FUSE demonstrator document

FUSE Application Experiment EPC1 EU Nr. 24744

Monitoring TTN: IAM F&E GmbH, Braunschweig, Germany

Magnetoresistive Current Sensor

Mixed Signal ASIC doubles Turnover in one Year

Abstract

The market for current sensor systems is steadily growing in traditional application areas with an additional explosive growth in automotive and domestic applications. Current sensors are used in numerous applications. However, the main application domain is drive control, which is a central aspect of industrial automation. The sensors supply the information for the electronic to control axis position, angle, torque and rotation speed. Without the sensors no immediate feed-back from the drive e.g. on the load could be obtained and control would be less efficient.

The company LUST Antriebstechnik GmbH has penetrated the market with new sensor microsystems based on the magnetoresistive technology. Compared to traditional current sensor technologies these systems offer drastic savings with respect to weight, volume and costs. However the over 100 million US$ market is dominated by conventional sensors. The sensors are used for own products and sold to industrial automation companies, that supply drives and drive control systems as well as complete automation systems.

The standard sensor product family CMS2000, which is already well established in the market, will be replaced by new products, based on a Mixed-Signal ASIC for signal conditioning. The existing sensor families use conventional technologies like discrete components with a lower overall precision and a larger size. However, LUST already used digital ASIC technology in other products. The aim of the FUSE project was the development and integration of a mixed-signal ASIC to integrate the appropriate analog signal conditioning circuitry for the sensor chip, together with digital functions for the system calibration and EEPROM storage of calibration data via a serial interface. This establishes significant improvements in the production process together with savings in production costs and application benefits for the end user. The application benefits for the end user are true RMS current measurement and overcurrent detection. If required, a reduction in size of 50 % can be realized.

Other products of Lust are drives, inverters and complex drive control systems for various requirements and power ranges.

The FUSE experiment with a duration of 15 months assured the technology and know-how transfer by extensive training related to the definition, design and manufacturing of CMOS ASIC's. The subcontractor has experience and is specialized in high performance Mixed Signal CMOS ASIC design and manufacturing as well as in the design and evaluation of magnetic field measurement systems.

The transferred knowledge and experience enables the First User (FU) to develop and design a new family of current sensor products, which establish unique selling properties and will guarantee a pay back period of less than 18 month and a ROI of approximately 90% during the first year of application or of 450% for the estimated lifetime of five years. The profitability can be related mostly to cost saving of about 50 % that are mainly realized through the improvement of the calibration process of the sensor device. Moreover, the ability to use this Mixed Signal CMOS ASIC technology is fundamental for future projects intended to develop sensor systems with improved measurement accuracy and extended signal conditioning

functions.

Keywords: Mixed signal ASIC, sensor, current, drive control, inverter, microsystem, EEPROM, drift and offset compensation, switched capacitor, magnetic field sensing, current sensing, operational amplifier with high rejection mode

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1 Company name and address

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2 Company size

The total number of employees is 248, with 30 employees involved in the development of electronic systems and components. The company had an annual turnover of 23Mio. EURO in 1997.

3 Company business description

The main activity of the company LUST Antriebstechnik GmbH is in the field of electrical and electronic equipment for AC drive systems. The company develops, manufactures and markets frequency inverters in the power range of 375W to 200kW and, as a newly introduced product line, highly sophisticated AC servo controllers intended for the use with synchronous and asynchronous motors in the range of 2A to 60A nominal phase current. Additionally there are development, manufacturing and sales off sub-components, like sensor devices.

The drives, frequency inverters and servo controllers are sold worldwide through 15 sales offices and representatives in Germany and 24 sales representation in the world. This also includes the sub-components, especially the magnetoresistive sensors that are used with our own frequency inverters and drives but are also sold through OEM customers and to other manufacturers of atomization equipment.

Distribution channels for the sensors are meanwhile established world wide. The devices are sold through different sales and marketing organizations. Besides the acquisition of key accounts by LUST’s internal sales personnel, different European sales representatives and the well-established US company F.W. Bell, a division of Bell Technologies Incorporation, are working in customer acquisition and distribution. F.W. Bell, which is a manufacturer of Hall effect based current transducers, sells the sensor devices of LUST as brand label products within it’s world wide sales organization, with focus on the American and the Far East markets.

4 Company markets and competitive position at the start of the AE

The market for isolated current measurement systems or current transducers, as they are often referred to, has seen a steady and healthy growth process during the last decades. Today the total annual turnover for this market is approximately 100 million US$ for 10 million units, as a rough estimation. Figure 1 gives an estimated overview of the market share.

This volume, which is mainly realized by application of well-established sensor technologies like open and closed loop Hall effect systems and shunt measurement with analog or digital optocoupler isolation, is based on stable long term growth processes in the traditional markets. Among others, these markets are the industrial sector with the whole range of automation applications in general and the market for AC and DC drive systems in the power ranges of several Watts to several Megawatts.

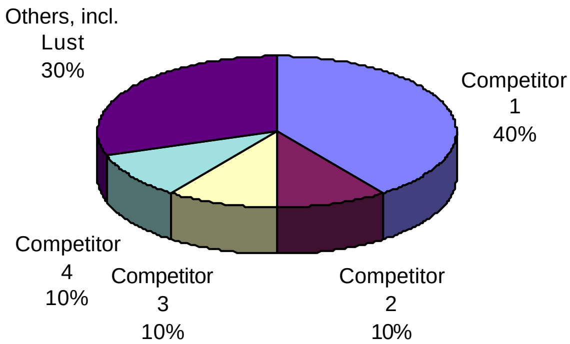

Figure 1 World wide market share for isolated current transducers (estimation)

In the past years the existing products with the conventional measurement scheme faced an ever increasing competition, resulting in the necessity to adapt the sales price (Figure 2).

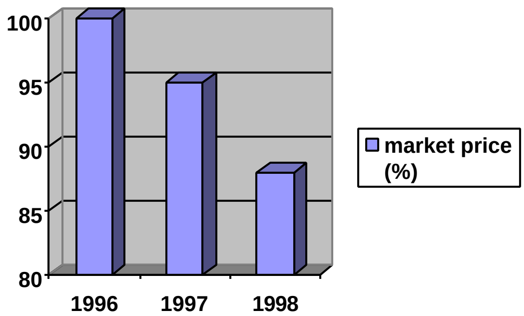

Figure 2 Development of market price for conventional current sensors

The completely new magnetoresistive current measurement technology of LUST is still in the stadium of being introduced into the market. This means that in 1998 the market share of LUST was less than 1% or 1 million US$, in Germany respectively Europe, as well as world wide. The sensor market typically is price sensitive. This was a problem with older magnetoresistive sensors, since the measurement electronic contributed significantly to the sensor costs. With a reduction of sensor costs however, it will become even more competitive since it is much easier to install than conventional sensors.

Typical prices of current sensors range between several hundred € for high currents and about 10€ for about 50 A. With the magnetoresistive sensor that has some clear advantages concerning mounting at a reasonable price within or below the current range, sales figures of 500.000 pieces are expected. Otherwise, with the current prices of the magnetoresistive sensor a stagnation at about 1000 pieces a year is expected.

In the near future an enormous increase of unit volume and turnover, some analysts expect doubling, is expected. This is due to new, aggressively expanding markets for current measurement like automotive and domestic applications and products for general purpose energy management. As a consequence, an explosion of device quantities is in sight, where the market share of the different sensor technologies will depend on their adaptability to high volume production processes. Besides the increase of unit quantities establishes the need for reduction of size and weight, as well as the simplification of the manufacturing processes, which is very obvious for automotive applications. This tendency will be accompanied by excessively decreasing market prices.

Today the market is shared by several manufacturers of such systems, e.g. LEM/Switzerland, NANA/Japan, Telcon/UK, Hewlett-Packard/USA, Honeywell/USA and Vacuumschmelze (VAC) GmbH/Germany, to name only some of the most important competitors. Most of them use the classical Hall technology. This technology is well-established in the market and is known to be reliable. The limiting factor for further shrinking in a microsystem manner is the ferromagnetic core used to concentrate the magnetic flux of the current carrying conductor. In any case, the core is needed in order to establish the appropriate level of field strength being applied to the Hall sensor device, which is mounted in the air gap of a ferromagnetic core. As a consequence, the use of the magnetoresistive sensor technology offers large advantages for the system design in new current measurement applications as well as to substitute conventional current sensor technologies in traditional applications with the goal to save weight and volume.

Concerning the drives and inverters, Lust is positioned as a German medium sized company with a market share of about 5%. There are about 50 companies in Europe, including several large companies like Siemens, Indramat, Bosch, Lenze, etc. in this extremely competitive market.

5 Product to be improved and it’s industrial sector

Within the conceptual phase of a new generation of servo controllers it turned out that isolated current sensors are one of the key elements for the design and control of the inverter power stage. At that time, the sensor devices available on the market did not sufficiently meet the requirements on the dynamic response, accuracy and, simultaneously, low profile and/or small footprint on the printed circuit board (PCB).

