MEMS Applications of Porous Silicon

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ABSTRACT

Porous silicon fabricated by partial electrochemical dissolution of bulk silicon, shows outstanding material properties. The nanostructure of the remaining Si-skeleton is used for specific optical devices, such as emitters and filters. The high internal surface of the material opens new opportunities for different types of microsensors and -actuators and microsystem concepts. The porous layers can be used as sacrificial layers due to the high reactivity of the material which leads to a new class of micromachined MEMS devices. A brief overview on the historic evolution of the material is given. The base technologies for the fabrication of porous silicon layers are described. An overview on specific applications is given to demonstrate the potential of the material and the technology behind.

Keywords : Porous silicon, MEMS

INTRODUCTION AND HISTORY OF POROUS SILICON

Porous silicon (PSi) has been subject of intensive investigations over the last decade. The potential of the material for MEMS applications has been underestimated for a long time and it should be considered that the discovery of PSi by UHLIR [1] goes back to 1956 at Bell Labs, USA. At this time the investigations on silicon had just started and UHLIR worked on the polishing of silicon- and germanium-wafers. The wafers were electrochemically polished using an electrolyte of hydrofluoric acid. Mostly, the result was a shiny and smooth surface, but on the wafer surface sometimes a brown film was formed. UHLIR disregarded this film and optimized the electropolishing process with high current densities. This process was studied in more detail by TURNER [2] in 1958, but he did not discover the porous structure.

At the same time UHLIR worked on the electrochemical polishing of silicon, FULLER and DITZENBERGER [3] reported the generation of similar films by use of HF-HNO₃ solutions in 1957. This phenomenon was further studied by ARCHER in 1960 [4].

In the 1970’s, WATANABE was the first to recognize the porous structure of these films. He visualized the sponge-like silicon structure with pores in the nanometer range. With this knowledge he realized the first application of porous silicon: oxidized PSi for the “Silicon on Isolator (SOI)” technology [5]. Thereby, PSi is formulated in regions between components of an electrical circuit and oxidized. This technique, using vertical isolation, enables the insulation of single components on chip (trench isolation). In 1981 IMAI [6] at NTT Labs, Tokyo, realized the entire insulation of electrical components and presented these as “FIPOS (Full Insulation by Porous Oxidized Silicon)” technique. By using oxidized PSi films it was possible to generate oxide layers which were thicker in comparison to standard silicon oxidation processes and which can be 3-dimensional processed.

The PSi characteristic of keeping the monocrystalline structure of the silicon substrate gave BOMCHIL [7] the possibility to epitaxially grow the first monocrystalline silicon layer on top of a porous silicon layer. Afterwards, he oxidized the porous silicon and thus realized a SOI-substrate. The possibility to grow up an epitaxial monocrystalline silicon layer upon porous silicon enables the first commercial product by the use of porous silicon.
Furthermore, the modification of the PSi surface in a gas atmosphere was used to generate, in addition to silicon oxide, thick silicon nitride and silicon oxinitride layers [8]. The fact that silicon could be converted into other materials is based on the average pore size between 2nm and several micrometers and the resulting high reactive surface of PSi up to several 100 m²/cm³.

Before 1990, there were less than 200 papers published on PSi, spanning a period of 35 years [9]. With the beginning of the 1990’s, the discovery of PSi photoluminescence caused a drastic increase in publications. By illuminating PSi with ultraviolet light CANHAM [10] observed a red lightning glow of the layers at room temperature.

Independently, LEHMANN [11] reported the increased band gap of PSi compared with bulk silicon and the fact that this property, as well as the formation mechanism itself, involved quantum size effects. This effect is the basis for the quantum confinement model, which is one of five formation theories, trying to answer the question: why does the silicon dissolution stop in the silicon skeleton? The first person speculating on the PSI formation was THEUNISSEN in 1972 [12]. His theory was took up by BEAL in 1985 [13] and explains the existence of SCHOTTKY-barriers and depletion layers in the silicon skeleton, which stop the etching process. Furthermore, in 1988 SMITH proposed the “Diffusion Limited Model” [14], which is based on the premise, that the rate of porous formation is limited by the diffusion of the reactant. The “SOARES Model of Hydrogen Passivation” of 1994 [15] explains the correlation of the amount of hydrogen present in the silicon/electrolyte interface, which determines the potential of porous silicon formation. The latest theory of pore formation, the “Hydrogen Incorporation Model” [16] is also based on the effect of hydrogen formation with proton formation: hydrogen is incorporated into silicon and stops the dissolution process.

