DEVELOPMENT OF RF TO DC CONVERSION CIRCUIT FOR ENERGY HARVESTING

by

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ABSTRAK

Permintaan peranti aplikasi tanpa wayar menunjukkan pertumbuhan yang ketara dalam era ini. Ini membawa kepada keperluan unit bateri berhayat panjang untuk membekalkan kuasa untuk peranti tersebut. Idea untuk memenuhi kenyataan ini adalah dengan menuai tenaga di persekitaran sebagai sumber untuk bateri. Di antara semua sumber, frekuensi radio mempunyai banyak manfaat kerana ia boleh didapati hampir di mana-mana, bebas biaya, dan ia tidak memerlukan penggunaan kuasa yang tinggi untuk menukarkan isyarat ke voltan yang dikehendaki. Walau bagaimanapun kajian terdahulu mengenai subjek ini mempunyai kesukaran untuk menukar isyarat RF kuasa rendah, kerana komponen diskret seperti diod, transistor dan MOSFET menggunakan operasi kejatuhan voltan yang tinggi. Satu lagi halangan yang alah isyarat frekuensi radio yang perlu ditukar harus berada dalam julat frekuensi tertentu. Oleh itu, matlamat tesis ini adalah untuk mengkaji, membangun dan mencadangkan litar penukar RF ke DC yang boleh mengatasi halangan-halangan yang akan dilaksanakan dalam aplikasi. Litar yang dicadangkan terdiri daripada penerus, pengayun cincin, pam caj dan pengatur voltan. Pennerus membetulkan isyarat input RF kepada voltan DC. Gabungan pam caj dan pengayun cincin bertindak sebagai penukar DC ke DC untuk menukarkan voltan masuk yang rendah ke voltan keluar yang lebih tinggi. Akhirnya voltan keluar DC akan dikawal kepada 1.2 V yang dikehendaki dan bersedia untuk disimpan dalam bateri. RF yang dicadangkan ke litar penukaran DC menggunakan teknologi CMOS 0.13 µm yang sesuai untuk aplikasi kuasa rendah. Litar yang dicadangkan disimulasikan dengan menggunakan perisian Cadence. Hasil simulasi menunjukkan litar penukaran RF ke DC boleh menukar isyarat RF -16.48 dBm ke voltan keluaran 1.2 V DC yang dikawal dengan beban 50 kΩ. Simulasi juga membuktikan bahawa litar yang dicadangkan boleh menukar jalur RF yang luas dari 900 MHz ke 2400 MHz.

Development of RF to DC Conversion Circuit for Energy Harvesting

ABSTRACT

The demand of wireless application devices shows significant growth in this era. This leads to the needs of a long life battery unit to supply power for wireless devices. Thus, the idea of fulfilling this demand is by harvesting the surrounding energy and channeling it as the source for the battery. Among all sources, radio frequency has a lot of benefits since it is available almost everywhere, cost-free, and it does not require high power consumption to convert the signal to a desired voltage. However, previous studies on this subject have highlighted difficulty in converting a low power RF signal, since the discrete components such as diode, transistor and MOSFET use a high voltage drop operation. Another common obstacle is the radio frequency signal that needs to be converted have to be within the specific range of frequency. Therefore, the objective of this thesis is to study, develop and propose the new RF to DC converter circuit that can overcome problems as to be implemented in the application. The proposed circuit consists of rectifier, ring oscillator, charge pump and regulator. The rectifier rectifies the RF input signal to a DC voltage. The combination of charge pump and the ring oscillator acts as a DC to DC converter to convert a low input voltage to a higher output voltage. Finally the DC output voltage will be regulated to a desired 1.2 V DC and ready to be stored in the battery. The proposed RF to DC conversion circuit uses a 0.13 µm CMOS technology which is suitable for low power application. The proposed circuit is simulated by using Composer Schematic Editor in Cadence software. The result shows that the RF to DC conversion circuit can convert a -16.48 dBm RF signal to regulated 1.2 V DC output voltage with the load of 50 kΩ. The simulation also proves that the proposed circuit can convert wide RF bands ranging from 900 MHz to 2400 MHz.

