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Development of a roadmap for advanced ceramics: 2010–2025

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Abstract

A roadmap for advanced ceramics for the period from 2010 to 2025 has been developed to provide guidelines for future investments for policy makers, scientists and industry alike. Based on questionnaires, interviews and a final workshop with well-balanced participation of members from industry and academia three roadmaps on application fields and two roadmaps on scientific areas have been developed and contrasted. The three application fields selected are: (i) electronics, information and communication; (ii) energy and environment; (iii) mechanical engineering and the two scientific fields are: (a) structural and functional properties; (b) process technology. Within these fields the tremendous growth opportunities for ceramics as an enabling technology are highlighted and manifold suggestions for future development are provided.

Keywords: Roadmap; Foresight; Advanced ceramics; Electronics, information and communication; Energy and environment; Mechanical engineering; Structural and functional properties; Process technology

1. Introduction

Science and technology are advancing at an increasingly rapid pace and the ways in which they interact with economy, society and environment are becoming increasingly complex.[1] Balancing the essential needs of science quality, of relevant R&D programs, of functional integration and of responsiveness to stakeholders can be very confusing. To remain competitive in the future, and to ensure long-term success, policy makers, other stakeholders and big companies must focus on future markets and apply a well-founded strategy for technology development. To achieve success in today's global economy, companies must be able to produce the right product at the right time. Technology foresight, especially roadmapping as a distinctive method, becomes significant.[1,2]

Technology foresight is a mechanism for strategic decision-making. It is a process which seeks systematically to look into the longer-term future of science, technology and economy, the environment and society with the aim of identifying the emerging generic technologies and the underpinning areas of strategic research likely to yield the greatest economic and social benefits. It helps to identify, select and develop technology alternatives to satisfy future service, product or operational needs.[3–5]

The wide application of technology foresight in certain countries dates back to the beginning of the 1980s.[6] Prior to that, few technology foresight activities using roadmapping have been carried out in the US.[7] It is also highly regarded as a tool for anticipating future market demand and designing development strategies for trans-national companies. Technology foresight is now being increasingly recognized worldwide as a powerful instrument for establishing common views on future development strategies among policy-making bodies, bridging the present and the future. One of its unique features is the participation of a large number of stakeholders, namely governmental

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institutions, scientific communities, industrial enterprises and civil society. This instrument has been implemented in several countries for certain R&D fields including materials research and development.[1]

The fact that materials issues pervade all aspects of our lives is well accepted. Whether these are modern medical procedures or changes in telecommunications, they all depend on materials developments.[8] Since 1992 the Semiconductors Industry Association (SIA) has coordinated a process for building consensus on the future technology requirements for maintaining the historical rate of advancement out of a 15-year horizon. The tremendous progress of silicon integrated circuits (ICs) has been and is still driven by the downsizing of their components. Affordable scaling constitutes one of the identified Grand Challenges quoted in the National Technology Roadmap for Semiconductors (NTRS) for the future.[9]

The "Advanced Ceramics" industry is fundamentally different from the silicon microelectronics industry, due to its higher diversity, higher interdisciplinarity, very different processing technologies and variety of application. This means that a straightforward anticipation of the ever increasing cost benefits from economy of scale and the continuous improvement of yield is inappropriate in the case of advanced ceramics. Unlike the NTRS, existing roadmaps for "Advanced Ceramics" do not simply focus on the reduction of feature size but are aimed at assessing potential advanced ceramics-based products, which will help the industry of the future to meet long-range visions for energy efficiency and pollution reduction, improved capital effectiveness and increased productivity and life quality.

2. International foresight activities

At the first International Congress on Ceramics (ICC) held in Toronto in 2006 for the purpose of creating a ceramics roadmap, researchers and engineers agreed that advanced ceramics, defined as non-metallic inorganic materials, would have a major impact on addressing future challenges and needs. A global roadmap for ceramics was developed, wherein the contribution and the ability of ceramics to solve problems in major markets like electronics, energy generation and storage, environment and transportation, processing and manufacturing, health and safety issues, was elaborated.[10]

The development of ceramics with improved properties will open up an increasing number of demanding applications, like advanced electronic ceramic materials for Si electronics and automotive industries. Furthermore, increasing global demand for energy has led to a strong need for established and alternative energy sources. Advanced ceramics have played and will continue to play a critical role in all aspects of energy production, storage, distribution, conservation, and efficiency. However, there are a number of issues which have to be addressed in terms of future needs for innovative and multifunctional ceramic material systems, robust and affordable manufacturing technologies, system level performance studies, system reliability and durability, and total life cycle cost. Finally, producers are always looking to improve the competitiveness and sustainability of manufacturing.

This progress in advanced ceramics technology will not occur without the continuous support of ceramics fundamental research by government agencies and industry.[10] In order to stimulate and to coordinate this support, technology foresight has been fostered in several countries in the last years. The most important ones are summarized below.

USA: The United States Advanced Ceramic Association (USACA) recognized that changes of present strategies for advanced ceramics R&D are needed. Identified drivers for such changes are unrealized market expectations due to technical challenges in many cases (e.g. CMCs, industry consolidation), soaring prices of petroleum-based goods, growing population, urbanization and aging population. The USACA 2020 vision of advanced structural ceramics is to make these materials cost-effective and to outperform other materials due to reliability, high-temperature capability and other unique properties.[11–13] Products are initially designed for ceramic materials, using established standards and design tools. Automation and other advanced fabrication processes optimize cycle times and yield, ensure predictable and controllable production, and eliminate the need for post-process inspection. New crosscutting R&D programs that impact the ceramics industry for the demonstration of key technology platforms for improving energy efficiency and reducing environmental problems are highly recommended.

