Elimination of Metal Fencing by Optimizing Evaporator Dome Alignment

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Abstract

Successful metal liftoff requires a retrograde photoresist profile, or one created using a bi-layer process. Coupled with an evaporator set up for liftoff, they ensure a discontinuity in metal coverage so that the unwanted field metal can be lifted off cleanly, without tearing or defects. An evaporator with an optimized liftoff configuration necessitates precise source to substrate alignment or defects will result. While a lot of development work has been reported on photoresist processes and liftoff techniques, a lack of publication on ideal evaporator geometry and proper set up suggest that the effects of source to substrate alignment have seldom been investigated or discussed. An evaporant flux with precise normality is essential to achieving clean liftoff. This paper examines how the evaporator geometry influences the liftoff process. We will reveal the working principle of a special alignment tool and how the tool is used to keep the evaporator in precise alignment.

INTRODUCTION

Metal fencing, stringers, wings and flaps are various names designating the same broad type of metal liftoff defect.

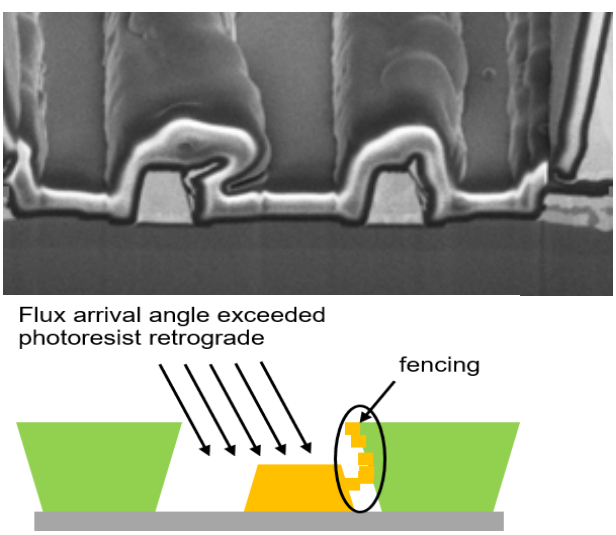


Fig. 1. Metal fencing defect and illustration of how the defect is formed.

It is a very common anomaly in any compound semiconductor fab where liftoff process is the mainstream metallization technique. Metal fencing can be described as a strip of excess metal that protrudes from the side of a metal feature. Generally, the defect is formed when the unwanted metal that lands on the photoresist attaches to the metal structure during film growth. See Figure 1.

More than just a cosmetic blemish, metal fencing on a capacitor bottom electrode will cause reliability failures as the sharp edges retain high charge concentration that promotes electrostatic discharge (ESD) strikes. Slivers of excess metal that break off can cause an electrical short elsewhere in the circuit.

Various proven photolithography approaches are in use today to generate a photoresist profile suitable for liftoff. Chemically Amplified Resist (CAR), image reversal, Bi-layer and LOR are popular among compound semiconductor fabs [1][2][3]. A tape lift process followed by a wet resist strip step [4] have become the industry standard. When metal fencing defects are observed, the photoresist profile is where troubleshooting often begins. Many times, the effort will expand into the liftoff process and eventually ends without any conclusion. In many cases, the real root cause is hidden in an unlikely place that is frequently overlooked – the evaporator.

Liftoff process is made possible if the evaporant flux is normal to the substrate. Because the substrate is flat and cannot conform to the curvature of the dome, the flux angle

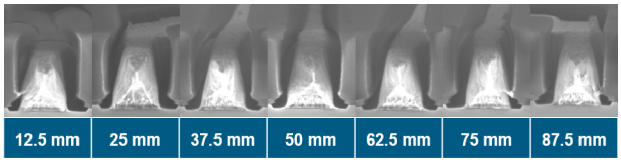


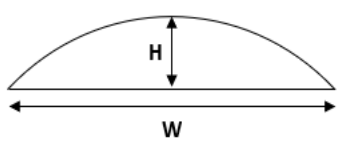
Fig. 2. Effects of gate walk across a 4" wafer as a result of throw distance being too short. Fencing is beginning to form on die 25mm from the edge.

increases in cosine from the center of the wafer to the edge. This angle shift creates the "walk" phenomenon where the position of the metal moves with respect to the resist opening. See Figure 2.

