

A New Approach to Gold Electron-Beam Evaporation with Improved Process Quality and Throughput

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Abstract

Gold (Au) is a common metal that is evaporated using an electron beam evaporation within the compound semiconductor industry. It is common to place a crucible liner into a hearth to ensure the Au can be evaporated with a low and stable power density level. Au slugs are placed into a crucible to evaporate a desired amount of gold on to the semiconductor surface. Evaporating Au using e-beam evaporation presents several challenges that can typically be mitigated by modifying the parameters of the e-beam system. One intrinsic challenge with evaporating Au is that it wicks over the crucible liner causing buildup on the side walls of the crucible as well as build up in the hearth pocket. To combat the issue of buildup on the crucible, the buildup is ground down; grinding the crucible liners is not a long-term solution as it changes the characteristics of the liner as it thins down the side wall after each grind. Changing the crucible material can impact how much gold wicks out of the crucible, but it will not change the thin film of gold that forms on the pocket walls from the evaporation cloud. To overcome this issue, a consumable part can be placed into the hearth that may be removed after a certain number of deposition runs. Implementing a new crucible material in combination with the hearth inserts could resolve both issues and create a robust process for evaporating Au. Additionally, the reduction of Au buildup on the crucible liner and the hearth pocket will result in potential CapEx and OpEx savings in operations.

INTRODUCTION

Compound semiconductor industry uses Au as one of the major metallic films in the gate as well as M₁ and M₂ stacks due to its outstanding electrical conductivity, resistance to oxidation, and exceptional ability to form reliable contacts.^{1,2,3} Electron beam evaporation is commonly used for metal evaporation in compound semiconductor manufacturing as it enables co-evaporation of multiple films in the respective metal stack at ultra low-pressure conditions for liftoff applications.⁴ It is a widely recognized approach to use a crucible liner for Au e-beam evaporation to thermally isolate the Au metal source to achieve optimal deposition power density levels.⁵ Optimal deposition power density ensures high quality film, for example fabrication of fencing/flagging free devices by lowering the chances of shadow evaporation,

reduction of x-ray and electron radiation damage at the wafer level, and lower metal spits.

One of the intrinsic challenges associated with Au e-beam evaporation using a crucible liner is that the Au wicks out of the crucible liner, forming a metallic buildup on both the crucible liner and the hearth pocket. This buildup could potentially cause the crucible liner to be thermally short circuited, resulting in sudden increase in deposition power density. Random spikes in the deposition power density compromises the evaporated film quality via tarnished film thickness, uniformity across the wafer and increased metal spits. Additionally, compromised process could also impose detrimental effects to the crucible liner lifespan, leading to early unforeseen crucible liner failures.^{6,7} Moreover, tantalum (Ta) addition to the Au metal source has been utilized as one of the effective ways of regulating Au spits in the compound semiconductor manufacturing industry.⁸

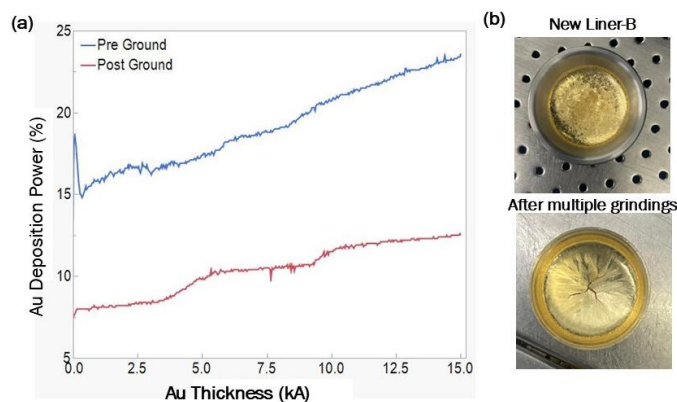


Fig. 1. Current Au e-beam evaporation process. (a) Au deposition power for pre and post crucible liner grinding for Liner-B. (b) Decrease in crucible liner wall width because of grinding.

