The Resonant Body Transistor

NEEDS 2012-2017 (needs.nanohub.org)
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May 2017

Background

Prior to the beginning of the NEEDS program, the HybridNEMS Lab at MIT, led by D. Weinstein, had developed and demonstrated a Resonant Body Transistor (RBT) [1], a novel, unreleased, active NEMS resonator that leveraged CMOS transistors for high efficiency electromechanical sensing at multi-GHz frequencies. These resonators are driven capacitively using the thin gate dielectric of the CMOS process, and are actively sensed with a Field Effect Transistor (FET) incorporated into the resonant body. The resulting RF-NEMS resonators operate at orders of magnitude higher frequencies than possible with passive devices. This device provided an interesting and challenging set of modeling issues that drove a big portion of our work in NEEDS. Design and optimization of the RBT required modeling across multiple domains, including mechanical (distributed stress and elastic wave models), electrical (semiconductor devices and RF small signal models), and thermal. These domains are all cross-coupled with nonlinear interaction, and require computationally intensive finite element multi-physics analyses. This prevented quick, intuitive parameterization of device design. A simulation-ready compact model parameterized across all three domains, therefore, was necessary for both device optimization as well as for system-level circuit design using the RBT.

What were the goals?

The ultimate goal for this part of the project was to develop and deploy Verilog-A models for NEM RBTs.

What was accomplished?

A.1 Released Resonant Body Transistor Model (2014)

An RBT is a micro-electromechanical (MEM) resonator with a transistor (FET) incorporated into the resonator structure to sense the mechanical vibrations. The electrostatic drive of RBTs using internal dielectric transduction, along with the FET sensing, enable these devices to easily scale to multi-GHz frequencies. Together with the potential for monolithic CMOS integration, they represent a potential candidate for uncountable timing and RF applications that continuously drive the technology towards minimization of size, weight and power. In our project we have developed a compact model for RBTs with the aim to capture the diverse and highly entangled physics intrinsic to the original RBT. The model was aimed to present a deep insight into the physics of the RBT while emphasizing the effect of the different parameters on the device performance. It was also intended to grant circuit designers and system architects the ability to quickly assess the performance of prospective RBTs, while minimizing the need for computationally intensive finite element method (FEM) simulations. The model has been deployed in public domain on nanohub.org and is now available at https://nanohub.org/publications/17/1.

A.2 Released Resonant Body Transistor Model with MIT Virtual Source Model (2015)

A *released* RBT Verilog-A compact model, based on the MIT Virtual Source (MVS) transistor model, has been developed as part of the work. A modified MVS implementation was used to model the active piezoresistive FET sensing in the RBT. The instantaneous stress in the channel, as found from the mechanical module of the model, modulates the FET mobility in the MVS model. The mobility is now a simulation unknown, as opposed to a static parameter. The MVS model captures the accurate dependence of the drain current on the instantaneous mobility. Another modified MVS implementation was adopted to model the MOS capacitor (MOSCAP) driving for the RBT. This module calculates the resulting electrostatic stress from the available charge on the gate dielectric. This accurately accounts for the dependence of the electrostatic force on the MOSCAP biasing conditions. The full RBT Verilog-A model has been deployed in public domain on nanohub.org in August, 2015. It is now available at https://nanohub.org/publications/72/1.

A.3 Unreleased 1D CMOS Resonant Body Transistor with MIT Virtual Source Model (2016)

A model for 1D *unreleased* RBTs has also been developed. The model relies on equivalent transmission line sections to model the acoustic Bragg reflectors (ABRs). These are used to confine the elastic vibrational energy and to create a completely solid resonator, without any air gaps or exposed moving surfaces [2]. The use of transmission lines closely matches the actual wave propagation physics in the device and allows for accurate device parameterization. The adoption of such implementation simplifies the study of random CMOS process perturbations, and more importantly, the *mismatch* between the individual ABR sections due to random manufacturing variations. This RBT model still relied on the MVS FET model for active piezoresistive sensing. The full Verilog-A model has been deployed in public domain on nanohub.org in March, 2016. It is now available at https://nanohub.org/publications/132/1.

References (* denotes work supported or partially supported by NEEDS)

[1] D. Weinstein and S. A. Bhave, “The Resonant Body Transistor” Nano Letters, vol. 10, no. 4, pp. 1234–1237, 2010.

[2] B. Bahr, R. Marathe, and D. Weinstein, “Theory and design of phononic crystals for unreleased cmos-mems resonant body transistors” *Microelectromechanical Systems, Journal of*, vol. PP, no. 99, pp. 1–1, 2015.