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Open Innovation of CMOS-MEMS Integrated Devices by Open Facility

Yoshio Mita

Department of Electrical Engineering and Information Systems, The University of Tokyo
MEXT Nanotechnology Platform VDEC Nanofabrication Site, The University of Tokyo
Room 111, Bldg. Eng. 3, TheUniversity of Tokyo
7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
Phone/FAX: +81-3-5841-6023 E-mail: mems@if.t.u-tokyo.ac.jp

Abstract

A research and development scheme "Integrated LSI" through open facility is proposed. The term "Integration" in the "LSI" stands for "putting homogeneous component (i.e. transistor switches) in a same chip", whereas the first term "Integrated" refers to "combining the LSI device together with various electro, mechanical, chemical, and (even) biological components". In accordance to recent trends in R&D, such integration with exotic materials is more and more demanded and on the same time has become accessible by public through the open facilities including the Nanotechnology Platform UTokyo VDEC site. Advantage of such technology together with a couple of device examples are presented in the paper.

1. Introduction

Since over 60 years, integration and miniaturization have been the guiding principles of electronic devices. As early as the invention of transistor in the 1950s, the concept of Integrated Circuit (IC) was proposed, and has rapidly been industrialized. Around 1970s, the term IC has been replaced by Large Scale Integration (LSI) then Very Large Scale Integration (VLSI), along with the technology evolution. Applying LSI components and / or fabrication technology to sensing device fabrication has as long history as VLSI; by careful design consideration, a solid material such as silicon can be used as deformable structural material [1]. Such devices have been called microsystems and / or Micro Electro Mechanical Systems (MEMS). To date, inertial sensors, display devices, and inkjet printing heads are most successful MEMS devices made out of LSI technology.

One of the principle causes of high MEMS sensitivity is its scale. For example, it is possible to create mechanical spring having spring constant k around 1, in both MEMS-sized (i.e. microns) and human-sized (i.e. centimeters to meters) scales, and applying force of micronewton gives the same amount of bending, i.e. microns. However, the bending is 1:10,000 (almost negligible) as compared to human-size spring, whereas for MEMS spring the movement is comparable to their size (~1:1). Therefore there is a strong interest in miniaturizing sensing elements. To eliminate parasitic components and / or to obtain parallelism, signal treatment circuits are integrated either on the same chip, or in the same package.

Towards the year 2020s, there are two tracks of increasing demands: one is from application (top-down) side, and the other is from material side (bottom-up). From application side, specialists try to further explore new abilities of sensing and actuation devices in their various R&D domains. The domain may directly attached to the society's problems such as devices that help peoples' healthy and secure life, and / or to devices that help R&D works such as devices that help quality assessment in production and experiments in fundamental research. From material side, many *new* (i.e. non-standard Silicon) materials are being integrated with LSIs, associated with new process methods.

To develop integrated LSI before year 2000s, each research group had to build a complete device fabrication facility before getting started. Initial installation cost, yearly maintenance cost, and time to learn machines and processes prevented researchers from integrated LSI research. The MEMS specialists, including the author, and governments of a couple of countries in the world were aware of such high hurdle, and launched national programs of open-use facility. From 2012 to 2021, Ministry of Education, Sports, Culture, Science and Technology (MEXT) is financing a National Nanotechnology Platform Project, by which 16 institutes are collaboratively offering their cutting-edge micro and nano fabrication apparatuses. A couple of sites such as Hiroshima University, Kitakyushu Foundation for the Advancement of Industry Science and Technology (FAIS) and Toyota Institute of Technology can fabricate MOS transistors. UTokyo VDEC is a Japanese representative institute of VLSI multi-chip fabrication and is developing an open post-CMOS MEMS process scheme [2]. Through such open facilities it is now possible for all above-mentioned researchers from material to application, to perform research efficiently.

2. CMOS Post-Process through UTokyo VDEC

Since the year 2010, a 0.6μm, 1-Poly, (maximum) 3-metal multi-chip VLSI run is performed every year. LSI wafers are delivered to participants and sub-diced 15mm chips are subsequently post-processed. Some user obtained in-process wafer – just after transistor fabrication – and some functional materials as well as wiring (Ti/Al/TiN) were post-processed. In this section two applications of LSI components as MEMS device materials are presented.

