APPLICATION NOTE: AN 03

PILLARHALL LHAR4 – COMPARING THE CONFORMALITY PERFORMANCE TO OTHER HIGH ASPECT RATIO STRUCTURES

This application note describes how the PillarHall LHAR4 film penetration depth profile results can be used to predict conformality in any high aspect ratio structure, when the dimensions of these structures are known.

PillarHall LHAR4 chip measurement enables to quantify thin film conformality by simple and accurate method. Conformality is determined from **the film penetration depth profile** measured from the PillarHall Lateral High Aspect Ratio (LHAR) test structures. This procedure is described in detail in Application Note 02.

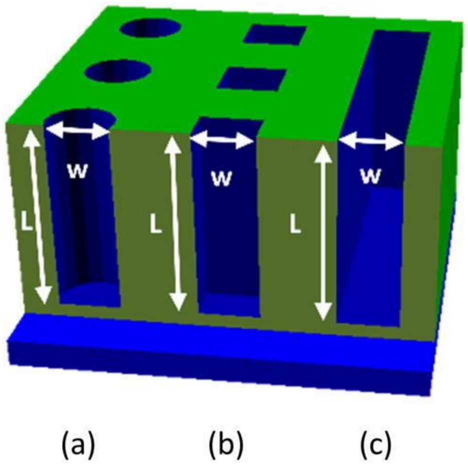
Conformality of the ALD or CVD thin film process depends on multiple parameters. Those can be cathegorized to 1) precursors and reaction kinetics (including molecular diffusion), 2) process conditions, 3) reactor design, and 4) high aspect reatio substrate geometry.

The PillarHall LHAR4 chip provides a set of standardized high aspect ratio structure geometries that enables to determine fast and accurately the influence of kinetics, process conditions and reactor parameters on thin film process conformality.

1. High Aspect Ratio: Variable geometries and dimensions

Typically, the final application of the conformal thin film process aims at certain High Aspect Ratio challenge. When presenting the correlation between PillarHall LHAR4 results and aimed high aspect ratio geometry requires some calculation.

The three basic high aspect ratio geometries are shown in Figure 1 and explained with more details in Ref [1].



(a) (b) (c)

Fig.1. High Aspect Ratio geometries:
(a) Cylindrical hole, (b) a square hole, (c) trench, with width w, and depth L

PillarHall LHAR structures are trench type geometry (as shown in Fig 1 c).
In many applications, the required HAR is a cylindrical hole (Fig 1 a), or even more complex shape.

The correlation between the geometries is based on a generalized expression for the aspect ratio (Ref [2]).

Equation (1): $a = \frac{Lp}{4A}$

with *a* being aspect ratio, *L* (m) being the depth of the hole, *p* (m) being its perimeter, and *A* (m^2) being the cross-sectional area. For trenches, the equation reduces to

$a=L/2w$,

while for holes it reduces to

$a=L/w$.

Since PillarHall LHAR is a trench, and if the aimed 3D structure geometry would be a hole (with similar dimensions) the effective aspect ratio in a trench will be 2 times less than in a hole.

2. Comparing conformality in PillarHall LHAR4 and other HAR structures

By using PillarHall LHAR4 in the experiments, the film penetration depth profile is obtained. The characteristic conformality measures can be exctrated from the profile. The following measures are needed to predict conformality in other HAR structures.

INPUT 1: PILLARHALL LHAR4 EXPERIMENTAL DATA VALUES

- *L [PillarHall]* = PD (Penetration Depth of the film) eg. PD at film thickness at 50% or 90% or PD95%, where % is relative film thickness compared to the thickness in the cavity opening.
- *d*= Film thickness in the cavity opening, or just outside the cavity

INPUT 2: TARGET STRUCTURE DIMENSIONS

Geometry and dimension of the targeted high aspect ratio structure
- *a* (target aspect ratio) for its corresponding geometry (see Fig. 1, and use Eq.1)
- *w* (width of the cavity, see Fig.1)

The comparison calculation is carried out for the same experimental conditions where the PillarHall LHAR measures were obtained. In that case, the conformality data depends on the aspect ratio of the substrate and we can state:

$$a_{PillarHall} = a_{Target}$$

By setting the PillarHall data and dimensions, as well as target's geometry and dimensions to the Equation (1), the Film Penetration Depth on the target can be solved for any HAR geometry by:

$$L_{Target} = L_{PillarHall} \frac{A_{Target}\, p_{PillarHall}}{p_{Target}\, A_{PillarHall}}$$

Where L [PillarHall] = PD, ie. film penetration depth in meters (typically in micrometers) value from the PillarHall experimental data. Then L [Target] = corresponding PD estimate for the target geometry. Since PillarHall LHAR structures in the main LHAR area have constant dimensions (Gap Height =500nm), the p/A [PillarHall] is constant 0,004 (nm).

3. Comparing PillarHall results to cylindrical holes

Since cylindrical hole is a common target HAR structure, the Table 1 presents the calculated comparison between PillarHall LHAR4 and various cylindrical hole diameters. The compared value is penetration depth distance (PD), which is known for PillarHall LHAR4 from the experimental data.

