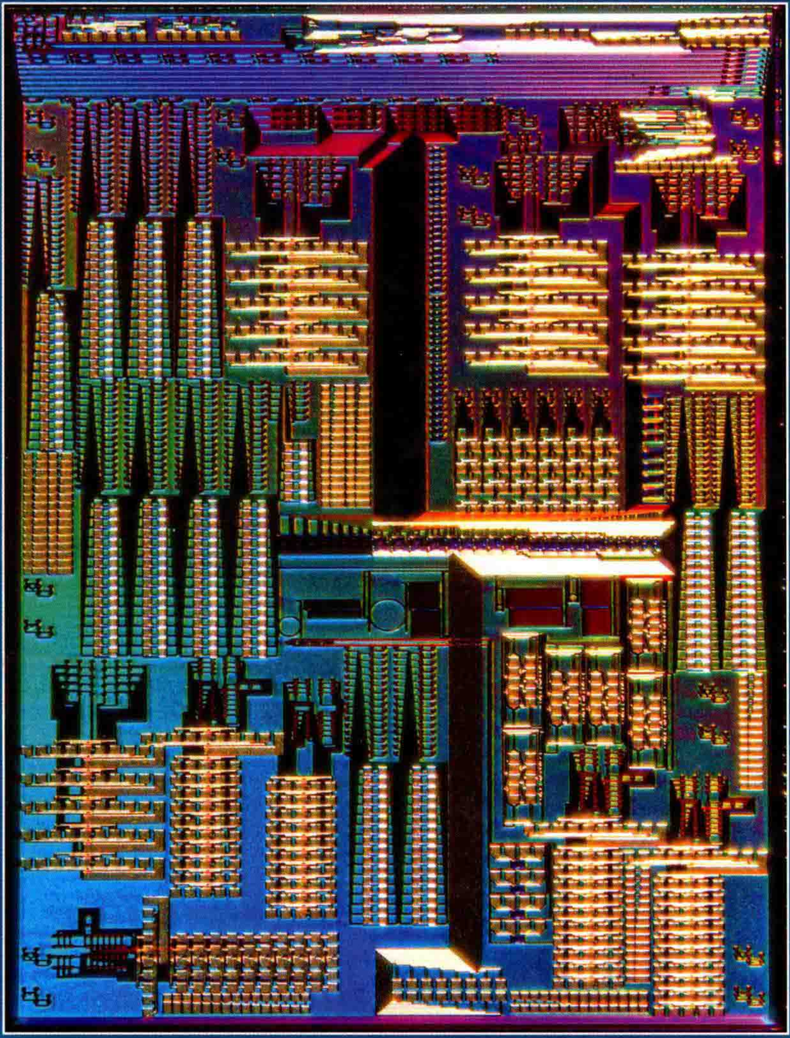
LUKAS CHROSTOWSKI
MICHAEL HOCHBERG



SILICON PHOTONICS DESIGN

FROM DEVICES TO SYSTEMS

Silicon Photonics Design

LUKAS CHROSTOWSKI
University of British Columbia

MICHAEL HOCHBERG
Coriant Advanced Technology Group

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Silicon Photonics Design

From design and simulation through to fabrication and testing, this hands-on introduction to silicon photonics engineering equips students with everything they need to begin creating foundry-ready designs.

Acquire practical understanding and experience
In-depth discussion of real-world issues and fabrication challenges ensures that students are fully equipped for future careers in industry, designing complex integrated systems-on-chip.

Cut design time and development cost
Step-by-step tutorials, straightforward examples, and illustrative source code fragments guide students through every aspect of the design process, and provide a practical framework for developing and refining key skills.

Industry-ready expertise
Providing both guidance on how a process design kit (PDK) is constructed and how to best utilize the types of PDKs currently available, this text will enable students to understand the design process for building even very complex photonic systems-on-chip.
Accompanied by additional online resources to support students, this is the perfect learning package for senior undergraduate and graduate students studying silicon photonics design, and academic and industrial researchers involved in the development and manufacture of new silicon photonics systems.

Lukas Chrostowski is Associate Professor of Electrical and Computer Engineering at the University of British Columbia. He is the Program Director of the NSERC CREATE Silicon Electronic-Photonic Integrated Circuits (Si-EPIC) training program, has been teaching silicon photonics courses and workshops since 2008, and has been awarded the Killiam Teaching Prize (2014).

Michael Hochberg is Director of Architecture and Strategy for Coriant Advanced Technology Group, based in Manhattan, NY, where he holds a visiting appointment at Columbia University. He has held faculty positions at the University of Washington, University of Delaware, and National University of Singapore, and was Director of the OpSIS foundry-access service. He has co-founded several startups, including Simulant and Luxtera and received a Presidential Early Career Award in Science and Engineering (2009).

"Photonics technology has created some of the most stunning achievements in human history, but the challenges of implementing even simple systems have made it the domain of a few specialized laboratories.

