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Resistivity-based modeling of substrate non-uniformity for low-resistivity substrate

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Abstract: This paper suggests the modeling methods of non-uniform substrate resistivity for substrate resistance extraction. Conventional substrate model of uniform resistivity for each substrate layer can cause about 40-80% resistance extraction errors. Though model of simulated doping profile theoretically provides fine accuracy, the doping profile cannot be corrected with measurement results. The stepwise and interpolation models which this paper suggests enable 10% precision of resistance extraction and correction with measured resistance values. We also reveal that the modeling of the surface diffusion also gives large impact for resistance extraction of substrate and well.

Keywords: substrate noise, substrate extraction, low-resistivity substrate

Classification: Integrated circuits

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1 Introduction

Substrate noise is commonly known as one of the factors which deteriorate performance of analog circuits on LSI. Accurate estimation of substrate noise is required for circuit design to reduce the impact of substrate noise and to minimize the area overhead due to noise immunity design. There are many reports about substrate noise, such as measurements of substrate noise on the fabricated chip [1, 2, 3, 4], extraction methods of substrate resistance [5, 6], simulation methods of substrate noise [2, 3, 7, 8], and modeling of noise source for fast substrate noise simulation [4].

For substrate resistance extraction, past works frequently assumed that resistivity of the substrate is uniform for each layer, or gave doping profile to extractors, and modeling of non-uniform resistivity of the substrate was scarcely discussed.

This paper discusses non-uniformity of the substrate resistivity. The contributions of this paper are as follows.
1) Revealing that non-uniformity of substrate resistivity causes considerable error in substrate resistance extraction.
2) Suggesting substrate resistivity models and modeling of the surface diffusion, as a solution of extraction problem due to non-uniformity of substrate resistivity.
3) Demonstrating the characterization of the suggested model with substrate resistance which can be easily obtained from fabricated chips.

2 Modeling of substrate profile for resistance extraction

Fig. 1 (a) shows the structure of low-resistivity substrate [9]. There are the surface layer, high-resistivity layer, and low-resistivity layer. On the other hand, doping profiles of these layers are not uniform. Fig. 1 (b) shows an example of the doping profile which is calculated based on equations of impurity diffusion [10] and Fig. 1 (a) resistivity profile. For substrate resistance extraction, the low resistivity substrate is frequently modeled with uniform resistivity for each substrate layer [2, 3, 5]. However, substrate model with uniform resistivity for each layer cannot accurately extract substrate resistance for specific layout structures. Fig. 1 (d) compares extraction results with doping profile (A) and the uniform resistivity for each layer (B). Extraction program is QRC [11]. LAYOUT.1 is basic structure with two contacts on p-substrate. There are adjacent n-wells by contacts in LAYOUT.2,3, and contacts are surrounded by n-well in LAYOUT.4. The sizes of contacts in LAYOUT.5,6 are much larger or smaller than those in LAYOUT.1. The model of

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uniform resistivity for each layer cause about 15-78% errors in comparison with doping profile model when adjacent n-well is placed or sizes of contacts are changed. Though extraction with doping profile model gives the most accurate resistance theoretically, doping profile itself is a simulation result, and it is difficult to correct doping profile with measurement results on silicon.

We suggest the following techniques for accurate extraction of substrate resistance.

1) Stepwise or interpolation model to approximate doping profile.
2) Modeling of the surface diffusion.

The concepts of the stepwise model and interpolation model are depicted in Fig. 1 (c). The stepwise model represents substrate resistivity with stepwise resistivity distribution. The interpolation model includes resistivity and depth of several points, and the resistivity between the points are interpolated. Extraction results with stepwise (C) and interpolation (D) models are also shown in Fig. 1 (d). Both of two models provide fine extraction results. Stepwise model consists of relatively small number of uniform resistivity layers (8 layers here), and suitable for the boundary element method extractors. Interpolation model includes smaller number of parameters in comparison with stepwise model (three resistivity points here), and its characterization cost is more reasonale. Following section describes the theoretical background of the suggested modeling techniques.

