CHIPMETRICS

PillarHall® LHAR4 Test Chip Analysis Guide

PillarHall®

Contents

INTRODUCTION

PillarHall® Lateral High Aspect Ratio (LHAR) test chip is a product and brand of Chipmetrics Ltd. The PillarHall® test chip has been originally developed in VTT Technical Research Center of Finland for the analysis of thin film or thin film related processes in three-dimensional substrate. The PillarHall® test chip product was commercialized by Chipmetrics Ltd in 2020. The PillarHall® trademark is registered in certain countries and technology is patent pending.

The various development versions, product models and other information of the PillarHall® Test Chips as well as information of their typical use in analysis are described in this PillarHall® Analysis Guide. In addition, the text in the Analysis Guide refers to scientific articles, application notes, technical notes, as well as links and other additional information.

PillarHall test chip product offering at Chipmetrics

Chipmetrics product portfolio covers only the PillarHall LHAR4-ADVANCED-type layout and model with the nominal 500 nm gap height. The LHAR4-ADVANCED model has been proven to be the most reliable and user-friendly design compared to many earlier PillarHall model variations. Notice that the Analysis Guide refer at certain sections also the other LHAR designs.

PillarHall delivery

Chipmetrics sells PillarHall LHAR4 test chips in packages as illustrated in Fig.1 and as follows:

a. A box with 5 pcs of LHAR4 test chips (default number of chips is 5 pcs in a box, vacuum release tray box)
b. Introduction pack for new customers (same box as in (a.) + 2 training chips for tape pulling training)
c. Diced wafer package on the dicing tape (include c. 50 chips)

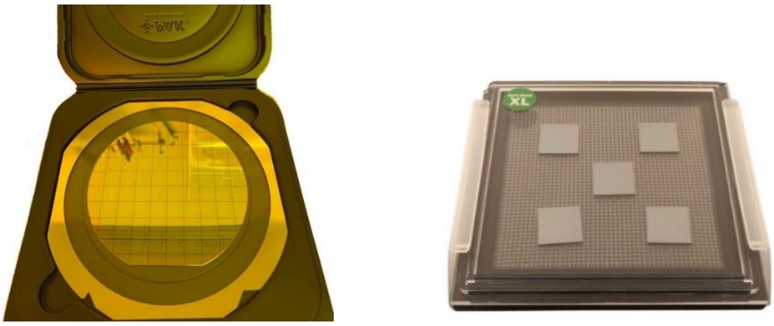


Figure 1. PillarHall shipment types. Left: diced wafer, Right: Vacuum Release Tray box..

The PillarHall test chips are delivered to all over the world from the Chipmetrics inventory in Espoo, Finland.

The delivery contains PillarHall LHAR4 test chips and following documents: a covering note (with product ID specification and tracking information of the shipment), chip handling guide and the certificate of conformance (CoC) and also other documents, if needed. New customers will receive also PillarHall Analysis Guide (this document).

Warranty

Chipmetrics makes available PillarHall® Lateral High Aspect Ratio LHAR4 test chips products for the following purpose: Recipient's internal experiments and analysis of thin film or thin film related processes in three-dimensional substrate. The product is fit to perform one (1) test per product. The chip handling guide defines the practices and instructions for the delivery inspection, chip handling and storage as referred in the warranty statement. Please, follow the guidance and instructions.

The full warranty statement and general terms are accompanied with the sales offer.

Manufacturing

The country of origin of the PillarHall LHAR4 test chip is Finland, European Union.

PillarHall test chip manufacturing is carried out in VTT's IC-compatible cleanroom in Micronova (Espoo, Finland) under agreement between Chipmetrics and VTT. The manufacturing process and product quality is assured by VTT Micronova personnel and management.

VTT Micronova's operating system is certified under quality standards ISO 9001:2015 and ISO14001:2015 and Chipmetrics operates in compliance with ISO 9001:2015.

Technology background

The core technology of the PillarHall® LHAR test structures is the existence of a wide area lateral air gap under the thin silicon membrane with controlled 500 nm gap height. The name PillarHall comes from the microscopic silicon pillars that stabilize the thin silicon membrane roof. This lateral 3D approach is the core invention and benefit of the PillarHall® technology. The controlled lateral high aspect ratio structures enable fast analysis of thin film conformality as described in this PillarHall Analysis Guide.

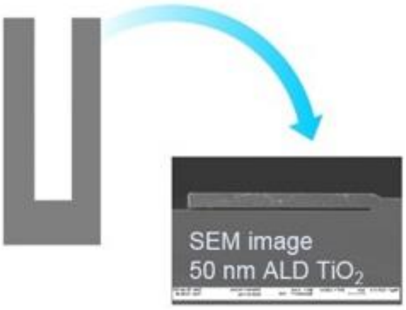


Figure 2. PillarHall® approach is based on the Lateral High Aspect Ratio (LHAR) test structures, not conventional vertical high aspect ratio test structures.

The LHAR substrate and its analysis concept is illustrated schematically in Figure 3. Schemes (not in scale) are shown before and after thin film deposition and after peeling off the top membrane.

Background of manufacturing

PillarHall® LHAR structures are fabricated on 150 mm silicon wafers by using various industrial and special validated MEMS-processes in the Micronova Micro- and Nanomanufacturing Center. In May 2017, the PillarHall 3rd generation prototypes (LHAR3-series) were introduced (test chip size 15x20 mm) and from July 2018 4th generation advanced LHAR4-series test chips (chip size 15x15 mm). Notice that in some published scientific papers the PillarHall chip models have been earlier prototypes or LHAR3-series.

The fabrication of the earliest, PillarHall 1st generation prototypes, was described in scientific article [*F. Gao, S. Arpiainen, R. L. Puurunen, J. Vac. Sci. Technol. A 33 (2015) 010601*]. The fabrication scheme of the 3rd and 4th generation is largely similar with 1st prototypes, while significant differences exist: for example, the pillars supporting the membrane are made of silicon in the LHAR3 and LHAR4 series while they were made of silicon dioxide in the 1st prototypes. The LHAR3 and LHAR4-series therefore have an **all-silicon** design. Common to all designs is that the last treatment experienced by the gap is an HF vapour treatment.

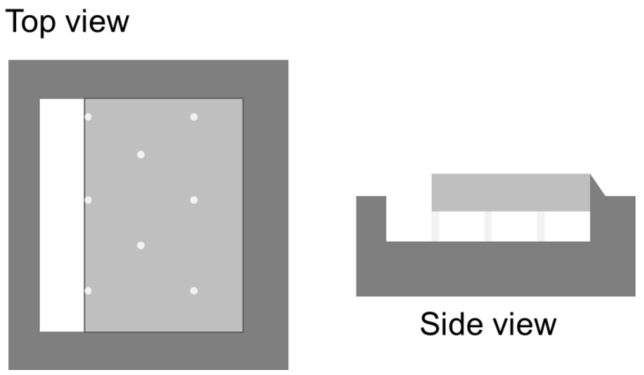
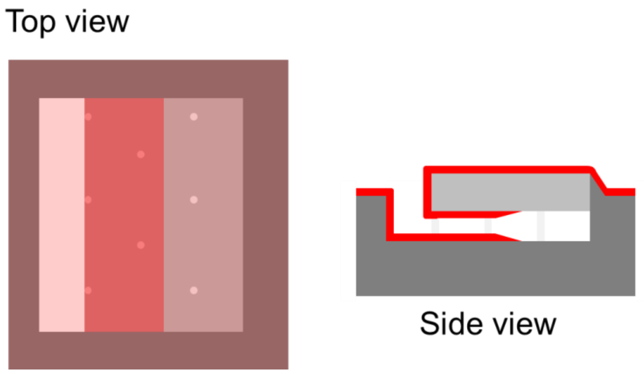
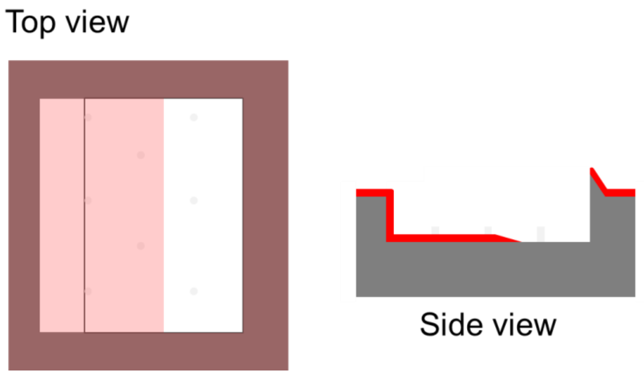
(a) Test structure before deposition	
(b) Structure after thin film deposition with ALD, CVD, …	
(c) Structure after peeling off the membrane	

