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D 2.12
Final sputtering tool for high quality and high volume fabrication on 200 mm available

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Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential , only for members of the consortium (including the Commission Services)	

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Deliverable name:	Final sputtering tool for high quality and high volume fabrication on 200 mm available
Work package:	WP 2 – Tool development
Lead contractor:	OER

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Abstract

The development of an automatic industrial PZT sputter deposition tool for 200 mm wafers was one specific goal of the piezoVolume project.

The Oerlikon cluster tool CLUSTERLINE 200 (CLN200) is already widely used in the semiconductor industry and therefore proven as a very reliable sputter equipment. Up to 6 process modules can be attached to the central robot handling and the tool can be optionally configured with 3 auxiliary stations (degasser, cooler and aligner).
Fully equipped the sputter tool allows to fabricate complete PZT film stacks including high quality bottom and top electrodes (e.g. Pt bottom electrode RC < 3°) on either 6" or 8" substrates in one run.

For the PZT film deposition a single ceramic target is sputtered by RF magnetron technology onto a very hot substrate. This high temperature deposition process allows the in-situ growth of the piezoelectric perovskite phase of PZT.

The crystallographic, microstructural, dielectric and ferroelectric properties show evidence for the high quality of the PZT films. The preferred orientation can be substantially influenced by the Pt electrode structure and therefore depending on the growth template either a strong (100) or (111) orientation of the PZT films can be achieved.
As an example the (111) oriented films exhibit a relative permittivity greater than 1800 and a maximum and remanent polarisation of 45 µC/cm2 and 20 µC/cm2, respectively.
Applying an optimized poling procedure to the test device structures helped to achieve the highest piezoelectric coefficients $-e_{31,f}$ of 20 C/m^2 for these films. This is an excellent value for sputtered PZT films and exceeds the project objectives by almost 50%. This transversal response is the key property for most applications, but values up to 150 pm/V were also measured for the longitudinal response $d_{33,f}$ of the PZT films.

A deposition rate greater than 1 nm/s allows a high volume process of PZT films with a throughput of more than 3.6 wafers/hour at 1 µm thickness. In combination with a thickness uniformity of ± 5% the 200 mm sputter equipment enables the customers to achieve a high productivity of their PZT fabrication.

All in all it has been demonstrated successfully during the piezoVolume project that the Oerlikon sputter equipment is capable of depositing high quality piezoelectric PZT films onto 150mm and 200mm wafer, respectively.

Public introduction[1]

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[1] According to Deliverables list in Annex I, all restricted (RE) deliverables will contain an introduction that will be made public through the project WEBsite

TABLE OF CONTENTS

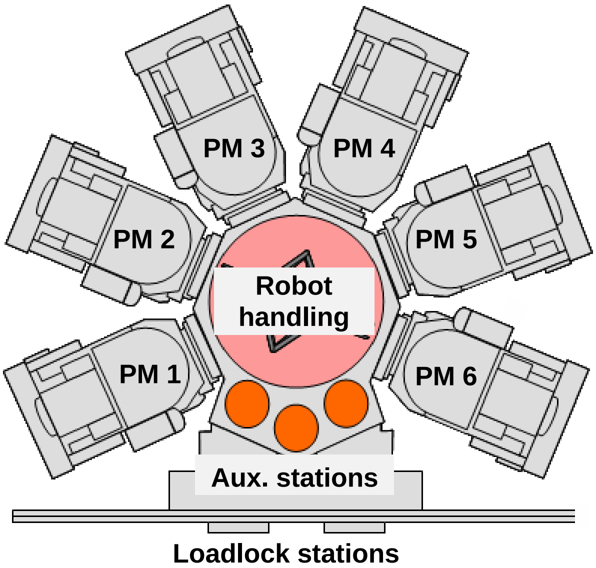
Page

1 SPUTTER EQUIPMENT FOR PZT FILM FABRICATION

1.1 Deposition tool architecture

1.1.1 General

The Oerlikon cluster tool CLUSTERLINE 200 (CLN200) is widely used in the semiconductor industry and therefore proven as a very reliable sputter equipment (fig.1). It consists of 2 load locks for wafer loading, a central robot for wafer handling and the sputter or etch modules for the depositions or the etching, respectively. Up to 6 process modules can be attached to the central robot handling and the tool can be optionally configured with 3 auxiliary stations (degasser, cooler and aligner) located close to the load locks.



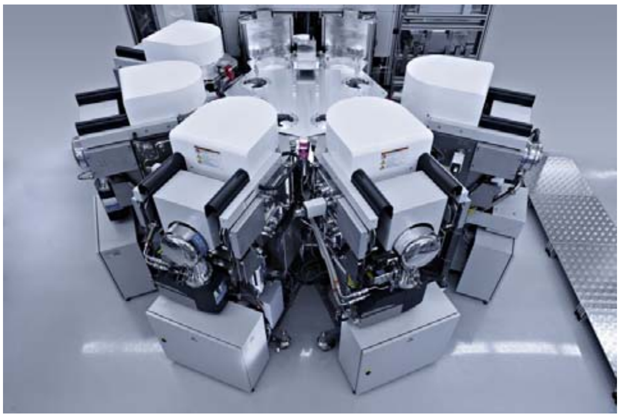


Figure 1: Oerlikon cluster tool CLN200

With this configuration complete PZT film stacks including bottom and top electrodes can be fabricated on 6" or 8" substrates in one run. Table 1 shows exemplary a configuration for such a process chain with Ti/TiO2/Pt bottom and CrAu top electrode, a typical layer stack which is used during the piezoVolume project. Equipped with a Multisource cathode (MSQ) for sputtering up to 4 targets such a configuration allows to install 3 PZT modules. The PZT deposition is the slowest process step and therefore this setup can provide the maximum wafer throughput to the customer.

