Introduction to the Special Issue on Microwave Circuits on Silicon Substrates

IF SOMEONE were to say that silicon (Si) integrated circuits (IC's) are responsible for the tremendous advances made by mankind over the past 40 years, they would be able to make a very strong defense of their statement. Si IC's are so woven into our lives that it is nearly impossible to find an appliance, automobile, communication device, toy, or any other common household or workplace tool that does not rely on them, and our children cannot even imagine our society without Si-based computers and worldwide communication systems. Yet, for ten years, the microwave engineering community pretended that Si did not exist. Instead, we developed GaAs and InP substrates and an entirely new fabrication technology and design logic for working with these exotic materials.

This was not done out of ignorance of Si or an arrogance on the part of microwave-circuit designers. It was done because Si did not provide the performance required for microwave circuits, and our customers were very different from the Si IC customers. With regard to performance, Si bipolar junction transistors (BJT's) and MOSFET's, the two transistors which the electronic-technology development relied upon, did not have a high enough maximum frequency of oscillation for microwave circuits operating above a few gigahertz. Also, the low resistivity of common-grade Si wafers (1–20 $\Omega \cdot$ cm) severely degrades microwave transmission-line characteristics when they are fabricated using the same technology used for circuits on ceramic and other low-loss printed circuit-board materials. The market for microwave IC's was primarily driven by government needs for higher frequency, secure communications, radars that could discriminate smaller objects, and sensors that could see through adverse weather conditions. For each of these uses, performance was the most important design criteria. Therefore, GaAs and InP technologies, two technologies that have excellent microwave-circuit characteristics, were developed under government leadership and, luckily for the microwave industry, these government customers were not driven by cost.

Market conditions have changed in the past ten years. Government funding has decreased and government purchasing agents have become increasingly more cost conscience. In addition, a very strong commercial industry, which is always low-cost/high-profit driven, has developed and is now selling microwave circuits for mobile communications, intelligent highway systems, sensors, and many other applications. Of course, these new markets would all be using GaAs and InP monolithic microwave integrated circuits (MMIC's) if fundamental advances in Si circuits did not occur.

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Microwave engineers and Si-device designers rose to the challenge. First, transmission lines on standard Si wafers with low loss were developed using multiple layers of thin insulators such as polyimide or glass to isolate the electromagnetic fields from the Si substrate. Alternatively, high-resistivity Si wafers became available on the commercial market which permit Si circuits to be designed using the expertise developed for GaAs circuits. At the same time, Si-device designers developed at first, active and passive Si diodes for operation at frequencies up to 100 GHz, and then, with the availability of advanced growth techniques such as molecular beam epitaxy (MBE) and ultra-high vacuum chemical vapor deposition, Si/SiGe/Si heterojunction bipolar transistors (HBT's). These transistors use the material properties of Ge to enhance the common n-p-n BJT and enable Si-based circuits to be fabricated which operate through 60 GHz. Best of all, these transistors are compatible with standard Si processing techniques and, therefore, enable mixed-circuit design; circuits that integrate digital and microwave analog circuits onto a single substrate.

There are several advantages of mixed circuits. First, systems requiring fewer circuits have lower packaging and handling costs and better reliability. Second, the overall electronic system is smaller since circuit-to-circuit interconnects are eliminated and the packages are smaller. These smaller circuits with fewer interconnects (wire bonds, ball bonds, or flip-chip bonds) also reduce parasitic reactances that degrade circuit performance. While these two advantages are surely worth the development of Si microwave circuits, it is the other possibilities that are more exciting. High-speed digital circuits combined with Si analog IC's will permit novel receivers and transmitters that use digital filtering, mixing, and frequency synthesis to replace the lossy microwave filters, mixers, and oscillators of our past. Also, microelectromechanical (MEM) devices, which are usually fabricated on Si substrates, may be integrated with Si microwave IC's and digital-logic circuits to create sensors that communicate with each other through RF transmissions.

This Special Issue on Microwave Circuits on Silicon Substrates is the first IEEE TRANSACTIONS MICROWAVE THEORY AND TECHNIQUES issue to deal entirely with the advances that are occurring in Si microwave circuits. As Editors of this Special Issue, we are pleased to be able to present 18 contributed papers and 2 invited papers which thoroughly present the current state of the art and the new options available to microwave-circuit designers. The issue starts with two outstanding invited papers which, together, present the state-of-the-art of Si microwave circuits and the potential that this technology possesses. These are followed by papers that present device models and characteristics, transmission-line models and characteristics, and finally circuits employing these new technologies.

This issue would not have been possible without the contributions of the outstanding review committee that aided us in selecting those papers which are included in this issue. Each paper was reviewed by a minimum of two reviewers with extra reviewers brought in if the editor required further comments and opinions. To accomplish this review cycle in the short time required for special issues is a great burden on the reviewers and we, therefore, thank them for their efforts in making this issue a success. The reviewers, in alphabetical order, are as follows:

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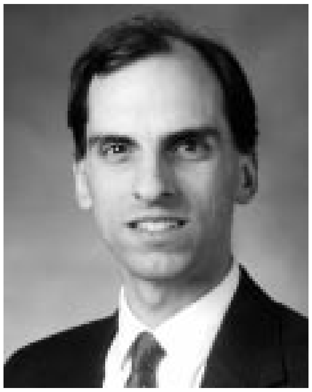
Johann-Friedrich Luy (M'86–SM'96) was born in Stuttgart, Germany, in 1958. He received the Dipl.-Ing. degree for his investigations on heat conduction in semiconductor lasers and the Dr.-Ing. degree for his thesis on the first silicon MBE-made IMPATT diodes from the Technische Universität München, Munich, Germany, in 1983 and 1988, respectively.

In 1983, he joined the former AEG Research Center and worked on silicon IMPATT diodes. Since 1989, he has been engaged in research on Si/SiGe millimeter-wave devices and circuits (SIMMWIC's). The development and application of these circuits in near-range radar sensors and communication links is the main focus of his current interest as Head of the Microwave Department, Daimler-Benz Research Center, Ulm, Germany. He was co-editor of *Silicon Based Mm-Wave Devices* (Berlin, Germany: Springer-Verlag, 1994), and Distinguished Lecturer of the IEEE Electron Devices Society in 1996/1997.



George E. Ponchak (S'82–M'83–SM'97) received the B.E.E. degree from Cleveland State University, Cleveland, OH, in 1983, the M.S.E.E. degree from Case Western Reserve University, Cleveland, OH, in 1987, and the Ph.D. degree from the University of Michigan at Ann Arbor, in 1997.

In July 1983, he joined the staff of the Communication Technology Division, NASA Lewis Research Center, Cleveland, OH, where he is currently a Senior Research Engineer. He is interested in the development and characterization of microwave and millimeter-wave printed transmission lines and passive circuits, multilayer interconnects, dielectric waveguides, uniplanar circuits, microwave microelectromechanical (MEM) components, and microwave packaging. He has been responsible for the technical management of GaAs, InP, and SiGe monolithic microwave integrated cirucit (MMIC) development grants and contracts. In addition, he is interested in the reliability of GaAs and SiGe MMIC's for space applications. He has authored and co-authored over 40 papers in referred journals and symposia proceedings. He is a Visiting Lecturer at Case Western Reserve University during the 1997/1998 school year.

Dr. Ponchak is a member of the IEEE Microwave Theory and Techniques Society (MTT-S) and a member of the International Microelectronics and Packaging Society (IMAPS). He received the Best Paper Award presented at the IMAPS 1997 International Microelectronics Symposium.