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High-Temperature Complementary Metal Oxide Semiconductors (CMOS)

John D. McBrayer

Sandia Laboratories

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John D. McBrayer
Semiconductor Devices Division 2117
Sandia Laboratories
Albuquerque, NM 87185

ABSTRACT

Silicon CMOS devices were studied, tested, and evaluated at high temperatures to determine processing, geometric, operating characteristics, and stability parameters.

After more than 1000 hours at 300°C, most devices showed good stability, reliability, and operating characteristics.

Processing and geometric parameters were evaluated and optimization steps discussed.

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HIGH-TEMPERATURE COMPLEMENTARY METAL OXIDE SEMICONDUCTORS (CMOS)

Introduction

The theory on which silicon (Si) metal oxide semiconductor (MOS) technology is founded states that this type semiconductor will perform adequately at 300°C. High temperature tests conducted on commercially-available MOS field-effect transistors (FET) have confirmed this hypothesis.¹⁻³ In this report we present the results of an investigation into the possibility of using CMOS technology at Sandia Laboratories (SLA) for high-temperature electronics. A CMOS test chip (TC) was specifically developed as the test bed. This test chip incorporates CMOS transistors that have no gate protection diodes; these diodes are the major cause of leakage in commercial devices.

We decided to use CMOS technology because both n- and p-channel devices could be evaluated. We also looked at small-scale integration, e.g., an inverter using CMOS technology.

Theory and actual data have been compared before.³ In this paper we intend to report on the aging and stability of CMOS devices, especially where requirements call for minimal drift when subjected to 300°C for 1000 hours. This drift must be less than that in devices taken from room temperature to 300°C.

Before developing circuits that operated best at high temperature, different processing techniques were employed. These techniques, as well as the best process, will be described below. We will also discuss geometric and mask layout considerations with respect to high-temperature applications.

Physics and Processing

Figure 1 shows a guard-ring junction-isolated type of CMOS inverter. This is the technology we used in this study. The actual test chip has been described elsewhere,⁴ and we will not repeat it in this paper. Likewise, the physics of MOSFET technology has been documented several times,^{5,6} and we will present only those equations that we think are pertinent to this study (see Table 1):

$$\phi_E = \frac{kT}{q} \ln \frac{N_a + \sqrt{N_a^2 + 4n_i^2}}{2n_i} \quad \text{for the n-channel,}$$

$$\text{where } n_i = \sqrt{N_c N_v} e^{-E_g / kT},$$

$$N_c = 12 \left[\frac{2\pi m_n^* kT}{h^2} \right]^{3/2}, \quad m_n^* = \text{effective mass of electron,}$$

$$N_v = 2 \left[\frac{2\pi m_p^* kT}{h^2} \right]^{3/2}, \quad \text{and } m_p^* = \text{effective mass of a hole.}$$

FIGURE 1

Guard Band Junction Isolated CMOS
Inverter without Protection

Table 1*

Summary of Important MOS Equations for n- and p-Channel Transistors

	p-Channel	n-Channel
Substrate doping type	p	n
Terminal polarities (V_G , V_D , V_S) in normal operation	-	+
V_T Threshold voltage for enhancement mode transistors	-	+
Q_B Bulk charge in depletion region	+	-
Q_{OX} Effective oxide and interface charge	Almost always +	Almost always +
ϕ_F Potential in bulk of intrinsic level with respect to Fermi level	+	-
ϕ_B Band bending at beginning of inversion ($\approx -2\phi_F$)	-	+
ϕ_{MS} Metal (Aluminum) to silicon work function	-	-
μ Effective surface mobility	$\mu_p = +$	$\mu_n = -$
N Substrate doping concentration	N_D	N_A

Threshold voltage

$$Q_B = \pm (-2 \epsilon_S q N \left[V + \phi_B \right])^{1/2} \quad V = \text{channel to substrate voltage}$$

(V < 0 for p-Channel, V > 0 for n-Channel)

Bulk depletion region charge*

$$V_T = \phi_{MS} + \phi_B - \frac{Q_{OX}}{C_{OX}} - \frac{Q_B}{C_{OX}}$$

*Derived from Ref. 7

Table 1 (Cont.)