Figure 3. Schematic presentation of the idea in lateral high-aspect-ratio test structures. (a) structure before deposition experiments, (b) structure after thin film deposition, (c) structure after peeling off the top membrane.

TEST CHIP DESCRIPTION

Over its existence PillarHall® Test Chips have been available in several version series, named as LHARx, where x is number between 1-4 reflecting the development generation such that LHAR4 is the most recent and most advanced version while LHAR1 was the earliest prototype.

TABLE 1. Specifications of the PillarHall ® LHAR4

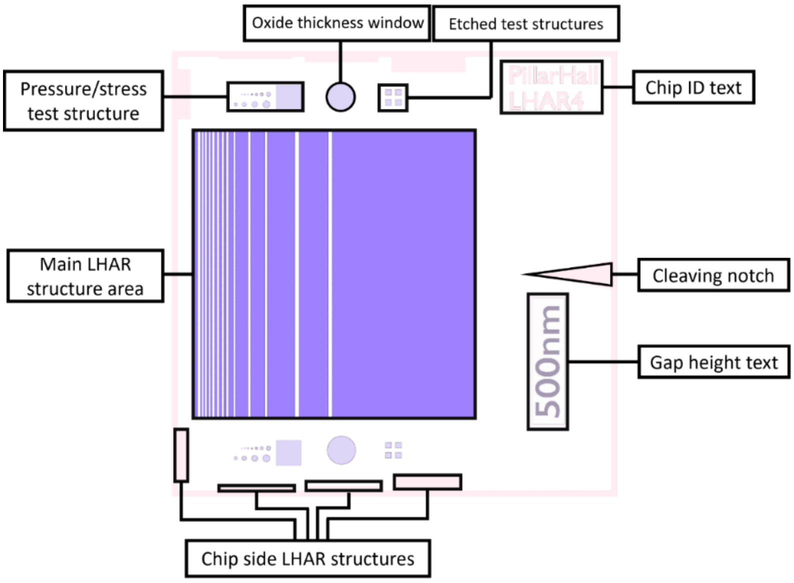
Technical specifications		Remarks
Product ID	PillarHall® Test Chip LHAR4	
Material	Silicon	
Chip size	15 mm x 15 mm	
Test structures	19 LHAR in the main area 8 LHAR in the chip side	Layout next page
Aspect ratios (AR)	From 10048:1; to 2:1 See the table in the next pages.	On 500 nm gap height (AR= *l : h*)
Gap height	*H (gap)* = 500 nm	
Gap width	$W_{(gap)}$= 10000 µm	In main LHAR structure area
Opening area ($W_{(opening)}$)	$W_{(opening)}$= 5 - 100 µm	Illustrated in Figure, details in Table
Temperature *	Up to 800°C	
Pressure *	From high vacuum to atmospheric	

LHAR4 chip layout

The PillarHall® LHAR4 Test Chip layout is shown in the Figure 4.

Text indicators

The target gap height can be viewed on the right.There is the version code (PillarHall LHAR4), and the chip number. Chip number will be useful for identification purposes, for unique identification, the chip number is used concurrently with the wafer code (not marked on chip).



LHAR4: CHIP SIZE IS 15 x 15 mm.

Figure 4. The main test structure area consists of 19 LHAR test structures. Each individual LHAR test structure has a different "opening width (w)" and a gap lateral width (l). Furthermore, there are 8 chip-side LHAR structures located at the edge of the chip which can be used for directional deposition test purpose. Rest of the test structures on the chip are for process monitoring purposes and several chip identification texts and cleaving notch.

Cleaving Notch

LHAR4 series have cleaving notch in the middle of the chip (Figs. 4 and 5). Cleavage is useful for cross-sectional SEM analyses or e.g. dividing sample to multiple analyses operations.

Figure 5 indicates the part of the chip which can be safely grabbed with wafer tweezers. Touching the main test structure area and other LHAR structures must be avoided, as the membranes are fragile.

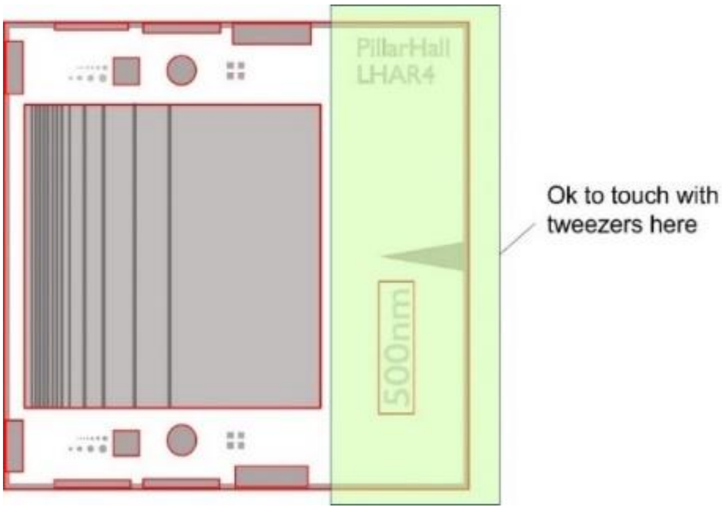


Figure 5. Indication of the area which can be safely touched with wafer tweezers.

LHAR test structures in the main test structure area

In LHAR4, the **main test structure area** consists of 10 different LHAR type test structures. There is a narrow opening gap with 1:240 aspect ratio structure located in the left side of the main test structure area.

Opening widths

Each individual LHAR test structure has a different "opening width (w)" and a gap lateral width (L), as illustrated in the Figure 6. The opening means the area located before the entry to the LHAR gap. The opening area is so wide that it is considered not to interfere the cavity penetration of the thin film or related process.

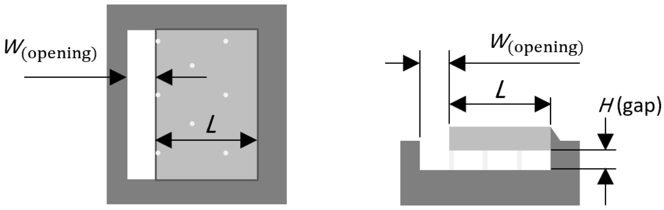


FIGURE 6. Schematic illustration of the opening width (w), lateral gap width (L) and gap height (H) used to specify different LHAR test structures in the PillarHall® Test Chips.