	Auxiliary	*PM 1*	*PM 2*	*PM 3*	*PM 4*	*PM 5*	*PM 6*
PZT including Pt bottom and CrAu top electrode	Cooler Degasser Aligner	Etch	Multi-Source Ti/TiO2 Cr Au Other (e.g. Ru)	Pt	PZT	PZT	PZT

Table 1: Example of a CLN200 tool configuration for a complete PZT layer stack including bottom and top electrodes

1.1.2 Process modules

For a process with bottom and top electrode according to table 1 the sputter modules will be typically equipped as shown in table 2.

	Etch	Multisource	Pt	PZT
PVD mode	ICP etch	DC Reactive DC RF optional	DC	RF
Max. heater temperature	No	500°C	500°C	800°C
Gas supply	Ar	Ar O2	Ar	Ar O2

Table 2: Example of CLN200 tool configuration for etch / sputter modules

The metals are usually sputtered by a DC magnetron process. The dielectric films can be sputtered either by a reactive pulsed DC or by a RF magnetron process from a dielectric target directly. The PZT films are deposited from a single oxide target and due to its non-conductivity a RF magnetron sputter process has to be established
To achieve the optimum film structure the sputter stations for the metals and dielectrics can be equipped with a heated substrate holder (chuck) for temperatures up to 500°C and provided optionally with a RF bias capability.
This setup facilitates a high quality of both the PZT film and the electrode layers, e.g. the rocking curve FWHM of the Pt bottom electrode is less than < 3°.

1.1.3 PZT deposition module

The module dedicated to the PZT process and optimized during the piezoVolume project is equipped with a RF cathode and auto-tuning matching network capable for a RF load power up to 5 kW.
To reach the very high substrate temperature required for an in-situ PZT deposition process a so called Very Hot Chuck for 6” and 8” wafer formats was developed for chuck temperatures up to 800°C (fig.2).
Further on the special design of the anode allows a very homogeneous gas distribution and finally the installed RF bias capability enables to tune the film properties.

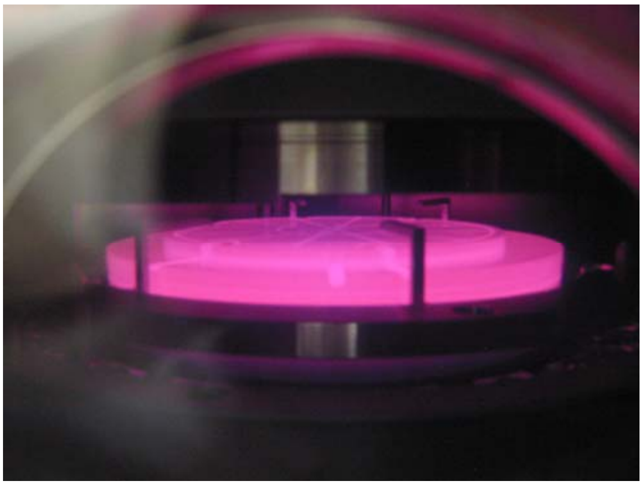


Fig. 2: Very hot chuck for 6” wafer.

2 HARDWARE FOR PZT IN-SITU SPUTTER DEPOSITION

2.1 General requirements

2.1.1 Substrate heating

The growth of piezoelectric PZT requires a sufficiently high substrate temperature during the sputter deposition. While for a 2 step PZT deposition process with sputtering and subsequent post annealing the deposition temperature is in the range of 400 – 450°C, the required substrate temperature for the direct in-situ growth of the perovskite phase is greater than 500°C.
To assure such a high temperature on the substrate the chuck temperature has to be heated to even higher temperatures to compensate the heat loss. Depending on the substrate the difference between chuck and substrate temperature can be even more pronounced with increasing temperature.
To enable this high temperature chucks for 6“ and 8” wafer have been engineered taking into account a high heat transfer to the substrate, a low heat loss to the environment, a sufficient cooling of the chuck base and the mechanical stability during temperature cycling.

2.1.2 RF sputtering

A second challenge is to deposit the PZT film from a single oxide target. Due to its high non-conductivity a RF sputter process has to be established. Although pure RF diode sputtering can be applied, it will suffer from a very low rate. Therefore the sputter performance has to be enhanced by a magnetron.
The design of the magnet array for PZT deposition has to balance out the requirements for deposition rate, thickness and composition uniformity taking into account the loss of lead due to such a high deposition temperature.
From the experience with a lot of materials one of the critical features which can dramatically influence the film properties is the DC bias voltage at the substrate during sputtering. It was shown during the project that this feature has also a substantial influence on the PZT film quality.

