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IonScan 800 – Ultra-precise film thickness trimming for Semiconductor Technology

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Summary

Many applications in semiconductor technology are characterised by extreme requirements in terms of film thickness homogeneity. When manufacturing Bulk Acoustic Wave (BAW) components, it is necessary to adjust film thickness values of different materials with accuracy values in the nm-range. Standard processes, such as the film deposition technique, do not fulfil these homogeneity requirements. Thus it is necessary to perform local correction of the film thickness in a follow-up process. [1,2]

The authors here introduce a new method of local film thickness trimming and its technical implementation. During the process, the wafer is moved in front of a focussed ion beam. The local milling rate is controlled upon the residence time of the ion beam at certain positions. A modulated velocity profile is calculated specifically for each wafer, in order to mill the material at the associated positions to the target film thickness.

Depending on whether an inert or reactive ion beam process is used, it is possible to apply the IonScan technology for any material desired, such as Si_3N_4, SiO_2, Al_2O_3, AlN, W or NiFe.

1. The principle of the ion beam trimming technology

Over the past years, ion beam technologies have increasingly found their way into material processing in optics and semiconductor technology. The reason for this success is based on the characteristics of the ion beam processes outbalancing alternative technologies in terms of quality. In ion beam methods, the ion angle of incidence may be adjusted in a defined manner. Moreover, the process is characterised by a narrow ion energy distribution, controllability of the ion beam composition, as well as a high time and spatial constancy of the ion flow. Consequently, ion beam methods are mostly used for large area milling processes whose removal depth accuracies get close to the atomic scale. These procedures enable homogeneous removal or structuring with outstanding anisotropy characteristics across the whole substrate surface. [3-5]

Ion beam technologies not only allow a homogeneous substrate removal, but also locally resolved etching by controlling the local ion dose. Upon this dose, it is possible to correct heterogeneities of particular characteristics. When correcting film thickness or depth values of a structure, an error function gets etched down to the required function. The terms “ion beam trimming“ or “ion beam correction“ were introduced for this technique.

Ion beam trimming can be performed with either an aperture- or a residence time method. In the aperture method, a large surface ion beam gets shaped with a shutter system in its temporal progression. The local ion dose is controlled in a defined way by variable aperture windows of different size, that are chronologically consecutive. However, the technical effort implementing the aperture method is notably high. At the same time, the process rates are low due to blanking a large share of the ion beam. Consequently, the aperture method is normally out of question for use in a production environment.

It is much easier to control the local removal characteristics by means of the residence time method. The residence time method uses a focused ion beam, which is moved in relation to the substrate to be corrected according to a defined motional strategy. It is possible to calculate the required residence time values at the corresponding positions and the appropriate motional mode being aware of the static etch profile of the ion beam. The basic process arrangement of the residence time method is shown in Fig. 1.

The residence time method does not require any additional aperture or shutter systems. This method always utilises the ion beam to its full extent for etching, and small-sized and economic ion sources are sufficient. For these reasons, the residence time method is commonly superior to the aperture method, both under technological and economic aspects. However, using the residence time method demands a sufficiently low width of the ion beam versus the local wavelength of the surface errors to be corrected.

A 2-axis system is required to implement the residence time method in order to carry out the necessary relative motion between the ion source and the surface. The layout of the axis system mainly depends on the motional strategy. Present default is to scan the surface following a meander-shaped course (Fig. 1). In this case, the performance of both axes may be clearly different, since one of the axes has only a linefeed function.

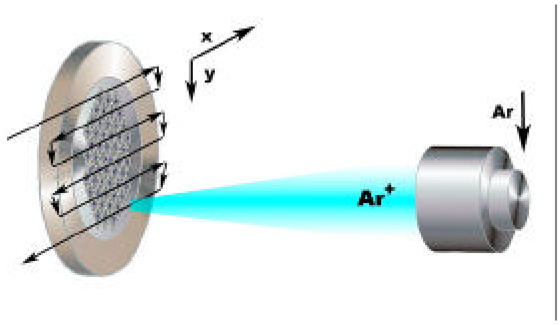


Fig. 1: *Function diagram of film thickness trimming controlled upon residence time*

Specific process variations may necessitate more complex axis systems. In the majority of cases, another axis in the substrate surface normal direction is used to adjust the ion source. This axis cannot only be used for feeding, but also for optimal adjustment of the ion beam focus.

