Springer Series in 
MATERIALS SCIENCE

Editors: R. Hull · R. M. Osgood, Jr. · H. Sakaki · A. Zunger

Springer Series in Materials Science covers the complete spectrum of materials physics, including fundamental principles, physical properties, materials theory and design. Recognizing the increasing importance of materials science in future device technologies, the book titles in this series reflect the state-of-the-art in understanding and controlling the structure and properties of all important classes of materials.

31 Nanostructures and Quantum Effects
By H. Sakaki and H. Noge

32 Nitride Semiconductors and Devices
By H. Morkoç

33 Supercarbon
Synthesis, Properties and Applications
Editors: S. Yoshimura and R. P. H. Chang

34 Computational Materials Design
Editor: T. Saito

35 Macromolecular Science
and Engineering
New Aspects
Editor: Y. Tanabe

36 Ceramics
Mechanical Properties, Failure
Behaviour, Materials Selection
By D. Munz and T. Fett

37 Technology and Applications
of Amorphous Silicon
Editor: R. A. Street

38 Fullerene Polymers
and Fullerene Polymer Composites
Editors: P. C. Eklund and A. M. Rao

Volumes 1–30 are listed at the end of the book.
Technology and Applications of Amorphous Silicon

With 279 Figures and 20 Tables
Hydrogenated amorphous silicon (a-Si:H) has become an established material in semiconductor technology, led by photovoltaic and active matrix display applications. The primary attribute of the technology is its large area capability, which provides applications that are otherwise unavailable. The extraordinary ability to make devices on one-meter glass plates or long rolls of metal foil is outside the scope of traditional semiconductor manufacturing. A-Si:H exhibits the full range of semiconducting properties, although with lower speed and current compared with single crystal silicon, and the most important devices are thin film transistors and photodiodes. The plasma deposition technology along with the amorphous structure provide a wide set of compatible materials that allows diversity in device design and considerable band gap engineering. For example, a triple solar cell structure (Chap. 6) has 10–12 distinct layers, each specifically optimized to its role.

The book describes both established and emerging applications. Active matrix addressing is ideally suited to a-Si:H thin film transistors, and is applied to liquid crystal displays (Chap. 2), and image sensor arrays (Chap. 4). Such arrays are made with > 10 million distinct a-Si:H devices, a number which compares respectfully with any silicon IC. The arrays are embedded in electronic and optical systems, and the chapters describe how the devices interact with the external systems to fulfill their role.

One focus of the emerging technology is the development of novel devices with complex layered structures. Examples are integrated color sensors (Chap. 7) and large area position sensors (Chap. 8). Another focus is the integration of laser recrystallized polycrystalline silicon into the technology (Chap. 3). Polysilicon adds flexibility to the large area technology since, in addition to co-existing with a-Si:H devices on the same array, parts of an individual a-Si:H device, such as the TFT contacts, can be selectively recrystallized. Finally, some revolutionary approaches to the manufacture of devices using printing technology are described in Chap. 5. The expanding range of device options makes the future of a-Si:H and large area electronics look very promising.

As editor I would like to thank the authors for their excellent contributions to this book. I am grateful to the Xerox Palo Alto Research Center for their
support of the project, and to many colleagues with whom it has been a pleasure to work on this subject.

Palo Alto, 1999

Bob Street
Contents

1 Introduction .............................................. 1
   Robert Street
   1.1 Overview of the Book ........................................ 1
   1.2 Development of Amorphous Silicon ..................... 2
   1.3 Basic Properties of Amorphous Silicon ............... 3
   References ..................................................... 5

