CASE 20

Optimization of the Back Contact of Power MOSFETs

Abstract: Since a large current flows in a power MOSFET for an automobile, its electric resistance (ON resistance) must be lowered to reduce the electric power loss. In our research we attempted to reduce the ON resistance by looking at the contact resistance of the back gate of a power MOSFET and optimizing the conditions for forming the back gate.

1. Introduction

In the development of automobile electronics, new technical issues, such as increasing space for control units or growing consumption energy, have emerged. To solve them, the power MOSFET, which is easy to obtain and is driven by low electrical power, is attracting much attention as a key next-generation device in the electronic field and is being developed as a reliable switching element to control large electric currents.

Since a large current flows in an automobile's power MOSFET, its electric resistance (ON resistance) must be lowered to reduce the electrical power loss. In our research we attempted to reduce the ON resistance by looking at the contact resistance of a back gate of a power MOSFET and optimizing the conditions for forming the back gate.

2. Structure of Back Contact

Figure 1 depicts the structure of a vertical-type power MOSFET. As illustrated in the figure, the current flows from the drain to the source. Figure 2 shows a structure of resistances.

To reduce the contact resistance between the back contact and silicon substrate, R_1, we optimize some factors, such as the condition for forming back contacts. This is because by abolishing the impurity doping and annealing processes instead of using the conventional method of contact-resistance reduction, we can both realize a thin silicon substrate, which has been difficult to manufacture to date, and lower the substrate resistance, R_2. It is said that if electronic devices become smaller in the future, the substrate resistance, R_2, will account for approximately 50% of the total resistance. Therefore, it should be possible to drastically reduce the ON resistance of a power MOSFET if the substrate resistance, can be lowered together with the contact resistance.

3. Fundamental Functions and Measurement Characteristics

The conventional technological development of back contacts has been dedicated to improvement of their quality and characteristics in terms of quality features such as back contact thickness and adhesive strength, which are measured by a peeling test. However, as a consequence of focusing on back contact's functions as a power MOSFET, by using voltage and current as measurement characteristics we established a forming technology for back contacts that have low resistance and maintain stable electrical characteristics for environmental fluctuations.

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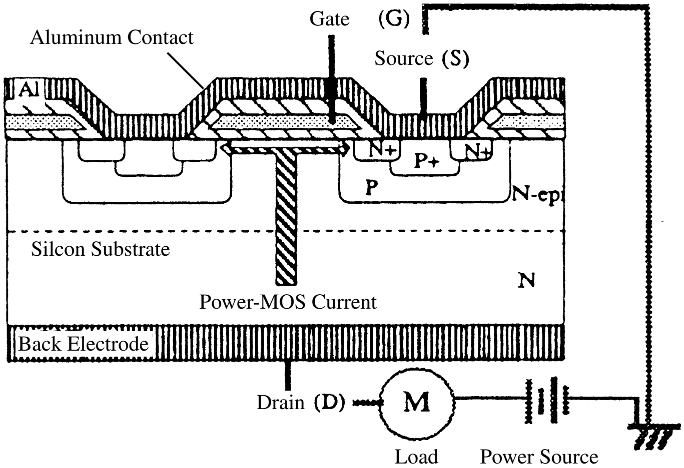


Figure 1
Structure of power MOSFET

We have also sought a way to reduce the contact resistance between the substrate and drain contact (back contact resistance, R_1) by concentrating on manufacturing processes. For measurement characteristics, we set different currents as signal levels (Table 1) and analyzed all data following the procedure for dynamic characteristics by measuring voltage outputs at the back contact (Figure 3). Although this measurement included both the back contact resistance, R_1, and substrate resistance, R_2, we judged that it is reasonably possible to assess a fluctuation of the back contact resistance because it

