Edited by S. Selberherr, H. Stippel, E. Strasser - September 1993

Electro-Elastic Simulation of Piezoresistive Pressure Sensor

P. Ciampolini, A. Rossi[†], A. Pierantoni[†], and M. Rudan[†]

Istituto di Elettronica, Università di Perugia
I-06131 Santa Lucia-Canetola, Perugia, ITALY
[†]Dipartimento di Elettronica, Informatica e Sistemistica, Università di Bologna
Viale Risorgimento 2, I-40136 Bologna, ITALY

Abstract

Transport properties of the silicon crystal are sensitive, to some extent, to mechanical perturbations: this allows for integrating mechanical sensors, together with the sensing circuitry, within a silicon chip by using an almost standard IC technology. In this paper, the numerical simulation of a silicon pressure sensor, based on the piezoresistive effect, is described. The simulated transducer is made of a thin silicon diaphragm, on top of which a four-resistor bridge is diffused. For a given pressure, the distribution of the stress components over the diaphragm is feeded to the program, which then computes the sensor response depending on its geometrical and physical features. To this purpose, an anisotropical, stress-dependent, mobility model has been introduced into the device simulator HFIELDS-3D.

1. Introduction

The progress in silicon technology makes it possible to fabricate sophisticated microsensors where sensing part, transducer, and signal amplifier are all integrated within the same chip. At the same time, the miniaturization makes the analytical simplifications describing the sensors' performance less and less reliable. The purpose of this abstract is to present preliminary results of the numerical analysis of a piezoresistive pressure sensor. More specifically, the attention will focus here on the sensing part and transducer which, as shown below, are combined in a single device. In this respect, a few analysis codes have already been implemented elsewhere to simulate mechanical deformation and stress. On the other hand, the underlying physics of the electro-elastic interrelations in semiconductor crystals has been investigated and well understood. This makes it possible to take the further step of incorporating the electrical aspects into the simulation.

2. Theory

From the microscopical point of view, deformations in the lattice of a semiconductor crystal (induced, e.g., by an external force) modify the shape of the energy function $E(\boldsymbol{k})$. Due to this, an extrinsic anisotropy caused by the deformation adds to the intrinsic one already possessed by the energy function in the non-deformed case. Hence, when a semiconductor crystal subject to a deformation is brought to a non-equilibrium state by forcing a current flow in the material, its macroscopic transport properties must inherit to some degree the effects of the deformation. This concept can better be illustrated with reference to a specific semiconductor material, e.g., silicon, in the simple case where the deformations are kept within the linear regime and a near-equilibrium condition holds as for the electric behavior. Thanks to the latter assumption, the current transport is well described by the drift-diffusion model. Taking by way of example the conduction band, the electron current density $\boldsymbol{J}_n$ is obtained by adding the contributions of six valleys, each of them giving rise to a 3×3 mobility tensor. In the non-deformed case the six mobility tensors happen to combine in such a way that the resulting (macroscopic) mobility is a scalar. This, however, is no longer true when the crystal undergoes a deformation: in this case, in fact, the macroscopic mobility retains a tensor nature, which is a direct effect of the deformation's anisotropy and can be exploited for measuring purposes. Letting $\boldsymbol{\mathcal{M}}$, μ_0 be the mobility in the deformed and non-deformed case, respectively, and $\boldsymbol{\mathcal{I}}$ the 3×3 identity tensor, one may introduce a tensor $\boldsymbol{\mathcal{D}}$ such that

$$\Delta \boldsymbol{\mathcal{M}} = \mu_0 \boldsymbol{\mathcal{I}} - \boldsymbol{\mathcal{M}} = \mu_0 \boldsymbol{\mathcal{D}} .$$

