Charge Pump Circuit Design

ABOUT THE AUTHORS

FENG PAN is doing circuit design at SanDisk Corporation, where he is involved in defining the architecture and implementing charge pumps and related high-voltage circuits over several generations of NAND Flash memory products. He is a holder of 18 U.S. design patents. Mr. Pan previously worked at AMD, where he contributed to the company's NOR Flash memory chip designs. He holds an MS degree from Stanford University and a BS degree from U.C. Berkeley.

TAPAN SAMADDAR is a design engineer at SanDisk Corporation, where he leads the company's high-voltage circuit designs. Previously, he was employed by T-RAM, Inc., where he was involved in the design of high-speed SRAM-compatible memory chips. He is a holder of several U.S. design patents. Mr. Samaddar has also worked on high-density NOR Flash memory at Atmel Corporation, and on high-speed cache memory designs at ST Microelectronics.

Charge Pump Circuit Design

Feng Pan
Tapan Samaddar

McGraw-Hill
New York Chicago San Francisco Lisbon London Madrid Mexico City Milan New Delhi San Juan Seoul Singapore Sydney Toronto

The McGraw·Hill Companies

Charge Pump Circuit Design

1 2 3 4 5 6 7 8 9 0 DOC/DOC 0 1 9 8 7 6

ISBN 0-07-147045-X

The sponsoring editor for this book was Wendy Rinaldi, the production supervisor was Jean Bodeaux, the editorial supervisor was Jody McKenzie, and the project manager was Samik Roy Chowdhury (Sam). It was set in New Century Schoolbook by International Typesetting and Composition. The art director for the cover was Margaret Webster-Shapiro.

Printed and bound by RR Donnelley.

Contents

Preface

Charge pumps are finding increased attention and novel diversified usage in the new era of nanometer-generation chips used in different systems, specifically those incorporating nonvolatile memory. Many of the present and future nanometer-generation chips' performance depend heavily on the ability to efficiently generate high voltages on-chip while meeting stringent power and area requirements. And yet, charge pump design, being purely analog in nature and involving high voltage, needs meticulous design techniques, intensive semiconductor device analysis, careful design layout planning, and accurate parasitic extraction process to produce excellent results in real implementation on silicon.

This book is a product of our years of quest for a practical book on charge pump circuit design. Having made significant contributions in different successful projects at various companies, we have always felt the need for a book on the topic of charge pump design. From our early days we constantly felt the challenge of working on a subject where there are no books and our sources of information were limited to only a few pages of description on various text books and different IEEE-published papers and journals. Most of these documents, while giving us skeletal ideas about the basic architecture and enhancements of charge pumps, did nothing to guide us intricately through different design conceptions and implementation processes. Charge pump, being a pure analog design, carries an inherent risk of unanticipated effects, which when overlooked can significantly reduce circuit performance or cripple the circuit operation.

Both of us have individually looked for books or materials on this topic and asked colleagues and veterans for any published materials, but we soon found out that everyone wished there was a book on this particular topic. By writing this book we have tried to bring our combined personal design experiences along with the knowledge assimilated from our study of different journals and research papers. This book covers the basics of charge pump circuits in detail and provides a thorough mathematical derivation and analysis of charge pump operation. It also strives to explain the different aspects for an excellent charge pump design, and explains each step in detail. Every effort has been made to provide enough hands-on design information, potential pitfalls to avoid, and practical ideas harnessed from our years of designing charge pumps, which are being used in many chips, finding mass scale adoption.

This book assumes a basic knowledge of semiconductor device physics and MOSFET operation and is targeted toward almost every semiconductor chip design engineer who is involved in analog circuit design and memory circuit design. The book takes a relatively novice reader through various aspects and gives sufficient information to enable him or her to complete their design from conception to actual layout implementation. Further audiences include systems designers and board level integrators. Also this book should be essentially helpful to almost all electrical engineering professors and students at all levels.