However, Ta acts as a catalyst for Au to wick over the crucible liner, resulting in excessive metal buildup on the crucible liner and the hearth pocket. We experimented with ultra-pure Au slugs (5N Au slugs that were cleaned via an additional rigorous thermal treatment under low-pressure followed by extensive chemical cleaning to remove bulk trapped carbon) without adding Ta to mitigate this Au overflow, which increased spits by about 60% compared to historical values. As shown in Fig. 1, we demonstrated an

alternative way at 2022 CS Mantech conference to combat this metal buildup on the crucible liner, where the crucible liner is gently grounded and cleaned based on the deposition thickness.⁹ Although this new approach resolved the intermittent process variability and high Au spits, it still has several challenges. For example, crucible liner walls get trimmed after multiple grindings: see Fig. 1b, causing process variations. Additionally, the cycle time increases in the metals area due to source chamber in the evaporator being opened over an extended period for hearth pocket cleaning to remove the excessive metal buildup.

The aforementioned process challenges related to Liner-B in Au evaporation motivated us to explore a novel approach to evaporate Au with reduced metal buildup on the liner as well as the hearth pocket. In this paper, we report on our new process development to e-beam evaporate Au using a new crucible liner material (Liner-A) that has favorable thermal properties compared to traditional liner (Liner-B). The new approach results in no Au wicking out of the liner preventing excessive metal from building up on the liner as well as the hearth pocket. It also enables us to decrease the Ta addition frequency while achieving the same if not lower deposition power density levels and spits as compared to Liner-B. Liner-A did not require grinding and cleaning, whereas Liner-B had to be ground and cleaned periodically. This resulted in decreasing the number of variables that impact the process in conjunction with decreased cycle time. Further, a new consumable part was designed to overcome the metal buildup on the hearth pocket, which can be placed into the hearth pocket to collect the precipitated metals inhibiting metals building up on to the pocket. This hearth insert can be removed and replaced with a new one after a certain amount of Au deposition when it reaches a thick enough buildup to touch the liner. We also demonstrate that the characteristics of the evaporated Au-film are intact with this new hearth insert while resolving a robust process for Au evaporation with free of buildup and improved process variability. Implementation of a new Au crucible liner material in conjunction with the hearth insert ensures a more robust process with potential CapEx and OpEx savings.

RESULTS AND DISCUSSION



Fig. 2. Excessive metal buildup on the hearth pocket due to Au wicking out of the liner.

One of the intrinsic challenges of conventional crucible liner (Liner-B) used for Au e-beam evaporation is that Au wicks over the liner, resulting in metallic buildup on the hearth pocket: see Fig. 2. The excessive metallic buildup on the hearth pocket leads to a thermally short circuit the liner, causing a sudden increase in deposition power density in addition to early crucible liner and emitter failures.

As a resolution, we probed an alternative liner material that has improved thermal properties compared to Process of Record (POR) Liner-B for Au evaporation. As illustrated in Fig. 3, a new crucible liner material, Liner-A, is a promising alternative for POR Liner-B for Au evaporation.

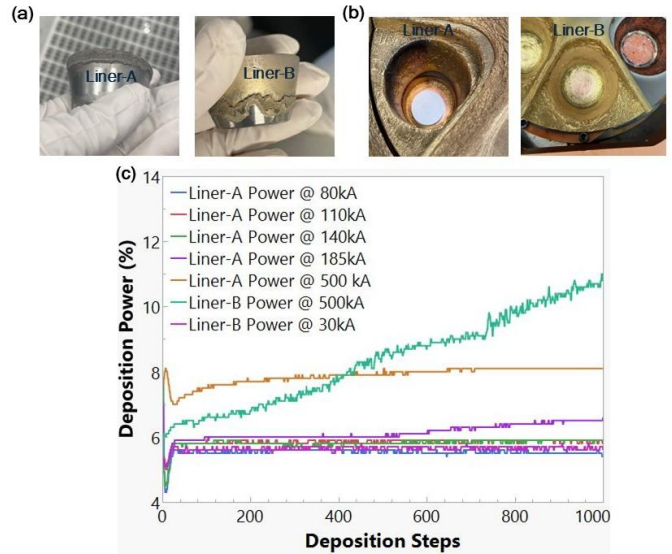


Fig. 3. Au e-beam evaporation using new liner material Liner-A. (a) Remarkable reduction of metal buildup on the Liner-A compared to Liner-B. (b) Improvement of metal buildup onto the hearth pocket from Au evaporation using the new liner. (c) Au deposition power as a function of deposited thickness for the new and the POR liners.