2.2 Sputter module overview

The sputter module to deposit PZT on 6” or 8”wafer consists a vacuum chamber equipped with a turbo pump, a RF sputter cathode with impedance matching network and a impedance matching network for application of RF bias to the substrate (fig.3).

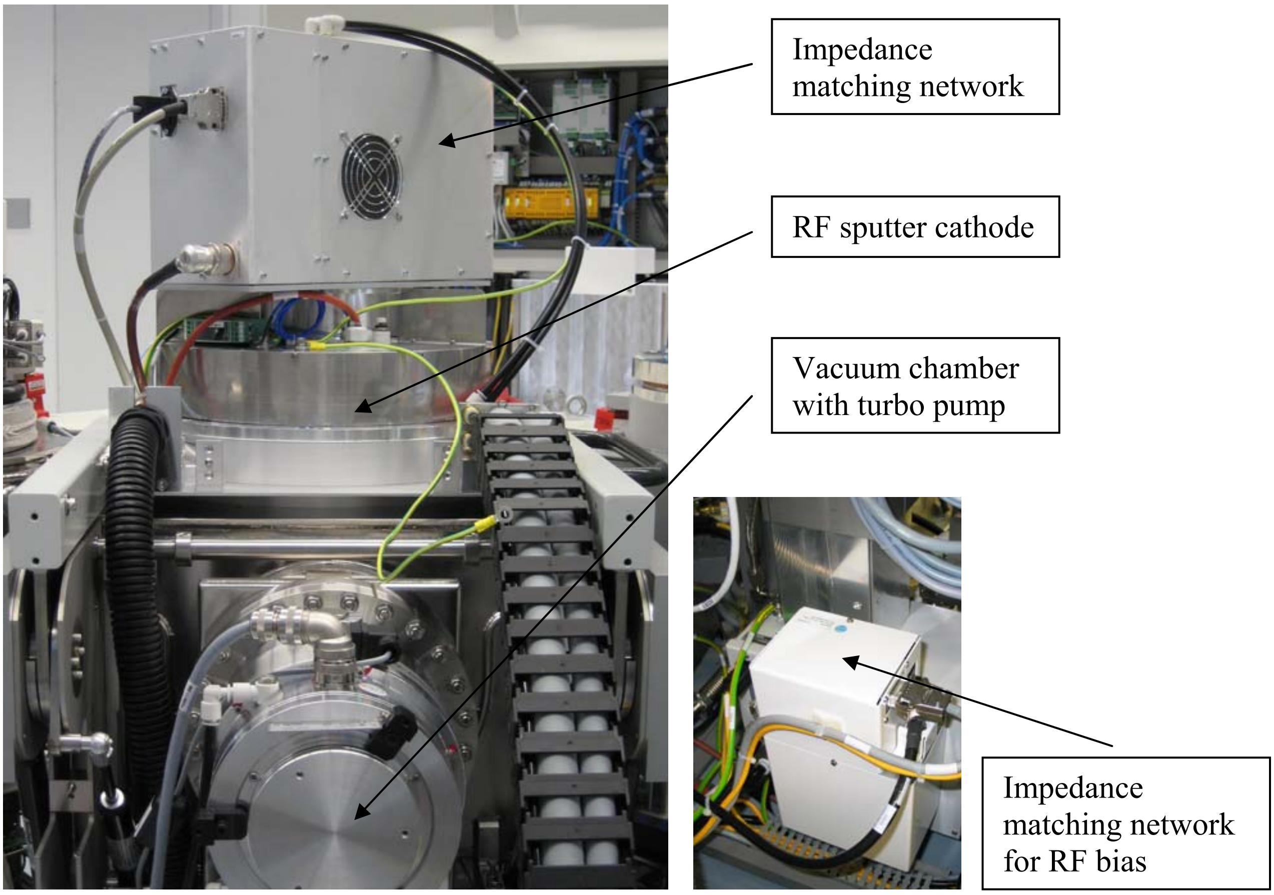


Fig. 3: Sputter module for 8” PZT deposition at CLN200 sputter tool.

During the sputter deposition in the vacuum chamber the substrate is placed on the very hot chuck to achieve the very high deposition temperature required for the PZT in-situ deposition process (fig.4).
To perform the sputter depositions, the module is supplied with cooling water, argon and oxygen sputter gas, nitrogen vent gas and compressed air.

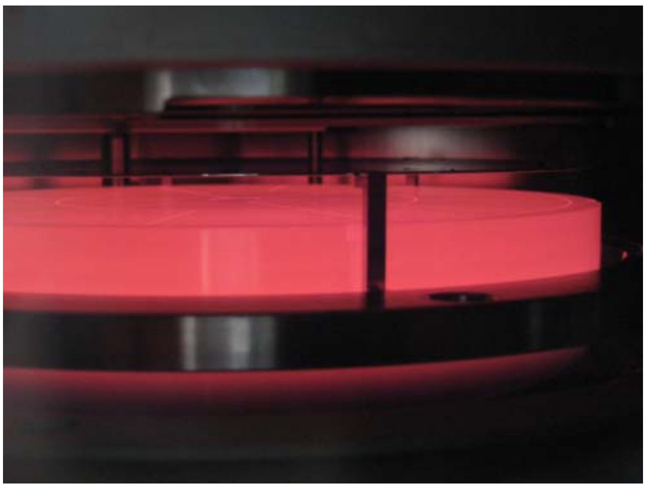


Fig. 4: Very hot chuck for 8” wafer.