In addition to milling removal, the ion beam can also be used for smoothing the surface and reducing the micro roughness values. To carry out these processes, it is necessary to adjust a defined ion angle of incidence and thus to tilt the substrate normal. For application in optics, to obtain the surface radii of curvature, it may be required to track the ion source along the surface normal and to control the etching distance. An axis system for such applications should have 2 tilt and 3 linear axes.

2. IonScan 800 system layout

The IonScan 800 system is designed for wafer based film thickness trimming in semiconductor technology. With the handler and the process module, it is possible to create a cluster layout of the entire system, which is able to integrate both two load-locks and up to three process modules (Fig. 2).

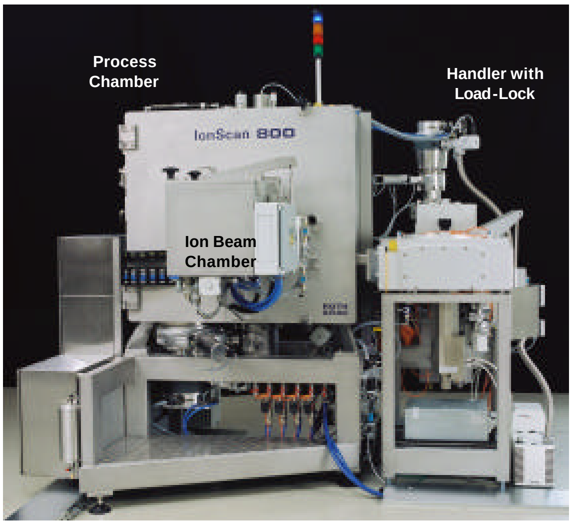


Fig. 2: *General view of the IonScan 800*

The process chamber is fed with a 4 port handling robot (Fig. 2 right) by Brooks Automation Inc. or ASYS Automatisierungssysteme GmbH & Co. KG. The robot comprises a separately pumped load-lock, fitted with cassette lift and indexer, as well as a prealigner with combined OCR and barcode reader. A cluster system with a number of process chambers can be set up by any residual port allocation desired.

The system components for ion beam trimming are housed in the process chamber (Fig. 2 left). The chamber size is about 0.80 m x 0.80 m x 0.50 m. Approximately 5 x 10^{-5} Pa residual gas pressure is feasible with the turbomolecular pump set (2300 l/s). All door flanges are fitted with double Viton O-rings and are pumped differentially.

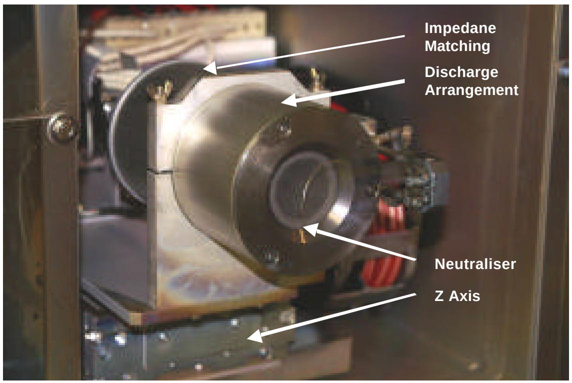


Fig. 3: *Filament-free RF ion beam source cyberis 40-i (Shields to protect against redeposition removed.)*

An additional chamber at the front door houses the ion beam source to be accessed for maintenance activities upon a separate lid. A filament-free ion beam source cyberis 40-i made by Roth & Rau is used in the IonScan system (Fig. 3) [6]. The source is mounted completely in the vacuum with discharge chamber and impedance matching. The plasma excitation consists of a primary cylindrical coil supporting the discharge housing in the middle. According to the ICP principle, radio frequency power (13.65 MHz) is transferred inductively to the gas discharge. The full RF impedance matching is integrated in the rear part of the source housing. Thus, the source may be supplied with a 50 Ω coaxial cable of arbitrary length. In addition to the ion beam source, a hot filament or a RF neutraliser are used to neutralise the ion charge during processing of isolating substrates.

Three different focussing multi-aperture grid systems made of graphite are available for the source. Each system consists of 3 individual grids of different geometry, which enable intentional control of both the ion flow and the focus characteristics. With the grid systems, it is possible to achieve a maximal total ion flow to 100 mA, as well as up to 2 keV ion energy. Typically, the processes on the IonScan 800 are run at a current ranging from 30 mA to 50 mA and an ion energy from 1.2 keV to 1.5 keV.

