Collimated Physical Vapor Deposition for Through-Silicon Via Barrier-Seed Deposition

Using inexpensive collimators and scanning deposition, production-worthy throughput is achieved

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Barrier-seed deposition by Physical Vapor Deposition (PVD) for Through-Silicon Via (TSV) is limited to lower aspect ratio (AR) unless more advanced and expensive equipment such as ionized PVD is used. By using the so-called long throw approach, conventional PVD is typically used up to AR=5. Another approach equivalent to long throw is to use a collimator between the sputter target and the substrate. This approach has long been used in the front end, for example, for Ti deposition in contact vias. A collimator is demonstrated to provide barrier-seed coverage for AR=5 and above. Collimators are inexpensive and easily adjustable to control overburden and avoid pinch off at the top of the via. By applying barrier and seed in the same chamber, the film adhesion to the collimator is improved, extending the collimator lifetime.

Introduction

3D die stacking to improve IC performance has driven the need to interconnect the stacked die using TSVs. These vias may be used to transport signals, power, or heat. A key challenge is filling the TSVs with conductor. The TSVs are significantly larger than front-end Damascene vias, being on a micron to tens of micron scale in diameter with ARs on a roadmap from 5 to >10.[1] The vias are generally etched using a process that leaves a rough scalloped vertical sidewall. An insulating liner must be provided which can serve to smooth out the sidewall structure. Sputter deposition, also know as PVD, is used to provide a layer of adhesion-barrier metal and a seed metal for electroplating. Electroplating fills the via with metal. The PVD process involves the sputtering of a given metal from a target usually situated directly above the wafer. The sputtered metal flux rains down onto the wafers and coats it. There are many integration challenges for the processes that form and fill the TSVs. We are concerned here with the challenges to the PVD process. To provide a seed metal for electroplating, a two-metal layer PVD deposition is used. The first layer provides adhesion to the via liner and the bottom metal surface. It also has to provide a barrier to intermetallic diffusion. Typical adhesion-barrier layers are titanium, titanium nitride, tantalum, or titanium-tungsten. The vias are usually filled with copper so a copper seed layer is deposited over the barrier layer. Standard PVD alone is usually applied to AR<3. By using filtering techniques such as long-throw or collimation, standard PVD can be extended to AR=5 or more.[2] AR=5 is not an intrinsic limitation of the process; one can always deposit longer and provide adequate seed coverage above AR=5. However, the cost effectiveness of using these filtered PVD techniques relative to more expensive techniques such as ionized PVD or CVD becomes less clear above AR=5.

Collimated PVD

When PVD is used to provide seed deposition in via, longer deposition times are requires as the AR increases. Deposition at shallow angles does not penetrate deep into the via and eventually begins to close off the top, preventing deep deposition. The shallow angle deposition also produces a thick top layer (overburden) that must eventually be etched away. A technique to avoid this is to filter out, or scrape off, the shallow angle metal flux so only the more vertical metal flux reaches the wafer.[2] Two approaches are typically used to do this. One, known as long throw, extends the distance between the target and the wafer so that shallow angle flux goes to the walls of the chamber, missing the wafer. Collimated PVD uses the same approach as long throw, mechanically eliminating all but the most vertical metal flux. In this case, rather than extending the target-wafer distance, a grid is placed between the target and the wafer. The grid is a metal plate with holes in it that allow some of the metal through to the wafer. For example, by making the diameter of the holes equal to the grid thickness, metal flux at angles greater than 45 degrees pass through to the wafer. This would be a collimator with AR=1. Collimators generally have an AR of 1-2. Collimators are usually designed as a hexagonal grid with thin walls (Figure 1) so that as little vertical flux as possible is intercepted.

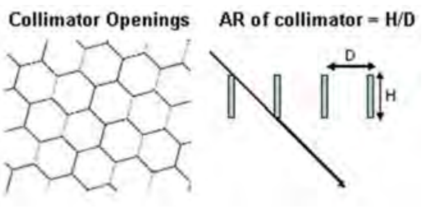

Figure 1. Collimator Design

As with long throw, 70-80% of the metal flux does not reach the wafer. While inefficient in the use of sputtered metal, these processes can provide seed coverage in vias when used in conjunction with RF biasing of the wafer. By applying RF, usually at 13.56 MHz, to the wafer, a glow discharge is produced in the argon background gas above the wafer. The RF also produces a DC self-bias on the wafer which attracts argon ions from the glow discharge to the wafer surface, resulting in sputtering of the deposited metal on the wafer. In the via opening, the sputtering produced by the RF bias technique reduces pinch-off and allows the metal flux into the via. It will also sputter metal off the via bottom and onto the via sides near the bottom. It is the bottom corner of a via with vertical sidewalls that is most difficult to cover since only a limited range of angles allows metal to reach this area. This process is known as respattering and may be applied during metal deposition or as a resputter-only process step.