Simultaneously to the discovery of photoluminescence, the feasibility to use the high reactive surface results in the implementation of PSi into microsystem technology [17]. One of the first applications was the use of PSi as sacrificial layer material. Therewith, sacrificial layers of several 10 µm can be achieved and the material can be removed with diluted alkaline solutions [18]. Furthermore, photoluminescence devices with PSi [19], as well as the photo diodes [20], wave guides [21] and interference filter [22] with PSi were presented. With this “porous silicon boom” investigations on the material properties also started: the morphology was analyzed [8], investigations of the pore distribution were performed [23], the thermal [24] and electrical behavior [25] as well as optical properties [26] were researched.

THE TECHNOLOGY OF POROUS SILICON FORMATION

In general, the sponge-like structure of PSi is formed by an electrochemical etching process of a silicon substrate in hydrofluoric acid (HF) based electrolytes. The mechanism of pore generation depends on the availability of positive charge in the substrate. Positive charge carriers react at the silicon surface with fluorine ions [14] [27]. Thereby, a parasitic oxidation is an important aspect to release silicon atoms with HF from the substrate to create pores. The free standing porous skeleton retains the same chemical properties as the bulk silicon and the crystalline structure of the silicon is not changed. The new resulting surface is enlarged and very reactive compared to the original silicon surface. Various pore dimensions can be formed and tuned by the fabrication parameters. The pore diameters range from a few nanometers up to several micrometers (Table 1) and they can be used as parameters to characterize the PSi structure.

<table>
<thead>
<tr>
<th>Pore width</th>
<th>Type of pore</th>
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</thead>
<tbody>
<tr>
<td>&lt; 2nm</td>
<td>micropores</td>
</tr>
<tr>
<td>2 – 50nm</td>
<td>mesopores</td>
</tr>
<tr>
<td>&gt; 50nm</td>
<td>macropores</td>
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A further important parameter for the characterization of PSi layers is the porosity (P) [23]. The porosity is given by the volume of pores within the layer that means by the mass differences of a PSi probe before porosification (m₁), after porosification (m₂) and after the removal of the porous silicon layer (m₃).
Nowadays, three different electrochemical processes for the PSi formation are discussed: anodization, stain-etch and galvanically formation.

**Anodization**

The mostly used PSi formation process is anodization [14] [28]. The term anodization is based on the anodic dissolution of the silicon in a fluoride containing electrolyte. Therefore, the silicon wafer is inserted into an etching cell for electrical contacting. The silicon wafer serves as anode. Two types of etching cells are used: double-cells and single-cells. By the use of a double cell (Fig. 1) the wafer is contacted with the aid of electrolyte on both sides. That means the electrodes of HF-resistant material (platinum or silicon) are placed into electrolyte and the induced current /applied voltage goes through the electrolyte to contact the wafer. The positive potential is applied on the backside and the negative potential on the front of the silicon wafer, where the porous layer is generated.

![Figure 1: Cross sectional view of a ‘double-anodization-cell’](image1)

The second etching-cell (Fig. 2) is a single-cell which means the silicon wafer is contacted by the electrode into an electrolyte only on one side. A metal contact is made to the backside of the wafer and sealed, so that only the front of the sample is exposed to the anodizing electrolyte. For a good ohmic contact a high-dose ion-implantation and a metal deposition is required for highly resistive silicon wafers.

![Figure 2: Cross sectional view of a ‘single-anodization cell’](image2)

Independently of the etching cell, the chemical reaction dissolving silicon is the same. The electrolyte consist of HF, H₂O and ethanol, HF for silicon dissolution and ethanol for better surface wetting. A typical concentration is
HF:H₂O:ethanol = 1:1:2. As lower the concentration of hydrofluoric acid is, as larger are the pore diameters and the porosity.