This effect is not directional. It is purely a geometrical relationship between the throw distance of the evaporator and the wafer diameter. Hence, the larger the wafer size is, the longer the throw needs to be to maintain the same flux angle. Rotating the wafer in the dome has no effects on the walk. When the flux angle approaches the resist retrograde angle, liftoff quality will suffer, and metal fencing will result.

The virtual source is a location above the hearth from which evaporation flux apparently originates. If the source, or more appropriately the virtual source, is not positioned at the spherical center of the wafer dome, the flux will no longer be normal to the wafer center. The effect is additive to the angle shift and manifests in different metal fencing characteristics on part of, or the entire wafer. It is, therefore, very critical to maintain a precise source to substrate relationship in an evaporator.

To determine if an evaporator is properly aligned, we need to first know whether the dome is matched to the throw distance. The radius of the wafer dome can be calculated by measuring the sagitta (H) of the arc and the chord (W). The throw distance can be estimated using a tape measure.



$$R = \frac{H}{2} + \frac{W^2}{8H}$$

Fig. 3. Radius of the dome can be determined by its height H and diameter W.

However, knowing the spherical radius and the throw distance does not imply that the two are positioned correctly with respect to each other, nor can we discern any distortion in the wafer dome. A modern wafer fab warrants a modern method of determining the alignment.

ALIGNMENT TOOL

The idea of a laser alignment tool was conceived after tracing some yield issues to a distorted dome damaged during the cleaning process. The tool was designed with three goals in mind. The first requirement is to allow the user to discern and quantify the precision of the source/substrate relationship. Secondly, it must be simple in construction. Finally, it needs to be easy to use. The alignment tool is comprised of a laser pointer and a metal disk that is machined to Semi-Standard. An integral thick-walled cylinder houses the laser pointer. Provisions are made to secure the laser pointer with three sets of screws positioned 120 degrees apart. Together they provide 6 degrees of freedom, so the laser beam angle can be adjusted. The laser pointer needs to be set up on a lathe by adjusting the set screws so that it projects a perpendicular beam.

Fig. 4. Laser alignment tool on a wafer dome

Once the alignment tool is configured correctly, it is placed into the substrate holder, see figure 4. Operating the evaporator with the wafer dome rotating slowly, the laser beam will track on the source. A paper target placed on the source will make the beam easier to see and prevent glare from reflecting off the shiny metal surface. Adding concentric rings on the paper target will allow the operator to read the precision of the alignment. A half inch radius on a 35" throw evaporator, for example, translates to approximately a one-degree angle on the wafer.

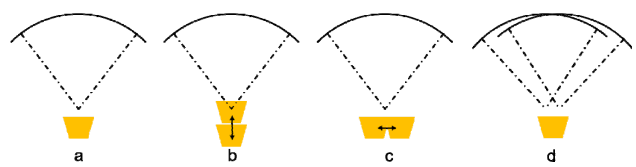


Fig. 5. Various ways an evaporator can be misaligned: (a) ideal alignment with the virtual source above the hearth, (b) throw mismatch, (c) concentricity, and (d) angular misalignment.

Figure 5 depicts several ways an evaporator can be mis-aligned. If the evaporator is configured correctly, the beam will describe a small circle concentric to the source. A stationary beam indicates that the source is exactly at the spherical center of the dome, see Figure 5a.

