Chapter 1

Introduction

Radio frequency identification (RFID) is a well known technology to identify objects by an electronic chip, that is bonded onto an antenna. These so called transponders or tags are powered by the electromagnetic field of a reader device (passive transponders) or by its own integrated power source - e.g. a small battery (active transponders). With increasing integration density of silicon chips and therefore decreasing costs of RFID-Tags, RFID is a rapidly growing market for many applications as e.g. supply chain management, asset control, toll collection, pallet tracking, brand mark, anti-theft and anti-counterfeit protection, product labelling, etc. The electronic product code (EPC) is established to prepare a global transponder-standard for item level tagging, which means that every product can be tagged with an unique identity number. But there is always a trade-off between the costs of RFID-Tags and the products the tags are applied to. For item level tagging, the manufacturing costs of RFID-Tags have to be further decreased by new mass production technologies. For high volume and small chip size, the costs of silicon based RFID-Tags are driven by packaging costs of the chips and the costs of bonding the chip onto the antenna.

Transponders based on organic semiconductors are a completely new

RFID technology which open the way to new fabrication processes and applications. The organic integrated circuit comprises all devices, which contain at least one active organic layer. Organic semiconductors are classified as polymers or small molecules and are more similair to conductors than to semiconductors due to their low purity and large densities of dopant. The notion of n and p-type must be redefined for organic electronics and is used as means of injecting charge-carriers at the electrode-semiconductor interface. However, the potential to constitute the basis of organic electronic devices as e.g. transistors, integrated circuits, displays, photovoltaics, sensors and RFID-Tags is now well established [36].

Polymer semiconductors are a sub-set of the organic semiconductors and are based on long regio-regular polymer chains as e.g. poly 3-alkyl-thiophene (P3AT). As these polymer semiconductors are soluble, new opportunities for inexpensive RFID-Tag production techniques such as printing processes [73] arise. Concepts for the production of fast integrated circuits based on p-type organic transistors have been demonstrated [42] using soluble polymers for the active layer and the insulating layer. A number of organic building blocks and components have been published [72, 54, 55, 56, 58]. The manufacturing process of these RFID-Tags must be compatible with a printing process for their mass production. Printed RFID-Tags would be suited for retail applications [55] due to low cost, mechanical flexibility and the possibility to integrate the circuits with antennas on packaged items.

Considering the performance limitations of printed polymer electronics, a proper communication method has to be selected to be applied to the polymer RFID-Tag. Table 1.1 shows a selection of some different radio frequency (RF) links between the reader and the RFID-Tag. The most promising communication methods for printed polymer RFID-Tags are capacitive and inductive coupling at 125kHz or 13.56MHz. In this frequency range, functional 125kHz and 13.56MHz RFID Systems, based on the polymer poly 3-hexylthiophene (P3HT) or the small molecules Pentacene, have been presented [73, 59]. One of the most important components is the rectifier, which provides the DC voltage supply for the chip on the RFID-Tag. Towards higher carrier frequencies (e.g. $>$ 10MHz), the losses inside today's organic rectifiers increase dramatically and the delivered DC voltage at the rectifiers output drops [72, 56]. At lower frequencies (e.g. $<$ 1MHz), the cost of antennas for inductive coupled transponders increases due to the high number of windings, while for capacitive coupling the read range is restricted to 1cm or less.

RFID Systems				
Coupling:	Backscatter	Capacitive Coupling	Inductive Coupling	
Range:	Long Range $1,\dots,300$m	Close Coupling $0,\dots,1$cm	Proximity Coupling $0,\dots,15$cm	Vicinity Coupling $0,\dots,1$m
Frequency:	UHF 433MHz, 860-960MHz, 2.45GHz, 5.8GHz, 24.125GHz	LF - HF DC,...,30MHz	LF - HF $<$ 135kHz, 6.78MHz, 13.56MHz, 27.125MHz	
Technology:	Silicon - -	Silicon Organic -	Silicon Organic Polymer	Silicon - -

Table 1.1: Outline of RFID communication methods.