This initiated the development of a new current sensor technology. The „Institut für Mikrostrukturtechnologie und Optoelektronik (IMO)“ in Wetzlar, Germany, was identified as the adequate partner for a cooperation in the field of microsystem technology, especially for systems intended to measure magnetic fields and derived physical quantities. IMO is located in Wetzlar, very close to the main place of business of the LUST company in Lahnau in the Federal State of Hessen in Germany. Mr. Lust, the managing director and owner of the LUST Antriebstechnik GmbH, was one of the decisive cofounders of IMO with the aim to introduce and gain basic knowledge and expertise in the technological subjects of microsystem and sensor/actuator technologies.

The intensive research activities at IMO led to the development of a variety of magnetoresistive sensor chips which are capable of measuring magnetic fields and field differences for the detection of electrical currents.

Based on these sensor chips LUST developed a variety of standard current sensor devices. In this context the fundamental know-how and experience of LUST is related to the appropriate signal conditioning circuit design, packaging technology and marketing and sales activities.

In the meantime the sensor design and manufacturing processes are ready for series production of current sensors for internal use in the drive system products of the company LUST as well as for delivery of small and medium quantities up to several thousand pieces to customers on the global market.

Currently an optimization and automation of the production processes is carried out in order to prepare for high volume production in the range of several million current sensor units per year, especially in order to meet the requirements for delivery in automotive markets.

The current sensor family CMS20xx (**C**urrent **M**easurement **S**ystem 20xx, with xx specifying the nominal current range) is based on the anisotropic magnetoresistive (AMR) field sensing technology and is already introduced in inhouse applications of LUST as well as in a broad range of industrial customer applications.

The functional core of the current sensors is a thin film device called DSKx, where DSK refers to „**D**ifferenzfeld-**S**ensor mit **K**ompensation (differential field sensor with compensation)“ and x designates the chip design revision.

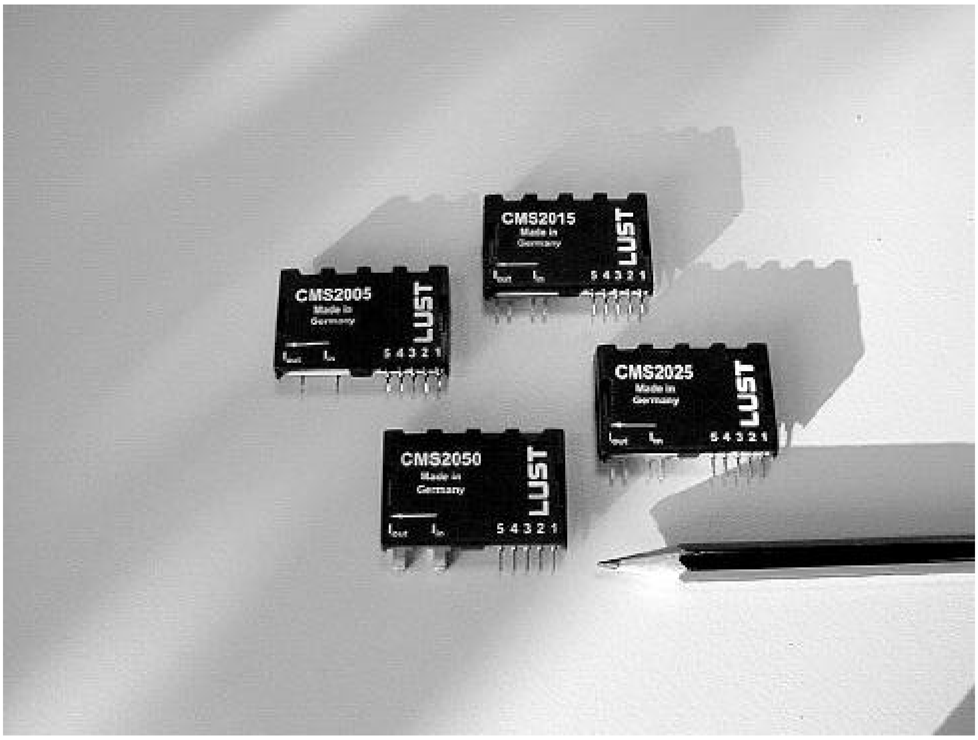

Figure 3 CMS20xx Current Sensors family. The nominal current measurement ranges are 5A, 15A, 25A and 50A.

The chip consists of a magnetoresistive Wheatstone bridge and an integrated, galvanic isolated strip conductor adjacent to the bridge resistors for purposes of magnetic field compensation. The bridge itself is formed by a combination of four resistors, each consisting of three individual magnetoresistive strips being connected in series. The layout of the magnetoresistive layer and connection of the strips forming the resistors is optimized for the detection of magnetic field differences across the width of the chip. Simultaneously the layout is designed so as to maximize the suppression of thermal phenomena (temperature variations and thermal gradients across the chip).

The current sensor family CMS20xx consists of four different types with nominal current ranges from 5A to 50A. A photograph of the latest generation of current sensors is shown in Figure . The total accuracy of the sensors within the industrial temperature range (-25°C to

85°C) is in the range of 1...2%, related to the nominal primary current output signal.

The sensor chip DSK4 and the peripheral signal conditioning circuitry are mounted on top of a thick film hybrid substrate. On the back of the substrate a copper bus bar is mounted by use of a special adhesive glue. The bus bar is U-shaped, the parallel legs of the U being located symmetrically to the width of the sensor chip.

The bus bar injects a symmetrical field gradient in the direction of the magnetic sensitivity of the sensor chip, with the field strength being zero in the middle of the chip area. Therefore, symmetrical positive and negative absolute field strengths are measured and compensated within the magnetoresistive areas on the left and right side of the chip by a discrete control circuitry. The compensation current is delivered by an operational amplifier with an additional bipolar driver stage, where the OPAMP tends to null it's input voltage by feeding back of the compensation current trough the sensor chip. As a result, the sensor chip is working at a single point of it's characteristic curve. This leads to a suppression of the relatively high temperature dependency of the magnetic sensitivity and the current sensor establishes highest accuracy and linearity. An illustration for the sensor operation principle is given in Figure .

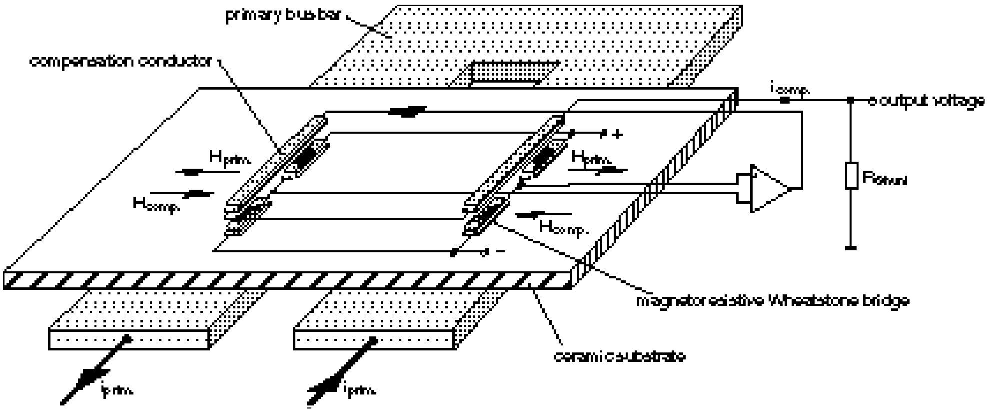

Figure 4 Operation principle of the current sensor CMS20xx.

This operation principle, which is already well known for traditional compensated Hall transducers with a ferromagnetic core and a dedicated compensation coil, is used within the CMS20XX sensor family in a microsystem realization.

A topographical map of the hybrid circuit is given in Figure 5. The ceramic material delivers a very high isolation voltage capability, which meets the requirements for galvanic isolation of the primary high voltage circuitry with the current to be measured flowing in the U-shaped bus bar and the low voltage sensor and signal conditioning circuitry. This is additionally supported with appropriate creepage and clearance distances being realized on the front and back side of the substrate and between the primary high voltage pins of the bus bar and low voltage pins of the output stage, respectively.

After mounting of all sensor system components, the transducers need to be calibrated due to existing manufacturing tolerances of the sensor chip itself as well as the system geometry, e.g. shape and placement of the primary bus bar and placement of the sensor chip. The functional calibration is carried out by a laser trimming process for several thick film resistors on top of the hybrid substrate (see figure 5).

