Passive SAW Based RFID Systems Finding their Way to Harsh Environment Applications

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***Abstract*—While CMOS (Complementary Metal Oxide Semiconductor) transponders clearly take the lead in the high volume markets, SAW (Surface Acoustic Wave) transponders continuously develop in niche applications for special industrial needs. Based on a completely different physical principle, SAW transponders draw their potential for harsh environment applications from their inherent temperature stability, radiation hardness and their low energy consumption. Obviously, SAW transponders for harsh environment are no low cost solutions and are therefore used for tracking of high value industrial goods and additional sensor telemetry like temperature sensing. The present work explains aspects of SAW transponder design to meet harsh environment specifications for temperatures up to 400°C. This includes the improvement of interdigital transducer stability through an Al/Ti sandwich structure, packaging aspects and robust metal antenna designs. An overview of application examples is given for heavy industries like steel production, oil and gas exploitation and automotive varnishing lines. Finally, a research outlook for high temperature RFID (Radio Frequency Identification) solutions will be given targeting applications at 600°C and higher.**

Keywords - Passive SAW transponders, SAW RFID system, harsh environment, wireless sensor

I. INTRODUCTION

SAW based RFID systems exist for a while now. One brand is the “SOFIS” from Siemens. It is a system mainly used for railway applications with references back to 1995 [1]. Among other applications it is for instance installed in the wheelset diagnostic system in the Eurotunnel, France/UK. The “OIS-W” system from Baumer Ident (now Identec Solutions) is another SAW RFID system among the first systems on the market. It specializes on car varnishing lines and was one of the first transponders with a specified cycling temperature up to 200°C [2]. One of the first drawbacks of SAW RFID tags was the limited code size. This issue was addressed by RF SAW, Inc. with the proposal of a global SAW ID Tag comprising a 128-bit tag platform, realizing a 64 bit EPC tag including anti-collision, multi-level error detection and other features [3]. While SAW RFID systems outperformed CMOS RFID systems until the early 2000's in terms of range, this is not the case anymore through the development of UHF (Ultra High Frequency) systems, which have a range up to several meters necessary in logistic applications. CMOS RFID transponders have the major advantage of being programmed during operation. Further they have the possibility to run communication protocols and encryption algorithms. Last but not least CMOS RFID transponders are very price competitive due to the economics of scale. Although CMOS transponders are established in many industrial logistic applications there is a number of interesting harsh environment niches for SAW RFID transponders and it is the intention of this work to show the technical progress of these systems and their key applications done at Carinthian Tech Research AG. Section II presents the basic principle of SAW transponders. In Section III, typical specifications for harsh environment are discussed and necessary SAW transponder adaptations are explained to meet these specifications. Harsh environment applications that were supplied in the past few years are presented in Section IV. Section V concludes and gives an outlook on future research targets in the field.

II. FUNCTION

A RF interrogation signal is transmitted by a transceiver and picked up by the antenna of the passive SAW transponder. The interdigital transducer (IDT) converts the received signal into a surface acoustic wave by the converse piezoelectric effect. The SAW propagates towards reflectors distributed in a characteristic barcode-like pattern and is partially reflected at each reflector. The acoustic wave packets returning to the IDT are re-converted into electrical signals by the IDT and re-transmitted to the transceiver by the transponder antenna. This response contains information about the number and location of reflectors as well as the propagation and reflection properties of the SAW. Common transceiver concepts to read out SAW RFID transponder are FMCW (frequency modulated continuous wave) or FSCW (frequency step continuous wave) radar designs in the open ISM band at 2.4 GHz. The bandwidth of 80 MHz in this band allows for a reasonable resolution of the transponder response. The acquired frequency domain data from the CW radar are converted in a time domain signal using inverse fast Fourier transformation (IFFT), where the pulses caused by each reflector are further evaluated according to the code design [4]. There are various ways to implement a code design in a SAW RFID transponder. A pulse position code as shown in Fig. 1 was developed [5]. Each reflector is assigned to a time slot in a digit block. Each of the n blocks can contain m different reflector positions resulting in m^n different codes.