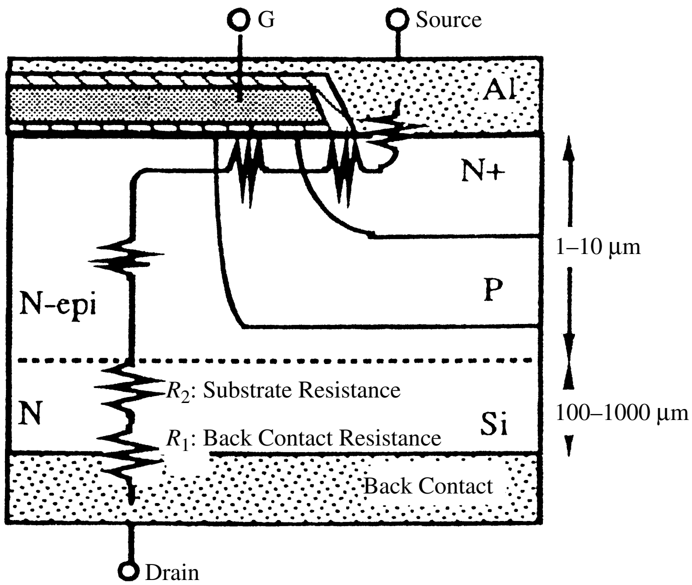


Figure 2
Structure of electric resistances

Table 1
Factors and levels

Factor	Level 1	Level 2	Level 3
Signal factor			
Current	0.5	1.0	1.5
Noise factors			
Environmental temperature	Low	Room	High
Heat cycle	Initial	1	2

is sufficiently larger than the substrate resistance in case the impurity density of the substrate is quite low. As noise factors, we selected environmental temperatures and heat cycles, as shown in Table 1.

4. SN Ratio and Sensitivity

Table 2 shows the data from experiment 1. Based on these data, we calculated SN ratios and sensitivity.

Total variation:

$$S_T = 428^2 + 523^2 + 597^2 + \cdots + 295^2 + 375^2 + 430^2 = 4{,}761{,}567 \qquad (f = 27) \qquad (1)$$

Effective divider:

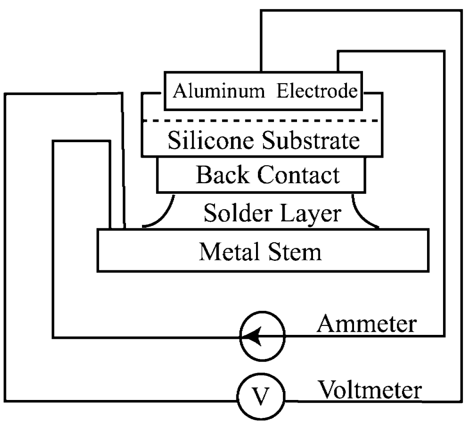


Figure 3
Voltage measurement

$$r = 0.5^2 + 1.0^2 + 1.5^2 = 3.50 \qquad (2)$$

Linear equations:

$$L_1 = (0.5)(428) + (1.0)(523) + (1.5)(597) = 1632.5$$

$$L_2 = (0.5)(295) + (1.0)(378) + (1.5)(435) = 1178.0$$

$$L_3 = (0.5)(365) + (1.0)(440) + (1.5)(495) = 1365.0$$

$$\vdots$$

$$L_9 = (0.5)(295) + (1.0)(375) + (1.5)(430) = 1167.5 \qquad (3)$$

Variation of proportional term:

$$S_\beta = \frac{(L_1 + L_2 + L_3 + \cdots + L_9)^2}{9r} = \frac{(1632.5 + 1178.0 + \cdots + 1167.5)^2}{9r} = 4{,}399{,}364.5710 \qquad (f = 1) \qquad (4)$$

Error variation:

$$S_e = S_T - S_\beta = 4{,}761{,}567 - 4{,}399{,}364.5710 = 362{,}202.4290 \qquad (f = 26) \qquad (5)$$

Error variance:

$$V_e = \frac{S_e}{26} = \frac{362{,}202.4290}{26} = 13{,}930.8627 \qquad (6)$$

SN ratio:

Table 2
Voltage data

Error Factor			Signal M_1	Signal M_2	Signal M_3	Linear Equation
I_1:	low temperature	J_1 (initial)	428	523	597	L_1
		J_2 (cycle 1)	295	378	435	L_2
		J_3 (cycle 2)	365	440	495	L_3
I_2:	room temperature	J_1	385	485	565	L_4
		J_2	288	365	424	L_5
		J_3	295	371	425	L_6
I_3:	high temperature	J_1	372	474	548	L_7
		J_2	276	356	418	L_8
		J_3	295	375	430	L_9

$$\eta = 10 \log \frac{(1/9r)(S_\beta - V_e)}{V_e}$$

$$= 10 \log \frac{[1/(9)(3.50)]\begin{pmatrix}4{,}399{,}364.5710 \\ -\ 13{,}930.8627\end{pmatrix}}{13{,}930.8627}$$

$$= 10.00 \text{ dB} \tag{7}$$

Sensitivity:

$$S = 10 \log \frac{1}{9r}(S_\beta - V_e)$$

$$= 10 \log [1/(9)(3.50)] \begin{pmatrix}4{,}399{,}364.5710 \\ -\ 13{,}930.8627\end{pmatrix}$$

$$= 51.44 \text{ dB} \tag{8}$$

Table 3 shows selected control factors. The second level of H was assigned to a dummy. Judging from our technical knowledge and insight, we chose