This book is organized into nine chapters. Chapter 1 starts with a history of charge pump evolution from the Noble award winning work of Cockcroft and Walton to the eventual adaptation of John F. Dickson. Chapter 2 is intended for a quick refresh of basic MOS device physics and different second order effects relevant to charge pump operation. It also discusses SPICE simulators and BSIM models while providing suggestions to avoid the dreaded SPICE convergence issue. Chapter 3 dives straight into the heart of charge pump operation and quantitatively analyzes the pump characteristics. Chapter 4 is where the basic implementation details are discussed along with different charge pump controlling blocks. It analyzes the different pump regulation schemes and quantifies them. Chapter 5, a prelude to Chapter 9, introduces the different parameters for charge pump specifications and discusses various implementation details. Now, once the basic operation of a 2-phase charge pump and its many characteristics and specifications have been understood, Chapter 6 takes it to the next level and discusses how to design a better charge pump. Chapter 7 discusses various charge pump architectures, such as the modified 2-phase charge pump, the 4-phase charge pump, and the CTS charge pump. Chapter 8 provides future design references and discusses different circuit and system effects that affect the performance of the pump. Finally, Chapter 9 provides a practical design example and discusses the influence of different parameters while analyzing the characteristics of a charge pump.

It is believed that if the reader applies appropriate techniques, which have been presented here, he or she should be able to design charge pumps that meet design and performance specifications and produce excellent operating circuits on silicon.

Feng Pan
Tapan Samaddar

Acknowledgments

I wish to acknowledge all the individuals who provided tremendous help and support. A special thanks go to Wendy Rinaldi and Alex McDonald, acquisitions editors, for believing in us as first-time writers, and guiding and supporting us throughout the entire duration of this project. I am thankful for Samik Roy Chowdhury (Sam) and his team at International Typesetting and Composition for all their assistance and hard work in making this timely production.

My co-author, Tapan Samaddar, for sparking the idea to write this book on charge pump design, and for his inspiring work in researching and completing this book.

My wife, Judy, for her patience and understanding. During the last year while she was pregnant, I had to work many late nights and weekends on this book. She encouraged me and supported me in many ways. I am very grateful to her. My lovely daughter, Tiffany, who was born in early April this year, for her trust and understanding in her daddy, and for forgiving her daddy for not being able to give her time. I am indebted to her. I would also like to thank my parents and my brother for their guidance and support throughout my life.

Many thanks to those who supported me in the past to make this book production possible.

Feng Pan

Writing this book began with a lot of energy and excitement. However, after about six months of persistent writing, drawing, and revising, while meeting tough deadlines, schedules, and surprises at the office, we reached midway in the book and immediately began to feel the streaks of insanity, realizing that the book will never finish on time. It was only through the continued efforts, support, and help of many outstanding individuals that we were able to complete this book.

A special thank you goes to Wendy Rinaldi and Alex McDonald, who have given us much needed guidance, helped encourage the progress, and collated the manuscript. Great appreciation is also given to Sam and his team, who did a marvelous job editing the manuscript, shaped it into a book, and helped finish everything on time.

My loving wife, Somali, has made many contributions, from typing characters and drawing figures to finding numerous errors and raising questions that made me reexamine my own understanding. I am very grateful to her for her support. I would also like to thank my mother and my father for providing me with emotional support and for all the help they have given me throughout the years.

Did I forget anyone? Thanks to all of you who inspired and provided support to write this book.

Tapan Samaddar

Introduction

The approaching nanometer generation of large-scale integrated (LSI) circuits requires power-supply voltages of less than 2 V to enable low-power operation and increased battery life. In addition, because low-power technology has become a primary target for the mainstream LSI designs to meet with the nomadic computing era, oxide thickness, transistor dimensions, and voltage-scaling approaches that are most effective for low power are accelerating and spreading at an unprecedented pace. Therefore, low-voltage circuit technologies for processors, memory, and analog circuits are intensively being investigated.