Each main area LHAR test structure has **an opening area** with different **"opening width" (w).** The opening area is located before the entry to the LHAR gap. The opening width in test structures varies from 5 micrometers to 100 micrometers.

The distinctly different opening widths in different LHAR test structures are due (i) to recognize the individual test structure through text codes in top-view analysis (especially microscopy) as well as in cross-sectional electron microscopy; and (ii) in top-view analysis as an additional length scale indicator.

Two directional and one directional LHAR

The largest LHAR structure with 5 mm length (l), rightmost on the main test structure area, is single-sided and not mirrored. The other LHAR test structures are mirrored, meaning that the LHAR cavity opens up on both sides from the opening in the middle. Figure 7 illustrates both types of test structures, mirrored and single-sided.

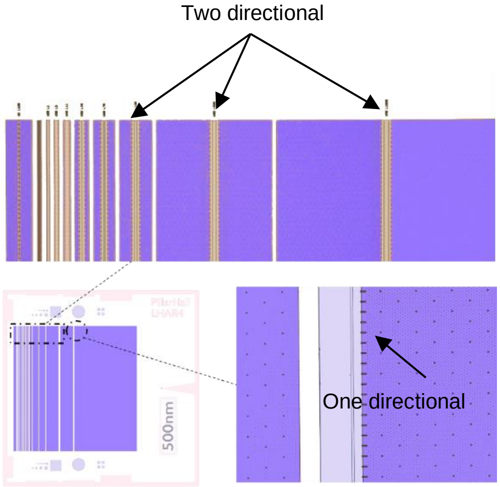


Figure 7. Example of top-view microscopy, the gap height is 500 nm. The structure W100L5mm is single-sided, whereas the other LHAR structures are mirrored.

Lists of individual LHAR test structures

In LHAR4, for 9 of the 10 LHAR structures (except W100 L5024, the longest gap lateral width structure), the opening is located in the middle of 2 mirrored gap structures. The Table below shows the opening widths and lateral gaps and corresponding code on the chip with nominal aspect ratio of each individual LHAR test structure on the main test structure area of the versions LHAR4.

TABLE 2: LHAR4 main test structure area LHAR test structures and their identification codes.

LHAR Structure ID	2-directional LHAR	Gap lateral width (l), µm	Opening width (w), µm	Aspect Ratio AR (L/H)
W100 L5024	No	5024	100	10 048 : 1
W90 L1020	Yes	1000	90	2 000 : 1
W80 L520	Yes	520	80	1 040 : 1
W70 L120	Yes	120	70	240 : 1
W60 L70	Yes	70	60	140 : 1
W50 L40	Yes	40	50	80 : 1
W40 L11	Yes	11	40	22 : 1
W30 L5	Yes	5	30	10 : 1
W20 L1	Yes	1	20	2 : 1
W5 L120	Yes	120	5	240 : 1

Vertical High Aspect Ratio structures (VHAR)

The main test structure area contains also vertical high aspect ratio (VHAR) test structure array as a reference. The location of the VHAR test structures is illustrated in Fig. 8 and the dimensional details of VHAR test structures are shown in Fig. 9.

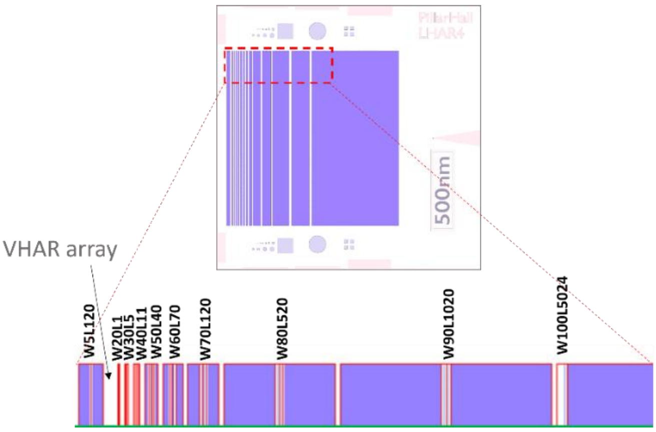


Figure 8. Location of the vertical high aspect ratio test structures in LHAR4.

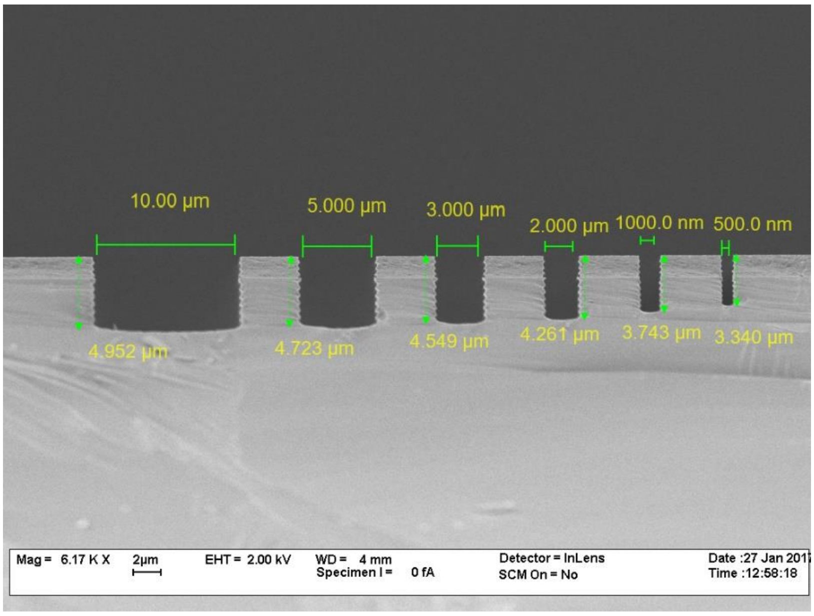


Figure 9. SEM cross-section image with dimensions of the vertical high-aspect ratio (VHAR) array test structures in the PillarHall LHAR4 Test Chip. The VHAR depths have c. 10% variation between individual chips.

Pillar designs

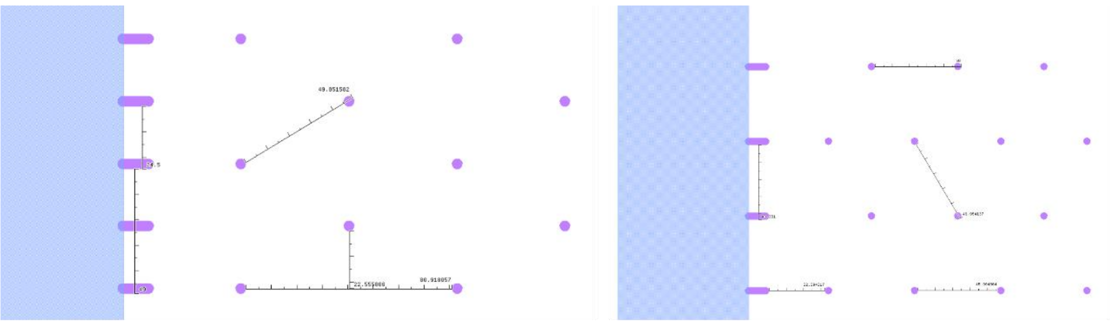
The silicon membrane roof of the LHAR test structures is stabilized by silicon pillars. Silicon pillars are characteristic to the PillarHall® technology. They are visible in microscope images as evenly distributed black spots. The development of pillar design has been crucial for optimizing usability, accuracy and reliability. The pillar designs have slight variations between test chip versions.