Table 3
Factors and levels

Control Factor		Level 1	Level 2	Level 3
A:	back contact metal type	1	2	—
B:	device temperature 1	20	150	350[a]
B':	sputtering temperature 1	Low	Mid	High
C:	treatment time 1 (min)	0[a]	1	5
D:	treatment time 2 (s)	0	20[a]	40
E:	treatment time 3 (min)	0[a]	1	5
F:	organic cleansing	None	IPA	Methanol
G:	treatment time 4 (min)	0	10[a]	20
H:	device temperature 2	Low	Low (dummy)	High[a]

[a] Current condition.

nine major factors supposed to affect back contact resistance significantly. These nine factors were assigned to an L_{18} orthogonal array (Table 4). This use of an L_{18} orthogonal array was so special that we added a new column, B', after the second column of B. By doing so, nine factors could be assigned. B' was not orthogonal to other columns because it is a column of interaction of A and B. Therefore, the independent effect could not be computed; however, for the columns of B and B', 75% of the total effects can be calculated with respect to the main effect. The analysis procedure is described later.

5. Design of Experiments and Results

Based on Table 4, we setup Table 5 of level-by-level averages of SN ratio and sensitivity. From this point on, we explain primarily how to calculate the effects of factors assigned to columns 2 and 2′. Except for this, the calculation procedure was exactly the same as the conventional procedure. While the averages of levels of factors A, C, ... , H are computed in the conventional way, those of factors B and B' are computed as follows:

$$\overline{B'_1} = \frac{\begin{array}{l} y_1 + y_2 + y_3) + (y_{16} + y_{17} + y_{18}) \\ - (y_{10} + y_{11} + y_{12}) - (y_7 + y_8 + y_9) \end{array}}{9} + \overline{T}$$

$$= \frac{\begin{bmatrix} (10.00 + 22.39 + 23.06) \\ + (11.80 + 9.64 + 7.75) \\ - (11.12 + 10.52 + 14.66) \\ - (5.27 + 5.17 + 17.67) \end{bmatrix}}{9} + 11.47$$

$$= 13.72 \qquad (9)$$

Table 4
Assignment of control factors, SN ratio, and sensitivity

	Column and Factor										
Exp.	1 *A*	2 *B*	2′ *B′*	3 *C*	4 *D*	5 *E*	6 *F*	7 *G*	8 *H*	SN Ratio	Sensitivity
1	1	1	1	1	1	1	1	1	1	10.00	51.44
2	1	1	1	2	2	2	2	2	1′	22.39	29.93
3	1	1	1	3	3	3	3	3	3	23.06	28.19
4	1	2	2	1	1	2	2	3	3	11.77	48.08
5	1	2	2	2	2	3	3	1	1	9.80	25.28
6	1	2	2	3	3	1	1	2	1′	9.68	42.23
7	1	3	3	1	2	1	3	2	3	5.27	38.19
8	1	3	3	2	3	2	1	3	1	5.17	38.46
9	1	3	3	3	1	3	2	1	1′	17.67	29.81
10	2	1	2	1	3	3	2	2	1	11.12	59.42
11	2	1	2	2	1	1	3	3	1′	10.52	61.12
12	2	1	2	3	2	2	1	1	3	14.66	52.72
13	2	2	3	1	2	3	1	3	1′	8.14	50.09
14	2	2	3	2	3	1	2	1	3	7.85	48.48
15	2	2	3	3	1	2	3	2	1	10.23	55.78
16	2	3	1	1	3	2	3	1	1′	11.80	44.94
17	2	3	1	2	1	3	1	2	3	9.64	59.55
18	2	3	1	3	2	1	2	3	1	7.75	48.55

Table 5
Level-by-level averages of SN ratio and sensitivity (dB)