Nonsaturated, channel current

Complete expression*
$$I_c = \mu C_{ox} \frac{W}{L} \left\{ \left[V_G - \phi_{MS} - \phi_B + \frac{Q_{ox}}{C_{ox}} \right] (V_D - V_S) - \frac{1}{2} (V_D^2 - V_S^2) - \frac{2(2 \epsilon_s q N)^{\frac{1}{2}}}{3 C_{ox}} \left(\left[\frac{1}{2} V_D + \phi_B \right]^{\frac{3}{2}} - \left[\frac{1}{2} V_S + \phi_B + \frac{3}{2} \right] \right) \right\}$$

Simplified expression,
Source at ground
$$I_c = \mu C_{ox} \frac{W}{L} \left\{ (V_G - V_T) V_D - \frac{1}{2} V_D^2 \right\}$$

Saturation, drain pinch-off
voltage

Complete expression*
$$V_{DP} = V_G - \phi_{MS} - \phi_B + \frac{Q_{ox}}{C_{ox}} + \frac{C_{S,qN}}{C_{ox}} \left\{ \left[1 + \frac{2 C_{ox}^2}{\epsilon_s q N} \left(V_G - \phi_{MS} + \frac{Q_{ox}}{C_{ox}} \right) \right]^{\frac{1}{2}} - 1 \right\}$$

Simplified expression
$$V_{DP} = V_G - V_T$$

Saturation, channel
current
$$I_{CP} = \frac{1}{2} \mu C_{ox} \frac{W}{L} (V_G - V_T)^2$$

*Use upper sign for p-channel transistors, lower sign for n-channel.

From the relationships expressed in these equations and general semiconductor physics, the following generalizations can be made:

- As temperature increases, the Fermi level moves toward the middle of the band gap, causing the built-in potential to decrease, thereby decreasing the threshold voltage.
- As temperature increases, the band gap narrows, causing a minor increase in the intrinsic carrier concentration, (n_i).
- Carrier mobility decreases with increasing temperature, causing transconductance to decrease.
- Increasing temperature increases leakage of generated and diffused currents.
- The more the doping, the greater the variation in threshold voltage as temperature increases.
- The zero temperature coefficient point occurs at higher gate voltages as the doping is increased.
- The overall transconductance decreases rapidly as temperature and doping increase.

With these generalizations in mind, we made the process variations listed in Table 2.

Table 2

Processing Variation

<u>Wafer</u>	<u>Substrate</u>	<u>P-well</u>
1	.8 -1.2 μcm n-type $\sim 5 \times 10^{15} \text{ cm}^{-3}$	Boron 60 keV 7×10^{13} $N_S \approx 4 \times 10^{16} \text{ cm}^{-3}$
5	.8 -1.2 μcm n-type $\sim 5 \times 10^{15} \text{ cm}^{-3}$	Boron 60 keV 2×10^{14} $N_S \approx 4 \times 10^{17} \text{ cm}^{-3}$
7	.2 -.4 μcm n-type $\sim 2 \times 10^{16} \text{ cm}^{-3}$	Boron 60 keV 1×10^{14} $N_S \approx 2 \times 10^{17} \text{ cm}^{-3}$
9	.2 -.4 μcm n-type $\sim 2 \times 10^{16} \text{ cm}^{-3}$	Boron 60 keV 2×10^{14} $N_S \approx 4 \times 10^{17} \text{ cm}^{-3}$

These variations are adjustments of the various doping levels that compose the MOSFETs, and they require many trade-offs in electrical performance, making optimization difficult (Tables 3 and 4). Table 3 shows that, although wafer 1 produces symmetrical gate voltages, leakage and transconductance vary greatly between the two channels. Wafer 9 performs well in leakage and voltage but not in transconductance.

All wafers except No. 5 performed as predicted by theory. The anomaly of wafer 5 remains unexplained. The tables show the average values derived after subjecting the wafers to 300°C for 1000 hours.

Threshold voltages for the surviving devices are within ± 0.1 V of those listed in Tables 3 and 4; leakages are within ± 5 μ A of those listed in Table 3, and 25 μ A of those in Table 4 (see Appendix). According to theory, the following pattern should appear:

- * For wafers 1 and 5, p-channel data should be similar.
- * For wafers 7 and 9, p-channel data should be similar.
- * For wafers 5 and 7, n-channel data should be similar.

