High-Performance RFID Systems

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Declaration of Originality

I declare that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge it does not contain any materials previously published or written by any other person except where due reference is made in the text.

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Abstract

In this thesis, I present and analyze two of the most fundamental constraints of Radio Frequency Identification Systems (RFID), power rectification and signaling. These two issues play an important role in the continuing development of RFID systems.

A passive RFID tag draws power from the RF field created by an RFID reader and uses it to energize its circuitry. It does this by rectification of the reader's radiated RF field using rectifying circuitry. The power then available to the tag is dependent upon both the available field strength and the efficiency of the rectification process. One option for increasing the operating range of an RFID system without increasing the reader's field strength is to increase the efficiency of the tag's rectification structure. A major component of any rectification circuit is a diode type device and so, the first part of the thesis focuses on the design and implementation of a novel high efficiency Schottky Barrier Diode (SBD) on a standard CMOS process. The forward voltage drop of the SBD diode was investigated and analytic equations formulated considering the Schottky barrier drift region resistance and the contributions from the p^+ guard-grid. A design procedure to minimize the drift region resistance for any blocking voltage was derived. The fundamental trade-off between the forward voltage and leakage current in the novel SBD concept was determined.

Based on the critical review of the Schottky diodes fabricated in the first part, new structures of novel SBD were designed to address most of the open issues related to its reverse break-down voltage and series resistance. Detailed analysis of the important design parameters of the novel Schottky barrier diode were performed using HSPICE with the parameter set used in the calibration process. The novel structure was also compared to an alternative fabrication approache, specifically, a NMOS and PMOS gate-cross-connected bridge. The comparison shows that the novel structure provides a 10% higher

figure of merit for power rectification.

In the later part of the thesis, an analysis of circuit advantages enabled by the novel SBD is given. The circuit simulation showed that by utilizing the novel SBD the operating frequency of the circuit can be increased to the UHF region while maintaining approximately the same power efficiency as that achievable when using a discrete Schottky diode. This leads to the possibility of dramatic improvements in size, weight and cost of the RFID transponder circuits.

Signaling also plays an important role in the development of RFID systems. The choice of signaling methods and protocols determines not only the spectrum bandwidth usage, but also the data throughput. Also with constantly changing standards and regulations, it is important to be able to characterize and optimize these issues.

Therefore the second part of this dissertation presents the design, implementation and evaluation of a novel RFID data logging reader architecture based on software radio concepts. The system is designed to overcome the many challenges and exploit the advantages of performing real-time signal processing and data logging in an RFID environment. The proposed concept has a unique multi-band RFID tag reader platform and has been designed to read tags conforming to the Electronic Product Code (EPC) specifications in both the HF and UHF frequency bands. The hardware architecture consists of a general purpose analogue front end up/down-converter for each band, followed by a software radio based architecture allowing easy adaptation to new frequencies and protocols if required.

The last chapter presents the results of investigations conducted to determine the ability of the proposed reader architecture to communicate with tags in typical channel noise and environmental conditions present in an

RFID operational environment. Studies of the effects of reader interference in multi-reader environments and the development of an anti-collision protocol signaling to address and mitigate those effects are also presented.

Publications

1. Behnam Jamali, Peter H. Cole "Design and Optimization of Schottky Diodes on Standard CMOS process", Proceedings of SPIE International Symposium in Smart Structures, Devices, and Systems II, Sysdney, Dec 2004.

2. Behnam Jamali "Brief comparison of different rfid rectifier structure", Auto-ID Lab, Zurich, Sept 2004, http://autoidlab.eleceng.adelaide.edu.au/

3. Behnam Jamali "Software Based Data Logging Reader", Frontline Conference & Expo, Chicago, Sept 2004, http://www.frontlineexpo.com/

4. Peter Cole, Behnam Jamali, Damith Ranasinghe "Coupling Relations in RFID Systems", Auto-ID Lab, Adelaide, Jun 2002, http://autoidlab.eleceng.adelaide.edu.au/Tutorial/

5. Peter Cole, Damith Ranasinghe, Behnam Jamali "Coupling Relations in RFID Systems II: Practical Performance Measurements", Auto-ID Lab, Adelaide, Jun 2003.