TABLE 1

PillarHall PD (microns)	Target dimensions hole diameter (nm)	Target estimated PD /target (microns)
100	200	20
200	200	40
300	200	60
400	200	80
500	200	100
100	100	10
200	100	20
300	100	30
400	100	40
500	100	50
100	50	5
200	50	10
300	50	15
400	50	20
500	50	25

Continuously increasing film thickness during the deposition shirinks the structure dimensions. Therefore, the film thickness has effect on the aspect ratio and film penetration depth. The comparison presented in Table 1 is accurate, when the film thickness effect is similar in both structures.

The equivalent (optimum) film thickness for the target structure for variable hole diameters and PillarHall experiment film thicknesses are given in Table 2.

TABLE 2

PillarHall Experiment Film thickness d (nm)	Target hole diameter (nm)	Target, equivalent film thickness d (nm)
100	200	20
50	200	10
20	200	4
10	200	2
5	200	1
100	100	10
50	100	5
20	100	2
10	100	1
5	100	0,5
100	50	5
50	50	2,5
20	50	1
10	50	0,5
5	50	0,25

In practice, the experimental design favours often same or similar film thickness in both: PillarHall LHAR4 chip and the target HAR structure.

In that case, the film penetration depth comparison should take into account the shrinking dimensions in very narrow cavities due to growing film. The Table 3 presents the predicted PD calculations for the target structure when film thickness is 5, 10 or 20 nm; and hole diameter varies 50, 100 and 200 nm.

TABLE 3

Equal film thickness used in
PIllarHall and target structure

Film thickness d (nm)	Target hole diameter (nm)	PillarHall PD (microns)	Estimate for Target PD (microns)
20	200	100	17,4
10	200	100	18,8
5	200	100	19,4
20	200	250	43,5
10	200	250	46,9
5	200	250	48,5
20	200	500	87,0
10	200	500	93,8
5	200	500	96,9
20	100	100	6,5
10	100	100	8,3
5	100	100	9,2
20	100	250	16,3
10	100	250	20,8
5	100	250	23,0
20	100	500	32,6
10	100	500	41,7
5	100	500	45,9
20	50	100	1,1
10	50	100	3,1
5	50	100	4,1
20	50	250	2,7
10	50	250	7,8
5	50	250	10,2
20	50	500	5,4
10	50	500	15,6
5	50	500	20,4

More modelling based calculations of the effects of various parameters are presented in Ref 3. Also, PillarHall experimental results with eg. variable gap heights are presented in Ref 4.

4. Designing PillarHall experiments and setting the objective

Once the target structure's geometry, dimensions and aimed penetration depth for the conformal films, as well as the target film thickness are known, the PillarHall experiments can be designed by using the same calculation principles. Table 4 presents PillarHall experiment objectives when target is cylindrical/square hole structure.

TABLE 4.

TARGET			**PillarHall**			
diameter (nm)	depth, PD (microns)	film thickness (nm)	Equivalent film thickness (nm)	PD (microns)	Experimental film thickness (nm)	PD (microns)
50	20	5	100	400	25	450
50	20	10	200	400	25	600
50	50	5	100	1000	25	1125
50	50	10	200	1000	25	1500
50	100	5	100	2000	25	2250
50	100	10	200	2000	25	3000
100	20	5	50	200	25	200
100	20	10	100	200	25	225
100	50	5	50	500	25	500
100	50	10	100	500	25	563
100	100	5	50	1000	25	1000
100	100	10	100	1000	25	1125
50	20	5	100	400	50	400
50	20	10	200	400	50	533
50	50	5	100	1000	50	1000
50	50	10	200	1000	50	1333
50	100	5	100	2000	50	2000
50	100	10	200	2000	50	2667
100	20	5	50	200	50	178
100	20	10	100	200	50	200
100	50	5	50	500	50	444
100	50	10	100	500	50	500
100	100	5	50	1000	50	889
100	100	10	100	1000	50	1000

References

Scientific articles

1. Conformality in atomic layer deposition: current status overview of analysis and modelling, V. Cremers, R.L. Puurunen, J. Dendooven, *Appl. Phys. Rev*. **6** (2019) art. 021302; https://doi.org/10.1063/1.5060967
2. A kinetic model for step coverage by atomic layer deposition in narrow holes or trenches, R. G. Gordon, D. Hausmann, E. Kim, and J. Shepard, Chem. Vap. Depos. **9** (2), 73-78 (2003). https://doi.org/10.1002/cvde.200390005
3. Conformality of atomic layer deposition in microchannels: impact of process parameters on the simulated thickness profile, J. Yim, E. Verkama, J. Velasco, K. Arts and R.L. Puurunen, https://doi.org/10.33774/chemrxiv-2021-2j4n1
4. Saturation Profile Based Conformality Analysis for Atomic Layer Deposition: Aluminum Oxide in Lateral High-Aspect-Ratio Channels, J. Yim, O.M.E. Ylivaara, M. Ylilammi, V. Korpelainen, E. Haimi, E. Verkama, M. Utriainen and R. L. Puurunen, *Phys. Chem. Chem. Phys*. **22** (2020), 23107, https://doi.org/10.1039/D0CP03358H

Product and service documents

- Application Note 2: PillarHall LHAR4 standard procedure in process monitoring
- PillarHall LHAR4 Product Data Sheet
- PillarHall Analysis Guide
- Chipmetrics Film Penetration Depth Profile Measurument Services
- Imaging Guide for PillarHall LHAR4

Further information

- www.chipmetrics.com (company web site)
- www.pillarhall.com (product and science behind PillarHall technology)