

Bio-compatible Insulated Substrate Impedance Transducers

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Abstract — An alternative *smart sensing* paradigm to large-scale biocompatible integration has been explored. Traditionally, conductive bio-labels detection profits from planar interdigitated electrodes (IDE) encapsulated between for instance a top thin alumina layer and a bottom thick silicon dioxide. Despite demonstrating good electrostatic sensitivity at strong micro-labels densities, such patterns however require sub-micron shrinking to work below 30 % conductive labels coverage. We therefore derived a spectroscopic field-effect transducer from micrometric IDE coupled to a thinly insulated surface-doped silicon channel. Thanks to capacitance enhancement that results between electrodes and semiconductor, label-induced field-effect modulation of channel's conductance gives rise to an intrinsic dielectric relaxation constant change subsequently measured by impedance spectroscopy. So-called Insulated Substrate Impedance Transducers (ISIT) have thereby been designed to sense an inter-digital impedance spectrum change following a frequency-dependent multi-parameter approach. In demonstration, metallic grains densities ranging from 1.2 % to 17 %, ensued from 0 to 1 nM concentrations of silver-labeled 30bp DNA targets were sensed in air on 100x100 μm^2 arrays through conductance and capacitance variations by factors of 6 and 3, respectively. Our presentation will focus on simulation, optimization and characterization of ISIT's electrical operation, and present on-chip tuning possibilities associated with substrate back-contact biasing.

Keywords — sensor, labels, interdigitated array, field-effect, dielectric impedance

I. INTRODUCTION

Although nano-structured devices may directly detect biomolecules, they still require expensive technological processing or problematic large-scale integration with regards to standard CMOS. The development of alternative measurement methods or other smart sensors fully exploiting the properties of present integrated circuit technologies thus remain of interest. Chemical labels are commonly used to enhance bio-molecular targets influence at micro-scales, in order to allow sensors sustained characterization down to their detection limits. We already demonstrated silver-labeled DNA hybridization sensing, down to 0.05 nM in concentration, by means of a few tenths of pico-Farads increase in air (+40 % versus calibration) [1] (fig. 1). Deriving from such capacitive detection of deca-nanometer silver

crystals with aluminum electrodes covered by thin alumina, we envisioned alternative structures supporting dielectric impedance spectroscopy in a complex parameters approach. Our semiconductor device [2] therefore couples micro-IDE to a surface-doped silicon channel insulated by a high-quality oxide, 30 nm thick (fig. 2). Solid-state Insulated Substrate Impedance Transducers (ISIT) are nothing like transistors, thin-film resistors or capacitors for they output an image of the outside medium as an intrinsic impedance spectrum. In presence of metal, channel's conductance field-effect modulation is measured through electrode-oxide-channel capacitors, thereby interpretable as a dielectric relaxation constant change. Dry silver DNA labels densities below 25 % were sensed on micrometric ISIT through about 38 dB admittance change, typically. Following design, fabrication and validation, devices dynamic tuning capabilities based on substrate back-contact bias will hereafter be exposed.

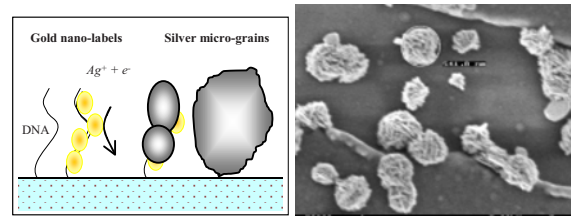


Fig. 1 DNA treatment and labels view (Ag \varnothing 0.7 μm , Scanning Electron Microscope)

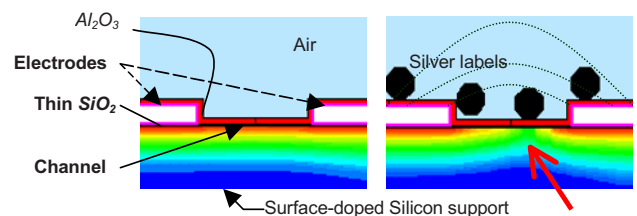


Fig. 2 ISIT normal cut (left) and target labels' influence (right)