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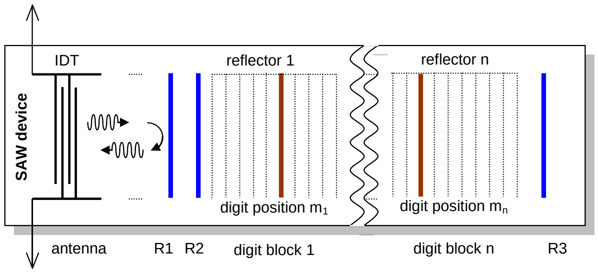

Figure 1. Pulse position code of SAW RFID transponder.

The reflectors R1, R2 and R3 are fixed and are used for optional temperature measurement. The SAW RFID transponder is processed on YZ-cut $LiNbO_3$ (LN YZ) due to its high electro-acoustic coupling coefficient and large TCD (temperature coefficient of delay) of -95 ppm/°C for temperature telemetry.

III. HARSH ENVIRONMENT SPECIFICATIONS

In industry "harsh environment" is a general term to describe working conditions, which are more stringent than what is considered as "normal". For this reason a detailed specification is needed for the exact working conditions. Generally, elevated temperatures and/or pressure in combination with mechanical abrasion, heavy shock loads or vibrations are to be considered. Some applications use high radiation doses or cryogenic temperatures. An exemplary overview of some typical harsh environment specifications is given below in Table I.

TABLE I. OVERVIEW OF HARSH ENVIRONMENT SPECIFICATIONS

Application / Industry	*Specification*
Tracking/Tracing of investment goods /steel industry	Temperature: 200°C – 300°C Long read ranges of several meters Mechanical collision, steel/slag splashes
Identification of slide-gate plates / steel industry	Temperature: 200°C – 380°C Shock loads and mechanical collision
Drill pipes / Oil and Gas	Temperature: 250 °C Pressure: 1300 bar Range: 0.5 m
Varnish line / Automotive	Temperature: 220 °C cyclic Range: several meters
Annealing of light alloy rim / Automotive	Temperature: 150°C - 540°C(max) Range: < 1 m
Autoclaving	Temperature: 200°C Pressure: 12 bar Saturated steam
Sterilisation (Gamma)	Food sterilization: 10 kGy Medical sterilization: 50 kGy
Cell banks / Life Science	Temperature: -196°C Range: 10 cm – 20 cm

In addition to harsh environment specifications of the transponder system specifications have often to be taken into account. Due to the hot environment reader antennas are exposed to temperatures exceeding 100°C. Often long RF cable lengths have to be installed as there is no space for reader electronics near to the reader antennas. Another practical problem is the heavy RF pollution of the ISM band in industrial environments. The SAW transceiver being limited to 10mW EIRP according to EN300440 contributes very little to this RF pollution. A typical industrial environment also contains a lot of metallic surfaces causing multipath propagation of the RF signal and even unwanted resonances. In some cases precaution has to be done using shielding or attenuation means.

IV. RUGGEDIZED SAW TRANSPONDER DESIGN

Generally, SAW devices are mass produced for the telecom market, but consequent cost optimizations lead to devices which are not suitable for harsh environment. Necessary adaptations are concerned with IDT metallization, packaging and antenna design, which are described below.

A. IDT Metallisation

Annealing experiments revealed that a single Al/Ti stack with a thickness of 50 nm degraded within 450 hours at 300°C [6]. The observed agglomeration is known to start with the Tammann temperature, which is defined as half the melting point of the bulk material (expressed in Kelvin). The thermal stability of the IDT metallization was significantly enhanced by putting two Al/Ti stacks (sandwich) on top of each other (Fig. 2). The Al/Ti sandwich has a total thickness of 70 nm and results in a tenfold better thermal stability.