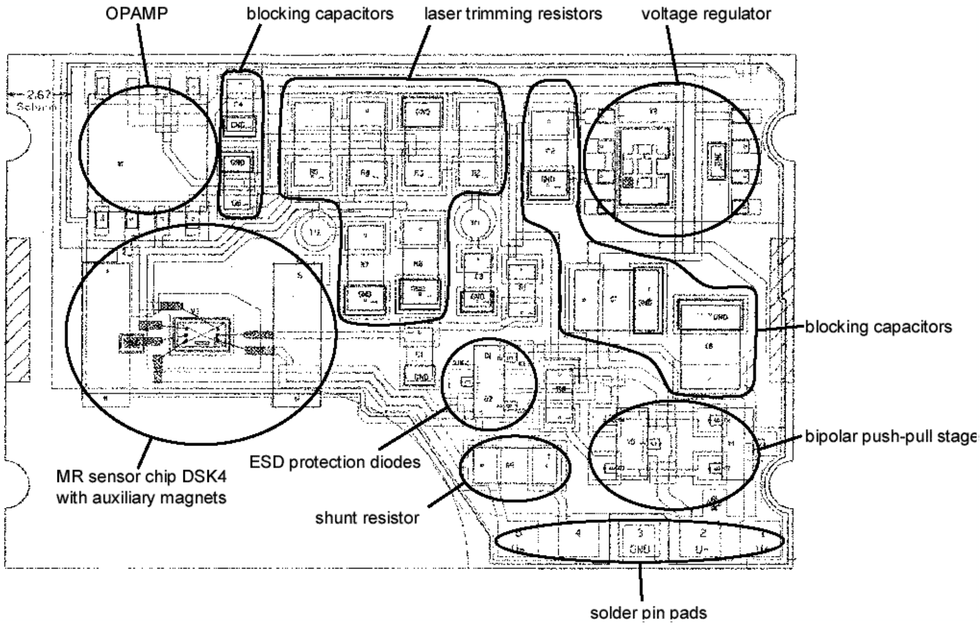

Figure 5 Topographical map of the CMS20xx current sensor hybrid circuit.

The current sensors are completed with a plastic cover that is labeled with the manufacturer information (type of sensor, manufacturer logo etc.; see Figure 3).

The project was intended to develop a compact low cost sensor system for use in all kind of current measurement applications that accomplishes the requirements for high volume production processes. For this, a 50% cost reduction for low current sensors is required. The main issue within this context was the availability of a completely integrated signal conditioning circuit.

The development project was focused on three main topics:

- Examination and choice of the appropriate packaging technology
- Specification, layout, design and prototype production of an ASIC with features closely adapted to the specific needs of magnetoresistive thin film sensors.
- Combination of the available sensor chips with the new ASIC for calibration purposes and functional testing of the current measurement system.

Besides the selection of an appropriate packaging and interface technology aimed to realize the smallest possible standard package outline, e.g. a dual inline (DIL) package, the design of the ASIC was of fundamental importance with respect to the functionality of the whole current measurement system.

Basically the new ASIC serves the purpose to replace the discrete SMD components which are used for the CMS20xx today. These are

1. A high performance bipolar operational amplifier with specific requirements related to (typical data, at $\vartheta_{ambient}$=25°C):
   - low offset voltage (V_{off}<300µV) and low thermal and long term offset voltage drift ($dV_{off}/d\vartheta$ < 1µV/°C and dV_{off}/dt < 0.01µV/month, respectively)
   - high gain-bandwidth product (GBWP>30MHz) and high slew rate (dV_{out}/dt>10V/µs)
   - High common mode rejection and power supply rejection ratios (CMRR>130dB and PSRR>140dB, respectively)
2. A bipolar transistor push-pull stage capable of delivering 25mA permanent compensation

current and 75mA pulse compensation current.

3. A bipolar voltage regulator
4. Diodes for ESD protection
5. Several voltage blocking capacitors
6. Thick film resistors for active laser trimming due to functional calibration of the sensor system

Furthermore, the whole laser calibration process for each individual unit, which today is performed by an expensive laser trimming system, should be replaced by data storage capabilities together with Digital/Analog converter functions, both internal to the ASIC. This was one of the most important topics due to both the high investment costs (>250.000,-EURO) for the laser trimming system together with it's role as a bottleneck of the manufacturing process with respect to approx. 20 seconds time consumption for the calibration of a single sensor system including electrical and mechanical adaptation and handling.

6 Description of the technical product improvements

The ASIC was designed to include EEPROM respectively One Time Programmable (OTP) cells for storage of the calibration information. D/A converter cells are used to transform the digital calibration data into analog voltage or current signals, which are injected in the amplifier circuitry. The calibration is realized by reference measurement with external high performance test equipment (a digital multimeter and a high precision current generator) and communication between the external calibration controller (e.g. a Personal Computer) and the ASIC via a serial interface. The investment costs for the test and calibration equipment including a simple rotation-table handling system for the new ASIC version of the sensor system as described above is less than 12.000,-EURO, such that the calibration may not only be done during manufacturing, but can also be adapted by larger customer. Obviously, this establishes the basis for flexible scaling of the manufacturing processes by implementation of multiple parallel calibration systems.

Extreme flexibility for adaptation to the sensor system behavior together with ergonomic handling of the calibration system should be established by use of the National Instruments software tool „Lab Windows CVI", which is intended for PC-based design of graphical test environments and control of measurement systems and equipment. The software tool runs under the Microsoft Windows 95/98 and NT operating system. It is based on a software development environment and toolbox together with a C/C++ programming language interface, but can be used to generate multiple stand alone runtime versions of the specific program to be used in the customer test application.

The human interface design can be kept very simple, so that the software may be handled by trained personal without extensive technical education. Furthermore, the data measured during the calibration of each sensor system may be stored and statistically evaluated for control purposes and improvement of the product quality.

Moreover, additional analog functions were integrated into the ASIC, which establish increased system functionality for the customer. In detail, these are

- True-RMS current measurement with user/customer-defined integration time by an external capacitor.
- Current-limit detection (open drain output) with user/customer-defined current limit value by an external resistor.

Today this new analog sensor functions cannot be found in current sensor systems of any competitor on the market, so that the ASIC gives rise to innovative system solutions that create unique selling properties for the product range of LUST.

Another important reason for the ASIC design was the need for single supply operation of new sensor products. Due to the tendency that supply voltages become lower and signal conditioning is realized by A/D-conversion and digital computation of the relevant system parameters, sensor device manufacturers must meet design requirements for operation of their products with a single supply voltage, e.g. 5 Volts, which is a common standard for digital supply voltages.

As a consequence, signal amplitudes become lower, so that signal amplification and conditioning should be realized on one chip. If this is not possible due to constraints for the sensor manufacturing process, the signal conditioning device (in this case the ASIC) should be placed in the immediate neighborhood of the sensor chip with short PCB interconnections. Related to electromagnetic interference, this is very fundamental in an extremely noisy environment, as it is often found in typical applications for current sensor systems, e.g. current measurement in power electronics.

In summary, the development of an ASIC with very specific functionality meeting the requirements for magnetoresistive sensor signal conditioning is very essential in order to develop a new competitive current sensor generation within LUST's product range. A functional diagram of the new current sensor system CDS30xx is illustrated in Figure .

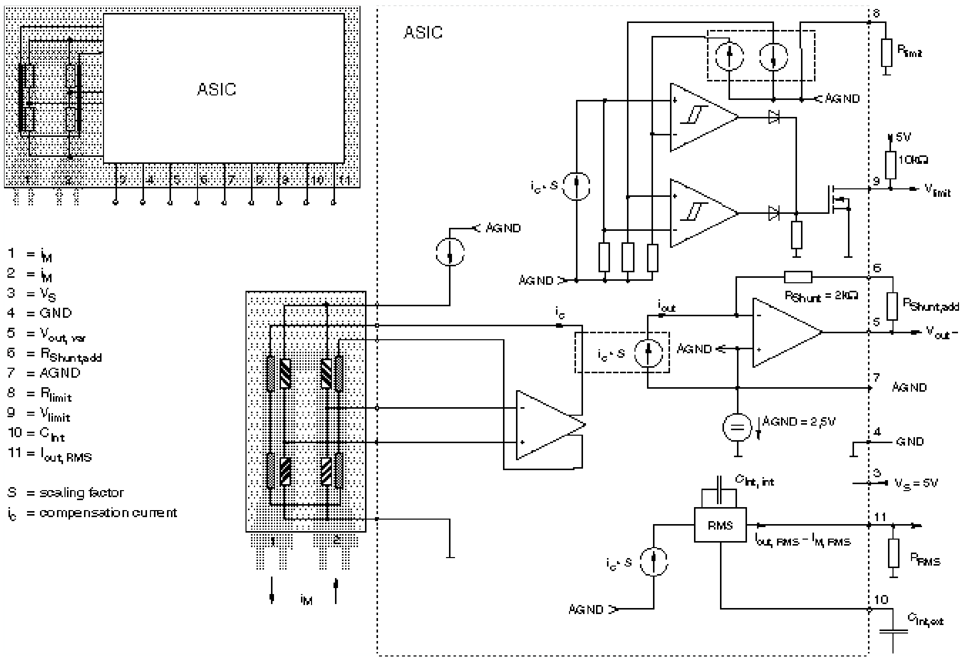

Figure 6 Functional diagram of the new ASIC-based current sensor system CDS30xx.

As a result, the ASIC designed during the FUSE Experiment (FE) together with a variety of available magnetoresistive sensor chips establish the basis for new current sensor microsystems with lowest weight and volume. This is due to the two-chip approach with a minimum of additional passive external components.

Figure 77 shows a photograph of the ASIC chip together with an indication of important function blocks. The dimensions of the chip are approximately 2.8mmx2.5mm. The ASIC is based on a 1.2 micron CMOS process with 47nm gate oxide thickness. This semiconductor process was especially selected with respect to automotive applications. It is very robust with respect to ESD and is capable to realize high voltage devices. Therefore it might even be supplied by and operated on the 12 Volt automotive voltage bus.

