# - Ambient Intelligence -
# Key Technologies in the Information Age

W. Weber[1],

C. Braun[1], R. Glaser[1], Y. Gsottberger[1], M. Halik[2], S. Jung[3], H. Klauk[2], C. Lauterbach[1], G. Schmid[2], X. Shi[1], T.F. Sturm[1], G. Stromberg[1], and U. Zschieschang[2]

[1]Infineon Technologies AG, Corporate Research, Laboratory for Emerging Technologies, [2] Memory Products, [3] now with Corporate Center, Wearable Technology Solutions

**Abstract**

In this paper, applications are discussed that describe achievements along the road towards 'Ambient Intelligence'. Appliances and devices disappear into the environment of the individual; instead services come into focus. Key to this development are system solutions that lead to a significant improvement of the human-machine interface. Along this line, we present important technologies and key system components ranging from low-cost electronic technologies and systems, to ubiquitous sensor networks and electronics in smart textiles. In conclusion, this presentation relates the semiconductor technology roadmap to a future world in which electronics meets human needs in a pervasive, intuitive and beneficial way.

## 1. Introduction

Ambient Intelligence (1) is the vision that technology will become invisible, embedded in our natural surroundings, present whenever we need it, enabled by simple and effortless interactions, attuned to all our senses, adaptive to users and context, and autonomously acting. High quality information access and personalized content must be available to everybody, anywhere, and at any time.

Some believe 'Ambient Intelligence' is a vision for the far future: we may be surrounded by various fantastic features such as intelligent electronic wall papers or 'smart dust' forming distributed intelligence with spectacular properties. Indeed, *such* visions lie at least 20 years ahead of us. They will require major progress of alternative technologies that have presently not even shown basic feasibility, such as large-size paper-like display technologies or printable, ultra-low cost, ultra-low power electronics. Experience tells that the introduction of new basic hardware technologies to the market takes a long time even when functionality-proof is accomplished.

On the other side, already today indications of a trend towards ambient intelligence are evident. While in the 1970s one computer served many users, and in the 1990s the personal computer served humans on a one-to-one basis, today more than one computing device serves each user. Peripherals which were rather dependent on central computing power a few years ago now contain powerful computing devices. This trend towards distributed electronic intelligence will likely prevail in the near future. Many interesting applications of 'Ambient Intelligence' are relevant in this context. They are feasible by today's technologies or need only limited innovation in sub-fields such as packaging or chip placement. They are based on existing hardware technology and may be products in 5-10 years. This is exactly the timeframe relevant for industrial research where those topics are investigated today.

Our research work strives for application demonstrators and technologies that enable semiconductor solutions for the technology lifestyle of the individual in the 21$^{st}$ century. Here, the individual is the subject whereas electronics is object. In some sense this represents a concept opposite to the one of 'Virtual Reality'. In the latter, the user is embedded into an electronic environment which gives inputs to his senses, in other words, he is controlled by the system and becomes object. The users of the targeted applications want to be served meeting their daily needs. They want an installation with an excellent interface between technology and user. Neither specific operation knowledge nor attention to the function of the appliance should be necessary. It is our vision to provide human individuals with means to enable the control of their surrounding, being assisted by highly-functional electronic appliances that operate invisibly in the background. In addition, other preconditions for the relevance of industrial research must be kept in mind. The potential market size must be above a certain minimum.

Our research heads for various aspects of application-oriented 'Ambient Intelligence':

Firstly, a low-cost wireless network is presented for ambient intelligence environments that creates the necessary link between the user and distributed electronics. Smart homes and hotel room infrastructures are among the first examples where this vision may become reality.

In a second project, we investigate chances for applications of smart RF ID tags that represent possible solutions for distributed intelligence. The prime challenge for those devices is the demand for extremely low cost which will demand innovation not only on the chip level but along the entire value chain.

An edutainment device for children is developed as an innovation study for a natural and intuitive computer interface. We intend to use this device as a platform to visualize innovations in this area.