LHAR4 pillar designs

The LHAR4 series include 2 pillar designs identified as: 1) LHAR4-ADVANCED and 2) LHAR4-BASIC. These design differencies are illustrated in Figure 10.

The LHAR4-ADVANCED has further improved pillar design. In LHAR4-ADVANCED the pillar design have advantages over LHAR4-BASIC due to 1) less densely populated elongated pillars on the membrane edge and thus enabling even more easier membrane removal, 2) interdistance layout of the pillars enable larger line-scan spot sizes in characterization and 3) interdistances between pillars is 50 micrometers, making distance indication ruling easier for user.

The 2 different pillar designs in LHAR4 have no effect in deposited thin film conformality performance



LHAR4-BASIC LHAR4-ADVANCED

Figure 10. The 2 different pillar design in PillarHall LHAR4 Test Chips.

Gap height

The default gap height is 500 nm *H(gap)* as illustrated in Figure 11) in PillarHall® LHAR4 Test Chips.There are many examples of analysis of 500 nm gap height in this document.

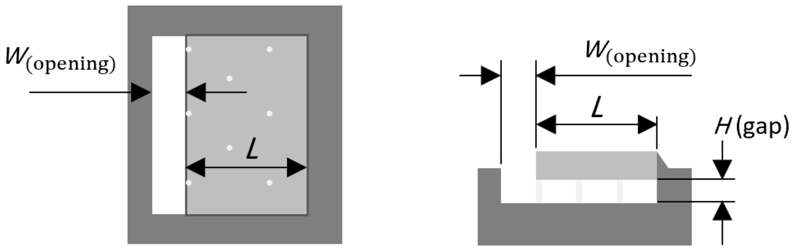


Figure 11. Gap height (H_{gap}) and other dimensional parameters *(w, L)* in PillarHall LHAR4 test chips.

The gap height is one critical parameter of the LHAR chips, what comes to the accurate analysis of the results. The gap height control is predominantly based on SiO_2 thickness control in VTT Micronova Fab. The fab has strict quality control operational and process monitoring procedures and SiO_2 thickness based gap height value relies on those. The final step in process is to etch SiO_2 totally away by HF vapour and that process step is to our understanding complete.

The quality control of gap height relies on following:
1) SiO_2 film reference thickness as monitored from PillarHall wafer,
2) optical profilometry of PillarHall wafers in special test points and
3) reference studies with e.g. AFM and cross-sectional SEM.

Dimensional uncertainties with the 500 nm gap height

The dimensional uncertainties to the best of our knowledge are due to

- Slight bending (< 20nm) of the membrane between pillars
- Small c. 5 nm step under the cavity, located c. 5 micrometers from the cavity edge point.
- Roughness of Si surface under the membrane
- Positioning the cavity edge point in analysis when membrane is removed (depends also significantly on the characterization method employed)

The 500 nm is optimum gap height due to its wide usefulness in various characterization and growth modelling approaches. It provides sufficiently wide distribution or penetration depth of the deposited thin film into the high aspect ratio structure and thus has good compatibility to larger spot size surface analytical tools. It has also good dimensional accuracy and good manufacturing reliability.

PillarHall test chip quality control relies on the thermal ALD process of Al_2O_3 (TMA+H_2O) at 300C, 500 cycles with defined protocol and profile measurement using line-scan reflectometer. Despite the inspection and quality control in manufacturing, the wide range of thin films and related process applications and conditions may lead to unpredictable concerns in interpretation and troubleshooting cases. Therefore, we **kindly ask all users to keep records of wafer and chip identification codes** used for each experiment and analysis. The test chip identification codes are given in the documents supplied with the delivery and marked on the test chips.

LHAR4: Membrane edge position indicator

In the PillarHall® LHAR4 version, there is an additional position indicator line on the opening area. It is designed to serve as a line-scan starting line to help analyses after membrane removal (namely exact position of the membrane edge after membrane removal is not always straightforward). The distance between the starting line to the real edge of the membrane is 20 µm. This is illustrated in Figure 12.

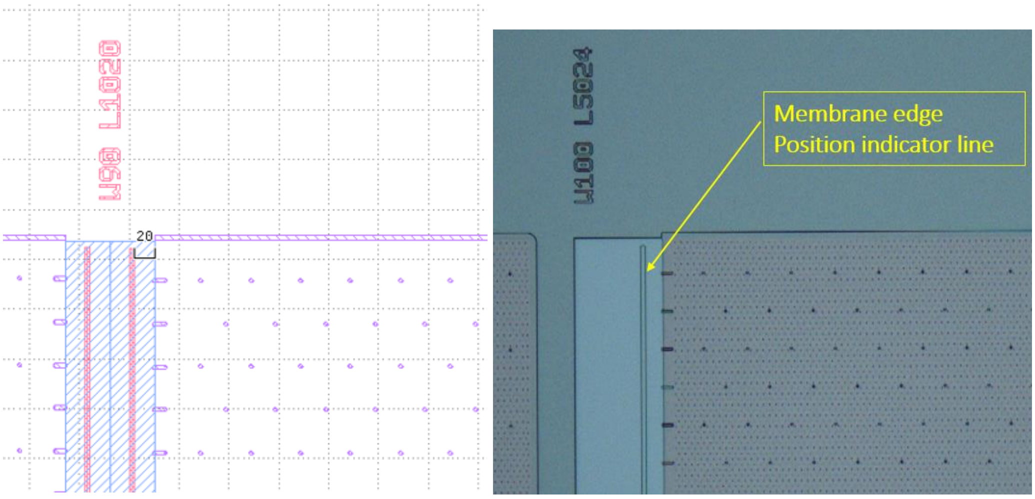


Figure 12. Membrane edge position indicator lines in LHAR4 in mirrored W90 L1020 (lef) and single-sided W100 L5024 (right) LHAR test structures. The distance from indicator line to the membrane edge is 20 micrometers.

Other test structures on the chip

In addition to the main test structure area, which contains both LHAR and vertical high-aspect-ratio (VHAR) structures, there are 8 additional LHAR structures **on the side edges** of the PillarHall® Test Chip. Their position in the chip layout is shown earlier in Figure 4. They can be useful when interest is **in directional thin film growth characteristics**. The gap height is the same as in main structure area LHAR test structures and their opening continues to the diced test chip edge as shown in Figure 13.

The other structures in the PillarHall® Test Chip contain eg. stress test structures which use is described elsewhere.

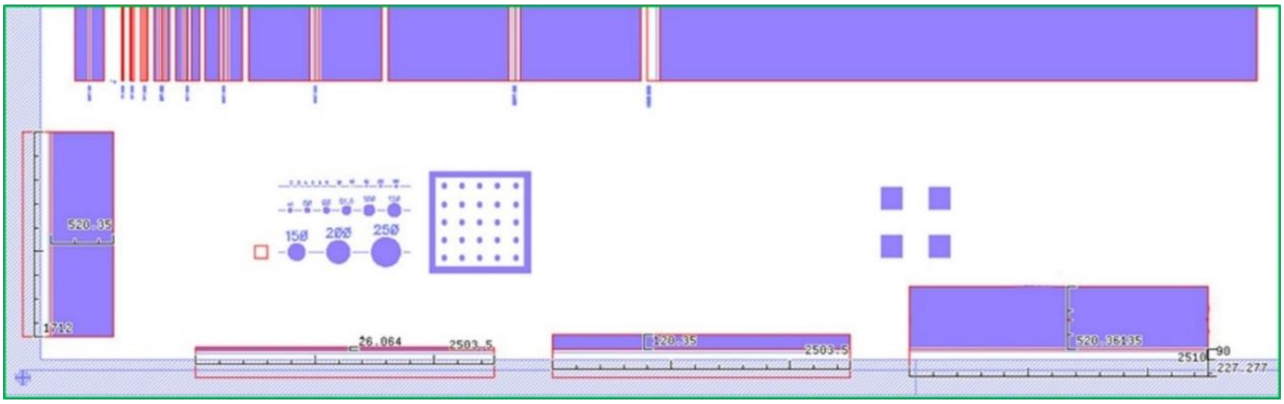


Figure 13. Chip-side LHAR structures in the PillarHall® LHAR4.