CHAPTER 1 : INTRODUCTION

1.1 Introduction

There are a lot of sources of the energy around our environment that are available and all those have different impacts on the environment. The energy sources can be classified into two types, which are nonrenewable and renewable energy sources (Alrikabi, 2014). The nonrenewable energy is finite and will replenish in a short period of time. The sources of nonrenewable energy come from our earth ground either in form of solids, liquids or gases. The good examples of this kind of energy sources are coal, nuclear, oil and petroleum gases. On the other side, the renewable energy sources are regenerated from time to time. Unlike non-renewable energy sources, these sources will not replenish for a long time. The typical renewable energy sources are biomass, hydropower, solar and wind. In today generation, the sources of nonrenewable energy are decreasing in volume from time to time and the demand of renewable energy is much more likely to be an option as a source for human usage.

These renewable energies can be captured or absorbed and converted to a usable energy that can be used in our daily life. The process of converting renewable energy to be stored in storage for later use is called as energy harvesting. Common source that is used in energy harvesting system is mechanical energy such as vibration and thermal energy like heaters and frictions (Puccinelli & Haenggi, 2005; Ostaffe, 2009; Mateuabd & Moll, 2005). The designs of energy harvesting processes are different from each other depending on the characteristics of the sources themselves. A device called transducer is needed for the conversion process from the energy source to an electrical energy. Each type of energy harvest use different transducer in their process. For example, the antenna is used as a device to receive the RF signal is sent to the electrical circuit for the RF conversion process. The solar panel is used to absorb the source of sunlight energy in solar energy harvesting process. Another example of transducer device is a wind turbine that rotates with the appearance of the wind and is used in the wind energy harvesting. However, some of the energy sources such as radio frequency provide energy in a very low power. Therefore these types of energy sources are significantly suitable for low power application such as wireless sensor network. It is also very suitable for battery backup application especially when a consumer is in the remote area or in an emergency situation. Table 1.1 below shows the study by Virginia Polytechnic Institute and State University (Virginia Tech) that presents the comparison of energy harvesting power based on different sources. As can be seen in Table 1.1, the average of power density generated by energy harvesting process is very low. Therefore, besides transducer, the energy harvesting process also needs electrical circuit to convert the small absorbed energy to a useful electrical energy before it can be stored in the battery. Generally, the circuit consists of a rectifier to convert the analog input to digital output and also the DC to DC converter to boost the input voltage to a higher output voltage. Some circuits implement additional option device such as a regulator or current limiter in their circuit for different purposes. The output voltage from the energy harvesting process finally is stored in the capacitive device such a battery or any storage elements.

Table 1.1 Power densities of multiple energy sources

Energy Source	Condition	Power Density
Solar	Outdoor	7.5 mW/cm^2
Solar	Indoor	100 $\mu W/cm^2$
Thermal	Δ T = 5° C	100 $\mu W/cm^2$
Vibration	1 m/s^2	60 $\mu W/cm^2$
Radio Frequency	Unless near to the transmitter	<1 $\mu W/cm^2$

The solar energy harvesting can be said as the most widely power harvesting technique. The power density that can be generated by the solar at noon is very high which is 7.5 mW/ cm^2. However, the geographical element plays significant role for this power harvesting technique. For example, the area that is directly under the sunlight receives high power density if compared to the area located near to the north and south pole. Moreover, the sunlight is only available at day time, which means that this technique cannot be used continuously. The weather also makes the result of the solar energy harvesting more unpredictable. Meanwhile the sources for thermal energy harvesting can be found easily. There are always sources of the thermal waste available such as machines and engines. The density of the thermal energy is also high; that is 100 μW/ cm^2. The problem is the application is very costly. The devices used in the thermal energy harvesting are expensive and the conversion process has low efficiency. The vibration energy harvesting technique use mechanical components as the sources of energy. The generated power is more predictable compared to other techniques since the components are usually controlled by human. But the problem is, some components are not reliable and have a limited operating period. As for RF energy harvesting, even though the power density is very low if compared to other sources the RF is much more available in the environment. The cost of the operation system is also considered very cheap. With the mentioned reasons, this study will focus on the radio frequency (RF) energy harvesting system.

1.2 Radio Frequency Based Energy Harvesting Application

Moving towards a non-stop technological invention eras, a possession of portable devices to do a routine work is a must. The increment of demand of wireless application devices especially for mobile phones and computers shows the importance of wireless application throughout the world. The usage of these devices however requires continuous supply or a long battery life in order to maintain the system. Without doubt, the batteries have a limited life time and present hazardous chemicals concern to safety matters. Therefore, it validates the importance of RF energy harvesting system.