UK: In October 2002 the UK government launched PowderMatrix, one of the 24 Faraday Partnerships, to create a network in particulate engineering, initially focussed on the advanced ceramic, powder metal, hard metal and magnetic industries. In December 2004 PowderMatrix released an advanced ceramics roadmap. It projected that advanced ceramic manufacturers will have a wide range of market opportunities from end users who want components to solve critical challenges.[14] Components with better performance characteristics, e.g. improved resistance to fracture, increased reliability, reduced manufacturing costs and increased conductivity will be increasingly needed. In the medium- and long-term the advanced ceramic base is seen to need more understanding and development for innovative materials and processes for new markets which will likely include reduced product development cycles and greater reuse of waste material and cost-effective reuse of materials at the end of life.[14]

Japan: In the past the Japanese Ministry of Trade and Industry has sponsored a national survey project on industrial technology of new inorganic materials (FY2001–FY2005), where three industries were identified to which advanced ceramics would strongly contribute. Those are the network/device industry (i.e. materials for next-generation semiconductors, sensors, storage devices, optical networks, high-speed wireless access and next-generation displays), the Bionic industry (i.e. materials for drug delivery system, medical micromachines, biocompatible materials, artificial organs, and biochips) and the environmental/energy industry which is concerned with issues like materials for fuel cells, transportation and electric power generation, environmental monitoring, elimination of toxins, and environmental improvement.[12] Meanwhile the Japanese government has launched a mid-term program with two main goals, promotion of nanotechnology-driven advanced materials research and promotion of advanced materials research on environment/energy materials and high-reliability/safety materials.[12] Therein nine research projects are directly related to advanced ceramics including, novel nanotubes and nanosheets, advanced nanoparticle processing, optoceramics, biofunctional materials, materials for fuel cells, high-performance superconducters, highly efficient photocatalysts and finally intelligent sensor devices.

Germany: Recently the German Ceramic Society (DKG) highlighted important requirements for advanced ceramic processing for the near future.[15,16] More general, DKG and the German Society for Materials Research (DGM) developed an advanced ceramic roadmap for setting the goals of ceramics R&D activities for the next 20 years for their membership base, thus focussing on Germany, Austria and Switzerland. This activity was also supported by the German Research Association (DFG). Recently, this roadmap for "Advanced Ceramics" for the period 2010–2025 was established and published.[17] This paper summarizes the findings from this roadmap.

3. Today's ceramics

Advanced ceramics represent an important technology which has considerable impact for a large variety of industries, branches and markets. It is considered as an enabling technology which has potential to deliver high-value contributions for solving the challenges of our future.

From a general point of view the advanced ceramics sector comprises the following categories:

- Functional ceramics: Electrical and magnetic ceramics (i.e. dielectrics, piezoelectrics, ferromagnetics), ionic conductors and superconductive ceramics.
- Structural ceramics: Monoliths and composites, e.g. oxides, nitrides, carbides, borides, and composite materials based on these materials.
- Bioceramics: e.g. hydroxyapatite and alumina.
- Ceramic coatings: Oxides, nitrides, carbides, borides, cermets and diamond-like coatings, deposited by technologies such as spraying, vapour deposition and sol–gel coating.
- Special glasses: Processed flat glass, fire resistant glazing and glasses for optoelectronics.[14]

The world-wide market for advanced ceramics is forecast to arrive at 40×10^9 US$ in 2009 (The Freedonia Group, 2007). Fig. 1 gives the expected development of the US market up to 2015, indicating that all sectors will exhibit a continuous growth. The growth rate in Germany was at a remarkable 7.7% from 2005 to 2006 (data from: Verband der keramischen Industrie e.V.).

These values do not consider the added value impact of most high-performance ceramic components on the product and system levels of a large variety of very different industries and branches. For example, advanced ceramics are playing a key role for the further development of more efficient and less polluting automobiles. While in 1980 the value of electronic components in automobiles was at 1% of the total value, this percentage has risen to about 20% in 2004 and is predicted to rise to about 28% in 2015. A multitude of advanced functional ceramics contributes to this noteworthy growth. Recently, the introduction of the piezoelectric injectors for the common rail technology for diesel engines has been the most striking example.[18] While automotive industry is projected to have good growth rates, mainly spurred by the increasing demands in the developing countries, the growth rate for electronics in automobiles will outperform these values by far (Fig. 2).

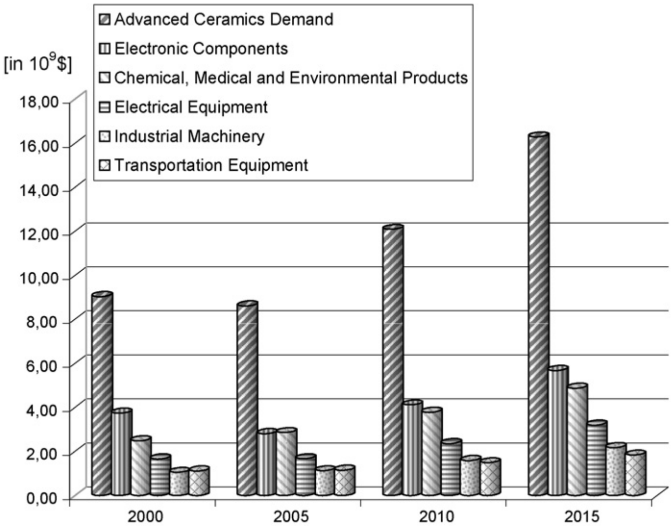

Fig. 1. Development of the US market for advanced ceramics from 2000 to 2015.

