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Chapter 1
From Si Towards SiC Technology for Harsh Environment Sensing

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1.1 Introduction

Since it is obvious that Moore's Law in its classical way of scaling, which proved to be powerful over the last decades, is coming to an end, alternative routes towards technological progress are investigated [1]. One of the main fundamental reasons for this is that the smallest features size in newest technology nodes is approaching the level of only a few atom layers. As a result, the development and implementation of technology nodes based on a scaled-down version of the previous one, gets increasingly more expensive. An alternative approach to ensure technological progress of the microelectronics world and the semiconductor industry is described by a trend called "More than Moore" (MtM) [2], based on diversification and integration. In terms of diversification, materials beyond silicon can be considered for the development of sensors and electronics, while the integration aspects come to expression by combining different parts of a system in a smart and optimal way. Wide bandgap (WBG) materials, such as gallium nitride (GaN) or silicon carbide (SiC) are mature for power applications, but for other applications such as low-voltage (Bi)CMOS and/or VLSI they are still in the research phase. By integrating electronics monolithically on a sensor chip, improved system performance can be obtained by having signal amplifications close to the physical transducer. The integration aspects are strongly related to the packaging of microelectronic and

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microfabricated devices, for example, when multi-physical sensors are considered. A recent example is the through polymer via enabling an optical channel through a package [3].

By investigating nonlinear effects in MEMS structures, the mechanical sensitivity can be boosted in a bulk micromachined and thus space limited chip. Furthermore, by the application of new materials such as SiC sensors and (low voltage) electronics can be yielded compatible with harsh environments and temperatures up to 500 °C. By investigating the monolithic integration of analog electronics with mature sensor technologies, the strengths of system integration can be implemented and exploited, resulting in more value from existing technologies. Especially, the latter two topics are examples of the "More than Moore" concept but still numerous challenges exist.

The development of SiC-based electronics to build up technologies for low-voltage CMOS, BJTs, or BiCMOS for both analog and digital circuits is still pre-mature. That this development is still in the research phase is illustrated by the given that numerous research works focus on device simulation and model extraction for SiC CMOS. Furthermore, when looking over the literature that is available on SiC technology, one could notice a trend in shifting interest from 6H-SiC to 4H-SiC [4–7].

Also, from junction formation by mesa etching on epitaxially grown layers to ion implantation techniques, which have been evolved during the last 10 years. Other challenges on the physical level are the chemical/physical effects in ohmic contacts and the long-term reliability and stability of metallization schemes [8]. So, even on the very basic physical level significant changes have taken place, illustrating that the SiC electronics development is in its pre-mature phase.

In addition to the development of SiC electronics, the compatibility of the fabrication processes is of utmost importance, when all SiC ASIC + MEMS monolithic system integration are considered. A cleanroom flowchart for the processing of MEMS can be very different from one for the processing of electronics in terms of thermal budget, contamination and topography. Silicon carbide being a harsh environment compatible material, and thus an inert material, involve more fabrication steps such as high temperature processing compared to standard silicon technology.

1.2 Silicon Technology and Its Limitations

Silicon technology has been mature for decades for the fabrication of a broad range of electronics, ranging from BJTs, analog CMOS, BiCMOS to digital integrated circuits such as VLSI. Based on this silicon technology, sensor technology is implemented. By reusing existing technologies and process steps such as oxidation, patterning, wet- and dry etching, and dopant formation, big steps are made and a powerful palette of fabrication methods are available for decades. The term "CMOS compatible" is very common in the field of sensors, which practically denotes that the sensors considered can be processed within a CMOS process flow, reducing costs dramatically. It should however be realized that this implicit choice for silicon and CMOS compatible technology can have some dramatic drawbacks in the sensor design for certain applications. For numerous applications, silicon is not the first-choice material, but is still chosen for its earlier mentioned widespread availability. Furthermore, a CMOS compatible process flow might put restrictions to the sensor design, negatively influencing overall design freedom and compromising sensor performance. Surface and bulk micromachining techniques, such as Deep Reactive Ion Etching (DRIE), have been developed based on etching technologies from silicon CMOS processing, for example, by extending etch times or increased etch power in case of plasma etching. This development has enabled the design and realization of Micro-Electro-Mechanical-Systems (MEMS) in silicon. Currently, the MEMS market covers application field such as Radar, Ultra Sonic, LiDAR, Chemical-, magnetic-, imaging-, and pressure sensors and has a value of around ten billion dollars [9].

