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Field-Effect Transistors in Integrated Circuits

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Macmillan Education

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Softcover reprint of the hardcover 1st edition 1974 978-0-333-15243-0

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First published in Great Britain by
THE MACMILLAN PRESS LTD
London and Basingstoke
Associated companies in New York Dublin
Melbourne Johannesburg and Madras

Authorised English language edition of
Fälteffekttransistorer, first published 1971 by
P. A. Norstedt & Söners Förlag, Stockholm

SBN 333 15243 3

ISBN 978-1-349-02055-3 ISBN 978-1-349-02053-9 (eBook)
DOI 10.1007/978-1-349-02053-9

Library of Congress catalog card no.: 73-19429

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Preface

Interest in field-effect transistors has been spurred by two new solid state electronic developments—large-scale integrated circuits (LSI) and semiconductor memories. The fact that field-effect transistors can be made smaller and less power consuming than conventional bipolar units explains their much faster growth, particularly in these areas. At present about 20 per cent of all transistors are of the field-effect type and this percentage is expected to grow to about 40 per cent in five years.

This book has a wide scope—from semiconductor physics to the design of large-scale integrated circuits. To encompass such a large field in a small volume it has been necessary to concentrate on essentials. For this reason analytical derivations have generally been omitted and straightforward expressions given, justified only by physical reasoning. It is believed that this is more useful to the circuit designer who may not be interested in the detailed evolution of the expressions but who needs to know and use them in order properly to design his circuits and to understand the limitations and trade-offs that are available. The equipment designer on the other hand, may be helped by a condensed compilation of the essentials of circuit design with field-effect transistors.

Field-effect transistors are used mainly in digital circuits and only fractionally in analogue circuits. For this reason this book strongly emphasises digital applications. However, a brief treatment of the essentials of analogue circuits is included for completeness.

The book starts with a short summary of the field-effect transistor to introduce the terminology and functions of the main components. It provides a form of abstract, just as all scientific papers are provided with an abstract, to help people in a hurry to find out what it is all about. Next follows a brief note on the history of the device.

Chapter 1 gives a short review of semiconductor physics in just enough detail to make it possible to understand the field-effect transistor and its performance, limitations and some of the adjustments needed between parameters such as speed, power, reliability, cost, life, and so on. This chapter is optional reading.

Chapter 2 describes the most important type of field-effect transistor, the metal oxide semiconductor (MOS) transistor, and gives details of its structure and performance. Some important special versions of the field-effect transistor other than the MOS are given in chapter 3, the *pn* junction gate field-effect transistor (JFET), the Schottky gate field-effect transistor and the MNOS memory transistor. Also included are the recent newcomers to the field—charge-coupled devices and bucket-brigade registers.

Chapters 4–7 treat on the use of field-effect transistors in different circuits with

special emphasis on integrated circuits. The basic building block for these is the inverter, which is discussed in chapter 4. The use of inverters in digital logic circuits is to be found in chapter 5. The most important application for field-effect transistors is in memory circuits, which are treated in chapter 6 starting with their main building block, the flip-flop circuit, proceeding through registers to very complex and large random-access memories (RAM) and read-only memories (ROM). However, there are also some important applications of field-effect transistors in linear circuits, which are examined in chapter 7.

What can be done with field-effect transistors, and just as important, what cannot be done, depends to a large extent on technological factors. Because of the widespread use of integrated circuits in modern electronic systems it has become necessary for the circuit designer to know at least the essentials of circuit and component processing in order to arrive at the best circuit design from among the many possibilities. The technology of devices and integrated circuits is given in chapter 8, while the special considerations that refer to MSI medium scale integration (12–100 stages) and LSI large-scale integration (>100 stages), have been summarised in chapter 9.

For assistance with the translation the authors are grateful to Mr S. S. Shivaraman. They would also like to thank the Intel Corporation of Santa Clara, California for permission to include the examples of FET junctions shown in figures 6.13 and 6.37 and the practical example of a MOS LSI circuit described in detail in chapter 9.

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Principal Notations

A	area. Also a constant
A, B	Boolean variables
a	channel height (in the z direction)
$b_{11}, b_{12}, b_{21}, b_{22}$	imaginary parts of the y -parameters
C	concentration. Also capacitance
C_d	drain capacitance
C_g	gate capacitance
C_{gd}	gate to drain capacitance
C_i	insulator capacitance. Also input capacitance
C_l	lead capacitance
d	insulator thickness
D	diffusion coefficient
E_c	energy of lower edge of the conduction band
E_f	energy at the Fermi level
E_g	band gap
E_o	quiescent energy loss in a COSMOS circuit without capacitive loss
E_v	energy of the upper edge of the valence band
f	frequency
G	gain, conductance
$g_{11}, g_{12}, g_{21}, g_{22}$	real parts of the y -parameters
g_m	transconductance
I_D	drain current
I_G	gate current
I_S	source current
k	Boltzmann's constant ($k = 1.38 \times 10^{-23}$ J/K)
l	channel length (in the x -direction)
n	electron density
N_A	density of acceptors
N_D	density of donors
p	hole density
q	electronic charge ($q = -1.6 \times 10^{-19}$ coulomb)
R_L	load resistance
t_{d0}	delay time to zero
t_{d1}	delay time to one
T	absolute temperature (room temperature plus 273°)
V_C	supply voltage
V_F	gate voltage of load transistor

V_{DS}	voltage between drain and source
V_{GS}	voltage between gate and source
V_i	noise immunity
V_m	noise margin
V_P	pinch-off voltage
V_T	threshold voltage
V_S	source voltage
v	normalised voltage with respect to the supply voltage V_C
w	channel width (in the y -direction)
x	direction parallel to the current, parallel to the surface
y	direction perpendicular to the current, parallel to the surface
$\mathcal{Y}_{11}, \mathcal{Y}_{12}, \mathcal{Y}_{21}, \mathcal{Y}_{22}$	$\mathcal{Y}$ -parameters
z	direction perpendicular to the current, perpendicular to the surface
α	ratio between the currents of driving transistor and load transistor
β	conductance factor defined in equation 2.9
ϵ_i	dielectric constant of the insulator (F/m); $\epsilon_i = \kappa \epsilon_0$
ϵ_s	dielectric constant of the semiconductor (F/m); $\epsilon_s = \kappa \epsilon_0$
ϵ_0	dielectric constant of vacuum ($\epsilon_0 = 8.85 \times 10^{-12}$ F/m)
κ	relative dielectric constant ϵ/ϵ_0 (silicon 12; silicon dioxide, thermal 3.8, grown in water vapour 4.5; silicon nitride 7)
μ_p	hole mobility (in silicon at room temperature $0.048 \text{ m}^2/\text{Vs}$)
μ_n	electron mobility (in silicon at room temperature $0.135 \text{ m}^2/\text{Vs}$)
ρ	resistivity
σ	conductivity
ω	angular frequency ($\omega = 2\pi f$)
τ	time constant
τ_f	time constant for fall time
τ_r	time constant for rise time
ϕ_F	Fermi potential