6. B. Jamali, D. C. Ranasinghe, P. H. Cole , "Analysis of UHF RFID CMOS rectifier structures and input impedance characteristics", SPIE International, Microelectronics: Design, Technology, and Packaging II, In proceeding

7. B. Jamali, D. C. Ranasinghe, P. H. Cole , "Design and optimisation of power rectifiers for passive RFID systems in monolithic CMOS", SPIE International, Microelectronics: Design, Technology, and Packaging II, In proceeding

8. Ranasinghe D., Jamali B., Lim D., Devadas S., Zhu Z. and Cole P.H. "Low-cost and efficient physical random number generator based on race conditions", in Smart Structures, Devices, and Systems II, S. F. Al-Sarawi, Editor, Proceedings of SPIE International Symposium MSN, & MSS, Vol. 5649, Sydney, Australia, 1215 December 2004.

9. Daihyun Lim, Damith C. Ranasingheb, Srinivas Devadasa, Behnam Jamali, Derek Abbott, Peter H. Cole "Exploiting metastability and thermal noise to build a re-configurable hardware random number generator" Proc. of SPIE Vol. 5844 (SPIE, Bellingham, WA, 2005)

10. D. Hall, D. Ranasinghe, Behnam Jamali, P. H. Cole "Turn-on circuits based on standard CMOS technology for active RFID labels" Proceedings of SPIE International Symposium, Proc. SPIE Vol. 5837, p. 310-320, VLSI Circuits and Systems II.

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Chapter 1

Introduction

This dissertation is about improving the performance of RFID systems. The work done has been partitioned into two main parts. The first part identifies the critical issues in developing high performance RFID systems and goes on to describe those aspects that become the focus of this work. It then proceeds to describe the design, fabrication and usage of a power efficient Schottky Barrier Diode (SBD) on a standard CMOS process. The second part describes design and construction of a software based data logging reader and its use in implementing, monitoring and evaluating recent RFID communication protocols.

The purpose of this first chapter is to present an introduction to Radio Frequency Identification Systems (RFID), the motivation and the outline of the work done in this dissertation.

1.1 Introduction to RFID

RFID is a relatively new technology, first appearing in tracking and access applications during the 1980s [1] or even 1940s[1]. These wireless systems allow for non-contact reading of data from electronic labels by electromagnetic signals, and consequently are effective in manufacturing and other hostile environments where bar code labels could not survive. RFID tags can be read in challenging circumstances when there is no physical contact or direct line of sight [2] [3]. RFID has established itself in a wide range of markets including livestock identification and automated vehicle identification systems because of its ability to track moving objects. RFID technology is becoming a primary player in automated data collection, identification and analysis systems worldwide [4].

RFID, its application, standardization and innovation are constantly changing. It is a new and complex technology, and there are many features of this technology that are not well known and understood by the general public, or by many practitioners.

Wider reading range, larger memory capacity and faster signal processing and data communications are a few of the areas which need development.

It is very unlikely that RFID will replace traditional bar code systems [?], because even with the cost reduction in fabricating CMOS chips, RF tags will never be as cost effective as bar code labels. However, RFID will continue to grow in areas where bar code or other optical technologies are not effective. This will be especially true when improved solutions to RFID problems can be devised.

[1]Many authors date RFID to 1940's when World War II pilots signaled home radars by dipping their wings. These dips produced modulation on the reflected radar signals.

The standardization of tags will further add to their uptake as equipment from different manufacturers can be used interchangeably [5].

The strong revival, during the past few years, of research and applications in the RFID region is attributed to the advance of new technology, and innovations in the context within which RFID can be used. The evolution of new requirements for reading range and communication links and the superiority of RFID over optical bar code systems for penetration of dust, smoke and other adverse environments, has generated much interest in both commercial and military applications [6] [7]. The improved technology includes better read range, faster communication links, higher capacities, multiple tag reading algorithms and better sensitivities. Of particular importance is the development of the Auto-ID Center concepts discussed in Section 1.1.5.

1.1.1 Reading Range

The reading range of a tag is essentially determined by:

- The power available at the reader to communicate with the tag, which is limited by electromagnetic regulations which restrict the amount of power that a reader can transmit.
- The amount of the power available within the tag to respond.
- The environmental conditions and structures. These become more significant at higher frequency.
- The way that the power is deployed within the tag circuitry.