If the source to substrate alignment is off that causes the flux angle to exceed the resist retrograde angle, fencing will result. Consider the spherical radius being shorter than the throw distance illustrated in Fig 5b, the flux will arrive at a progressively increased angle from the outside edge of the wafer to the edge close to the center of the dome. The horizontal metal line on the wafers will have fencing on the top while the opposite edge sees a reduced flux angle and, therefore, is clean, see Figure 6a. If the throw distance is too short for the radius of the dome, the opposite will be observed.

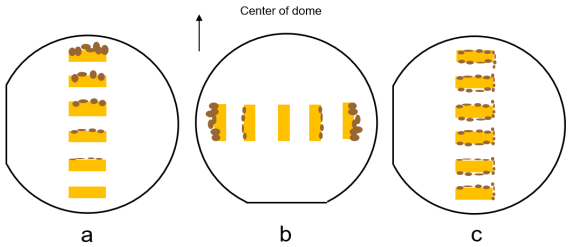


Fig. 6. Different fencing signatures. a. throw mismatch with the dome radius shorter than the throw distance. b. gate-walk due to throw distance too short for the wafer size. c. concentricity misalignment or poor photoresist profile

If the dome and the source are not concentric, Figure 5c and d, it will be indicated by the circle that the laser beam describes not having a common center as the source. A concentricity issue is more difficult to correct. The solution would involve either repositioning the E-gun assembly and/or the dome, which is not always possible. The laser alignment tool is useful for determining empirically the amount of adjustment needed. Depending on the dome drive mechanism, in some tools it may be easier to shim the substrate holder to bring it into alignment.

Results

We used the tool to assess multiple evaporation systems and found some level of alignment inaccuracy across different tools. Figure 7A and B are examples of how the laser beam looked in an out of alignment system and after adjustment respectively. The wafer dome is fabricated using a spinning process where a sheet of stainless steel is spun against a form or mandrel.

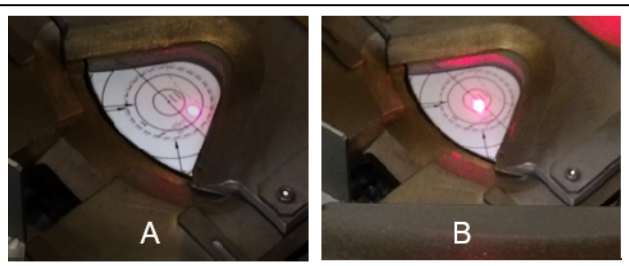


Fig. 7. Out of alignment wafer dome (7A) and corrected source to substrate alignment (7B).

Wafer recesses are then machined using a 3-D milling machine. Built-in stress from the spinning process can relax and repeated cleaning and sandblasting can warp the dome. It is worthwhile to periodically inspect and replace defective parts when found.

One of the evaporators had a history of gate flags when the resist thickness/profile was marginal. When checked with the alignment tool, the laser beam described a circle about ½" larger than the source. Calculation revealed that the throw distance was two inches longer than the dome's radius. Once the throw mismatch condition was identified, new domes of the correct radius were fabricated, and fencing was eliminated. Figure 8A depicts gate flagging on the horizontal metal lines due to throw mismatch. 8B is a picture of the same structure after installing the new dome of the correct radius.

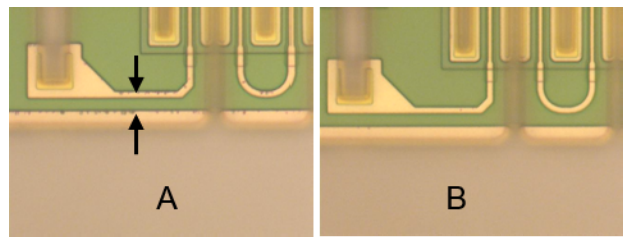


Fig. 8. Arrow showing gate metal fencing before alignment (A). After alignment, metal fencing is eliminated (B).