This is because among all energy harvest sources, the RF is available and very easily found at any places at any time. In other words, unlike other sources the RF energy is independent from the time limitation, geographical elements or weather conditions. The RF is an electrical oscillation, with a frequency ranging about from 3 KHz to 300 GHz and carrying an alternating current. Some prominent electronic devices such as radio system (Frequency Modulation and Amplitude Modulation), wireless router (Internet and Bluetooth) and television transmission transmitted the radio frequency signal for data transferring. The idea is to harvest those RF energy sources and store it for our use in certain applications such as a laptop, mobile phone and others. Figure 1.1 below shows the principal of RF energy harvesting system.

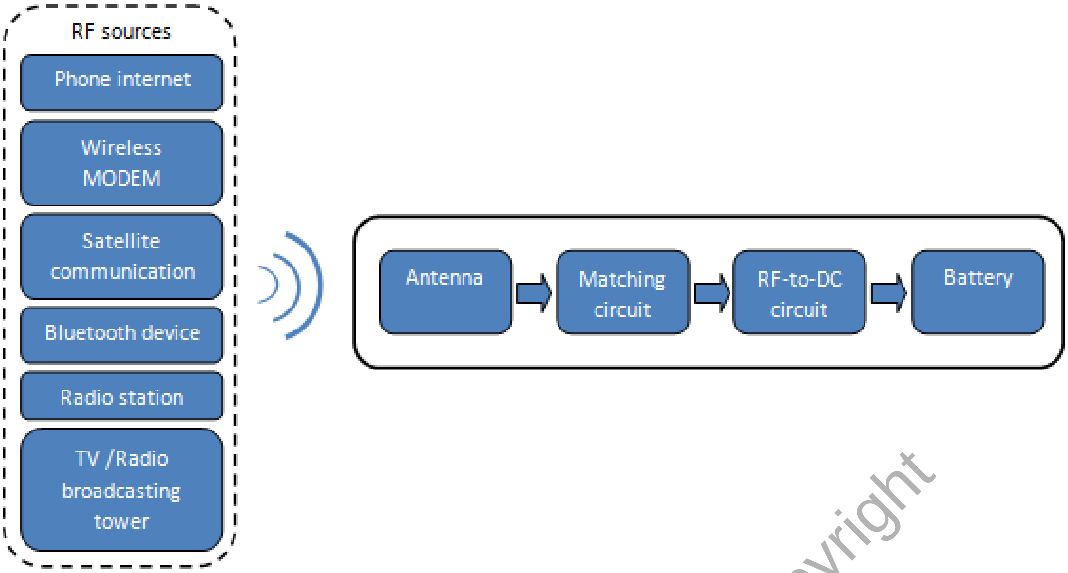

Figure 1.1 RF energy harvesting system

By using this concept, devices such as mobile phones can be used to make a call or access the internet while charging the battery at same time. Therefore, the study of power energy harvesting now becomes highlighted topic in order to optimize the supply of these technology devices. This outcome power can make the wireless application becomes affordable; promising more low cost maintenance and a longer battery life by implanting the device module with the ability to receive and convert the energy and store in a storage device.

1.3 Problem Statement

One of the objectives for this research is to determine whether the available RF has enough power to convert RF to DC voltage. As been discussed in section 1.1, the emitted RF signal has specific power range that is below 1 μW/ cm^2. Therefore the design of rectifier is important to ensure the rectifier is able to convert a small RF signal. A simple RF to DC converter can be created with simple diodes and capacitors.

Previous studies used this circuit as reference that focused on the antenna and layout of the RF energy harvesting circuit (Bouchouicha, Dupont, Latrach & Ventura, 2010; Harrist (2004).

However, the voltage is still considered high since the RF signal is usually in a very low amplitude voltage. This low power characteristic will make the conversion has a very low efficiency. Therefore, the importance of designing a circuit with the ability to convert a low RF signal is very high. The selection of components used in the design should be well considered.

Another difficulty is in regulation process where the desired DC output voltage is around 1.2 V. The regulator used in the design should have a very low power dissipation to ensure high efficiency of the circuit. Since V_{OUT} is designed to be fixed at 1.2 V and the current also depends on the load, the input voltage V_{IN} should be well considered. This is to avoid the devices from reaching maximum power dissipation. The input voltage should have maximum tolerance to avoid the elements inside the voltage regulator to be broken or having abnormal behaviour. Besides, the output voltage should have minimum ripple current to avoid the effect on load threshold characteristic. Ripple is a form of noise appear derives from an alternating current source.

