Silicon-Germanium Heterojunction Bipolar Transistors for mm-Wave Systems: Technology, Modeling and Circuit Applications

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Silicon-Germanium Heterojunction Bipolar Transistors for mm-Wave Systems: Technology, Modeling and Circuit Applications

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Preface

The demand for high-speed circuits and systems has steadily increased over time. Led initially by automotive safety (radar), silicon-germanium (SiGe) heterojunction bipolar transistors (HBTs) and their combination with complementary metal-oxide-semiconductor (CMOS) transistors into highly integrated BiCMOS process technologies have become a very attractive solution for a plethora of present and prospective applications operating at frequencies from 30 GHz up to several 100 GHz (so-called mm-waves). Such applications range from communications (presently driven by 5G) to imaging in public transportation (security), medicine and biology, just to name a few. Requiring device performance beyond CMOS, above applications were traditionally placed into the realm of III–V technologies. With the goal of providing highly integrated and cost effective mm-wave electronic systems employing high-speed SiGe HBT front-end circuitry integrated with high density CMOS digital processing capability, the two European Commission funded joint research projects DOTFIVE (2007–2010) and DOTSEVEN (2013–2016) were instrumental in making SiGe HBTs and BiCMOS technology competitive and attractive for the above mentioned applications.

DOTSEVEN was a highly successful project, which not only lifted SiGe HBT performance to an unprecedented level but also provided the theoretical understanding of this new HBT technology as well as the demonstration of its capabilities. Key to the project's success was the excellent cooperation within the consortium consisting of partners from the different and complementary areas of process engineering, device modeling and circuit design. This book summarizes the important results of DOTSEVEN in more detail than the many associated publications and thus addresses not only expert readers familiar with the technology but also students and others who like to learn more about SiGe HBT technology or need a concise overview in one of the associated research areas. In each chapter, the research described is motivated and put in perspective by an introduction that provides sufficient background and additional literature for supporting the understanding.

Not covered though are fundamentals of device physics, process technology and circuit design. Here, the reader is referred to the standard text books in each area.

This book is organized as follows. The Introduction provides the motivation for pursuing HBTs, in particular those based on SiGe, and for setting-up the DOTSEVEN project. Its organization and a brief description of the various work packages are presented, which mirror the relevance of the respective topics for the project. Here, also the most important results are briefly summarized in a single place.

Chapter 1 “SiGe HBT Technology” first introduces the relevant metrics used to evaluate transistor performance. Then, those HBT device and process architectures are explored that have been pursued within DOTSEVEN. It is shown why the conventional double-polysilicon self-aligned selective epitaxial growth approach limits the simultaneous increase of transit and power gain cut-off frequency. The solutions overcoming these issues and leading to the new vertical and lateral architecture developed within DOTSEVEN is described and documented by experimental results.

Chapter 2 “Device Simulation” addresses different types of numerical simulation and visualizes the results through many examples. First, the simulation of isothermal (in terms of the device temperature) carrier transport is discussed. In particular, deterministic solutions for the Boltzmann transport equation and the trade-offs necessary for applying computationally more efficient simulation approaches for device optimization are described as they were pursued within the project. The second part covers electro-thermal simulation based on coupling the impact of phonon scattering and corresponding self-heating with carrier transport simulation. The resulting simulated temperature increase is used to develop methods for accurately determining the thermal resistance from the simulated DC characteristics. Third, hot-carrier effects in advanced SiGe HBTs are investigated employing microscopic simulation.

Chapter 3 “SiGe HBT Compact Modeling” starts with an overview on the standard HBT compact model HICUM Level 2. Afterwards, the most recent extensions related to DOTSEVEN, which were mostly targeted towards the intrinsic device operation are described. This is followed by a detailed discussion of the corresponding parameter extraction methods, including bias, geometry and temperature dependence. Geometry scaling and modeling of the intra-device substrate coupling concludes this chapter.

Chapter 4 “(Sub)mm-wave Calibration” addresses the electrical high-frequency on-wafer characterization of the fabricated HBTs, which

becomes inaccurate beyond 220 GHz when using traditional methods. The conventional calibration and deembedding techniques are reviewed, followed by a discussion of the signal propagation modes in transmission lines on lossy substrates as they are encountered on a silicon wafer. Direct on-wafer calibration up to the device-under-test ports is then introduced, using a special transmission line configuration. As a demonstration, a comparison of measurements using this technique with HICUM is shown for frequencies up to 325 GHz.

Chapter 5 “Reliability” reports on the medium- and long-term degradation of the fabricated advanced HBTs due to hot carrier stress. The measured impact of hot carriers generated during device operation on DC and low-frequency noise characteristics is shown and compared to the results of a correspondingly extended HICUM version. Furthermore, self-heating is investigated, which is becoming increasingly important in downscaled high-performance devices and plays an important role in device degradation. A method for determining the thermal resistance is described and corroborated on thermal simulation data. Finally, different analytical models for describing the thermal resistance as a function of geometry are compared.