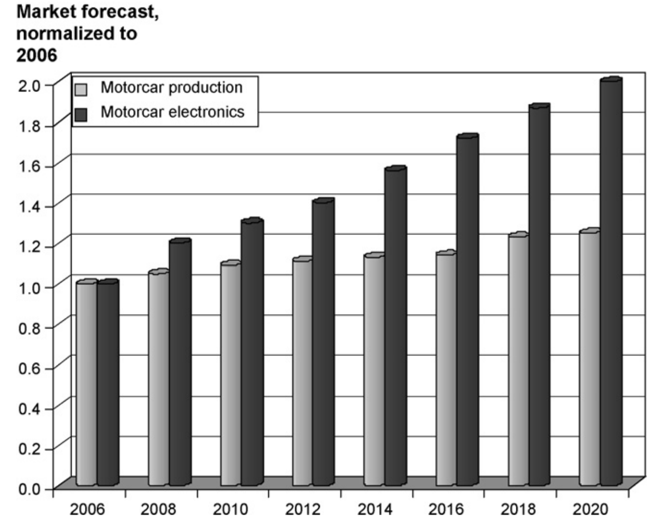

Fig. 2. Projected development of automobile electronics as compared to car production.

4. Methodology for roadmap development

The development of this roadmap started with an analysis of current roadmaps in the field of advanced ceramics. These roadmaps are being developed by different researchers and institutions, using different methodologies and covering different topics.[19] Thus, the first step was to cluster these roadmaps in order to develop a suitable meta-structure. The focus was laid on sectors with high relevance for the German economy.

These sectors of application were clustered according to similar requirements for different materials and were specified within the roadmaps.

After defining the structure, a questionnaire was deployed and conducted in a large survey and in a focussed version in interviews with experts. This questionnaire was constructed in collaboration with experts from academia, industry and the members of the described material societies. In total 500 questionnaires were sent with 125 being sent back. The experts also provided ratings for different areas and considered "Energy" highly important for the future of ceramics research. The respondents also evaluated the areas of applications like "Mechanical Engineering" and "Transport & Mobility" as significant future research fields for advanced ceramics. The significance of these results was further supported and explained in a more detailed manner by trend and market analysis.

At the same time face to face interviews with experts from science and industry started. In total 25 interviews were carried out, mainly with experts in Germany, Austria and Switzerland. Additionally there were discussions held in the UK and USA.

The current effort focussed on a well-balanced interaction between research and application, afforded by a balance of all participants from industry, national laboratories and universities. Therefore, application-oriented roadmaps were developed and contrasted to science-based roadmaps.

After developing the results from the questionnaire and the interviews, experts were invited to a symposium to discuss the results in detail. The symposium consisted of different workshops and open discussions. During the discussion at the workshop both types of roadmaps could be further quizzed and developed by considering the matching issues between application and science. In order to manage resources in an optimum manner, we focussed on three roadmaps in the area of application:

- electronics, information and communication,
- energy and environment,
- mechanical engineering.

In the area of science two roadmaps were developed:

- structural and functional properties,
- process technology.

Both, a short-term development and a long-term, extrapolation were attempted. In the first instance, predictions were provided for the time after 2010, while a long-term vision based on a consideration of megatrends was derived for the time span up to 2025. After the symposium, a team of experts finished and revised the roadmaps in groups addressing different topics.

The roadmaps can be used for different purposes by various stakeholders. Companies can use the roadmaps to develop their own strategies for meeting future trends and lead markets.[20] Research organizations can identify technology avenues they want to follow or they can pursue opposite or complementary directions.[21] Of course, research funding organizations can use the roadmap to identify future needs and valuable trends.[22] In order to update the roadmaps continuously patent and trend monitoring systems can deliver further market and R&D characteristics.

5. Roadmaps for selected application and knowledge fields

Results are presented in the form of roadmaps for three specific areas of application and two specific scientific areas. They span the time frame from 2010 to 2025 with the key topics placed along the time axis centred at the year where the first prototypes become available. The length of the attendant arrow suggests a time span for the crucial developments.

5.1. Electronics, information and communication

The electronics industry not only is one of the largest industries but also impacts many other industries, which rely on electronic components for further innovation and growth. Among these are mechanical engineering, the automobile industry, and the energy and environmental industries. In 2008 in Germany a growth rate of at least 5% is expected, bringing the total turnover to 200 billion €. Electronic components for automobiles came in at 6 billion € in 2006, providing a boost of almost 7% in total turnover. The world market for automobile electronics is predicted to be at about 200 billion € in 2015.

Advanced ceramics are prominently featured in passive electronic components and are providing key components for subsystems like printers, fine positioning, medical and optical devices, injection systems, actuators and sensors. In the microelectronics and high-power electronics industry they are utilized as components prepared by laminate and substrate technology.

In the following, salient trends and perspectives will be listed starting with goals for applications, followed by goals for basic science. Finally, Fig. 3 provides the complete roadmap for electronics, information and communication.

5.1.1. Electronics

- Adaptronic and mechatronic components are expected in the short term for active noise and vibration suppression.[23] Sensors and actuators often covering large areas are required, thus demanding fibre composites or ceramic tapes.
- Environmental concern necessitates that the increasing market of piezoceramics for sensors and actuators can be delivered with lead-free piezoceramics.[24,25] Although strong advancements have been noted and many small volume components have been produced from lead-free piezoceramics, a complete market switch away from lead-containing materials is not expected in the next 10 years, but soon thereafter.
- Ceramic micro-electromechanical systems (MEMS) are expected to gain momentum.[26] Recent problems with electrostatic MEMS may hopefully be overcome using piezoelectric thin film drives.
- Highly integrated modules based on low temperature cofired ceramics (LTCC) for power electronics and microwave technology are about to integrate additional functional ceramics.