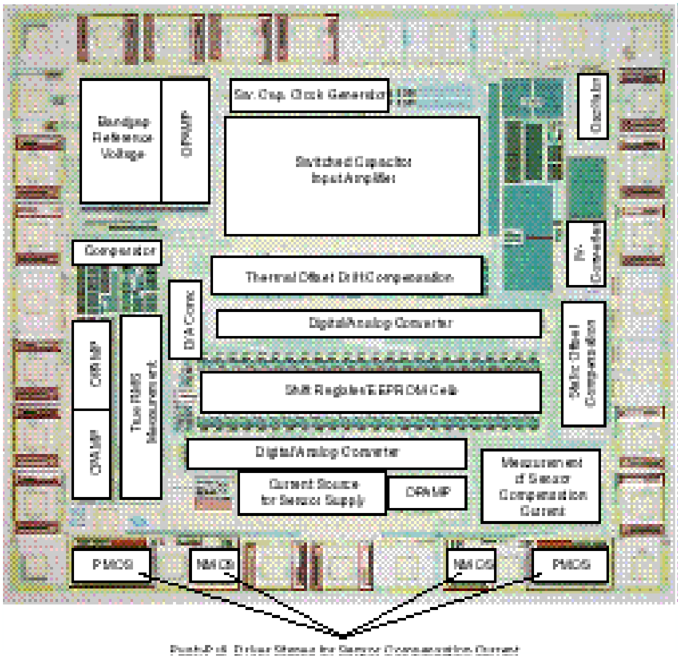

Figure 7 ASIC photograph with description of important function blocks.

LUST does not directly make use of the latter feature (the chip is solely designed for 5 Volts operation and supply) but first experiences and measurement results confirm the excellent EMV capabilities, which are essential in the above described target markets. Furthermore, the process includes single poly EEPROM cells, which are relatively simple to implement. The pin count for the series design will be 24 pins.

As can be seen in Figure 77, approximately 85% of the total chip area are consumed by analog circuit functions, whereas the digital part is only of minor significance. The ASIC is clearly a state-of-the-art high sophisticated analog CMOS circuit with the focus on excellent offset precision and highest accuracy related to the signal conditioning of very low sensor signals.

A photograph of the new ASIC based current sensor system CDS30xx, together with it's predecessor CMS20xx is shown in figure 8. The PCB area effectively used for active components on the hybrid substrate is significantly reduced. The minimum device dimensions in this package technology are mainly determined by the blocking voltage required to meet safety regulations for galvanic isolation (UL, VDE, ISO).

The new ASIC based current sensor system CDS30xx will have the same geometrical dimensions as the old CMS20xx family with the low voltage pin count being higher. But it will establish added value for the customer due to

- 5 Volts single supply
- analog output signal compatible to A/D converter
- user defined digital overcurrent detection signal
- user defined True RMS current measurement

The CDS30xx can be seen as a starting point. The two-chip solution of the magnetoresistive sensor chip in combination with the new ASIC has an enormous potential for further shrinking of new generations of current sensor microsystems.

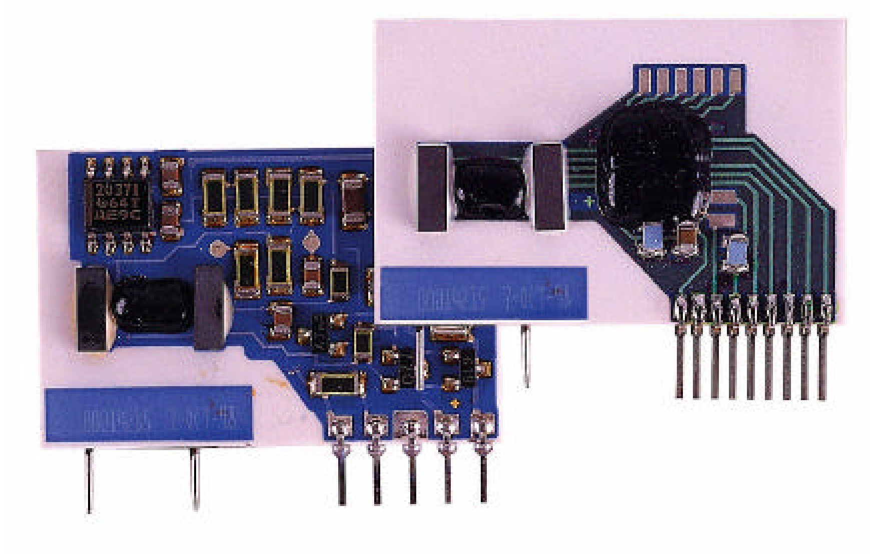

Figure 8 Photograph of the new ASIC based current sensor CDS30xx (right) and it's predecessor CMS20xx (left).

Feature	Existing product	New product
Calibration	Laser trimmed	(User-) programmed
Overcurrent detection	-	User defined
True RMS	-	User defined
Diagnosis	-	Through PC
Supply current	+/- 15 V	5 (12) V

Figure 9 Comparison of features

7 Choices and rationale for the selected technologies, tools and methodologies

At the beginning of the project different strategies for the implementation of a mixed analog and digital signal conditioning circuitry were investigated and compared to each other.

7.1 Combination of commercially available analog and digital circuits

Although a large variety of such standard devices, often with specifically optimized performance and parameters, is offered by several manufacturers, they do not meet the requirements for the total system:

- The analog device(s) must establish excellent stability with respect to offset and offset drift, together with the capability do drive a bipolar compensation current with 75mA maximum amplitude at 5V supply voltage. The latter feature requires two high current push-pull stages, which should be integrated with the high performance OPAMP(s) on a single chip. Furthermore, additional OPAMP's are required for the compensation of static offsets and temperature related offset drift.
- Related to the measurement, respectively current-to-voltage conversion, of the compensation current no additional shunt resistor is acceptable in the compensation current path. This is due to the limited supply voltage and the relatively high resistance of the compensation conductor being part the sensor chip. Therefore a special concept for the compensation current measurement task must be realized.
- Beside this basic features, the analog part has to include a high accuracy reference voltage section.

- The digital device(s) must deliver the appropriate serial interface to an external calibration station. It has to contain several digital/analog converters (digital potentiometers) for the calibration functions and, furthermore, has to include EEPROM cells for calibration data storage purposes.

Although specialized analog and digital integrated circuits are available for some of the above mentioned tasks, the total system would require a complex combination of such circuits. Therefore the system would have to be realized by a combination of SMD packaged devices, eventually with function that are not used but have to be paid for with device pin count, PCB board space and unit costs. Even if it is possible to find the devices providing all required system functions on the market, the total system costs, system volume and system PCB area would exceed the acceptable limit. The goal for an extremely compact microsystem integration of new current sensors would not be reachable with this solution.

7.2 Mixed Signal Application Specific Integrated Circuit (ASIC)

As described above, the technical system requirements for the signal conditioning and calibration functions are very specific. Additionally the expense budgeting for new sensor products demands a low cost single chip solution. These considerations lead to the decision that the solution for the given task solely could be an ASIC, namely realized by a low cost CMOS technology.

Within the technology comparison stage at the beginning of the FU the usage of a bipolar process for this ASIC was considered due to it's excellent analog signal conditioning capabilities. But it turned out relatively early that due to the given limitations with respect to digital functionality this would be out of the question.

BiCMOS processes, as a further option, were crossed off the list due to their inherently increased wafer manufacturing costs, which would result in higher chip size related costs.

The CMOS ASIC was defined to include all required building blocks for power supply of the sensor chip, for signal amplification and conditioning (including true RMS measurement) and for the creation of a reference voltage. This was specifically a concern for the single supply system operation. Furthermore, it had to be capable to directly drive the compensation current for the sensor chip. Additionally, the ASIC has to deliver protection functions with respect to external electromagnetic interference (EMI).

The extraordinary requirements for low offset and low drift for the ASIC are met by appropriate circuit design with switched capacitor methods, alternating operation of dually implemented parallel amplifier paths including alternating offset elimination for each amplifier path. This is due to the fact that the ASIC is realized in CMOS technology, which does not inherently meet high precision performance for analog functions.

Additionally, a very fundamental consideration was the fact that the CMOS technology in general is driven by high volume semiconductor applications like DRAM memories and microprocessors/controllers with special focus on chip size shrinking. This establishes the basis for future cost reductions.

Due to missing experiences with Mixed Signal ASIC design, LUST cooperated with a subcontractor, the „Fraunhofer Gesellschaft, Institut für Mikroelektronische Schaltungen und Systeme (FhG-IMS)“ in Duisburg and Dresden, Germany.

For the design the CADENCE design system and the SPECTRE Mixed Signal simulator were used. The basic analog design was done using HSPICE. Some system simulation was done with a tool named ANSYS. In the project mathematical models of the sensor chip had to be evaluated. For this the tool MATHEMATICA was used.

For high volume series production the ASIC manufacturer ELMOS in Dortmund, Germany operates a semiconductor fabrication, which includes processes being compatible with those of the IMS. Therefore the important second source manufacturing requirement can be fulfilled.

8 Expertise and experience in microelectronics of the company and the staff allocated to the project

Currently LUST develops, manufactures and sells a standard product range of current sensors as described previously. With respect to the drastically growing need for high precision current measurement systems, especially in automotive applications, LUST plans to increase it's annual turnover in such sensor products accordingly to the overall growth of these current sensor markets. This requires the development of advanced sensor products, which will consist of new standard as well as application specific implementations. The development will be mainly driven by cost reduction requirements.

