Porous Silicon for Microdevices and Microsystems

Luca De Stefano and Ilaria Rea

Contents

Abstract

An updated literature survey is provided of the various uses of both macroporous and mesoporous silicon in individual microdevices and complex microsystems. The material has been used (a) as a silicon wafer processing tool wherein it is sacrificial (b) in a passive role where it can provide thermal or electrical isolation and (c) in an active role where it can perform a number of diverse functions. Examples of active functions available for microsystems include culturing cells, sensing, delivering drugs, providing sources of energy for microactuators, or having a catalytic role in microelectrodes.

Keywords

Porous silicon · Microdevices · Integrated systems

L. De Stefano (✉) · I. Rea
Institute for Microelectronics and Microsystems, Naples, Italy
e-mail: luca.destefano@na.imm.cnr.it; ilaria.rea@na.imm.cnr.it

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Introduction

The incredible explosion of solid-state technologies in the last 30 years has made the consumer electronics as we know it nowadays: sophisticated electronic equipment are largely available in entertainment, communications, and office productivity. The ability of material science in fabricating, and also mixing together, very different materials, both organic and inorganic, has launched what is expected to be the next technology revolution: the integrated microsystems. Micro (or even nano)-opto-electro-mechanical systems, M(N)OEMS, or micro total analysis systems, micro-TAS, are the acronyms that can be found so often in scientific production (Gad-el-Hak 2010). These devices will combine sensing, processing, actuation, and power management functions in order to achieve multispectral functionality, adaptability in response to a changing environment, and real-time data analysis. Beyond its peculiar and exciting electrooptical and chemical properties, porous silicon has shown, from the beginning of its discovery, very interesting features for integrated microsystems fabrication and applications. Both macroporous structures from n-type silicon and mesoporous layers created from heavily doped silicon are currently used in a wide set of devices, from chemical and biological analytical sensors to micro fuel cell, and many other microsystems can be found in the academic literature and industrial patents. In the following updated review, the range of micromachined devices realized via sacrificial porous silicon is illustrated; porous silicon-based optical or electrical transducers as sensing part of microsystems devoted to biological and chemical monitoring are then presented; finally a range of diverse functions demonstrated within devices is summarized.

Sacrificial Use of Porous Silicon in Microsystems

Macroporous silicon technology found its principal application in integrated microsystems as sacrificial layer: multilayered and suspended structures, such as bridges, membranes, and cantilevers, often require fabrication, almost always by isotropic etching and removing, by alkaline-based water solution, of a porous layer. The thickness of this layer can be up to 100 μm, or more, which is very much greater with respect to those obtained by thin film deposition techniques (<10 μm): in this sense, porous silicon passive layer is an exclusive technology. In Table 1 are reported some references of porous silicon sacrificial layers together with the functionalities of the resulting microsystems.

Silicon on insulator technology and thermal insulation are other important fields where porous silicon morphology plays a key role, and thus, it is often used in complex microsystems: thermal properties of porous silicon layers can be strongly modulated by changing the porosity, i.e., the amount of air present in the silicon volume. On the other hand, pores can be completely filled by silicon dioxide, so that a nanocrystalline film can be transformed by thermal oxidation in an oxide layer preserving the desired geometry. Quite a few works on this subject can be found in the literature (Bomchil et al. 1988; Perichon et al. 2001; Friedberger et al. 2001; Lysenko et al. 2002; Mondal et al. 2009). Chapters in this handbook of relevance

Table 1 Porous silicon as sacrificial layer

Sacrificial structure	End product	Reference
Freestanding film	Flow channels	Lang et al. (1994)
Bridge	Flow sensor	Lang et al. (1995)
Thin films, wires	Bolometer, anemometer	Steiner and Lang (1995)
Cantilever	Micromachining	Bischoff et al. (1997)
Wick	Wall of heat pipe	Holke et al. (1998)
Cantilever	Accelerometer	Sim et al. (1998)
3D plates	MEMS	Lammel and Renaud (2000)
Membrane	Microelectrodes	Kalinowski et al. (2000)
Cantilevers, disks	MEMS	Lee et al. (2000)
Nanoporous structures	MEMS	Benecke and Splinter (2001)
Sacrificial layer	Microphone	Kronast et al. (2001)
Thin (1 micron) layer	MEMS	Dantas et al. (2008)
Sacrificial layer	Microcoils	Liu et al. (2003)
Nanoporous structures	Transducers	Mescheder (2004)
Sacrificial layer	Microphone	Ning et al. (2004)
Thick layers	MEMS	Valera et al. (2005)
Patterned layer	Microneedles	Rajaraman and Henderson (2005)
Sacrificial layer	Micro turbine	Rajta et al. (2009)
Thin film	Microresonator	Olivares et al. (2010)
Thick (15 micron) layer	Nanowire array transfer	Weisse et al. (2013)
3D patterned layers	Photonic crystals	Dang et al. (2013)

include ► “Oxidation of Mesoporous Silicon,” ► “RF Electrical Isolation with Porous Silicon,” and ► “Thermal Isolation with Porous Silicon.”