A major field of application where silicon technology is not enough is the field of harsh environments. Harsh environments are considered environments with high temperatures, corrosive species, vibrations, or radiation. Silicon is in general not capable of being compatible with harsh environments. Firstly, because the electronic behavior is compromised at temperatures of 200 °C and beyond. This effect is caused by the intrinsic carrier density of silicon being several orders of magnitude larger than WBG counterpart materials, such as GaN or SiC. The intrinsic carrier concentration is increasing with increasing temperature and as soon as the intrinsic carrier density is exceeding the dopant concentration of the junctions defined by implantation, the electronic device fails in operation. It can thus be concluded that the electronic properties of silicon do not obey the high temperature requirements for harsh environments. The intrinsic carrier concentrations as function of temperature for silicon and the most common polytypes of silicon carbide are included in Fig. 1.1. It can be seen from this figure that the intrinsic carrier density for silicon is approaching typical dopant levels (1×10^{14} # /cm^3) for lowly doped regions, while the carrier density for 4H-SiC is around 13 orders of magnitude lower at the same temperature.

From a mechanical point of view, silicon is known to show plastic deformations under small loads from 500 °C and beyond, which limits the feasibility for the development of harsh environment microsystems.

To make silicon-based sensors as compatible as possible with harsh environments, Silicon On Insulator wafers are used and extensive packaging is typically required, resulting in higher cost and complexity. Interfacing a harsh environment physical transducer at high temperatures, typically involves fiber optics, because analog front-end electronics do not work at elevated temperatures for reasons described above.

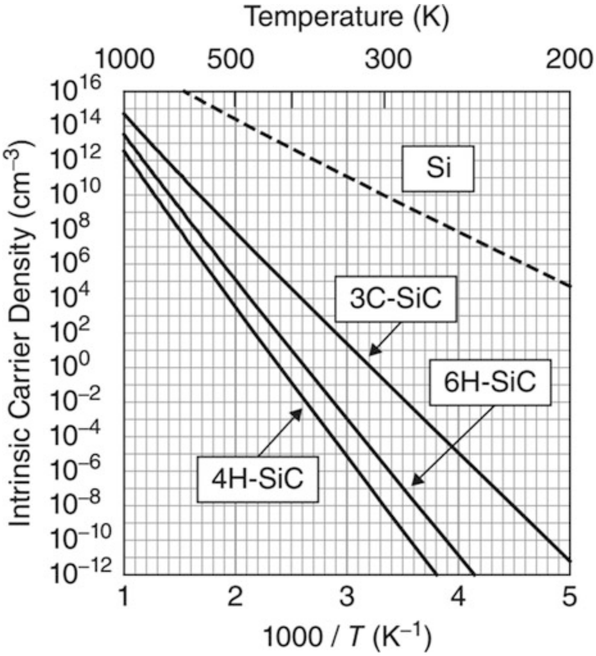

Fig. 1.1 An overview of the intrinsic carrier concentration of silicon, compared with the most common polytypes of SiC ([8], with permission)

1.3 Wide Bandgap Semiconductors

Apart from the well-known silicon, many more semiconductors exist. Wide bandgap (WBG) semiconductors (WBS) are semiconductors with an increased bandgap compared to silicon. Well-known examples are silicon carbide, gallium nitride (GaN), or gallium arsenide (GaAs). Both are the so-called compound semiconductors, SiC being a group IV–IV semiconductor, while GaN and GaAs is a group III–V semiconductor. These group number denotes the column in the periodic table. The wider bandgap manifests itself in the physical properties of the material. Here, the focus will be on silicon carbide. Thanks to the high critical electric field, the high thermal conductivity SiC technology is mature in the field of power electronics already. As a result of these two physical properties, higher switching speeds are feasible, resulting in lower losses and more compact form-factors of power electronics in general. Devices such as IGBTs and Power MOSFETs exploit largely from the high thermal conductivity and critical electric field. Larger voltages can be used, and less stringent cooling requirements simplifies the packaging of these devices.

1.3.1 Polytypes

One can distinguish the following different types of silicon carbide in terms of polytypes, indicated in Fig. 1.2. There are two main categories of SiC: α-silicon carbide and β-silicon carbide. When considering a mono-crystalline material, the structure is build up in unit cells, the smallest cell is called a primitive cell. In the case of α-silicon carbide, this privative cell is hexagonal, typically denoted by an H. The two main polytypes which are commercially available in wafer form are the 4H-SiC and 6H-SiC. In these polytypes, the stacking sequence of the hexagonal bi-layer consisting of silicon and carbon atom repeats itself after 4 and 6 layers, respectively [11]. Apart from α-SiC here is β-SiC. The main polytype in this category is 3C-SiC, showing a cubic primitive cell, similar to silicon. In addition to these mono-crystalline occurrences of silicon carbide, poly-crystalline and nano-crystalline silicon carbide exists, from which poly-crystalline 3C-SiC is most common, because it can be grown by CVD techniques [12]. Generally, it can be said that in existing silicon carbide technology, 4H-SiC and 6H-SiC are mainly occurring in wafer form and exploited for their excellent electronic properties, whereas poly-3C-SiC and amorphous SiC are mainly occurring in thin film deposition and strongly related to MEMS processing, thanks to the lower cost and larger flexibility.