2.3 Very hot chuck for 8" wafer

Based on a resistive coaxial heater the same technology is used for the heating of both 6" and 8" wafer. They are equipped with suitable top plates to fit the particular wafer format and for a good thermal contact Argon gas is supplied at the wafer backside.

A maximum temperature of more than 800°C is achievable with the very hot chuck which results in a maximum substrate temperature of about 600°C measured on a Si sense array test wafer (fig.5). This is well above the chuck temperature range of 550 - 700°C necessary for in-situ deposition of PZT. Therefore the very hot chuck can also be utilized to deposit other materials which need an even higher temperature to nucleate in-situ in the required crystal structure such as perovskite $BaSrTiO_3$ (BST).

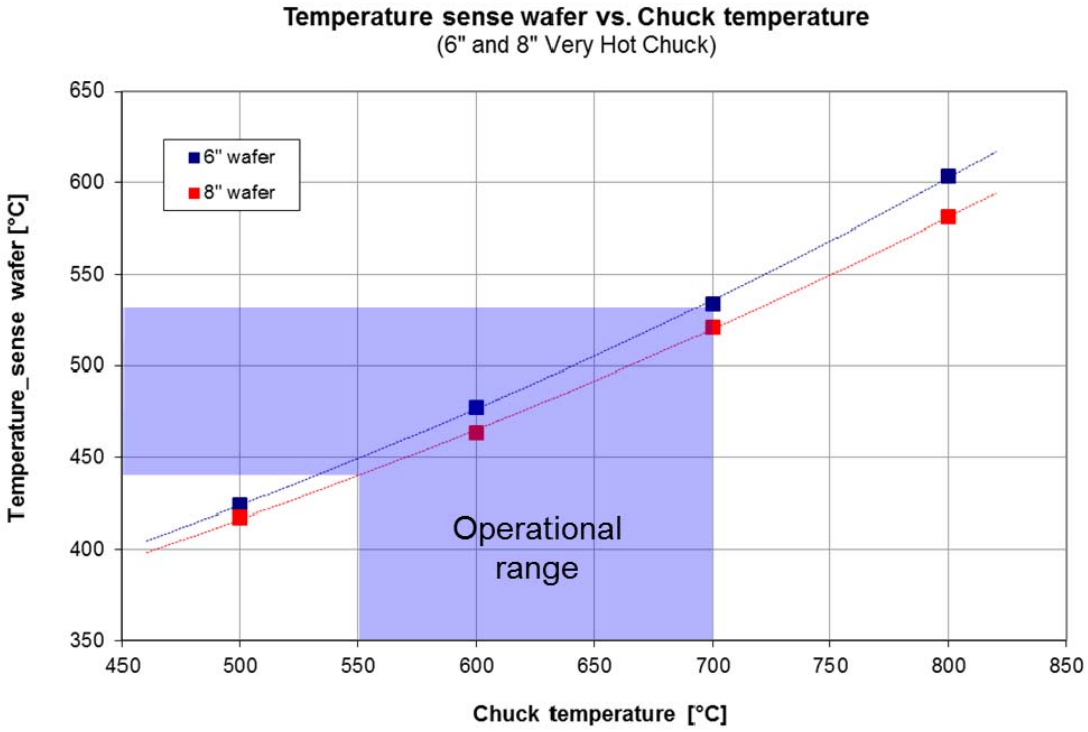


Fig. 5: Mean temperature of a Si sense array test wafer as a function of the chuck temperature for the 6" and 8" very hot chuck

Due to the separated heater circuits for the heating of the inside and outside area of the chuck and the design of the back gas inlet a very good temperature uniformity within the wafer of ± 2% can be achieved (fig.6).

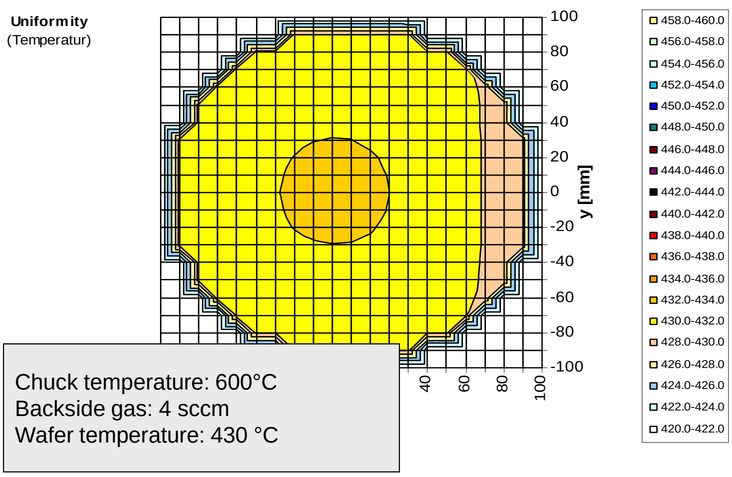


Fig. 6: Temperature distribution on a Si sense array test wafer at a chuck temperature of 600°C.