Trough the last years LUST has gathered extensive knowledge on the production of current sensor systems based on the magnetoresistive effect. This is due to the design of application specific sensor chips as well as to the design and development of discrete high performance signal conditioning circuitry for operation of these chips.

The sensor system technology is based on

- thick film hybrid circuit design and manufacturing,
- placement and mounting (soldering) of SMD components,
- bare chip die- and wire-bonding,
- adhesive bonding of mechanical components (ferrite magnets, copper bus bars) and
- active laser trimming.

Furthermore, an important aspect is the development of the specific packaging technology which must be capable to meet the requirements of

- electrical isolation given by international standards and laws,
- thermal management and
- adequate mechanical mounting of the system in customer applications.

The project was carried out by three staff members of LUST's sensor division, who have a degree in electronics or microelectronics engineering. Two of them (one of them being the project manager and author of this report) took part in the subcontractor training on ASIC design and development. They mainly worked on the definition and specification of the ASIC and supported the subcontractor within the ASIC design process, e.g. with contributions to the system simulation and low level circuit design. The third person worked on the development of the PC-based LabWindows software required for automated digital calibration of the new ASIC based sensor system. Furthermore, testing of the ASIC prototypes in a special test environment as well as in the designated sensor system was carried out by these three staff members.

Beside this team, an additional employee with a degree in physics took part in the project. He had a consulting function related to the overall sensor system design, functionality and packaging technology with a special focus on requirements from the market.

Up to the time this project was carried out, the developers of LUST had no experience in the design and usage of Mixed Signal ASIC technologies.

9 Work plan and rationale

The original working plan for the project was based on the assumption that two Multi Project

Wafer (MPW) production runs (design and one redesign) would be required for realization of the ASIC with all functionality being defined during the early specification stage. The time schedule reflecting this original working plan is given in Figure 10 (see page 14).

During the project it turned out that due to the excessive time consumption for the specification and design of the analog part of the ASIC the production of two MPW's including the ASIC with solely analog functionality was better adjusted to the project flow. This was due to the fact that the analog functions of the ASIC had to be looked upon as the critical path. Therefore early test results were required in order to assure the feasibility of a CMOS based ASIC for high precision signal conditioning of magnetoresistive sensor signals in conjunction with high power current drive capabilities.

Therefore a third MPW run had to be included into the project sequence. This MPW run included a realization of the ASIC with full analog and digital functionality.

As a consequence, the project encountered a time delay, which is illustrated in the updated time schedule in Figure .

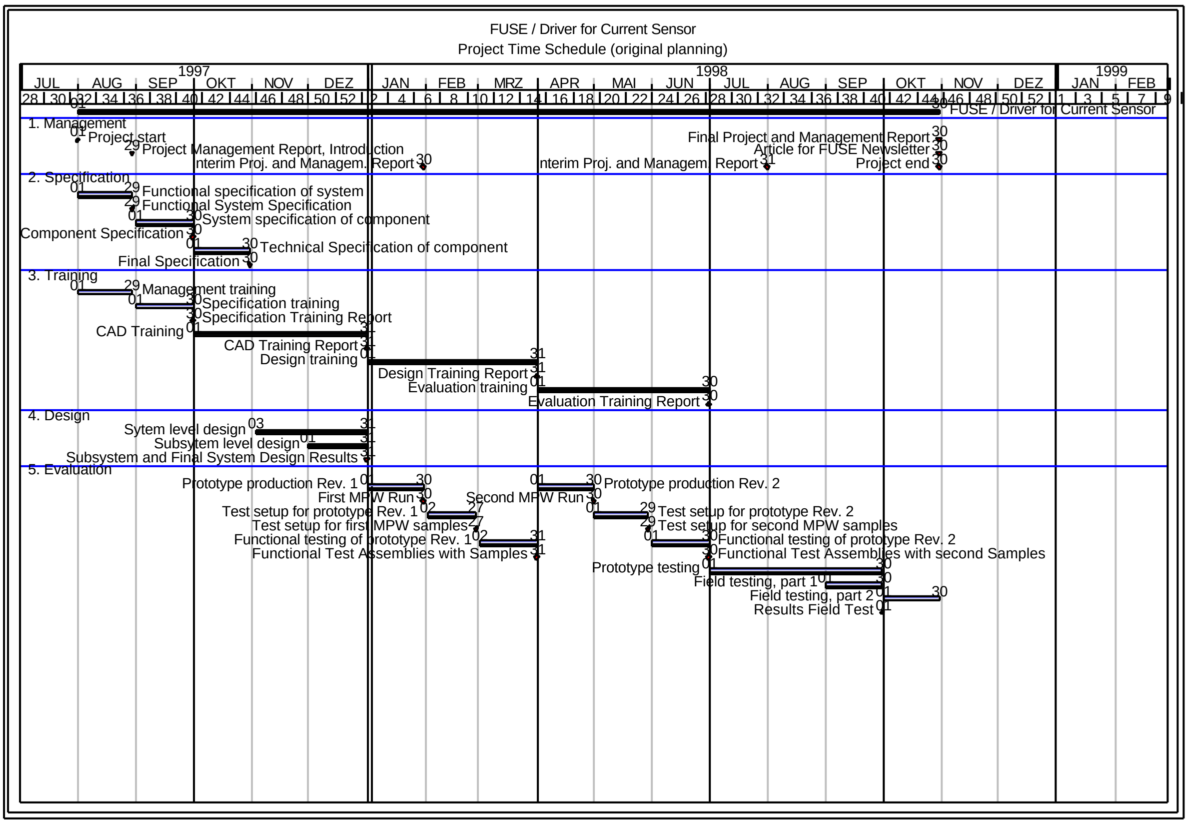

Figure 10 Original project time schedule.

The effort for the different project stages is given in Table 1. It is related to the real costs being caused by the delayed time schedule given in Figure .

Table 1 First User and subcontractor effort

	First User, amount of work (hours)	Subcontractor, costs (ECU)
1. Project Management	239	2.500,-
2. Specification	624	7.500,-

3. Training	448	9.800,-
4. Design	919	28.700,-
5. Evaluation	450	22.333,-
Totals	**2680**	**70.833,-**

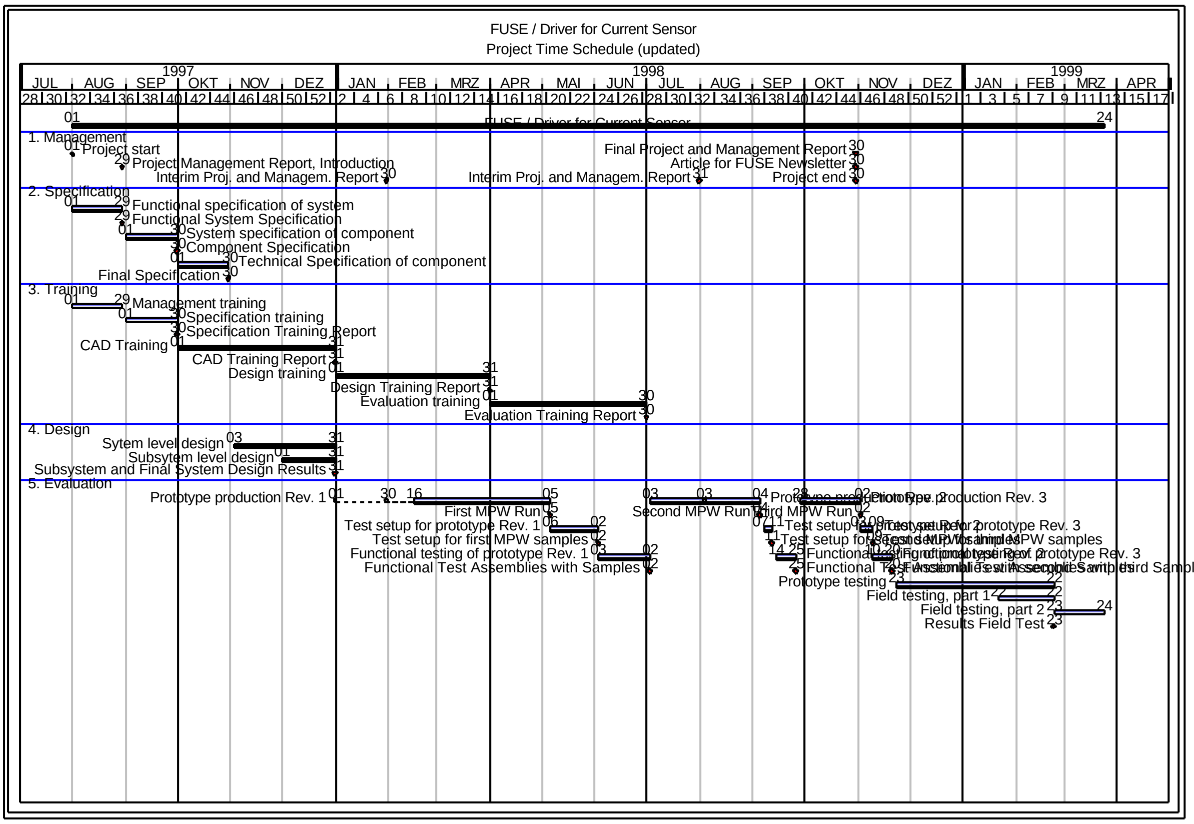

Figure 11 Updated project time schedule.