2 Active-Matrix Liquid-Crystal Displays .................... 7
   Toshihisa Tsukada
   2.1 Introduction .................................................. 7
   2.2 TFT LCD .................................................. 9
      2.2.1 TFT LCD Configuration ........................................ 9
      2.2.2 Pixel Design .............................................. 14
      2.2.3 Design Analysis ...................................... 17
      2.2.4 Scaling Theory of TFT LCD ............................... 26
      2.2.5 Fabrication of TFT Panels ............................. 34
   2.3 Thin-Film Transistors ....................................... 36
      2.3.1 Hydrogenated Amorphous Silicon Thin-Film Transistors ... 39
      2.3.2 TFT Characteristics ...................................... 41
      2.3.3 Threshold Voltage Shift .................................. 49
      2.3.4 Simulation of TFT Behavior ............................. 53
      2.3.5 Two-Terminal Devices .................................. 60
   2.4 Liquid Crystal .............................................. 61
      2.4.1 Physical Constants of Liquid Crystal ............. 64
      2.4.2 Twisted-Nematic Cell ............................... 69
      2.4.3 In-Plane-Switching Cell .................. 81
      2.4.4 Super-Twisted Nematic (STN) Cell .................... 87
   References ..................................................... 89

3 Laser Crystallization for Polycrystalline Silicon Device Applications .......................... 94
   James B. Boyce and Ping Mei
   3.1 Introduction ................................................ 94
   3.2 Laser Processing of Polysilicon .......................... 96
3.2.1 Polysilicon .................................................. 96
3.2.2 Laser Crystallization ....................................... 101
3.2.3 Grain Growth ............................................. 105
3.2.4 Surface Roughening ....................................... 110
3.2.5 Laser Doping ............................................. 111
3.3 Low-Temperature Poly-Si Devices ............................ 117
  3.3.1 Device Fabrication ....................................... 118
  3.3.2 CMOS Device Performance ............................... 121
  3.3.3 Device Leakage Currents ................................ 126
  3.3.4 Device Stability ........................................ 130
3.4 Integration of a-Si and Poly-Si TFTs ......................... 132
  3.4.1 Development of Hybrid a-Si and Poly-Si Devices ...... 133
  3.4.2 Hybrid Materials Processing ............................ 135
  3.4.3 Device Fabrication and Performance ..................... 138
3.5 Conclusion .................................................. 142
References ..................................................... 143

4 Large Area Image Sensor Arrays ................................ 147
Robert Street
4.1 Introduction ................................................. 147
4.2 Devices ..................................................... 148
  4.2.1 P-i-n Photodiodes ...................................... 148
  4.2.2 Thin Film Transistors .................................. 157
4.3 Sensor Array Designs ........................................ 160
  4.3.1 Matrix Addressed Readout ............................... 161
  4.3.2 TFT Addressed, p-i-n Photodiode Arrays ............... 161
  4.3.3 High Fill Factor Array Designs ......................... 171
  4.3.4 TFT Addressed, X-Ray Photoconductor Arrays .......... 172
  4.3.5 Diode Addressed Arrays ................................ 175
  4.3.6 CMOS Sensors ......................................... 178
4.4 Imaging Systems and Their Performance ...................... 178
  4.4.1 Electronics ........................................... 179
  4.4.2 Electronic Noise ...................................... 185
  4.4.3 X-Ray Detection ..................................... 191
  4.4.4 The Performance of X-Ray Detectors ................... 194
4.5 Applications of Large Area Image Sensors .................... 204
  4.5.1 Medical X-Ray Imaging ................................. 204
  4.5.2 Other Radiation Imaging Applications .................. 211
  4.5.3 Document Scanning ................................... 214
4.6 Future Developments ........................................ 216
References ..................................................... 217

