Overview of Floating-Gate Devices, Circuits, and Systems

THIS Special Issue of the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS II is focused on circuits using floating-gate MOS transistors. These devices are well known from EPROMs, EEPROMs, and flash memories. The primary principle is that the polysilicon gate of an MOS transistor completely wrapped in silicon dioxide maintains stored charge for a long time. Since the first report of floating-gate devices in 1967 [1], digital floating-gate circuits have developed into a mature technology present in every personal computer [2].

Since the floating-gate devices are full-blown MOS transistors, it is tempting to utilize them as analog circuit elements. Already in the late 1980s, floating-gate devices were used in analog circuits for analog nonvolatile memory elements (the Intel ETANN chip [3]) and for circuit tuning (Mead's ultraviolet adaptive retina [4]). During the 1990s, an increasing number of applications were published, uncovering new and exciting ways of using floating-gate devices [5]–[8], including audio recording products based upon analog floating-gate memories [9]. Another surprising aspect is that floating-gate devices are available in standard CMOS processes [10], [11], although double polysilicon layers are recommended for floating capacitors. As a circuit available in standard CMOS technology, floating-gate circuits should find wide use in analog microelectronics by giving researchers a wider set of solutions. As a result, floating-gate devices are not just for memories anymore, but are circuit elements with analog memory and important time-domain dynamics.

As part of the 1999 International Symposium on Circuits and Systems (ISCAS) in Orlando, FL, we organized a special session on "Floating-Gate Circuits and Systems" that attracted a significant number of good contributions. Based on this positive response, we organized a special issue of this TRANSACTIONS and issued a call for papers. After a normal reviewing procedure, a total of ten regular papers and five short papers were selected for publication in this special issue.

The aim of our efforts is to present advanced floating-gate circuits and systems exhibiting the versatility of floating-gate devices. To our best knowledge, this collection of papers represents the state-of-the-art within this exciting field. Most of the papers have verified results in silicon. We hope to remove something of the exotic "special effect" image of floating-gate devices and to promote floating-gate circuits to a place as part of the standard engineering repertoire. Hopefully, we will have triggered some interest, making more people join this exciting research.

Floating-gate devices and circuits are classically divided into three major directions. We will briefly describe the 15 papers in this Special Issue within the framework of these three areas. Floating-gate devices are used: 1) as analog memory elements; 2) as part of capacitive-based circuits; and 3) as adaptive circuit elements. Two papers in this issue that begin to address the use of floating-gate circuits in systems will be introduced separately.

I. ANALOG FLOATING-GATE MEMORY AND TRIMMING ELEMENTS

Floating-gate devices can be used for long-term nonvolatile information storage devices for analog applications. Because a floating gate is a polysilicon gate surrounded by silicon dioxide, charge on the floating gate is stored permanently, providing a long-term memory. Because a large number of electrons can be stored on an integrated circuit capacitor, we can store a nearly continuous analog voltage. Furthermore, the charge on this floating gate can be modified by projecting ultraviolet (UV) light on the chip, by applying large voltages across a silicon-oxide capacitor to tunnel electrons though the oxide, or by adding electrons using hot-electron injection [6], [8].

This TRANSACTIONS presents three different applications of programming floating-gate elements for analog memories, to optimally set threshold voltages, and to trim errors in analog circuits. Analog or mixed-mode VLSI chips typically have a large number of inputs and analog parameters, and the number of available pins is often a limiting factor in these systems. "A CMOS Programmable Analog Memory Cell Array using Floating-Gate Circuits" by Harrison *et al.* proposes an analog floating-gate memory element for on-chip storage of bias voltages, therefore saving external pins. Harrison *et al.* used floating-gate technology to eliminate off-chip-biasing voltages in the existing system by providing these voltages on-chip with arrays of programmable floating-gate voltages. The array of floating-gate memory elements can be individually programmed either up or down by straightforward digital controls. More than 13-bit resolution is achieved with a simple off-chip tuning scheme.

In "Programming Floating-Gate Circuits with UV-Activated Conductances," Berg *et al.* explain how shot-wave ultraviolet (UV-C) light applied to floating-gate devices may be used to tune threshold voltages for optimal performance. By building circuits with a programmable threshold voltage, the threshold voltage can be set to a convenient location for a given circuit. Threshold tuning will also enable ultralow supply voltages in regular CMOS technology, reducing headroom to a minimum. They describe a UV threshold-voltage programming scheme of coupled pFETs and nFETs where the power rails are inverted during programming. The UV-activated tuning technique imposes significant circuit restrictions.

In the short paper titled "A Programmable Current Mirror for Analog Trimming Using Single-Poly Floating-Gate Devices in

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Standard CMOS Technology," Jackson *et al.* present a tunable current mirror where high precision is achieved even with small devices. In the short paper "A Practical Floating-Gate Muller-C Element Using vMOS Threshold Gates," Rodriguez *et al.* approach digital gates using floating-gate devices for threshold adjustment. Dense structures are achieved using multiple control gates to a common floating gate.

