Porous Silicon Gas Sensing

Giuseppe Barillaro

Contents

Abstract

In this chapter, the state of the art on porous silicon gas sensors, both electrical and optical, is reviewed by paying special emphasis on the advancement of gas sensor architectures that has occurred over the two last decades, as well as on the different functionalization approaches implemented in and chemical species sensed with such architectures. Ten main architectures, five for the electrical domain (capacitor, Schottky-like diode, resistor, FET-like transistor, and junction-like diode) and five for the optical domain (single layer, waveguide, Bragg mirror, resonant cavity, and rugate filter), have been proposed so far for improving gas sensor features. Several functionalization schemes have been integrated in such architectures to improve sensor performance, and more than 50 different chemical species have been sensed using porous silicon gas sensors. The latest trends on multiparametric sensing on single devices as well as on multisensor integration in a single chip, for both optical and electrical domains, are also discussed.

G. Barillaro (✉)
Dipartimento di Ingegneria dell'Informazione, Università di Pisa, Pisa, Italy
e-mail: g.barillaro@iet.unipi.it

L. Canham (ed.), *Handbook of Porous Silicon*,
DOI 10.1007/978-3-319-05744-6_86

Introduction

Gas sensors, which are a subset of the broader family of chemical sensors, allow inferring on the chemical species present in the surrounding environment. An ideal gas sensor should have high sensitivity, high specificity, small limit of detection, high resolution, high accuracy, high precision, large dynamic range, null offset, high linearity, null hysteresis, short response time, and long operation life (see Korotcenkov (2013)). Of course, no current gas sensors meet all these requirements simultaneously, which are, on the other hand, neither achievable nor necessary at the same time in real-world applications.

The analysis of the state of the art of porous silicon gas sensors highlights how the early studies were mostly focused on the development of suitable readout approaches with the aim of investigating the sensing properties of porous silicon layers in sensor structures featuring both basic architecture (e.g., capacitor, monolayer) and simple surface chemistry (e.g., native surface or oxidized surface). On the other hand, the latest studies are mostly focused on the integration of porous silicon layers in sensor structures featuring advanced architectures (e.g., FET-like transistors, stacked rugate filters, etc.) and sophisticated surface chemistry (e.g., silanization, carbonization, metallization, etc.) with the aim of improving sensitivity, selectivity, and reliability performance. Finally, optical and electrical sensing platforms integrating array of porous silicon sensors with advanced features on the same chip are envisaged in the near future, though still in their infancy today (see handbook chapter "▶ Porous Silicon for Microdevices and Microsystems") (Fig. 1).

Gas Sensing with Porous Silicon

In the last two decades, micro-, meso-, and nanostructured forms of silicon, namely, porous silicon, have been demonstrated to be very effective for the fabrication of integrated gas sensors with low-cost process and room temperature operation (see Mizsei (2007), Ozdemir and Gole (2007), Saha (2008)). The increased specific surface (by definition, accessible surface to volume ratio) of porous silicon, up to 10^7 times larger than bulk materials, ensures a stronger interaction between material

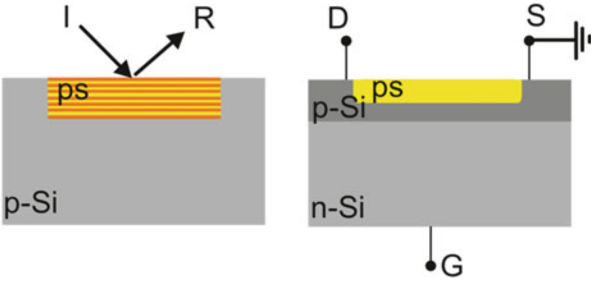

Fig. 1 Sketch of a multilayered optical device (on the *left*) and a FET-like electrical device (on the *right*) representative of the last-generation architecture of porous silicon gas sensors

