

7.10 FIELD PERFORMANCE OF MODULES

7.10.1 Lifetime

Long lifetime is claimed as one of the main virtues of PV and some manufacturers currently offer warranty for more than 20 years, with 30-year lifetime being the objective for short-term development. This should mean that for this period of time the module will keep working, that is, producing electrical power with an efficiency similar to the starting efficiency and without deterioration that compromises the safety or the visual appearance. Two factors determine lifetime: reliability, that refers to premature failure of the product, and durability, that attends to slow degradation that eventually decreases production to unacceptable levels. Cost effectiveness, energy payback balance and public acceptance of photovoltaic energy strongly rely on the reliability and the long lifetime of modules.

PV systems worldwide have been working for more than 20 years, and this allows us to gather information concerning degradation mechanisms. Modules in the field are subjected to static and dynamic mechanical loads, thermal cycling, radiation exposure, ambient humidity, hail impact, dirt accumulation, partial shading and so on. Common failure modes [124, 141] are related to the action of weather agents in combination with deficiencies in fabrication.

Location-dependent steady degradation of module output is also observed, with short-circuit current and fill factor being the most affected parameters. In many cases, this has been proved to correlate with degradation of EVA encapsulation [127]. EVA, like most polymers, is known to undergo photothermal degradation: UV radiation breaks molecular chains. Diffusion of chemical species is also relatively easy through it, so that moisture and corroding agents can enter while absorbers and stabilizers can out-diffuse.

Yellowing or browning of EVA reduces its optical transmission affecting module current. For this reason, EVA incorporates UV absorbers in its formulation. Cerium-containing glasses alleviate this problem. Degradation also decreases the strength of the encapsulant, leading to loss of adhesion to the cells and even detachment of the layer (delamination). This is promoted by the shear stress that accompanies different expansion coefficients upon diurnal thermal cycles. Delamination brings about optical and thermal degradation. Besides, the degraded encapsulant can be penetrated more easily by moisture and chemicals. Among these, sodium from the glass and phosphorus from the cell emitter are known to precipitate at the cell surface, corroding solder joints and increasing series resistance [141]. Encapsulant formulations are being continuously improved to address these problems.

7.10.2 Qualification

Several organisms, such as the International Electrotechnical Commission (IEC), the Institute of Electrical and Electronic Engineers (IEEE) and so on, have designed tests aimed at guaranteeing the quality of PV products [142]. Test procedures have been defined that, if successfully passed by a product, should guarantee the reliability of the PV module.

Manufacturers voluntarily submit their products for qualification tests in an accredited laboratory. These include verification of the module performance claimed in the datasheets as well as reliability tests. The certifications obtained are intended as a quality assurance for the customer.

Qualification tests consist in verifying the module integrity by visual inspection, measurement of the electrical performance at STC and of the electrical isolation before and after treatments that simulate, in an accelerated manner, real operation conditions. For instance, the IEC Standard 61 215 [143] specifies the following:

- Ultraviolet exposure using xenon lamps.
- Thermal cycling (-40°C to 50°C , 50 cycles) in climatization chamber.
- Humidity freeze cycling (thermal cycling with 85% relative humidity).
- Damp heat (1000 h at 85°C and 90% relative humidity).
- Twist test for testing resistance to torques.
- Pressure is applied to the module to test resistance to static mechanical loads.
- Hail impact test, where the module is stricken by 25 mm diameter ice balls at 23 m seg^{-1} .
- Outdoor exposure.
- Hot spot tests, where the module is selectively shaded.

Different test combinations are applied to a sample of a few modules. The modules will qualify if no major failures are found and the visual inspection reveals no damage, the electrical power is within 90% of specifications, and isolation is maintained.

7.11 CONCLUSIONS

This chapter has reviewed current state of crystalline silicon solar cells and modules. The main lines defining the structure of the described situation can be summarized as follows:

- *Changing scale*: The current booming of the markets enables and fosters technological and processing improvements.
- *Laboratory-industry gap*: There is a mature technology at the laboratory that has led to impressive performance levels, on the one hand, and a reliable, fast, 30-year-old industrial process producing modest efficiency, on the other hand. Closing this gap is the key to a lower $\$ \text{ Wp}^{-1}$ figure of merit.
- *Novel silicon materials*: Market growth and the threat of silicon shortage stimulates new materials and very thin substrates that demand new technological solutions.
- *Technology diversification*: These two challenges are to be faced by solar cell production technology in the coming years. Intensive preindustrial research is being conducted and solutions are being developed along several different lines.
- *Quality*: Product reliability and durability and environmental and aesthetical friendliness are as important as cost for the growth of PV industry and this also influences technology.
- *Long-term scenario*: Alternatives to crystalline silicon technology are being researched thoroughly and presumably some of them will succeed in reducing photovoltaic costs to competitive ones. Nevertheless, for these so-called “leapfrogs” to take place, a mature PV market should consolidate, for which silicon technology is essential at least for the next decade.