2.4 Sputter components

2.4.1 RF sputter cathode

The system is equipped with an Oerlikon RF cathode for 300 mm target, an impedance matching network optimized by Oerlikon and a RF generator to deliver a maximum load power of 5kW to the cathode (fig.7). Usually the amount of sputtered material is proportional to the applied power and hence the deposition rate can be varied over a wide range.
To reach a deposition rate higher than 60 nm/min as specified in the piezoVolume project goals a sputter power of approximately 3 kW has to be applied. This RF power is clearly within the operational range of the RF equipment. However, a further enhancement has to be done carefully step by step because, as discussed in the next section, a sufficient cooling of the target surface has to be assured.

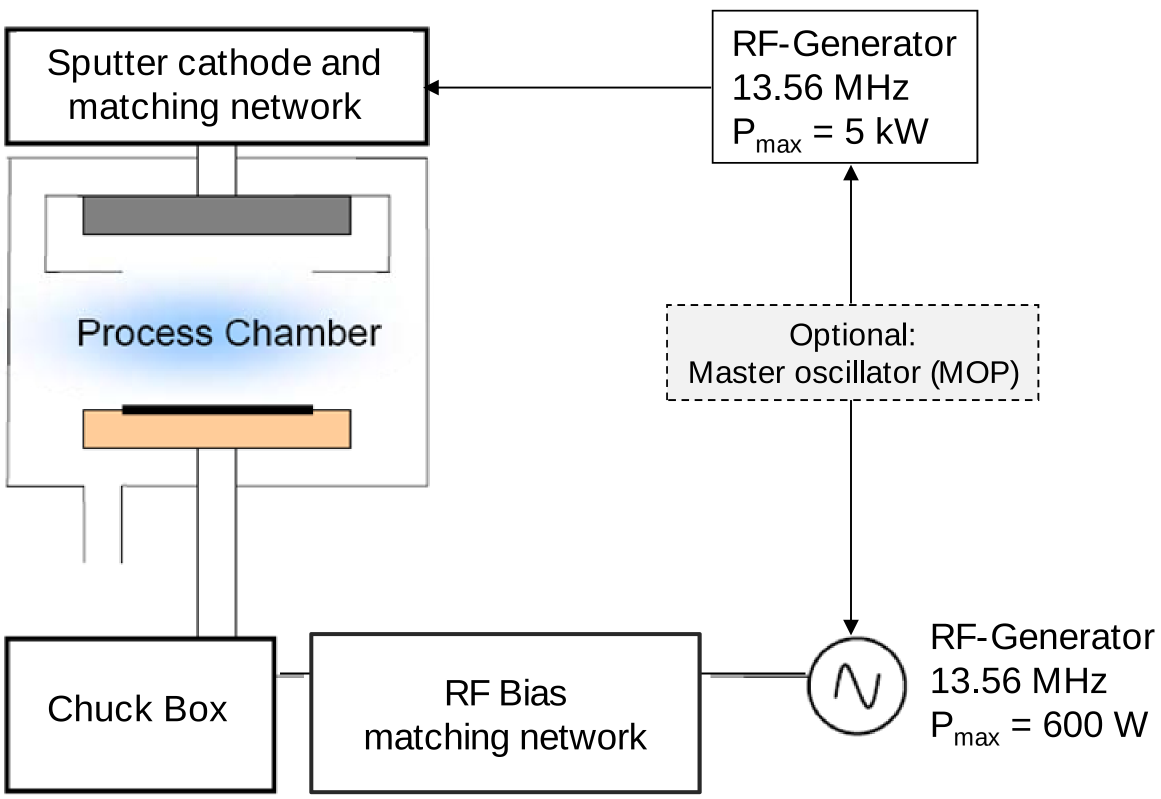


Fig.7: Schematics of RF components installed at PZT module

2.4.2 PZT target

The target is a single ceramic target with a diameter of 300 mm and a thickness of 4 mm bonded onto a 11mm Cu backing plate. Due to the low PZT heat conductivity, the target thickness is very critical to assure a sufficient heat transfer from the target surface to the cooling plate. If the target cooling is insufficient this can cause a change in the target composition due to enhanced diffusion and evaporation of lead.
In order to deposit a PZT film with a composition close to the morphotropic phase boundary, the target has a Zr/Ti ratio of 52/48 and an appropriate excess of PbO to compensate for the lead loss due to evaporation at the high substrate temperature.

2.4.3 Magnet array

The cathode is equipped with a magnet array suitable for the 300 mm PZT target. In contrast to other materials (e.g. metal alloys) the thickness and composition uniformity at PZT deposition is determined not only by the magnet array but also by the lead loss due to the high deposition temperatures. Therefore the design of the magnet array for PZT deposition has to account for this material loss.