As the shape and orientation of the transmitter antenna determines the shape of the electromagnetic field created around it, the read range will be influenced by the orientation of the tag antenna in relation to the interrogating electromagnetic field. The issues are different at different frequencies, as we may be operating at some frequencies in the near field and in the far field at other frequencies [8].

Another important factor is the strength of the field as the tag moves farther from the reader antenna. In free space, in the near field, the strength (power) of the field reduces in inverse proportion to the sixth power of the distance from the antenna. In free space, in the far field, the strength (power) of the field reduces in inverse proportion to the second power of the distance from the antenna.

Although it is possible to choose a high power level to achieve a long read range, it is not possible to exercise complete freedom of choice [9]. There are legislative constraints on power levels emitted from the reader antenna [10]. This makes the near field quite interesting [11], as it provides energy storage with minimum amount of electromagnetic radiation, which always occurs and needs to be minimized. There is also the issue that high transmitted power automatically generates high receiver noise into the receiver circuit of the reader, due to their homo-dyne receiver architecture [12]. Thus, techniques to deal with such noise need to be developed.

1.1.2 Data Transfer Rate

The data transfer rate depends mostly on the frequency bandwidth. Generally speaking, the higher the bandwidth the higher the transfer rate. It should also be mentioned that transferring data to and from the tag requires a finite amount of time. This can be an important consideration in applications where a tag is passing swiftly through an interrogation zone. The considerations which limit data transfer rate in the interrogator to label direction are those of electromagnetic compatibility regulations [9] [10]. The principal consideration which limits data transfer rate in the label to interrogator direction is the employment of a coding methodology which is robust in the face of interfering signals which may be generated by other users of the spectrum.

1.1.3 The Reader

The readers or interrogators can differ quite considerably in complexity, depending on the type of tags being used and the functionality expected from them [13]. Their main purpose is to communicate with the tags and retrieve information contained within them. The functions performed by the interrogator may include signal conditioning, error checking and correcting, collision detection, sending commands to the tags in the field and processing the reply. In an environment where multiple tags are present, the amount of processing a reader must do is much more. Contention management is a vital issue, and a variety of techniques have been developed to improve the process of batch reading [14].

1.1.4 Standardization

The proliferation of incompatible RFID standards is provoking much debate among RFID developers. All major RFID vendors offer proprietary systems, which operate on different protocols. The current state of RFID standards is that of severe disarray, and this lack of system inter-changeability has severely crippled RFID industry growth. However a number of organizations, influenced in a variety of ways [5], have been working to address, and hopefully bring about, some commonality among competing RFID systems. One of them will be discussed further in the next section.

Just as standardization enabled the tremendous growth and widespread use of barcodes, cooperation among RFID manufacturers will be necessary for promoting the technology development and refinements that will enable the broad based application growth.

1.1.5 The Auto-ID Center Concepts

In 1999 researchers at Massachusetts Institute of Technology (MIT) established an Auto-ID Center, and developed the concepts of Electronic Product Code, the Object Naming Service, and the Physical Markup language [4] [5]. These concepts have been enthusiastically embraced by the RFID user community, (even if not the vendor community) for automatic identification. These concepts are substantially in harmony with the views of this author as to how the RFID technology should be developed, and my work is therefore of such a nature as to enhance the utility and applicability of those concepts.

1.2 Problem Statement

The literature review from Section 1.1.1 to 1.1.5 highlights, in general, which elements are of importance. A major conclusion which emanated from this review is that there exists difficulties with the current RFID systems that may need to be addressed:

- Electromagnetic propagation losses and polarization mismatch between the label and the interrogator. This can result in a significant reduction of power transfer across the electromagnetic link. For this reason the study and development of an efficient power rectifier circuit is imperative [15] [16] [17].

- Inefficient label antennas. Label antennas need to be small, for such antennas it is difficult to keep the loss resistance within the antenna and the matching network small compared with the radiation resistance. Also, it is difficult to achieve adequate bandwidth with small antennas to meet the operational needs required for different UHF frequencies in different jurisdictions [18] [19].

- Transmitter power constraints, which are limited by both radio frequency licensing authorities and human exposure to RF fields [9] [10].

- The behavior of CMOS circuits at variable, unpredictable and low supply voltages, such as can be extracted by rectifying the interrogation signal, needs further exploration and optimization [27] [28].