Silicon photonics enables the design of photonic systems in a much more streamlined manner, and the resulting designs can be fabricated by highly evolved silicon manufacturing facilities.

This book provides a complete guide, from physical principles of device operation through fabrication and testing, using real system examples. It gives non-specialists access to what may be the most important next step in information technology."

Carver Mead, California Institute of Technology

"The book covers everything one would need to design, lay out, simulate, and fabricate an actual silicon chip for processing, detecting, and modulating light signals. The book's focus on the practical side of chip implementation means that it is quite different, and frankly more useful, for chip designers than other photonics books. I highly recommend *Silicon Photonics Design* for both experienced designers and those wishing to get up-to-speed quickly in the nascent field of silicon photonics chip design."

R. Jacob Baker, University of Nevada

"*Silicon Photonics Design* is an essential text for anyone with an interest in the application of silicon-based optical circuits, either in a commercial or academic research environment. The authors have captured all of the essential elements of silicon photonics while ensuring the text remains accessible. The inclusion of so many worked examples mixed with detailed fundamental physical descriptions is an approach that must be applauded."

A. P. Knights, McMaster University

Contributors

Arghavan Arjmand
Lumerical Solutions, Inc., Canada

Tom Baehr-Jones
University of Delaware, USA

Robert Boeck
University of British Columbia, Canada

Chris Cone
Mentor Graphics Corporation, USA

Dan Deptuck
CMC Microsystems, Canada

Ran Ding
University of Delaware, USA

Jonas Flueckiger
University of British Columbia, Canada

Samantha Grist
University of British Columbia, Canada

Li He
University of Minnesota, USA

Nicolas A. F. Jaeger
University of British Columbia, Canada

Odile Liboiron-Ladouceur
McGill University, Canada

Charlie Lin
University of Delaware, USA

Amy Liu
Lumerical Solutions, Inc., Canada

Yang Liu
University of Delaware, USA

Dylan McGuire
Lumerical Solutions, Inc., Canada

Kyle Murray
University of British Columbia, Canada

Ari Novack
National University of Singapore, Singapore

James Pond
Lumerical Solutions, Inc., Canada

Wei Shi
University of British Columbia, Canada
Université of Laval, Canada

Matt Streshinsky
National University of Singapore, Singapore

Miguel Ángel Guillén Torres
University of British Columbia, Canada

Xu Wang
University of British Columbia, Canada
Lumerical Solutions, Inc., Canada

Yun Wang
University of British Columbia, Canada

Han Yun
University of British Columbia, Canada

Preface

The academic literature on silicon photonics is sufficiently rich that one might legitimately ask whether another book in this field is needed. Certainly all of the basic physics of waveguides, modulators, lasers, and photodetectors is covered in great detail in a series of landmark texts, from Yariv and Yeh [1] to Sze and Ng [2] to Siegman [3] and Snyder and Love [4]. More specifically integrated photonics theory is covered comprehensively in texts by Hunsberger [5], Coldren *et al.* [6], Kaminow *et al.* [7], etc. Several excellent volumes have come out in recent years describing the state of the field in silicon photonics, and discussing design considerations for a variety of devices [8–15].

So what are we aiming to add to this body of literature? Our aim is not to replicate any of the existing texts' approach, but instead to provide a practical, examples-driven introduction to the practice of designing practical devices and systems. Our (admittedly ambitious) goal for this text is to do something similar to what Mead and Conway did with their landmark text on VLSI [16]: to treat the minimal possible level of device physics, and to focus primarily on the practical design considerations associated with using state-of-the-art silicon photonic foundry processes to build real, useful systems-on-chip.

In order to do this, we focus on a series of tutorials, using the tools that are in use in our own labs. That doesn't mean that these tools are perfect, or that they are necessarily the best tools for any given application: they are just what we have used. Wherever there are alternative approaches, we highlight them and provide some context for why we choose to do things in a certain way. This is obviously an area where errors of omission are very easy to make: we welcome feedback and input.

The vendors of the commercial software we use provide in-kind access for educational institutions. For example, Lumerical Solutions software is available via the Commitment to University Education (CUE) program [17], which provides access to students in undergraduate and graduate classes. Similarly, Mentor Graphics has a higher education program [18] that provides software for classroom instruction and university research. The software has been available at the silicon photonics instructional workshops we have offered.

We also provide a cursory literature review in each chapter, as well as some exercises.

Silicon photonics – training programs

This book was developed in the context of training programs in silicon photonics led by the authors, specifically in the NSERC Si-EPIC Program (Canada) [19] and the OpSIS Workshops (United States) [20].

There are and have been several training opportunities in silicon photonics around the world, including the following.

- CMC Microsystems – University of British Columbia Silicon Nanophotonics Course (Canada) [21, 22], 2007–
- OpSIS Workshops (United States), 2011–2014

  OpSIS offered five-day intensive training workshops that have trained over 100 researchers and students in the design of silicon photonic systems.
- ePIXfab Europractice (Europe) [23]
- JSPS International Schooling on Si Photonics (Japan) [24], 2011
- Silicon Photonics Summer School (St. Andrews, UK) [25], 2011
- Summer School on Silicon Photonics (Peking University, China) [26], 2011–
- NSERC Silicon Electronic Photonics Integrated Circuits (Si-EPIC) Program (Canada) [19], 2012–

  This program offers four annual workshop/courses each of which includes a design-fabrication-test cycle. The workshops are on the topics of: (1) Passive silicon photonics, (2) Active silicon photonics, (3) CMOS electronics for photonics and (4) Systems Integration and Packaging
- plat4M Summer School Silicon Photonics (Ghent University, Ghent, Belgium) [27], 2014

Hochberg's acknowledgements

I'd like to thank Lukas for all the work that he's put into this volume over the past few years. Lukas is a truly gifted educator, and I'm constantly impressed by his ability to communicate complex ideas to students, both in a classroom and in writing. The overwhelming majority of the work that went into this book was his, with help from a number of the students in both his and my groups.

I'd like to thank both my and Lukas' graduate students, and Dr. Tom Baehr-Jones. Individuals contributing to the book are acknowledged below.

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Chrostowski's acknowledgements

I would like to thank Michael and Tom Baehr-Jones for their vision and pioneering efforts in silicon photonics over the past 15 years. In particular, their leadership at establishing a multi-project wafer foundry service for silicon photonics is greatly appreciated by me, my students, and colleagues throughout the world. I have enjoyed learning about silicon photonics design from both Michael and his group, and I appreciate Michael's willingness and efforts at educating silicon photonics designers and supporting the development of instructional workshops.

I am grateful for my colleague, Professor Nicolas Jaeger, with whom I have worked closely on both research and educational initiatives such as the silicon photonics workshops and the SiEPIC program. He has given me tremendous technical insight into guided-wave optics, microwave design, and high-speed testing, just to name a few topics.

I thank the numerous students and colleagues who contributed to this book, including those in Michael's group, students at UBC, and students across Canada and around the world with whom I have interacted via collaborations and at silicon photonics workshops. Numerous topics described in this book are a result of questions asked by participants at workshops and the interesting discussions that ensued. I also thank the readers of this book who have provided feedback over the past two years, particularly Robert Boeck and Megan Chrostowski. I thank colleagues for insightful discussions and collaborations that led to topics discussed in this book, including: James Pond, Dylan McGuire, Jackson Klein, Todd Kleckner, and Amy Liu at Lumerical Solutions; Chris Cone, John Ferguson, Angela Wong, and Kostas Adam at Mentor Graphics; Professors Shahriar Mirabbasi and Sudip Shekhar, and Han Yun at the University of British Columbia; Professors David Plant, Odile Liboiron-Ladouceur, and Lawrence Chen at McGill University; Professor Andrew Knights and Edgar Huante-Cerón at McMaster University; Professors Sophie Larochelle and Wei Shi at Laval University; Professor Dan Ratner and Dr. Richard Bojko at the University of Washington; Professor Jose Azana and Dr. Maurizio Burla at INRS; and Professors Joyce Poon and Mo Mojahedi, and Jan Nikas Caspers at the University of Toronto. I thank the foundries and services that have provided access to silicon photonic fabrication from which I have benefited, including CMC Microsystems, Imec, IME, OpSIS, BAE, and the University of Washington. I thank NSERC for funding our research, and in particular for funding the Silicon Electronic Photonics Integrated Circuits (Si-EPIC) CREATE research training Program.

Finally, I thank my wife, children and parents for their love and support.

Contributions

We acknowledge the direct contributions to the content in this book: Ari Novack – photodetector theory and experimental data (Chapter 7); Wei Shi – ring resonator model (Section 4.4, pn-junction model (Section 6.2) and ring modulator model (6.3);

Yun Wang and Li He – fibre grating couplers (Section 5.2); Dylan McGuire – model development for the modulator and detector (Section 6.2.4, 7.5); Amy Liu – scripts for the modulator (Section 6.2.4); Arghavan Arjmand – scripts for the detector (Section 7.5); Jonas Flueckiger – photonic circuit circuit simulations (Chapter 9) and automated testing (Section 12.2); Miguel Guillén Ángel Torres – directional coupler FDTD S-parameters (Section 9.4); Robert Boeck – fabrication corner analysis (Section 11.1.2) and directional couplers (Section 4.1); Dan Deptuck and Odile Liboiron-Ladouceur – design for test and check-list (Section 12.3); Yang Liu and Ran Ding – WDM transmitter (Section 13.1); Matt Streshinsky – Mach–Zehnder modulators; Kyle Murray – parasitic coupling (Section 4.1.7); Chris Cone – process design kit; Samantha Grist – SEM images; Han Yun – test setup and diagrams; and Nicolas Jaeger and Dan Deptuck – co-development of the CMC-UBC Silicon Nanophotonics Fabrication workshops and Si-EPIC workshops which formed the basis for this text.

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Contents