Table 3

TC-1 Process Comparison at 300°C

Wafer	Average Leakage (μ A)		Average Gate Voltage (V_G) @ 10.0A		Average Transconductance (mmhos)	
	n-Channel	p-Channel	n-Channel	p-Channel	n-Channel	p-Channel
1	12.41	18.85	1.45	-1.45	0.45	0.24
5	21.44	25.86	2.72	-1.26	0.22	0.26
7	3.90	6.15	1.60	-2.41	0.34	0.21
9	4.43	6.07	2.56	-2.50	0.10	0.14

Table 4

Wafer	Average Leakage (μ A)		Average V_G @ 100 μ A				Average G_m (mmhos)			
	n-Channel	p-Channel	n-Channel	n-Channel	p-Channel	p-Channel	n-Channel	n-Channel	p-Channel	p-Channel
1	280	460	1.54	1.55	- .79	- .78	1.10	1.07	1.82	1.75
5	88	163	3.08	3.08	-1.18	-1.21	0.61	0.61	1.79	1.79
7	107	139	1.77	1.78	-2.12	-2.14	1.07	0.99	1.27	1.27
9	88	139	2.77	2.49	-2.02	-2.22	0.66	0.68	1.16	1.14

TC-4 Process Comparison at 300°C

The tables show that, except for wafer 5, the theory and the actual data generally agree.

The guard-ring, junction-isolated CMOS process is quite clean and uses Q_{ss} , N_{st} reduction techniques and other schemes to reduce oxide contamination.⁸⁻¹¹ For example, by annealing with N_2 we decrease Q_{ss} , and by annealing with H_2 we decrease N_{st} . Careful and clean processing decreases sodium and potassium contamination. The circuits were metallized with standard aluminum 1 μm thick, and standard p-glass passivation was used over the metal. The components were packaged in a ceramic, 16-pin flat pack. A computer printout of the process is included in the Appendix.

Stability Data

Although we will not discuss all the parameters tested, as an indication of stability, we will discuss data for gate voltage at 10 μA (TC-1) and 100 μA (TC-4), and leakage currents.

Gate Voltage (V_G)

To determine gate voltage, each transistor was measured separately. The source and substrate were connected to ground, and the drain was connected to an 8-V source. The voltage on the gate was slowly increased until 10 μA was measured between source and drain; this voltage was recorded (Figure 2).

FIGURE 2
Gate Voltage Measurement Setup

The 10 μ A value includes the reverse leakage current from drain to substrate but not from p-well to n-substrate. In all data obtained, 10 μ A was not exceeded in the gate voltages measured for TC-1 (10 μ A) or for TC-4 (100 μ A). See Table 4.

Leakage Current

The leakage currents discussed are drain-to-source channel leakage, drain-to-substrate reverse bias leakage, and p-well to n-substrate leakage. They were measured with the transistors connected as a CMOS inverter. With one transistor biased strongly on, we then measured the current that the other transistor allowed to pass while it is turned off (Figure 3). Thus, we have a worst-case measurement for leakage. In all cases, leakage was small enough ($I_L < I_{DSS}$) to allow the semiconductor to remain useful in actual circuits.

FIGURE 3

Measurement of Leakage Current for n Channel

- (1) Drain to Source Leakage
- (2) Drain to p-well Leakage
- (3) P-well to n-substrate Leakage

This type data is shown in the Appendix for TC-1. In all cases, we determined that the n- and p-channel devices were reasonably stable and functional except for wafer 5 which remains an unexplained anomaly.

Wafer 9 demonstrated good stability, low leakage, and a reasonable V_G at 10 μA on both the n- and p-channel devices. TC-4 data supports this finding but has an order of magnitude increase in leakage because of its larger size.

Inverters

Data from transistors connected as inverters, show that they will perform as a small-scale integrated circuit (SSIC) at high temperatures.

V_{NL} and V_{NH}

In this test, we measured the output voltage with the inputs at 1.5 V (V_{NL}) and 3.5 V (V_{NH}) obtaining functionality and noise margin parameters.

I_{DN} and I_{DP}

With these tests we determined the drive current capability of the n- and p-channel devices when hooked together as an inverter.

Results

The data for inverters, listed in the Appendix, show that all processes were functional at 300°C after 1000 hrs. In all cases, drive currents decreased with increasing temperatures as theorized; current is lost to ground through several leakage paths (Figure 3) as temperature increases.