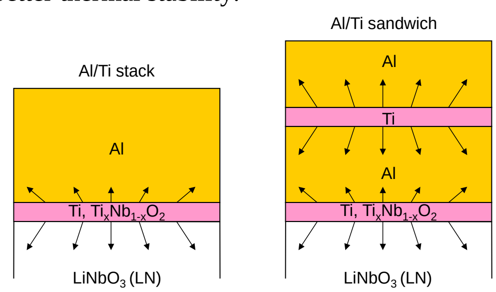

Figure 2. Scheme of the Al/Ti and Al/Ti sandwich metallisation.

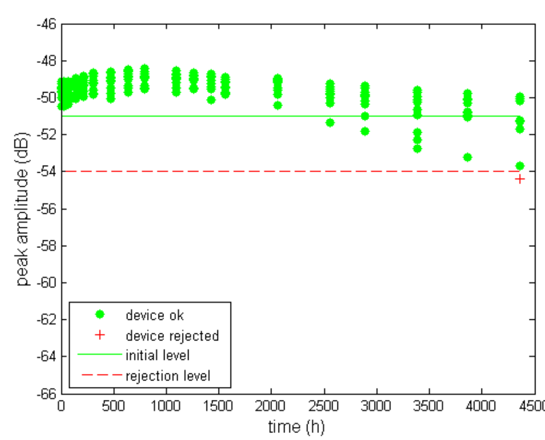

Figure 3. Amplitude of the minimum signal level after long-time annealing at 300°C.

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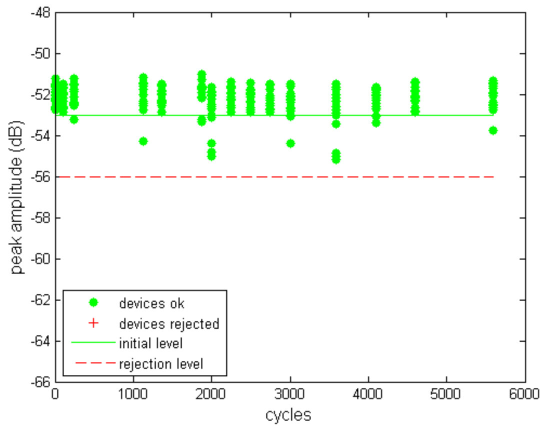

Figure 4. Amplitude of the minimum signal level after temperature cycling from 30°C to 230°C.

In the long-time annealing in Fig. 3, the devices show a run-in effect during the first 1000 hours, where the signal amplitude actually increases. After 4350 hours (more than 6 months) the first of ten devices dropped below the rejection limit of 3 dB. The effect of temperature cycling was tested by sequential cooling of 15 devices every 15 minutes from 30°C to 230°C. The development of signal amplitudes over cycles was measured. As can be seen from Fig. 4 even after 5600 cycles no device fell below the rejection limit. The deviations in the peak amplitude are presumably artifacts of the measurement (e.g., variations of the electrical contact resistance due to oxidation of contact pins).

B. Packaging

The bare SAW die is very sensitive to surface pollution. Thus it has to be hermetically sealed and protected with inert gas (N_2). Metal housings have a very good thermal stability, which is limited by the glass feed-through at approximately 450°C. The SAW is die-bonded to the metal housing using a silver-filled polyimide adhesive. Silicon based adhesives can only be used up to +250°C maximum. Ceramic adhesives were found to be inappropriate as they are too brittle to assimilate the non-uniform expansion of LN YZ substrate (13.4 ppm/°C along the a-axis and 4.1 ppm/°C along the c-axis). Wire bonding was performed using a 25 µm Al bond wire (wedge-wedge). The lid is welded to the socket using projection welding. Metallic housings were manufactured for different application purposes. A TO39 housing as shown in Fig. 5 can serve as a simple and cost effective housing for applications up to 400°C without further specifications on space requirements or mechanical pressure. On the other hand a TO39 housing can be used for cryogenic applications when the housing is enclosed in vacuum instead of nitrogen. A small custom housing with dimensions of 1.9 x 3.1 x 10.0 mm^3 was developed for applications that require a good thermal contact between tagged object and SAW transponder (Fig. 6). For high pressure applications like oil and gas exploitation a custom Inconel housing was designed (Fig. 7).