Many of the system blocks—such as EEPROMs, Flash memories, power management blocks, audio and video codecs, image sensor circuits, and displays—require internal voltages higher than the system supply voltage. This internal high-voltage supply needs to be generated in-system or on-chip. The traditional approach of switch-capacitor circuits or inductor-based linear regulators consumes too much power and silicon area to justify today's shrinking needs. An on-chip charge pump design provides an excellent solution and eliminates the need for an inductor. Having no inductor alleviates any potential electromagnetic-interference concerns that could have an impact on sensitive RF receivers or wireless chipsets. Another advantage is to reduce the cost of using discrete off-chip components. The charge pump solution eliminates the need for DC/DC boost converters and expensive low-profile inductors that are required to meet the size limitations of handheld devices and cellphones.

The advent of personal information devices, digital cameras, and MP3 players has fuelled a boom for nonvolatile memories, particularly Flash memories, because of their high-density, moderate power consumption and high endurance for mechanical shock and vibration. Solid state memories, such as Flash, contain no moving parts and allow for easy and fast data storage. EEPROMs and Flash memory have been some of the biggest drivers to create better and efficient charge pumps. Even though the supply voltage is decreasing, a Flash memory will still need a high internal programming/erase voltage, up to 30 V, regardless of the power supply trend, and this voltage also needs to be controlled precisely to achieve a narrow deviation in the threshold voltages of its memory-cell transistors.

A familiar problem in system engineering is the subsystem whose power requirements are not met by the main power supply. In such cases, the available supply rails are not directly usable, nor is the direct use of battery voltage (when available) always an option. Lack of space can prevent inclusion of the optimal number of batteries, and in other cases the gradually declining voltage of a discharging battery is not acceptable for the application. Voltage converters can generate the desired voltage levels, and charge pumps are often the best choice for these applications requiring some combination of low power, simplicity, and low cost. Charge pumps are easy to use, because they require no expensive inductors or additional discrete components. Further, charge pumps can be the only option for certain applications, such as those in telecom applications, which require generating +5 V from the available –48 V.

With the increasing popularity of color LCD displays in cellphones, PDAs, and digital cameras, white LEDs are becoming popular illumination sources. Whereas monochrome displays can use colored light sources, such as electroluminescent backlights or colored LEDs, color displays require a white light source to properly display color. The ubiquitous red and green LEDs have a typical forward-voltage drop of about 1.6 V to 2.4 V and can be driven by a simple battery pack. White LEDs, however, typically have a forward-voltage drop of 3 V to 4 V and are more likely to need a separate power supply. The traditional direct LED drivers and inductor-based boost converters have their own limitations. Charge pumps are increasingly finding ground in these applications due to their better performance—they provide the smallest and lowest-cost solution because they rely only on small capacitors for high voltage generation. As video features become more integrated into mobile phone use, improvements in power consumption for LCD backlighting are essential for the maintenance and improvement of overall battery life. Chip vendors competing for a share of this red-hot white LED driver market are pitching advanced charge pump sources that deliver greater backlighting power for the color displays in larger and more complex portable/wireless devices.

Therefore, much of the present and future chip performance will depend heavily on the ability to efficiently generate high voltages on-chip while meeting stringent power and area requirements. And yet, charge pumps, being purely analog in nature and involving high voltage, need meticulous design techniques, intensive semiconductor device analysis, careful design layout planning, and an accurate parasitic extraction process to produce excellent results in real implementation on silicon.

To summarize, charge pumps are finding increased attention and novel diversified usage in the new era of nanometer-generation chips used in different systems. This book strives to explain the different aspects for an excellent charge pump design, and explains each step in detail. It is full of extra hands-on design information, potential pitfalls to avoid, and practical ideas harnessed from the authors' years of charge pump design experience, which are currently being used in many chips, finding mass scale adoption.