surface and gas molecules and allows high sensitivity and good limit of detection to be achieved for a large number of gaseous species (e.g., NO_x and other inorganic gases, organic compounds, among which explosives, hydrocarbons, alcohols, halides, amines, ketones, etc.). Optical, electrical, and electrochemical approaches have been established to be valuable for the detection of a multitude of different gas species (both inorganic and organic). Changes in optical (e.g., refractive index, radiative recombination processes, etc.) and electrical (e.g., dielectric constant, conductivity, etc.) properties of the porous silicon material upon interaction (adsorption and/or condensation processes) with the specific gas species have been demonstrated through quantitative monitoring of the variation of different parameters (e.g., photoluminescence spectrum; reflected, transmitted, and diffracted optical power; capacitance; current; resistance; etc.) as a function of the gas concentration. A number of architectures have been proposed for both electrical (e.g., metal-based devices, among which capacitor, resistor, and Schottky diode, and pn junction-based devices, among which diode, transistor, etc.) and optical (e.g., monolayer-based devices, among which waveguide, and multilayer-based devices among which Bragg mirror, resonant cavity, rugate filter, etc.) gas sensors with the aim of improving sensor performance (e.g., improve sensitivity, limit of detection and selectivity, compensate for baseline drift, compensate for measurement angles, etc.). An equivalent large number of readout approaches (e.g., spectrometry, interferometry, ellipsometry, birefringence, conductometry, impedance spectroscopy, etc.) have been reported for monitoring the sensor parameters, by using both single-parameter and multiparameter approaches. Besides, a number of functionalization schemes (e.g., oxidation, hydrosilylation, carbonization, metallization, etc.) of the porous silicon surface have been proposed with the aim of reducing aging and interfering effects while improving reliability, sensitivity, and selectivity. See, for example, the handbook chapter "▶ Silicon-Carbon Bond Formation on Porous Silicon." Tables 1 and 2 provide the main architectures of porous silicon electrical and optical gas sensors, respectively, since 1990. The porous silicon physical parameters that mainly account for the variation of the sensed quantity for the specific sensor architecture are also indicated along with the gas species sensed (Table 3).

Sensing Platforms

More recently, in addition to mere sensor devices exploiting either single-parameter or multiparameter monitoring, miniaturized sensing platforms integrating a number of porous silicon optical sensors featuring different surface chemistry on the same chip, as well an array of porous silicon electrical sensors together with CMOS electronic driving/readout circuits on the same chip, have been demonstrated to be feasible, thus envisaging the realization of a new class of electronic and photonic system-on-chips with gas sensing capability.

Table 4 provides study examples on up-to-date sensing platforms exploiting porous silicon either electrical or optical gas sensors.

Table 1 Main architectures of porous silicon electrical gas sensors since 1990

Electrical Sensors					
	Metal-based devices			Junction-based devices	
Sensor architecture	Capacitor	Schottky-like diode	Resistor	FET-like transistor	Junction-like diode
Physical parameter	Dielectric constant	Energy barrier	Conductivity	Conductivity	Energy barrier
		Conductivity		Dielectric constant	Conductivity
Sensed quantity	Capacitance	Current	Resistance	Current	Current
				Impedance	
Sensed species	Inorganic gases	Inorganic gases	Inorganic gases	Inorganic gases	Inorganic gases
	Aliphatic organic substances	Aliphatic and aromatic organic substances	Aliphatic and aromatic organic substances	Aliphatic organic substances	Aliphatic organic substances
Study examples	(Andersson et al. 1990; Ben-Chorin and Kux 1994; Rittersma et al. 2000; Foucaran et al. 2000; Belhousse et al. 2004; Björkqvist et al. 2004a, b, 2009; Gabouze et al. 2005)	(Ben-Chorin et al. 1994; Schechter and Ben-Chorin 1995; Mareš et al. 1995; Stievenard and Deresmes 1995; Bilenko et al. 1997; Foucaran et al. 1997; Zhang et al. 2000; Pancheri et al. 2003; Gaburro et al. 2004a, 2006; Razi et al. 2010; Kanungo et al. 2010)	(Gabouze et al. 2005; Björkqvist et al. 2009; Motahashi et al. 1995; Taliercio et al. 1995; Angelucci et al. 1999, 2000; Mulloni et al. 2000; Di Francia et al. 2000; Baratto et al. 2000, 2001; Boarino et al. 2000; Šetkus et al. 2001; Seals et al. 2002; Oton et al. 2003; Chakane et al. 2003; Galeazzo et al. 2003; Massera et al. 2004; Amato et al. 2004; Gaburro et al. 2004b; Lewis et al. 2005, 2007; Luongo et al. 2005; Rahimi and Iraji zad 2007; Sankara Subramanian et al. 2007; Gole et al. 2007; Galstyan et al. 2008; Kovacs and Meister 2009; Peng et al. 2009, 2012; Ozdemir and Gole 2010; Moshnikov et al. 2012; Laminack and Gole 2013)	(Barillaro et al. 2003, 2004, 2005; Archera et al. 2005; Barillaro et al. 2006, 2010a, b; Lazzerini et al. 2013)	(Barillaro et al. 2007a, 2008; Prabakaran et al. 2008)
Timeline	Chronological order of exploitation of the different architectures for gas sensing since 1990				

