Effects of Deposition Rate, Beam Sweep and Crucible in an Evaporation Process

Kezia Cheng, Guoliang Zhou

Skyworks Solutions Inc., 20 Sylvain Road, Woburn, MA 01801
kezia.cheng@skyworksinc.com (781) 241-2821

Keywords: Crucible, Liner, Gate leakage, Wave-particle theory, Gate foot

Abstract

The impacts of deposition rate, beam sweep, and use of hearth crucible liners, for E-beam evaporation on device performance and reliability have seldom been published. Here, we broaden a previous study of the effects of beam sweep and deposition rate to include the use of crucible liners for gold (Au) evaporation. The results confirmed that all three variables, namely high Au deposition rate, the use of a crucible liner and beam sweep contribute to gate leakage in a pHEMT. The resulting mechanism can manifest in failures of other devices such as the contact layers of an HBT. The findings are consistent with the results of our previous report. This paper analyzes the results of the experiments to study the gate foot and details how the size of the foot corresponds to the deposition condition. A comprehensive explanation of the resulting failure mechanism is included.

I. Introduction

Increasing chip demands prompts many wafer foundries to look for ways to boost throughput and trim cycle time. Of all the front-end processes, the Thin Film group is often the center of focus. Interconnect processes such as M1 and M2 can have up to 3 microns of Au with deposition times exceeding one hour. Increasing the deposition rate is intuitive and seems like an attractive solution; but first, the effects of increasing the deposition rate on device parametric must be studied.

An issue that accompanies high Au deposition rate, unfortunately, is metal spitting [1] [2]. Moreover, elevated deposition power often leads to premature gun emitter failure and power supply alarms. To address these difficulties, crucible liners are commonly used to thermally isolate the source from the water-cooled hearth. This allows high deposition rates to be attained at low powers. The addition of tantalum (Ta) to the Au source has been proven to effectively reduce metal spitting during evaporation [3].

The use of a crucible liner and the addition of Ta pellets to the Au source make it possible to evaporate thick metal layers at high deposition rates with reduced risk of Au spitting. From a throughput increase standpoint, these combinations are the perfect answers. However, from a process and device perspective, the risks of using crucible liners for evaporation must be understood.

E-beam evaporation and liftoff remain the mainstream metallization technique for compound semiconductor device fabrication. The process starts in high vacuum. The long mean free path and minimal scattering that ensue offer line-of-sight deposition characteristic. Under SEM inspection, however, a foot may be observed on the edges of metal lines. It is a characteristic associated with the process where a very thin layer of metal extends from the main body beyond the photoresist defined CD. See Figure 1. The physics of foot formation is closely related to metal fencing formation [4]. The foot poses a quality risk if the Au overlaps the underlying titanium (Ti) layer.

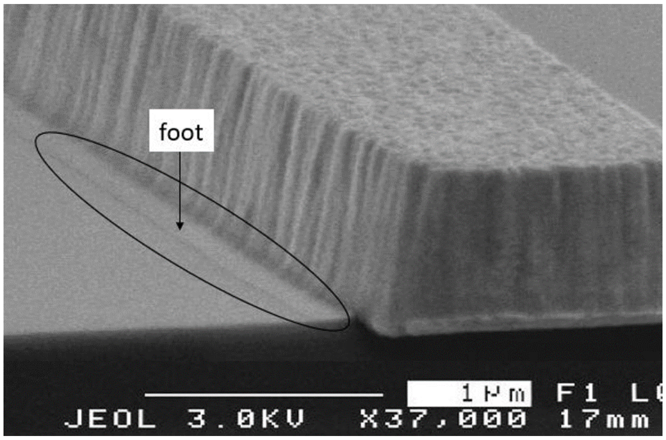

Figure 1 SEM image of a metal line shows the typical columnar growth and a metal foot, which is a characteristic feature of liftoff evaporation. If the Au overlaps the Ti, it will be a reliability concern.

II. Experiment

Skyworks' Woburn site uses evaporators for pHEMT processes. Au is evaporated directly from the copper hearth without a liner. Deposition rate for Au is optimized with a static beam optimally focused to prevent spitting. In the interest of throughput increase, experiments are designed to assess the feasibility of using a liner in copper hearth for metal evaporation in pHEMT processes.

In a previous study, we demonstrated that high deposition rates combined with beam sweep resulted in a pronounced foot at the base of the gate electrodes [5]. High Au deposition rates add energy and mobility to the condensing Au atoms. We hypothesize that the use of a crucible liner similarly produces an exaggerated foot because of increased scattering and flux angle variation. If the Au overlapped the Ti, diffusion of Au into the channel can occur in downstream processing causing high leakage failure just like high deposition rates and beam sweep did.