1.3.2 Physical Properties

The unique physical properties are the result of the larger bandgap and the strong covalence bond between the silicon and carbon atom. A comparison is made between silicon, silicon carbide, and gallium nitride, while being the latter two common WBG semiconductors. The most important physical parameters are summarized in Table 1.1. It can be noted from this table that the bandgap of

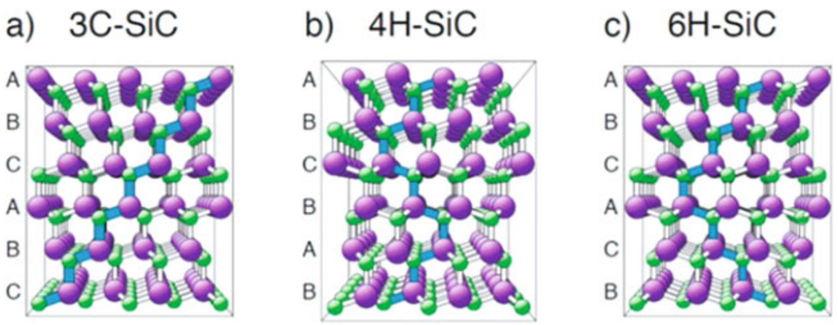

Fig. 1.2 An overview of the three common polytypes [10], with (**a**) 3C-SiC; (**b**) 4H-SiC and (**c**) 6H-SiC

Table 1.1 Comparison of physical properties of Si, SiC, and GaN

Figure	Unit	Si	SiC	GaN
Bandgap *Eg*	eV	1.12	3.0–3.6[a]	3.45
Maximum electric field	Vcm^{-1}	3×10^6	2.5×10^6	5×10^6
Relative dielectric constant ε_r	F/m	11.8	9.8	8.9
Thermal conductivity	$\mathrm{Wcm}^{-1}\ \mathrm{K}^{-1}$	1.5	4.9	1.5
Carrier mobility	$\mathrm{cm}^2\ \mathrm{V}^{-1}\ \mathrm{s}^{-1}$	1350 and 480	980 and 200	1000 and 30
Density	kgm^{-3}	2330	3210	6150
Young's modulus	GPa	62–202	410–700	398
Acoustic velocity	m/s	8415	13,100	8044

[a] Depends on polytype

silicon carbide is with 2.3 eV for 3C-SiC, 3.26 eV for 4H-SiC, and 3.03 eV for 6H-SiC significantly larger than the 1.12 eV of silicon. The larger bandgap dramatically reduces the electron-hole pairs caused by external thermal energy, which reduces leakage currents at elevated temperatures which is one of the major issues with silicon technology in the application of electronics. The wider bandgap also influences the spectral band where the semiconductor can be used to detect the light, which will be discussed later onwards. As mentioned above in the section introduction, silicon carbide shows a high electric breakdown field, 1.8–3.8 MV/cm (depending on the polytype) compared to 0.3 MV/cm for silicon [13], which is in combination with its high thermal conductivity advantageous for power applications. Further, silicon carbide has a high chemical inertness making it an excellent material for transducers in corrosive environments, while it relaxes stringent packaging requirements. The high Young's modulus opens new design opportunities for the development of silicon carbide MEMS, looking into miniaturization of structures that have mechanically not been feasible in silicon MEMS. This aspect is especially exploitable since it is known that silicon carbide exhibits a piezo-resistive effect [14].

Silicon carbide is moreover known to have a high radiation tolerance, ideal for space applications [11] and a high acoustic velocity: $11.9 \times 10^3\ \mathrm{ms}^{-1}$ for SiC vs. $9.1 \times 10^3\ \mathrm{ms}^{-1}$ for Si [15].

1.4 Harsh Environment Sensing

As sensors fabricated in silicon carbide technology have advantages in terms of harsh environment compatibility, in this section the fields and possible applications for such sensors are discussed. Before discussing specific sensor examples, the definition of a harsh environment is further specified.