Table 2 Main architectures of porous silicon optical gas sensors since 1990

Optical sensors					
Sensor architecture	Monolayer-based device		Multilayer-based devices		
	Single layer	Waveguide	Bragg mirror	Resonant cavity	Rugate filter
Physical parameter	Radiative recombination efficiency	Refractive index	Refractive index	Refractive index	Refractive index
	Refractive index				
Sensed quantity	Photoluminescence spectrum/intensity	Transmission losses	Reflectance spectrum	Resonance peak position	Reflectance peak position
	Reflectance spectrum				
Sensed species	Inorganic gases	Aliphatic organic compounds	Aliphatic and aromatic organic substances	Aliphatic and aromatic organic substances	Inorganic gases
	Aliphatic and aromatic organic substances				Aliphatic and aromatic organic substances
Study examples	(Ben-Chorin et al. 1994; Baratto et al. 2000; Lauerhaas et al. 1992; Lauerhaas and Sailor 1993; Coffer et al. 1993; Lee et al. 1995; Rehm et al. 1995; Rehm et al. 1996; Harper and Sailor 1996; Kelly et al. 1996; Song and Sailor 1997; Kelly and Bocarsly 1998; Content et al. 2000; Holec et al. 2002; Chvojka et al. 2004; Salcedo et al. 2004; Dian et al. 2005, 2010; Vrkoslav et al. 2006, 2007; Jelínek et al. 2007; Bjorklund et al. 1996; Zangooie et al. 1997; Gao et al. 2000, 2002a, b; Letant and Sailor 2000; Létant et al. 2000; Wang and Arwin 2002; Liua et al. 2002; Lin et al. 2004; Geobaldo et al. 2004; Torres-Costa et al. 2009)	(Arrand et al. 1999; Rea et al. 2009)	(Zangooie et al. 1998; Snow et al. 1999; Allcock and Snow 2001; Torres-Costa et al. 2005; Moretti et al. 2007; Descrovi et al. 2007; Kim et al. 2010, 2011; Jalkanen et al. 2010)	(Mulloni et al. 2000; Zangooie et al. 1999; De Stefano et al. 2003, 2004a, b)	(Li et al. 2003; King et al. 2007; Ruminski et al. 2008, 2010; Chapron et al. 2007; Shang et al. 2011a; Kelly et al. 2011a, b)
Timeline	Chronological order of exploitation of the different architectures for gas sensing since 1990				

Table 3 Sensed species with electrical and optical porous silicon gas sensor architectures of Tables 1 and 2

Substances sensed with electrical and optical porous silicon gas sensors	
Inorganic gases	Hydrogen, oxygen, water, carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), halogens (F_2, Cl_2, Br_2, I_2), hydrofluoric acid (HF), hydrochloric acid (HCl), ammonia (NH_3), hydrogen sulfide (H_2S), sulfur dioxide (SO_2), phosphine (PH_3)
Aliphatic organic substances	Methane, ethane, propane, butane, pentane, hexane, heptane, liquified petroleum gas (LPG), cyclohexane, ethylene, methanol, ethanol, 1-propanol, 2-propanol, 1-butanol, 1-pentanol, 1-hexanol, glycerol (1,2,3-propanetriol), diethyl ether, tetrahydrofuran, acetone, metylethylketone (2-butanone), n-propylamine, n-butylamine, n-pentyamine, triethylamine, tri-n-propylamine, ethyl acetate, acetonitrile, dimethylformamide, chloroform (trichloromethane), methylene chloride (dichloromethane), trichloroethylene (C_2HCl_3), cyclohexyltrichloroethylene
Aromatic organic substances	Benzene, toluene, chlorobenzene, nitrobenzene, 1,4-dinitrobenzene, dinitrotoluene (DNT), trinitrotoluene (TNT)

Table 4 Electrical and optical sensing platforms with porous silicon

Porous silicon sensing platforms				Study examples
Electrical	Array of FET-like transistor sensors	On-chip electronics	NO_2 detection	(Barillaro et al. 2007b; Barillaro and Strambini 2008)
Optical	Array of rugate filter sensors	Different surface chemistries on chip	HF, HCl, aliphatic organic substance detection	(Ruminski et al. 2011; Shang et al. 2011b; Sweetman and Voelcker 2012)

Summary

Over the last two decades, electrical and optical gas sensors based on porous silicon have been tremendously improved, in terms of architectures, performance, and sensed species. On the one hand, single devices with high sensitivity, low limit of detection, and good selectivity have been achieved for different analytes, although reliability and lifetime still remain among the major challenges for both electrical and optical sensors. On the other hand, multiparametric sensing on single devices and multisensor integration in a single chip have been very recently reported for both optical and electrical approaches, thus pushing porous silicon gas sensors to a new generation of miniaturized sensing platforms. As to the latter, tremendous improvement due to simultaneous integration of sensors with electronic and photonic silicon circuits is expected for both approaches, respectively, in the next future.