2.4.4 Substrate bias voltage

The RF module for PZT sputtering is equipped with a so called RF-Bias consisting of a 600W RF generator and an impedance matching network designed by Oerlikon. This feature allows to apply a defined DC voltage to non-conductive substrates during the deposition. With this biasing technique the growth of the PZT film can be substantially influenced.

2.4.5 Sputter gas supply

To assure a very homogenous sputter gas supply into the plasma volume a special gas distribution integrated in the anode is used. The design consists of 8 gas inlets equally distributed over the circumference with same length of the gas channels for all inlets. This leads to a very homogeneous plasma density over the circumference which results in a good tangential uniformity.

2.4.6 Anode

In the actual design the target to substrate distance is fixed. This allows the construction of an anode which confines the plasma very well and assures a small difference between plasma and ground potential. Even at higher RF power a plasma spill out don’t occur which would be detrimental for the film properties.

3 SPUTTER AND FILM PERFORMANCE

3.1 Thickness uniformity

With the actual magnetron design a film uniformity of ± 5% (fig.8) and a deposition rate of about 1.1 nm/s can be achieved at 3 kW RF load power. Both values are within the specifications of the piezoVolume project for sputtered PZT films. It is expected that further improvements can be achieved by fine-tuning of the magnet array.

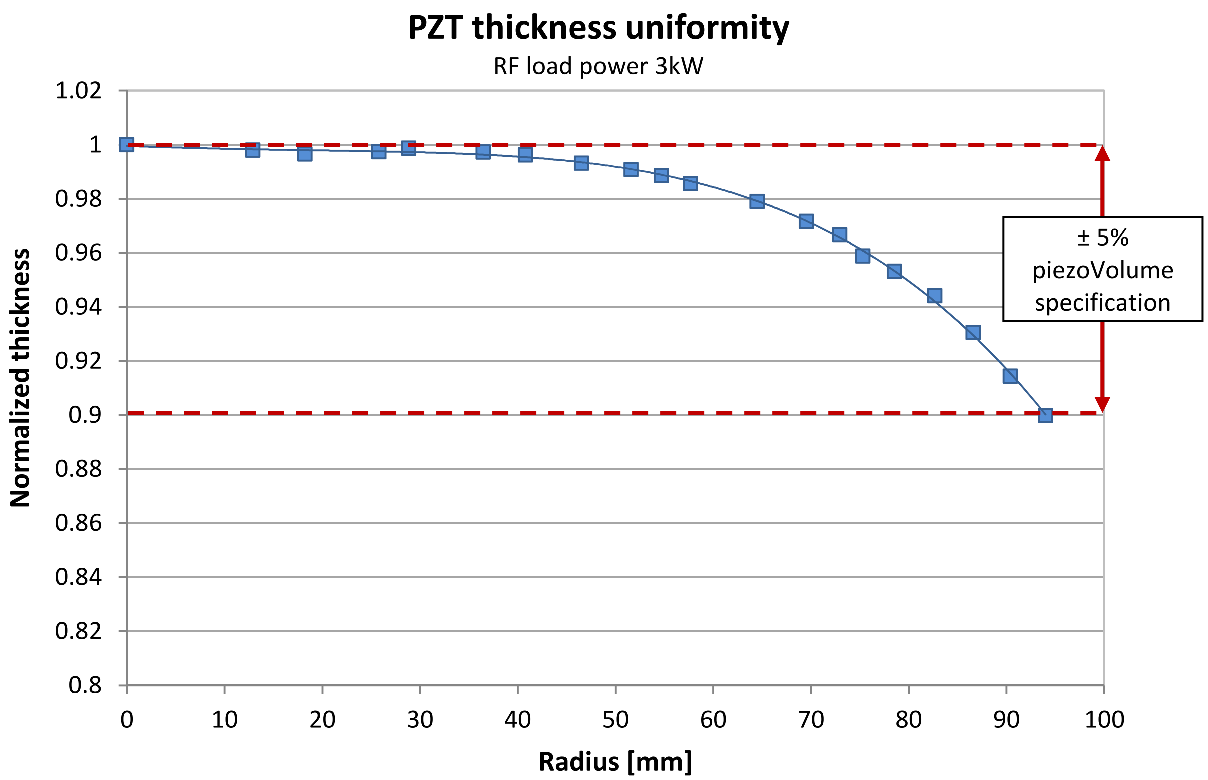
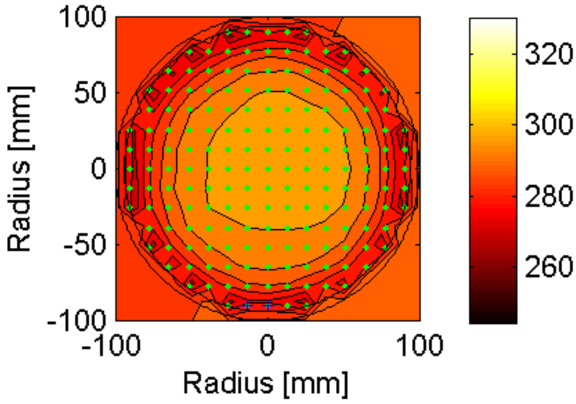


Fig. 8: Radial thickness uniformity of PZT film deposited at 3 kW



Due to the design of the symmetric sputter gas distribution the tangential thickness uniformity is typically ~1% which means a very good value. Therefore the total thickness non-uniformity results mainly from the decrease of thickness in radial direction (fig.9).
As mentioned above this can be influenced by a further fine-tuning of the magnet array but also the anode and the sputter shields have to be considered in this optimization process.

