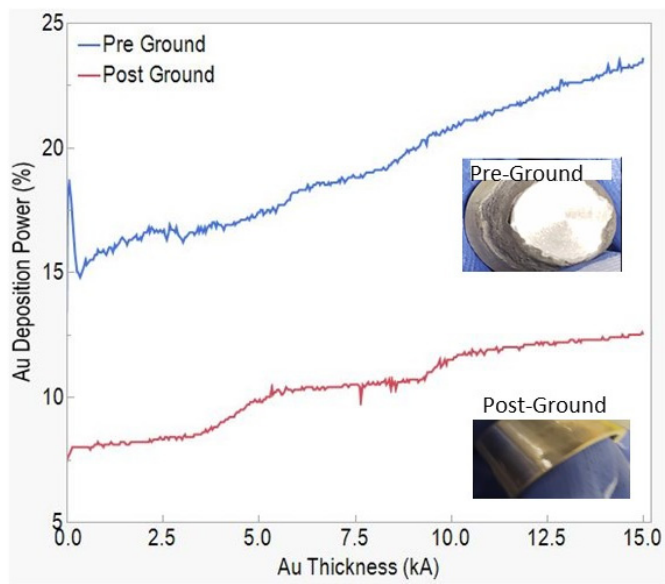

Fig 3. Au deposition power profiles as a function of deposited thickness for the same tungsten liner at pre-ground and post-ground. Pre-ground liner is with excessive material buildup on the backside wall and post-ground liner is after going through the backside material buildup grinding followed by IPA/acetone cleaning.

Adding Ta to Au is a very common practice in Au e-beam evaporation in order to sustain a lower level of spitting. As Ta is a carbon getter, it ensures an Au melt with free of carbon from the top surface, preventing elevated power density during deposition. However, added Ta causes molten Au source to wick out of the crucible liner as a result of declined sticking coefficient of Au, which is a function of surface condition, thickness and temperature[6]. Consequently, a thick layer of metal/carbon/Ta is built up on the outside wall of the crucible liner, resulting an interrupted heat dissipation between the crucible liner and Cu hearth as depicted in figure 3. Figure 3 shows 46% reduction in the mean deposition power for Au because of a cleaned crucible liner with free of material buildup on the backside wall. Cleaned tungsten crucible liner without excessive material buildup on the backside of the liner yields optimal heat dissipation during deposition, ensuing lower probability of commencing Au spitting.

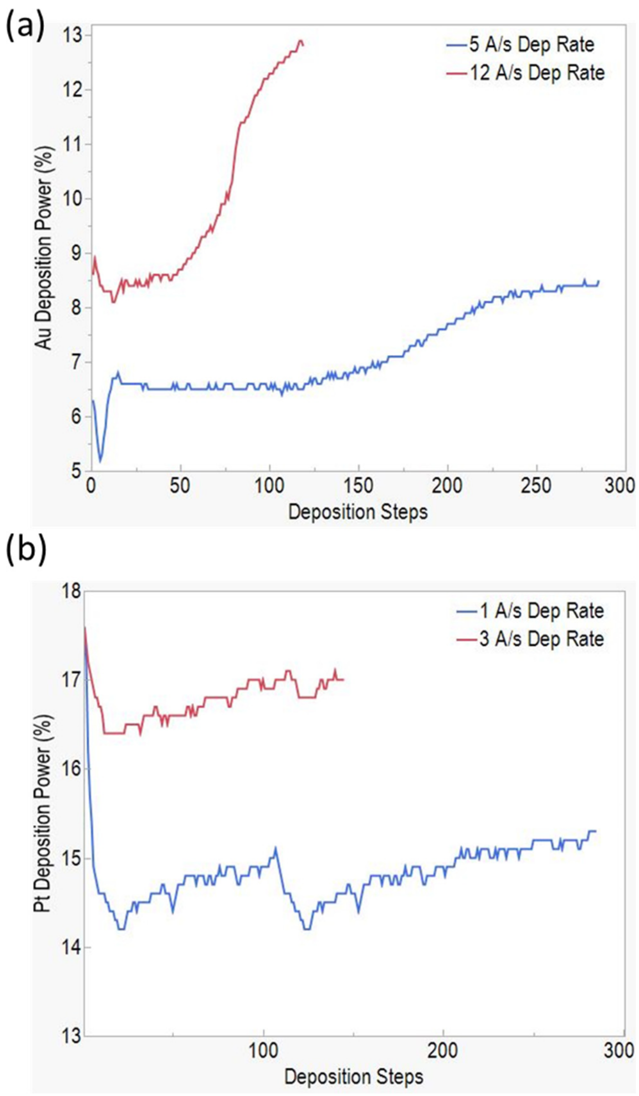

Fig 4. a) Improved and uniform deposition power profile for Au and b) for Pt, because of lower deposition rates.

Further, figure 4 highlights the benefit of slowing down the deposition rate to achieve lowered deposition power density in both Au and Pt e-beam evaporation. As shown in figure 4, mean deposition power went down by 20% and 11% for Au and Pt with the slower deposition rates, respectively. Cleaned crucible liners and pockets in the Cu hearth along with reduced deposition rates collectively decreased the overall spit count by about 70% from historical values as shown in figure 5. Deposited thickness driven periodic crucible liner grinding and post wet cleaning in conjunction with Ta addition were implemented in each evaporator in order to ensure consistent improvement in spit counts. Additionally, slower Au and Pt deposition rates were utilized in the applicable processes to further warrant the reduced spit counts. Moreover, reduced deposition rate was beneficial to prevent photoresist from polymerizing, eliminating likelihood of metal stringer formation as discussed by Cheng et al.[3].

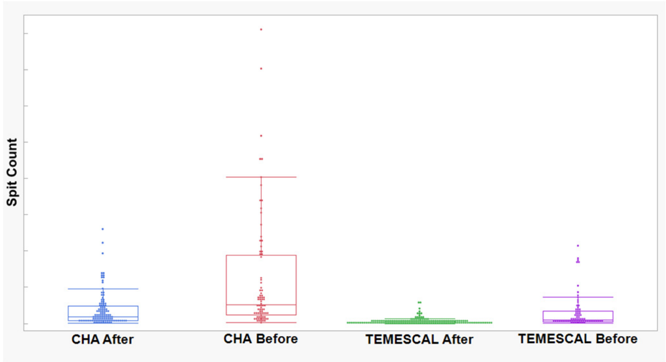

Fig 5. Remarkable improvements in spit counts in various metal evaporators due to recent process improvements.

CONCLUSIONS

It is crucial to have an optimal heat dissipation between the Au crucible liner and the Cu hearth in order to achieve extremely low-level of spits. Ta addition to Au helps to attain Au melt source with free of carbon from its top surface prior to deposition starts, which decreases the chance of spitting. However, adding Ta on the other hand escalates the metal over spill around the liner outside wall, resulting a thicker material buildup. This thick material buildup on the liner results in increased deposition power density. When the resultant higher deposition power density exceeds a certain threshold value, Au spitting commences. Deposited thickness driven periodic crucible liner sidewall cleaning to remove the excessive material buildup yields about 50% reduction in the mean Au deposition power density. Deposition power is further reduced by lowering the deposition rate, which is highly favorable to avoid commencing spits. Collectively, average spit count is reduced by 70% as a result of lower deposition power densities achieved via periodic crucible liner sidewall cleaning and reduced deposition rates.

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