Discussion

Consider a retrograde resist profile having a typical 4 to 5-degree angle. Theoretically, if the flux arrival angle is less than 5 degrees, there should not be any issue on the entire wafer. Hence, for a 4" wafer, the minimum throw distance is 25". However, this is seldom the case. Process variation, machine tolerance and most importantly sticking coefficient of the metal, can all influence how the metal coats the photoresist [6]. For example, Gold (Au) does not have a sticking coefficient of unity. It will coat the resist sidewall and result in fencing. Given that the photoresist retrograde angle is limited by many process contraints, it is desirable to minimize the flux angle by extending the throw distance of the evaporator.

Other than fencing defects, a misaligned evaporator can affect parametric performance and/or yield loss. On a self-aligned emitter HBT process, flux variation can coat the emitter core sidewall and cause emitter to base short. In a pHEMT with delicate T-gate structures, such misalignment can cause liftoff difficulties and aggravate gate stringer formation. A frequent root cause for high leakage is gate stringers shorting the gate to the Source or Drain.

CONCLUSIONS

Source to substrate misalignment is a common yet seldom discussed issue in the evaporation process. It is one of the leading causes of metal fencing defects. We have described different ways a liftoff evaporator can be misaligned and how each of the conditions drives distinctive metal fencing characteristics.

If the radius of the wafer dome is shorter than the throw distance of the evaporator, the horizontal metal lines will have progressively worse fencing on the top edges that face the center of the dome. Fencing will appear on part of, or the entire, wafer if the dome and the source are not concentric. In a planetary system where the wafers self-rotate, if misaligned, all the edges on the wafer will be exposed to flux angle variation.

Gate walk is exacerbated by inadequate throw distance for the wafer size. The effect is characterized by increased fencing away from the center of the wafer. In the tool selection process, throw distance needs to be part of the consideration. Because of the low sticking coefficient of Au, short throw distance will promote the coating of the photoresist sidewall. This coating will become fencing or stringers after liftoff. While an optimal photoresist profile is crucial in preventing metal fencing, the extra flux angle variation caused by a poorly aligned evaporator can hold the dominant effect.

The proper use of the laser alignment tool has been demonstrated, achieving perfect source to substrate alignment in an evaporator optimized for metal liftoff. Misalignment, seemingly small, in the source to substrate geometry can prevent proper liftoff and cause metal fencing. The user can monitor the precision of the evaporator by adding markers on the paper target. A pHEMT with T-gate structures are more susceptible to this type of misalignment. This type of misalignment may result in metal stringers that can cause short circuits in the FET and HBT technologies.

The laser alignment tool sheds new light on an old problem and makes precision alignment of a source to substrate possible. It is a valuable addition to the maintenance tool box.

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REFERENCES

[1] J. Golden, H. Miller, D. Nawrocki, J. Ross. Optimization of Bi-layer Lift-Off Resist Process. 2009 CS ManTech conference

[2] S. Kulkarni, T. Brown, S. Tiku, M. Singh. Impact of Loading Effect on Retrograde Profile of CAMP Negative Photoresist in Metal Lift-off Applications. 2018 CS ManTech conference

[3] H. Chen, A. Ketterson, M. King, K. Salzman, V. Milam, J. Halvorson, J. Campbell. Improved T-Gate Yield Using E-Beam Trilayer Resist Process. 2011 CS ManTech conference

[4] C. Carpenter. Optimization of a Metal Liftoff Process in a GaAs Semiconductor Device. 2005 CS ManTech conference

[5] L. Gunter, W. Zhu, J. Hulse, J. Diaz, P. Seekell, W. Kong, K. Nichols, P.C. Chao. Mechanisms of Premature HEMT Breakdown. 2007 CS ManTech conference

[6] K. Cheng. Palladium barrier cuts materials bill. Compound Semiconductor magazine, Sept 2007 issue

[7] F. Radulescu, P. Miller, L. Cunnane, M. Harris, H. Lam and C. Bowers. Introduction of Complete Sputtering Metallization in Conjunction with CO2 Snow Lift-Off for High Volume GaAs Manufacturing. 2002 CS ManTech