Fig. 1: Mapping of thickness uniformity for PZT film deposited at 3 kW

3.2 Crystallographic and microstructural properties

XRD measurements at a 2 µm PZT film on an evaporated Ti/Pt electrode exhibit a pure perovskite PZT structure with an almost perfect (111) preferred orientation (Fig.10c). The cross section and top view SEM images show the dense and void free PZT film structure (fig.10a) and the (111) oriented triangular grains with an average grain size of about 200 nm (fig.10b).
The preferred orientation is substantially influenced by the Pt electrode structure and therefore on a different template a strong (100) orientation of the PZT films can be achieved as well.

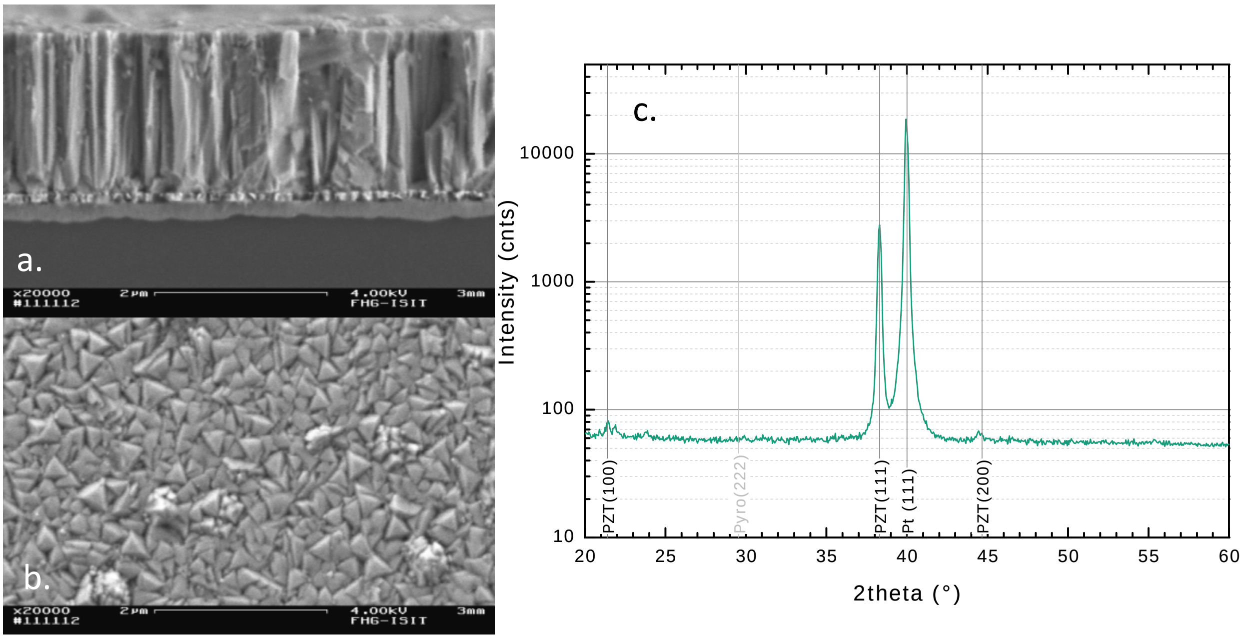


Fig. 10: SEM cross section (a), SEM top view (b) and XRD graph (c) for a 2 µm PZT film in-situ sputtered on a 200 mm Ti/Pt electrode.

3.3 Ferroelectric properties

In fig.11 the typical ferroelectric hysteresis loop for a standard 1 µm PZT (111) film deposited on a 200 mm Pt electrode is shown (light green).
The film exhibits a maximum polarization of approximately 45 µC/cm^2 and a remanent polarization of 20 µC/cm^2. A coercive field of about 30kV/cm is achieved.
The second graph (dark green) displays the large signal displacement in longitudinal direction during AC voltage application. From the data a $d_{33,f}$ value of approximately 150 pm/V can be estimated for the small signal actuation.

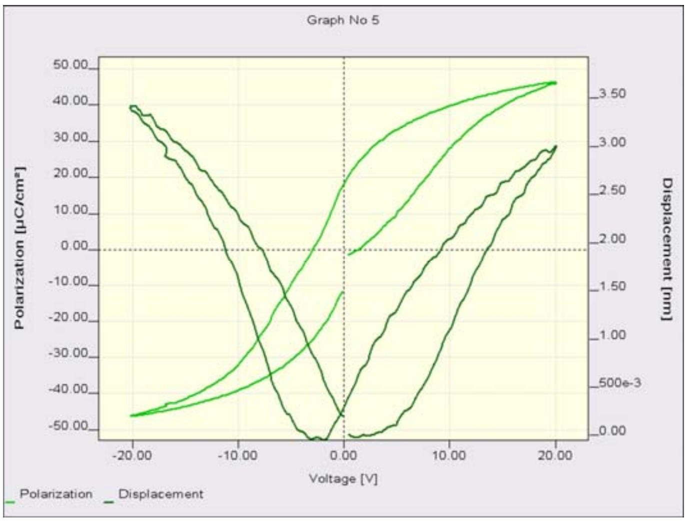


Fig.11: Polarisation hysteresis loop and large signal longitudinal displacement for a 1 µm PZT film on a 200mm Ti/Pt electrode.