CHARACTERIZATION PRACTICES

While there are no standard ways of using the PillarHall® LHAR test chips yet and each user may develop their own practices, below are described some of the recommended and typically employed practices.

Microscopy analysis non-destructively after the coating

The simplest way of analysing the penetration depth is to take a **microscope image** after the thin film deposition. In a favourable case, one can see from a colour difference the extent to which the film has grown. Notice that penetration depth can indeed be visible through the silicon membrane and measurable from the test chip directly. This is because silicon membrane roof is such thin that it is in some extent transparent to visible light. The color differences are predominantly based on the changes in gap height due to deposited thin film into. The other factors influencing the image colors are optical constants of the material (n, k), film thickness and illumination light source. The microscopy analysis of the film penetration depth through the membrane should create highest throughput and measurement simplicity, although with limited resolution. Optical modelling tools can help user in designing the experiment in advance so that the effect becomes best visible in optical microscope.

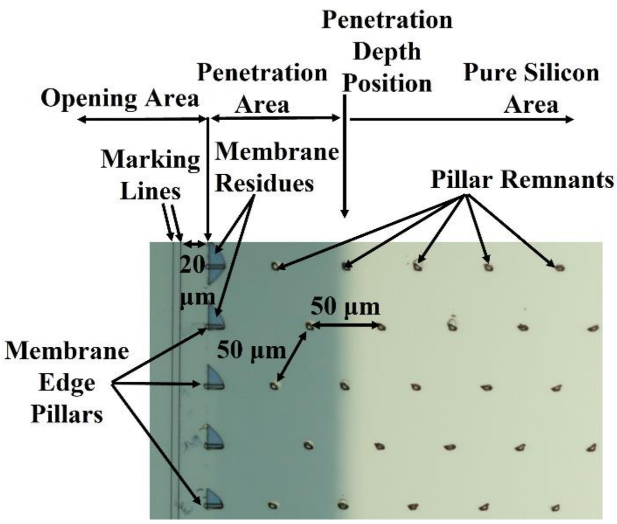


Figure 14. Top view microscope image after removal of the top membrane roof. Various indicators are used to improve the dimensional accuracy in the microscope image analysis.

From the digitalized microscope image, one can measure film penetration simply visually also e.g. with Pixel Ruler (https://pixel-ruler.en.softonic.com/) or other more sophisticated software. Notice that the distance indicators in the PillarHall LHAR structures are valuable for calibrating the dimensions. For example, Figure 15 gives an example how the opening width has been used as length calibration to measure a penetration depth of about 70 µm for the film. Also, the distances between pillars are useful for the length scale calibration purpose.

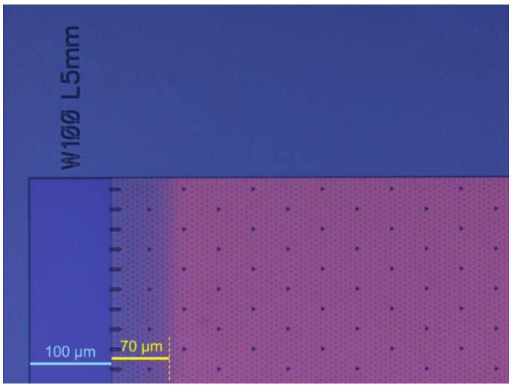


Figure 15. Example of measuring penetration depth of the deposited thin film in PillarHall by optical microscope through the silicon membrane (50 nm ALD TiO_2 film in LHAR3, gap height 500 nm).

In addition to visible light microscopy, some microscopes have options to operate in near-infrared range and even longer wavelengths and that way provide better visibility to the film penetration depth. This is especially due to the fact that silicon membrane has higher transparency in the infrared region. An example of the visible light filtered microscope image of the thin film in LHAR3 is shown in Figure 16.

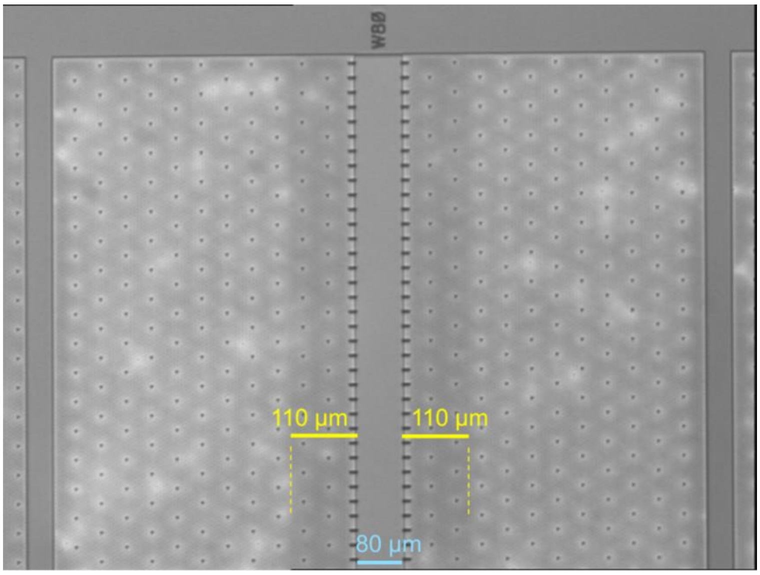


Figure 16. Example of measuring penetration depth of the deposited thin film in PillarHall by IR microscopy through the silicon membrane (Microscope: visible light filtered, CCD detector, Hamamatsu model C7500-II; Thin film: 50 nm ALD Al2O3; Test chip: LHAR3A, gap height 500nm).

Peeling off the membrane

Even more accurate information of the deposited thin film penetration depth as well as valuable information of structural and chemical properties of the thin films "on the trench wall" can be obtained after removing the silicon membrane. PillarHall® LHAR test chips have been designed so that one should easily be able to detach the membrane by applying adhesive tape. The peeling off the membrane is easy and straightforward requiring minimal training. Procedure to remove membrane is illustrated in Figure 17.

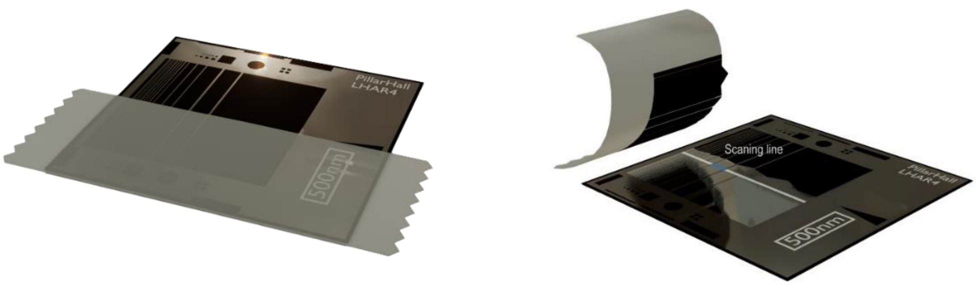


Figure 17. Example of removing the top membrane.