It is possible to adequately fit the beam current profile of the ion beam by means of superposition of the Gaussian functions. The ion beam width is a relevant criterion for the film thickness correction quality (s. pt. 3). For typical film thickness errors, a beam profile standard deviation of 5...10 mm is sufficient for a satisfying machining result. With the cyberis 40-i, it is also possible to achieve standard deviations down to 2 mm without reduction of the total beam current. The ion beam standard deviation is mostly influenced by the geometry of the grid system and the D.C. voltage applied. Ion current densities up to 20 mA/cm^2 are generated in the ion beam focus under typical operating conditions.

In most of the processes, the ion beam source is run with inert gases (Ar, Xe). The discharge chamber of the source is completely made of aluminium oxide, so that fluorine-containing process gases are used without any constraint, too.

At the right of Fig. 4, the axis system with the wafer chuck are shown at opened chamber door. The axis system is dimensioned to machine wafers up to 200 mm. Wafer chucks are available in versions with 4“, 5“, 150 mm and 200 mm, both for wafers with flat and with notch.

The wafer chuck is equipped with a clamping and transfer mechanism actuated by compressed air. The handler places the aligned wafer on 4 lift-off pins. The pins and the clamping ring are pneumatically operated and press the wafer against the body of the wafer chuck. A helium back side cooling is used for efficient heat transfer from the wafer to the water cooled chuck body. With this cooling principle, a power input of typically 100 W may be deduced efficiently out of the ion beam. As a rule, the resultant temperature at the wafer front side is below 120 ^{o}C, so that it is possible to process even wafers with photoresist without any problem.

In addition to ion beam source and wafer chuck, the following components are functionally relevant:

Rotational axis:

The wafer chuck is mounted on a rotational axis. The rotational axis is first of all designed to tilt the wafer from the horizontal handling into the vertical processing position. It is possible to continuously vary the tilting angle of the wafer holder from 0 to 100 deg. Generally the wafer is processed

Fig. 4: *Interior view of the process chamber with ion beam source (left) and axis system with wafer chuck (right)*

at vertically incident ions, but one may also adjust any angle of incidence desired in order to increase the process rate.

X-Y axis system:

The x-y axis is designed to run the calculated residence time profile. The x-axis is equipped with a linear drive. Providing velocity values up to 500 mm/s and acceleration values of 20 m/s^2, one may exactly run the residence time data. Due to the high velocity, base etching may be kept very low, at 0.5 … 1 nm only. Base etching defines the minimal removal carried out at each position of the wafer. The y-axis is designed for linefeed in the meander shaped motion, it is engineered as a spindle axis.

Z axis:

The z-axis is applied for positioning of the ion beam source related to the wafer. This way, the exact focus distance may be adjusted automatically. The z-axis is additionally necessary to process the wafer if the ion angle of incidence is different from 90°. Focus distance to the current line is automatically readjusted with each linefeed.

Faraday array:

The IonScan 800 system is equipped with a Faraday array consisting of 2 x 8 current probes. The probes and the wafer holder are mounted on the axis system. With the Faraday array, it is possible to run a complete current density profile of the ion beam within a few seconds. The array is used for routine check of the ion beam stability. Thus it is designed to determine the exact focus position of the ion beam related to the wafer as well as the current density profile of the source can be mapped.

All IonScan 800 components and functions are controlled upon a PC system. The system environment is fitted with various modes for manual and automatic wafer processing, recipe administration, an MS SQL data base to log the system operation data, as well as an SECS/GEM interface for the process control system.

3. Process flow and calculation of residence time

To fulfil with the high homogeneity requirements in the IonScan applications, each wafer has to be processed in a specific way. Before ion beam trimming, it is required to measure the film thickness error of each wafer separately. This measurement is regularly carried out by an appropriate metrology (RF probes, Ellipsometry).