References

Allcock P, Snow PA (2001) Time-resolved sensing of organic vapors in low modulating porous silicon dielectric mirrors. J Appl Phys 90(10):5052–5057

Amato G, Boarino L, Bellotti F (2004) On the apparently anomalous response of porous silicon to nitrogen dioxide. Appl Phys Lett 85:4409–4411

Andersson RC, Muller RS, Tobias CW (1990) Investigations of porous silicon for vapor sensing. Sens Actuator A21-A23:835–839

Angelucci R, Poggi A, Dori L, Cardinali GC, Parisini A, Tagliani A, Mariasaldi M, Cavani F (1999) Permeated porous silicon for hydrocarbon sensor fabrication. Sens Actuator 74:95–99

Angelucci R, Poggi A, Dori L, Tagliani A, Cardinali GC, Corticelli F, Marisaldi M (2000) Permeated porous silicon suspended membrane as sub-ppm benzene sensor for air quality monitoring. J Porous Mater 7(1–3):197–200

Archera M, Christophersen M, Fauchet PM (2005) Electrical porous silicon chemical sensor for detection of organic solvents. Sens Actuator B 106:347–357

Arrand HF, Benson TM, Loni A, Arens-Fischer R, Krueger MG, Thoenissen M, Lueth H, Kershaw S, Vorozov NN (1999) Solvent detection using porous silicon optical waveguides. J Lumin 80:119–123

Baratto C, Comini E, Faglia G, Sberveglieri G, Di Francia G, De Filippo F, La Ferrara V, Quercia L, Lancellotti L (2000) Gas detection with a porous silicon based sensor. Sens Actuator B 65:257–259

Baratto C, Faglia G, Comini E, Sberveglieri G, Taroni A, La Ferrara V, Quercia L, Di Francia G (2001) A novel porous silicon sensor for detection of sub-ppm NO2 concentrations. Sens Actuator B 77:62–66

Barillaro G, Strambini LM (2008) An integrated CMOS sensing chip for NO2 detection. Sens Actuators B 134:585–590

Barillaro G, Nannini A, Pieri F (2003) APSFET: a new, porous silicon-based gas sensing device. Sens Actuator B 93:263–270

Barillaro G, Nannini A, Pieri F, Strambini LM (2004) Temperature behavior of the APSFET – a porous silicon-based FET gas sensor. Sens Actuator B 100(1–2):185–189

Barillaro G, Diligenti A, Marola G, Strambini LM (2005) A silicon crystalline resistor with an adsorbing porous layer as gas sensor. Sens Actuator B 105:278–282

Barillaro G, Diligenti A, Nannini A, Strambini LM, Comini E, Sberveglieri G (2006) Low-concentration NO2 detection with an adsorption porous silicon FET. Sens J IEEE 6(1):19–23

Barillaro G, Diligenti A, Strambini LM (2007a) p + −n diodes with a lateral porous layer as gas sensors. Phys Stat Solid (a) 204(5):1399–1403

Barillaro G, Bruschi P, Pieri F, Strambini LM (2007b) CMOS-compatible fabrication of porous silicon gas sensors and their readout electronics on the same chip. Phys Stat Solid (a) 204(5):1423–1428

Barillaro G, Diligenti A, Strambini LM, Comini E, Faglia G (2008) NO2 adsorption effects on p + −n silicon junctions surrounded by a porous layer. Sens Actuator B 134:922–927

Barillaro G, Lazzerini GM, Strambini LM (2010a) Modeling of porous silicon junction field effect transistor gas sensors: insight into NO2 interaction. Appl Phys Lett 96:162105

Barillaro G, Bruschi P, Lazzerini GM, Strambini LM (2010b) Validation of the compatibility between a porous silicon-based gas sensor technology and standard microelectronic process. Sens J IEEE 10(4):893–899

Belhousse S, Cheraga H, Gabouze N, Outamzabet R (2004) Fabrication and characterisation of a new sensing device based on hydrocarbon groups (CHx) coated porous silicon. Sens Actuator B 100:250–255

Ben-Chorin M, Kux A, Schechter I (1994) Adsorbate effects on photoluminescence and electrical conductivity of porous silicon. Appl Phys Lett 64(4):481–483

Bilenko D, Belobrovaya O, Jarkova E, Coldobanova O, Mysenko I, Khasina E (1997) Sensors on low-dimensional silicon structures. Sens Actuator A 62(1–3):621–623

Bjorklund RB, Zangooie S, Arwin H (1996) Color changes in thin porous silicon films caused by vapor exposure. Appl Phys Lett 69(20):3001–3003

Björkqvist M, Salonen J, Paski J, Laine E (2004a) Characterization of thermally carbonized porous silicon humidity sensor. Sens Actuator A 112:244–247

Björkqvist M, Salonen J, Laine E (2004b) Humidity behavior of thermally carbonized porous silicon. Appl Surf Sci 222:269–274

Björkqvist M, Salonen J, Tuura J, Jalkanen T, Lehto V-P (2009) Detecting amine vapours with thermally carbonized porous silicon gas sensor. Phys Stat Solid C 6(7):1769–1772