The elongated pillars at the entrance of the structure often result in incompletely removed membrane, as illustrated in Figure 18. For top-view microscopy this can be even useful, as it helps to determine, where the gap started. For thickness line scans and many other characterization solutions, remnants of the membrane are of course disturbing. Experience has shown that it is often possible to find areas, where the membrane between the pillars has been completely removed. Along the development rounds, the easiness of removing the membrane has improved. In LHAR4, there is typically less residuals than earlier versions.

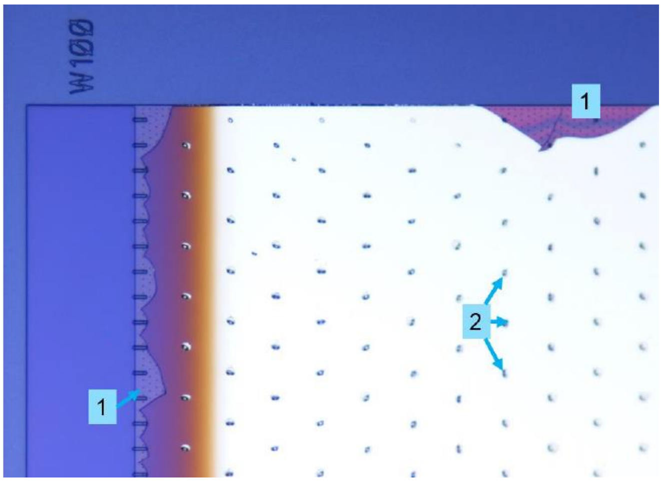


Figure 18. Example of a sample after peeling off the membrane by an adhesive tape. Typically, the membrane is lifted off from the main area and residuals tend to remain on the edge areas. (see text below)

Pay attention to the following which are visible and numbered in Fig.18.

1. **Membrane residues**: Especially elongated pillars at the entrance area often result in incompletely removed membrane. Caution when there is membrane residuals, they can disturb certain film characterization data.

2. **Pillar residues**: The pillar residues are actually holes on the underlying silicon surface, since pillars tend to remove with the membrane when peeled off by adhesive tape.

Visible-light microscopy analysis, after peeling off the membrane

Removal of the membrane exposes the deposited thin film for surface analysis, as shown schematically in Figure 3(c) and above. In Figure 19, an example of the measurement of the film penetration depth from the visible light microscopy after removal of the top membrane is given. Same sample visualized through the membrane was shown earlier in Figure 15. Gradual change of colour becomes observable. Color variation can be employed also to quantify penetration depth profile (and paying attention to proper calibration). In this case, clear colour differences are observed at distances of about 36 and 73 µm from the entrance.

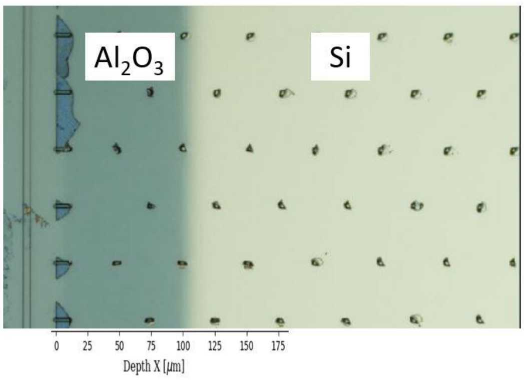


Figure 19. Example to measure penetration depth of the deposited thin film on PillarHall by optical microscope after removal of the silicon membrane (50 nm ALD Al_2O_3 film in LHAR, gap height 500 nm).

Line scan example by reflectometry after removal of the membrane

By measuring a thickness line scan, one can accurately evaluate the thickness profile inside the high aspect ratio trench. Assuming the reflectometry is calibrated properly for the employed thin film material.

Figure 20 shows the microscope images of LHAR as well as measured values for the thickness series obtained by varying the number of ALD cycles.

The averages of individual measurements lead to graph shown in Figure 20 and that graph can be used to extract data of thin film process characteristics for conformality. This data can be utilized in process tuning as well as in reaction kinetics modelling and eventually for monitoring and control of the thin film processes.

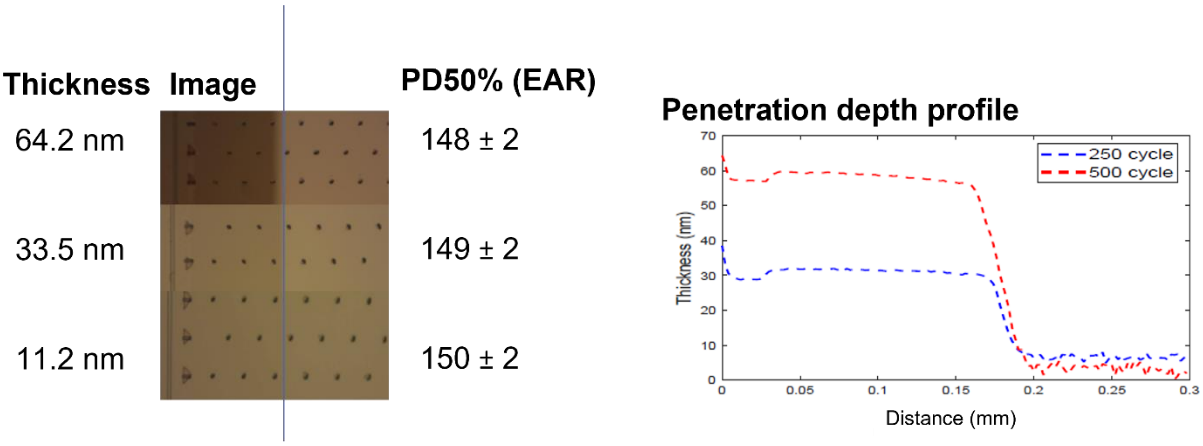


Figure 20. Results from the film thickness series of ALD Al2O3 of 500, 250, and 125 ALD cycles. The film penetration depth for 50% film thickness (PD50%) is calculated by a software tool from the image. The value for conformality is given as a hole equivalent aspect ratio (EAR) which is the same as film penetration depth in micrometers in 500 nm gap height and wide lateral trench.

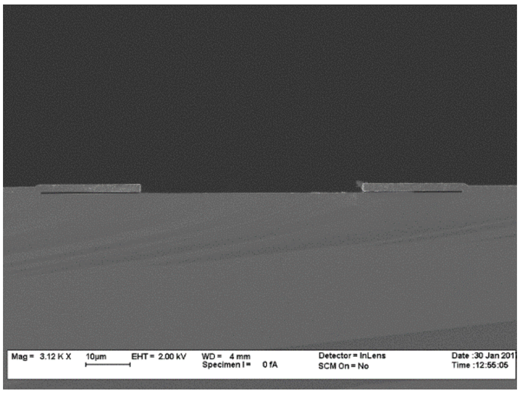
Other ways to measure by using surface analysis tools

There are lots of different compatible surface analysis tools that can be employed with PillarHall. In addition to those described above, we have gained good experiences with plan view SEM/EDS, AFM, XPS, ellipsometry (with focused spot size), confocal microscopy and various reflectometry instruments with small optical spots for line-scans as well as those providing spectral imaging capabilities.