1.4.1 Harsh Environments

Because the term harsh environments can be interpreted in different ways, it will be quantified in this section. Harsh environments are seen by this work as environments with elevated temperatures. A temperature of 200 °C and beyond can already be seen as harsh, silicon-based electronics start to fail namely, but the temperature range can even go up to 800 °C. Other aspects which make environments harsh in this context are the presence of corrosive species (gasses, liquids), vibrations, radiation, and/or a high pressure. Examples of harsh environments include the geographical poles, very arid deserts, volcanoes, deep ocean trenches, upper atmosphere, Mt. Everest, outer space, and the environments of every planet in the Solar System except the Earth. In applications, examples are boreholes, automobiles under the hood (motor area), and/or power applications like seen in energy grids.

1.4.2 Overview of Applications

From an application perspective, there are many challenges in our technological world, for example, food security, pollution, global warming, growing demand for energy, health, and well-being. This results in applications such as environmental sensing, air quality monitoring, gas sensors for cleaner combustion, sensors for the Smart Grid and Structural and Mechanical Health Monitoring. A more structured overview of fields, specific applications, and corresponding sensors is given in Table 1.2.

1.5 Harsh Environment Pressure Sensing

1.5.1 Applications

Numerous applications can be thought of like measurements of absolute pressures and pressure changes in combustion engines, gas turbines, and jet- and rocket engines. Furthermore, reaction containers and vessels in the industry can be applications where pressure sensors can have added value when they are harsh environment compatible. The harsh environments for pressure sensors come most to expression in applications where both high temperature and corrosive environments are included. This is the case in applications where combustion is involved such as aviation jet engines or space applications.

Most pressure sensors consist of a membrane which is basically a transducer of a difference in air pressure to a stress on the membrane. The stress is transferred to a strain by the Young's modulus and needs to be read out. From this reasoning it could be stated that pressure sensors and strain/strain sensors are closely related to each

Table 1.2 An overview of field, applications, and sensor classifications

Field	Application	Sensor classification
Automotive	Exhaust gas monitoring Engine instrumentation Combustion monitoring Electrical drive monitoring Particulate filter monitoring	Temperature Humidity Gas species Vibrations, resonance Particulates
Aviation	Jet engine monitoring Structural health monitoring Mechanical health monitoring	Temperature, pressure, flow Stress, strain, pressure Vibrations, flow
Space	Navigation/position sensing	UV blind photo detectors
Earth monitoring	Gravimetry Ocean behavior Oil/gas well monitoring	Deviations in gravity Flow, pressure, temperature Sensing systems
Environment sensing	IoT distributed monitoring System	Particulates 10 nm–10^1 m VOCs Humidity CO, NOx, SOx UV index Occupation/traffic density Radiation level, etc.
Health/sport/well-being	Monitoring in vivo Excitation	Blood pressure, heartbeat pH, salinity Pacemaker, neurostimulation
Food security	Measuring toxic substances	Heavy metals Pesticide residues
Industry	Process monitoring	Temperature, gas species pH value, ion concentration Pressure Flow, radiation
Energy	Power grid sensors Offshore wind parks Nuclear energy monitoring	Current, hall sensor EM fields Temperature Stress Strain
Communication	High frequency/RF compatible Sensors Antenna/base station Monitoring	Latency Response time
Consumer electronics	RF cooking	Temperature

other. Health monitoring of electrical and electronic devices such as power devices, smart grid components, or electrical drives are possible application areas. But health monitoring of mechanical systems like bearings could be a possible application for harsh environment pressure sensors.

Regarding the multi-sensor platform, the monolithic integration of a temperature sensor and/or a photo sensor can be especially relevant in processes like combustion

Table 1.3 Specifications based on applications

Application	Pressure	Temperature
Medical	69 mbar [18]	50 °C
Oil wells	344 bar [18]	
Combustion engine	0–100 bar [19]	574 °C [20]
Geothermal wells	14 bar [16]	350 °C [21]
Oil and gas exploration		275 °C
Aircraft/turbine engines	1–50 bar [22]	−50 up to 650 °C [18]
Industrial gas turbines	345 bar [18]	450–600 °C

monitoring. The integration of multiple sensors on wafer scale, and thus all-SiC has the huge advantage of a system which is harsh environment compatible. Regarding the integration of electronics, this is especially powerful in the application of harsh environments, since on-chip electronics can modulate and amplify the measured signals and can simplify read out of the sensor, which is currently commonly done with optical fibers. Examples are:

- Combustion monitoring for automotive
- Jet engines for aviation
- Health monitoring by stress measurement in SiC electronic components, for example, in electric power domain
- Smart grid health monitoring, for example, transformer oil pressure
- Pressure measurement on drill-heads for the oil/gas industry
- Geothermal wells [16]
- Improve jet engine testing (NASA)
- Space applications, such as the VENUS project KTH [17]

Specification based on applications are listed in Table 1.3 and an overview is depicted in Fig. 1.3.