Judging from the data obtained, there seems to be no outstanding advantage in one process over the other. There should be more

dynamic testing to determine this. The data do suggest that drive currents for the higher-doped devices (wafer 9) are more symmetrical for a given geometry and are less temperature dependent than lower-doped devices. Furthermore, CMOS, when digitally operated, works in a complementary mode; that is, when one transistor is on, the other is off. This is helpful for reliable high-temperature performance because it allows both devices to go depletion yet still perform a given digital function (Figures 2 and 3). Therefore, we can leave the threshold voltages closer to zero than when the devices must remain enhancement at 300°C, making higher speed devices possible. Wafer 5 has not been discussed because of its unexplainable behavior; V_{NL} and V_{NH} data from wafer 9 was inadvertently destroyed.

Optimization

Many trade-offs are necessary to determine the best way to build high-temperature CMOS circuits. The principal parameters that must vary are doping profiles and size; oxide growth and overall cleanliness make the circuit possible.

Process (Doping Profile)

Judging from the results of this study, doping profiles like those of wafers 7 and 9 are best for high-temperature use. Application is extremely important because we must know what is expected from the circuit before the right process is found. For example, wafer 9 (n^- sub $\approx 2 \times 10^{16} \text{ cm}^{-3}$ and p-well $N_S \approx 4 \times 10^{17} \text{ cm}^{-3}$)

might appear to be the best choice for high-temperature electronics--it has good symmetry, exhibits small variation with temperature, and has reasonable drive-current capability. However, in some applications, it may have too high a threshold voltage and too low a breakdown voltage (~ 12 V). Therefore, depending on the circuits used, increasing the doping to increase the temperature range of the CMOS does not always produce an ideal circuit. In fact, some electrical requirements may make it impossible to develop a high-temperature circuit by using silicon planar technology.

An improvement in processing would be to use laser¹² instead of thermal annealing (not done in the study). This would decrease leakage and increase switching speeds by doing a better job of repairing the damage caused by implantation, i.e., decrease trapping sites and improve the crystalline structure.

Geometry

When designing the mask set for high-temperature circuits, we must include several considerations not necessary when designing room temperature circuits. For example, of major importance is the fact that the area between the p-well and the n-substrate must be as small as possible to decrease reverse leakage. This means that each n-channel transistor should have its own p-well. The price for this is an undesirable increase in the silicon area.

The mobility of holes and electrons decreases with increasing temperature but not at exactly the same rate. However, the ratio of Z/L n-channel to Z/L p-channel should be the same as in room temperature circuits to keep the circuits complementary. Keeping their ratio the same as in room-temperature circuits seems to be a good compromise.

For high-temperature circuits, the area from the drain to the substrate junction should be as small as possible to decrease reverse leakage. This is accomplished by horseshoeing the Z/L s, thereby increasing circuit density--this method is already in common use.

To make high-temperature circuits more reliable, metal lines should be as broad and deep as possible, again sacrificing chip area.

Conclusions and Recommendations

Existing CMOS technology can be used to produce stable and useful circuits that operate at 300°C for 1000 hours. This accomplishment, however, sacrifices some chip area and does not provide gate protection. For this latter problem, high-temperature GaAs and GaP diodes should be developed as protection devices. Although these diodes would probably be outside the CMOS chip, they could be part of the same flat pack.

The behavior of wafer 5 remains unexplained; however, processing and testing will continue in an effort to explain this anomaly.

More complicated SSIC will be studied to determine how well or how far junction isolation will operate, and different gate materials will be investigated.