REFERENCES

1. Luque A, *Solar Power*, Notes of the Cycle d'études de Postgrade en Energie, 5–12, EPFL (2001–2003).
2. Maycock P, *Photovolt. News* **20** (2), 1 (2001).
3. Turton R, "Band Structure of Si: Overview", in Hull R (Ed), *Properties of Crystalline Silicon*, INSPEC, Stevenage, UK (1999).
4. Green M, Keevers M, *Prog Photovolt.* **3**, 189–192 (1995).
5. Kolodinski S, Werner J, Wittchen T, Queisser H, *Appl. Phys. Lett.* **63**, 2405–2407 (1993).
6. Clugston D, Basore P, *Prog. Photovolt.* **5**, 229–236 (1997).
7. Sproul A, Green M, *J. Appl. Phys.* **70**, 846–854 (1991).
8. Altermatt P *et al.*, *Proc. 16th Euro. Conf. Photovoltaic Solar Energy Conversion*, 102–105 (2000).
9. Dzierwior J, Schmid W, *Appl. Phys. Lett.* **31**, 346–351 (1977).
10. Altermatt P *et al.*, *Proc. 16th Euro. Conf. Photovoltaic Solar Energy Conversion*, 243–246 (2000).
11. Green M *et al.*, *Nature* **412**, 805–808 (2001).
12. Thurber W, Mattis R, Liu Y, Filliben J, *J. Electrochem. Soc.* **127**, 1807–1812 (1980).
13. Thurber W, Mattis R, Liu Y, Filliben J, *J. Electrochem. Soc.* **127**, 2291–2294 (1980).
14. Kane D, Swanson R, *Proc. 20th IEEE Photovoltaic Specialist Conf.*, 512–517 (1988).
15. Sze S, *Physics of Semiconductor Devices*, Chap. 5, John Wiley & Sons, New York (1981).
16. King R, Sinton R, Swanson R, *IEEE Trans. Electron Devices* **37**, 1399–1409 (1990).
17. King R, Swanson R, *IEEE Trans. Electron Devices* **38**, 365–371 (1991).
18. Narasimha S, Rohatgi A, Weeber A, *IEEE Trans. Electron Devices* **46**, 1363–1370 (1999).
19. Honsberg C *et al.*, *Proc. 16th Euro. Conf. Photovoltaic Solar Energy Conversion*, 1655–1658 (2000).
20. Grauvogl M, Hezel R, *Prog. Photovolt.* **6**, 15–24 (1998).
21. Gan J, Swanson R, *Proc. 21st IEEE Photovoltaic Specialist Conf.*, 245–250 (1990).
22. Taguchi M *et al.*, *Prog. Photovolt.* **8**, 503–514 (2000).
23. Cuevas A, Basore P, Giroult-Matlakowski G, Dubois C, *Proc. 13th Euro. Conf. Photovoltaic Solar Energy Conversion*, 337–342 (1995).
24. Cuevas A, Stuckings M, Lay J, Petravic M, *Proc. 14th Euro. Conf. Photovoltaic Solar Energy Conversion*, 2416–2419 (1997).
25. Aberle A, *Prog. Photovolt.* **8**, 473–488 (2000).
26. Aberle A, Hezel R, *Prog. Photovolt.* **5**, 29–50 (1997).
27. Eades W, Swanson R, *J. Appl. Phys.* **58**, 4267–4276 (1985).
28. Aberle A, Glunz S, Warta W, *Sol. Energy Mater. Sol. Cells* **29**, 175–182 (1993).
29. Luque A, "The Requirements of High Efficiency Solar Cells", in Luque A, Araújo G (Eds), *Physical Limitations to Photovoltaic Energy Conversion*, 1–42, Adam Hilger Ltd, Bristol (1990).
30. Green M, *Silicon Solar cells. Advanced Principles and Practice*, Chap. 7, Centre for Photovoltaic Devices and Systems, University of New South Wales, Sydney (1995).
31. Tiedje T, Yablonovitch E, Cody G, Brooks B, *IEEE Trans. Electron Devices* **31**, 711–716 (1984).
32. 5th Framework Programme EC Project ERK5-1999-00002 "High efficiency silicon solar cells concentrator (HISICON)".
33. Verlinden P *et al.*, *Proc. 14th Euro. Conf. Photovoltaic Solar Energy Conversion*, 96–100 (1997).
34. Ohtsuka H, Sakamoto M, Tsutsui K, Yazawa Y, *Prog. Photovolt.* **8**, 385–390 (2000).
35. Luque A, Ruiz J, Cuevas A, Agost M, *Proc. 1st Euro. Conf. Photovoltaic Solar Energy Conversion*, 269–277 (1977).
36. Zhao J, Wang A, Green M, *Prog. Photovolt.* **7** 471–474 (1999).
37. Saitoh T, Hashigami H, Rein S, Glunz S, *Prog. Photovolt.* **8** 535–547 (2000).
38. Myers S, Seibt M, Schröter W, *J. Appl. Phys.* **88** 3795–3819 (2000).

39. McHugo S, Hieslmair H, Weber E, *Appl. Phys. A* **64**, 127–137 (1997).
40. