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Ferroelectric Memories

With 170 Figures

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For my wife, Galya

Preface

The photograph opposite was taken by me in November 1970 in front of the old Department of Natural Philosophy on Drummond Street at The University of Edinburgh. The occasion was historic in that it was the first meeting of Dr. K. Alex Mueller (left) with Prof. William Cochran (centre) and Prof. Roger A. Cowley (right). It was my pleasure to spend that year with Cowley and Cochran (I shared an office with Bill). During the year I learned why certain crystals were considered ferroelectric at room temperature in Scotland but not in the USA. The buildings were unheated, and our basement laboratory hovered around 10°C summer and winter!

In the present book I try to combine the present knowledge of device physics for ferroelectric thin-film memories with information about circuit design, materials deposition and characterization, and testing protocols. It is my hope that this will serve as a useful reference for engineers and device physicists in industry and in government laboratories, and as a book that will assist the teaching of this topic in senior or graduate-level engineering and applied physics university classes.

With this book, I would like to honour the four people who most influenced directions of modern research on ferroelectricity – the three pictured in the photograph, and Dr. Helen Megaw, whose early role in the study of ferroelectric crystals at Cambridge is one I seem to have inherited.

Special thanks are also due to my colleagues of 1984–1992 at Symetrix, Carlos Araujo and Larry McMillan, without whom this work would never have begun.

Cambridge
March 2000

James F. Scott

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Glossary of Symbols

α	Activation field for ferroelectric switching; critical exponent characterizing specific heat divergence slightly above T_0
α'	Critical exponent characterizing specific heat divergence slightly below T_0
A	Lateral area of memory cell
a	Lattice constant or jump distance for electrons in a ferroelectric semiconductor with hopping conduction
a'	Accommodation length (region of charge diffusion near an electrode)
a_0, b_0	Lateral dimensions of capacitor surface, with $a_0 < b_0$
ANNNI	Axial Next Nearest Neighbor Ising model
β	Activation energy for electrical conduction; critical exponent characterizing $P(T)$ near T_C
BMF	Barium Magnesium Fluoride $BaMgF_4$
BST	Barium Strontium Titanate $Ba_xSr_{1-x}TiO_3$
C	Capacitance
CMOS	Complementary Metal-Oxide Semiconductor
χ	Semiconductor electron affinity; electrical permittivity
C_V	Specific heat
CVD	Chemical Vapour Deposition
δ	Characteristic length in $\mathrm{d}P/\mathrm{d}z$ at ferroelectric film surfaces; critical exponent characterizing P versus E response at T_C
D	Displacement vector; dimension of domain (1, 2, or 3)
d	Film thickness
d_d	Depletion width
Δ	Trap energy in a ferroelectric, measured down from conduction band
$\Delta\Phi$	Image field reduction term
d'	Distance between dendritic microshort tips extending from cathode and anode
dc	Direct current
DRAM	Dynamic Random Access Memory

e	Charge of the electron
E	Electric field
ε	Relative dielectric constant
E_{B}	Breakdown field
E_{c}	Coercive field
EBDW	Electron Beam Direct Writing
ECR	Electron Cyclotron Resonance
EEPROM	Electrically Erasable Programmable Read-Only Memory
EXAFS	Extended X-ray Absorption Fine Structure
F	Helmholtz free energy
FeRAM, FRAM	Ferroelectric Random Access Memory
FET	Field Effect Transistor
Φ	Metal work function
Φ_{B}	Schottky barrier height
Φ_{FE}	Ferroelectric work function
γ	Critical exponent characterizing isothermal susceptibility slightly above T_0
γ'	Critical exponent characterizing isothermal susceptibility slightly below T_0
h	Planck's constant
i	Displacement current density
J	Leakage curent density
j	Exponent characterizing field dependence of switching time
JFET	Junction FET
k	Exponent characterizing frequency dependence of coercive field
K	Thermal conductivity
k_{B}	Boltzmann's constant
K_{s}	A ratio of surface charge density to remanent polarization useful for parametrizing the read operation of a ferroelectric memory
λ	Electron mean free path
L	Ratio of maximum displacement current $i(t)$ times the time at which it is maximum $t_{\max}$, divided by spontaneous polarization P_{s}
m	Exponent characterizing temperature dependence of switching
m^*	Effective mass
MBE	Molecular Beam Epitaxy
MOD	Metal-Organic Decomposition
MOSFET	Metal Oxide Silicon FET
μ	Mobility
n	Carrier concentration

N	Number of microshorts or nucleation sites or space-charge density per unit area
N_s	Number of bipolar switching cycles
NDRO	NonDestructive ReadOut
NV	NonVolatile
P_+, P_-	Delta-function polarization at ferroelectric surfaces
P_i	Polarization due to charged defects
P_r	Remanent polarization
P_s	Spontaneous polarization
p_{tr}	Trapped hole density
PLD	Pulsed Laser Deposition
PLZT	PZT with lanthanum doping
PT	Lead titanate $PbTiO_3$
PZT	Lead zirconate titanate $PbZr_xTi_{1-x}O_3$
Π	Pressure
Q	Quality factor
q	Total electric charge
R	Nucleation rate (sites per cm^3 per second)
RAM	Random Access Memory
RBS	Rutherford Back-Scattering
READ	To decode and output the information stored in a memory
RIE	Reactive Ion Etching
RTA	Rapid Thermal Annealing
ρ	Charge per unit volume
σ	Electrical conductivity
σ_0	Electrical conduction in the high-temperature limit
SBN	Strontium Bismuth Niobate $SrBi_2Nb_2O_9$
SBT	Strontium Bismuth Tantalate $SrBi_2Ta_2O_9$
SBTN	Strontium Bismuth Tantalate-Niobate $SrBi_2Ta_{2-x}Nb_xO_9$
SCLC	Space Charge Limited Currents
SRAM	Static Random Access Memory
τ	Reduced temperature $(T - T_C)/T_C$
$\tan\delta$	Loss tangent
t_B	Breakdown time
t_c	Rise time for increasing film temperature dT/dt or applied field dE/dt
T_C	Curie temperature
TDDB	Time Dependent Dielectric Breakdown
TEM	Transmission Electron Microscope
t_N	Nucleation time
t_s	Switching time
U	Potential energy
UPS	Ultraviolet Photoelectron Spectroscopy

v	Domain wall speed
V	Voltage
WRITE	To encode and input data into a memory
XPS	X-ray Photoelectron Spectroscopy
XRD	X-Ray Diffraction
ξ	Correlation length in bulk for ferroelectric polarization
YBCO	Yttrium Barium Copper Oxide
z	Depth into film from surface or interface