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Appendix

High Temperature Process

TC-1 Discrete Data

TC-1 Inverter Data

TC-4 Test Chip

APPENDIX

High Temperature Process

1. BASIC SUBSTRATE

2. OXIDE ETCH: TUB DIFFUSION AND OXIDATION

3. OXIDE ETCH: SOURCE AND DRAIN DIFFUSION AND OXIDATION FOR P-CHANNEL DEVICE

4. ETCH: DIFFUSION OF N-CANNEL SOURCE AND DRAIN AND OXIDATION

5. ETCH: GROWTH OF GATE OXIDE; FOLLOWED BY CONTACT CUTS AND METALLIZATION

High Temperature Process

<u>Step No.</u>		<u>Process</u>	<u>No. Wafers</u>
1	1106BA	CLEAN W/SCRUB	25
2	3102AB	DRY/STEAM OX, 15/90	25
3	5100AA	747/60, LEV1, 3.5S, A	25
4	5124AA	TX-100 PRE-WET	25
5	5111AA	ETCH C1 HPO + 1 M, NOTE 4	2
6	9200AA	INSPECTION	25
7	1100AA	CLEAN W/SCRUB	25
8	3107AB	DRY OX, 60M	25
9	4703BH	IMP W1, 2 + C1, 3, 6	5
10	4104BH	IMP, NOTE 5	8
11	4204BH	IMP, NOTE 6	8
12	5111BB	ETCH, 4M	25
13	1106AA	CLEAN	25
14	3105AA	P-WELL DRY, 16H	25
15	5100AA	747/60, LV2, 3.5S, A	25
16	5124AA	TX-100 PRE-WET	25
17	5111AA	ETCH, C2 HPO + 1M, A	25
18	9201AA	MEAS CHAN CD	25
19	9200AA	INSPECTION	25
20	1100AA	CLEAN W/SCRUB	25
21	3111AA	P + PREDEP, NOTE 1	25
22	5112AA	BORON GLASS ETCH	25
23	3102DB	DRY/STM	25
24	5112AA	STAIN REMOVAL	25
25	3107AF	DRY OX, 30M, 1000C	25
26	2106CA	CVD OX, 3.5-4.5K, FRNT	25
27	5100AA	747/60, LV3, 3.5S, A	25
28	5124AA	TX-100 PRE-WET	25
29	5111AA	ETCH, NOTE 7	25
30	9201AA	MEAS CHAN CD, 7.7 MIC	25
31	9200AA	INSPECTION	25
32	1100AA	CLEAN W/SCRUB	25

High Temperature Process (Cont.)

<u>Step No.</u>		<u>Process</u>	<u>No. Wafers</u>
33	3112DA	N + PREDEP, 30M, NOTE 1	25
34	5111AA	ETCH, A+C, C5 HPO + 1M	25
35	1106AA	CLEAN	25
36	3107AF	N + DRV, 30M, 1000C	25
37	2106CA	DEP OX, 12KA, FRONTS	25
38	5100BB	747/60, LV4, 3.5S A	25
39	5124AA	TX-100 PRE-WET	25
40	5111AA	ETCH, A+C, C4 HPO + 2M	25
41	9200AA	INSPECTION	25
42	1100AA	CLEAN W/SCRUB	25
43	3107AB	DRY OX, 60M	25
44	4112BB	IMP A+C	25
45	5124AA	TX100 DIP	25
46	5111BE	ETCH, 3M	25
47	1106AA	CLEAN	25
48	3107AV	GT OX, 700+-25A, T15	25
49	3110HB	875C, 40M N2 ANN	25
50	5100AA	747/60, LV5, 3.5S A	25
51	5124AA	TX-100 PRE-WET	25
52	5111AA	ETCH A+C1-3, 8-15 HPO + 2M	25
53	9200AA	INSPECTION	25
54	1100BB	25A ETCH, A + C4-6	25
55	9101AA	MEAS RS&XJ, C1-3, 8-15	25
56	9105AA	GAET OC TH, C4-7	25
57	6104BB	10KA, A, C5, 6 DOTS, N2	25
58	5105CC	HR100, LEV6, 12S, A	24
59	9200BA	INSPECTION	24
60	5124AA	TX-100 PRE-WET	24
61	5113AA	AL ETCH, A	24
62	9200BA	INSPECTION	24
63	1109AB	RESIST REM, J100, A	24
64	3109AA	SINTER, 20M, A + C5, 6	25

High Temperature Process (Cont.)

<u>Step</u> <u>No.</u>		<u>Process</u>	<u>No.</u> <u>Wafers</u>
65	9104AA	OXIDE MEAS, C9	24
66	5151AA	SILOX P-GL, FRONTS, N3	24
67	5106AA	747/110, LV7, A	24
68	9200AA	INSPECTION	24
69	5122AA	H3P04/HF ETCH, A	24
70	1109AA	J-100 STRIP, A	24
71	5121AA	BACK ETCH W STICK, C	24
72	6105AA	CR AU, BACKS, C	24
73	1107AA	SCRUB	24
74	9250AA	INSPECTION, DLX	9