3 Theoretical background of suggested models

The stepwise or interpolation model we suggested can model the nonuniformity of the each substrate layer, and this is important for accurate resistance extraction. Figs. 2 (a) and 2 (b) depict the distribution of current density of the substrate cross-section. The current distribution is calculated with Raphael RC3 program [12]. Current paths between contacts and bottom low-res. layer can be observed in Fig. 2 (a). As shown in Fig. 2 (b), large amount of current distributes in low-res. layer, and the most of the current between two contacts go through the high-resistivity layer between the surface and the low-res. layer.

Figs. 2 (c) and 2 (d) show the current distribution of the substrate surface. Fig. 2 (c) is simulated with doping profile and Fig. 2 (d) is simulated with uniform resistivity for each substrate layer. The widespread current distribution is observed only in Fig. 2 (c). It is natural that current spread at relatively low-resistivity surface layer before passing the high-res. layer, and Figs. 2 (c) and 2 (d) indicate that current distribution cannot be adequately simulated with the uniform resistivity for each layer, which results in the significant resistance extraction errors. Our stepwise or interpolation model can approximates resistivity distribution of each substrate layer, and achieves fine precision in resistance extraction.

The surface diffusion is also important when distance between two contacts is short. The resistivity of diffusion is much lower than substrate. When two adjacent contacts are placed, diffusion behaves like a short path into sub-

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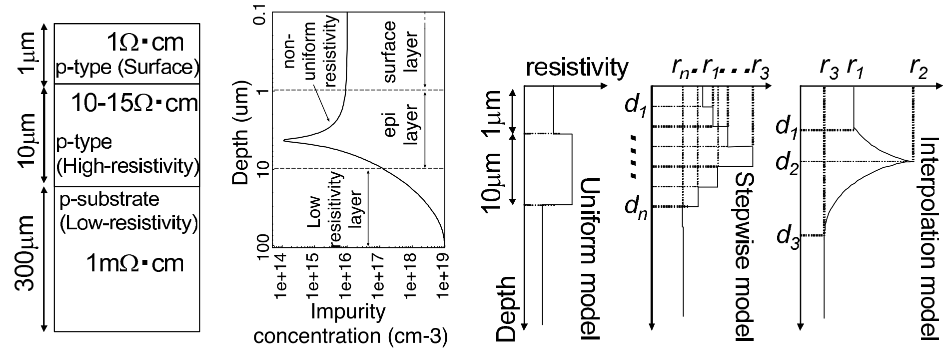

(a) Low-resistivity substrate (b) An example of doping profile (c) Substrate resistivity models

	Fig. 1(b) profile				Industrial process			
	A	B	C	D	A	B	C	D
LAYOUT.1	12771	13234	12830	12768	1242	1169	1239	1354
LAYOUT.2	13163	13294	13332	13284	1313	1192	1322	1425
LAYOUT.3	15822	13336	16402	15115	1380	1060	1369	1472
LAYOUT.4	81433	17664	92937	85985	7042	1258	7837	5998
LAYOUT.5	4027	2379	4312	3774	669	353	649	715
LAYOUT.6	6049	9157	5328	6868	531	913	558	578

(d) Resistance extraction result(Ω). A: Detailed doping profile, B: Uniform resistivity for each layer, C: Stepwise model with diffusion, D: Interpolation model with diffusion

Fig. 1. Resistivity models of substrate and evaluation of them.