		SN Ratio			Sensitivity		
Control Factor		1	2	3	1	2	3
A:	back contact metal type	12.76	10.19	—	36.93	53.41	—
B:	device temperature 1	14.95	10.70	8.76	46.74	44.00	44.75
B′:	sputtering temperature 1	13.72	9.90	10.79	43.18	47.94	44.38
C:	treatment time 1 (min)	9.68	10.89	13.84	47.81	43.80	42.88
D:	treatment time 2 (s)	11.64	11.33	11.45	50.96	40.91	43.62
E:	treatment time 3 (min)	8.51	12.67	13.24	48.45	44.99	42.06
F:	organic cleansing	9.55	13.09	11.78	49.08	44.05	42.37
G:	treatment time 4 (min)	11.96	11.39	11.07	42.11	47.63	45.75
H:	device temperature 2	11.19	—	12.04	44.75	—	45.99
Total average			11.47			45.17	

$$\overline{B'_2} = \frac{\begin{bmatrix}(y_4 + y_5 + y_6) + (y_{10} + y_{11} + y_{12}) \\ - (y_1 + y_2 + y_3) - (y_{13} + y_{14} + y_{15})\end{bmatrix}}{9} + \overline{T} \tag{10}$$

$$\overline{B'_3} = \frac{\begin{bmatrix}(y_7 + y_8 + y_9) + (y_{13} + y_{14} + y_{15}) \\ - (y_4 + y_5 + y_6) - (y_{16} + y_{17} + y_{18})\end{bmatrix}}{9} + \overline{T} \tag{11}$$

$$\overline{B_1} = \frac{\begin{bmatrix}(y_1 + y_2 + y_3) + (y_{10} + y_{11} + y_{12}) \\ -(y_{16} + y_{17} + y_{18}) - (y_4 + y_5 + y_6)\end{bmatrix}}{9} + \overline{T}$$

$$= \frac{\begin{bmatrix}(10.00 + 22.39 + 23.06) \\ + (11.12 + 10.52 + 14.66) \\ -(11.80 + 9.64 + 7.75) \\ - (11.77 + 9.80 + 9.68)\end{bmatrix}}{9} + 11.47$$

$$= 14.95 \tag{12}$$

$$\overline{B_2} = \frac{\begin{bmatrix}(y_4 + y_5 + y_6) + (y_{13} + y_{14} + y_{15}) \\ - (y_{10} + y_{11} + y_{12}) - (y_7 + y_8 + y_9)\end{bmatrix}}{9} + \overline{T} \tag{13}$$

$$\overline{B_3} = \frac{\begin{bmatrix}(y_7 + y_8 + y_9) + (y_{16} + y_{17} + y_{18}) \\ - (y_1 + y_2 + y_3) - (y_{13} + y_{14} + y_{15})\end{bmatrix}}{9} + \overline{T} \tag{14}$$

On the basis of Table 5, we created a factor effect diagram. H_1 is averaged together with the dummy level of H_2.

6. Analysis of Optimal Conditions and Confirmatory Experiment

To reduce the back contact resistance as well as to improve its stability, we should lower the sensitivity as much as possible. Looking at Figure 4, we noticed that for factors *A*, *B′*, *C*, *E*, and *G*, we should select the levels that had a higher SN ratio because they were consistent with the levels that had a lower sensitivity. On the other hand, for factor *B*, whose tendency of SN ratio differed from that of sensitivity, we chose level 1 because it greatly affects SN ratio. For factors *D*, *F*, and *H*, by prioritizing the results of sensitivity, we selected levels 2, 3, and 1, respectively. The optimal condition was $A_1B_1B'_1C_3D_2E_3F_3G_1H_1$.