For symmetry reasons, $\boldsymbol{\mathcal{D}}$ has only six independent components which, for the sake of simplicity, are thought of as a 6×1 vector $\boldsymbol{d}$. The components of the latter in terms of the deformation could in principle be derived by direct calculation; however, a much simpler way is that of determining these relationships experimentally, and recasting the result in terms of the stress components. More precisely, one obtains $\boldsymbol{d} = \boldsymbol{\mathcal{P}} \boldsymbol{s}$, where the 6×1 vector $\boldsymbol{s}$ is made of the independent components of the stress tensor, and $\boldsymbol{\mathcal{P}}$ is the 6×6 piezoeresistive tensor. The form of the latter is particularly simple in crystals with cubic symmetry like silicon [1]. Moreover, for a purely ohmic transport due to a uniform electron concentration n it turns out $\Delta \boldsymbol{\rho} / \rho_0 = -\Delta \boldsymbol{\sigma} / \sigma_0 = \boldsymbol{d}$, where $\boldsymbol{\rho}$, $\boldsymbol{\sigma}$ are made of the independent components of the resistivity and conductivity vectors, respectively, and $\sigma_0 = 1/\rho_0 = q \mu_0 n$. The calculation of the stress components is made easier by the simplicity of the structures at hand; typically, one takes a rectangular diaphragm in the xy plane, with built-in boundary conditions, whose thickness h is large compared to the deflection w. The latter is then found by solving

$$C_x \frac{\partial^4 w}{\partial x^4} + 2H \frac{\partial^4 w}{\partial x^2 \partial y^2} + C_y \frac{\partial^4 w}{\partial y^4} = p ,$$

where p is the pressure (the coefficients are different due to anisotropy). The stress components are derived from w in the customary way [2].

3. Implementation and Results

The capability of handling stress components in a simplified manner has been added to the drift-diffusion version of the in-house developed, three-dimensional device simulator `HFIELDS-3D`. A number of tests have been carried out on the code, aiming at

detecting the variations in the electrical behavior of identical devices placed at different position on a diaphragm. As a first example, the structure presented in [3] has been simulated, i.e., a pressure sensor.

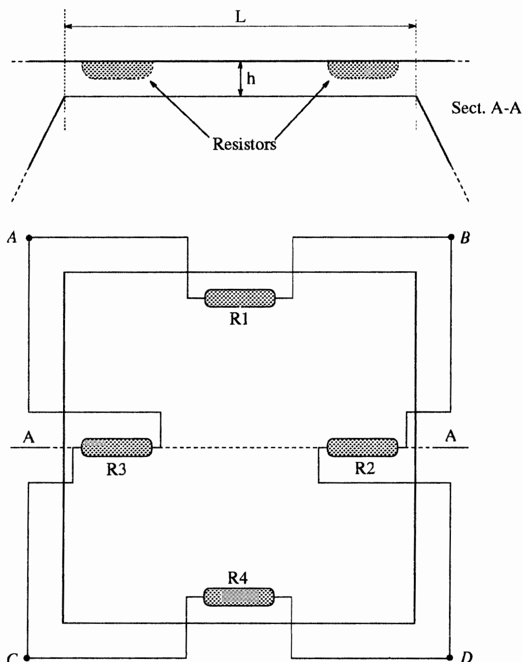

Fig. 1

The device is made of a square diaphragm, obtained by anisotropically etching a silicon wafer (Fig. 1). Three different thicknesses h of the diaphragm have been considered, namely 10, 20 and 30 μm, as well as three different side lengths L (100, 200 and 300 μm). Two etching modes were taken into account: in the first one, the sides L are oriented along the principal axes of the crystal while, in the second, they form a 45° angle with the latters. Four $20\times4\times2$ μm^3 resistors are diffused near the sides' midpoint and connected to form a bridge. Their longer side belongs to the [110] plane in the first etching mode, and to the [100] plane in the second one. Let R_0 be the common value of the resistance when the diaphragm is not deformed; the relative unbalance of the bridge when a variation occurs in the resistances, at a given bias V_{AD}, is expressed by

$$\frac{V_{BC}}{V_{AD}} = \frac{\Delta V_{BC}}{V_{AD}} = \frac{-\Delta R_1 + \Delta R_2 + \Delta R_3 - \Delta R_4}{4R_0} .$$