The goal of this work is to present a concept study for a passive polymer 13.56MHz transponder for item level tagging purpose that can be produced by roll to roll printing techniques at low cost and high volume. RF characteristics of printed polymer components such as e.g. rectifiers, capacitors and transistors are widely unexplored. Therefore, the electrical equivalent circuits and system parameters of these components are identified and device models are derived. Using these models, a system simulation is implemented, that helps to understand and optimize the performance and interaction of the polymer devices inside a polymer RFID-Tag. The system simulation includes the reader device, the air interface and the polymer transponder and enables the improvement of the overall RFID-System.

Chapter 2 gives an outline of the available polymer devices and their most important characteristics for the design of a polymer transponder. An overview of the physical principles of existing RFID systems using backscattering, capacitive coupling and inductive coupling is given, and inductive coupling at a commercially used carrier frequency of 13.56MHz is derived as the proper solution for the polymer transponder.

In order to achieve an optimized power transfer from the reader to the transponder, the basics of inductive coupled resonance circuits are discussed in more detail in chapter 3. This chapter also explains the principles of power transmission and antenna matching to be applied to the reader frontend.

In chapter 4, the focus is on the polymer rectifier. First, the polymer diode and the parameter extraction from measurements are discussed in more detail. Then, the polymer diode model is applied in simulations of various rectifiers. The static and dynamic behavior of polymer rectifiers and their interaction with the transponder antenna and the polymer transponder chip are analyzed here as well.

In chapter 5, a model of the polymer transponder is presented and the most important parameters of the complete RFID system are identified. To avoid a time and error critical simulation of the RF carrier, a baseband model is derived to simulate the communication between the polymer transponder and the reader. Applicable communication protocols for the polymer transponder as Non Return to Zero coding (NRZ) and Manchester coding are compared.

Chapter 6 summarizes the results of this work and gives an outlook for future investigations.

Chapter 2

Basic Considerations

The RFID system, developed in this work, consists of a conventional reader, made of silicon based devices, and a polymer RFID-Tag, as illustrated in figure 2.1. Regarding the reader, a driver circuit supplies a tuned reader antenna with the carrier signal at a certain frequency, while the reader antenna transmits this carrier signal via an electromagnetical field to supply the transponder. The function of the transponder is to store data without a permanent power supply and to transmit this data when the transponder is put into the field. Hence, the transponder is able to absorb a certain amount of energy from this field to activate its own power supply. When activated, the transponder transmits data back to the reader by modulating the carrier signal. The received transponder signal is then demodulated within the reader, the information is recovered and provided for any kind of application.

The main components of the polymer transponder are the antenna as an interface to the carrier signal, the polymer rectifier as a power supply for the polymer chip and the digital circuitry. The polymer chip itself contains a clock generator, polymer logic circuits to read stored data and a modulation circuit to transmit the data back to the reader.

In section 2.1, the available polymer devices and their RF characteris-

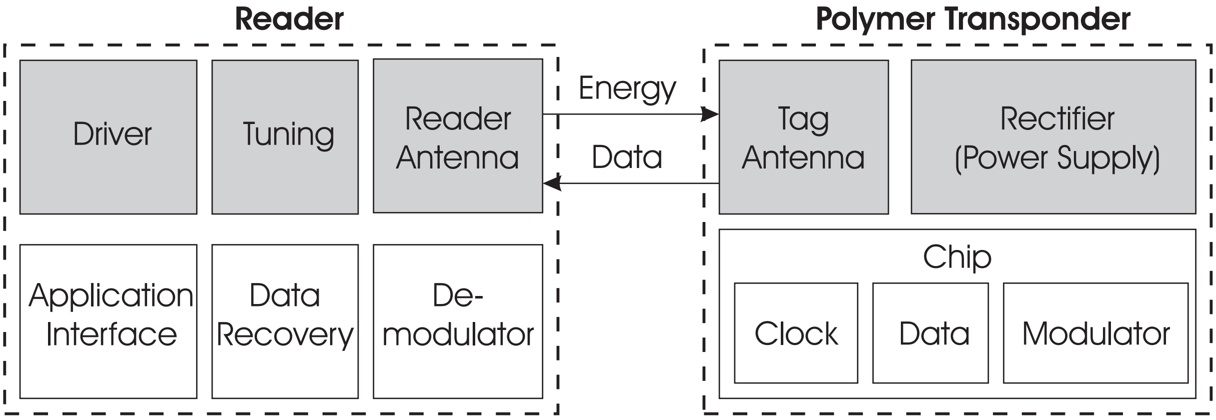

Figure 2.1: Components of a RFID system with polymer Transponder.

tics are presented and their application in RFID transponders is analyzed. The physical principles of antennas and wave propagation will be clarified in section 2.2, which leads to various applicable energy and data transfer methods for the RFID system.