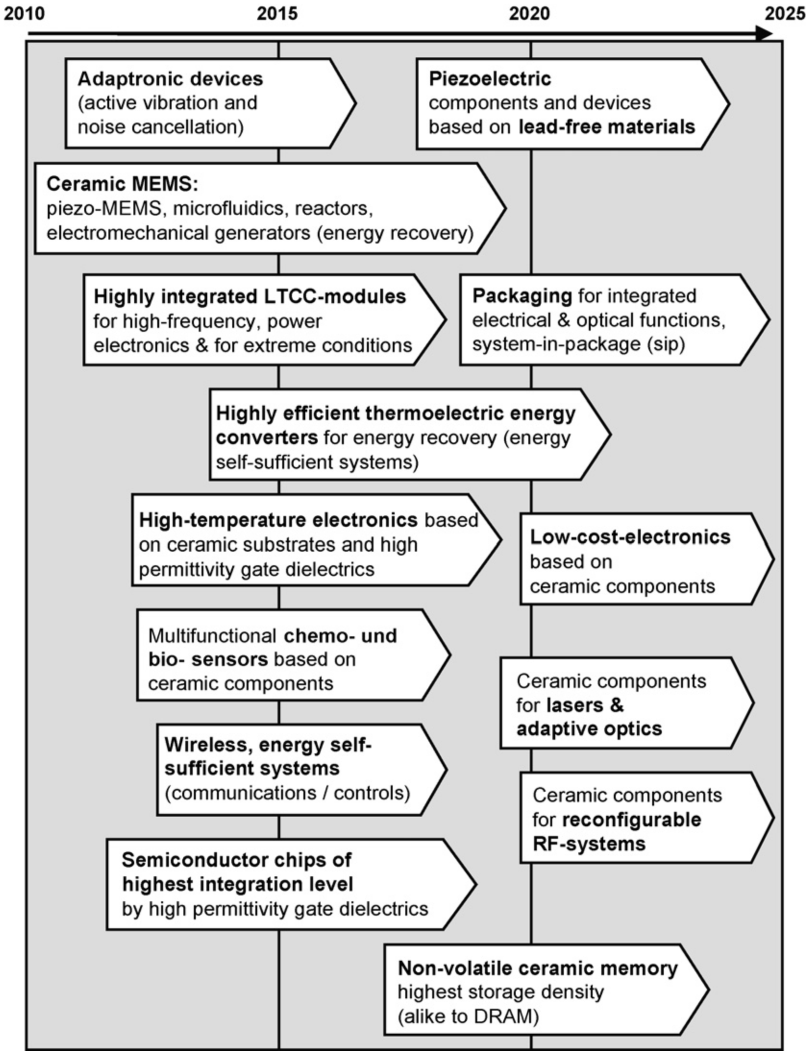

Fig. 3. Roadmap for electronics, information and communication.

Specific cavity designs, channel structures, improved thermal management and the integration of thermoelectrics will enable utilization in additional applications, e.g. under extreme conditions.

- Ceramic packages are predicted on the long term for an integration of important optical functions, including light sources, light modulators, light sensors and light guides. These, in combination with electrical components will provide a complete optical information package (system in package, SIP).
- Highly efficient thermoelectric energy converters[27] are seen to be available for energy harvesting from process heat to provide energy-autonomous systems and for cooling of electronic components.
- For high-temperature electronics advanced ceramics are expected to play a stronger role as thick films, multilayers and tapes and as thin films for high-permittivity gate oxides in power semiconductors.
- Robust and flexible chemical sensors, especially gas sensors and biosensors are predicted to be available for combination of several sensor principles for increased sensitivity and selectivity.

5.1.2. *Communication*

- Optical communication systems of the future may rely on system in the packages as described above, but may also utilize periodic particle structures and layered systems for photonic band gap structures (metamaterials) for compact optical signal processing.
- Wireless, energy-autonomous communication requires advanced ceramics for the above-mentioned system in packages for energy harvesting and storage.
- For reconfigurable radio-frequency systems tuneable functional ceramics[28] are required for frequencies between 0.4 and 40 GHz.

5.1.3. *Information*

- In the near future high-permittivity gate dielectrics, for example HfO_2 and PrO_x, will be applied to reduce the transistor gate length, thus increasing the integration density for semiconductor technology.
- Non-volatile high-density storage media[29] require bistable material properties and means for nanostructuring. On a long-

term basis, further advances in ferroelectric, magnetic and resistive storage media are predicted.

The goals for the applications listed above demand advances in basic science. Briefly, these can be categorized as follows:

- *Materials*: New or improved functions and attendant materials are required in the areas of lead-free piezoceramics, high-temperature electronic ceramics, magnetically and electrically tuneable ceramics and for storage media. New functionalities are predicted from utilizing nanostructures and the use of biological concepts.
- *Processing*: Cost reductions are envisaged in the broad areas of miniaturization, integration and process technology through reductions in sintering temperature, thin film techniques and techniques like free forming, printing and micro-injection moulding. Biologically inspired processing techniques may offer completely new processing solutions.
- *Simulation*: In the near future simulation tools are expected to follow the complete processing chain from material to system enabling also an analysis of reliability and lifetime.

5.2. Energy and environment

Worldwide energy consumption has increased in the last decade with predictions ranging up to a further increase by 75% until 2030. With the impending shortage of resources and the threat of global warming there is urgent demand for increased efficiency in mining energy resources, energy conversion, energy storage and utilization of energy, all with low emissions in CO_2 and NO_x, next to other environmental pollutants. In analogy to the need for energy, the relevance of environmental technologies is increasing. Pollution of soil, water and air has reached dramatic levels in some areas. Already an increase of environmental technologies from 4% to 16% of gross national product is predicted for Germany from 2006 to 2030. The environmental tasks are manifold. Emissions of dust, ashes and exhaust fumes need to be eliminated or reduced, pollutants from industrial processes need to be retained and environmentally harmful materials require replacement through environmentally benign materials. Ceramic coatings with additional functionality (catalytic, etc.) as well as filter materials and membranes are in use but offer considerable potential for more impact.

Again, we describe the goals for application followed by the demands placed on scientific development.