The contributions to the different project stages were shared between LUST and the subcontractor:

9.1 Project Management

- Technical and economical project management
- Project scheduling
- Management of contractual issues
- Project monitoring and documentation
- Dissemination and marketing

The project management work package was dominantly carried out by LUST.

9.2 Specification

- Definition of new sensor system products and resulting requirements for the ASIC
- Selection of the appropriate ASIC CMOS process
- Specification of analog and digital interfaces to the sensor system

- Specification of the test and evaluation environment

Based on close cooperation between LUST and the subcontractor the specifications lead to a technical specification document describing the system functions, user and sensor interfaces and technical parameters of the ASIC. The document was worked out in an iterative process during several project meetings and Email document exchange between both project partners.

9.3 Design and Training

- Analog system level design and simulation including the behavior modeling for the magnetoresistive sensor chip based on a mathematical implementation
- Analog and digital circuit design and simulation of the Mixed Signal ASIC
- Circuit layout of the ASIC
- Design verification by extraction of the simulation parameters from the actual ASIC layout and re-simulation of the device and system

LUST was involved in the design flow and introduced it's knowledge concerning the sensor system behavior and modeling. In this manner, the analog design was strongly influenced and controlled by LUST. This was accomplished due to carrying out most training seminars in the subcontractor facilities on the occasion of the actual design and simulation work. Therefore the staff members of LUST were able to gain deep insight into the design process of a Mixed Signal ASIC and to influence important decisions with respect to the circuit performance and functionality.

The knowledge transfer was accomplished by means of basic training and by training on the project. LUST supplied the basic information and did part of the design. Towards the design backend more and more work was done by the subcontractor (like layout) but the work done and the decisions were explained and discussed with LUST.

9.4 Evaluation

- Manufacturing of the ASIC in three MPW runs with different circuit revisions
- Fabrication and assembly of sensor system prototypes based on thick film substrates for bare chip die- and wire-bonding of the ASIC and the sensor chip
- Implementation of the calibration software and digital function testing
- Verification of the analog technical data of the ASIC and of the complete sensor system
- EMI and EMC measurement and testing in „real world" applications of the sensor system

The evaluation work package was carried out by intensive cooperation of LUST and the subcontractor. Again LUST contributed the knowledge concerning the intended sensor system performance and behavior. This was accomplished by a realization of prototype systems being physically very similar to the existing series type sensor system. This assured the direct comparability of the measurement results to the well known „state-of-the-art" being established by the old system generation. The subcontractor itself conducted all tests of the ASIC using a simple test environment based on only a few passive components to model the sensor chip. This had the advantage that unintended physical phenomena of the sensor chip could be suppressed for evaluation of the pure technical parameters of the ASIC.

The EMC testing was of fundamental importance due to the intended application of the current sensor systems in an extremely „noisy" power electronics system environment. Measurement results were directly fed back into the analog and digital design of the ASIC in order to establish high level immunity against electromagnetic interference.

9.5 Project deviations from the original planning

The following reasons contributed to cost and effort deviations between the original planning in the „Technical Annex“ compared to the real project flow. More detailed and specific information was given in the monthly monitoring reports. Comments are only made for deviations of more than 5000,-ECU.

- **work package 2 - Specification**

The specification process for the mixed-signal ASIC caused more effort than originally planned due to extreme requirements for the analog system functionality, e.g. static offset and thermal offset drift as well as EMI requirements.

Further on, new solutions for new system functions, which shall deliver added value for the customer and establish unique selling properties for the product range of LUST, took more time for specification than estimated.

- **work package 4 - Design**

The same observation as for the specification process applies to the ASIC design process. More effort had to be spend due to the complexity of the analog part of the Mixed Signal ASIC. The design process was widely accompanied by detailed involvement of project staff members of LUST.

- **work package 5 - Evaluation**

The total costs for the evaluation work package could be reduced trough direct co-operation of personnel of LUST and the subcontractor by bundling of training seminars, project meetings and evaluation work.

9.6 Risk analysis

Especially with analog circuitry there is a significant risk of not meeting the design objectives. There always is a risk of insufficient gain, drift, noise or other shortcomings of the analog part, which can not be precluded from pure simulation. Therefore, the typical design process is iteratively, i.e. a number of chips need to be produced and gradually refined. We expected to need two MPW production runs (which actually was not enough) and later decided to use the MPW service until the chip would meet the design objectives.

10 Subcontractor information

Main subcontractor selection criteria have been experience in the application domain (sensors) and immediate access to a semiconductor process. Additionally, the options for small volume and later high volume production series have been considered. A relative geographical proximity was also considered.

The subcontractor IMS, that was eventually selected, consists of two separate divisions. The older one is located in Duisburg in the federal state of Nordrhein-Westfalen and essentially works in the field of development and manufacturing of Mixed Signal CMOS devices, SmartPower circuits, analog FPGA´s and high temperature CMOS circuits.

After the reunification of eastern and western Germany, the IMS founded a second subsidiary in Dresden, in the new federal state of Sachsen. This part of IMS predominantly works on the development of ASIC´s in commercial and industrial sensor applications like the CMOS one chip camera. Further on, IMS Dresden has experience in the design of components for magnetic measurement such as flux-gate sensors and integration of Hall sensors into standard CMOS processes. This fact was one important criterion for the choice of IMS Dresden as the appropriate subcontractor.

The ASIC developed within this FUSE project was designed by LUST and IMS in Dresden, whereas the later MPW wafer production was carried out by IMS in Duisburg.

The fact that the silicon foundry for production of the ASIC is part of the subcontractors facilities proved to be helpful during the design and evaluation process. The response time for questions concerning the detection of manufacturing errors and analysis of CMOS process related implications to the sensor system performance has been relatively short.

The subcontractor's application experience for conditioning and processing of analog magnetic and optical sensor signals was fundamental for the successful closing of the project. Their knowledge on switched capacitor amplifier implementation and related questions on stability and noise were essentially helpful to find the appropriate circuit design concept.

Concerning contractual matters, clear responsibilities and interfaces between LUST and the subcontractor have been agreed on. The knowledge transfer and frequent project meetings have been fixed in advance. However, there has to be a general confidence in the subcontractor, because the in-deep knowledge that would be required to thoroughly control the subcontractor may only be a result of such a FUSE project. It proved to be valuable to draw control criteria from the application domain and not from the technology domain. The contract stated a fixed price, to be paid according to the work accomplished as handed over to LUST.

11 Barriers perceived by the company in the first use of the AE technology

At the beginning of the project LUST had little experience concerning Mixed Signal ASIC design and it's implications, advantages and shortcomings. Resulting from this status a variety of questions presenting different kinds of barriers were discussed.

11.1 Knowledge and technology barriers

The sensor division staff of LUST was already familiar with discrete circuit design and simulation, but had only little knowledge of low level IC design, especially with respect to high performance analog functions. As a logical result one of the first questions was whether there would exist any adaptable discrete IC solutions already available on the market.

Furthermore, the project staff had no detailed knowledge on technological aspects, e.g. what would be the most appropriate technology (bipolar, BiCMOS, CMOS).

Prior to this project no direct contacts with IC design centers and wafer fabs were established, so that LUST missed fundamental experience in the terminology and working methods of this electronics business segment.

11.2 Cultural and inertia barriers

The company LUST as an innovative manufacturer of electronic drive systems has long experience in circuit design including the application of discrete integrated components. Therefore the psychological barrier to start an ASIC development project was relatively low.

Nevertheless, at the beginning of the project LUST was relatively new on the sensor market. As a consequence, the development of such an ASIC contained both strategic (is the ASIC what the market needs?) and economical risks.

11.3 Financial barriers

The financial effort for the development of an ASIC and a new product family based on this ASIC is relatively high. This is especially true because of high initial costs related to the circuit design and fabrication process of the ASIC. Therefore the commitment for high volume production of new products including the ASIC was essential.

The related financial risk is enormous for a medium size company like LUST. The total cost for the development of the ASIC and the later costs for series production, including costs related to packaging and test, had to be evaluated.

The situation was further complicated by the initial uncertainty concerning the market situation. This included the need for estimation of the economical benefit for the improved product compared to the old product based on discrete circuit design.

12 Steps taken to overcome the barriers and arrive at an improved product

12.1 Knowledge and technology barriers

Prior to the project start a number of ASIC design houses were contacted. The contents of the project and related requirements were presented and each of these design houses delivered an offer including development costs and series costs of the later ASIC, based on a rough estimation of the chip area. As a result a decision matrix was created including all relevant information concerning prices and development competence. The latter was a result from oral discussions and the documented offers including suggestions for the Mixed Signal ASIC realization. It turned out that although bipolar processes are predestined for high precision analog integrated circuits, the intended digital calibration functionality could not be realized in a pure bipolar process. Therefore, only CMOS solutions were taken into account.