TABLE 1
GDMS ANALYSIS OF THE AU FILMS EVAPORATED USING THE NEW AND THE POR LINERS

Element	Liner-B	Liner-A	Element	Liner-B	Liner-A	Element	Liner-B	Liner-A	Element	Liner-B	Liner-A
	Concentration	Concentration		Concentration	Concentration		Concentration	Concentration		Concentration	Concentration
	[ppm wt]	[ppm wt]		[ppm wt]	[ppm wt]		[ppm wt]	[ppm wt]		[ppm wt]	[ppm wt]
Li	< 0.01	< 0.01	Ag	0.09	0.19	Fe	0.41	0.92	Ho	< 0.005	< 0.005
Be	< 0.01	< 0.01	Cd	< 0.01	< 0.01	Co	11	4.7	Er	< 0.005	< 0.005
B	< 0.01	< 0.01	In	Binder	Binder	Ni	0.02	0.04	Tm	< 0.005	< 0.005
F	< 0.05	< 0.05	Sn	< 0.05	< 0.05	Cu	0.59	0.67	Yb	< 0.005	< 0.005
Na	0.14	0.12	Sb	< 0.05	< 0.05	Zn	< 0.05	< 0.05	Lu	< 0.005	< 0.005
Mg	< 0.05	< 0.05	Te	< 0.01	< 0.01	Ga	2	8	Hf	< 0.005	< 0.005
Al	< 0.05	< 0.05	I	< 0.05	< 0.05	Ge	< 0.05	< 0.05	Ta	Source	Source
Si	0.07	< 0.05	Cs	< 0.1	< 0.1	As	1.5	3.5	W	< 0.05	< 0.05
P	0.02	0.03	Ba	< 0.01	< 0.01	Se	< 0.05	< 0.05	Re	< 0.005	< 0.005
S	0.03	0.06	La	< 0.005	< 0.005	Br	< 0.01	< 0.01	Os	< 0.005	< 0.005
Cl	< 0.05	0.1	Ce	< 0.005	< 0.005	Rb	< 0.005	< 0.005	Ir	< 0.005	< 0.005
K	< 0.05	< 0.05	Pr	< 0.005	< 0.005	Sr	< 0.005	< 0.005	Pt	< 0.1	< 0.1
Ca	< 0.05	< 0.05	Nd	< 0.005	< 0.005	Y	< 0.005	< 0.005	Au	Matrix	Matrix
Sc	< 0.001	< 0.001	Sm	< 0.005	< 0.005	Zr	< 0.05	< 0.05	Hg	< 0.1	< 0.1
Ti	0.008	1.1	Eu	< 0.005	< 0.005	Nb	< 0.005	< 0.005	Tl	< 0.005	< 0.005
V	< 0.005	< 0.005	Gd	< 0.005	< 0.005	Mo	< 0.01	< 0.01	Pb	< 0.05	< 0.05
Cr	< 0.01	< 0.01	Tb	< 0.005	< 0.005	Ru	< 0.01	< 0.01	Bi	0.11	0.71
Mn	< 0.01	< 0.01	Dy	< 0.005	< 0.005	Rh	< 0.005	< 0.005	Th	< 0.005	< 0.005
Fe	0.41	0.92	Ho	< 0.005	< 0.005	Pd	< 0.01	< 0.01	U	< 0.005	< 0.005

The new liner did not require to be ground and cleaned, whereas POR liner had to be ground and cleaned periodically. This resulted in decreasing the number of variables that impact the process in conjunction with decreased cycle time. As shown in Fig. 3c, the power levels for the new liner showed to be very steady for multiple runs unlike the POR liner where it was only achievable with a new or freshly ground liner. The new liner-A is replenished with a new one on a set schedule based on the total deposited thickness that is determined by the deviation in the deposition power density from a desired range. One of the unique characteristics observed in the new liner in contrast to POR liner is that the deposition power stays almost steady throughout the entire deposition even for the thicker runs.