2.1 Devices for a Polymer Transponder

This section introduces the available polymer devices and estimates their potential to build the basic components of a polymer RFID transponder. The basic polymer devices are capacitors, diodes and field effect transistors, on which more complex circuits as gates, ring oscillators, rectifiers etc. are based. The polymer devices, presented in the following sections, are prototypes which are produced under clean room conditions while the manufacturing process is completely compatible with a prospective printing process for mass production [48]. Regarding these prototypes, the electrodes are patterned with a mask using standard photolithography. The minimum feature size when using this method is 5μm. The substrate used for all devices is a flexible polyester film. Up to six different layers are deposited as there are source and drain-electrodes, polymer semiconductor, insulator for transistors, semiconductor for diodes, insulator for capacitors and the gate-electrodes.

2.1.1 Polymer Capacitors

Interconnect layers are used to make traditional parallel plate capacitors. The polymer capacitors are made with a proprietary blend of soluble insulating polymers between two metal electrodes [42]. The production of polymer capacitors is described in [41] in more detail. In conjunction with diodes, the polymer capacitors are used to build a rectifier circuit which is a basic component of RFID. Figure 2.2 shows the side view of the polymer capacitor's layers.

The electrodes represent a parallel plate capacitance C with a plate surface A and a plate separation d_{ins}.

$$C = \varepsilon_0 \varepsilon_{ins} \frac{A}{d_{\text{ins}}} \tag{2.1}$$

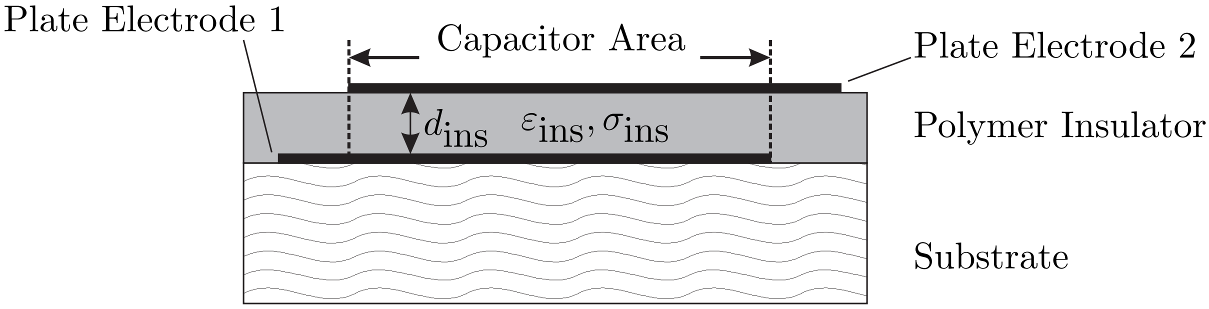

Figure 2.2: Side view of a polymer capacitor.

The insulator has to sustain high electric field strengths up to $E = U/d_{\text{ins}} \leq 10^8\text{V/m}$ [41] for an applied voltage U across the capacitor and should possess a low leakage conductivity σ_{ins} to reduce losses. The quality of the capacitor can be expressed by the dissipation factor D_{loss} that represents the ratio between the losses - due to the dielectric insulator and lead wires - and the energy stored in the electric field of the electrodes. The relative dielectric constant in air is 1. For polymer insulators as e.g. Polyethylen (PET) $\varepsilon_{ins} = 2.3 \ldots 2.4$ and is defined by the polarization properties of the dielectric. Polarization needs a certain amount of time $10^{-8}, \ldots, 10^{-10}$s for the orientation of the molecules [23], while increasing temperature vibrations disturb the orientation of the dipole molecules. Therefore, ε_{ins} is frequency and temperature dependent and decreases with increasing frequency and temperature. R_{ins} represents the losses of the dielectric insulator and the *series loss tangent* $\tan_{\Delta}(f)$ is specified at various frequencies f [23]. The frequency dependent conductance of the insulator $G_{ins}(f)$ is then given by:

$$G_{ins}(f) = \frac{1}{R_{ins}(f)} = \omega C \tan_{\Delta}(f) \tag{2.2}$$

At high frequencies the *skin effect* cannot be neglected when the connection wire width and thickness is large compared to the *skin depth* δ. The *skin effect* is discussed in more detail in section 3.1.1. If the connection wire width and thickness is small compared to δ, the series resistance R_w will be calculated by the lead wire geometry:

$$R_w = \frac{l}{l_h l_w \sigma_{lead}} \tag{2.3}$$

where l is the total length, l_h is the thickness, l_w is the width and σ_{lead} is the specific conductance of the lead wire. The cut-off frequency f_g marks the frequency where the influence of R_w are no longer negligible.

$$f_g = \frac{1}{2\pi R_w C} \tag{2.4}$$

The parasitic resistance of connection wires and electrodes in conjunction with the capacitance represent an RC low-pass. Table 2.1 gives a comparison of various materials and their cut-off frequencies for electrodes of 50nm thickness. To reduce losses and to increase the cut-off frequency of the polymer capacitor, thicker electrode layers or metal can be used instead of polymer conductors as e.g. Polyanilin (PANI) or Poly(ethylendioxy-thiophene) (PEDOT) [41].

Figure 2.3a shows the model of the polymer capacitor. The parasitic inductance L_w is introduced by the inductance of the lead wires. Accordingly, L_w is determined by the geometrical layout of the lead wires. At low frequencies and short lead wires, L_w can be neglected, but it has

Material		$l = 10\text{mm};\ l_h = 50\text{nm};\ l_w = 1\text{mm}$	
	σ [S/cm]	$R_w[\Omega]$	f_g
Gold (Au)	$4.9 \cdot 10^5$	4.08	39.0 MHz
Silver (Ag)	$6.1 \cdot 10^5$	3.28	48.5 MHz
Copper (Cu)	$5.8 \cdot 10^5$	3.45	46.1 MHz
Aluminum (Al)	$3.5 \cdot 10^5$	5.71	27.9 MHz
Polyanilin (PANI)	~ 40	$50 \cdot 10^3$	3.2 kHz
Poly(ethylen-dioxy-thiophene) (PEDOT)	~ 200	$10 \cdot 10^3$	15.9 kHz

Table 2.1: Comparison of various electrode materials [23].

to be taken into account at higher frequencies and long lead wires. At high frequencies the capacitor resonates due to the inductance of its lead wires. The impedance Z and phase ϕ of a capacitor as a function of the frequency can be measured by a network analyzer (NWA) as shown in figure 2.3b.

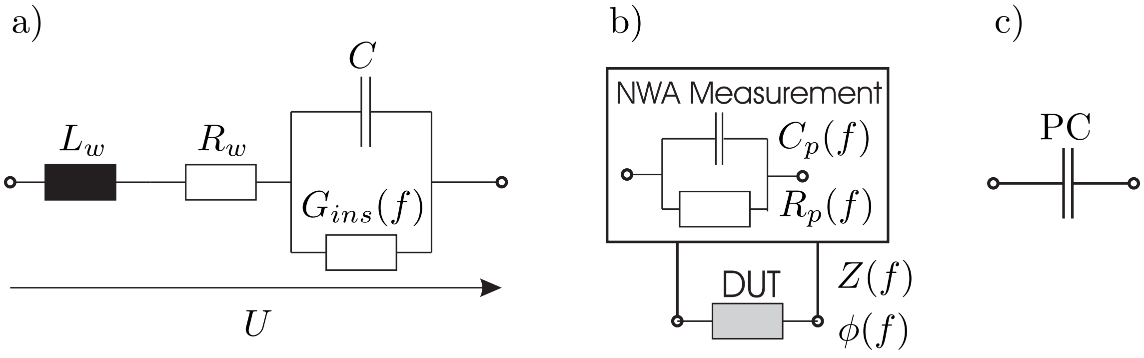

Figure 2.3: a) Equivalent circuit model of a polymer capacitor. b) Network analyzer measurement of the impedance, phase, apparent shunt capacitance and resistance of a polymer capacitor device under test (DUT) at various frequencies. c) Symbol of the polymer capacitor (PC).