1.4 Objective

The objectives of this research are:

- To study the RF to DC conversion circuit for low power application in radio frequency harvesting system
- To propose and design a 900 MHz and 2400 MHz RF to 1.2 V DC conversion circuit using 0.13 µm CMOS technology
- To simulate and analyse the performance of RF to DC conversion circuit for RF energy harvesting

1.5 Research Scope

This project will present a development of RF to DC circuit for energy harvesting. The goal of the project is to have a complete RF to DC circuit that can convert the RF signal and convert it to a DC signal so that it can be stored in the storage device. Therefore, it is essential that the circuit should have the ability to convert a RF signal which is in very low state, to a higher DC voltage. In this project, in order to convert the RF input signal to DC signal, the rectifier is used. The reason of the conversion process is that storage devices such as a battery only allowed to operate in DC. However, the rectified DC voltage is usually in very low amplitude. Therefore, after the conversion process, the DC signal is boosted to a higher DC level by using a charge pump. This is to ensure the DC voltage is high enough to meet the specification of the storage input specification. Finally, the regulator is used to regulate the DC voltage to 1.2 V output voltage. This value is chosen because 1.2 V is commonly used for RF front end circuit design.

The analysis and implementation of the circuit are simulated by using Composer Schematic Editor in the Cadence software. The topologies are analysed and studied to find the best design to be used in the circuit. The design is optimized to ensure that the output generated has better performance compared to previous studies. This project did not cover the measurement and test verification due to the limitation of the budget.

1.6 Thesis Organization

This thesis consists of five chapters. Chapter 1 discusses the overview of the study, the problem statement of the study, the objectives, the research scope and also the outline of the thesis.

The literature review is defined in Chapter 2. The basic RF energy harvesting system is described with block system. Then the architecture of each circuit is explained. The basic concept of each process is clearly defined. Chapter 2 also present the topologies that were used in previous studies, discussing the advantages and limitations of topologies used.

In Chapter 3, the design procedures are elaborated. The flowchart or structure of the study process is presented. In this chapter too, the schematic of proposed RF to DC circuit is defined in detail. The equation is stated to explain the theoretical effectiveness in the design. The last part of Chapter 3 indicates the concern arise during study.

Chapter 4 focuses on the simulation results of the proposed RF to DC circuit, the effects of the frequency, load, input voltage and other parameters. The result of each circuit is presented in table and plotted with elaboration. In addition, the comparison between the proposed circuit and previous works is also presented in this chapter.

Chapter 5 concludes the finding obtained in this research. In this chapter, the discussion of all works is summarized. The contributions of the research and the plans for further research are also included in this chapter.

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

In this chapter, the flow of the process that is used in the radio frequency energy harvesting system will be described in detail. There are several steps required in the whole system process, starting with rectification from the RF signal to DC voltage, then followed by combination of charge pump and ring oscillator then finished by regulator.

2.2 RF Energy Harvesting

2.2.1 Overview of RF Energy Harvesting

Energy can be harvested through lots of sources such as light, heat, vibration pressure and RF signals. The process of the radio frequency energy harvesting can be simply explained in Figure 2.1 which shows the common diagram for RF energy harvesting (Arrawatia, Baghini & Kumar, 2010). The basic concept of RF energy harvesting involves several devices such as antenna, matching circuit and RF to DC converter. The antenna is a device that is used as a signal receiver. The antenna will receive desired available signals in the surrounding area. The antenna should be able to suit certain frequency ranges which are commonly used in our environment. The RF signal received will be delivered from the antenna through the matching circuit which consists of inductive and capacitive elements. The purpose of the matching circuit is to allow the maximum power transfer from the input to the output. The signal then will go through rectifier circuit that converts it from RF power to DC power before filtering and smoothing the power to be stored in a battery (Nintanavongsa, Muncuk, Lewis & Chowdhury, 2010; Kim, 2011; Yaldi, Rahim & Ramli, 2016; Lau & Siek, 2017).