Boarino L, Baratto C, Geobaldo F, Amato G, Comini E, Rossi AM, Faglia G, Lérondel G, Sberveglieri G (2000) NO2 monitoring at room temperature by a porous silicon gas sensor. Mater Sci Eng B69–70:210–214

Chakane S, Gokarna A, Bhoraskar SV (2003) Metallophthalocyanine coated porous silicon gas sensor selective to NO2. Sens Actuator B 92:1–5

Chapron J, Alekseev SA, Lysenko V, Zaitsev VN, Barbier D (2007) Analysis of interaction between chemical agents and porous Si nanostructures using optical sensing properties of infra-red Rugate filters. Sens Actuators B 120:706–711

Chvojka T, Vrkoslav V, Jelínek I, Jindřich J, Lorenc M, Dian J (2004) Mechanisms of photoluminescence sensor response of porous silicon for organic species in gas and liquid phases. Sens Actuators B 100:246–249

Coffer JL, Lilley SC, Martin RA, Files-Sesler LA (1993) Surface reactivity of luminescent porous silicon. J Appl Phys 74:2094–2096

Content S, Trogler WC, Sailor MJ (2000) Detection of nitrobenzene, DNT, and TNT vapors by quenching of porous silicon photoluminescence. Chem Eur J 6(12):2205–2213

De Stefano L, Moretti L, Rendina I, Rossi AM (2003) Porous silicon microcavities for optical hydrocarbons detection. Sens Actuators A 104:179–182

De Stefano L, Moretti L, Rendina I, Rossi AM (2004a) Time-resolved sensing of chemical species in porous silicon optical microcavity. Sens Actuators B 100:168–172

De Stefano L, Rendina I, Moretti L, Tundo S, Rossi AM (2004b) Smart optical sensors for chemical substances based on porous silicon technology. Appl Opt 43(1):167–172

Descrovi E, Frascella F, Sciacca B, Geobaldo F, Dominici L, Michelotti F (2007) Coupling of surface waves in highly defined one-dimensional porous silicon photonic crystals for gas sensing applications. Appl Phys Lett 91:241109

Di Francia G, La Ferrara V, Quercia L, Faglia G (2000) Sensitivity of porous silicon photoluminescence to low concentrations of CH4 and CO. J Porous Mater 4(1–3):287–290

Dian J, Chvojka T, Vrkoslav V, Jelínek I (2005) Photoluminescence quenching of porous silicon in gas and liquid phases – the role of dielectric quenching and capillary condensation effects. Phys Stat Solidi C 2(9):3481–3485

Dian J, Vrkoslav V, Jelínek I (2010) Recognition enhancement of oxidized and methyl-10-undecenoate functionalized porous silicon in gas phase photoluminescence sensing. Sens Actuators B 147:406–410

Foucaran A, Pascal-Delannoy F, Giani A, Sackda A, Combette P, Boyer A (1997) Porous silicon layers used for gas sensor applications. Thin Solid Films 297:317–320

Foucaran A, Sorli B, Garcia M, Pascal-Delannoy F, Giani A, Boyer A (2000) Porous silicon layer coupled with thermoelectric cooler: a humidity sensor. Sens Actuator A 79:189–193

Gabouze N, Belhousse S, Cheraga H (2005) CHx – Porous silicon structures for gas sensing applications. Phys Stat Solid C 2(9):3449–3452

Gabouze N, Belhousse S, Cheraga H, Ghellai N, Ouadah Y, Belkacem Y, Keffous A (2006) CO2 and H2 detection with a CHx/porous silicon-based sensor. Vacuum 80:986–989

Gaburro Z, Oton CJ, Pavesi L, Pancheri L (2004a) Opposite effects of NO2 on electrical injection in porous silicon gas sensors. Appl Phys Lett 84:4388–4390

Gaburro Z, Bettotti P, Saiani M, Pavesi L, Pancheri L, Oton CJ, Capuj N (2004b) Role of microstructure in porous silicon gas sensors for NO2. Appl Phys Lett 85:555

Galeazzo E, Peres HEM, Santos G, Peixoto N, Ramirez-Fernandez FJ (2003) Gas sensitive porous silicon devices: responses to organic vapors. Sens Actuator B 93:384–390

Galstyan VE, Martirosyan KS, Aroutiounian VM, Arakelyan VM, Arakelyan AH, Soukiassian PG (2008) Investigations of hydrogen sensors made of porous silicon. Thin Solid Films 517:239–241

Gao J, Gao T, Sailor MJ (2000) Porous-silicon vapor sensor based on laser interferometry. Appl Phys Lett 77:901–903

Gao J, Gao T, Li YY, Sailor MJ (2002a) Vapor sensors based on optical interferometry from oxidized microporous silicon films. Langmuir 18(6):2229–2233