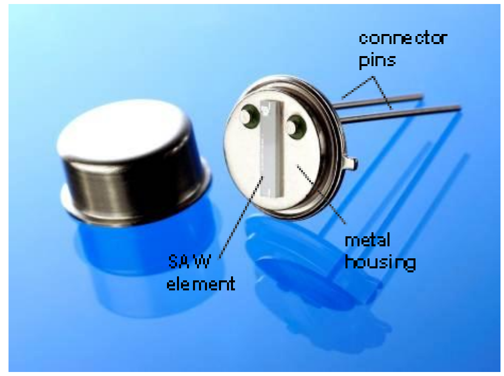

Figure 5. Transponder housing TO39, diameter 10 mm x 4 mm.

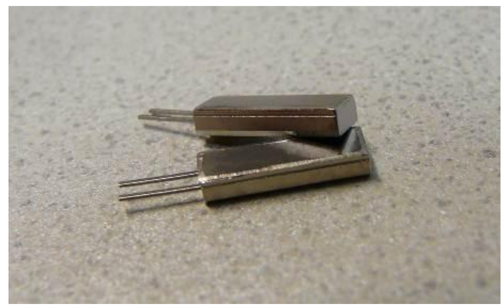

Figure 6. Custom Kovar housing 1.9 x 3.1 x 10.0 mm^3.

Figure 7. Custom Inconel housing for high pressure applications, diameter 9.1 mm x 5.1 mm.

The basic design was taken from TO39 standard, but all wall thicknesses were increased to withstand pressure up to 1300 bar. The diameter of the feed-through was changed from 1.5 mm to 1.3 mm to reduce the pressure on the glass.

C. Antenna design and transponder assembly

The antenna has to operate in the same working conditions as the transponder. For operation temperatures exceeding +250°C full metal antennas were designed. The electrical interconnection between transponder and antenna is laser welded, providing better temperature stability compared to soldering. Another aspect of the antenna design is to protect the transponder from mechanical shock loads and vibrations. This has been achieved by the development of a ruggedized slot antenna (Fig. 8).

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Figure 8. Ruggedized, stainless steel slot antenna 100 mm x 40 mm with a thickness of 5 mm.

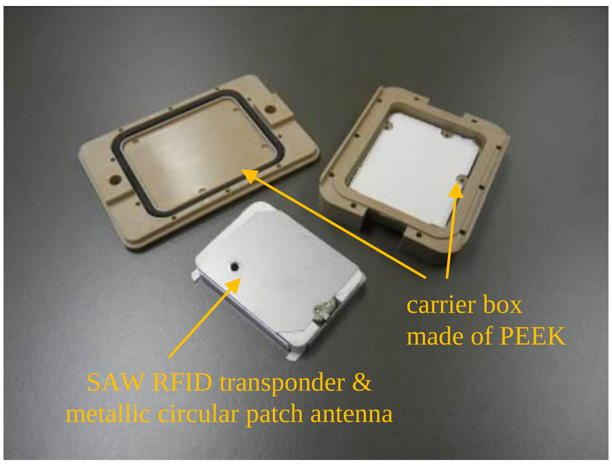

Figure 9. Metal circular patch antenna and PEEK housing, assembled: 95 mm x 64 mm x 17 mm.

The antenna is made of 5 mm thick stainless steel and is typically mounted on metal surfaces, which act as a reflector to increase the signal gain. As transponder housing a standard TO39 is used. The TO39 is well protected inside a cavity of the antenna. Whereas the slot antenna is linear polarized, a circular polarized metallic patch antenna has been developed. Fig. 9 shows the patch antenna, which is placed in between a carrier box made of PEEK (Polyether ether ketone). The metal patch antenna replaces a former design based on a PCB patch antenna and solder connections. The solution with metal antenna and welded electrical connection proved to be much more stable in temperature cycling conditions up to 220°C.