5.2.1. Energy

- The use of fossil fuels for the generation of electricity demands higher usage temperatures. These can be accomplished using improved thermal barrier coatings[30] with reduced thermal conductivity and enhanced high-temperature stability. Damage tolerant ceramic composites for, e.g. gas turbines, burner nozzles and heat exchangers as well as sensors for structural integrity are also predicted. Further, self-healing ceramics may be a solution for the expected high thermo-mechanical loading scenarios.
- Solar thermal energy may demand heat exchangers for the high-temperature regime.
- High-temperature fuel cells in the high-power regime (>100 kW) require more affordable process technology and improved electrolyte and electrode systems.[31] Reduced usage temperatures and increased reliability are envisaged in the long term.
- High-temperature superconductors (HTS) are awaiting a further boost, possibly with the advent of new materials, which could bring a break-through in transformers, electromotors and high-field magnetic systems.
- New nanoscale ceramics for batteries of higher storage capacity,[32] storage capacitors and for hydrogen storage are predicted to bring improved opportunities for energy storage.

5.2.2. Environment

- Ceramic filter membranes and catalytically active materials can provide a key technology for the provision of clean and affordable drinking water.
- Ceramic separation membranes[33] for combustion processes through the use of high-efficiency ionic conductors, meso- or nano-filters and catalytically active materials free of noble metals are expected to make a big impact both in the short- and long-term.

The technological goals above can be directly translated into scientific challenges:

- Optimized combination of properties governed by crystal chemistry and microstructure to realize new materials, composites and coatings for high thermal, mechanical and corrosive loading providing damage tolerance and high lifetime.
- Reliable process technology for reduced costs especially for composites and special joining techniques.
- Broad-ranging damage models as basis for component simulation and lifetime prediction for extreme environment.
- Multi-scale materials and device modelling for computer-supported process development.
- Integration of sensor and actuator functions into ceramic materials and devices.

The Roadmap for energy and environment is provided in Fig. 4.

5.3. Mechanical engineering

In this chapter we summarize the expected developments for advanced ceramics for industrial machinery and production technology. An increase in world population and increased living standards combined with scarce resources will inevitably increase the demand for machinery. In order to keep up with intensified global competition there is an increased pressure for innovation, which of course raises the demand for technological development. In addition, faster and more cost efficient manufacturing with reduced energy consumption through both increasing

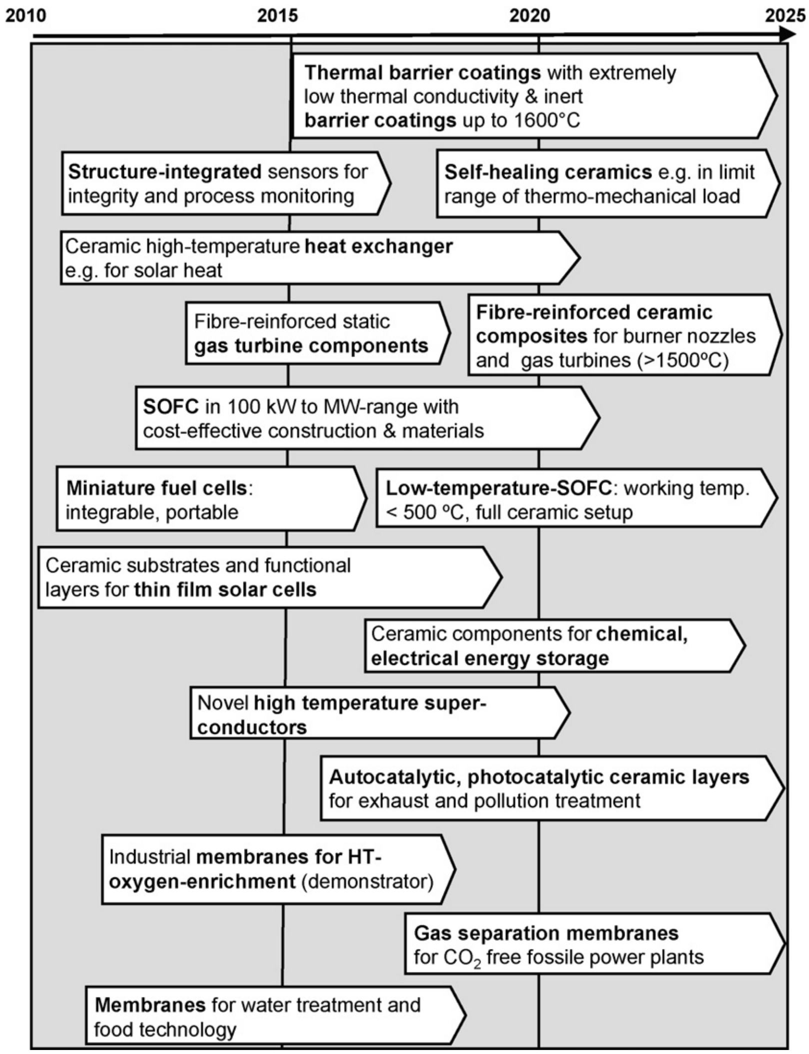

Fig. 4. Roadmap for energy and environment.

the productivity of machinery and energy recovery is essential. The innovation, combination and integration of conventional and new technologies and materials allow for and drive the development of new, improved and more economical products and manufacturing processes. The goals for application are as follows:

- Wear: Thread guides, pipes, paper ledges, valves, all will benefit from higher wear resistance. Better reproducibility, optimized friction coefficients and surface topography will help towards this goal.
- Pumping technology (pumps and compressors): Fluids in machinery are subjected to high pressures and are susceptible to wear through debris and contaminations. Ceramic fittings may render cooling agents and lubricants obsolete and greatly improve components.
- Forming and cutting tools: Further developments of forming and cutting tools will become increasingly important. Due to their good mechanical and tribological properties, cubic boron nitride and other ceramic matrix composites are expected to gain market share.
- Chemical industry: Large heat exchangers with superior corrosion resistance, also with respect to cavitation are to be expected. Ceramic filters with high corrosion resistance are needed.
- Extreme upscaling: Large components as in wind power plants demand large ball bearings.
- Miniaturization: The trend for miniaturization is expected to continue, allowing us to use micromachines, requiring ceramic microcomponents, in many areas such as medicine and communication. Miniature gas turbines and miniature fuel cells can be seen as an alternative to batteries for mobile phones and laptops.
- Sensors and actuators: Improvements in precision into the sub-μm scale, e.g. through piezoceramics, including wireless communication, are expected to be of high importance. High precision is also pertinent for precision optics, large components, zero expansion demands, etc.
- Multifunctionality: Ceramic components which can adapt to a multitude of requirements are considered an important goal for the future.