1.5.2 State-of-the-Art Harsh Environment Pressure Sensors

For overview and clarity reasons, the found literature is tabulated in Table 1.4. To identify each pressure sensor, the substrate material was listed, along with the main membrane dimensions and the sensor performance and the transduction type.

Beker et al. [16] write on a surface micromachined circular concentrically matched capacitive pressure intended for measurements on geothermal wells. The substrate material used was silicon, but the structural layer is poly-crystalline SiC. Chen et al. [19] uses a poly-SiC substrate enabling an all-SiC device. Hung et al. [24] did a comparative study on both mono-crystalline and poly-crystalline SiC and concluded that the gauge factor in the case of a piezo-resistive pressure sensor

Fig. 1.3 An overview of pressure sensors by Yole Development ([23], with permission)

implementation is significantly larger for 3C-SiC. Eickhoff et al. [25] used an SOI substrates to isolate the different poly-SiC piezo-resistive elements on the (silicon) membrane. Fonseca et al. [26] uses a rather classical approach to make their devices compatible with elevated temperatures, in this case 400 °C, namely the usage of ceramic materials. Fricke et al. [27] claim pressure sensor operation at 800 °C by making use of platinum strain gauges in a sapphire substrate. Jin et al. [18] write on the capacitive surface micromachined capacitive structures on a standard silicon substrate, resulting in a pressure sensor for in-cylinder pressure measurements on 574 °C. Lalinksy et al. [28] show a pressure sensor based on an active device, a high-electron mobility transistor in AlGaN/GaN technology on a silicon substrate. Okojie et al. [5, 7] showed a fully mono-crystalline SiC implementation based on the piezo-resistive effect. Thanks to full exploitation of the electronic and mechanical properties, the devices in these two works show operation up to 600 °C, resp. 800 °C. Jiang et al. [34] described an optical pressure sensor based on an Fabry-Perot cavity. The readout is done with an optical fiber to interface the harsh environment.

When analyzing all the literature found, it can safely be said that the majority of the harsh environment pressure sensors work with non-SiC substrate materials such as Si, SOI, sapphire, or another ceramic. The high temperature compatibility of the silicon substrate-based implementation is compromised in general, except for the work of Jin et al., which uses a capacitive surface micromachined implementation and claims operation up to 574 °C. The three implementations based on 4H-SiC

Table 1.4 An overview of harsh environment pressure sensors in literature

Substrate	Transduction	Membrane thickness	Sensitivity	Pressure range	Temp.	Ref
Si	Capacitive SiC-poly	2 µm	Circular R = 120 µm	1.03 fF/kPa:0–1.4 MPa	180° C	[16]
Poly-SiC	Capacitive SiC-poly	2.8 µm	272 µV/psi	5 MPa	574° C	[19]
Si	Piezo-resistive poly-SiC	15 µm	177 mV/V.psi	0.5 MPa	25–450 °C	[24]
SOI	Piezo-resistive 3C SiC (poly)	100 µm	3.5 mV/V.bar	0.35 MPa	200 °C	[25]
Ceramic	LC tank w. Antenna	100 µm	−141 kHz/bar	10 MPa	400 °C	[26]
Sapphire	Pt strain gauges	200 µm	10 µV/V.bar	3 MPa	800 °C	[27]
Si	Poly-SiC capacitive	2.7 µm	7.2 fF/psi		574 °C	[18]
Si	AlGaN/GaN HEMT	1.9 µm		1 MPa		[28]
6H-SiC	Piezo resistive	50 µm, circular $R = 600$ µm	32.5 µV/V.Psi	1.4 MPa	600 °C	[5]
4H-SiC	Piezo resistive	50 µm		1.38 MPa	800 °C	[7]
6H-SiC	Piezo resistive		200 µV/bar	12 MPa	400 °C	[29]
Si	Capacitive, mono-3CSiC	0.5 µm, circular $R = 400$ µm	7.7 fF/torr	146 kPa–235 kPa	400 °C	[30]
SiC wafer	Capacitive cavity	18 µm	10.6 kHz/kPa	200 kPa	600 °C	[31]
GaAs	Res.Tunnel diode	1 µm	6 kHz/kPa	1–50 kPa	Around RT	[32]
Si	Piezo-resistive 3C-SiC poly	30 µm	3.9 mV/psi	83 kPa	Around RT	[33]
SiC	SiC Fabry-Perot cavity	50 µm circular $R = 1.5$ mm		0.1–0.9 MPa	RT	[34]

and 6H-SiC, respectively, do not describe the etching process or the way the membrane was fabricated or formed. It is known from literature that etching of mono-crystalline SiC, and silicon carbide in general, is very challenging. Dry etching methods require in general metal hard-masks, which can in turn result in micromasking issues. Furthermore, the etch rate relatively low, in conventional ICP etchers only up to 500 nm/min [35].