Discrete

V_G @ $10 \mu a$ TC-1 N-CHANNEL WAFER 1

V_G @ 10 μa TC-1 P-CHANNEL WAFER 1

I_L TC-1 N-CHANNEL WAFER 1

V_G @ $10 \mu a$ TC-1 N-CHANNEL WAFER 7

$V_G @ 10 \mu a$ TC-1 P-CHANNEL WAFER 7

$\Delta V_{G_{MAX}} @ 300^\circ C = -0.32 \text{ VOLTS}$

$\Delta V_{G_{MAX}} 25^\circ C \text{ TO } 300^\circ C = -0.62 \text{ VOLTS}$

V_G @ $10\mu a$ TC-1 N-CHANNEL WAFER 9

V_G @ 10 μ a TC-1 P-CHANNEL WAFER 9

$\Delta V_{G_{MAX}}$ @ 300°C = -0.32V

$\Delta V_{G_{MAX}}$ 25°C TO 300°C = -0.60V

I₁ TC-1 N-CHANNEL WAFER 9

I_L TC-1 P-CHANNEL WAFER 9

Inverter

NOISE IMMUNITY-INVERTER-WAFER 1

I_{DP} INVERTER WAFER 7

INVERTER-NOISE IMMUNITY-WAFER 7

$$V_{NL} : V_{IN} = 1.5 \text{ VOLTS}$$

$$\Delta V_{NL} \text{ MAX } 25^{\circ}\text{C TO } 300^{\circ}\text{C} = 0.13 \text{ VOLTS}$$

$$\Delta V_{NL} \text{ MAX @ } 300^{\circ}\text{C} = 0.06 \text{ VOLTS}$$

I_{DN} INVERTER WAFER 9

I_{DP} INVERTER WAFER 9

Test Chip

Glossary of Technical Terms

BAND GAP	The difference in energy between two bands of energy in a semiconductor or insulator.
CARRIER	Also known as charge carrier--a mobile electron or hole (see HOLE).
CMOS	Complementary Metal Oxide Semiconductor--a device that combines a p-type MOS device with an n-type MOS device (see PMOS, NMOS).
DEPLETION (region)	Region between n- and p-type semiconductor. Region depleted of carriers in semiconductor junction.
DOPE, DOPING	Adding impurities to a semiconductor to produce n- or p-type material.
DRAIN	An electrode in a thin-film transistor.
FERMI LEVEL	Also called Fermi energy; the energy level that is constant throughout the crystal.
FIELD EFFECT TRANSISTOR	A transistor in which a transverse electric field modulates the conductance between two nodes.
FLAT PACK	A thin, rectangular, ceramic package, the connecting pins projecting from the edges.
GATE	Modulating terminal in a FET.
GUARD RING	Doped region that decreases parasitic transistor action.
HOLE	A vacant electron energy state which behaves as if it were a positively charged particle.
JUNCTION	The region of transition between the two semiconducting regions, in this case, the pn junction.
METALLIZE	To coat or impregnate with metal.
n-TYPE SEMICONDUCTOR	See n-TYPE SEMICONDUCTOR.

NMOS	n-type MOS device (see CMOS, n-TYPE SEMICONDUCTOR).
n-TYPE CONDUCTIVITY	Conduction associated with electrons in a semiconductor (see p-TYPE CONDUCTIVITY).
n-TYPE SEMICONDUCTOR	A semiconductor in which electron density exceeds that of the holes.
PASSIVATION	Growing a layer of oxide on the surface of a semiconductor thereby isolating it from the environment and providing electrical stability.
p-CHANNEL	See p-TYPE SEMICONDUCTOR.
PMOS	p-type MOS device (see CMOS, p-TYPE SEMICONDUCTOR).
p-TYPE CONDUCTIVITY	Conductivity associated with holes in a semiconductor (see n-TYPE SEMICONDUCTOR).
p-TYPE SEMICONDUCTOR	A semiconductor in which excess mobile hole concentration is very high.
p-WELL	P region in which n-channel transistors are made.
SUBSTRATE	The material on which a microcircuit is built.
TRANSCONDUCTANCE	The change in drain current divided by the change in gate voltage causing it, if all other voltages are constant.
TRAPPING SIGHT	Allowable energy state within band gap.
ZERO TEMPERATURE COEFFICIENT POINT	That point on the transfer curve which is independent of temperature.

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