II. FLOATING-GATE CIRCUITS

Floating-gate circuits provide IC designers with a practical continuous-time capacitor-based technology, instead of the resistor-based technology used in discrete circuits. A floating gate occurs when we have no dc path to a fixed potential, precisely the effect traditionally avoided by many circuit designers and circuit simulators. The floating-gate voltage can modulate a channel between a source and drain and therefore can be used in computation. Capacitors coupling into this floating gate become effective gates of this transistor, where the gate strength depends upon the capacitor size.

Floating-gate devices can compute a wide range of translinear functions by capacitive couplings into floating-gate devices with exponential current-voltage relationships [7]. "Multiple-Input Translinear Element Networks" by Minch *et al.* explores multiple inputs to a shared floating gate for implementing translinear functions with subthreshold MOS or BiCMOS devices. Another paper by Minch *et al.*, "Multiple-Input Translinear Element Log-Domain Filters," explains how useful circuits like log-domain filters may be implemented using the "multiple input translinear element" (MITE) structure.

Floating-gate devices can become integral parts of continuous-time amplifiers and filters. In "Ultra-Low-Voltage Floating-Gate Transconductance Amplifiers," Berg *et al.* describe highly linear amplifiers with rail-to-rail operation with supply voltages of less than 1 V. In "MITE Circuits: The Continuous-Time Counterpart to Switched-Capacitor Circuits," Ramirez-Angulo *et al.* address the wider application of floating-gate circuits in arenas typically addressed only by switched-capacitor filters. They therefore give an alternative approach for several analog design problems. This paper addresses a range of problems, from basic voltage dividers to fixed coefficient finite impulse response filters and digital-to-analog converters.

In the short paper "Floating-Gate-Based Tunable CMOS Low-Voltage Linear Transconductor and its Application to HF GM-C Filter Design," Muñoz *et al.*use floating-gate structures to create a low-voltage transconductance amplifier. Even at 1.2-V supply, high-frequency operation is achieved. The following short paper, "Low-Voltage CMOS Op-Amp with Rail-To-Rail Input and Output Signal Swing for Continuous-Time Signal Processing Using Multiple-Input Floating-Gate Transistors" by Ramirez-Angulo *et al.*, presents an analog signal-processing element for weighted signal summing.

III. ADAPTIVE FLOATING-GATE CIRCUITS

Floating-gate circuits have the inherent ability to adapt to the incoming and outgoing signals by continuously enabling various programming mechanisms. This property was the fundamental motivation behind the development of single-transistor synapses: single floating-gate FETs that emulate some of the computational and adaptive properties of biological synoptic elements [6]. These elements enable floating-gate currents to be modulated in a continuous fashion (using complementary electron tunneling and hot-electron injection processes) without significantly altering the circuit's behavior. "Continuous-Time Feedback in Floating-Gate MOS Circuits" by Hasler illustrates the spectrum of continuous-time adaptation dynamics and shows a method to take advantage of devices that, under normal operation, have nonnegligible hot-electron and tunneling currents. This paper builds the foundation to use a dynamic adaptation scheme to maintain circuit properties, to build stable continuously adapting floating-gate circuits, and to use small-signal modeling of floating-gate devices including programming currents. "Correlation Learning Rule in Floating-Gate pFET Synapses" by Hasler *et al.* presents the first report of floating-gate elements that continuously adapt to correlations of terminal voltages; correlation elements are fundamental to building adaptive filters and neural networks. Once the adaptation is finished, the resulting network state is preserved nearly indefinitely, due to the nonvolatile property of floating-gate devices.

Of the several examples of continuously adapting floating-gate circuits, one of the most elegant examples of an adaptive floating-gate pFET circuit is presented in "An Autozeroing Floating-Gate Amplifier (AFGA)" by Hasler *et al.* The AFGA uses tunneling and pFET hot-electron injection to adaptively set its dc operating point. Because of feedback applied to the floating gate, this adaptation is an inherent part of the circuit's operation—no additional control circuitry is required. The AFGA demonstrates how to use continuous-time floating-gate adaptation in amplifier design and is an example of how one of many classical engineering problems is solvable using floating-gate techniques. The short paper titled "A Second-Order Section Built from Autozeroing Floating-Gate Amplifiers" by Hasler *et al.* uses the AFGA structure to implement a second-order filter with tunable corner frequency and quality factor. This paper shows one of many examples of using AFGAs as the basis of many capacitor-based continuous-time filters and sensor interface circuits.

IV. FLOATING-GATE SYSTEMS

Two full papers report systems using floating-gate devices. The first, "Floating-Gate Adaptation for Focal-Plane On-Line Nonuniformity Correction" by Cohen *et al.*, presents a stochastic scheme for adaptive gain correction in photovoltaic systems like cameras. The second,"A Programmable Continuous-Time Floating-Gate Fourier Processor" by Kucic *et al.*, carries out the complex task of weighting different frequency bands with an analog weight stored on floating gates. The bandpass mapping is done with analog signal processing. We expect several more system-level designs using floating-gate devices and circuits in the near future.

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