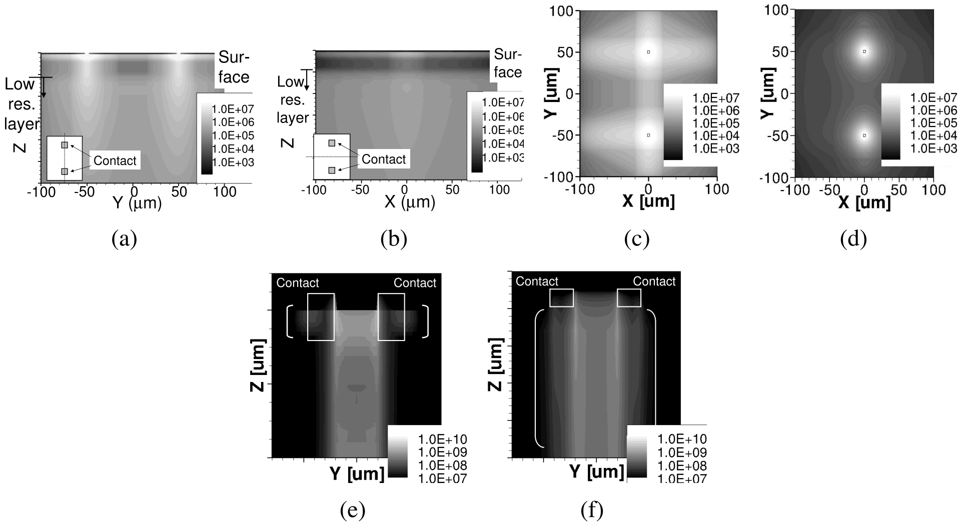

Fig. 2. Analysis results of current distribution in the substrate.

strate, and mitigates the resistance between two contacts. Figs. 2 (e) and 2 (f) depict the current distribution of the well simulated with doping profile and uniform resistivity. The current concentrates on the diffusion area and the surface (marked by brackets) in Fig. 2 (e). On the other hand, wide resistance path spreading into deep area (marked by brackets) below the contacts is observed in Fig. 2 (f), which increases substrate resistance.

4 Evaluation of characterization

This section demonstrates characterization of suggested interpolation model using reference substrate resistance values, and presents that suggested model

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can be characterized with measured resistance values.

This section characterizes the interpolation model for an industrial process. The depth and resistivity of surface diffusion is assumed to be known, and the characterized parameters are three resistivity values (surface layer, peak value of high-res. layer, and low-res. layer) and two depth values (depth of peak value and depth where low-res. layer starts). Since the doping concentration behaves logarithmically with respect to the depth [13], we interpolate the resistivity $R(d)$ with the following log-linear interpolation: $R(d) = R_1 e^{\alpha}, \alpha = \frac{d-d_1}{d_2-d_1} log_e \frac{R_2}{R_1}$, where d is the depth in the interval $[d_1, d_2]$, and R_1, R_2 are resistivities at d_1, d_2 respectively.

The parameters of the model are fitted so that extraction results correlate the reference resistance. QRC extractor is adopted for resistance extraction. The layout patterns used in characterization is following PAT.1.1-5.3. In addition to layout patterns for characterization process, we prepared CASE.1-4 which are used for evaluation of the characterized model. The reference values are obtained by resistance extraction with detailed doping profile.

- PAT.1.1,1.2: There are sufficiently distant two contacts.
- PAT.2.1,2.2: Two close contacts are placed.
- PAT.3.1,3.2: Two contacts are close to N-well respectively.
- PAT.4.1,4.2: Two contacts are surrounded by N-well respectively.
- PAT.5.1-5.3: Sizes of the two contacts are large or small.
- CASE.1: Two small synchronous contacts.
- CASE.2: A mesh structure contact and alternatively placed N-wells and contacts.
- CASE.3: A long rectangle contact and a large square contact.
- CASE.4: Long contacts and scattered small contacts.

The procedure of the characterization is as follows.

1) Deciding initial parameters for the model at first based on doping profile.
2) Deciding sweep range according to initial parameters. Sweep patterns are selected based on a design of experiments.
3) Obtaining extraction results of each layout pattern for each sweep pattern.
4) Calculate parameters which minimize error based on 3) results by solving nonlinear programming problem.
5) Repeating 2-4 until extraction error becomes acceptable or error improvement stops.

