Chapter 7

Integration and Packaging

The collective architectures presented in Chapters 4, 5, and 6 are best utilized when integrated in the sensing plane as the sensors themselves. This “smart pixel” technique has worked well in focal plane processing applications because phototransistors and photodiodes can be made compactly using standard CMOS fabrication techniques. The operation of a typical photodetector causes minimal interference with the surrounding surface; light interference in the surrounding circuits can be easily minimized by using guard rings or by covering the circuits in a sacrificial layer of opaque material such as metal. The fabrication of chemical sensors on substrates designed for integrated circuits, however, is not as straightforward. Such fabrication is complicated by the following key issues:

- Operating temperature compatibility: integrated circuits (room temperature) do not operate well at typical operating temperatures for chemical sensors (over 100°C).
- Adhesion: chemically sensitive materials have difficulty adhering to standard interconnect metals in semiconductor fabrication processes.
- Packaging: integrated circuits need to be protected from potentially damaging chemicals in the sensing environment.

Integration of the signal processing architectures described in this research with chemical sensors has been outside the scope of this research. However, the basis for integrating circuits and thin-film sensors has been well established in the research community and indirectly, the basis for integrating these same circuits with ChemFETS has been established as well. Because of the importance of integrating our signal processing architectures onto the chemical sensing plane, two potential integration schemes are described in Sections 7.1 and 7.2 to convince the reader of the feasibility of complete chemical microsystems. The issue of packaging for operating in unfriendly sensing environments is discussed in Section 7.3 of this chapter. Despite the fact that completion of this integration is beyond the scope of this research, one of the next steps in our larger research effort, in a collaboration with NIST, will be the monolithic integration of chemical sensors with the signal processing architectures developed herein.

7.1 Integration of Thin-Film Sensors with aVLSI Circuits

The primary obstacle to placing CMOS circuits on the sensing plane with chemical sensors is the difference in operating temperature between the two types of devices. Using conventional micromachining techniques, however, this obstacle can be easily overcome. The potential integration scheme is shown in Figure 7.1 and can be fabricated using the MOSIS prototyping service and two simple, post-fabrication steps that are carried out after the prototype chip is fully fabricated and bonded to its package.

The chemical sensors are suspended on a platform, thermally isolated from the surrounding substrate using a generic technique developed by the National Institute of Standards and Technology in conjunction with MOSIS [13] for micromachined structure applications. The foundation for these suspended platforms is established during the fabrication of the chip itself through two specialized layers called OPEN and PSTOP. Areas of the substrata designated by the OPEN layer are masked during the final passivation step of fabrication, so that exposed silicon remains in these areas. The OPEN areas outline the region that, once etched in postprocessing, will create the empty space under the suspended platform. The PSTOP layer is a heavily doped p-diffusion layer that is used to surround the OPEN layer and prevents the isotropic etchant used during postprocessing from etching into the surrounding substrate where integrated circuits have been fabricated. (Figure 7.2)

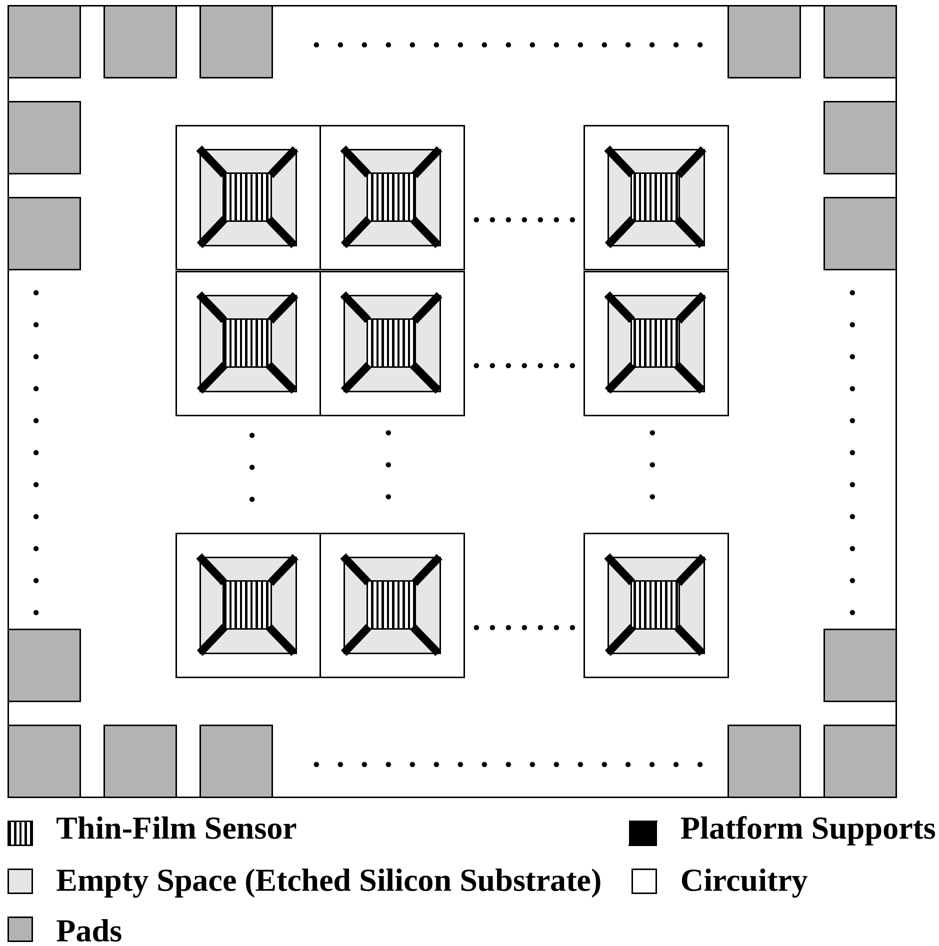

Figure 7.1: Thermal Isolation of Chemical Sensors from Surrounding Substrate

This technique simply isolates the thin-film chemical sensors from the surrounding substrate by fabricating the sensor itself on an elevated platform. Since these suspended platforms are connected to the surrounding circuits and substrate only through four thin arms that support the platform, little heat is actually transferred to surrounding circuits.

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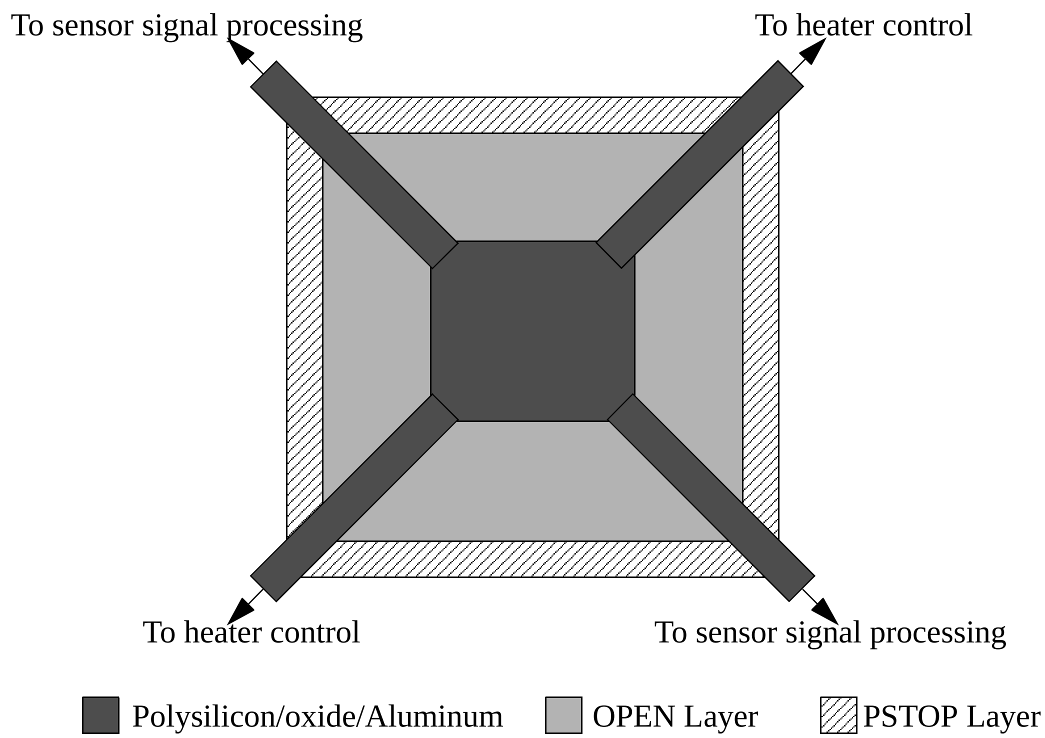

Figure 7.2: Layout of the Suspended Platform

In fabricating a suspended platform, the polysilicon/oxide/aluminum platform is surrounded by an OPEN layer except for the four arms that will support the platform after etching. The OPEN layer is simply exposed silicon substrate that can be selectively etched after the integrated circuits portion of the chip is fabricated. The PSTOP layer prevents any subsequent etching from damaging circuits in the substrate that surrounds the OPEN layer.