Three qualification lots were split in a DOE to study how FET parameters can be affected by Au evaporation with a crucible liner. The wafers were randomized and split into three groups. Group 1 received Gate metal deposition with Au evaporated without a liner at nominal deposition rate 1.0A/s. The Gate deposition for Group 2 was done with a molybdenum (Mo) crucible at the same nominal 1.0A/s rate. Group 3 was the control. Au deposition was done without a crucible liner and at half of the nominal rate (0.5A/s). Since we already know that beam sweep increases gate leakage, we used a stationary beam in this experiment. In all cases, except for the soak and deposition powers, the final metal thickness of each layer was identical.

III. Results

The control wafers with low Au deposition rate of (normalized 0.5A/s) have the lowest leakage. I_{off} at 0.15µA is right in the historic median distribution for this parameter. Group 1 that ran without a liner but at high deposition rate (normalized 1.0A/s) has significantly higher leakage. In fact, leakage more than doubled to 0.34µA. The higher leakage starts to impact probe yield of this group.

The impacts of Au evaporation with a crucible liner are obvious comparing leakage between Group 1 and Group 2. At the same nominal deposition rate of 1A/s, wafers that had gate deposition with a crucible liner have leakage current more than twice of the no-liner counterparts. I_{off} increased from 0.34µA to 0.79µA. The high leakage accounted for a yield loss of 40% in this group. Since the same deposition rate was used, the difference in leakage can be attributed solely to the use of liners for Au evaporation.

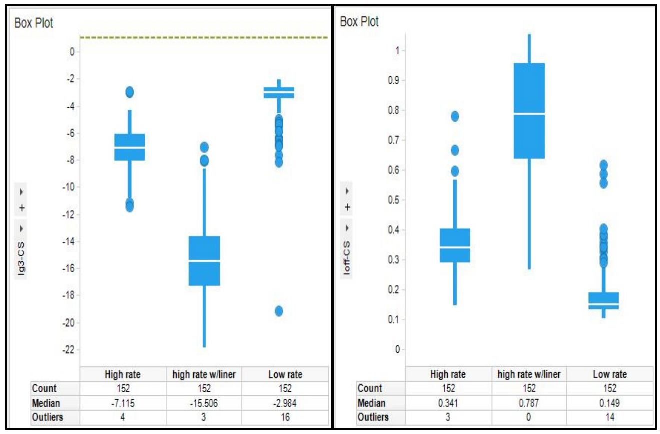

Figure 2 High deposition rate evaporation resulted in gate leakage current two times higher than POR. Gate deposition with a crucible liner has higher leakage compared to no liner at the same deposition rate.

Table 1 leakage comparison

PCM	Group 1 High rate no liner	Group 2 High rate with liner	Group 3 Low rate no liner
I_g	-7.115 µA	-15.506 µA	-2.984 µA
I_{off}	0.341 µA	0.787 µA	0.149 µA

These results are very similar to a previous deposition rate and beam sweep study done [5]. In the preceding work, we proved that high-rate deposition coupled with beam sweep resulted in an obvious gate foot. Au and Pd diffusion at the foot caused high leakage failure. The combined effects of beam sweep and high deposition rate doubled the circuit leakage to 9.6µA. See Figure 3. High deposition rate and beam sweep did not adversely impact most other FET parameters.

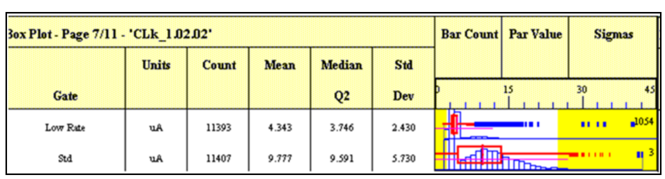

Figure 3 Low deposition rate without beam sweep has half the leakage current compared to high deposition rate with beam sweep.

Photo Emission Microscopy (EMMI) analysis of the wafers revealed marked difference in emission signature. FETs with gate metal deposited at high deposit rate (nominal 1.0A/s) and a circular beam sweep have many glowing emission sites. By contrast, the wafer that received low deposition rate and a stationary beam has a uniform glow in the FET. See Figure 4.

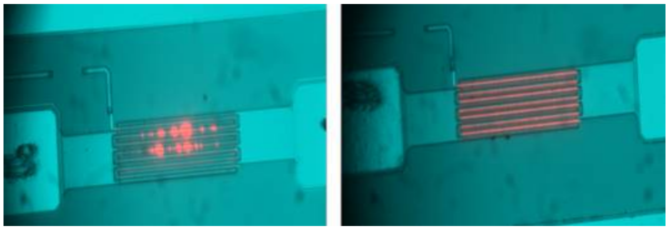

Figure 4 The FET on the left received high deposition rate and has several emission sites. The FET on the right received the low-rate recipe and has a uniform glow.