The relative variations in the resistances have been calculated by HFIELDS-3D. The results can be summarized by defining the pressure sensitivities α_i of the individual resistors as

$$\frac{\Delta R_i}{R_0} = \alpha_i \, p \,, \qquad i = 1, \ldots, 4$$

and using the expression of the relative unbalance to obtain the total pressure sensitivity β :

$$\frac{V_{BC}}{V_{AD}} = \beta \, p \,, \qquad \beta = \frac{1}{4} \left(-\alpha_1 + \alpha_2 + \alpha_3 - \alpha_4 \right) .$$

The values of β corresponding to different conditions are reported in Figs. 2, 3 and 4 (expressed in 10^{-10} $cm^2/dyne$ units). From Fig. 2 (3) it is seen that doubling the diaphragm length (thickness) results in increasing (decreasing) the pressure sensitivity by about a factor 4. This is consistent with the fact that in the linear regime and in the simpler, one-dimensional case, the deflection is proportional to L^2/h^2. The larger differences in sensitivity as a function of the resistors' orientation are a direct consequence of the properties of the piezoresistive tensor. In fact, its elements give rise to individual sensitivities α_i which, in the case [110], have all the same sign and similar magnitudes; in the case [100], on the contrary, the magnitudes are still similar while the sign of α_1 and α_4 is opposite to that of α_1 and α_4. Fig. 4, finally, illustrates the dependence of β upon the position of the resistor: d indicates the distance of the bridge resistors from the diaphragm edge ($L = 100\,\mu$m, in this case). As expected, the sensitivity decreases as the resistors move toward the center; this is due to both the smaller stress experienced by each element (for a given pressure) and the decreasing unbalance of the bridge. The sensible elements have then to be placed as close to the edge as possible: the accurate evaluation of the stress components in such regions, however, needs the actual profile of the transition between the thin and thick silicon layers to be taken into account. This, in turn, calls for the full numerical simulation of the mechanical system as well.

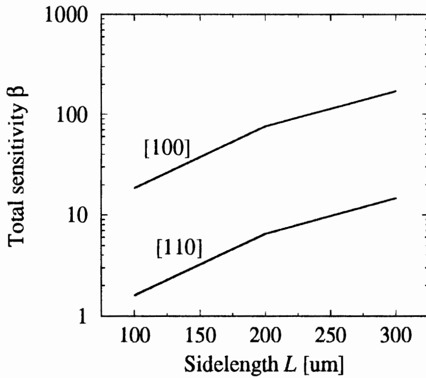

Fig. 2

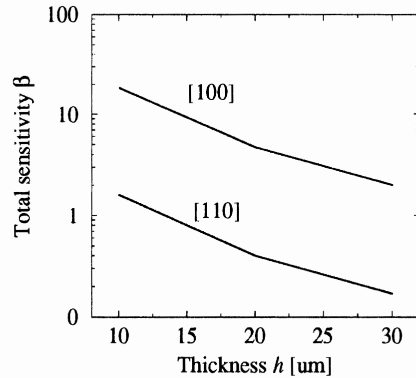

Fig. 3

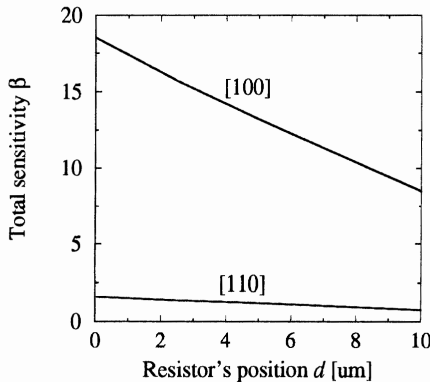

Fig. 4

References

[1] Y. Kanda, *A Graphical Representation of the Piezoresistance Coefficients in Silicon*, IEEE Trans. ED, Vol. ED-29, No. 1, Jan. 1982, p. 64.

[2] S. Timoshenko, S. Woinowsky-Krieger, *Theory of Plates and Shells*, McGraw-Hill, New York, 1959.

[3] K.W. Lee, K. D. Wise, *SENSIM: A Simulation Program for Solid-State Pressure Sensors* IEEE Trans. ED, Vol. ED-29, No. 1, Jan. 1982, p. 34.