After fabrication, the packaged chip is wet-etched using a direction-selective silicon etchant such as EDP (ethylene-diamine pyrocatechol) [62], TMAH (tetramethyl ammonium hydroxide) [63], or XeF_2 (xenon diFlouride)[64] to selectivity etch through the OPEN areas at a constant angle. The etching progresses until a pit is formed underneath the area where chemical sensors will be fabricated. The structure at this point in fabrication consists of an elevated polysilicon/oxide/aluminum sandwich (Figure 7.3) suspended above the substrate and connected to the surrounding substrate by four relative thin supports. The supports are sufficiently thick to support the structure mechanically yet they are also thin enough to minimize thermal communication to the surrounding substrate.

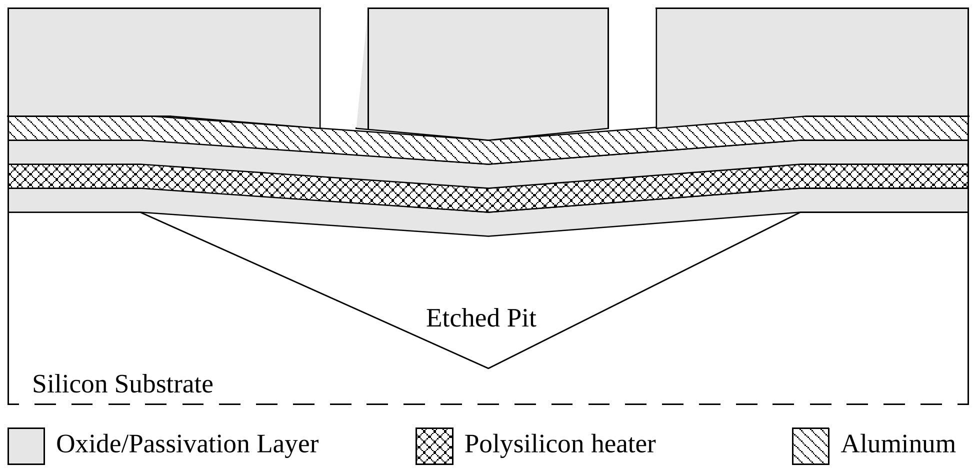

Figure 7.3: The Suspended Platform after Etching

During etching, a pit is formed underneath the oxide/polysilicon/oxide/aluminum sandwich that forms the heating platform. The etch is direction selective so that etching stops when etching from either side of the platform reaches a point underneath the platform. All areas of the platform are covered with a passivation layer, except for two exposed aluminum pads that will later connect to the chemical sensor. The aluminum layer shown here consists of two metal layers separated by another oxide layer. The metal 1 layer distributes the heat generated by the polysilicon heater and the metal 2 layer connects to the chemical sensor.

All but the OPEN areas are protected during etching from attack by the passivation layer deposited during the final step of the IC fabrication process. Exposed bonding pads and sensor connection pads can be mildly attacked by the etchant, depending on the exact etchant used; for the most part, however, the material selectivity of the silicon etchant minimizes its effect on the exposed metal of the pads. In a fully developed manufacturing process for these structures, these pads would be masked during etching to fully protect them from any attack by the silicon etchant.

After the platforms are suspended from the surrounding substrate, chemical sensors may be formed in one of two ways:

- Maskless deposition of chemically sensitive materials where sensors are formed only where:
  - the substrate is heated to enable conductivity of the deposited material
  - selective reaction of process chemicals with the substrate enable sensor formation

- Masked deposition of chemically sensitive materials: materials are selectively deposited on the sensor areas using standard photolithography techniques.

A maskless process has advantages both during prototyping and during manufacturing of complete chemical microsystems. During the research and development phase, maskless processing makes sensor fabrication more accessible to the average circuit design. Once a chemical microsensing product has reached manufacturing, maskless processing has the added advantage that, in most cases, it is less expensive and less prone to error than masked processes. However, masked deposition of materials using photolithography techniques are more standardized within the semiconductor fabrication industry and require less investment to adapt to the production of chemical sensors.