1.6 SiC System Integration: Advantages and Challenges

To fully exploit the advantages of WBG semiconductors in harsh environments, the monolithic integration of readout and communication electronics in SiC is a major advantage. In this way, both the sensor itself and electronics for readout and the communication are harsh environment compatible. In order to make the entire sensor system harsh environment compatible, an optical readout can be used to interface the transducer in its hostile environment [34]. In such a case, conventional silicon-based electronics for amplification, processing and further communication are then placed in less hostile environments.

When electronics can be integrated with the physical transducer, being the sensor, signal amplification can be done directly in the physical location of the transducer by analog front-end electronics, thereby boosting signal power. These electronics do not necessarily have to be complex circuitry, already an output-buffer or relatively simple differential amplifier can be of great value in terms of increasing signal power. In this way, noise contributions caused by interference on the interconnect to the sensor is compromising the analog signal to a smaller extend. This would result in a significantly increased Signal-to-Noise Ratio (SNR).

When more extensive and complex SiC circuitry is considered, also circuits like data converters can be considered and an even larger part of the sensor system might be integrated in a single chip, including both analog and digital signal processing as well as communication.

The advantages of monolithic integration lie in the nature of dealing with "one-piece-of-substrate." Integration on package level typically requires the combination of multiple dies, yielding the so-called System-in-Package (SiP) solution. Such an approach requires interconnects between different dies, by for example 3D packaging or wire-bonding techniques. Such solutions are undesirable from a reliability perspective in case of the applications in harsh environments. Different CTEs of the used materials in such a SiP in combination with extremely large temperature variations and vibrations will influence the durability and reliability of such a solution dramatically. When monolithic integration of the ASIC part with the sensor, i.e., MEMS, part is considered, one dies has to be packaged.

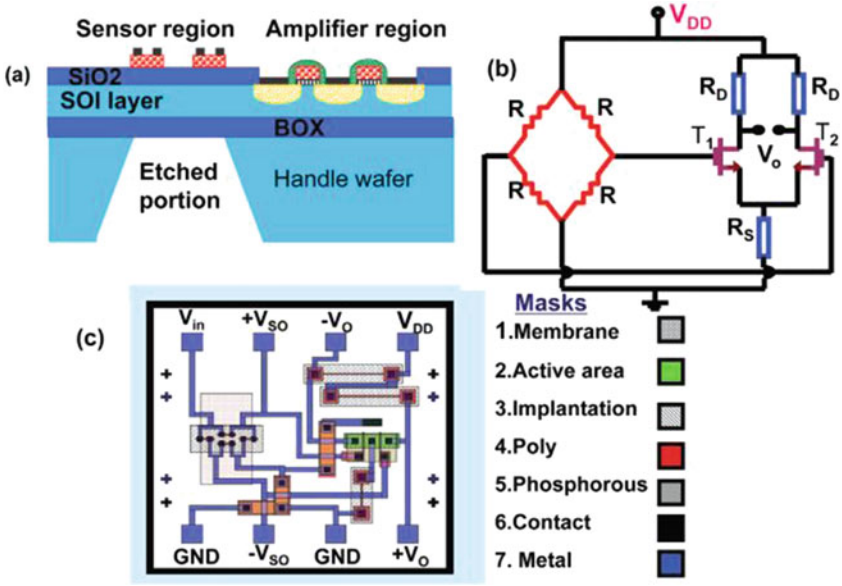

Fig. 1.4 An example from literature for the concept of monolithic integration of a pressure transducer and readout electronics in silicon [37], with (**a**) cross-section view, (**b**) schematic and (**c**) top view on the IC