- Transistor noise, which shows itself as variation in amplitude and phase of the RF signal. These variations are due to thermal noise, shot noise and flicker noise. These phenomena decrease the spectral purity of the transmitted signal, and increase the error rate of the overall system [23] [24] [25] [26].

- Detecting signals in a crowded and noisy channel requires lots of signal processing. Software Radio based RFID readers can be implemented to handle complex signal processing tasks [13] [100] [101].

- Reader proliferation causes reader-to-reader interference, resulting in probability of ghost reads that emphasize the need for reader networking [20].

- Work needs to be done to bring harmony into the currently diverse standards for communications and reading algorithms [21] [22].

Current developments in RFID technology continue to yield larger memory capacities, wider reading ranges, the capability to read multiple tags present in the interrogation field and faster processing of information. For more information about the development and standards of RFID systems, readers are referred to the following references [31], [10], [32], [33], [9].

Although considerable progress has been made over the past few years in the understanding of the aforementioned intriguing properties, many of them have remain unresolved.

1.3 Approach

The major part of this thesis is spent on the development of specialized CMOS circuits which function correctly under the small, unreliable and highly variable power supplies that can be extracted from the interrogation field of an RFID system. In this dissertation, a number of the issues presented in Section 1.2 are highlighted and discussed.

The principal purpose of this work is to extend the bandwidth of the sampling circuits so that future generations of the RFID systems can operate well into the millimeter wave length frequency range. The first important improvement needed was to increase the RC cutoff frequency of the Schottky diodes that were used in power rectification circuits. By changing the doping concentration profiles of the diode and scaling down their geometries, a substantial improvement in circuit speed can be achieved. But, a problem with standard CMOS process is that we have no control over the doping concentration, so only the latter option, geometry, can be optimized. By using these techniques we managed to reduce parasitics, reduce loss and increase efficiency from 9% to almost 20%.

The other outcome of this work was the development of a turn-on circuit. A turn-on circuit is an interrogation field sensing circuitry which allows the battery to be connected to an active transponder (battery powered) only when communication is needed, thus lengthening the life of the battery.

Another outcome of this work was the development of an RF detector circuit for sensing a burst of high power microwave signal, even a nanosecond long. This kind of RF pulse can produce a shock that indiscriminetly disrupts and destroys unprotected CMOS circuits and devices.

Another aspect of the work is establishing, by the construction of experimental non-integrated prototypes prior to making a major commitment to IC fabrication, the practical feasibility of the fast multiple reading methodology referred to above.

Software Radio is a new technology where signal processing software is implemented on general purpose hardware platforms. Another aspect of this work is the implementation of a Software based Data Logging RFID reader, from here on referred to as SDLR. This approach can be used to solve many of the issues that traditional RFID readers face today. It can be used to enhance and accelerate the development of RFID wireless communication protocols.

As in RFID, signal processing tasks involve hard real-time constrains, the SDLR (with its built-in dedicated and powerful Digital Signal Processor) was used to perform low level tasks such as FFT, filtering, waveform shaping, etc. The results were then passed to a host PC for further study and analysis. Some of the analysis performed and documented in this work are RFID Communication Protocol Optimization, Baseband Recovery Timing Measurements, Read Range versus Frequency measurements and Reader Collisions Protocol Development.

Another focus of the work is the development of new multiple label reading and collision detection algorithms that will allow hundreds of labels to be read in a second. The design approach here is firstly to make use of advanced electromagnetic theorems which suggest a particular collision detection mechanism, and secondly to keep the label structure as simple as possible, at the expense of adding complexity to the interrogator.

The other outcome developed during this research was development of circuits for detection of signaling pulses and for stable time reference generation.

Experimental work was also carried out on labels with a kernel of state storage elements for temporary, unpowered, preservation of key data supporting the multiple read algorithm described below. Experimental work on extremely low power synchronous counter circuits for time reference generation were also studied.

Also under investigation are interrogator signaling methods that employ a combination of amplitude and phase modulation to improve signaling reliability, while still adhering to EMC regulations. Different but successful approaches for both HF and UHF systems are developed.

1.4 Organization

The first chapter of this dissertation, this chapter, offers an insight into the motivation and a brief overview of the thesis topics. The state of the art technology and how it can be improved as a result of this research is presented. The goals which should be finally achieved are mentioned in this chapter as well.

The rest of the chapters are separated into two parts. The first part is concerned with optimization and application of Schottky Barrier diodes on a standard CMOS process. The second part of this work deals with the optimization and implementation of a software based data logging reader and its applications in reader-to-reader and tag-to-reader protocol development. These two parts are outlined in more details in the following two sections:

There are also several appendices in which the work of the candidate is recorded.

1.4.1 Part One

Part one is divided into eight chapters. Chapter 2 begins with introduction to various theoretical and experimental techniques used for the characterization of planar Schottky diodes using a standard CMOS process. It is then followed by the compilation of important material and model parameters of the novel SBD.

Chapter 3 explains the detailed implementation of the diode environment. Most of the concepts and implementation know-how are documented here. Some sample IP cores for the novel Schottky Diode have been implemented and their performance is elaborated in Chapter 4. Previous work had shown that the designed diodes suffer from low breakdown voltage. In chapter 5 methods have been suggested to overcome these shortcomings and simulation results are presented.

The next three chapters emphasize the system advantages gained frm the implementatoion of SBD in an RFID transponder. The first case describes the use of the novel SBD in a turn-on circuit. The second case, analyzes and simulates its use in an RF detector circuit. Lastly, a comprehensive analysis of a charge pump circuit based on the novel SBD is presented.

1.4.2 Part Two

Chapter 9 reviews the technology background of SDLR and provides a basic system definition, while chapter 10 deals with the implementation issues. Chapter 11 deals with two cases where SDLR was used to investigate and improve the development process of particular aspects of RFID systems. The first scenario is about optimization of small antennas designed for objects with metallic surfaces and the second section is dedicated to the development of an anti-collision protocol for RFID readers in high density area.

The status of this thesis and possible future works are described in Chapter 12. Also, included in that chapter is a statement of my contributions to knowledge. Finally the appendix gives additional background information on the system development. Finally, the derivations of some of the equations which appear in the main body of the thesis are relegated to the appendices.

1.4.3 Appendices

In appendix A, we describe aspects of semiconductor theory relevant to the thesis and introduce the concept of Schottky diodes and their electrical activity. Further, an introduction to semiconductor theory, which forms the foundation for the interpretation of the Schottky diode property measurements, is given.

Appendix B lists the Matlab source codes of the scripts used in this dissertation. Appendix C lists the SPICE parameters, values of some important Physical constants, formulae derivations and sample calculations.

The basic research has been carried out in HSPICE. The VHDL implementation of the reader's decoder algorithm is based on the results obtained from the MATLAB simulations. Mentor Graphics FPGA Advantage for

Xilinx Spartan II FPGA has been used for the hardware implementation. All the signal processing algorithm are written in the C++ programming language and have been complied into machine code using Code Composer Studio from Texas Instruments.

1.5 A Note On Units

Although Standard International (SI) units have been defined for a long time, the literature describing semiconductor theory frequently make uses of units of cm or angstrom units for length, and units of $[cm]^{-3}$ for carrier concentration. In some equations this usage does not matter, as inappropriate units may sometimes form dimensionless ratios. In other cases serious errors may occur if one inserts numerical values not in SI units into one part of a formula for which it is traditional to use SI units in other parts of the equation.

We take the view that in a scholarly work SI units should prevail and we have adopted them throughout this thesis. We offer the caution that the reader who may extract numerical data from the literature should first check the units in which the data is offered and covert them into SI units before using them in the equations provided here.

Part I

Chapter 2

Novel Schottky Barrier Diode on Standard CMOS

The purpose of this chapter is to describe a layout design which can be used to implement a novel Schottky diode on a standard CMOS process. Thus, the design can be directly implemented into a standard CMOS process without adding costly extra process steps or mask layers.

2.1 Introduction

Fast switching speed and low forward voltage drop are favorable characteristics of Schottky diodes. These properties of Schottky diodes are primarily determined by majority carrier phenomena, while minority carriers determine those properties for pn junction diodes. Due to their excellent high frequency performance, Schottky diodes have been widely used in power detection and microwave circuits [57]. They are often fabricated by depositing metals such as titanium on n-type or p-type semiconductor materials such as GaAs or SiC [58].

In order to increase high frequency performance and decrease the power loss in rectifier circuits, it is important to integrate Schottky diodes into a modern CMOS process. But a process that can integrate Schottky diodes on CMOS are not widely available as they require extra mask layers and processing steps to be implemented.