Some chemically sensitive materials, such as tin oxide, are known to become conductive only when sputtered onto a heated substrate [62]. The suspended platforms described previously consist of a polysilicon/ oxide/aluminum sandwich (Figure 7.3) that can be heated by applying voltage across the polysilicon heater. When heated in this way during sputtering, tin oxide sputtered onto these heated platforms forms chemical sensors while tin oxide deposited elsewhere on the substrate is not conductive and has no effect on the operation of other components. Problems with tin oxide deposition can occur, however, when tin oxide does not adhere to the underlying aluminum pad on the chemical sensor and fails to make a sound electrical connection to signal processing in the surrounding sensing plane. These adhesion problems can be overcome by choosing some intermediate metal such as chromium to bond the tin oxide to aluminum; these adhesion problems are currently the primary obstacle to integrating tin oxide sensors using this fabrication scheme. In the long term, however, it is more likely that chemical microsystems would use a more adhesion-friendly metal, such as Tungsten, to electrically connect chemically sensitive semiconductors to signal processing circuits in these systems.

Alternatively, chemically sensitive material may be selectively deposited using chemical vapor deposition in a maskless sensor formation step. Semancik *et al* [65] use such a method of selective chemical vapor deposition to deposit various metal oxides on the micro-hotplates described previously. Once fabricated and packaged, these microhotplates are selectively heated during the introduction of a precursor gas or vapor present in the CVD chamber. The precursor gas is thermally decomposed into an oxide only on those areas of the substrate that are heated, thereby laying the foundation for subsequent deposition of metal additives. Metal additives are then introduced and deposited selectively on the selected hotplates, creating a metal-oxide chemical sensor. This technique, in addition to being maskless, allows multiple types of chemical sensors to be fabricated on the same substrate. Using these chemical vapor deposition processes, single chip systems can be fabricated that contain on-board signal processing and a broad range of sensors for multiple applications.

Any of the deposition methods described above can also be performed using a masked process. A masked process can also enable the deposition plane for chemical sensors to be flat as the passivation layer deposited during standard IC fabrication can be removed, leaving a relatively flat layer of metal (aluminum) and metal. Deposition on a flatter surface can minimize some of the adhesion problems experienced in sputtering tin oxide and other problems associated with maskless chemical vapor deposition process. Masking also allows chemically sensitive materials to be deposited that do not have the thermally-selective properties that would enable them to be handled in a maskless process.

7.2 Integration of ChemFET Sensors with aVLSI Circuits

Using the suspended platform techniques described in the previous section, ChemFETs may also be fabricated on suspended platforms on a silicon substrate using a slight modification of the wet etch described in Figure 7.1. The wet etchant TMAH not only etches the substrate beneath and around the OPEN layers in a fabricated chip, but also etches the n-well and p-diffusion on the platform itself. These two layers are required to create a FET structure on the platform.

Reay *et al* have investigated the use of an electrochemical TMAH etch to retain n-well and p-diffusion material on a suspended platform during etching. They have successfully fabricated npn bipolar transistors on these platforms for application to low-power, temperature regulated circuits. By biasing the n-well above the p-type substrate and maintaining a constant potential between the substrate and the etching solution, it is possible to protect the n-well during TMAH etch [66].

Slight modification of this process and a subsequent processing step could make this electrochemical etch suitable for the fabrication of thermally isolated ChemFETs on standard silicon substrates. Using the electrochemical etch, it can be possible to retain the structure of Figure 7.4 on the platform after etching. Subsequently, a chemically sensitive material such as Palladium or Platinum could be deposited onto the platform to form the gate of the ChemFET. A ring of polysilicon around the ChemFET heats the sensor to suitable operating temperatures for chemical sensing. Since this process involves the deposition of Platinum, Palladium, or similar material, it does require a mask. Using a mask enables multiple types of ChemFETs to be deposited on a single substrate. Although this device has not yet been fabricated in the research community, it is a viable extension of current research efforts in this area.

