Corrosion research agenda:
"Robustness against Climate in Electrical Engineering/Electronics"
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Summary:
Society is under the influence of the global megatrends of climate change/scarcity of resources, shifting of economic powers, urbanisation, demographic change and digitalisation. In order to successfully counter these changes and even shape them positively, power electronics will (have to) be used in all fields of society. In order to meet the increased demands on the robustness and reliability of power electronic components, comprehensive knowledge of their corrosion behaviour is necessary. However, corrosion mechanisms are highly complex. They depend on the material, the environment and the respective protective measures. Accordingly, efforts must urgently be taken up in the most diverse research fields in order to create a comprehensive and secured data situation.

In the future, society will undergo changes due to **5 global megatrends**.

- **Climate change and scarcity of resources**
  Power electronics, through their integration with photovoltaic and wind energy, can curb the increased consumption of limited natural resources and the resulting increased emission of greenhouse gases. Power electronics furthermore enables the stabilisation and capacity expansion of existing power grids. In the development of systems for alternative generation of energy, transport, use and storage (incl. battery and fuel cell technology and hydrogen economy), power electronics will play a key role in terms of sustainability and resource conservation.

  Through miniaturisation, systems such as so-called wareables, i.e. electronics that can be worn on the body and in clothing, can be expanded to include power electronics where this was previously inconceivable. In this way, a fully electrified society based on renewable energies can be created. But power electronics are also indispensable in environmental measurement technology for long-term monitoring of ocean and climate changes.

- **Shift of economic powers**
  The economic power is shifting from West to East. The demands on the power electronics industry and research in Europe and especially in Germany are changing accordingly. In order to remain competitive, Germany and Europe must maintain and expand the current lead in highly reliable power electronics. In addition to the temperature-cycle stress, the focus is hereby put on corrosion research, including the development of corresponding lifetime models. Furthermore, it is the point to develop special applications with SME relevance and high added value, e.g. in the area of alternative drive concepts and in the medical sector.

- **Urbanisation**
  By 2030, 60 percent of the world's population is expected to live in cities. Power

electronics can contribute to the establishment of smart buildings, electric and autonomous mobility on the road, on the rails, on the water and in the air, as well as to the intelligent logistics of our goods.

- **Demographic change**
  An ageing society has consequences for the medical sector, the pension system, the working world and purchasing behaviour. In this context, power electronics enable the development and establishment of service and care robots as well as small electric vehicles for extended independent mobility to relieve the care system.

- **Digitalisation and connectivity**
  Digitalization causes large amounts of data in the use of cloud services, artificial intelligence or in the establishing 3D printing in industrial production. This requires self-learning systems and automation processes as well as Industry 4.0. This requires highly efficient power sources and energy storage systems and their management systems, i.e. reliable power electronics.

Electronic systems will thereby be omnipresent in society in the future. Accordingly, the requirements for resource-saving production and moisture resistance, thus reliability in use, are increasing. Improving the corrosion resistance and the corrosion protection has a double effect in terms of sustainability. The service life of the power electronics increases, which conserves resources. Furthermore, power electronics systems can be used in harsher climate conditions where mechanical solutions were previously used, which also reduces the energy and resource consumption of the systems.

What are the biggest challenges at present and in the next five years?
Due to the increased demands on power electronics, corrosion research in the field of electronics / electrical engineering will have to take on an increasing role.

In addition to moisture, sulphur, chlorine, amine compounds, etc. from the atmosphere are also responsible for corrosion of electronic components. Besides to assembled electronic components, components and printed circuit boards such as relays, cables, plugs, etc. from the field of electrical engineering will also be affected by corrosive failures.

For example, the hydrogen economy will play a decisive role in the alternative energy concepts and the adequate storage of this energy, which is not generated at the time of consumption. Here, in the initial phase, proportions of pollutant gases that cannot yet be estimated will also accompany the green hydrogen, favour corrosion reactions and thus in turn severely limit the usability or service life of the components used. Exactly here are also long and especially reliable service lives necessary in order to create added value in terms of application technology.
In the application area of electromobility, a higher moisture load on the electronic components will probably result. This is caused by the reduction of waste heat collectives during operation due to the absence of a combustion engine. Electromobility must therefore meet harsh operating conditions as well as the demand for minimum weight and installation space.

What are the benefits for the economy and society?
In the field of power electronics, Germany is currently one of the leading nations. In order to maintain this position, it is important to make optimal electrical use of the power electronics components (especially semiconductor components such as Si-IGBTs or SiC-MOSFETs). However, this increases the operating loads and electrical sensitivity of the modules. This can be compensated for by improved corrosion protection and thus minimised leakage currents.