These application goals lead to a set of demands for basic research:

- Affordable raw materials and optimized processing technologies are the key factors for making inroads into this market. Improved milling techniques, tape casting, coating, sinter and joining technology all are highly pertinent in order to achieve improved precision and a long lifetime.
- In the field of materials, high-toughness ceramics with high strength and wear resistance are envisaged for the future. In addition, both ceramics with electrical conductivity and composites in general are of interest.
- Akin to the other application fields, a simulation of the complete process chain is to be developed.

The Roadmap for mechanical engineering is provided in Fig. 5.

5.4. Structural and functional properties

High-performance ceramics reveal the broadest spectrum of properties compared to all other classes of materials such as metals or polymers. Many ceramics are multifunctional and therefore predestined to solve the upcoming technological challenges especially in the field of energy and environment. It is suggested that ceramics still offer an unexplored potential. Most recently researchers became interested in oxide electronics due to the discovery of a 2D electron gas system at heterogeneous interfaces in multilayer devices. A related article of Ramirez on “Oxide Electronics Emerge”[34] closed with the sentence: “The present experiment suggests that we have entered the era of oxide electronics, and research in this field promises exciting discoveries for many years”. This enormous potential can only be exploited with a knowledge-based materials science. Therefore we need to analyse the correlation between crystal chemistry, chemical composition including dopants, microstructural parameters (texture, interfaces). The following aspects will play a key role for future developments:

- Structural ceramics: An enhancement of mechanical stability is expected based on new composite material concepts, which may be advanced using new reinforcements like carbon nanotubes or SiBCN fibres. Reliability can be improved

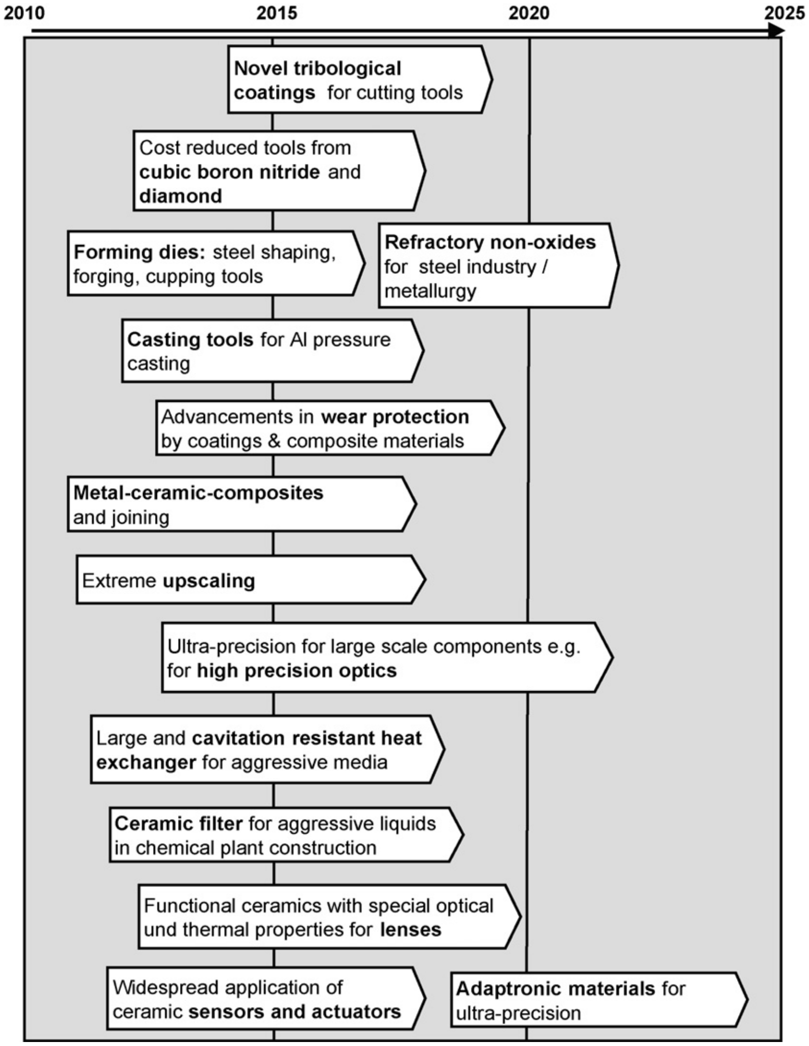

Fig. 5. Roadmap for mechanical engineering.

by integrating sensors leading to structural health control or through the development of self-healing ceramics. Adaptive structures based on piezoceramics are expected to push the limits in mechanical engineering and production technology[35] (e.g. higher revolutions in engines, higher precision in production).

- Functional ceramics, defect structures: Full exploration of the potential of ceramic semiconductors, sensors and actuators demands an in-depth understanding of the temperature dependent influence of atomic and electronic point defects. A combination of high-resolution spectroscopy in conjunction with ab initio computations is considered highly advantageous.
- Functional ceramics, properties: Multifunctional ceramics often do not merely exhibit additive effects, but especially a coupling of their properties (piezoelectric effect, electrooptic effect, optostrictive effect, etc.). The limits of these effects are not yet explored, but promise to provide exciting scientific and technological advancements in the future. Further, the effect on scale on properties in general (ionic conductivity, ferroelectricity and piezoelectricity in thin films[36]) has not yet been fully determined.
- Miniaturization and integration: Miniaturization und intregration density of devices and systems will significantly increase in the medium and long term. This requires a better understanding and the control of the corresponding changes of specific properties of materials and interfaces, as for example in the development of new materials for hydrogen storage (complex hydrides) or super caps for fast storage of electric power in hybrid electric vehicles. Parallel to this, new testing methods must be developed to characterize the physical properties on a much smaller scale, as for example the electrical resistivity of a single grain boundary in a ceramic or the interfacial strength in complex layered structures. In parallel, new measurement techniques for physical and mechanical characterization of interfaces and small structures need to be developed.
- Modelling: The development of new materials and devices based on simulation especially in cases of coupled properties (e.g. multiferroic materials[37]), requires a true multi-scale modelling which has been realized up to now only for a few

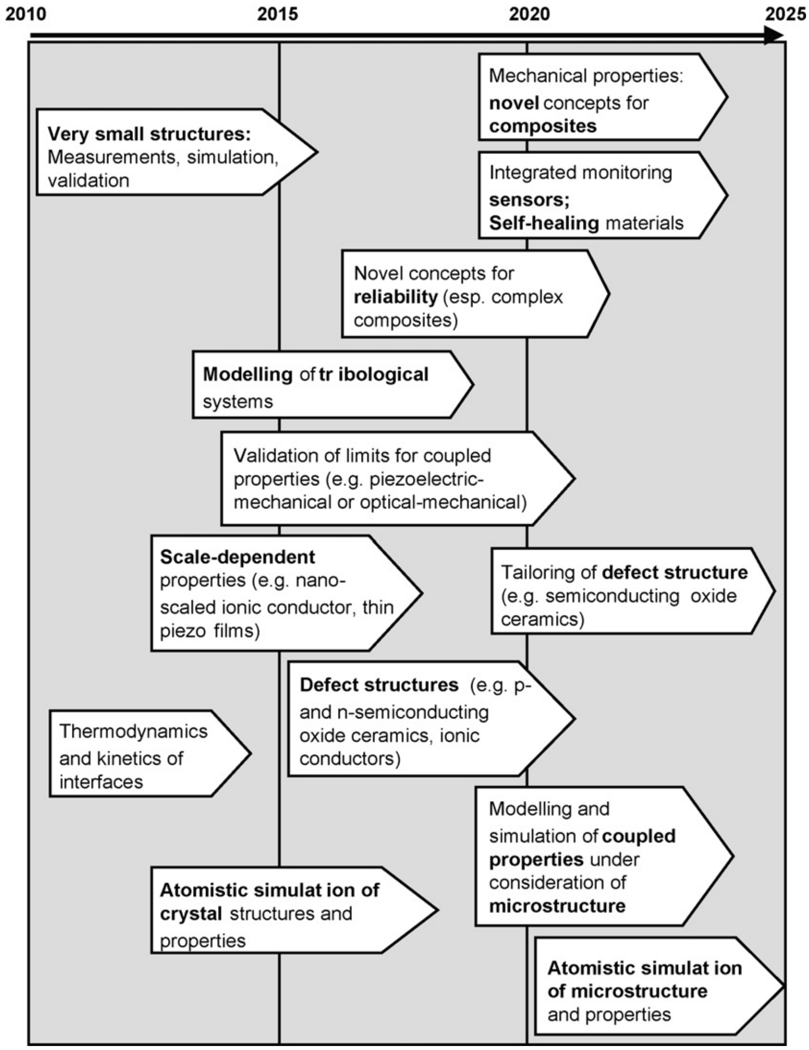

Fig. 6. Roadmap for structural and functional properties.

systems. Atomistic simulations will become more important due to the increasing impact of interfaces with increasing miniaturization, but they are not able to handle complex microstructures or even larger length scales. Phase field modelling[38], thermodynamic models for the calculation of phase diagrams (CALPHAD), micromechanical models, or finite element modelling can handle larger length scales, but without considering the atomistic level. In order to bridge the gap between modelling technique on different length scales, well-defined interfaces are required for data reduction and data exchange. Enhanced kinetic models will help to predict optimum microstructures and functionalized interfaces of porous materials used as catalyst, electrodes in solid oxide fuel cells, or gas sensors. Grain boundary engineering is also essential to adjust optical properties of transparent ceramics or single crystal conversion.[39] Finally, the modelling of tribological systems promises great benefit by aiding knowledge-based improved materials design.

The Roadmap for the exploration of structural and functional properties is provided in Fig. 6.

5.5. Process technology

Development of innovative process technologies is an absolute requirement to transfer new knowledge on functional and structural properties into ceramic materials and devices. New products will only be marketable, if they are cost efficient and environmentally benign and are of high quality. The following aspects have been identified:

5.5.1. Robust, simple and affordable processes

- Powder and sol–gel route: An optimization of organic additives focusing on the organic–inorganic interaction is deemed crucial. As a result, optimized processing technologies for defect-free ceramics may result. Further, binder burn-out and other thermal processes (microwave sintering, influence of electric field, etc.) need to be studied in more detail. In the long turn, usage of tailor-made powders (complex composition, compositional gradient in particle, well defined particle shape) and reliable usage of nanoscale powders will become more important.
- Precursor route: Solid-state thermolysis of preceramic polymers[40] offers a high degree of flexibility. Processing of