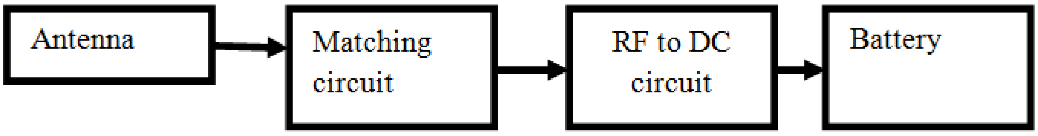

Figure 2.1 Block diagram of RF-DC energy harvesting system

Our surrounding is full of radiated emission from variety of electrical devices. The radio tower can provide around 5 µW/ cm^2 even in a kilometre distance. The effective area of antenna in cm^2 as signal receiver, A_{eff} and the power received by antenna, $P_{RECEIVED}$ can be described as;

$$A_{eff} \sim \frac{1}{8}\lambda^2 = \frac{1}{8}\left(\frac{c}{f}\right)^2 \tag{2.1}$$

where c is the speed of light (cm/s) and f is the signal frequency (Hz).

$$P_{RECEIVED} = A_{eff} \times Power\ densities \tag{2.2}$$

For example, the minimum area of effective antenna needed to receive the 900 MHz signal is 1.39 cm^2. If the power density of 5 µW/ cm^2 is provided by the radio tower, the power that can be generated from the RF circuit is 6.95 µW. The closer RF source is to the antenna device, the higher power densities can be received hence the higher power can be charged to a battery.

Some antennas are designed on PCB board with a rectifier circuit (Indumathi, & Karthika, 2015; Chen & Chiu, 2017; Abdullah, Shire & Mohd, 2016). This design is known as rectenna and the big advantage of this design is, it can save a lot of spaces. This rectenna includes the impedance matching circuitry and filters to immune noise generated by the external source. However, in this study the focus is on designing RF to DC circuit, which means the ability of antenna and matching circuit is neglected. Previous RF to DC converter circuit also didn't focus on the ability of the return loss and the efficiency of the converter circuit (Arrawatia et. al, 2010, Yaldi et. al, 2016, Nguyen et. al, 2014).

The development of RF to DC circuit is discussed in this paper. There are quite a number of challenges faced in previous RF to DC studies. The main challenge is to find the circuit that can convert as low as RF signal in our surrounding. This is to ensure the circuit can utilize the RF signal and has high efficiency. Besides that, the current RF to DC design usually has small range of frequency that can be converted. Since the RF is a wide band application, it is important to have a circuit that can convert a wide band of frequency. Previous studies also mainly focusing to have a higher DC output voltage. The amplitude of the output DC voltage represents how good the circuit is. However, in this study, the output voltage is desired to be 1.2 V because the value is suitable for RF front end circuit design. Hence, the proposed circuit can be used in many applications such as Low Noise Amplifier, PA and mixer in CMOS 0.13 µm technology. By using the Cadence software, the simulation and analysis of the circuits can be implemented to verify the circuit's performance.

2.3 RF to DC System Architectures

The RF to DC circuit is a combination of several systems that have different functionality in order to meet the target or goal of the complete circuit. Figure 2.2 below shows the block diagram of RF to DC conversion circuit.

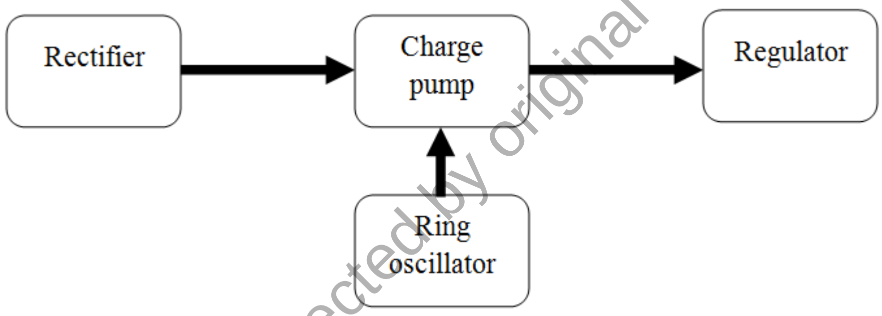

Figure 2.2 Block diagram of a complete RF to DC circuit

As can be seen in Figure 2.2, the signal comes in from the matching circuit; which is a radio frequency signal in an alternative current (AC). The AC signal will be rectified by the rectifier before it goes to a charge pump. The output from the rectifier, which is already in a direct current (DC) will be amplified using the charge pump circuit. While the ring oscillator is responsible to generate the pulse or frequency for the charge pump to operate. After that, the amplified DC signal will go to a regulator circuit. The purpose of regulator is to regulate or fix the voltage level of DC to the desired voltage. Since the application of the DC voltage is to be stored in the battery with requirement of voltage specification, therefore comes the need of the regulator.