II. ISIT FUNDAMENTALS

A. Structure and work principle

As evoked in introduction, ISIT operation involves its channel's Fermi level alignment to the outside metal work-

function. In parallel with extrinsic capacitance increase due to target labels therefore occurs a decrease of its intrinsic conductance (fig. 3). One practical advantage at low targets densities resides in getting information by field-effect through the channel when the outward capacitance yet doesn't shift much. The major distinction of ISIT with regards to other devices however refers to its actual MOS structure. Channel's resistance is indeed observed through surface capacitance C_{SiO_2} , which converts a conductance change into a relaxation constant shift: $\tau = R_{channel} \cdot C_{SiO_2}$. Such approach follows an innovative paradigm of intrinsic dielectric spectroscopy guiding the solid-state transducer design. Among remarkable properties, one can cite frequency tuning capabilities through surface oxide modification and/or electrodes' sizing, which determine C_{SiO_2} , or through doping adjustment that determines $R_{channel}$. Last but not least, randomly distributed labels will produce a non-scalar distribution of relaxation constants as an image of local grains densities, also carrying statistical data about the outside stimulus.

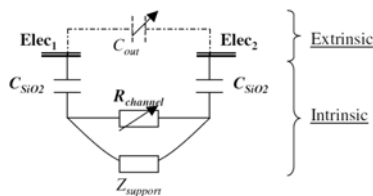


Fig. 3 Lumped elements electrical model

B. Design, materials and methods

In order to optimize labels-channel interaction with regards to semiconductor energy bands curvature induced by silver or other metallic labels (fig. 4), N-type phosphorous channel doping was selected as starting condition. Numerical simulations (Synopsys ISE-TCAD) allowed evaluating optimum doses and implantation energies, which will be discussed later.

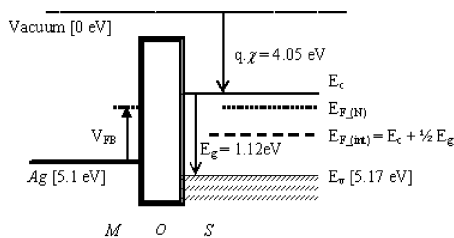


Fig. 4 ISIT sensing area's energy band diagram

The fabrication of 350 x 350 μm² ISIT was conducted as follows. After bulk wafers piranha cleaning (10¹⁵ Boron-doped <100> Silicon), the CMOS process consisted in thermally growing 80 nm field SiO₂ (950°C, 2:44' with C₃₃ gas), subsequently wet-etched in HF after photolithography and re-oxidized up to 27 nm to create active zones (950°C, 0:45'). Following phosphorous full-wafer implantation (5.10¹¹ cm⁻², 20 keV), complementary MOS re-oxidation (950°C, 0:10') elevated the channel oxide's thickness to 31 nm while annealing impurities and returning about 100 nm thick field oxide. Electrodes' fingers having 2 μm width and equal spacing were then patterned on top of active zones through 300 nm thick pure aluminum lift-off (Microchemicals AZ5214 photoresist), subsequently covered by 100 nm of alumina ensued from supplementary 50 nm thick Al layer sputtering and anodization (with U_{max} = 70 V at 3 mA/cm² in ammonium pentaborate and ethylene glycol). Annealing (30 minutes at 432°C) finally followed backside Al contact deposition.

The biochemical process was already detailed in previous publication [3].

C. Results and discussion

Three operation regimes can be identified on the equivalent capacitance curves measured and simulated in air (fig. 5 and 6, resp.):

- at low frequency, planar MOS C_{SiO2} contribution dominates;
- at higher frequencies, parasitic Z_{support} base value due to bulk support and far-field air emerges;
- in between, intermediate cut-off frequencies depend on labels density influence on channel conductance.

In addition to capacitance shifting therefore occurs a parallel conductance change in measurements, in accordance with simulations (fig. 7 and 8). In spite of significant standard deviations due to low number of test chips and measurement hazards, including fabrication mismatches and biochemical noise, practical results generally match very well computed characteristics. Smooth decrease in capacitance curves is typical of multiple relaxation constants: a unique dipole would instead manifest itself at one, sharper cut-off frequency. The "20% Ag" simulated characteristic of figure 6 typically shows a couple of such decrease rates, associated with either 1 or 2 labels per interdigital space. Note that conductance curves are given in absolute value since ISIT display negative dynamic resistance in certain frequency ranges, attributed to transmission line behavior along the fully insulated channel.