In LED-based lighting solutions, the silver compounds must be effectively protected against harmful gas corrosion so that the anticipated savings can really be achieved through a significant increase in service life and minimisation of maintenance.
The upcoming modernisation of the railway, from the track to the smart goods wagon, also requires very good corrosion protection due to the often harsh environmental conditions in order to exploit the economic benefits through the best availability of the systems. Intelligent housing solutions in particular will play a key role here in the future.
The development of corrosion-resistant solders, especially against so-called electrochemical migration, and improved thermal transfer injection moulding processes suitable for mass production can be seen as a key to implementation in field use.

Corrosion mechanisms are highly complex. They are based on various reactions and a multitude of driving forces and degradation-fostering influencing factors as well as their almost unlimited combinations. Accordingly, it is necessary to develop rapid tests for a reliable indication of robustness against possible damaging loads. It is equally important to make progress in the field of combined stress tests in order to better evaluate the respective corrosion acceleration factors resulting from different environmental conditions in their combination and to be able to derive target-oriented countermeasures from them.
The analytical strategy of modern corrosion research consists of the following approaches:

- Characterise and understand corrosion processes using high spatial resolution methods (electrochemistry, impedance spectroscopy (EIS), microscopy, scanning electron microscopy with microanalysis) with a focus on in-situ/operando methods (e.g. Kretschmann setup).
- Coupling theory and experiment in
    - accelerated testing,
    - combined corrosive/thermomechanical loading, and
    - determining the acceleration factors and their dependencies.
- Correlation of electronics manufacturing and corrosion-promoting residues
- Correlation of electrical damages and corrosion damages
- Lifetime modelling

Through these analytical approaches, mechanisms of corrosion can be resolved even in complex environments, which contributes to the predictability of corrosion and consequently to its prevention. Corrosion research must go hand in hand with solder and protection development and the improvement of electrical design for robust electronics.

What has corrosion research achieved in the field of power electronics in the last ten years?
Regarding the understanding of the susceptibility of silver/sintered compounds to corrosion, great progress has been made through the joint project KorSikA. With regard to optimising the protection of power electronics modules against moisture exposure, the topic is currently being continued by the joint project IsoGap, among others.
For the risk assessment after rework and repair with regard to electrochemical migration, operational instructions on actions for avoiding moisture or corrosion failures for electronics production were developed in the IGF project N17960N/1.
The IGF project 19715 BR on adhesive degradation has provided in-depth insights and findings into the ageing and thus protective effect of epoxy systems which are used for the protection of electronics. This form of electronics in particular is produced in large quantities and used primarily for electromobility.
The KMU-innovativ joint project REWAKO 02WQ1464 has led to the development of weak point sensors for electrical systems. These shall be used especially in the water industry as corrosion early warning systems to prevent imminent system failures.

Where is demand needed for further research?

In order to achieve the reliable implementation of the mentioned social goals as well as increased sustainability (energy saving, resource conservation, ...) by increasing service life and efficiency, corrosion research must address the following fields:

- Aluminium and copper corrosion at chip level, i.e. the influence of moisture and the smallest impurities on power semiconductors.
- Corrosion protection of the so-called aluminium guard rings by glass or polymer passivations in order to keep the reverse voltages of power semiconductors stable
- Prediction of corrosion processes, especially from the so-called anodic migration phenomenon (AMP) and electrochemical migration in complex environments such as wind power plants, railway systems or in electromobility
- Development and verification of damage models and their simulation
- Development of rapid tests and combined endurance tests to shorten reliability tests, especially in the harmful gas range
- Development/optimisation of high-voltage and high-temperature resistant corrosion protection systems
- Improved smart enclosure design solutions for condensation/corrosion protection to avoid expensive protective coatings that hinder the recycling of old assemblies
- Development of solders resistant to electrochemical migration

This results particularly in the following research topics:

- Ageing durability of protective coatings, potting and thermal transfer molds
- Expansion of knowledge on the role of pergulating networks in the anodic migration phenomenon in potting or epoxy molding compounds
- Development of alternative high-voltage protection systems such as parylene for so-called sandwich modules, which enable smaller and more universally applicable power electronics
- Development of ultrathin filmic coatings for inexpensive connectors and mechanical components which are currently not coatable/protectable
- AMP-resistant solder resist and protective coating systems for moisture-robust and ageing-resistant power electronics
- Cost- and time-reduced quality monitoring for harmful gas and moisture robustness
- Development of appropriate evaluation criteria for moisture robustness in relation to the active service life