2.3.1 Rectifier

Rectifier is an electrical device that converts the alternating current (AC) to direct current (DC). The process of this conversion is called rectification. The reason why rectification process is required in the system is because the input for storing devices such as a battery only allows the operation in DC voltage input. The basic rectifier can consist of a single diode that only allows forward current going through the component itself. Figure 2.3 shows basic voltage multiplier that uses diode based circuit as a rectifier (Bouchouicha et al., 2010).

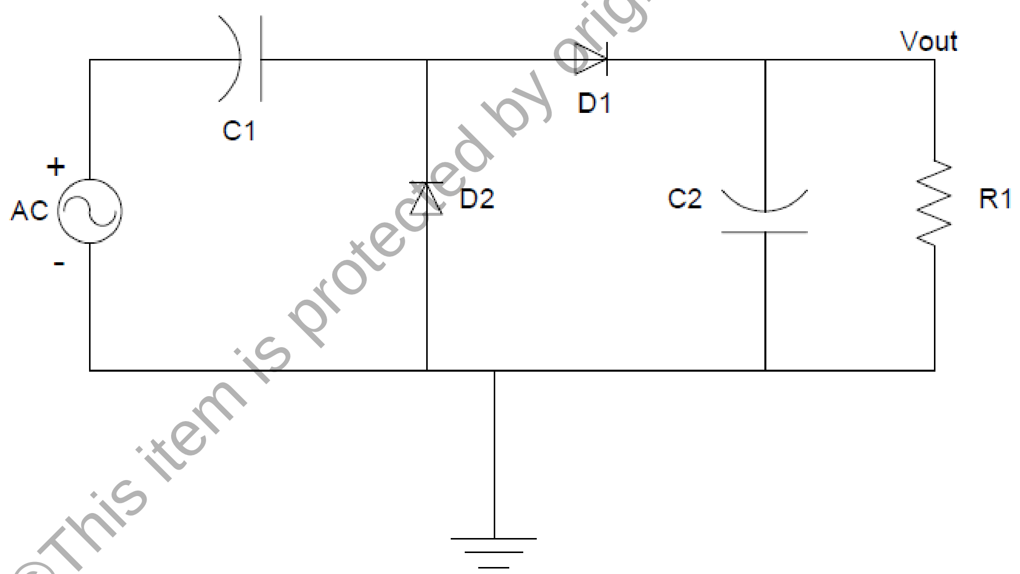

Figure 2.3 Diode based voltage multiplier (Bouchouicha et al., 2010)

A diode base rectifier multiplies the input voltage with the number of stages exist in the circuit. Assuming the diode's voltage drop is equal to zero; the output voltage, V_{OUT} can be calculated as Equation (2.3) (Lin et. Al, 2012):

$$V_{OUT} = N \times V_{IN} \tag{2.3}$$

where N is the number of stages. However this ideal case cannot be implemented in real application since the voltage drop of diode, V_F cannot be ignored. Hence previous equation should be as:

$$V_{OUT} = N \times (V_{IN} - V_F) \quad (2.4)$$

From Equation (2.4) it can be seen that the output is only valid if the diode voltage drop is lower than input voltage. As mentioned early, the available RF signals are ranging within small amplitude, usually lower than 250 mW. Therefore, the conventional diode cannot be implemented in the design which involving low input application since the voltage drop is usually around 0.65 V to 0.7 V. The usage of another type of diode which has lower voltage drop, that is schottky diode can be used in this design, but the efficiency of the circuit is questioned since the output voltage generated is low.

In early 2000, the usage of transistor rather than diode was studied. Figure 2.4 shows a new approach with the use of Pseudo-Schottky NMOSFETs appears to reduce threshold voltage. The Pseudo-Schottky diode is an NMOS diode with its body connected to the gate. Such device does reduce the body effect and thereby increase efficiency. However, since one of the MOSFET bulk terminals is connected to the ground and one terminal is connected to a voltage other than ground, isolation must be provided between bulk terminals.