Another project aims at electronics integrated into clothing. This represents nothing but another step towards portability which is envisioned after the successful introduction of notepads and mobile phones. We follow the idea of seamless integration of electronics into clothing.

Finally, a recently started project heads for providing sensoric and/or display functions distributed in regular grid, especially for textile applications. Security, guiding and surveillance functions will be provided by the technology developed in this project in 2D devices such as carpets, wall papers and various kinds of canvas covers.

## 2. Ubiquitous Sensor Networks

In the past decades progress in microelectronic integration has allowed an increase of the complexity of electronic appliances at constant cost level. This fact was used to extend their functionality (PC, TV, game consoles) which defined the added value of each new generation against the previous one. Little effort was, however, devoted to improving the usability of those highly functional devices which causes many of the new features to remain unused. Especially unsatisfying is the poor coupling between different appliances (how many buttons must be pressed to start a CD player?).

Here, we address the problem of interoperability of various appliances in our daily environment. We want to improve the interaction between the user and the technical devices. By an improved inter-device communication new applications become feasible to fulfill demands for more comfort, higher mobility and improved communication. Besides improved cooperation of existing devices in our daily environment new small components may be added to gather and exploit information on temperature, movement, humidity or light level. This information may be used to check whether windows or doors are closed or open and react according to weather conditions. The efficiency of appliances in the household may be improved, or inexpensive security or fire alarm systems in private homes realized.

Various standards have already been defined and are in use to connect appliances wirelessly on the physical layer such as Bluetooth (2), IEEE 802.11x (3), RKE (4) etc.. On application level it is, however, usually assumed that all devices possess a specific communication and control software. The Universal Plug and Play (UPnP) (5) concept goes into a different direction. It defines a universal language which allows the specification and control of various devices. Although this open standard supports an efficient and easy configuration of interdevice links, the technical realization is expensive and power-hungry. For this reason many small devices are excluded from integration into the UPnP network.

This project aims at an efficient networking solution for small appliances by integrating intelligent and inexpensive transceivers which allow wireless communication. Two types of devices are distinguished.

1. The *transceiver* is an inexpensive device whose power consumption is low. It has an input/output to receive/send information, e.g. from a sensor and an output for communication to
2. the *terminal*. This is a computer system that has high computing power and large memory (PC, Laptop, PDA, mobile phone etc.). It can communicate with the transceiver and takes over most of the software tasks in order to keep the transceiver as simple as possible.

In order to allow for a large variety of applications, the transceiver carries its own control application for the terminal through which it is controlled. Fig. 1 shows the schematics of a distributed system in which a terminal communicates with a previously unknown transceiver.

1. During initial communication both devices get in contact with each other in a 'discovery phase' using a standardized UPnP protocol.
2. If the terminal does not already carry the application software for the specific transceiver, the application code is downloaded from the transceiver. It is preferentially the code for a middleware platform such as the Java Virtual Machine, to integrate seamlessly into the system of the terminal (e.g. as part of a web browser).
3. Further communication between the downloaded so-called service application on the terminal and its counterpart, the transceiver control can then be completely application specific and needs not to follow any standards.

This system has significant advantages over existing solutions. Despite demand for only small memory volume and computing power an application level interface is provided. The architecture allows various hardware platforms. Moreover, depending on the service application code on the transceiver side a great variety of terminal applications is possible. This leads to a large variety of customer services which are easily and cheaply realized.

Although this technology specifies a methodology for the download of the transceiver application, the application itself is independent of it. This allows control of arbitrary transceivers largely independent of the terminal properties. Today's and future applications with increased complexity thus stay interoperable.