Comparing long throw and collimated PVD, long throw has the disadvantage that the long distance between the target and wafer allows more scattering of metal atoms off of the background argon gas atoms, spreading the angular distribution of the metal so there is less vertical flux. Typical target wafer distance is 25cm to 30cm, which is on the order of the scattering mean free path for typical sputtering pressures of around 1mTorr argon pressure. Avoiding this effect completely forces operation at lower than normal sputtering pressures.[2] Another disadvantage of long throw when applied to single wafer chambers is that there is a wafer edge effect where the sidewall coverage is not symmetric around the via wall.[2] A disadvantage of the collimator is that it is situated directly above the wafer so any flaking of metal from the collimator may land on the wafer.[2] Therefore, good metal adhesion to the collimator is critical. Since the target-wafer distance can remain lower with the collimator, scattering is less of an issue. It is also easy to control overburden since the collimator is a simple inexpensive part that can be made in a variety of aspect ratios depending on the application. Both collimated PVD and long throw are used successfully in production. These techniques have limitations as the via AR increases because the amount of deposition required to achieve continuous coverage in the via increases faster than linear with AR. Figure 2 shows a calculation of via bottom coverage and lower sidewall coverage versus aspect ratio. This calculation does not include gas scattering but does model resputtering from the bottom.

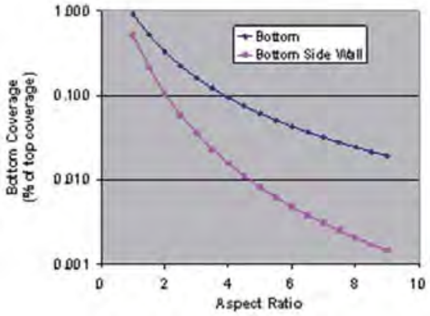

Figure 2. Model calculation of via coverage vs. aspect ratio

Challenges to Via Coverage at Higher AR

As the AR increases, details of the via formation can limit the ability to produce continuous seed coverage in the via. If the via is highly scalloped or has an overhang at the top, shadowing of the metal flux on the underside of these features may result. Figure 3a shows a SEM image of an AR=5 via which has had seed deposition using collimated PVD.

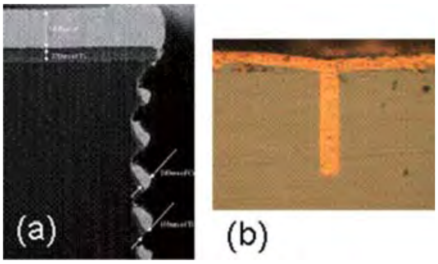

Figure 3. Successful seed deposition for highly scalloped AR=5 via using collimated PVD

Thick build-up of metal can be seen on the top side of each scallop with thinning underneath, making continuous coverage a challenge. This build-up sticks out farther than the scallops on the sidewall, causing further shadowing. Using RF bias to resputter from the top of the scallop onto the sidewall can reduce the shadowing but longer deposition time is also necessary when scallops are deep. The optical image in Figure 3b shows a plated sample of this via, demonstrating that a continuous seed was produced using a collimator for this AR=5 via with highly scalloped sidewalls. Figure 4 shows a via with an oxide liner that smoothes out the scalloped sidewall,

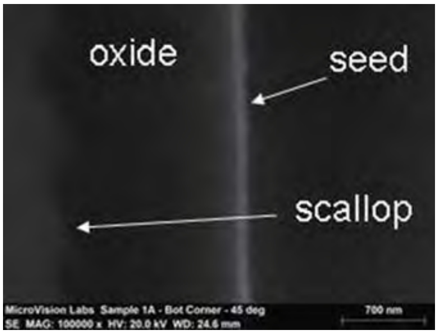

Figure 4. Oxide liner smoothes scalloped sidewall

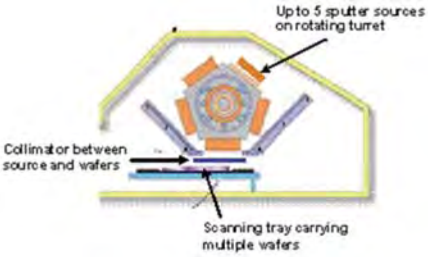

Figure 5. Collimator implementation in multi-wafer, multi-target chamber configuration

providing an easier surface for continuous seed deposition.

The quality of seed deposition is directly related to the via sidewall quality so there are important integration issues for seed deposition in high AR vias.