V. APPLICATIONS

The applications presented below give an overview of implemented RFID installations and pilots carried out in the past five years. The main asset of passive SAW RFID transponders in all those cases were the operability at temperatures >200°C, meaning that tags do not only withstand, but can also be read out at higher temperatures.

A. RFID in steel plant

RFID applications in the steel plant are motivated by the logistics optimization of moving investment goods or consumables. One of the main topics is the retraceability of the steel grade or the slag as a by-product for further process treatment [7]. Sometimes the transmitted temperature of the SAW tag is interesting add-on information.

1) Identification of a steel ladle

SAW RFID tags have been installed on the steel coating of steel ladles. The tags are positioned with a distance to the steel coating not to be in direct contact with the outer temperature of +300°C to +400°C. The tags are protected against slag splashes with refractory material on the outside (Fig. 10). The ladle is tracked along 10 different process positions in the steel plant. As the ladle moves along the plant the range between installed reader antennas and tag varies between 2 m and 5 m. At 5 m range stability problems of the SAW transponder read-out were reported. In the ongoing test, SAW RFID tags were long-term stable for several months. Through automated ladle tracking, process logistics is optimized, security is increased and a better retraceability achieved.

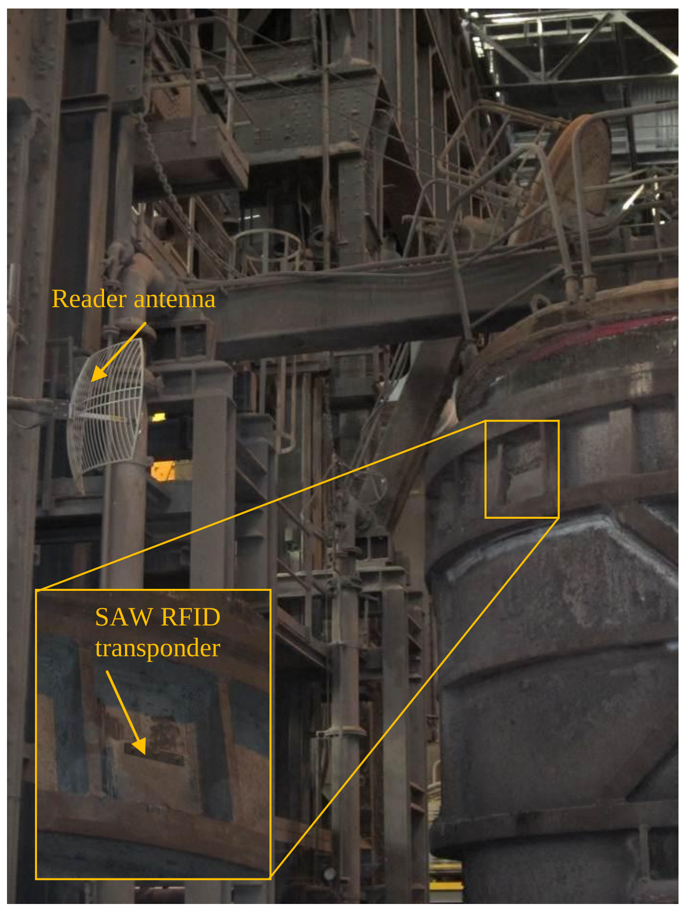

Figure 10. SAW RFID installation on a steel ladle (Georgsmarienhütte, Germany).