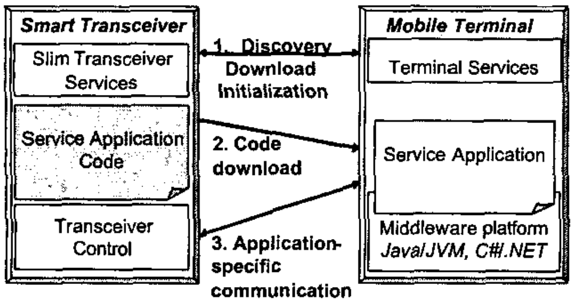



Fig. 1 Basic architecture of the communication between smart transceiver and mobile terminal

Due to the proprietary character of the communication between transceiver and terminal, error correction for secure operation in disturbed environments or encrypted data transfer for operation in secure environments can be installed.
The goal to embed the described concept into a series of existing protocol families using UPnP does not contradict those initiatives but causes a new field of application for them. Depending on the services provided, peer-to-peer networks can be created. Also multi-hop networks and inter-networks using bridges and routers can be formed. In the following, we present two examples for application of this technology.

### *2.1 Maintenance and control service for industrial and home appliances*

A first example for application of the ubiquitous sensor network is an improved service interface for home appliances such as a washing machine. The latter usually has a very simple display giving only a number which is sufficient for normal use but insufficient in case of malfunction. A mobile terminal connected to the washing machine through the sensor network can provide a more user friendly interface to the customer by providing sophisticated displaying features.

### *2.2 A ubiquitous personal sensor network*

Today, the user carries around a quite large number of different devices such as a cell phone, a wrist watch, a PDA and an MP3 player. Those devices are independent and cannot communicate with each other. An inexpensive link as presented above can enable new functions and more functionality for more user comfort. E.g. the wristwatch can be used as a remote display and control panel, the cell phone keypad can be used for other input functions than the ones of the mobile phone alone and the earphone of the MP3 player can be used as a generic audio I/O.

## 3. Distributed electronics

In the previous chapter a sensor network was discussed in which peripheral devices can be considered 'low-cost'. The one in this chapter must then be considered 'extremely low-cost'. Pushing the ambient intelligence concept to the extreme, let us consider a huge number of peripheral devices at extremely low cost level.
Today, the radio frequency identification tag (RF ID Tag) is already the smallest and least expensive electronic system on the market. It consists of a tiny (typically 1 $mm^2$) silicon chip embedded into a planar antenna structure which connects two contacts on the chip. Total cost is below 1 €. Neither external leads nor a battery are necessary. Both power supply and I/O are performed by the antenna. A reader device that emits electromagnetic waves at a specific frequency provides power and sends data that are modulated and sent back by the tag. The business of RF ID tags is rather limited, today. However, as the cost level is continuously reduced an increasing number of applications will become feasible. Applications competitive on a comparatively high cost level are baggage handling systems at airports or logistic systems for libraries. As the cost level goes down ticketing applications and electronic article surveillance systems may come into play and at extremely low cost level of about one cent the replacement of the barcode in food stores and warehouses may become feasible. The total number of goods produced each year by companies interested in tagging is about 500 billion (6). If those are tagged by a one-cent tag a business of 5 billion € arises.
Today a variety of technological concepts is under investigation and it is not decided which one will finally win the race for the visionary goal of a one-cent tag. In the following we will discuss two of them. First, a more conventional silicon-based concept is presented; then we turn over to the more innovative polymer technology.

### *3.1 Innovations in Si-based RF ID tags*

The contributions to the cost of a modern RF ID tag are to almost equal parts distributed over the chip, the antenna, and the assembly. Effort for price reduction will push the price of the chip down at a rate according to the productivity improvements to be expected from silicon technology of about 25% per year. The other two components will, however, require specific ideas and major innovation to similarly reduce the cost level.
In the following, we present a few such ideas.
Today, for assembly, RF ID chips are precisely aligned and placed face-down on a plastic foil that contains the two leads to the antenna. Here, we propose a chip with two sidewall contacts that facilitate the assembly process considerably (7). The process of formation of the sidewall contacts is as follows: frst the wafer with processed chips undergoes a sawing step with sawing grooves terminating at a certain depth. Then a sidewall oxidation is performed (Fig. 2, top right) followed by conformous metal deposition and etching to separate the two contacts on the chip. In this way, contacts are formed between the pads on the chip surface and the sidewall contacts. Up to this point, all process steps are performed on