Collimator in a Multi-target Chamber

In many cases, long throw is easy to implement. For example, in a single wafer chamber, an insert can be installed between the sputtering source and the wafer to increase the distance between them. For some PVD equipment that run simultaneous deposition on multiple wafers and use scanning techniques to achieve good uniformity, a collimator may be the easier implementation. A collimator has been implemented in a multi-wafer, multi-target chamber configuration. In this configuration, both adhesion-barrier and seed metal are deposited in the same chamber. Rectangular magnetrons are used (Figure 5) with the wafers scanned under the magnetrons to produce good uniformity.

The configuration also includes RF bias for resputtering. RF bias is important to get continuous seed coverage at AR>3. Figure 6 shows two cases with the same seed deposition with and without RF bias. To illustrate that the seed coverage is continuous, electroplated Cu is applied to thicken the deposition on the sidewalls and bottom so it can be seen clearly in cross-section.

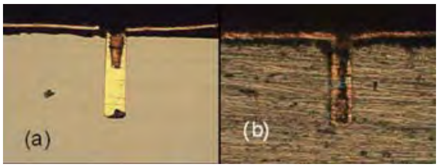

Figure 6. Improved seed coverage using collimator and RF bias for resputter. Plated vias with (a) no RF bias (b) RF bias

In Figure 6a, without RF bias, there is no plated Cu at the bottom of this AR=4 via, indicating that seed metal is missing in the bottom corners. Figure 6b shows the same via structure plated after seed deposition with RF bias. Continuous coverage of the plated metal demonstrates that the seed is also continuous.

Another key issue is throughput using collimated PVD. Since most of the metal flux is deposited on the collimator, longer depositions are required to get continuous coverage in high AR vias. To maximize throughput, deposition time should be kept to a minimum for a given via structure. Figure 7 shows this effect. Figure 7a shows an AR=5 via after plating, illustrating that the seed coverage was continuous. Figure 7b shows an AR=6 structure on the same wafer did not plate all the way to the bottom, indicating that the seed was not continuous.

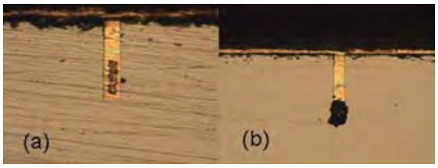

Figure 7. Aspect ratio limit for a given recipe and a given via structure. Via (a) AR=5 has full seed coverage and plates to the bottom, via (b) AR=6 does not

This is the limitation of the particular recipe. By depositing longer and adding resputter steps, a continuous seed for AR=6 can be achieved. Figure 8 shows an FIB image of an AR=6 via plated all the way to the bottom. These techniques can be extended to even higher ARs at the expense of throughput.

Figure 8. AR=6 via plated to the bottom using longer deposition and additional resputter steps

A disadvantage of collimated PVD is the potential for metal flaking from the collimator onto the wafer. To avoid this may require frequent collimator changes. By depositing both the adhesion-barrier and the seed in the same chamber, the collimator is coated with interleaved layers of two metals. This enhances adhesion to the collimator and balances the film stress. In this way the collimator cleaning cycle is extended. This technique, known as "pasting" is sometimes used for standard PVD in chambers that deposit only one metal. Separate pasting steps are done periodically to reduce flaking and extend the preventive maintenance cycle of the chamber at the expense of throughput. In the case that barrier and seed metals are deposited on the same collimator, pasting occurs with every deposition with no cost to throughput. As deposition builds up on the collimator, the opening will begin to close off. For the AR~1 collimator that produced the results shown in this paper, >100kW-hours of deposition reduced the openings <10% and showed no evidence of flaking or peeling. **Figure 9** shows this collimator after >100kW-hours of deposition. A slight rounding on the top edge of the collimator can be seen but there is no evidence of particulation. This was a stringent test since the chamber was vented many times during the testing. Exposure to atmosphere oxidizes the metal surfaces and can degrade adhesion.

Figure 9. Collimator after >100kW-hours of deposition shows little reduction in opening area and no evidence of particulation

Conclusions

The results presented in this paper show that the collimator approach to PVD deposition can be used to provide the seed required for electroplating to fill through-silicon vias in the same manner as other PVD techniques. It is particularly well suited for PVD system designs that use multiple target chambers, multiple wafer processing, and wafer scanning for uniformity. These systems have high throughput, low cost of ownership, and small footprints that make them well suited for the packaging market. As the roadmap for TSV pushes aspect ratios well above 5, all PVD techniques suffer from loss of throughput and therefore are more costly. Many new technologies are being pursued that will compete with PVD in this market, including CVD, particularly for the adhesion-barrier layer, and electroplated wet seeds for Cu. This approach is known as "direct on barrier." It is possible that PVD will eventually be circumvented by these other technologies. In the interim, there are many applications at AR=5 and <10 where PVD can still play an important role. The key will be to have the most reliable, cost-effective solution.

References

1. ITRS Roadmap, 2007
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