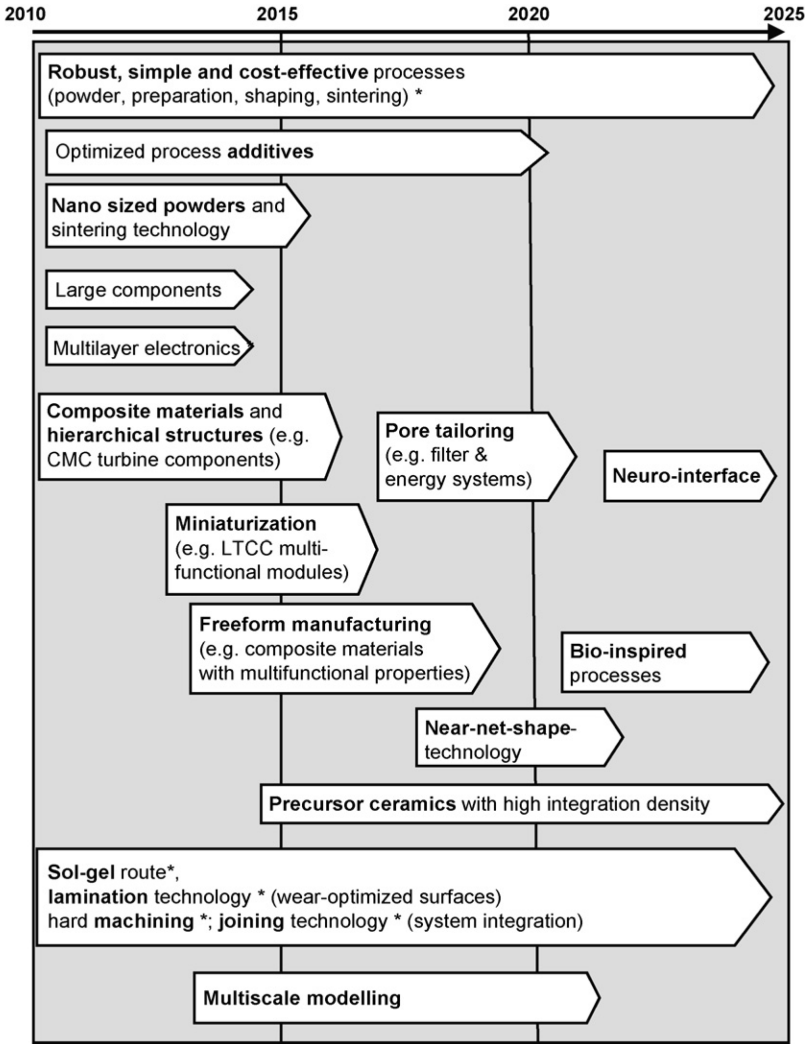

Fig. 7. Roadmap for process technology, techniques marked * are already established but require further fundamental considerations.

the precursors and thermodynamics governing the heat treatment need to be understood to a better degree. In the long run, molecular design will enable better routes for miniaturization and increasing levels of integration.

- Biomimetic route: Biomaterials offer a building design based on hierarchical structures, which require new processing routes. Self-organization at low temperatures in aqueous solutions is hoped to offer technologies in the future for cost-effective processing techniques.

5.5.2. Shaping

- Free-form manufacturing: Computer-aided design affords processing of components with complex structure through either removal or building processes (print and lamination techniques or photonic techniques)[41]. Except for the processing aspect, many opportunities arise with manufacturing complex designs or material combinations.
- Near-net shape forming[42] and hard machining: Hard machining is responsible for a large percentage of processing costs for ceramics. While some techniques for near-net shaping are available, this is considered a field for fruitful further activity; the same holds true for investigations into hard machining.
- Joining and coating technologies: Increasing complexity in material combinations demands improved joining techniques. Coatings with organic, inorganic or metallic components provide functionally optimized surfaces with low demand on resources and energy. An improvement in resistance to corrosion and wear will lead enhanced lifetime and savings in energy and material resources.

5.5.3. Modelling

- Nanoscale and microscale: On an atomic and molecular scale particle interactions need to be understood in order to provide means to control particle packing during shaping and densification.[43] The ongoing trend for miniaturization demands better control of grain boundaries and gradients inside of grains (PTC ceramics or X7R capacitor materials).
- Mesoscale: Most ceramics are anisotropic in the single crystal, however, many products demand ceramic technology, e.g. multilayer actuators and capacitors. Fortunately, controlled texturing affords the means to produce affordable components with properties mimicking single crystals. Texturing[44] can be achieved with oriented seeds, methods for texturing in the green body or directional grain growth.
- Macroscale: Densification of packed green bodies is expected to be the major processing route in the future also. An increase in integration will enhance the relevance of layered structures, which exhibit composite stresses during densification[45] (cosintering) and lead to anisotropic microstructures.[46] Hence, densification is complicated considerably and requires further development of modelling tools to handle densification of anisotropic microstructures during constrained sintering. Simulation of shaping processes also is deemed highly relevant, particular in conjunction with near-net shape forming processes.

The Roadmap for process technology is depicted in Fig. 7.

6. Conclusion

The roadmaps presented for three application and two knowledge fields are indicating a variety of important development goals. In summary, they can be grouped into four major research topics which should be addressed in the future to secure a sustainable development and growth of the advanced ceramics markets:

- novel ceramics with enhanced and new properties,
- high-performance key components for system application,
- highly efficient processing technology,
- holistic modelling and simulation techniques.

Therefore, increasingly multi-disciplinary approaches and R&D cooperations will be required including contributions, interfaces and leadership from the industrial side. For generating the expected progress at all levels, from ceramic materials to applications, various 'small' and 'large' breakthrough developments are required which cannot be listed here. But it is important to understand that the entire value-added-chain has to be considered for highly effective improvements and innovations. To leverage the entire innovation potential of advanced ceramics along the complete value-added-chain requires major efforts which have to be shared between the academic and the industrial side. Also, research funding will be an essential part to sustain and support this ambitious but essential goal. Funding should not be allocated in large framework programs alone, but, in addition be allocated for individual contributors and ideas which are not following the existing mainstream. Although high risk, they offer the opportunities for fundamental breakthroughs.

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