Clever techniques exist to build Schottky diodes but they are fabricated with special processes which are not available in a full-scale standard CMOS fabrication facility [51]. Others require post processing of the CMOS chip using Focused Ion Beam (FIB) to build the Schottky diode after CMOS chip has been fabricated. Although the results might be promising, again it does not apply to RFID as the price of tags would increase dramatically if it were to add any extra process steps, such as FIB. It also worth mentioning that, FIB is a very lengthy process and it takes a long time, up to two hours, to implement a Schottky diode on a pre-fabricated CMOS chip.

Therefore this work is quite unique in that no publications were found on building a power rectifier circuit for RFID transponders using Schottky diodes on a Standard CMOS process.

2.2 Planar SBD on Standard CMOS Process

In designing a Schottky diode for RFID systems, both non-linearity of the capacitance and the RC cut-off frequency of the diode are of primary concern. A brief discussion of the diode fabrication is necessary at the outset because parasitics of the diode are functions of its geometry and physical implementation.

Implementing diodes on a standard CMOS process is designed specifically for ease of integration into circuits where the devices must be heavily packed and fabricated as a monolithic system. Figure 2.1 shows a cross-sectional view of the proposed novel Schottky Barrier diode that was fabricated for this project. It consists of a Schottky contact to an n-well active region and ohmic contacts to a heavily doped n+ layer. With this diode geometry the layout is compact and the extrinsic parasitic effects are minimized. That is an important factor for high frequency operation of the circuit.

Figure 2.2 shows a cross-sectional view and the schematic of the Schottky diode and its associated equivalent circuit elements. The Schottky contact has width of W, the length of the diode into the plane of the page is L and the separation between Schottky contact and ohmic contact is D. The capacitance of the Schottky diode, C, as given in Equation 2.1, is from the depleted space charge region with depth, d, where d is a function of applied reverse bias and is given by:

$$C = \frac{\epsilon W L}{d} \tag{2.1}$$

$$d = \sqrt{\frac{2\epsilon}{qN_d}\left(V_{bi} - V_{bias} - \frac{kT}{q}\right)} \tag{2.2}$$