2) Identification of slide gate plates

A slide gate is steel equipment used to control the steel flow during casting. The core element is a sliding valve made of two plates (Fig. 11). These slide gate plates are refractory wear elements. Being crucial parts exposed to high temperatures, they must be replaced before a critical degree of wear has been reached. Failure (e.g., breakthrough of liquid metal) can cause great damage. An RFID and temperature monitoring system gives the manufacturer better control over the usage and the logistics are documented. Although at the center of the slide gate plates the temperature equals 1540°C, the melting temperature of steel, the temperature rapidly decreases towards the edges. A SAW transponder was installed on the outer rim (Fig. 12) of the plate. It faces a cavity in the slide gate mechanics, where a ruggedized reader antenna was mounted. The temperatures during casting were moderate around 250°C as cooling was applied. The maximum temperature was reached with 320°C on the maintenance station, when cooling is switched off. During a pilot test of several weeks about 100 slide gate plates were tested. All SAW transponders remained functional over all casts. In average a slight signal degradation of 2 dB to 5 dB was observed [8].

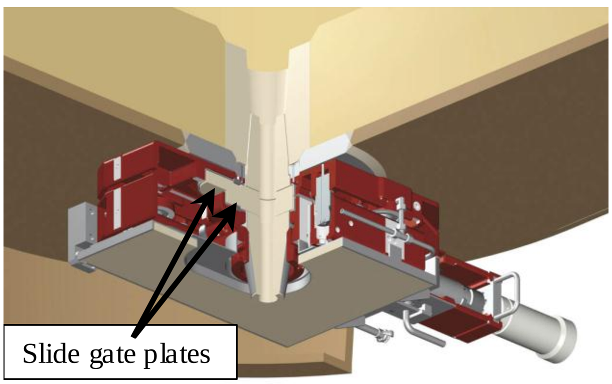

Figure 11. Cut of a slide gate mechanics to control the steel flow during casting (RHI AG, Austria).

Figure 12. SAW RFID installation on slide gate plate (RHI AG, Austria).

B. Asset tracking in the oil and gas industry

CMOS RFID transponder for down-hole equipment which are based on glass encapsulated low frequency (LF) transponder withstand the operating conditions, but have small read ranges. Applications like the automatic down-hole asset monitoring [9] call for significantly longer read ranges > 0.5 m. For a deep well specification temperatures up to 250°C and pressures up to 1300 bar have to be considered. A custom Inconel housing (Fig. 7) was developed to meet these requirements. The Inconel housing is connected to a spiral antenna and encapsulated in PEEK. The PEEK radome has a sacrificial layer to allow for wear on the tool in down-hole operation. The SAW RFID transponder is mounted in a bore hole with a depth of 16 mm via a press fit (Fig. 13). Although first down-hole tests with a few tags are promising a test with a representative number of tags is still due. The oil and gas industry demands a RFID solution for drill pipes to be applicable in static and dynamic cases for life-cycle management and asset predictability. The latter is more difficult as the pipes have to be read in and out dynamically at the rig. A rig floor reader has been designed which consists of a circular arrangement of reader antennas around the pipe. As the drill pipes are inserted the reader identifies them at arbitrary angular position. By tracking the pipe usage time and known parameters as well depth, well type and drilling method a fatigue prediction for each pipe can be derived. The benefit of this database is to preclude drilling down-time and fishing costs due to pipe breakage. Also a load-dependent maintenance of drill pipes can be implemented.

C. Automotive varnishing line

In automotive paint shops the varnish has to be cured at elevated temperatures >200°C. As different car bodies run through the paint shop each body has to be identified to start the correct painting process. Starting in the bodyshell work the SAW RFID transponder is mounted. At the assembly

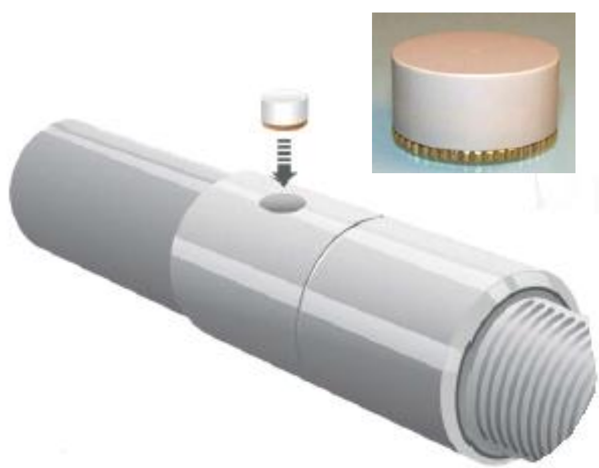

Figure 13. SAW RFID inserted into drill pipe collar/tool joint (HM Energy, LLC, USA).