The induced current must change from electronic form in the silicon to an ionic current in the electrolyte, this means a reduction-oxidation (redox) reaction must occur at the silicon-electrolyte interface. Generally one can consider two chemical reactions in parallel [25]. Firstly, the ‘direct’ dissolution of silicon:

\[
\begin{align*}
\text{Si} + 2 \text{HF} + \lambda h^+ & \rightarrow \text{SiF}_2 + 2 H^+ + (2-\lambda) e^- \\
\text{SiF}_2 + 2 \text{HF} & \rightarrow \text{SiF}_4 + \text{H}_2 \uparrow \\
\text{SiF}_4 + 2 \text{HF} & \rightarrow \text{H}_2\text{SiF}_6 
\end{align*}
\]

And secondly the silicon oxidation reaction:

\[
\begin{align*}
\text{Si} + 4 \text{H}_2\text{O} + \lambda h^+ & \rightarrow \text{Si(OH)}_4 + 4 \text{H}^+ \\
\text{Si(OH)}_4 & \rightarrow \text{SiO}_2 + \text{H}_2\text{O} \\
\text{SiO}_2 + 4 \text{HF} & \rightarrow \text{SiF}_4 + 2 \text{H}_2\text{O} \\
\text{SiF}_4 + 2 \text{HF} & \rightarrow \text{H}_2\text{SiF}_6
\end{align*}
\]

Both reaction processes strongly depend on the current flow in the silicon (typically 1 – 100 mA/cm²). An increase of current densities leads to higher porosity. For high current densities electropolishing occurs. The starting point of electropolishing depends on the electrolyte composition and the substrate resistivity.

For the chemical reaction positive charge carriers are necessary, in p-type silicon enough holes are available, for n-type silicon holes are minority carriers and can be generated by illumination of the silicon. By the use of p-type silicon we obtain higher porosity by higher substrate resistance. And the pore size of n-type silicon depends extremely by illumination. By anodization, PSi layer thicknesses up to 100 µm and more can be obtained with p- and n-type silicon.

Stain Etch

An alternative technique for porous silicon formation is the electro-less ‘stain etch’ process [3] [4] [29]. Stain films are produced in HF:HNO₃(nitric acid):H₂O solutions without external current generation. As with the anodic oxidation of silicon under anodic bias (Eqn (3)), a key component to stain etch routes to PSi formation is the redox-reaction (generation of positive charge carriers). In stain etch methods employing HF and HNO₃, initially NO is produced which serves as an injector of positive charge carriers (see Eqn. (4)). Analogous to anodization the reaction product is H₂SiF₆ [25].

\[
\begin{align*}
\text{Cathode:} & \quad \text{HNO}_3 + 3 \text{H}^+ & \rightarrow \text{NO} + 2 \text{H}_2\text{O} + 3 h^+ \\
\text{Anode:} & \quad n \text{h}^+ + \text{Si} + 2 \text{H}_2\text{O} & \rightarrow \text{SiO}_2 + 4 \text{H}^+ + (4-n) e^- \\
\text{SiO}_2 + 6 \text{HF} & \rightarrow \text{H}_2\text{SiF}_6 + 2 \text{H}_2\text{O} \\
\text{Overall:} & \quad 3 \text{Si} + 4 \text{HNO}_3 + 18 \text{HF} & \rightarrow 3 \text{H}_2\text{SiF}_6 + 4 \text{NO} + 8 \text{H}_2\text{O} + 3(4-n) \text{h}^+ + 3(4-n) e^- 
\end{align*}
\]

The stain films only form in HF containing low concentrations of nitric acid. The nitric acid acts as oxidizing species in the etch (see above), and it is their reduction that drives the current in the porous silicon formation, rather than the application of an external bias. A typical concentration is HF:HNO₃:H₂O = 1:3:5 [25]. Also a situation analogous to electropolishing during anodization occurs if the concentration of HNO₃ is too high. The dependence of HF-concentrations is the same as obtained by anodization: as lower the concentration of hydrofluoric acid is, as larger are the pore diameters and the porosity. The thickness of the films only reach a maximum of several µm.
The advantage of the technology is the easy handling and no specific equipment as required for anodization (etching cell and current source) is needed. The disadvantage is that the resulting porous layers have a maximum thickness of only a few µm. The backside of the wafer has to be protected with a masking material, if no porosification on the backside is desired.

**Galvanically formation of porous silicon**

A new method for porous silicon formation has recently been described [30] [31]. A galvanic element of a silicon wafer and a precious metal layer, which generates an internal current, is used for porous silicon formation (Fig. 3). A metal layer (gold or platinum) is deposited on the backside of the silicon wafer to create the galvanic element. At the front of the wafer a masking layer for patterned porosification can be used. The same masking material as applied is feasible for the other porous silicon fabrication technologies (e.g. silicon carbide, silicon nitride or a sandwich structure of silicon dioxide and polysilicon).