According to Fig. 4, there is a dramatic reduction of the Au usage and run-to-run repeatability for the new liner compared to POR liner. The mean Au usage for 8 kA thick Au runs from the new liner was decreased by 30% from POR liner. This reduction in gold usage for the new liner during evaporation can be attributed to the reduced mean deposition power density and not rising the mean deposition power during the run as gold in the liner depletes. Moreover, as shown in Fig. 5b and Table 1, cleanliness of the Au films evaporated using new and POR liners were studied via Glow Discharge Mass Spectroscopy (GDMS) and Secondary Ion Mass Spectroscopy (SIMS) and confirmed no difference. Additionally, improved Au spits are achieved using new liner in contrast to POR liner: see Fig. 5a.

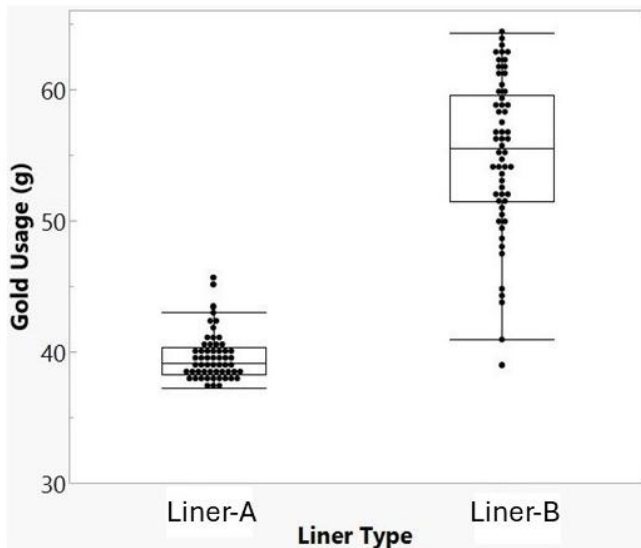


Fig. 4. Au used to evaporate 8 kA of gold as a function of crucible liner material type.

However, we had to come across a unique process challenge where the new liner sporadically cracked during the deposition, which was attributed to the thin metal buildup on the hearth pocket. Originally, it was thought that all the Au

coating on the hearth pocket was caused by Au wicking over the liner. However, it was observed another mode of Au buildup on the hearth pocket after implementing the buildup-free new liners. It was later realized that the precipitation of the Au fume on to the hearth pocket during the Au metal source cooling down caused this thin metal buildup, which was harder to clean, especially on the used copper hearth due to its thinner nature.

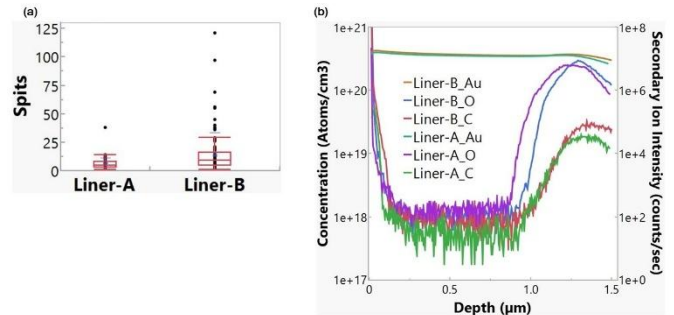


Fig. 5. Deposited Au film characteristics using new liner compared to POR liner. (a) Au spits as a function of crucible liner type. (b) SIMS analysis of deposited Au film.

To combat this unique process challenge associated with the new liners, a removable consumable part can be placed in the pocket to mimic a new hearth that can then be replaced once the thin layer of Au builds up enough that the liner can no longer fit in the pocket free of touching the hearth insert: see Fig. 6a. As shown in Fig. 6b, we also demonstrated that the characteristics of the resulting Au film are intact with this new hearth insert.