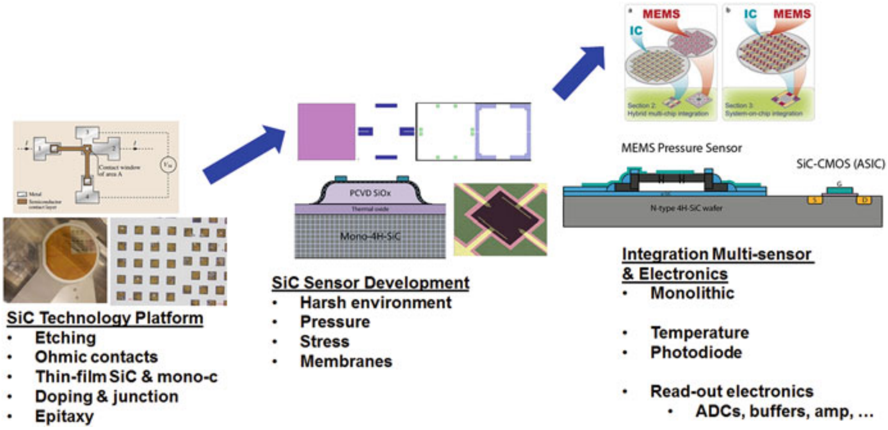

Fig. 1.5 The technology roadmap for the SiC pressure sensor platform

Some research is conducted on a CMOS SiC process [36] and the monolithic integration of front-end electronics with a pressure sensor for silicon technology is demonstrated in literature, see Fig. 1.4.

The technology roadmap for the SiC pressure sensor platform is indicated in Fig. 1.5.

References

1. M.M. Waldrop, The chips are down for Moore's law. Nature **530**, 144 (2016)
2. G.Q. Zhang, A. Roosmalen, *More than Moore: Creating High Value Micro/Nanoelectronics Systems* (Springer, Berlin, 2009), p. 330
3. J. Hamelink, R.H. Poelma, M. Kengen, Through-polymer-via for 3d heterogeneous integration and packaging, in *2015 IEEE 17th Electronics Packaging and Technology Conference (EPTC)*, pp. 1–7
4. R.S. Okojie, A.A. Ned, A.D. Kurtz, Operation of 6h-sic pressure sensor at 500c, in *TRANSDUCERS '97. 1997 International Conference on Solid-State Sensors and Actuators, Chicago*, vol. 2, pp. 1407–1409
5. R. Okojie, G. Saad, G. Beheim, E. Savrun, Characteristics of a hermetic 6h-sic pressure sensor at 600 c, in *AIAA Space 2001 Conference and Exposition*, (2001), p. 4652
6. R.S. Okojie, D. Lukco, V. Nguyen, E. Savrun, Demonstration of sic pressure sensors at 750c, in *Additional Papers and Presentations 2014*, (2014), p. 000028
7. R.S. Okojie, D. Lukco, V. Nguyen, E. Savrun, 4h-sic piezoresistive pressure sensors at 800c with observed sensitivity recovery. IEEE Electron. Device Lett. **36**, 174 (2015)
8. T. Kimoto, J.A. Cooper, *Fundamentals of Silicon Carbide Technology: Growth, Characterization, Devices and Applications* (Wiley, New York, 2014)
9. Status of the Mems Industry 2018 Market and Technology Report by Yole Développement. https://www.slideshare.net/Yole_Developpement/status-of-the-mems-industry-2018-market-and-technology-report-by-yole-dveloppement
10. M. Wijesundara, R. Azevedo, *Silicon Carbide Microsystems for Harsh Environments*, vol 22 (Springer Science & BusinessMedia, Berlin, 2011)
11. N.G. Wright, A.B. Horsfall, Sic sensors: A review. J. Phys. D. Appl. Phys. **40**, 6345 (2007)
12. M. Eickhoff, M. Möller, G. Kroetz, M. Stutzmann, Piezoresistive properties of single crystalline, polycrystalline, and nanocrystalline n-type 3 c-sic. J. Appl. Phys. **96**, 2872 (2004)
13. M. Willander, M. Friesel, Q.-u. Wahab, B. Straumal, Silicon carbide and diamond for high temperature device applications. J. Mater. Sci. Mater. Electron. J. **17**(1), 1–25 (2006)
14. H.P. Phan, D.V. Dao, K. Nakamura, S. Dimitrijev, N.T. Nguyen, The piezoresistive effect of sic for mems sensors at high temperatures: A review. J. Microelectromech. Syst. **24**, 1663 (2015)
15. D.G. Senesky, B. Jamshidi, K.B. Cheng, A.P. Pisano, Harsh environment silicon carbide sensors for health and performance monitoring of aerospace systems: A review. IEEE Sens. J. **9**, 1472 (2009)
16. L. Beker, A. Maralani, L. Lin, A.P. Pisano, A Silicon Carbide differential output pressure sensor by concentrically matched capacitance, in *Micro Electro Mechanical Systems (MEMS), 2017 IEEE 30th International Conference on (IEEE)*, (2017), pp. 981–984
17. M. Ericson, J. Silverudd, *Design of Measurement Circuits for Sic Experiment: Kth Student Satellite Mist* (2016)
18. S. Jin, S. Rajgopal, M. Mehregany, Silicon carbide pressure sensor for high temperature and high-pressure applications: Influence of substrate material on performance, in *2011 16th International Solid-State Sensors, Actuators and Microsystems Conference*, pp. 2026–2029
19. L. Chen, M. Mehregany, A silicon carbide capacitive pressure sensor for in-cylinder pressure measurement. Sens. Actuat. A Phys. **145**, 2–8 (2008)
20. C. Li, M. Mehregany, A silicon carbide capacitive pressure sensor for high temperature and harsh environment applications, in *TRANSDUCERS 2007–2007 International Solid-State Sensors, Actuators and Microsystems Conference*, pp. 2597–2600
21. S. Shao, *4h-Silicon Carbide Pn Diode for Harsh Environment Sensing Applications* (2016)
22. Flowmeters & pressure sensors. http://www.flowmeters.com/differential-pressure-technology
23. Y. Dévellopment, *Mems Pressure Sensor 2018—Market & Technologies Report* (2018)
24. W. Chien-Hung, C.A. Zorman, M. Mehregany, Fabrication and testing of bulk micromachined silicon carbide piezoresistive pressure sensors for high temperature applications. IEEE Sens. J. **6**, 316 (2006)

