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Solid State Devices A Quantum Physics Approach

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To
Anne and Dominic

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Preface

The changes which have taken place in electronics are truly astonishing. It is difficult to believe that within a single lifespan we have come from the cat's-whisker diode, via the thermionic valve, to the 256K random access memory and beyond. These developments would not have come about without an increased understanding of the physics and technology of the solid state.

Although the progression from Planck's quantum postulate to single chip electronic systems within eighty years has resulted in an increased level of specialisation of the fields of knowledge, solid state nevertheless continues to be a cross-disciplinary subject. The design and fabrication of solid state devices involve large elements of chemistry, physics and materials science. However, books on the subject tend to be written by specialists in one or other area. Thus a physics-based text is likely to have more details on quantum theory than is necessary for a technologist. Similarly, texts which concentrate on devices and their applications frequently ignore the fundamental background which is vital for a true understanding.

This book attempts to bridge the gap by presenting a clear résumé of the background to semiconductor device theory in a multidisciplinary way. It has its origins in a course which has been taught in Electrical and Electronic Engineering at Nottingham University for several years. This was intended to give students a simple grounding in quantum theory and wave mechanics in order to provide the conceptual and manipulative skills for subsequent courses in integrated circuit technology, VLSI and power semiconductor electronics. Although the book follows the essential outlines of the course, it has been adapted for a wider readership who will nevertheless find it beneficial to have some background in physics and mathematics — probably equivalent to that required for entry to an undergraduate course in science or engineering.

Crystallography is used as the starting point. There is an introduction to the reciprocal lattice and the application of Fourier's theorem to X-ray structural analysis. The use of Fourier methods is extended in the next chapter to provide a building block for wave mechanics. The implications of wave mechanics are not far removed from concepts which students might well encounter in an electromagnetics course. Basic ideas which are common in the area of molecular bonding theory are used to lead the reader towards the solid state. The solution

of Schrödinger's equation for extended problems is treated in terms of the Free Electron and Band theories. The introduction of the reciprocal lattice in the first chapter should assist with an understanding of k -space.

Once a quantum mechanical foundation for solids has been provided, attention is then focussed on semiconducting materials and semiconductor devices. Further background includes treatments of diffusion, drift and recombination processes which are used when considering two-terminal, three-terminal unipolar and three-terminal bipolar structures. The final chapter on the properties of semiconductor surfaces and semiconductor surface devices provides an introduction to MOS, with some pointers towards MOS integrated circuits.

Space constraints have limited any detailed discussion of optical and thermal properties to implicit treatments within the framework given above. For similar reasons, mention of magnetic properties has had to be omitted.

Although the level is not particularly sophisticated, there has been no dilution of mathematical content. I have attempted to avoid the dreaded phrase "it can easily be seen that . . ." and all derivations are given in full. Where relevant, references for background reading have been provided. These appear at the end of chapters along with a set of problems. The problems have been designed with several aims in mind, the most important being the consolidation of comprehension and the conceptual extension of text material. Solutions are provided for all numerical examples.

In the preparation of this book I would like to thank Professor B. Tuck and the pre-publication referees whose comments have helped in no small way to convert a set of course notes into a broad-based text. I would also like to thank the succession of Nottingham students who have, by means which were sometimes diplomatic, sometimes less so, forced a gradual evolution of which this is the end product.

Finally, few authors can be so lucky as to have an artist for a father. I would like to thank mine for the many hours which he has devoted to the illustrations.

Symbols used for Variables

C	capacitance
d	Cartesian space distance
d^*	reciprocal space distance
D	diffusion constant
$\mathcal{E}$	electric field
E	energy (for example, E_f = Fermi energy, E_g = band gap energy)
$[E]$	total energy or Hamiltonian operator
f	frequency
F	flux (for example, F_p, F_n = hole and electron flux)
$[H]$	alternative symbol for total energy or Hamiltonian operator
k	wave number
L	diffusion length (for example, L_p, L_n = hole and electron diffusion length)
m	mass
m^*	effective mass
n	electron concentration (for example, n_p = electron concentration in p-type semiconductor)
N	impurity concentration (for example, N_A, N_d = acceptor and donor concentrations)
p	hole concentration (for example, p_{n_0} = hole minority carrier concentration at equilibrium)
P	momentum
$[P]$	momentum operator
Q	electrical charge
R_H	Hall coefficient
$S(E)$	density of electron states
T	temperature
$U_k(x)$	block function
v	velocity
V	potential
W	depletion layer width
W_b	base width of a bipolar transistor
x	position in Cartesian space

γ	injection efficiency
ϵ	permittivity
λ	wavelength
μ	mobility
ρ	electrical resistivity
σ	standard deviation of a normal distribution
τ	minority carrier lifetime (for example, τ_p, τ_n = hole and electron life-times)
ϕ	work function
ϕ_B	built-in potential of a p-n or metal/semiconductor junction
ψ	wave function
ψ^*	conjugate of wave function
ω	angular velocity