wafer level which allows low production cost (Fig. 2, top left). The chips are now separated by grinding or etching processes. This geometry has major advantages during chip placement. The chip is placed on a bottom landing area which represents the first antenna contact. Its orientation and position can be arbitrary as long as one of the contacts faces the landing pad (Fig. 2, bottom). A rather inaccurate placement method will be sufficient as provided by future "shooting placers" which can place up to 100 000 devices per hour at very low cost but only a few hundred micron placement accuracy. The proper landing of the chip may be facilitated by giving it a rectangular form factor. The second contact can either be realized by top wire bonding or placement of a top contact ribbon (the latter is shown in the figure). Through this sequence of process steps for assembly a very low cost level will be achievable, suitable for a 1-5 cent tag.

Furthermore, we propose a way to reduce the size of the chip using ac-powered circuits. In other words, $V_{SS}$ and $V_{DD}$ are ac voltages. Logic gates are designed based on this idea and a system is demonstrated that shows the operation of this novel kind of circuits. Area consuming circuit blocks such as the rectifier, buffer capacitances, clock generator and (due to the data format chosen) power-up circuits are not necessary and thus abandoned. This concept leads to a system design with a silicon area of only 0.02 $mm^2$ for chips using a 128bit code word. Considering the area for the dicing lines the total area is around 0.04 $mm^2$.

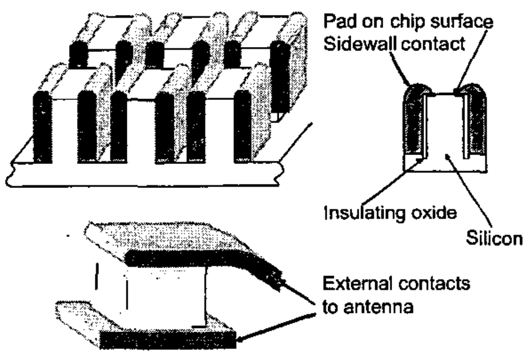



Fig. 2 Schematics of the proposed packaging concept. The top left sketch shows the final geometry on wafer level. To the right the process architecture of a single chip is shown. The bottom sketch shows the chip after assembly on a plastic foil with the antenna (not shown).

*3.2 Polymer electronics*

Whereas the use of a silicon chip and the placement into a preformed antenna structure still has some chances this method of system integration is complicated and has limited cost reduction potential. Plastic electronics may be the solution to the problem. It promises printing in a reel-to-reel process of the complete electronics using semiconducting polymers and of the antenna in one homogeneous line of processes. Specific placement and contacting processes are then obsolete. Direct application of that process to the consumer good without the use of an interfacing carrier is a long-term vision that may allow cost levels at or below 1 cent and the replacement of today's bar code even on extremely low-priced goods.

Although challenges for achieving this goal are still high, certain important steps were already accomplished. A functioning transistor device is realized on ordinary unfilled paper (8). This is an important prerequisite for the placement of polymer electronics on various surfaces, needed for the above-proposed application.

A complete ring oscillator on aluminized plastic foil is shown to operate at a stage delay of 650 µs (9). This substrate is used for food packages such as chips bags, tetra packs etc. and provides an opportunity to realize a low-cost antenna by simply removing material from the preformed aluminum layer (Fig. 3 a).

The third example realizes direct printing of the antenna together with the first metal layer of a polymer electronics process (10). This process is continued using lithographic steps. Functional devices result from this work.

The next example is a device with low operating voltage (2-3 V) as required in tag applications (11). This is achieved using a self-assembled monolayer of molecules as the gate dielectric. The thickness of the monolayer is only 2-3 nm (Fig. 3 b).

The last example is a 5-stage ring oscillator based on pentacene thin film transistors with a channel length of 5 µm on a flexible substrate. The design has integrated level-shifting and output buffer and achieves a frequency of 4.5 kHz that corresponds to a stage delay of 22 µs (12). This result is only a factor of 3 away from the value 8 µs required for an RF ID tag that operates at a frequency of 125 kHz. This is the lowest frequency used as a standard in modern tag applications (Fig. 4).