The silicon has the negative potential, the positive charge carriers in the substrate move to the surface and react electrochemically with the electrolyte (see redox-reaction above). Silicon atoms are partially dissolved from the bulk silicon. The same mechanism is used by porous silicon anodization.

Also for this formation technique the electrolyte composition is one important fabrication parameter for well-defined porous layers. The electrolyte consists of hydrogen peroxide (H₂O₂) as support for the electrochemical oxidation of silicon, comparable with nitric acid used by stain etch. Its second component is HF for the dissolution of the silicon, i.e. the parasitic oxide in order to create the pores. The third consistence of the electrolyte is ethanol in order to reduce the surface tension of the solution for surface wetting (as well as for anodization). A typical electrolyte composition is HF : H₂O₂ : ethanol : H₂O = 9 : 1 : 4 : 11. An increase of H₂O₂ has the same effect as a high current by anodization or a high amount of nitric acid by stain etch: electropolishing starts.

A special fabrication parameter for this porous silicon fabrication technology is the metallization with precious metal. The etch process depends on the precious metal species, e.g. gold or platinum. Every metal layer has a different normal potential and, therefore, another resulting current in combination with silicon. The influenced current change and, therewith, the porous layer (in comparison to anodization) as well. Platinum increases the catalysing effect of hydrogen peroxide extremely, resulting in induced current increase and higher etch rates.

This technique has the advantages of contactless stain etch but results in more uniform and reproducible results and thicker PSi layers.
APPLICATIONS

Optical systems and transducers

The observation of room temperature luminescence from PSi in 1990 has stimulated intensive efforts to investigate the optical material properties. The light-emitting capabilities, such as luminescence, strongly depend on the size of the remaining Si crystallites and are not directly linked to the pore size and distribution of the porous layer. Light emission from Si, an indirect gap semiconductor, is coupled to low-dimensional nanostructures (quantum dots or wires) created during porosification of bulk silicon. The efficiency may reach 10% at room temperature [32]. Optically active structures, such as all-PSi LED's have been realized and show interesting electroluminescent properties [33]. The LED's consist of a highly porous PSi layer sandwiched between two Bragg reflectors also made from multilayered PSi. The wavelength ranges from 670-750 nm with high directionality for microcavity LED's. The electroluminescence is tunable depending on anodization parameters. Optical filters used in transmission or reflection can be realized via multilayered PSi structures with different porosities (high/low porosity) adjusted by the anodization parameters. As an example Bragg reflectors with a total thickness of 2.4 μm have been realized [33]. The structure consists of a 10 stack (80/160 nm) sandwich of low and high porosity layers. Microcavity resonators using these type of reflectors narrow the luminescence to a single peak with FWHM of 10 nm [34]. The position of the peak strongly depends on changes of the refractive index, which is, due to the high internal surface of the PSi, affected by adsorbed species. Therefore these structures are candidates for advanced biosensing systems. DNA detection with appropriate sensitivity, selectivity and response time has been successfully demonstrated [34]. Modifications of the PSi surface chemistry is possible within wide ranges in order to adapt the structures to specific applications [35] [36]. PSi formation allows gradual index profiles, which offers high flexibility in the design, e.g. for Rugate filters. Bragg reflectors of oxidized PSi layers, containing 183 periods with sinusoidal modulation of the index of refraction between 1.31 and 1.42 have been realized and integrated in a movable cantilever-type MEMS structure [37]. This allows tuning of the filter by tilting the element with respect to the optical axis. The movable structure has been realized by sacrificial layer etching of Psi, too. Optical effects of PSi are used in different sensing setups, e.g. Fabry-Perot, ellipsometry and waveguide based systems [35].