5 Novel Processing Technology for Macroelectronics .......... 222
S. Wagner, H. Gleskova, J.C. Sturm, and Z. Suo
5.1 Introduction ................................................. 222
5.2 Resolution and Registration:
   The Density of Functions Achievable by Printing .................. 225
5.3 Printed Toner Masks for Etching and Liftoff ..................... 228
   5.3.1 Toner Masks via Paper Transfer: TFTs on Glass Foil ........ 228
   5.3.2 All Masks Printed Directly: TFTs on Steel Foil .......... 230
5.4 Printing Active Materials: Jetting Doped Polymers
   for Organic Light Emitting Devices .......................... 232
5.5 Substrates and Encapsulation for Microelectronic Circuits .... 236
5.6 Plastic Substrate Foil: TFT on Polyimide ....................... 244
5.7 3-D Integration on a Foil Substrate:
   OLED/TFT Pixel Elements on Steel ............................ 246
5.8 Outlook .................................................... 249
References ..................................................... 250

6  Multijunction Solar Cells and Modules .................. 252
   Subhendu Guha
6.1 Introduction ................................................. 252
6.2 Deposition Methods .......................................... 254
   6.2.1 Glow-Discharge Deposition Technique ...................... 254
   6.2.2 Plasma Chemistry and the Growth Process ................. 254
   6.2.3 Factors that Influence Film and Cell Quality .......... 256
6.3 Single-Junction Cells ......................................... 258
   6.3.1 Cell Structure ........................................... 258
   6.3.2 Cell Characteristics ...................................... 259
   6.3.3 Numerical Modeling ..................................... 261
   6.3.4 Light-Induced Degradation ............................... 264
6.4 High Efficiency Cells ......................................... 268
   6.4.1 Introduction ............................................ 268
   6.4.2 Multijunction Cell ....................................... 269
   6.4.3 Key Requirements for Obtaining High Efficiency .......... 270
   6.4.4 Back Reflector .......................................... 270
   6.4.5 Doped Layer ............................................ 275
   6.4.6 Intrinsic Layers ......................................... 277
   6.4.7 Optimization of the Component Cells
       and Current Matching ................................... 281
   6.4.8 Tunnel Junction ......................................... 282
   6.4.9 Top Conducting Oxide ................................... 285
   6.4.10 Cell and Module Performance ............................ 285
6.5 Manufacturing Technology .................................... 287
   6.5.1 Manufacturing Process ................................... 287
   6.5.2 Production Status and Product Advantage ................. 293
6.6 Alternative Technologies and Future Trends ..................... 295
References ..................................................... 299
8.4.1 Static Detection Limits of 1D TFPSD .......................... 371
8.4.2 Linearity and Spatial Resolution of 1D TFPSD ................. 372
8.4.3 Position Response to Multiple Light Beams ..................... 374
8.4.4 Static Predicted and Experimental Performance of the 2D TFPSD Device ...................................................... 376
8.5 Dynamic Performance of the 1D and 2D TFPSD ..................... 376
  8.5.1 Response Time of the TFPSD .................................. 379
  8.5.2 Detection of Light Signals with Different Wavelengths ...... 381
8.6 Characteristics of the a-Si:H p-i-n Structures Used to Produce the TFPSD ............................................................. 383
  8.6.1 J–V Curves .................................................. 383
  8.6.2 Dependence of the Saturation Current of the Device on $T$ .......... 385
  8.6.3 Spectral Response and Detectivity ................................ 386
8.7 Peripherals for 1D and 2D TFPSD Signal Processing .................... 387
  8.7.1 Optical Methods ............................................ 387
  8.7.2 Peripherals for Signal Processing .............................. 389
8.8 Simulated and Experimental Data in 2D Optical Inspection Systems with TFPSD Detector .................................................. 392
8.9 Linear Array of Thin Film Position Sensitive Detector (LTFPSD) ... 393
  8.9.1 Principles of the Optical Methods Used ........................ 394
  8.9.2 Positional Resolution of the Array ............................ 395
  8.9.3 Hardware to Control Arrays of Multiple 1D Sensors ............ 396
  8.9.4 Bandwidth Requirements for the Preamplifiers Used in the Hardware Control Unit of the LTFPSD ............... 398
8.10 Summary and Future Outlook ....................................... 399
References ..................................................... 400

Symbols and Abbreviations .............................................. 404

Subject Index ....................................................... 411