The specification document for the ASIC was defined during several project meetings with the subcontractor. Starting with a very rough description, the ASIC functions were then step by step refined by means of system simulation and rough estimation. Within this process it was essential to start with the most critical (analog) ASIC parameters in order to be able to prove the feasibility of the project as early as possible.

Related to the fact that analog circuit design is well practiced by LUST Antriebstechnik GmbH in standard frequency inverter and servo amplifier applications with discrete design solutions (already involving integrated circuits commercially available), the design of an ASIC offers complete new perspectives and enables new degrees of freedom for design considerations. Consequently, for the project team members of LUST it was of great importance to get rid of thinking in conventional and known design approaches. This fact required some effort not to block new and unknown design solutions and methods.

Otherwise, the monolithic design approach with the chosen manufacturing process sets certain limitations which had to be learned and accepted by the design engineers.

The method chosen to overcome the „conventional thinking“ was the formulation of system specifications and operational needs for the sensor chip as the system key element regardless to any low level IC design approaches.

12.2 Cultural and inertia barriers

An external consultant was hired to complete the information already available on the potential new markets opened by the modified product including the ASIC. Market data was collected and analyzed in order to define the required functions for the ASIC and the overall sensor system.

Although the costs for the consultant were not covered by the project funding, it turned out that the consideration of this marketing issues was essential for the success of the development project.

12.3 Financial barriers

The above mentioned activities for studying of market share and market valuation in conjunction with contacts to potential customers for new current sensor product resulted in the realization that automotive applications will be of great importance in the future. The market research activities ended up in the recognition that a substantial market for current measurement systems with steadily growing quantities and turnover can be expected and will justify the effort for the ASIC development project.

The uncertainty concerning the market situation together with the limited financial resources of LUST as a medium size enterprise, which were the most important barriers against starting an expensive ASIC development project of this order of magnitude, could therefore be overcome.

The cost situation for high volume production was of great importance for a well-founded decision. The subcontractor IMS disclosed the chip area calculation and after a comparison of the technological capabilities of the processes the CE12 CMOS process was identified as the suitable option with respect to technical and economical requirements.

13 Knowledge and experience acquired

Fundamental knowledge for analog CMOS circuit design has been revealed by the subcontractor. This is especially due to

- the use of professional IC design environment (e.g. the CADENCE design system and SPECTRE Mixed Signal simulator in a UNIX operating system environment),
- the principles for high precision operational amplifier design that meet respectively overcome the limitations of the CMOS technology,
- the limitations and restrictions due to technological aspects (temperature range, noise, offset, thermal and long term drift parameters etc.),
- the methodology for „debugging“ a circuit layout, e.g. with respect to thermal offset phenomena,
- the importance to consider specific design rules related to the chosen process and
- the work sequence of micro electronics development (design, 1st MPW run, redesign, 2nd MPW run), where in this special case the first run was reduced to only analog functions due to the above mentioned reasons.

We expected to acquire basic knowledge on identifying possible applications for the new technology, to evaluate its economic potential, as well as to plan the project, select suitable subcontractors and evaluate the outcome of the subcontractors work. All goals have been met, and even more, LUST now is capable to plan and partly execute its own mixed signal ASIC projects.

14 Lessons learned

The participation within this project led to a variety of learning effects, which may be summarized as follows:

- The complexity of Mixed Signal ASIC design in general was realized and understood, with a focus on „mission critical“ analog process parameters.
- The importance of regular and early information exchange in the company and with the subcontractor, e.g. by regular project meetings and design reviews during all project stages (work packages) became clear.
- The requirement to identify important process parameters, which establish the critical path with respect to the later application of the ASIC, became clear. Further more it could be realized that „real world“ test in the designated application can avoid flawed circuit design, especially with respect to environmental influences (thermal, EMC and EMI).
- The importance to have intermediate test steps to validate the concept and decide the

next steps was recognized and accepted. As an example, during the project it turned out that originally planed functionality had to be altered due to technical limitations and new economical objectives.

A final perception of the project was to realize that some misunderstandings and design errors could have been avoided in case that the project engineers of LUST would have spend more time in the subcontractors facilities. Although the subcontractor owns extensive knowledge concerning the CMOS process itself, the preferable circuit design and the design rules for the special process, it turned out that the operation conditions of the later system can (and must) have severe influence on the actual design! This shows the importance of a close cooperation with a subcontractor, which however requires a sound basic knowledge.

The knowledge about this conditions, e.g. thermal coupling mechanism and EMI, must be supplied by the customer as early as possible and has to be reviewed during the complete development process. „Real world“ tests in the customer application should be carried out as early as possible. This also requires a close cooperation of all partners in the project.

15 Resulting product, its industrialization and internal replication

A new generation of single supply current sensors realized in the standard hybrid technology will be introduced to the market at the beginning of the year 2000. The systems will be named

- the CDS30xx family including all system features and
- the CMS30xx family with only the minimum linear current measurement feature and smaller package outline.

Furthermore, several customer specific projects are under way to implement high sophisticated solutions with respect to packaging, weight and system integration. Among others, several automotive customers are interested in these new solutions. The first specific products will be available in course of the year 2000.

A first customer project that was already started for the development of technology demonstrators and prototypes provides an example on the tasks to industrialize the sensor device. The background of the project comes from a new concept for an integrated starter and generator system for automobiles, which is called Camshaft Starter/Generator (CSG). A prototype of this system was presented to the public by the Mannesmann-Sachs AG on the occasion of the „Internationale Automobilausstellung IAA“ in Frankfurt in September 1999. It included two magnetoresistive current sensor systems fabricated by LUST, which are based on the new ASIC. The sensor systems are part of a control box, which contains all necessary digital control circuitry together with the power inverter electronics. The system will establish the basis for new 42 Volts power supply configurations needed to cover the electrical power demand for innovative new generations of automobiles.

The inverter drives a high performance synchronous AC machine being directly attached to the camshaft of the motor. The sensors are packaged in a dual inline SMD configuration and are directly mounted on a PCB. The primary conductor carrying the current to be measured is part of the customers power bus bar. Due to the resulting tolerances in mechanical placement and mounting, this application makes use of the ASIC’s serial calibration interface and calibration data storage capability. The final system calibration within the CSG fabrication process is accomplished by communication between the internal microcontroller of the CSG and the ASIC.

Series production of this special version will not be established before the year 2001 due to the time cycles for introduction of completely new technologies are relatively long in this kind of business. On the other hand, the projected turnover volume in terms of unit quantities will become very high (e.g. 500.000 pieces a year).

With the positive experience from the FUSE project concerning shrinkage of weight and size new standard sensor products are planned by LUST. These will use mixed signal ASIC technology and also shall introduce special packaging technologies, which will incorporate state-of-the-art technologies like flip-chip die-bonding. As a result, it may be possible to bring new SMD mountable current sensors into the market, which will establish new perspectives for current sensing.

The new ASIC is a key element for such new standard systems, because it offers the possibility for two-chip sensor system integration in plastic packages with only a few external passive components.

As the above described facts show, the ASIC development project can be described as very successful with respect to the technical and economical aims that were reached. Cost to industrialize ranges from a few kECU for systems where an existing sensor needs to be replaced to possibly several ten or hundred kECU if the device needs to be adapted to specific requirements.

16 Economic impact and improvement in competitive position

To discuss the economic potential of the sensor system with the new ASIC it is important to understand the various application areas and markets for such devices. The variety of potential markets for magnetoresistive sensors can be classified in four main application areas:

16.1 General purpose current sensor applications

- Inverters (measurement of phase and DC-link current)
- Switching power supplies
- Solar Technologies
- Robotics
- Automotive (power and energy management for automotive systems)
- Electrical powered vehicles

16.2 Low voltage applications

- Shunt replacement
- Solid state relays
- Intelligent terminals and remote monitoring devices
- Bi-metal sensor replacement
- Thermal overload fuse replacement and overload and overcurrent detection devices

16.3 Power measurement and energy management

- Battery energy management (power monitoring)
- Watt meters in a wide range of applications
- Measuring different types of power (apparent, relative, etc.) as well as the power factor

16.4 Safety applications

- Monitoring of control systems (e.g. signaling lights)
- Elements for meeting and maintaining safety regulations

- RPM monitoring
- Stationary equipment monitoring
- Automotive applications (e.g. ABS)
- Uninterrupted power supplies

Besides the above mentioned the sensor system also can be used for other applications as an isolating and/or coupling device up to a bandwidth of approximately 100 kHz. First engineering studies show excellent price/performance ratios e.g. for current to voltage transducers and isolating amplifiers.

16.5 Market potentials

The market potential mostly results from the added value for the customer that are lower product costs and improved functionality, especially resulting in a reduced mounting effort and new application domains for the sensor.

Based on a market survey, LUST decided in August 1996 to invested more than 1,5 Million EURO in a complete clean room facility for manufacturing the sensor systems in an automated production line. This also includes the latest technologies like die- and wire-bonding. Also Multi-Chip-Modules (MCM) can be assembled locally by the end of 1999.