Electrical transducers and systems

The high internal surface of PSi has lead to the development of chemical/biochemical sensors and microreactors. By surface modifications the systems can be adapted to specific chemical and biochemical reactions. As an example enzyme microreactors show in increase in the glucose oxidase activity by a factor of 350 compared to planar silicon surfaces [38] [39]. Microreactors have been adapted and integrated into μ-TAS for studies of glucose transformation and proteomics [40] [41]. Furthermore, PSi layers show extended changes in physical parameters, such as electrical resistivity, during interaction with reactive gases. For NO2 the resistivity increases several orders of magnitudes for concentrations below 1 ppm in dry air at RT [42]. A gas sensor has been fabricated by front-side wafer processing and final selective etching to create free-standing PSi membranes. The layers show low cross sensitivities to other gases, like ozone, methanol, and CO. Metal-Oxide (SnO2/Sn-V-O) permeated PSi membranes exhibit significant changes in electrical resistivity at elevated temperatures if the layer is exposed to reactive gases, such as CO, or different types of hydrocarbons [43]. This is well-known for thin-film-metal-oxide gas sensors, but the high internal surface leads to improved characteristics. PSi layers coated with catalytic layers, e.g. with Pt or Pd, are used for the detection of gases like H2 which are converted at the surfaces at elevated temperatures. The exothermic reaction and the related temperature shift can be correlated to the gas concentration [44]. Catalytic converters can be directly used as an active component in gas analyzing instruments [45]. Pd coated PSi layers are used to convert reactive species, such as CO to non-reactive compounds, such as CO2. They are used as chemical filters and/or reference gas' generators on board of a μ-Lab [46] [47]. Figure 4 shows a schematic drawing of the device. The active catalytic area of Pd impregnated PSi is located in the center of the membrane and directly struck by the gas to be analyzed. The membrane also carries a heating resistor and temperature sensing resistors. For thermal isolation, in order to reduce the operating power a ring of PSi is created in the surrounding. A SEM picture of the membrane is shown in figure 5. The capillary structure with a layer of Pd is shown in figure 6, 7. The typical diameter of the pores in the range of a few μm. The efficiency of the converter has been determined with a commercial gas sensor directly connected to the outlet of the converter unit. The corresponding sensor signal in shown in figure 8.
The capabilities of PSi for humidity sensing has been investigated intensively [48] [49] [50]. PSi is used within a capacitor type transducer, e.g. within plate capacitors. Due to the high internal surface adsorption of gaseous species, such as water vapour, can be directly detected via the shift of capacitance. The large dipole moment of water leads to a significant change of the dielectric constant which easily can be handled with standard microelectronic circuits. A typical configuration is schematically shown in figure 9. A grid electrode is used on top of the sensor structure which allows the water vapour to diffuse into the PSi layer beneath. The bulk Si is used as counter-electrode. The typical thickness of the PSi layer is in the range of 1-2µm with an active area of approx. 2mm² exposed to the ambient air. A SEM picture of the chip is shown in figure 10, 11. A heating resistor fabricated in the surrounding is used to operate the sensing structure at elevated temperatures. This allows to reduce the response time and to refresh the sensor if required (reset). A resistor network is integrated for temperature control. Back-side micromachining steps can be added to improve the thermal isolation of the active structure in order to reduce the overall power consumption.
Compared to conventional humidity sensors, e.g. based on polymer materials, the sensor shows high sensitivities. A typical response signal is shown in figure 12. In addition the sensor is stable in high temperature environments, due to the all inorganic structures. Pre-oxidation of the PSi layer improves the long-term stability of the device.

Figure 8: Gas sensor resistivity (Figaro, TGS 2600) as response of the microreactor efficiency (1000 ppm CO) [47]

Figure 9: Schematic cross-section of porous silicon humidity sensor [50]

Figure 10: SEM top-view of humidity sensor [50]  
Figure 11: SEM close-up of humidity sensor with grid electrode
Porous silicon for micromachining

The high surface/volume ratio of PSi offers unique possibilities for micromachining and device design. The formation of macropores in n-type Si has been introduced to create microstructures with steep sidewalls and high aspect ratios [51]. Trenches up to a depth of 150µm and aspect ratios of 10-15 have been realized. The characteristics do not compete with LIGA structures or structures obtained with advanced dry-etching techniques, but are of interest for a number of applications, such as via holes in pneumatic or fluidic systems. A key advantage is, that these type of structures can be random structured and processed within low cost standard equipment and facilities. In p-type Si substrates similar results have been obtained and trenches up to a depth of 300µm have been fabricated [52]. PSi, especially in an oxidized state, shows a significant reduced thermal conductivity [53]. This is of relevance for a number of MEMS devices, such as anemometers and low power devices operated at elevated temperatures [47].