As the first next step, it is necessary to calculate the residence time for a known etch profile of the ion beam. The mathematical representation of the problem leads to a convolution between the residence time t(x,y) to be found and the etch function R(x,y) of the ion beam, which has to be comply with the film thickness error $z_0(x,y)$ (Fig. 5). The two-dimensional etch function of the ion beam has to be found with static and dynamical test etching operations, which are carried out specifically for each material and for each parameter set of the ion beam source.

$$\begin{aligned} z_0(x,y) &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} t(x',y')\; R(x-x',y-y')\; dx'dy' \\ &= t(x,y) \circ R(x',y') \end{aligned} \qquad /2.1/$$

In the frequency domain, convolution operations can easily be executed as multiplications of the Fourier transformed functions.

$$FT[z_0] = FT[t] \cdot FT[R] \qquad /2.2/$$

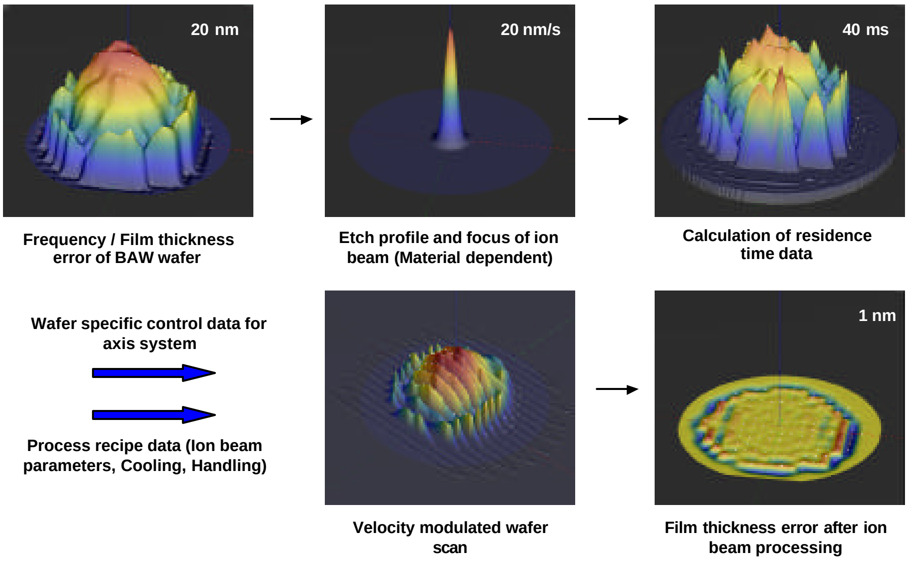


Fig. 5: Flowchart representation of wafer processing on the IonScan 800

As a result, the inverse problem turns out to be in the frequency domain as follows

$$t = FT^{-1}\left[FT[z_0]\,FT[R]^{-1}\right] \qquad /2.3/$$

Inverse problems are generally known as sophisticated subjects in mathematical and numerical techniques, and are mostly used for applications in image processing. [7] Real problems according to /2.4/, as a rule, can not be solved exactly, they can only be solved as approximations. Approximate solutions for t(x',y') may be found by iterative methods when predefining special objectives or target criteria. In any case it is necessary to do additional arrangements in order to make these methods numerically stabile.

When executing the iteration in the frequency domain, transformation back into the space domain is carried our after each iteration step i, and residual error f of the calculation is determined:

$$f^{(i)} = z_0 - FT\left[t^{(i)}\right]FT[R] \qquad /2.4/$$

Based on the error function, the new residence time matrix $t^{(i+1)}$ is calculated with an damping factor α. The iteration is aborted either after achieving a predefined cycle number or if dropping below a residual error of the iteration.

$$t^{(i+1)} = t^{(i)} + \alpha FT^{-1}\left[FT\left[f^{(i)}\right]FT[R]^{-1}\right] \qquad /2.5/$$

The residence time matrix provides the wafer specific data for the axis system control. Finally, they are transformed into local velocity and acceleration data.

Into process control, there are not only incorporated the wafer specific residence time data, but also recipe data specific to each material to be trimmed. These recipe data include the two-dimensional removal function of the ion beam, the settings of ion beam source and neutraliser, wafer geometry, as well as data for helium cooling (Fig. 5).

The wafer is machined with these input data, without additional feedback of the process.

In the IonScan 800 system, a special software IonTrim is available for residence time calculation according to the above described method. IonTrim was particularly engineered for this technique. Fig. 6 illustrates the user interface enabling access to various functionalities:

Interpolation:

Information about the film thickness error may be provided in any local distribution. Both layer thickness error and removal function of the ion beam have to be inter- and extrapolated to unified calculation matrices. Multiple choice methods are available for inter- and extrapolation. The program is additionally capable of considering a correction function for local deviations in the removal rate.