These examples demonstrate that quite a few milestones are already accomplished on our way to a 1 cent RF ID tag. Presently, those results are achieved only separately but need to be combined in one single system which shows that our way to go is still long and challenging.

Envisioning the rapid progress in productivity improvement of Si-based systems polymer electronics will never be able to replace silicon completely. The biggest effect on it will be through additional products used in reader appliances possibly starting a new phase of exploitation of Si technology in various applications of ambient intelligence.

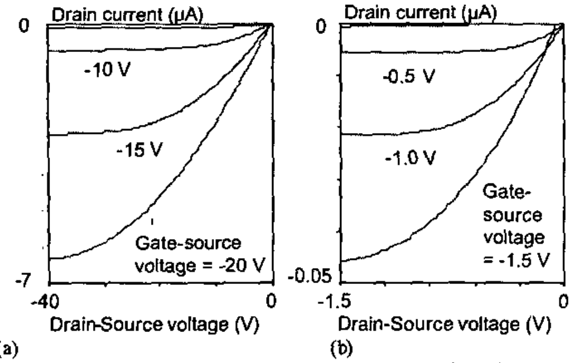



Fig. 3 Device characteristics of polymer FETs on an aluminized plastic foil (a) and using a self-assembled molecular monolayer as a gate dielectric (b)

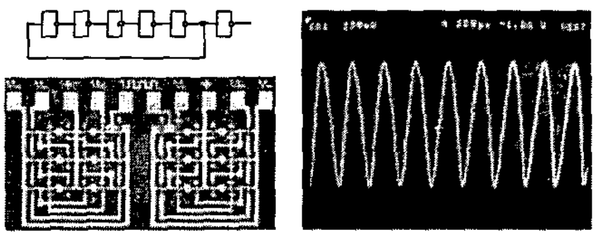


Fig. 4 Circuit schematics (top left), photograph of the circuits, and measured result of a ring oscillator realized by a polymer technology

## 4. Virtual personal tutor

The quality of man-machine interaction is key to exploitation of ambient intelligence. We envision a virtual personal tutor to be used by learning children. This device is inspired by the behavior of a human teacher and set up to interact naturally with the child.

In this way we depict future application for chip products, create a playful incidental learning environment and provide a natural human computer interface using speech recognition, a touch screen, and a display. The children will use the device intuitively without major training and simply have fun of action.

Children below the age of 5 often speak family-specific dialects and pose almost insurmountable barriers to speech recognition. Kids above the age of 10 usually want to have a full size computer. Thus, it is the age between 5 and 10 that appears suitable for our study. The software is adapted to the specific needs of this age using an animated agent, a tomcat, supporting voice browsing and single word recognition. An anthropomorphic agent would cause higher expectations and cause aggression in case of failing or misunderstanding. The use of the tomcat agent reduces this problem because users are more empathetic with pets. We realized a design study and demonstrator for a unisex casing suitable for children from 5 to 10.

In the near future we will demonstrate a solution in the field of 'context to speech' and plan case studies to clarify technical demands and challenges.

## 5. Wearable Electronics

Today, the interaction of human individuals with electronic devices demands specific user skills. In future, improved user interfaces can largely alleviate this problem and push the exploitation of microelectronics considerably. In this context, the vision of smart clothes promises greater user-friendliness, user-empowerment, and more efficient services support. Wearable electronics responds to the acting individuals in a more or less invisible way. It serves him in his needs thus making life much easier. We believe that today, the cost level of important microelectronic functions is sufficiently low and enabling key technologies are mature enough to exploit this vision. In the following we present various technology components to enable the integration of electronics into textiles. Key elements are a packaging and interconnect technology for deep textile integration of electronics, a silicon-based micro-machined thermoelectric generator chip for energy harvesting from body heat, and an interwoven antenna concept for RFID labels for the identification of textiles.