The derivation of the above equations are given in the appendix A. The

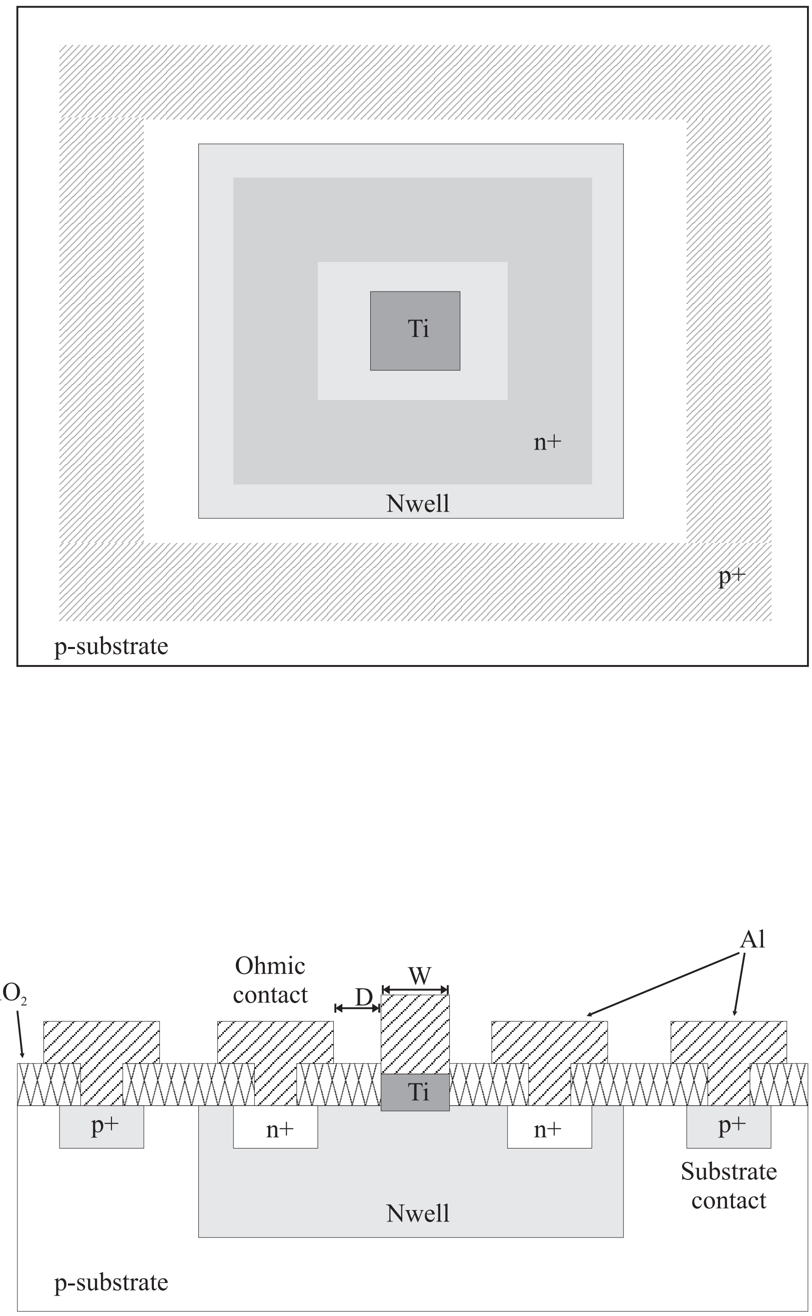

Figure 2.1: Top and Cross sectional view of a planar Schottky Barrier Diode.

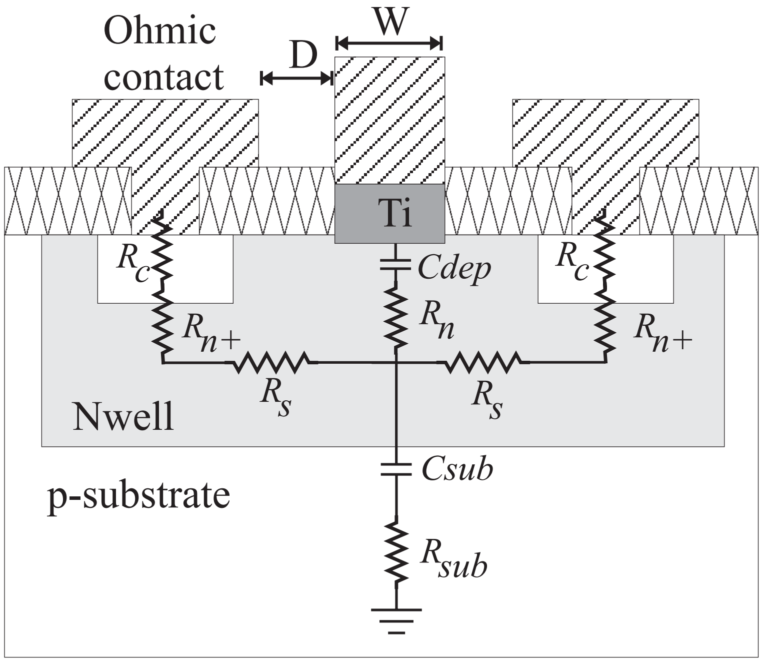

Figure 2.2: Equivalent circuit of Schottky diode, illustrating the various components of the series resistance.

sum resistance in series with this capacitance, R_{sum}, can be modeled as the sum of four components. The first element, R_n, is the n-well vertical resistance through the un-depleted portion of the n-well layer, where, the amount of un-depleted material is a function of bias. A 0 V bias is used as a conservative value because this resistance will be at its largest value, that is given by:

$$R_n = \rho_n \cdot \frac{T_{undep}}{WL} \tag{2.3}$$

where ρ_n is the resistivity of the n-well material and T_{undep} is the thickness of the un-depleted region at $0V$ bias. Because this is a sheet resistance, it is an area term and so its value is inversely proportional to $W \cdot L$. The second component of the resistance is the spreading resistance, R_s, that accounts