Gao T, Gao J, Sailor MJ (2002b) Tuning the response and stability of thin film mesoporous silicon vapor sensors by surface modification. Langmuir 18(25):9953–9957

Geobaldo F, Rivolo P, Salvador GP, Amato G, Boarino L, Garrone E (2004) Free carriers reactivation on p + −mesoporous silicon through ammonia adsorption: a FTIR study. Sens Actuators B 100:205–208

Gole JL, Lewis S, Lee S (2007) Nanostructures and porous silicon: activity at interfaces in sensors and photocatalytic reactors. Phys Stat Sol (a) 204:1417–1422

Harper J, Sailor MJ (1996) Detection of nitric oxide and nitrogen dioxide with photoluminescent porous silicon. Anal Chem 68:3713–3717

Holec T, Chvojka T, Jelínek I, Jindřich J, Němec I, Pelant I, Valenta J, Dian J (2002) Determination of sensoric parameters of porous silicon in sensing of organic vapors. Mater Sci Eng C 19:251–254

Jalkanen T, Tuura J, Mäkilä E, Salonen J (2010) Electro-optical porous silicon gas sensor with enhanced selectivity. Sens Actuators B 147:100–104

Jelínek V, Vrkoslav T, Trojan J, Jindřich JD (2007) Host-guest interactions in gas phase chemical sensing of permethyl-6I-alkenoylamino-6I-deoxy-β-cyclodextrin derivatized porous silicon. Phys Stat Solidi C 4(6):2083–2087

Kanungo J, Saha H, Basu S (2010) Pd sensitized porous silicon hydrogen sensor-Influence of ZnO thin film. Sens Actuator B 147:128–136

Kelly MT, Bocarsly AB (1998) Mechanisms of photoluminescent quenching of oxidized porous silicon. Applications to chemical sensing. Coord Chem Rev 171:251–259

Kelly MT, Chun JKM, Bocarsly AB (1996) A silicon sensor for SO2. Nature 382:214–215

Kelly TL, Gao T, Sailor MJ (2011a) Carbon and carbon/silicon composites templated in rugate filters for the adsorption and detection of organic vapors. Adv Mater 23:1776–1781

Kelly TL, Garcia Sega A, Sailor MJ (2011b) Identification and quantification of organic vapors by time-resolved diffusion in stacked mesoporous photonic crystals. Nano Lett 11:3169–3173

Kim H-J, Kim Y-Y, Lee K-W (2010) Multiparametric sensor based on DBR porous silicon for detection of ethanol gas. Curr Appl Phys 10:181–183

Kim H-J, Kim Y-Y, Lee K-W (2011) Sensing characteristics of the organic vapors according to the reflectance spectrum in the porous silicon multilayer structure. Sens Actuators A 165:276–279

King BH, Ruminski AM, Snyder JL, Sailor MJ (2007) Optical-fiber-mounted porous silicon photonic crystals for sensing organic vapor breakthrough in activated carbon. Adv Mater 19:4530–4534

Korotcenkov G (2013) Handbook of gas sensor materials. Springer, New York. ISBN 978-1-4614-7165-3

Kovacs D, Meister UM (2009) Investigation of humidity adsorption in porous silicon layers. Phys Status Solid A 206(6):1343–1347

Laminack WI, Gole JL (2013) Light enhanced electron transduction and amplified sensing at a nanostructure modified semiconductor interface. Adv Funct Mater 23(47):5916–5924

Lauerhaas JM, Sailor MJ (1993) Chemical modification of the photoluminescence quenching of porous silicon. Science 261(5128):1567–1568

Lauerhaas JM, Credo GM, Heinrich JL, Sailor MJ (1992) Reversible luminescence quenching of porous silicon by solvents. J Am Chem Soc 114(5):1911–1912

Lazzerini GM, Strambini LM, Barillaro G (2013) Addressing reliability and degradation of chemitransistor sensors by electrical tuning of the sensitivity. Sci Rep 3:1161

Lee EJ, Ha JS, Sailor MJ (1995) Photoderivatization of the surface of luminescent porous silicon with formic acid. J Am Chem Soc 117:8295–8296

Letant SE, Sailor MJ (2000) Detection of HF gas with a porous silicon interferometer. Adv Mater 12(5):355–359

Létant SE, Content S, Tan TT, Zenhausern F, Sailor MJ (2000) Integration of porous silicon chips in an electronic artificial nose. Sens Actuators B 69:193–198

Lewis SE, DeBoer JR, Gole JL, Hesketh PJ (2005) Sensitive, selective, and analytical improvements to a porous silicon gas sensor. Sens Actuator B 110:54–65

Lewis SE, DeBoera JR, Gole JL (2007) A pulsed system frequency analysis for device characterization and experimental design: application to porous silicon sensors and extension. Sens Actuator B 122:20–29