One of the first applications of PSi in microsystem technology are sacrificial layers [18] [54] [55]. In comparison to standard surface micromachining PSi enables any layer thickness up to 100 µm. After porosification of bulk Si additional layers can be deposited and microstructured (cantilevers, beams, bridges). Finally the PSi is etched away with standard Si etchants, such as KOH or TMAH. Due to the high surface/volume ratio of PSi highly diluted etchant can be applied at room temperature. A large area of application is the generation of thermally isolated gaps by the aid of porous silicon sacrificial layers [56]. Thick porous silicon sacrificial layers are used to combine the advantages of standard surface micromachining with the advantages of bulk micromachining: no design limitation based on the silicon crystallographic orientation, realization of free standing structures thermally decoupled of the substrate and only front-side micromachined. Compared to standard surface micromachining processes the thickness of the sacrificial layer is much more higher which solves a number of technological problems around sticking and adhesion of microstructures and thermal isolation and decoupling is much more efficient. The technique has been successfully applied for movable microstructures, such as thermomechanically driven cantilevers [37] and suspended membranes for low power thin-film gas sensor arrays operated at high temperatures [57]. The technology has the potential to replace standard wet chemical anisotropic etching of bulk-Si in a number of applications. In addition to the advantages mentioned above, the process requires a minimum footprint for the MEMS structure and the final PSi etching can be performed after dicing with the chips on tape. This allows to protect the highly sensitive structures during the harsh dicing process [57].

For membrane generation it is possible to format the patterned porous silicon by the use of masking techniques. Different masking materials could be utilized: silicon carbide, silicon nitride or combinations of HF-resistant polysilicon and electrical isolating oxide. For generation of thicker porous silicon layers it is important to find out HF-resistant layers which enable long anodization times. A further approach are ion-implanted masks. Based on different porous silicon formation mechanisms for n- and p-type silicon, it is possible to use n-implanted layers as masking material during the anodization of p-type silicon [58].
For free standing membrane generation it is possible to deposit e.g. a PECVD-layer on top of the porous silicon layer. Based on the plane surface, the membrane contains no topology between silicon surface and masking layer. There are no resulting sharp bend which are critical points for structure destruction. After deposition the membrane must be structured to open the PSi for sacrificial layer removal.

The technology is used for the realization of gas sensors with thermally isolated membranes [57]. An approx. 100 µm thick, patterned porous silicon sacrificial layer is formatted by the use of a phosphorous-implanted layer (see figure 13). Afterwards, a 1 µm PECVD-nitride membrane layer is deposited on top. Without structuring of the membrane layer a complete gas sensor device with platinum heater, electrical isolation, interdigital structures and gas sensitive tin dioxide is deposited and structured. After these fabrication steps the PECVD-membrane is structured to open the porous silicon and the sacrificial layer can be removed with diluted alkaline solutions as TMAH or KOH. But for this application the silicon wafer is diced before sacrificial layer removal. The advantage of this process is the membrane protection during dicing. Dicing had a high failure rate for free standing, movable structures. The sacrificial layer removal with diluted alkaline solutions at room temperature is very selective to all used layers including the dicing tape. For sacrificial removal the single chips glue on the dicing tape and could be picked up completely processed (see figure 14). Based on the protection of the membrane during gas sensor processing and dicing the yield of devices is very high. The result is a membrane with a 100 µm gap for thermal isolation realized with low cost surface micromachining technology. A 2x2 sensor array is shown as SEM in figure 15.

Figure 13: SEM cross-section of porous silicon well realized with implanted mask technology [57]

Figure 14: Process-flow for the realization of thermally isolated membranes [57]
CONCLUSIONS

Porous silicon has been rediscovered as a new and interesting material for applications in the broad field of MEMS fabrication and microsystem technology. The material properties related to the nanostructure of the Si-skeleton and the high internal surface area offer a number of routes for the use of the material as a functional layer and as a sacrificial layer for micromachining. Different types of sensors, actuators and systems have been realized on the basis of the technology and show interesting characteristics. Emphasis of current and future work is on the optimization of the technology which requires a detailed understanding of the layer formation process. A reliable pool of know-how will allow to introduce the technology for the commercial device fabrication and lead to improved device performance and reduced costs for device processing.

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Figure 15: Array of thermally isolated membranes for gas sensor applications [57]
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