FIB analysis is equally telling and echoes the EMMI results. SEM images of the high deposition rate sample showed a prominent foot on either side of the gate electrode. There are obvious signs of diffusion of the Au from the foot into the channel. Evidently, Au has overlapped the Ti and Pt and contacted the semiconductor. In subsequent downstream processes, thermal energies drive the Au into the channel resulting in high leakage failure.

On the contrary, SEM images of the low deposition rate wafer reveal that Au coverage terminated on the sidewall of the Ti layer and did not extend onto the GaAs. The absence of gate foot from the channel reflects in the low FET leakage. The two gate profiles look very similar otherwise with the size of the gate foot being the only difference. See Figure 5.

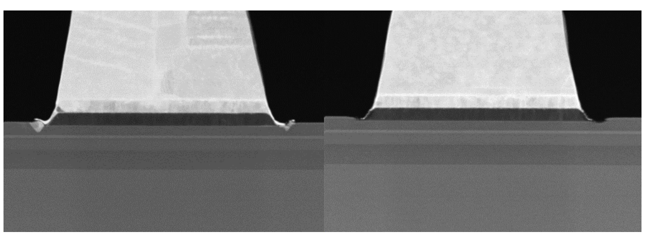

Figure 5 Gate electrode with high deposition rate for Au has pronounced foot and Au diffusion (left). Gate electrode with low deposition rate and no beam sweep has minimal gate foot and no diffusion (right)

IV. Discussion

Many techniques have been attempted to reduce the size of the Au foot without success. Doubling the Ti thickness and reducing the Au thickness did not reduce the size of the Au foot nor the leakage current. The gate foot formation occurs throughout the entire deposition but is more significant early in the process when the resist opening is unobstructed. As the film growth progresses and the deposited metal increases in thickness, the probability of the Au atoms reaching the base of the resist opening is greatly diminished. Thus, a reduction in the Au thickness does not affect the leakage current.

Evaporation processes typically start under high vacuum and exhibit the deposition characteristics of long mean free path, and line-of-sight coverage. Theoretically, a clean liftoff with a well-defined edge should result. However, because of its low sticking coefficient, one can find evidence of Au scattering even in the high vacuum regime. Telltale signs include a thin but discernable layer of coating on the backside of the dome after a long Au deposition run.

A. Crucible liner

An Au source in a copper hearth without a liner can turn completely liquid if the Au is clean, and the beam properly adjusted. Because the molten Au source is in contact with the copper hearth, a steep temperature gradient exists from the center to the edge. The Au in contact with the copper hearth is kept at a lower temperature with evaporation mainly in the center where the beam strikes. Hence Au deposition without a crucible behaves as a virtual point source and exhibits such characteristics in actual practice.

The use of a crucible liner thermally isolates the source from the water-cooled hearth. Consequently, the Au source is completely molten even at low power. Since Au is a good thermal conductor, we can expect the temperature of the molten source to be uniform across the entire surface. The effect can be compared to that of source-to-substrate misalignment [4]. See Figure 6. Along these same lines, because beam sweep keeps the source molten where the beam passes, applying beam sweep during deposition has the similar effect.

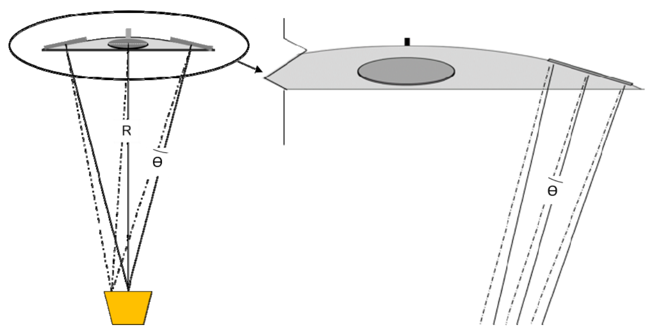

Figure 6 The use of a crucible has the similar effects as source-to-substrate misalignment

B. Influence of deposition rate

With higher deposition rate (or higher vapor pressure) comes an increase of collision between Au atoms as they leave the source. The scattering increases the spread of the flux arrival angle and enhances the metal foot.

High deposition rate and high evaporation temperature cause an increase of thermal radiation from the

Au source to the shields inside the chamber. As a result, Au re-evaporation from the areas where the sticking coefficient is low becomes more probable. Figure 6 is a picture of the back of a wafer dome with clear evidence of such Au deposition. The wafer clip masked the reflected Au atoms and left its outline on the dome surface. Since there is no direct line-of-sight to the crucible, we attribute the observation to Au re-evaporation from surfaces where the Au sticking coefficient is low.