2.1. Use of LSI components as Mechanical Sensor

The LSI generation employed in this article is 0.6-μm technology. Polysilicon as well as source-drain layer are

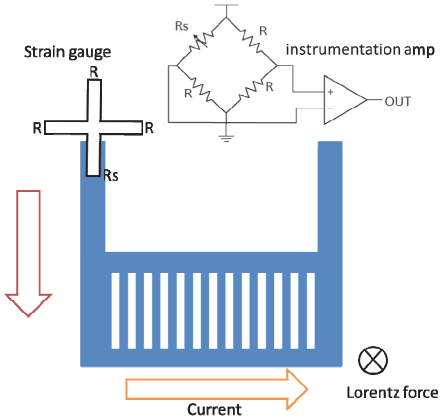

Fig.1 micro cantilever and strain gauge for gas sensor application

not covered with silicide. This is a good news for MEMS sensor application, because polysilicon layer can be used as a piezo-resistive sensing element. Polysilicon gauge has lower sensitivity than that of bulk silicon, but has no crystalline orientation dependence, and is electrically isolated as soon as its fabrication, so it provides more flexibility to designers. By making a 1mm-size U-Shaped free-standing cantilever, on which polysilicon gauge is integrated at the bottom of the cantilever, it has been possible to both actuate the cantilever and obtain an output of polysilicon Wheatstone-Bridge. A clear linearity between the cantilever move and bridge output was obtained in the range of ±8μm move at the end of cantilever. Such mechanical-electrical interface is useful for many sensors applications. In the authors group, DRIE-made vibrating gas sensors have been studied [3]. The device was made with U-shaped cantilever beam with trenches, in which sensitive materials such as zeolite are integrated. A frequency shift was obtained due to chemical exposure. Selectivity between ethanol and water has been confirmed by using two different zeolite materials (hydrophilic and hydrophobic ones).

2.2. Use of LSI components as Biological Sensor

Another example is to use a post-processed extended-gate transistor as a sensing head of biological sensor. The authors have collaborated with specialist of insect cell that is odor-sensitive cells, and fabricated an Odor-Sensitive FET (OSFET) [4]. The proof-of-concept device contains an FET with extended gate. The extended gate electrode was covered with dielectric material, and cells were directly put on the electrode. The cell that the authors used has a particularly good compatibility with LSI; it not only survived but also adhered on the pad. By exposing several different odorants to that (living-cell-) *Integrated* Transistor, a clear signal of odor reception has been measured. The signal was not pronouncing on the extended-gate alone, nor with the cell that is insensitive to the used odorant. The time between the project launch to the silicon result was around 5 months, thus showing the clear advantage of proposed open facility and foundry scheme in terms of turn-around-time for R&D.

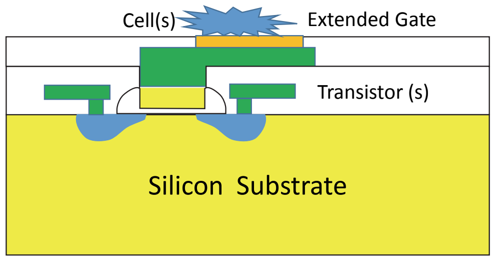

Fig.2: An Extended-Gate integration with Living Cells

3. Reliability Assessment by Series-Connected Devices

The Practical advantage of such system is device quality: semiconductors (including P-N junctions), insulators (SiO2), are made with controlled environment at an LSI company. So all the components works as an electrical device. Such quality is not easily obtainable in an Open University facilities, despite all the efforts to keep them clean, because the nature of the university facility is "try new things", including new materials and processes that inevitably results unexpected quality variation, especially for frontend (high temperature) process. However such high quality in LSI foundry is obtained by excluding "new" materials and processes so that it is impossible to try non-standardized processes. Post-processing an LSI wafer can combine advantage and eliminate disadvantage of both sides; designers can try new functionality with high quality of silicon. The quality has been experimentally confirmed by fabricating a series-connected silicon photovoltaic cell that demonstrated over 60V [5]. P-N junction cells were designed to be connected in series by LSI wiring. The device was fabricated on an SOI wafer. SOI is an excellent electrical isolator so it is possible to isolate electrical circuit blocks by post-process fabricating silicon mesa islands on an SOI SiO_2. Such process can easily be done with standard DRIE machine, by intentional long-time etching. Series-connected PV cells readily generated n times single cell in voltage, while generating the same current as single cell. This means that all (maximim n = 125 tested) cells have been made identically.

4. Conclusions

LSI device components can be used as electro and mechanical transducers, and integration can be done through open facility. Such scheme provides both reliability and new functionality. Two examples of such technology application are reported in the paper.

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