Li YY, Cunin F, Link JR, Gao T, Betts RE, Reiver SH, Chin V, Bhatia SN, Sailor MJ (2003) Polymer replicas of photonic porous silicon for sensing and drug delivery applications. Science 299:2045–2047

Lin H, Gao T, Fantini J, Sailor MJ (2004) A porous silicon-palladium composite film for optical interferometric sensing of hydrogen. Langmuir 20(12):5104–5108

Liua R, Schmedake TA, Li YY, Sailor MJ, Fainman Y (2002) Novel porous silicon vapor sensor based on polarization interferometry. Sens Actuators B 87:58–62

Luongo K, Sine A, Bhansali S (2005) Development of a highly sensitive porous Si-based hydrogen sensor using Pd nano-structures. Sens Actuator B 111–112:125–129

Mareš JJ, Krištofik J, Hulicius E (1995) Influence of humidity on transport in porous silicon. Thin Solid Films 255:272–275

Massera E, Nasti I, Quercia L, Rea I, Di Francia G (2004) Improvement of stability and recovery time in porous-silicon-based NO2 sensor. Sens Actuator B 102:195–197

Mizsei J (2007) Gas sensor applications of porous Si layers. Thin Solid Films 515:8310–8315 (Review)

Moretti L, Rea I, De Stefano L, Rendina I (2007) Periodic versus aperiodic: enhancing the sensitivity of porous silicon based optical sensors. Appl Phys Lett 90:191112

Moshnikov VA, Gracheva I, Lenshin AS, Spivak YM, Anchkov MG, Kuznetsov VV, Olchowik JM (2012) Porous silicon with embedded metal oxides for gas sensing applications. J Non-Cryst Solid 358:590–595

Motahashi A, Kawakami M, Aoyagi H, Kinoshita K, Satou A (1995) Gas identification by a single gas sensor using porous silicon as the sensitive material. Jpn J Appl Phys 34:5840–5843

Mulloni V, Gaburro Z, Pavesi L (2000) Porous silicon microcavities as optical and electrical chemical sensors. Phys Stat Solid (a) 182:479–483

Oton CJ, Pancheri L, Gaburro Z, Pavesi L, Baratto C, Faglia G, Sberveglieri G (2003) Multiparametric porous silicon gas sensors with improved quality and sensitivity. Phys Stat Sol (a) 197:523–527

Ozdemir S, Gole JL (2007) The potential of porous silicon gas sensor. Curr Opin Solid State Mater Sci 11:92–100 (Review)

Ozdemir S, Gole JL (2010) A phosphine detection matrix using nanostructure modified porous silicon gas sensors. Sens Actuator B 151:274–280

Pancheri L, Oton CJ, Gaburro Z, Soncini G, Pavesi L (2003) Very sensitive porous silicon NO2 sensor. Sens Actuator B 89:237–239

Peng K-Q, Wang X, Lee S-T (2009) Gas sensing properties of single crystalline porous silicon nanowires. Appl Phys Lett 95:243112

Peng S, Ming H, Mingda L, Shuangyun M (2012) Nano-WO3 film modified macro-porous silicon (MPS) gas sensor. J Semicond 33(5):054012

Prabakaran R, Aguas H, Fortunato E, Martins R, Ferreira I (2008) n-PS/a-Si:H heterojunction for device application. J Non-Cryst Solid 354:2632–2636

Rahimi F, Iraji zad A (2007) Characterization of Pd nanoparticle dispersed over porous silicon as a hydrogen sensor. J Phys D Appl Phys 40:7201–7209

Razi F, Irajizad A, Rahimi F (2010) Investigation of hydrogen sensing properties and aging effects of Schottky like Pd/porous Si. Sens Actuator B 146:53–60

Rea I, Iodice M, Coppola G, Rendina I, Marino A, De Stefano L (2009) A porous silicon-based Bragg grating waveguide sensor for chemical monitoring. Sens Actuators B 139(1):39–43

Rehm JM, McLendon GL, Tsybeskov L, Fauchet PM (1995) How methanol affects the surface of blue and red emitting porous silicon. Appl Phys Lett 66:3669–3671

Rehm JM, McLendon GL, Fauchet PM (1996) Conduction and valence band edges of porous silicon determined by electron transfer. J Am Chem Soc 118:4490–4491

Rittersma ZM, Splinter A, Bodecker A, Benecke W (2000) A novel surface-micromachined capacitive porous silicon humidity sensor. Sens Actuator B 68:210–217

Ruminski AM, Moore MM, Sailor MJ (2008) Humidity-compensating sensor for volatile organic compounds using stacked porous silicon photonic crystals. Adv Funct Mater 18:3418–3426