Scanning electron microscopy of cross sections

Cross-sectional electron microscopy is the traditional way of analysing vertical high-aspect-ratio test structures, and as a reference to this state-of-art, one may want to take cross sections of the LHAR structures, too.

Examples in Figure 21 show results for a chip, cut manually in half by scratching with a diamond pen, and thereafter imaged by SEM. This case shows a film of ~50 nm of TiO2 in the W50L22 structure. Film thickness is the same at the entrance and at the bottom of the test structure. The gap opening is slightly larger at the opening. It is believed that the structure has been straight during the ALD experiment and the opening has taken place during the cutting of the sample for SEM observation.



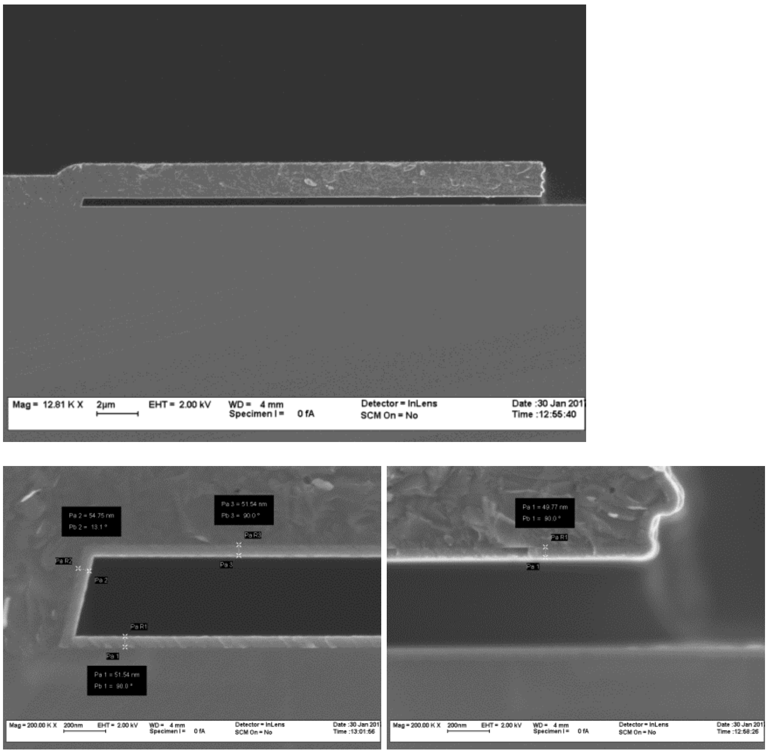


Figure 21. Examples of SEM cross-sections of ~50 nm ALD TiO2 inside W50L22 structure.

ANALYSING THIN FILM GROWTH WITH PILLARHALL®

While LHAR structures can also be analysed as cross sections, the possibility to make top-view analysis greatly expands the analysis possibilities of a single test structure. After removal of the top membrane, thickness profile can be measured by any technique which has an appropriate xyz-resolution. For example, small microscopic spot size in spectroscopic methods (like reflectometry, scatterometry or ellipsometry)- from micrometers to some tens of micrometers should be suitable. Assuming that the coating does not penetrate to the end of the gap, which is many times unlikely for an aspect ratio of 10000:1, in the thickness profile, the film termination profile becomes visibile. In ALD processes, the film termination profiles have been used as a qualitative measure of process aggressiveness in underdosing experiments carried out in cross-flow reactors; with microscopic LHAR, film termination profiles can be measured also for other types of reactors (showerhead, etc). Using full wafers, where test chips are at different locations on a carrier wafer, it further becomes possible to quantify the uniformity of a 3-D coating process.

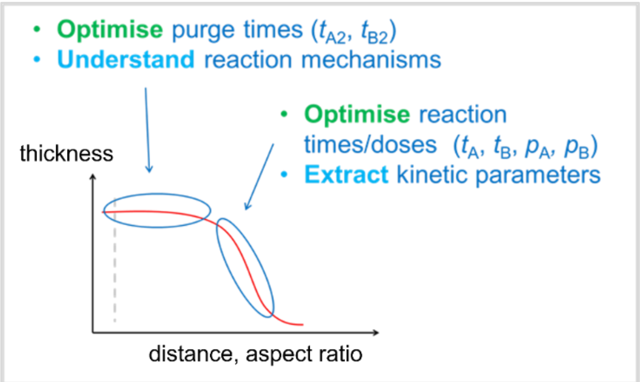


Figure 22. Schematic representation of a thickness profile in ALD thin film process and a proposal for interpretations which can be made on the basis of them.

The LHAR structures in the PillarHall® Test Chips expose parameter spaces which have been inaccessible before. Likely, the measurement results will reveal phenomena earlier unseen. This is one of the features which makes PillarHall a promising new data source to accelerate thin film R&D as well as material science. To facilitate comparison of different experiment, Figure 23 shows the parameters which are proposed by the developers of the chips to be paid attention to in experiments.

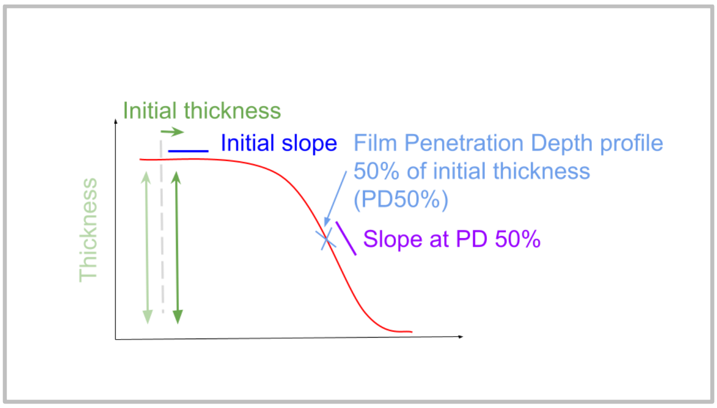


Figure 23. Proposed parameters to be experimentally recorded for LHAR line scans.

HOW TO COMPARE THE CONFORMALITY PERFORMANCE TO OTHER HIGH ASPECT RATIOS STRUCTURE

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.
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.

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 24 and explained with more details in Ref [1].

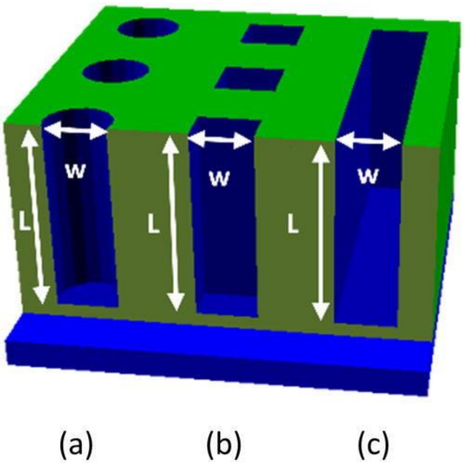


Figure 24. High Aspect Ratio geometries: (a) Cylindrical hole, (b) a square hole, (c) trench, with width w, and depth L

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.

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).

APPLICATIONS OF PILLARHALL

PillarHall LHAR4 test chip is a measurement tool to fast and easy development of ALD/CVD process parameters to meet high aspect ratio substrate requirements. PillarHall LHAR measurements has been also used to demonstrate the capability of conformality of ALD thin film processes. The record public demonstration is 4000:1 high aspect ratio conformal thin film deposition by stop-flow-type ALD process.