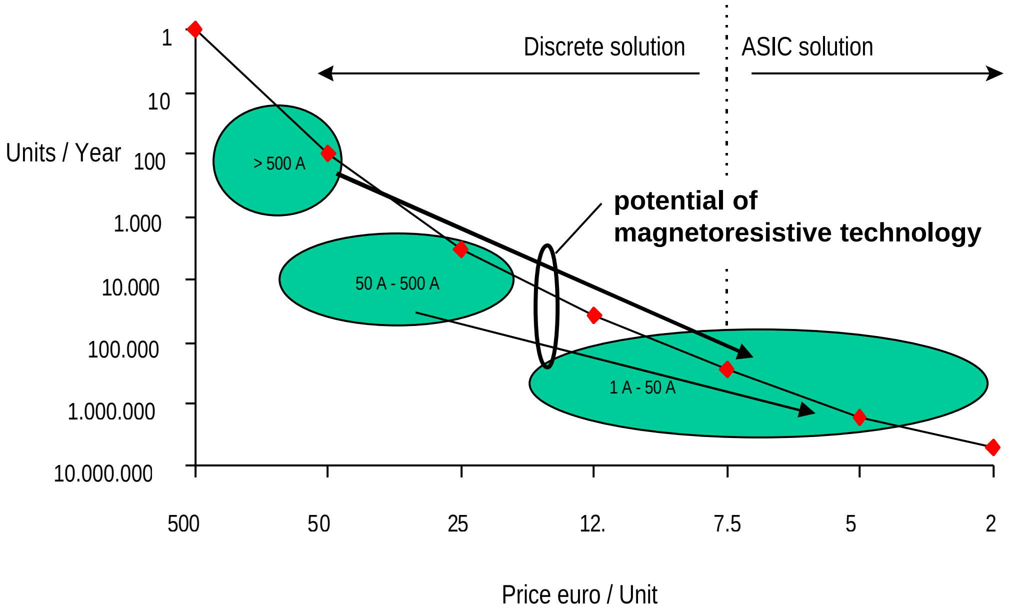

Figure 22 Projection of sales quantities with respect to nominal current ranges and pricing. The two arrows indicate the potential of the magnetoresistive technology to shift traditional high current/low quantity/high price applications into regions of low prices and extraordinary high turnover and unit quantities.

At the moment the first CMS200xx generation of current sensors is produced at LUST's facilities in Lahnau. As already described, it is a thick film hybrid based technology using discrete SMD components. However the potential to reduce costs in production is limited to the amount of components and the effort for the manufacturing process. Further cost reductions would mean to reduce the performance, which is not possible due to the competitive situation compared to other solutions available on the market.

On the other hand, the new technology allows to design components which are of significantly smaller size compared to the competitive parts. This advantage can be even greater if it is possible to combine the sensor element with the Mixed Signal ASIC in smaller packages with improved specifications at lower prices. With sensor costs less than that of the standard CMS20xx system, new application areas open up where at the moment current measurement is not implemented because the costs for the required sensor systems are too high. As only one important example we would like to mention current measurement in wall socket outlets or remote power readings in households to establish intelligent power management systems in local or wide areas, remotely controlled.

The investment for the improvement of the existing sensor amounted to 250 k€. However, with the improved functionality and especially the reduced production costs of over 50%, the investment is well justified. A large percentage of the cost reduction is related to the automated calibration process that only became possible with the new technology.

The overall growth potential of current sensors as a function of price is shown in Figure 2 on page 233.

16.6 Marketing strategy and economic impact

The marketing strategy therefore can be described as follows:

- sell the available magnetoresistive current sensor in conventional hybrid technology
- introduce ASIC (Plan: pre-series production at the end of 1999) in new CDS30xx system
- introduce new products with state-of-the-art packaging:
  - Multi Chip Modules (MCM, including the sensor chip and ASIC) based on conventional hybrid (ceramic) or PCB solutions with chip-on-board technology
  - MCM's in plastic/SMD packages

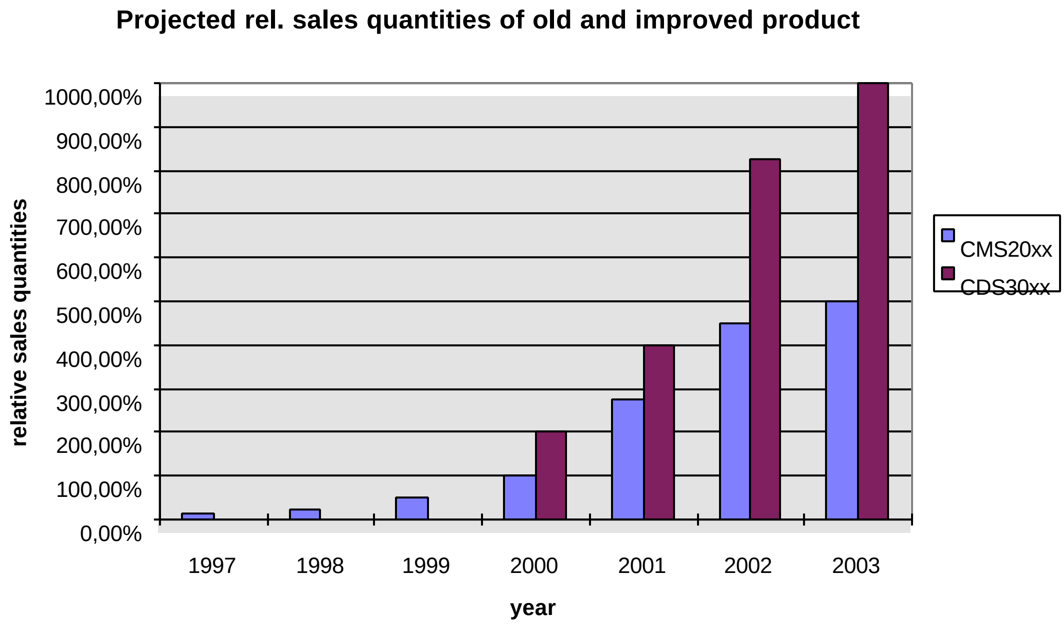

Figure 33 Projected relative sales quantities of the old product (CMS20xx) and the new improved product with ASIC (CDS30xx).

Figure 33 shows a projection of the relative unit sales quantities of the old CMS20xx product compared to the new ASIC based sensor system CDS30xx. It reflects the fact that only with the new technology the sensors price can be reduced to 2.5 ECU (for some applications) and that a suitable price is a prerequisite for wide market acceptance.

Based on these estimated quantities a projection of the annual Return On Invest (ROI) for the first four years of selling the new CDS30xx system, related to the costs of the ASIC development project, is shown in Figure 4.

As a result, a payback period of approximately 18 month is estimated. The overall return on investment for an estimated product lifetime of 5 years is over 1000%.

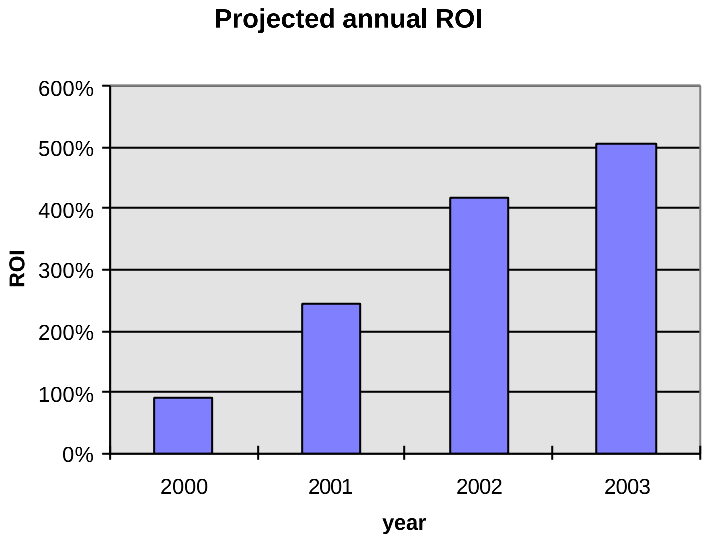

Figure 44 Projected Return On Invest (ROI).

17 Target audience for dissemination throughout Europe

The contents of the above described ASIC development project will generally be interesting for all companies being involved in analog and digital circuit design and application of related components.

The functionality of the Mixed Signal ASIC may be applicable to other sensor products, even if the physical effect these sensors are based on may be quite different. Due to the assumption that the ASIC will be a mass product, the chip costs will be low enough for applications in price sensitive markets.

Partial redesign for different sensor applications of third party sensor system manufacturers may be accomplished by contractual agreement with LUST but will require development time and significant cost effort.

The results of this project may be of interest for the following industries:

- sensor system manufacturers in general
- manufacturers of industrial instrumentation and transducers
- industrial automation system manufacturers, especially for drive systems
- automotive suppliers; automotive manufacturers
- manufacturers of electric and electronic household installations
- microsystem manufacturers in general

This document may especially provide information to any company in the domain of industrial automation with sensor products that need an additional signal conditioning. In general this is the PRODCOM code 3110 class ‘Electric Equipment’. LUSTs experience shows that mixed signal ASICs are a suitable technology for certain applications and that a project can be handled with limited risk.

The project shows a good practice of sound analysis of the product state before innovating and the definition of objectives for the improvements of the product. An important aspect is to base the initial planning on the application experience (in this case current sensors) and only later to introduce technologies, such that the selection of a suitable technology actually is the outcome of the design process.