### *5.1 Interconnect and Packaging Technology*

An interconnect and packaging technology (13,14) is demonstrated using a polyester narrow fabric with several warp threads replaced by copper wires which are coated with silver and polyester. Six of those parallel conductive warp threads form one lead. For the electrical connections the coating of the wires and the surrounding textile material is removed by laser treatment forming holes as shown in Fig. 5, middle. A thin flexible printed circuit board (PCB) is then attached to the polyester fabric before the holes in the fabric are soldered. Then the module is encapsulated for mechanical protection. The complete unit is molded forming a hermetically sealed casing that protects it against mechanical and chemical stress caused by wearing and cleaning the textile (Fig. 5, left). As a demonstrator, a speech-controlled MP3 player system is realized which is based on a DSP/μC-two-processor system (15) (Fig. 5 right). The demonstrator system architecture shown in Fig. 6 is composed of four units, all connected via the conductive textiles: the audio module which is a miniaturized PCB containing the audio chip with several auxiliary elements, a detachable module containing a rechargeable Li-ion battery and a MultiMediaCard for data storage, an earphone and microphone module, and a capacitive keyboard module. The user can control the music player either by speaker-independent voice recognition or by means of the keypad. When integrating the proposed system into clothing,

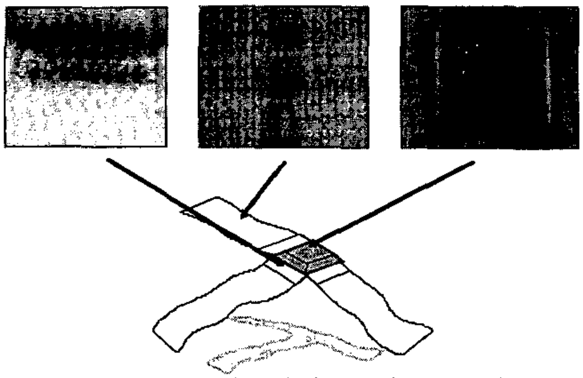


Fig. 5: Textile integration of electronic circuitry using a small printed circuit board that contains the electronic function (right). A polyester fabric is used with warp threads locally replaced by electrically isolated copper wires. The contact areas in the fabric are prepared by laser treatment (middle). For contacting a flexible printed circuit board is used. Finally the structure is encapsulated by a molding process (left).

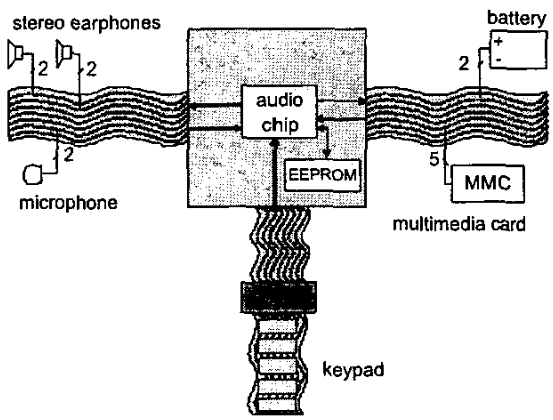



Fig. 6: Schematic overview of the system demonstrator. The core of the speech-controlled MP3 player is the audio chip described in (15).

special care is necessary for the textile design. The materials are chosen according to maximum wear comfort and environmental compliance. E.g., the audio module has been fully covered by garment, so that the wearer still feels a textile touch. The demonstrator system was designed into a jacket to demonstrate the technology (Fig. 7).