Wafer level conformality measurment
In wafer level conformality monitoring we recommend 5-7 chips positioned on center and edge areas of the carrier wafer. Particularly useful and safe approach is to use carrier wafers having eched pocket holders for the LHAR4 chips. Presently, Chipmetrics offers 150 mm and 200 mm pocket wafers targeted for wafer level conformality monitoring.

More information can be obtained from **Application Note – PILLARHALL LHAR4 STANDARD PROCEDURE IN PROCESS MONITORING.**

PillarHall LHAR4 - USE IN DIRECTIONAL DEPOSITION
In PillarHall LHAR4 test chips, there is several test structure use scenarios and experimental arrangements that can help in directional thin film growth process studies. Those are:

- Penetration depth evaluation from 4 major compass directions
- Vertical aspect ratio reference structures
- Opening area variation in AR=240:1 structure
- Positioning the test chip vertically in the deposition reactor chamber

Please refer **to Technical Note - PillarHall LHAR4 USE IN DIRECTIONAL DEPOSITION** for more information.

PillarHall LHAR4 – Compatibility to PE and CVD processes
PillarHall LHAR4 test chip (and its previous model LHAR3), has been used predominantly in ALD process development. However, the high performance in CVD and plasma enhanced process development has also been demonstrated.

More information about PillarHall compatibility to PE – CVD are provided in Application note - **PillarHall LHAR4 – Compatibility to PE – CVD**.

Compatiblity with atomic layer etching (ALE) studies
Upon request we can offer tailored pre-deposited ALD thin films onto PillarHall test chips to study ALE.

DELIVERY

Vacuum Release Tray

The PillarHall test chips are packed and delivered vacuum release trays (VR trays, Figure 25). The following links provide assistance regarding the use of VR trays:

- YouTube video on sample release from a VR tray: https://youtu.be/3978cTLZybo.
- Gel-Pak's VR accessories: http://www.gelpak.com/--vr-accessories

The shipment includes the chips packed in the VR trays and documents related to delivery.

Figure 25. Example of PillarHall chips delivered in a vacuum release box.

Chip identification

Each chip on the delivered pack has identification code to trace it back to the manufacturing process. The ID code mark is on the chip as well as with more defined coding given to user upon delivery (either written on the cover note letter or written on the delivery pack).

We advise users to keep record of this chip code through their experiments and analysis. It will help us to help you, if the experimental results will need any specific and unexpected problem solving or further studies to ensure your conclusions.

REFERENCES AND FURTHER INFORMATION

Product documents:

- PillarHall Chip Handling Guide
- PillarHall Warranty Statement and General Terms for PillarHall Test Chip Products
- PillarHall LHAR4 Data Sheet
- Technical Note TN-01: PillarHall LHAR4 Measurement Uncertainty and Surface Roughness
- Technical Note TN-02: PillarHall LHAR4 Use in Directional Deposition Process Studies
- Application Note AN-01: PillarHall LHAR4 Compatibility to PE-CVD

Video links:

- Animation introducing PillarHall Test Chip: https://www.youtube.com/watch?v=hOuprlmLy2E
- Video: How to Use PillarHall Test Chip: https://www.youtube.com/watch?v=860t2ZfJi20
- Video: How to remove Membrane by an Adhesive Tape: https://www.youtube.com/watch?v=mos-BfXHgjQ

Scientific articles (Full list at: http://pillarhall.com/references.htm)

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

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

Film Conformality and Extracted Recombination Probabilities of O Atoms during Plasma-Assisted Atomic Layer Deposition of SiO_2, TiO_2, Al_2O_3, and HfO_2, K. Arts, M. Utriainen, R. L. Puurunen, W. M. M. Kessels, H. C. M. Knoops, *J. Phys. Chem. C* 123 (2019), 44, 27030-27035, https://pubs.acs.org/doi/10.1021/acs.jpcc.9b08176

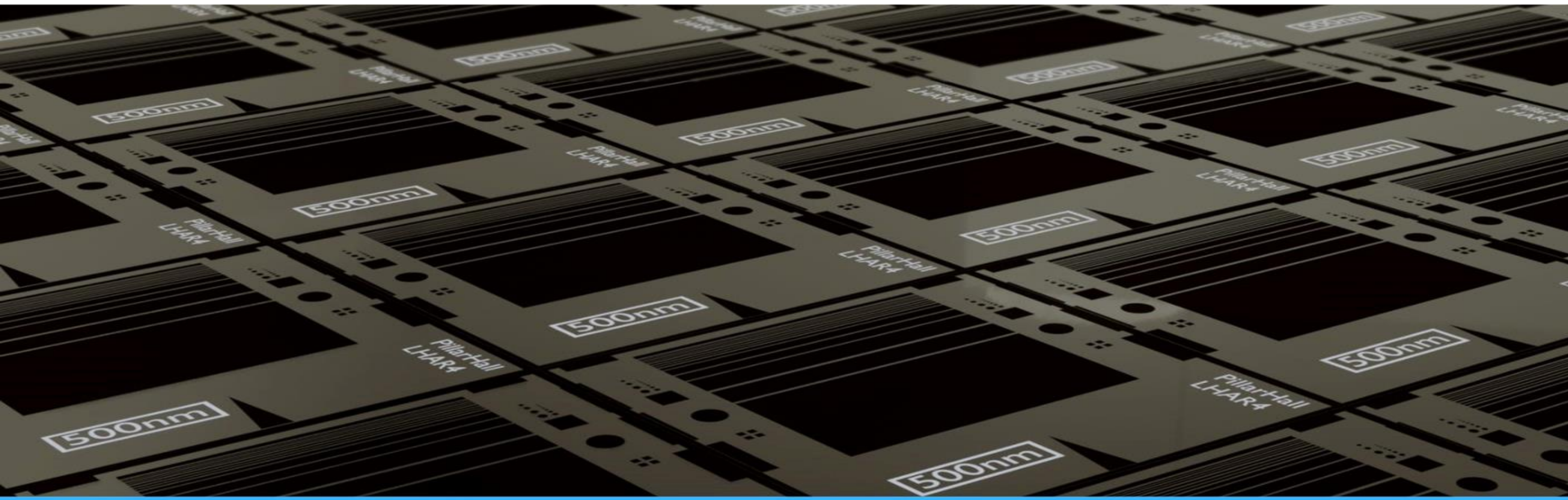
Sticking probabilities of H_2O and $Al(CH_3)_3$ during atomic layer deposition of Al_2O_3 extracted from their impact on film conformality, K. Arts, V. Vandalon, R.L. Puurunen, M. Utriainen, F. Gao, W.M.M. Kessels, H.C. Knoops, *J. Vac. Sci. Technol. A* 37 (2019) art. 030908; https://doi.org/10.1116/1.5093620

CHIPMETRICS SERVICES AND SUPPLEMENTARY OFFERINGS

In addition to PillarHall® Test Chips, Chipmetrics Ltd offers also services, as follows:

- Optical microscope image analysis service. This service transfers microscope image to a relative conformality data (ie. film penetration profile and graph).
- Measurement services (eg. by calibrated thickness line-scanner) as a third party service.
- Customized chips, customer proprietary chip design, R&D project services for other test chip designs.

Chipmetrics offers also special carrier wafers for the wafer level use of PillarHall LHAR4 test chips (150 mm and 200 mm silicon wafers, containing etched pockets, specifically designed dimensions for the LHAR4 test chips). Our know-how and technical support eg. for characterization, modelling, ALD and MEMS-processes are also available to our customers.



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@chipmetrics

info@chipmetrics.com
www.chipmetrics.com
+358 40 753 7415
Address: Länsikatu 15, Joensuu, Finland