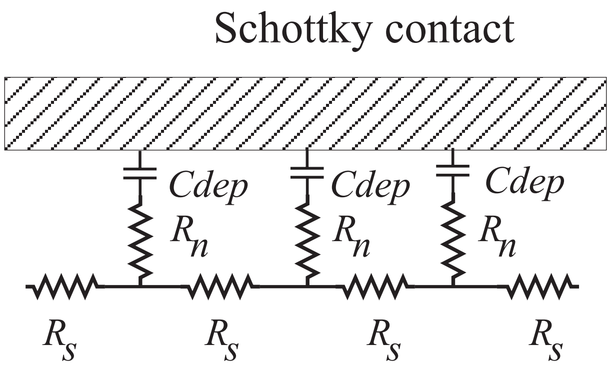

Figure 2.3: Diagram, illustrating the distribution nature of the resistance and capacitance of the Schottky contact [50].

for the spreading of the current flow under and around the Schottky contact into the n-well region. The value of R_s is given by:

$$R_s = \frac{1}{3} \cdot \frac{W}{4} \cdot \frac{1}{L} \cdot \frac{\rho_n}{T_n} \tag{2.4}$$

where ρ_n is the resistivity of the n-well material and T_n is thickness of the n-well layer. A factor of $W/4$ comes from the fact that the current travel only half the contact's width as it spreads out to either side, and that these resistances are in parallel. Another additional factor of 1/3 arises from the distributed nature of the spreading resistance and capacitance under the contact, which is analogous to the spreading resistance in the base of a bipolar junction transistor or the distributed resistance of the gate finger of a MESFET (Figure 2.3) [65].

The third component, R_{n+}, comes from the resistance of the $n+$ contact region due to the separation between the n-well and ohmic contacts:

$$R_{n+} = \frac{1}{4} \left(\rho_{n+} \cdot \frac{D}{L \cdot T_{n+}} \right) \tag{2.5}$$

and again the factor of 1/4 arises because there are four of them in parallel. The final component of the series resistance, R_c, is from the ohmic contacts:

$$R_c = \frac{1}{4L}\sqrt{\rho_{cont} \cdot \frac{\rho_{n+}}{T_{n+}}} \tag{2.6}$$

where ρ_{cont} is the specific contact resistivity. Because R_s, R_N, and R_c are inversely proportional to L and the capacitance is directly proportional to $W \cdot L$, decreasing W and increasing L to maintain a constant diode area reduces R_{sum} in proportion to C and consequently increases the cut-off frequency of the diode,f_{cls}, which is defined using the large signal capacitance of the diode:

$$f_{cls} = 1/(2\pi C_{ls} R_s) \tag{2.7}$$

This is analogous to the design of the base-emitter junction of a bipolar transistor where the dominant resistance is the base resistance, which is also a periphery dependent term, so by decreasing the emitter strip width, the $R_{base}C_{eb}$ time constant is reduced.

Equation 2.7 for the diode cut-off frequency is valid at low frequencies, but neglects several high frequency phenomenon that adversely affect the series resistance of the diode. The following discussion of these effects is taken directly from the work by Champlin and Eisenstein [63] and also includes their references to original work. Dickens [66] was the first to treat this problem in the context of a Schottky diode and showed that the high-frequency extension of the spreading resistance is an impedance Z that for circular geometries given by:

$$Z = \frac{1}{2\pi\sigma a}\arctan(b/a) + \frac{(1+j)}{2\pi\sigma\delta}\ln(b/a) \tag{2.8}$$

where b and a are the radii of the semiconductor and contact, respectively, σ is the dc conductivity of the semiconductor and δ is the skin depth given by:

$$\delta = \sqrt{\frac{2}{\omega\mu_0\sigma}} \tag{2.9}$$

in which μ_0 is the magnetic permeability of free space.

Equation 2.8 is based on two assumptions that are not generally valid for semiconductors in the sub-millimeter wave region. They are

$$\omega \ll \omega_{dr} = \frac{\sigma}{\epsilon} \tag{2.10}$$

where ω_{dr} is the dielectric relaxation angular frequency and

$$\omega \ll \omega_{\mathrm{scat}} = \frac{q}{m^*\mu_e} \tag{2.11}$$

where ω_{scat} is the scattering frequency, m_e^* is the effective mass of the electrons and μ_e is the mobility of the electrons. Making assumption 2.10 is tantamount to ignoring the displacement current and is the usual assumption that leads to 2.9. Assumption 2.11 is equivalent to ignoring the inertial mass behavior of the carriers in their response to an applied electric field [67].

Both assumptions can be removed from 2.8 by replacing the DC conductivity σ with the complex quantity