*5.2 Thermogenerator for Harvesting Electric Power from Body Heat*

Numerous wearable devices such as small remote wireless sensor units for medical applications dissipate only a small

Fig. 7 The speech-controlled MP3-player designed into a sports jacket.

amount of power. The human body produces several 10 W of heat energy. Miniaturized thermoelectric generators can harness part of this energy and convert it into electrical power. Most available thermogenerators are realized using compound semiconductors such as bismuth telluride. However, those are expensive, difficult to produce, and non-disposable. They will thus not be the optimal choice for low cost applications such as wearables. In line with these arguments, silicon appears to be a better choice. Fig. 8 (left) shows a technological cross-section revealing the micromachining technology (16). Recently, a chip with 16.000 thermocouples on a silicon chip measuring 7.0 $mm^2$ was realized. A quadratic dependence results for the output power versus the temperature difference $\Delta T$. In order to gain a large difference between body and ambient temperature a generator is integrated directly into the fabric of the clothes (17) with good thermal contact to the skin. It is found that an effective $\Delta T$ of up to 5K can be achieved. For this value an output power of 1.6 $\mu W/cm^2$ is obtained which is sufficient to power devices like a wrist watch or a heart beat sensor. Along the way to those applications technologies for good thermal contact, for hermetic encapsulation and connection to the electronic consumer device are developed (Fig. 8, right).

*5.3 Interwoven Antenna for a Transponder System in Textile Fabric*

RF ID tags (cf. section 3) are self-contained systems allowing a hermetically sealed package. This fact facilitates their integration into fabrics subject to harsh cleaning procedures.
For integration of RF ID tags into textile fabrics the concept of a transponder system with a woven antenna coil structure is proposed (14). Applications include the item management in laundries or in logistics supply chains, the protection of branded goods and security applications such as access

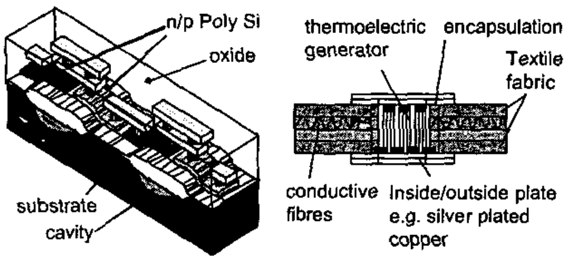



Fig. 8: Cross-section of a silicon-based micro-machined thermoelectric generator chip (left). The vertical heat flow generates a voltage within the junctions of n- and p-polysilicon. The schematic to the right shows details of the integration of a thermogenerator into the textile fabric.

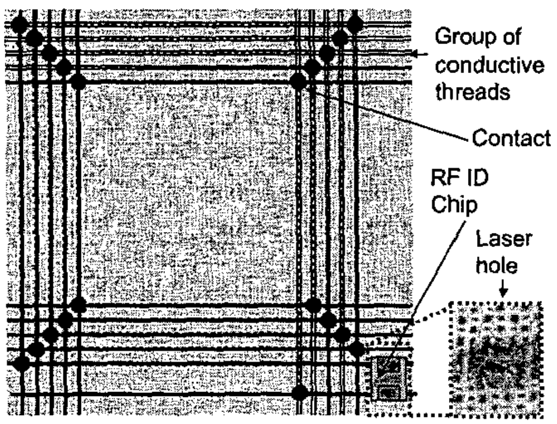



Fig. 9 Concept of a woven antenna structure for a textile transponder system. Conductive warp and weft threads are connected to realize a spiral.

controls. Due to the self-contained nature of RF ID tags they have excellent properties in withstanding elevated temperatures, pressures, chemicals, and mechanic stress. Existing RF ID antenna structures are not suited for the rough environment in textile applications. A conducting spiral can be realized by connecting orthogonally oriented conductive warp and weft threads in a fabric according to Fig. 9. By this means, the antenna structure is fully embedded into the fabric in an unobtrusive and robust way. The chip can be mounted by one of the integration methods described earlier.