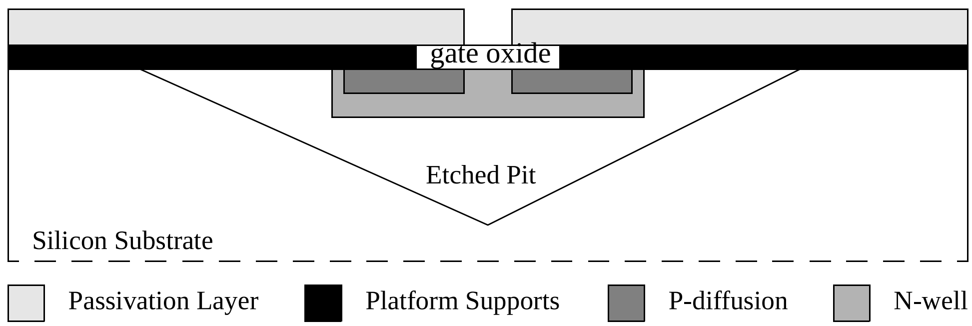

Figure 7.4: Fabrication of a ChemFET on a suspended platform

During etching, the n-well on the platform itself is retained by electrochemical methods. A voltage is applied between the n-well and the p-type silicon substrate; a potentiostat maintains a constant voltage from p-substrate to the etching solution, thereby preventing etching of the n-well. After the device is etched, it is masked and the polysilicon gate is removed and replaced with a chemically sensitive material is deposited as the gate of the FET. Polysilicon surrounds the ChemFET structure to provide heat. The support arms carry sensor output lines and heater control lines off the platform to the surrounding substrate. Although the platform does sag somewhat under its own weight, it is shown flat here for simplicity.

7.3 Packaging of Integrated Chemical Microsystems

In any integrated chemical sensing microsystem where circuits are exposed to potentially harsh chemicals in the sensing environment, the packaging is also critical to the final performance and reliability of the system. Although packaging is not directly addressed in this research effort, viable packaging options are nevertheless included in this discussion for completeness. Both the issues of sensor and circuit performance are of interest in a variety of potentially harsh sensing environments to which the entire system might realistically be exposed.

Enabling and protecting the performance of circuits on the sensing plane can be done in one of two major ways:

- Coating of circuit surfaces
- Minimizing contact between the sensing environment and the circuit space by:
  - moving sensing environment to the back-side of the wafer
  - using a cover wafer to protect circuits while exposing sensors to the sensing environment

Coating the circuit surface is the simplest and most straightforward approach to the protection of circuits on the sensing plane. A number of microelectronic materials are suitable for such coating in a chemical sensing environment and are summarized in Table 5.1. Despite the need for specialized fabrication equipment, the polymer Paralene (polyxylylene) has the best resistance to gas permeability of these materials and seems well suited to chemical sensor packaging applications. Multiple passivation layers may also be used to further protect circuits on the sensing plane. Using appropriate coating techniques, the sensors in the microsystem can remain accessible to the chemicals in the sensing environment while the circuits themselves are protected by suitable, nonporous, multiple passivation layers.

TABLE 7.1: Materials for Encapsulation of Circuits in Chemical Sensing Systems

Material	Advantages	Disadvantages	REF
Paralene (Polyxy-lylene)	Good Resistance to Gas Permeability Ultra-thin conformal coatings possible Excellent moisture barrier High resistance to organic solvents	Difficult to coat vertical devices Requires custom deposition equipment	[67], [68]
Glasses	Uses standard fabrication processes Good chemical resistance	Coefficient of thermal expansion mis-match with silicon is very high; leads to residual stress and cracking	[69]
Methyl-Silicone gel	Good chemical resistance Low water absorption Inherently flame retardant	High cost Attacked by halogenated solvents	[68] [70]
Polyimides	Excellent adhesion Good solvent resistance	High cost Difficult to fabricate Leaves high residual stress; vulnerable to substrate warping	[68] [69]
Silicon Nitride Al-Oxide	Pinhole-free (gas resistant) films Uniform, conformal thin-films possible Processing has minimal effect on dopant redistribution in silicon.	High processing temperatures required for high quality films (>400° C): - causes aluminum diffusivity into oxides and silicon - over 650° C, requires a different interconnect (e.g. silicides)	[69]

In addition to coating the circuit surface, it is also possible to minimize contact between circuits and sensing environment. Two examples of such a packaging philosophy are shown in Figure 7.5.

In one case (Figure 7.5a), circuits are partially sheltered from the sensing environment by introducing the gases and chemicals from the back part of the wafer. The wafer is bulk micromachined so that a hole is opened up to the underside of the suspended hotplates containing chemical sensors as described in the previous sections. During the last step of fabrication, a material like silicon nitride is deposited as passivation both on the front and back side of the wafer. The passivation on the front side is then masked and the entire wafer exposed to hydrofluoric acid (HF), thereby making the passivation layer on the back side of the wafer porous. Gases and chemicals are then able to diffuse directly from the back side of the wafer to the chemical sensor, minimizing their contact with the signal processing portions of the wafer [71].Alternatively, the portions of a chip containing circuits can be protected by a cover wafer that is bonded to the main wafer using a glass or anodic bonding that is standard in the semiconductor processing industry. (Figure 7.5b). The cover wafer is then bulk micromachined to open holes between the sensing environment and the chemical sensors on the primary wafer. The remaining sections of the primary wafer are isolated from the sensing environment by the cover wafer [72].