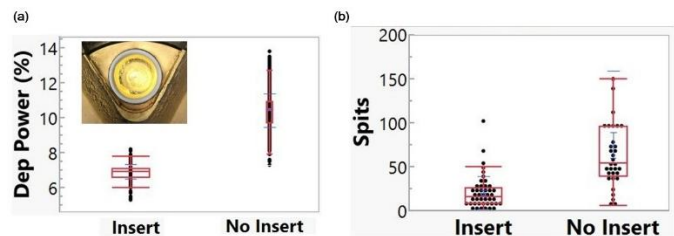


Fig. 6. Au e-beam evaporation with hearth insert. (a) Au deposition power with and without hearth insert. Inset shows the newly designed hearth insert. (b) Au spits with and without hearth insert.

Once the characteristics of the insert were determined, experiments were done to understand the lifetime of the hearth inserts as well as any changes that would be needed to the insert. As depicted in Fig. 6a, when using the insert during Au deposition, it was noticed that Au buildup was mainly on the side walls of the insert creating a thick layer of Au. This was not ideal because the consumable part would only be able to be used a few times before needing to reclaim it. By raising the source from POR source height, the evaporating cloud would no longer be coating the side walls at such a fast rate. The raised source height is negligible when considering the throw

distance from source to substrate, as well as the change in source height in the crucible as the source depletes during each run. This way the hearth insert could be used for an extended period before the liner touches the Au coated insert, causing the liner to fail.

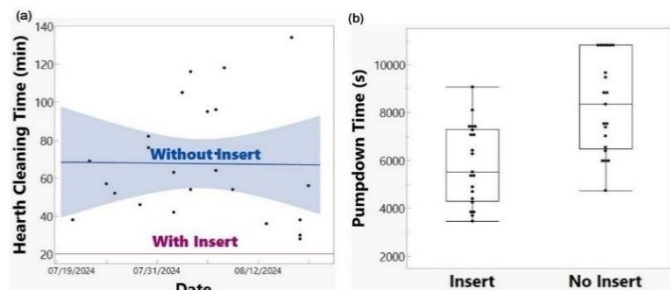


Fig. 7. Impact of source chamber open time for hearth pocket cleaning into e-beam evaporation pumpdown time. (a) Hearth cleaning time with and without a hearth insert. (b) E-beam evaporator pumpdown time with and without hearth insert.

There are numerous variables that could affect the thickness deviation from the target in e-beam evaporation, for example hearth pocket cleanliness, which is one of the leading factors as well as the most challenging one to be controlled. The new approach with hearth inserts would eliminate this variability as it mimics a new pocket state at each run. Another important aspect of the cycle time that was addressed by this hearth insert is the evaporator pumpdown time. As depicted in Fig. 7a, the source chamber is left open for hearth pocket cleaning for 40-120 min, which is significantly reduced to about 20 min or less with the new hearth insert approach. As a result of the reduced source chamber opening time with the insert, the evaporator pumpdown time reduced by 30%, which has a direct positive impact on the fab WIP cycle time and tool utilization.

The new crucible liner and the modified hearth insert were launched in production after confirming there is no change to visual or electrical data via production split lots. These two changes were able to create an environment within the evaporator that eliminated the need to scrape away gold or grind the liners daily.

CONCLUSIONS

Changing the crucible liner material showed low and steady power density levels during evaporation. There is also minimal buildup on the crucible liners, so there is no longer a need to grind the crucible liners at a set schedule. The hearth insert approach decreased the cycle time substantially as there is no longer a need to chip away gold on the hearth pockets. Instead, now after a certain amount of gold has been deposited on the hearth insert it may be reclaimed, and a fresh one can be inserted into the pocket. This novel approach offers a

robust, repeatable, and ergonomic Au e-beam evaporation process with potential CapEx and OpEx savings.

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ACRONYMS

POR: Process of Record
 GDMS: Glow Discharge Mass Spectroscopy
 SIMS: Secondary Ion Mass Spectroscopy
 CapEx: Capital Expense
 OpEx: Operating Expense
 WIP: Work in Progress