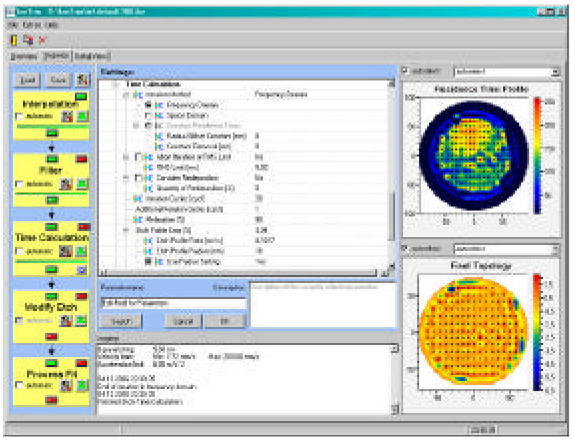


Fig. 6: *User interface of the IonTrim software for residence time calculation*

Filtering:

If necessary, it is possible to use different filters for the film thickness error function whose filter parameters may be configured.

Residence time calculation:

In this menu, the residence time is calculated according to /2.5/. However, not all residence time data calculated may be travelled by the real axis system. IonTrim checks all calculated time values and adapts them to the value range actually feasible.

Turning after completing each meander line, together with the residual beam ratio remaining on the wafer, may act on the machining result. For this reason, in calculation, the residence time matrix exceeds the wafer radius by a definable radius.

Error analysis:

With error analysis, one can estimate consequences of inaccuracies in mechanical adjustment or deviations in the removal function.

Calculation of axis data:

Finally, IonTrim calculates the entire control records for the axis system and transforms the binary data to the control.

For modelling and optimisation of layer thickness trimming, IonTrim cannot be only installed at the IonScan 800 system, but also any other PC.

4. Use in frequency trimming of Bulk Acoustic Wave (BAW) components

High-frequency components for the mobile radio technology increasingly use Bulk Acoustic Wave (BAW) rather than the Surface Acoustic Wave (SAW) components, which have been established up to now. The reasons for this change result from several advantages like enhanced product characteristics, smaller device size, less sensitivity against influences from the outside, such as temperature or electrostatic discharge, as well as the lower production costs based on as wide as possible standard CMOS technologies, thus avoiding special materials for substrates.

The main item of each BAW component (Fig. 7) is a piezoelectric film regularly made of aluminium nitride and contacted by two electrodes. To generate an acoustic resonator, the thickness of the piezoelectric film has to be $\lambda/2$ of the wavelength of the transversal acoustic wave.

The resonator has to be sufficiently acoustically isolated from the substrate material. In the past, so called Free Bulk

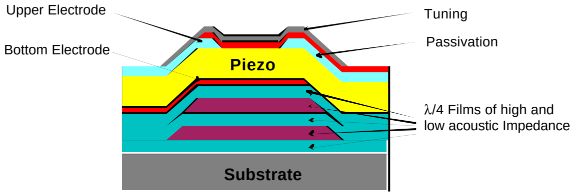
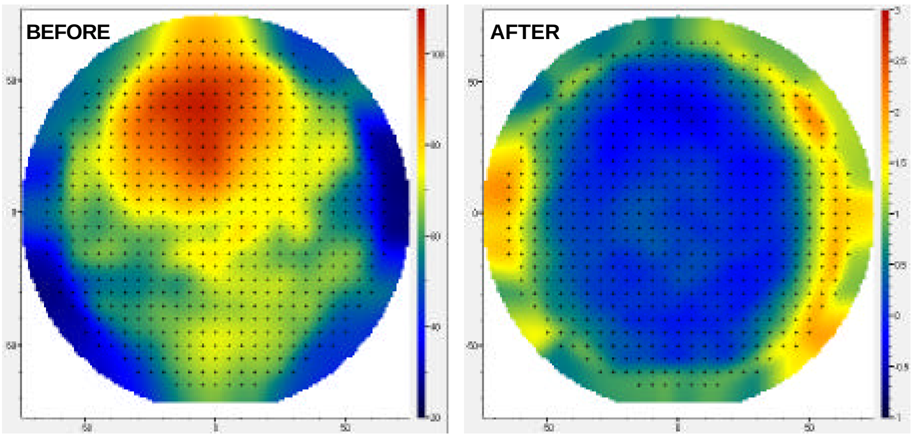