Porous Silicon-Based Sensing Microsystems

Mesoporous silicon is by far the most intriguing material for optical and electrical monitoring of chemical and biological molecular interactions. The integration of porous silicon transducers in microsystems is not trivial or straightforward: each step of the fabrication process (photolithography, etching, bonding/sealing, inlet/outlet) should be designed and realized, just preserving the physical and chemical characteristics of the sensing material. In case of porous silicon, pores accessibility, surface chemical features, and signal readout (both optical and electrical) should be maintained, if not optimized in microsystems fabrication. The utilization of biological bioprobes, which can recognize specific analytes in complex mixtures, thus enhancing the selectivity of the sensor systems, makes things even more difficult: biological molecules work in the so-called physiological conditions that could not match technological requirements. On the other hand, microsystems can really boost sensing features through electronics and microfluidic circuits. Onboard electronics allow signal amplification, restoration, storage, and transmission, which correspond

Table 2 Porous silicon sensing microsystems

Transduction	Sensing application	Reference
Electrical	Humidity	Rittersma et al. (2000)
Electrical	Bacteria	Misra et al. (2001)
Optical	Volatile compounds	De Stefano et al. (2004)
Optical	Liquids/gases	De Stefano et al. (2006a)
Optical	DNA	De Stefano et al. (2006b)
Optical	Liquids/gases	De Stefano et al. (2006c)
Electrical	Gases	Barillaro et al. (2007)
Electrical	Gases	Zellers et al. (2007)
Optical	DNA	Rendina et al. (2007)
Optical	DNA	De Stefano et al. (2007a)
Optical	Gases	De Stefano et al. (2007b)
Optical	Liquids/gases	De Stefano et al. (2007c)
Optical	Gases	De Stefano et al. (2007d)
Optical	Protein/ligand	De Stefano et al. (2007e)
Optical	Peptide/ligand	Politi et al. (2015)
Electrical	DNA	Chen et al. (2007)
Mechanical	Antibody/antigen	Stolyarova et al. (2008)
Electrical	NO_2	Barillaro and Strambini (2008)
Optical	DNA	Rea et al. (2010)
Electrical	Gases	Barillaro et al. (2010)
Electrical	Gases	Sainato et al. (2015)
Optical	DNA	Rea et al. (2011)
Optical	Liquids	Surdo et al. (2012)
Mechanical	Liquids	Strambini et al. (2012)
Optical	Liquids	Barillaro et al. (2012)
Optical/electrical	Liquids/gases	Caliò et al. (2015)

to higher sensitivity, low drift, and possibility of actuation. Microfluidics ensure small volume consumption, safe operations, rapid analysis time, and protection of the transducer against the environment. For all these reasons, a great effort has been spent in porous silicon integration in microsystems for substance monitoring: Table 2 reports many successful applications of chemical and biological sensing that can be found in literature together with the method of transduction exploited in the device. Chapters in this handbook of particular relevance include ▶ "Porous Silicon Gas Sensing," ▶ "Porous Silicon Immunoaffinity Microarrays," and ▶ "Porous Silicon Optical Biosensors."

Microdevices and Microsystems Incorporating Porous Silicon

Spongelike or coordinated ensembles of pores have been attractive for a lot of on-microsystems applications that span a wide range of interesting fields. Porous silicon membranes for hydrogen storage and release have been studied and

Table 3 Active functions of porous silicon in microdevices and microsystems

Structure	Application	Reference
Active layer	LED	Hirschman et al. (1996)
Layer	MALDI-TOF MS	Ekstrom et al. (2000)
Multilayer	MEMS spectrometer	Lammel et al. (2002)
Membrane	Electro-catalysis	D'Arrigo et al. (2003)
Array	Ultrasounds	Hirota et al. (2005)
Membrane	Particles filter	Wallner and Bergstrom (2007)
Membrane	Micro-propulsion	Lazaruk et al. (2007)
Channel	Gas concentration	Camara et al. (2007)
High-porosity layer	Field emission device	Dantas et al. (2008)
Membrane	H2 storage	Nagayama et al. (2008)
Membrane	Micro fuel cell	Torres et al. (2009a, b)
Micro-column	Chromatography	Mery et al. (2009)
Buried contact	Solar cells	Vitanov et al. (2009)
Membrane	Smart patch	Dardano et al. (2016)
Hybrid layer	Light generation	Robbiano et al. (2015)
Active layer	Drug delivery system	McInnes et al. (2015)
Nanowire	Microfluidic device	Xia and Zheng (2015)
Microneedles	Drug delivery system	Chiappini et al. (2015)
Microneedles	Drug delivery system	Van der Maaden et al. (2015)
Layer	Cell culturing	Mondal et al. (2015)
Hybrid layer	Fuel cell electrode	Yu et al. (2016)

characterized; mechanical properties of these membranes have been used in integrated microphones; microturbine and field emission devices are among the most advanced MEMS structures that can be obtained by porous silicon micromachining technique: from all those experiments, it results to the conclusion that researchers' fantasy and imagination are the real limits for porous silicon application in microsystems. Very recently, a burst of porous silicon-based microsystems for biomedical applications appeared in specialized literature: from basic biologic studies, such as cell culturing, to biomedical devices, such as microneedles array or smart patch for drug delivery, have been presented. Table 3 shows the references on this heterogeneous subject. The chapters in this handbook on related topics include ▶ "Porous Silicon in Immunoisolation and Bio-filtration," ▶ "Porous Silicon Photonic Crystals," ▶ "Porous Silicon and Micro Fuel Cells," and ▶ "Porous Silicon Based Mass Spectrometry."

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