Ruminski AM, King BH, Salonen J, Snyder JL, Sailor MJ (2010) Porous silicon-based optical microsensors for volatile organic analytes: effect of surface chemistry on stability and specificity. Adv Funct Mater 20:2874–2883

Ruminski AM, Barillaro G, Chaffin C, Sailor MJ (2011) Internally referenced remote sensors for HF and Cl2 using reactive porous silicon photonic crystals. Adv Funct Mater 21:1511–1525

Saha H (2008) Porous silicon sensors-elusive and erudite. IJOSSAIS 1(1):34–56 (Review)

Salcedo WJ, Fernandez FJR, Rubim JC (2004) Photoluminescence quenching effect on porous silicon films for gas sensors application. Spectrochim Acta A 60:1065–1070

Sankara Subramanian N, Vivek Sabaapathy R, Vickraman P, Vimal Kumar G, Sriram R, Santhi B (2007) Investigations on Pd: SnO2/porous silicon structures for sensing LPG and NO2 gas. Ionics 13(5):323–328

Schechter M, Ben-Chorin AK (1995) Gas sensing properties of porous silicon. Anal Chem 67:3727–3732

Seals L, Gole JL, Tse LA, Hesketh PJ (2002) Rapid, reversible, sensitive porous silicon gas sensor. J Appl Phys 91:2519–2523

Šetkus A, Galdikas A, Mironas A, Strazdiene V, Šimkiene I, Ancutiene I, Janickis V, Kačiulis S, Mattogno G, Ingo GM (2001) The room temperature ammonia sensor based on improved CuxS-micro-porous-Si structure. Sens Actuator B 78:208–215

Shang Y, Wang X, Xu E, Tong C, Wu J (2011a) Optical ammonia gas sensor based on a porous silicon rugate filter coated with polymer-supported dye. Anal Chim Acta 685(1):58–64

Shang Y, Zhang H, Wang X, Wu J (2011b) An optical olfactory sensor based on porous silicon infiltrated with room-temperature ionic liquid arrays. Chem Eur J 17:13400–13404

Snow PA, Squire EK, Russell PSJ (1999) Vapor sensing using the optical properties of porous silicon Bragg mirrors. J Appl Phys 86(4):1781–1784

Song JH, Sailor MJ (1997) Quenching of photoluminescence from porous silicon by aromatic molecules. J Am Chem Soc 119:7381–7385

Stievenard D, Deresmes D (1995) Are electrical properties of an aluminum–porous silicon junction governed by dangling bonds? Appl Phys Lett 67(11):1570–1572

Sweetman MJ, Voelcker NH (2012) Chemically patterned porous silicon photonic crystals towards internally referenced organic vapour sensors. RSC Adv 2:4620–4622

Taliercio T, Dilhan M, Massone E, Gué AM, Fraisse B, Foucaran A (1995) Realization of porous silicon membranes for gas sensor applications. Thin Solid Films 255:310–312

Torres-Costa V, Agulló-Rueda F, Martín-Palma RJ, Martínez-Duart JM (2005) Porous silicon optical devices for sensing applications. Opt Mater 27:1084–1087

Torres-Costa V, Salonen J, Jalkanen TM, Lehto V-P, Martín-Palma RJ, Martínez-Duart JM (2009) Carbonization of porous silicon optical gas sensors for enhanced stability and sensitivity. Phys Stat Sol (a) 206:1306–1308

Vrkoslav V, Jelínek I, Broncová G, Král V, Dian J (2006) Polypyrrole-functionalized porous silicon for gas sensing applications. Mater Sci Eng C 26:1072–1076

Vrkoslav V, Jelínek I, Trojan T, Jindřich J, Dian J (2007) Porous silicon with β-cyclodextrin modified surface for photoluminescence sensing of organic molecules in gas and liquid phase. Physica E 38:200–204

Wang G, Arwin H (2002) Modification of vapor sensitivity in ellipsometric gas sensing by copper deposition in porous silicon. Sens Actuators B 85:95–103

Zangooie S, Bjorklund R, Arwin H (1997) Vapor sensitivity of thin porous silicon layers. Sens Actuators B 43:168–174

Zangooie S, Jansson R, Arwin H (1998) Reversible and irreversible control of optical properties of porous silicon superlattices by thermal oxidation, vapor adsorption, and liquid penetration. J Vac Sci Techol A 16(5):2901–2912

Zangooie S, Jansson R, Arwin H (1999) Ellipsometric characterization of anisotropic porous silicon Fabry–Pérot filters and investigation of temperature effects on capillary condensation efficiency. J Appl Phys 86(2):850–858

Zhang W, de Vasconcelos EA, Uchida H, Katsube T, Nakatsubo T, Nishioka Y (2000) Study of silicon Schottky diode structures for NOx gas detection. Sens Actuator B 65:154–156