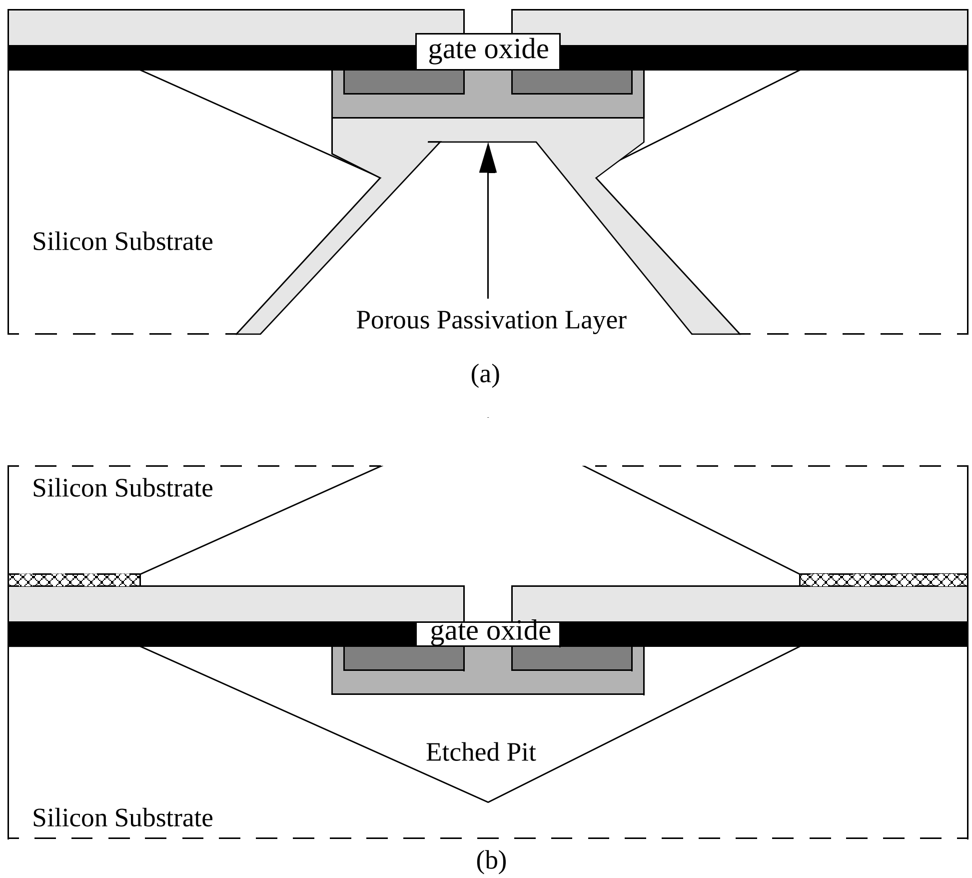

Figure 7.5: Packaging Methods for Isolating Circuits from the Sensing Environment

The backside machining shown in (a) allows a gas or chemical to be exposed to the chemical sensor from underneath the heated platform, thereby minimizing its contact with the passivated circuits on the top side of the wafer. In the covered wafer technique (b), another wafer is placed on top of the primary wafer, and bulk micromachined to allow only those areas of the primary wafer continuing chemical sensors to be exposed to the sensing environment. The cover wafer is bonded to the primary wafer using a standard sealing technique such as glass or anodic bonding.

Also of concern in the development of these chemical microsystems is the lifetime and reliability of the chemical sensors themselves. When continuously exposed to a changing sensing environment, tin oxide, for example, has been known to experience lifetimes as short as six months due to irreversible, poisoning reactions on the sensor surface. To extend the lifetime of the sensors and the accompanying microsystems, discontinuous use of the system is recommended where appropriate filters are used to shield the sensors from the sensing environment for a designated percentage of its operating time. The closed filter system, although it adds some cost to the system, allows the chemical sensors to be exposed only to a filtered, non-poisoning environment while the system is not in use. The use of any one or a combination of these shielding techniques can provide sufficient protection to circuits and sensors to make integrated chemical microsystems a viable option for addressing a variety of low-cost chemical sensing applications.