25. M. Eickhoff, H. Möller, G. Kroetz, J. v. Berg, R. Ziermann, A high temperature pressure sensor prepared by selective deposition of cubic silicon carbide on soi substrates. Sens. Actuat. A Phys. **74**, 56 (1999)
26. M.A. Fonseca, J.M. English, M.v. Arx, M.G. Allen, Wireless micromachined ceramic pressure sensor for high-temperature applications. J. Microelectromech. Syst. **11**, 337 (2002)
27. S. Fricke, A. Friedberger, H. Seidel, U. Schmid, A robust pressure sensor for harsh environmental applications. Sens. Actuat. A Phys. **184**, 16 (2012)
28. T. Lalinský, P. Hudek, G. Vanko, J. Dzuba, V. Kutiš, R. Srnánek, P. Choleva, M. Vallo, M. Držík, L. Matay, I. Kostiˇc, Micromachined membrane structures for pressure sensors based on algan/Gan circular hemt sensing device. Microelectron. Eng. **98**, 578 (2012)
29. G. Wieczorek, B. Schellin, E. Obermeier, G. Fagnani, L. Drera, Sic based pressure sensor for high-temperature environments. IEEE Sens. J., 748–751 (2007)
30. D.J. Young, D. Jiangang, C.A. Zorman, W.H. Ko, High-temperature single-crystal 3c-sic capacitive pressure sensor. IEEE Sens. J. **4**, 464 (2004)
31. R. Zhang, T. Liang, Y. Li, J. Xiong, A novel mems sic pressure sensor for high-temperature application, in *2015 12th IEEE International Conference on Electronic Measurement & Instruments (ICEMI)*, vol. 3, pp. 1572–1576
32. K. Fobelets, R. Vounckx, G. Borghs, A gaas pressure sensor based on resonant tunneling diodes. J. Micromech. Microeng. **4**, 123 (1994)
33. M.A. Fragaa, H. Furlan, M. Massia, I.C. Oliveiraa, L.L. Koberstein, Fabrication and characterization of a sic/sio2/si piqaezoresistive pressure sensor. Proc. Eng. **5**, 609 (2010)
34. Y. Jiang, J. Li, Z. Zhou, X. Jiang, D. Zhang, Fabrication of all-sic fiber-optic pressure sensors for high-temperature applications. Sensors **16**, 1660 (2016)
35. K.M. Dowling, E.H. Ransom, D.G. Senesky, Profile evolution of high aspect ratio silicon carbide trenches by inductive coupled plasmaetching. J. Microelectromech. Syst. **26**, 135 (2017)
36. A. Rahman, A.M. Francis, S. Ahmed, S.K. Akula, J. Holmes, A. Mantooth, High temperature voltage and current references in silicon carbide cmos. IEEE Trans./Electron Devices **63**, 2455 (2016)
37. K. Bhat, M. Nayak, MEMS pressure sensors-an overview of challenges in technology and packaging. J. Smart Struct. Syst. **2**, 1–10 (2013)