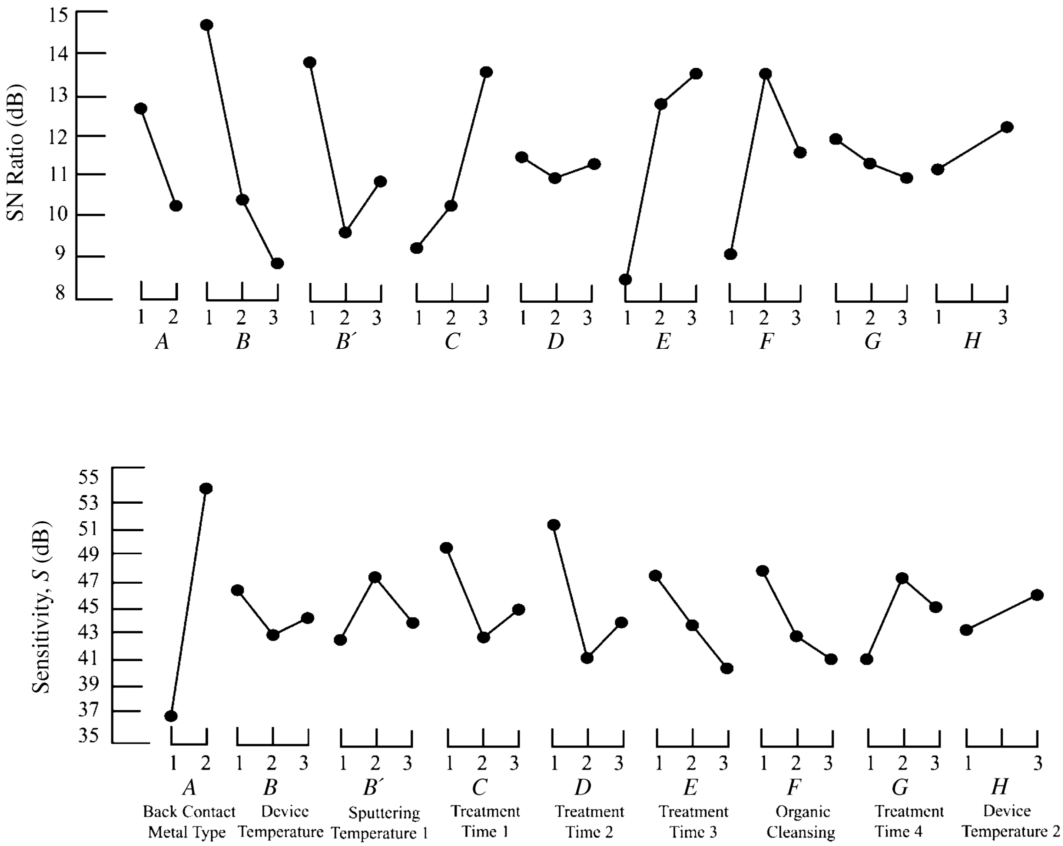


Figure 4
Response graph of SN ratio and sensitivity

Next, by using the five factors A, B, B', C, and E, whose differences between the SN ratio and total average were large, we estimated the SN ratio of the optimal condition selected above.

$$\eta = (\overline{A}_1 - \overline{T}) + (\overline{B}_1 - \overline{T}) + (\overline{B}'_1 - \overline{T}) + (\overline{C}_3 - \overline{T}) + (\overline{E}_3 - T) + \overline{T} = \overline{A}_1 + \overline{B}_1 + \overline{B}'_1 + \overline{C}_3 + \overline{E}_3 - 4\overline{T}$$

$$= 12.76 + 14.95 + 13.72 + 13.84 + 13.24 - (4)(11.47)$$

$$= 22.63 \text{ dB} \qquad (15)$$

On the other hand, we estimated the ratio of the current condition of $A_1B_3B'_3C_1D_2E_1F_3G_2H_3$ using A, B, B', C, and E.

$$\eta = (\overline{A}_1 - \overline{T}) + (\overline{B}_3 - \overline{T}) + (\overline{B}'_3 - \overline{T}) + (\overline{C}_1 - \overline{T}) + (\overline{E}_1 - \overline{T}) - 4\overline{T}$$

$$= \overline{A}_1 + \overline{B}_3 + \overline{B}'_3 + \overline{C}_1 + \overline{E}_1 - 4\overline{T}$$

$$= 12.76 + 8.76 + 10.79 + 9.68 + 8.51 - (4)(11.47)$$

$$= 4.62 \text{ dB} \qquad (16)$$

As a next step, to estimate the sensitivity of the

Table 6
SN ratio and sensitivity estimation from confirmatory experiments (dB)

	SN Ratio		Sensitivity	
Condition	**Estimation**	**Confirmation**	**Estimation**	**Confirmation**
Optimal	22.63	22.96	21.41	23.99
Current	4.62	4.77	39.25	40.35
Gain	18.01	18.19	−17.84	−16.36

optimal condition, we calculated the process average using the six factors *A*, *C*, *D*, *E*, *F*, and *G*, whose differences between the sensitivity and total average were large.