Chapter 6 “Millimeter-wave Circuits and Applications” is divided into three parts. First, simple basic building blocks termed benchmark circuits are considered which serve mostly for verifying the compact models in a circuit environment, but can also be used for benchmarking the technology performance. For each of the selected examples a sensitivity study reveals the most important transistor parameters. The second part reports on larger circuit building blocks as they would be used in a system. Examples are given that demonstrate competitive high-frequency circuit operation down to 0.5 V supply voltage and thus very low power consumption. The third part describes the three mm-wave demonstrator systems and their building blocks that were realized with DOTSEVEN technology, namely a 240 GHz Transceiver for ultra-high data rate wireless communication, a 210–270 GHz circularly polarized radar, and a 0.5 THz computer tomography system. The latter is the first-ever purely silicon based tomography system operating at such frequency.

Chapter 7 “Future of SiGe HBT Technology and Its Applications” puts the DOTSEVEN results in perspective by comparing, based on the standard performance metrics, the different technology options for mm-wave and future sub-mm-wave applications. A more intriguing perspective is provided when looking at the transistor operation within circuits, where the load

comprised of parasitics from connections to other devices and the latter themselves paints a different picture of transistor speed as given by standard metrics. In view of the ITRS/IRDS roadmap for SiGe HBTs, which grew out of the modeling effort in DOTFIVE and DOTSEVEN, it is shown that HBTs in general have a bright future for realizing high-frequency systems. Their near future is discussed for different (sub-)mm-wave application areas based on DOTSEVEN results as a reference.

We hope that this book is a useful reference for a wide range of readers interested in mm- and sub-mm-wave technology, devices, and applications.

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List of Abbreviations

ATSF	Aging Time Scale Factor
BBA	Broadband Amplifier
BC	Base–collector
BEOL	Back-end-of-line
BiCMOS	Bipolar Complementary Metal Oxide Semiconductor
BJT	Bipolar Junction Transistor
BTB	Band-to-band
BTE	Boltzmann transport equation
CB	Common base
CE	Common emitter
CL-ICPW	Capacitively loaded inverted coplanar waveguide
CM	Compact model
CMC	Compact model coalition
CML	Current mode logic
CMOS	Complementary Metal-Oxid-Semiconductor
CMP	Chemical mechanical polishing
CPW	Coplanar wave guide
DC	Direct current
DPSA	Double-poly-Si self-aligned
DT	Deep trench
DUT	Device under test
DUV	Deep ultraviolet
EB	Emitter–base
EBL	Epitaxial base link
EM	electro-magnetic
FEM	Finite-element method
f _{max}	Maximum oscillation frequency
FoM	Figure of Merit
fps	Frames per second
f _T	Transit frequency
Gbps	Gigabit per second

GCPW	grounded coplanar wave guide
GICCR	General integral charge-control relation
G-R	Generation-Recombination
HBT	Heterojunction Bipolar Transistor
HBT	Heterojunction bipolar transistor
HC	Hot carrier
HD	Hydrodynamic
HF	High-frequency
HICUM	High Current Model
IFX	Infineon Technologies AG
IHP	Innovations for High Performance microelectronics
II	Impact ionization
IIP3	Third-order input intercept point
IMD	Inter metal dielectric
InP	Indium phosphide
ITRS	International technology roadmap for semiconductors
LDD	Low-doped drain
LNA	Low-noise amplifier
LRM	Line reflect match
LSQ	Least squares
MM	Mixed-mode
mm-wave	Millimeter wave
MOSFET	Metal-Oxid-Semiconductor Field Effect Transistor
NSEG	Non-selective epitaxial growth
P_DC	Power dissipation
PA	Power amplifier
PDK	Process design kit
PPW	Parallel plate waveguide
RF	Radio frequency
RTP	Rapid thermal processing
RTS	Random telegraph signal
SCR	Space charge region
SEG	Selective epitaxial growth
SEM	Scanning electron microscope
SH	Self-heating
Si	Silicon
SIC	Selectively implanted collector
SiGe	Silicon germanium
SOI	Silicon on insulator

SOLR	Short open load reciprocal
<i>s</i> -parameters	Scattering parameters
SPICE	Simulation Program with Integrated Circuit Emphasis
SRH	Shockley-Read-Hall
ST	Shallow trench
STI	Shallow trench isolation
STM	STMicronics
TCAD	Technology computer-aided design
TE	Transverse electric
TEM	Transmission electron microscopy
TM	Transverse magnetic
TRL	Thru reflect line
VCO	Voltage controlled oscillator
VNA	Vector network analyzer
W-band	90 to 110 GHz frequency range
WP	Work package