Fig. 7: *Principle structure of a Bulk Acoustic Wave (BAW) resonator*



	Before		After
Error Range:	**20 ... 110 nm**	**Error Range:**	**-1 ... 3 nm**
Mean Error:	**69.1 nm**	**Mean Error:**	**0.46 nm**
Standard Deviation:	**16.6 nm**	**Standard Deviation:**	**0.59 nm**

Fig. 8: *Film thickness error of an Si$_3$N$_4$ layer before (left) and after ion beam trimming (right) (position coordinates left/bottom [mm], film thickness error right [nm])*

Acoustic Resonator (FBAR) arrangements were used. In this construction, isolation is obtained by building an air cavity. The resonator is built up unsupported over this cavity. In the meantime, the Solid Mounted Resonator (SMR) principle has become accepted (s. Fig. 7). In this structure, acoustic isolation is achieved with an acoustic Bragg mirror made of alternating $\lambda/4$ layers with high and low acoustic impedance. Depending on the impedance differences, such as between tungsten and silicon oxide, it may be possible to achieve an excellent acoustic isolation even with only a few films.

The frequency is finally tuned with a low additional mass, which is deposited onto the upper electrode as another film, mostly silicon nitride.

The operation that makes the production of BAW resonators mainly demanding, is exact adjustment of the required film thickness values, in order to keep the low frequency tolerance range of about 0.1 %. It is also necessary to guarantee an adequate accuracy of the film thickness values across the whole wafer, which can not be obtained in these narrow tolerances with standard semiconductor technology equipment.

The IonScan 800 is a system suitable to manufacture these components. The IonScan 800 is capable of adequately trimming of all films in a BAW stack. In addition to the film thickness trimming of the mass load, IonScan can also be applied for trimming of the piezo-resonator and the acoustic mirror. With this step like trimming strategy not only the final variation of the device frequency is better met but also other device parameters like the Q-Factor gets clearly improved.

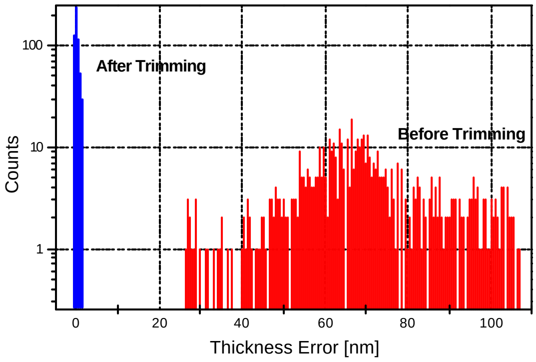


Fig. 9: *Film thickness distribution before and after ion beam trimming*

Fig. 8 elucidates the thickness distribution of a Si$_3$N$_4$ film, measured by ellipsometry, before and after ion beam trimming. With the IonScan 800 system, it is possible to correct film thickness errors arbitrarily distributed across the wafer. The local resolution of the technique is significantly determined by the standard deviation of the ion beam profile. In the example demonstrated, the ion beam was run with argon. For Si$_3$N$_4$, in the focus of the ion beam a removal rate of 20.0 nm/s and a volume rate of 6.1×10^{-3} mm^3/s are achieved. Under these working conditions, base etching at all wafer positions is only 1.7 nm.

Typical rates for materials to be processed range from approximately 10 to 30 nm/s for argon processing. With reactive gases, one may rise the rates to the three- or fourfold, depending on each material. Due to the reserves in the axis parameters, the IonScan 800 system is capable of handling such high milling rates without any problem.

In the example demonstrated in Fig. 8, the average error is diminished by about a factor of 150, and the standard deviation of the film thickness error by about 30. After machining, there remains only a 0.46 nm deviation from the nominal film thickness at a standard deviation of 0.57 nm across the whole wafer. Fig. 9 represents the film thickness distribution before (red) and after trimming (blue). The process time to machine the wafer was less than 5 min.

A slight processing error appeared towards the wafer edge. These marginal effects result from the calculation and the extrapolation procedures used, on the one hand, and from a slightly changed neutralisation at the wafer margin, on the other hand. These deviations may be compensated in the software when defining a locally variable milling rate.

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