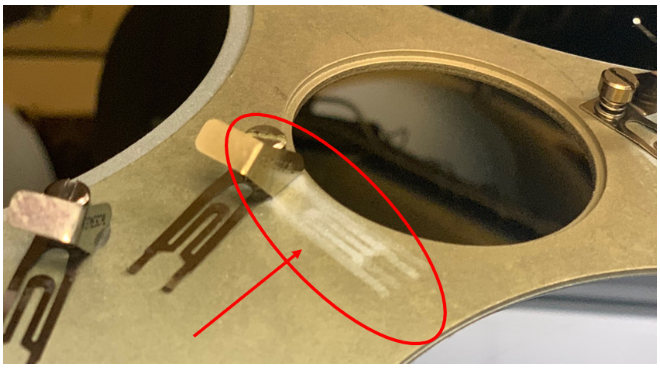

Figure 6 The wafer clip left a shadow on the back of the wafer dome which is a clear evidence of Au re-evaporation due to low sticking coefficient

Gate leakage is not the only issue caused by the foot. A prominent foot can add undesirable parasitic capacitance. The same physics can manifest in other process issues. We have observed the same Au diffusion in the HBT base contact where the Au at the foot has diffused into the GaAs around the perimeter of the base contact. See Figure 7.

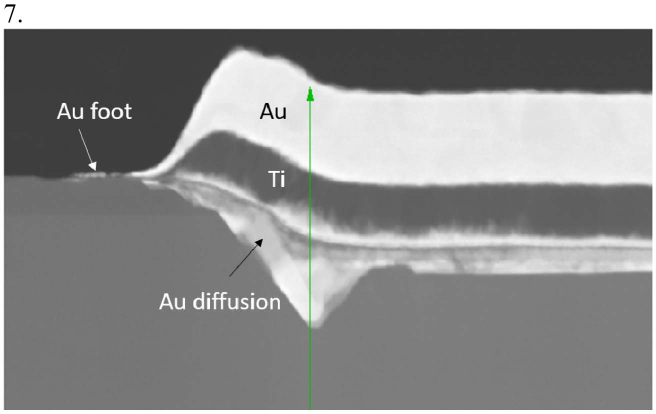

Figure 7 Au diffusion at the edge of base metal contact

V. Conclusions

We have demonstrated that both high Au deposition rate and the use of a crucible liner increased the size of the undesirable gate foot. When the Au foot overlaps the Ti barrier, Au migrates and diffuses into the underlying material from the thermal energies of downstream processing. For pHEMT, this causes high gate leakage. In a prior study, we also proved that beam sweep alone can likewise enlarge the size of the foot.

In summary, increasing the rate by 2x to a new nominal rate of 1.0 A/second doubled the leakage current. Given the same deposition rate, the use of a liner for Au evaporation accounted for a two-fold increase in leakage. High deposition rate results in more collision between Au atoms as they leave the source thereby causing an increase in the angular spread of Au flux. The poor sticking coefficient of Au causes flux angle variation and redeposition.

Higher Au deposition rates from using a crucible increase the probability of scattering and increase the mobility of the atoms. The use of a crucible thermally isolates the source so that the Au remains molten. The combined effects can translate into significant yield loss for sensitive devices.

The same physics can manifest in other device failure. Base contact leakage has been confirmed due to metal foot diffusion in some HBT masks. The foot can also add unwanted parasitic capacitance affecting device performance.

While the main goal of using a crucible liner is to lower the deposition power and increase deposition rate, the throughput advantage can cause increased leakage and yield loss. For some of our pHEMT devices, high deposition rate and the use of a crucible cause up to a 5-fold increase in leakage current. The significant yield loss does not justify the gains in throughput. The use of crucible and high deposition rates are not recommended for devices that are sensitive to leakage.

VI. Acknowledgements

The authors would like to thank James Oerth, David Petzold and Kim Smith for their support and Aida Y Castro for her assistance in carrying out the experiments

VII. Reference

[1] J. Cotronakis, M. Clarke, R. Lawrence, J. Campbell, C. Shaw, "Continuous Defectivity Improvements and Impact on High Density Metal-Insulator-Metal (HDMIM) Capacitor Yields", CS ManTech conference 2004.

[2] K. Cheng, "Electron radiation as an indicator of gold nodule defects during E-beam evaporation", CS ManTech conference 2011.

[3] L. G. Feinstein, M.J. Bill, H.P. "Reduction of nodules in electron-gun-evaporated Au films", Journal of Vacuum Science and Technology. Vol.12, no.3 May/June 1975.

[4] K. Cheng, "Elimination of Metal Fencing by Optimizing Evaporator Dome Alignment", IEEE Transactions on Semiconductor Manufacturing. Vol. 33, no. 4, November 2020.

[5] K. Cheng, "Palladium barrier cuts materials bill," Compound Semiconductor magazine, Sept 2007 issue, p 19-21.