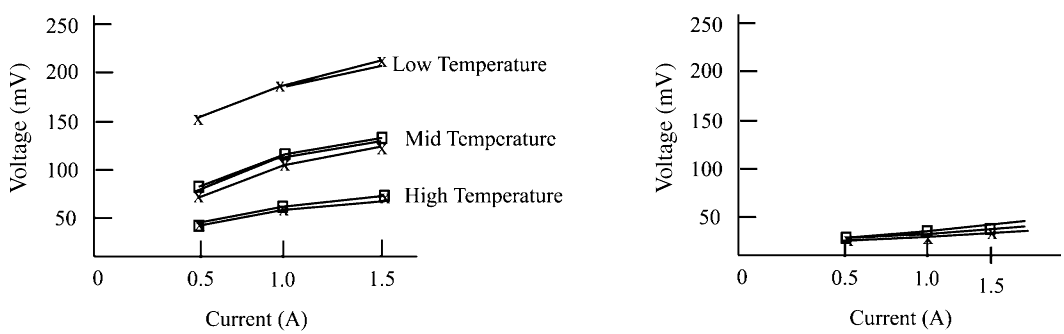
$$\begin{aligned} S &= (\overline{A}_1 - \overline{T}) + (\overline{C}_3 - \overline{T}) + (\overline{D}_2 - \overline{T}) \\ &\quad + (\overline{E}_3 - \overline{T}) + (\overline{F}_3 - T) + (\overline{G}_1 - T) + \overline{T} \\ &= \overline{A}_1 + \overline{C}_3 + \overline{D}_2 + \overline{E}_3 + \overline{F}_3 + \overline{G}_1 - 5\overline{T} \\ &= 36.93 + 42.88 + 40.91 + 42.06 \\ &\quad + 42.37 + 42.11 - (5)(45.17) \\ &= 21.41 \text{ dB} \end{aligned} \tag{17}$$

Similarly, we computed the ratio of the current condition of $A_1B_3B'_3C_1D_2E_1F_3G_2H_3$ using *A*, *C*, *D*, *E*, *F*, and *G*.

$$\begin{aligned} S &= (\overline{A}_1 - \overline{T}) + (\overline{C}_1 - \overline{T}) + (\overline{D}_2 - \overline{T}) \\ &\quad + (\overline{E}_1 - \overline{T}) + (\overline{F}_3 - \overline{T}) + (\overline{G}_2 - \overline{T}) + \overline{T} \\ &= \overline{A}_1 + \overline{C}_1 + \overline{D}_2 + \overline{E}_1 + \overline{F}_3 + \overline{G}_2 - 5T \\ &= 36.93 + 48.81 + 40.91 + 48.45 + 42.37 \\ &\quad + 47.63 - (5)(45.17) \\ &= 39.25 \text{ dB} \end{aligned} \tag{18}$$

This result showed that the optimal condition is 18.01 dB better that the current condition; in other words, we can reduce the standard deviation of resistance by approximately 87.5%. Additionally, we can also lower the sensitivity by the same percentage of about 87.5%, which is equivalent to 17.84 dB.

Under the estimated optimal and current conditions, we formed back contacts and conducted



(*a*) Current Configuration (*b*) Optimal Configuration

Figure 5
Confirmatory experiment results

confirmatory experiments. For the sake of convenience here, we omit details of the data measured and calculation procedure. The results are shown in Table 6.

Looking at the results, we see that both the SN ratio and sensitivity are consistent with the estimation and, in fact, the SN ratio was improved by 18.19 dB. This indicates that the standard deviation of resistance was lowered by approximately 87.5%. On the other hand, the sensitivity at the optimal condition was reduced by 16.26 dB, approximately 85.7% of the current resistance.

Figure 5 shows the results of the confirmatory experiment. We concluded that the back contact resistance is dramatically better stabilized for the fluctuations of environmental temperature selected as noise factors, whereas the optimal magnitude of resistance is considerably reduced compared to the current resistance.

Through our research, we developed a new manufacturing technology that achieves a back contact resistance equal to the current one without the impurity doping and heat treatment processes regarded as essential to reduce back contact resistances in conventional manufacturing. Furthermore, since abolishing these processes enabled us to make the thickness of a silicon substrate thinner and to lower its resistance, R_2, more reduction of ON resistance can be anticipated. For instance, halving the substrate thickness will lead to reducing its resistance by 50%. The 50% reduction in substrate resistance would be equivalent to a 25% enhancement of device performance were devices to become much smaller. For devices whose power loss is at the conventional level, we can shrink their chip size by approximately 25% and as a result, improve productivity and reduce production cost. In addition, the change in manufacturing conditions helps shorten production processes and solve process problems such as substrate defects. Consequently, 20% improvement in yield and 10% reduction in inspections can be achieved.

Reference

Koji Manabe, Takeyuki Koji, Shigeo Hoshino, and Akio Aoki, 1996. Characteristic improvement of back contact of power MOSFET. *Quality Engineering*, Vol. 4, No. 2, pp. 58–64.

This case study is contributed by Akio Aoki.