3.4 Dielectric and piezoelectric properties

In fig.12 the dielectric properties and the longitudinal piezoresponse $d_{33,f}$ of a 1 µm PZT film are shown as a function of the applied bias voltage using a double beam laser interferometer (aixDBLI) from aixACCT.

The C-V curve (red) exhibits the typical "butterfly" shape with a maximum relative permittivity exceeding 2000 and a remanent value greater than 1800.

As estimated from the large signal displacement the longitudinal piezoresponse $d_{33,f}$ (blue) is greater than 150 pm/V for the small signal actuation.

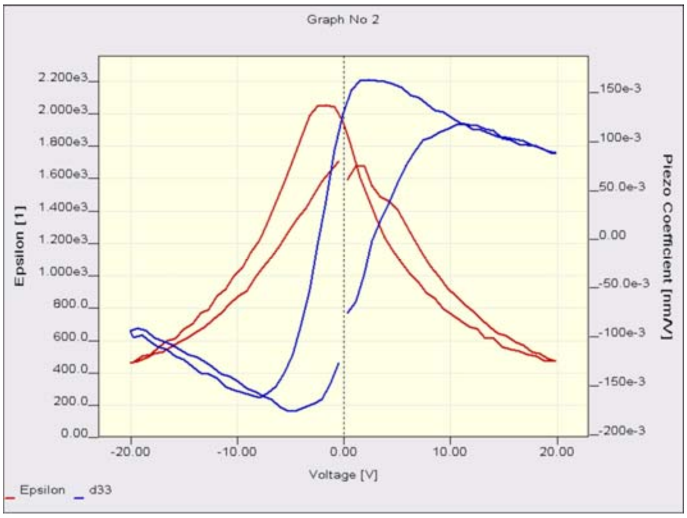


Fig.12: C-V curve (red) and longitudinal piezoresponse $d_{33,f}$ (blue) as a function of applied bias field for a 1µm PZT film.

In fig.13 the charge accumulation during bending of a cantilever in the 4-Point bending system (aix4PB) from aixACCT is plotted. From the data and the geometry of the measurement system and the test device the transversal piezoresponse $e_{31,f}$ can be derived. For the film shown here a value of $e_{31,f} = -17.2$ C/m^2 is calculated which is a remarkably high value for in-situ sputtered PZT films.

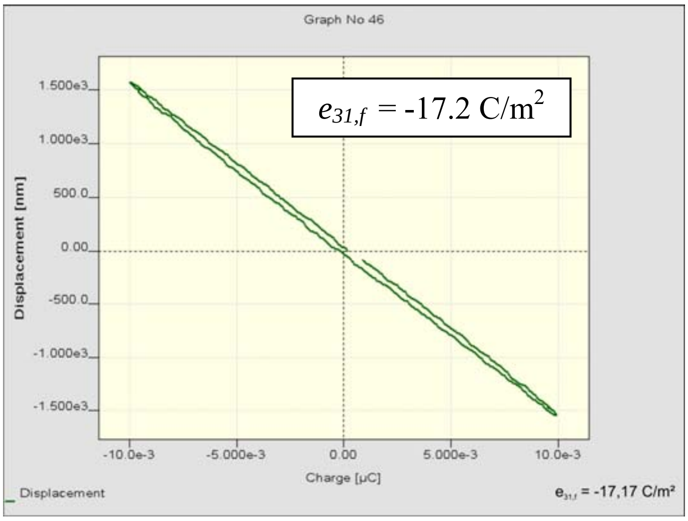


Fig.13: Charge accumulation as a function of cantilever deflection for a 1µm PZT film.

3.5 Productivity

With a deposition rate of 1.1nm/s it is possible to deposit 1 µm PZT films in the sputter tool at a throughput of 4 wafers/h. Taking into account the time necessary for the wafer conditioning and handling the effective throughput will be about 3 wafers/h. Usually the thickness of the PZT films is between 1 and 2 µm but if required films with a thickness up to 4 microns are achievable. The typical target lifetime for a 4mm target is approximately 1000 kWh which enables the production of more than 1300 wafers at 1µm thickness.

4 SUMMARY

The Oerlikon cluster tool CLUSTERLINE 200 (CLN200) is already widely used in the semiconductor industry and therefore proven as a very reliable sputter equipment. Fully equipped the sputter tool allows to fabricate complete PZT film stacks including high quality bottom and top electrodes (e.g. Pt bottom electrode RC < 3°) on either 6” or 8” substrates in one run.

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