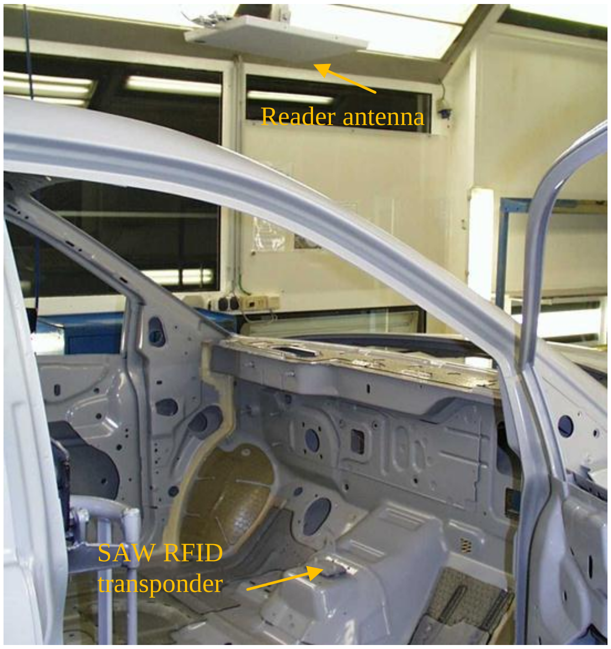

Figure 14. SAW RFID in an automotive varnishing line (Identec Solutions, Austria).

stands in the bodyshell work, before and after the paint shop and at some working areas in the end assembly the transponder is read out. In this way the car body is identified, processes are triggered and the car is consistently tracked within the networked assembly stands. The SAW RFID transponder according to Fig. 9 is attached to each car body. The transponder does not remain on the car body, but is recycled in the process. Fig. 14 shows the mounting of the transponder and in 1.5 m distance the read-out antenna. The main advantage of SAW RFID in this application is that the transponder offers a long lifetime and further the code can be read at elevated temperatures. One of the drawbacks of using SAW is the fixed code, which cannot be changed in the field. This has been solved using a code conversion table on the host side.

VI. Research Outlook for a 600°C SAW RFID Transponder

State of the art SAW RFID transponder surpass the operation temperature of CMOS RFID transponder, but the SAW technology offers more potential to increase the current operation limit of +350°C to +400°C by far. Key elements of a high temperature SAW transponder that works beyond 600°C are the availability of a suitable substrate and IDT metallization. Aubert, et.al., have experimentally studied a Ir/Ti/AlN/Sapphire structure that exhibits a good stability of up to 1050°C for several hours [10]. The measurements were carried out on 392 MHz devices. The main degradation which occurred was due to agglomeration of the Iridium electrodes. Based on this very promising result, future research has to focus on the design and verification of 2.4 GHz devices. The ISM band at 2.4 GHz is a good choice due to the legal availability of 80 MHz bandwidth needed for pulse position coding. A second research focus has to deal with a suitable high temperature package. Metallic packages fail at 450°C because of the glass feed-through. Either a brazed ceramic feed-through or whole ceramic packages with a thermally stable metallization have to be developed.

VII. Conclusion

The work describes optimization of the thermal stability of Lithium Niobate based SAW RFID transponders, including IDT metallization, packaging and antenna design. At 300°C a thermal stability and operability of >4000 hours was achieved, thereby outperforming standard CMOS RFID transponders by far. The given application examples of industry pilots and ongoing RFID installations demonstrate the good potential SAW RFID transponders for harsh environment.

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