## 6. Integration of Microelectronics in Smart Textiles

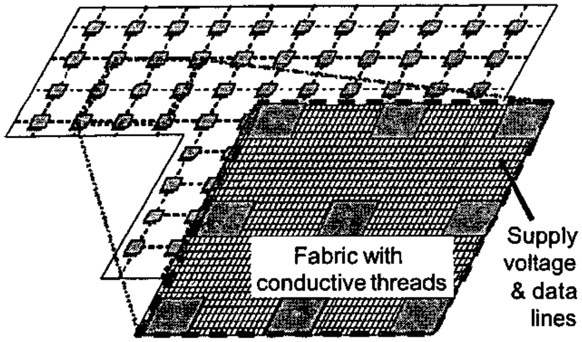
In the following, we present the concept of technical textiles containing active microsystems spatially distributed over the fabric (18). The variety of applications for such a system is huge: pressure sensors and display units in floor and wall coverings for surveillance or guidance systems in public buildings, intelligent sheets for monitoring vital signals of patients in hospitals, defect detection for condition monitoring in textile concrete constructions, and many more. Each of these applications poses high technical requirements regarding functionality, reliability, and ease and cost-efficiency of manufacturing.

The idea is realized by microelectronics integration in a coarsely meshed fabric. The fabric can be a basic or intermediate layer of floor or wall covering or any kind of technical textile. Figure 10(a) shows the schematic of an embedded network of processing elements in a textile fabric. A small microelectronic module is connected at the cross-over points of the wires. In this way, each module is connected at each of its four sides to the supply and data lines. After encapsulation, a smart fabric is realized featuring a regular grid of integrated microelectronics modules. For ease of use we invented a self-organizing technique based on simple locally processed algorithms (19). Small microprocessors on the integrated modules control the data flow. After an initial learning phase, each module in the fabric network knows its exact physical position within the grid. Moreover, the network automatically configures data flow paths through the grid, routing sensor or display information even around defective regions. Figure 10(b) shows the final status: the channels for data flow within the grid are established, automatically routing around defective regions.

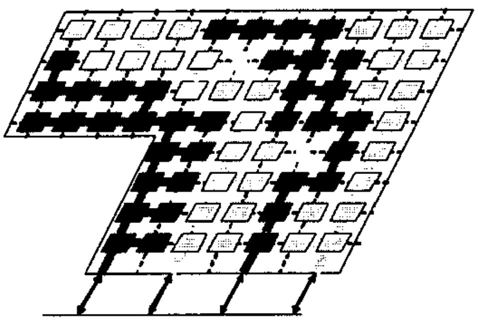
The unique feature of the proposed integration concept is its fault-tolerance: by means of a self-organization technique, the fabric network automatically recognizes defective regions. It therefore remains operational even if a microdevice fails, or conductive threads are damaged. The fabric may even be cut to arbitrary shapes to fit into a given room while maintaining its function. Moreover, due to the self-organization there is no need for a manual configuration of the grid microelectronics. Fig. 11 shows the photograph of a concept study of a smart carpet.

## 7. Conclusion

In this paper various technology demonstrators were presented which consistently aim for improving the interaction between the human individual and information technology. Although we focused on the application-specific technologies to be explored and developed, at this point we want to emphasize the challenges mainstream Si-based technology pose to technology innovation. Indeed the progress of the latter is not automatic. Major creativity and hard work are necessary to maintain a constant rate of progress in this field. It was the goal of this paper to show that this endeavor is worth the effort. The described projects may open the way to promising applications that may lead to completely new fields of application for microelectronic technologies in just a few years time.




(a)



(b)

Fig. 10 Schematic of an embedded network of processing elements in a textile fabric (a). Final status of the self-organization: the channels for data flow are established, automatically routing around defective regions (b)

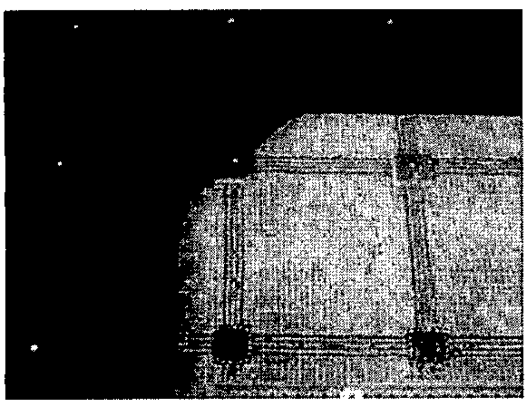


Fig. 11 Concept Demonstrator of a network of electronic units connected via conducting leads in the fabric

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