Table I (a) describes reference values and extraction results of the model of uniform resistivity for each layer, interpolation model with initial parameters while characterization, and the characterized interpolation model. The characterized interpolation model shows file correlation with reference values, and the characterization of the suggested model has succeeded.

5 Modeling of the surface diffusion and resistance extraction of well

The impact of the surface diffusion is important for not only p-substrate but also wells. This section presents that the model including the surface

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Table I. Resistance extraction results.

(a) Resistance extraction results (Ω) of characterized p-substrate model.

Layout pattern	Detailed Profile (Reference) Res.(Ω)	Uniform res. for each layer Res.(Ω)	Error (%)	Suggested model (init.) Res.(Ω)	Error (%)	Suggested model (characterized) Res.(Ω)	Error (%)
PAT.1.1	1406	1513	7.6	1593	13.3	1397	0.7
PAT.1.2	1541	1598	3.7	1804	17.1	1524	1.1
PAT.2.1	571	1019	78.6	728	27.6	557	2.4
PAT.2.2	875	1309	49.6	1072	22.5	864	1.3
PAT.3.1	1850	1489	19.5	1986	7.4	1838	0.6
PAT.3.2	1645	1377	16.3	1752	6.5	1639	0.4
PAT.4.1	9320	1690	81.9	5491	41.1	8726	6.4
PAT.4.2	3034	1247	58.9	2081	31.4	3029	0.2
PAT.5.1	2703	4301	59.1	3391	25.5	2651	1.9
PAT.5.2	452	216	52.1	418	7.6	455	0.6
PAT.5.3	74.0	22.6	69.4	52.7	28.7	75.4	2.0
CASE.1	1074	1045	2.7	1181	10.0	1070	0.4
CASE.2	20.3	7.34	63.8	20.5	1.0	20.5	1.1
CASE.3	556	434	21.9	575	3.4	556	0.0
CASE.4	63.3	39.0	38.4	53.1	16.1	64.8	2.3

(b) Resistance extraction results (Ω) of p-well on deep n-well structure.

Layout pattern	Doping profile Res.(Ω)	w/o diffusion. Res.(Ω)	Error (%)	w/ diffusion Res.(Ω)	Error (%)
PAT.6.1	821	933	13.6	812	1.1
PAT.6.2	3817	3693	3.2	3840	0.6
PAT.6.3	396	592	49.6	387	2.4
PAT.7.1	997	1001	0.4	945	5.2
PAT.7.2	772	1007	30.5	793	2.8
PAT.7.3	835	1306	56.5	898	7.6

diffusion is effective for the well resistance extraction.

We prepared following six layout patterns with two contacts on p-well on deep n-well. The sizes and distance of contacts are changed in six patterns.

- PAT.6.1: Distance=1x, Size=1x - PAT.6.2: Distance=8x, Size=1x
- PAT.6.3: Distance=1/4x, Size=1x - PAT.7.1: Distance=1x, Size=1/2x
- PAT.7.2: Distance=1x, Size=2x - PAT.7.3: Distance=1x, Size=4x

Table I (b) compares extraction results with doping profile, uniform resistivity for whole p-well, and two resistivity values for diffusion and p-well. By including diffusion in the model, extraction errors of substrate resistances were reduced from 49.6/30.5/56.5% to 2.4/2.8/7.6% in PAT.6.3/7.2/7.3.

6 Conclusion

This paper discussed modeling of non-uniformity of low-resistivity substrate, and characterization of the substrate model. We first described extraction errors of conventional assumption of uniform resistivity for each substrate layer. Stepwise moel, interpolation model and modeling of the surface diffusion were suggested to approximate non-uniformity of substrate instead of doping profile which cannot be corrected by substrate resistance measurement results. The suggested stepwise and interpolation model with diffusion modeling achieved fine extraction precision. The modeling of diffusion also improved well resistance extraction errors. We also demonstrated the characterization of interpolation model with reference resistance.

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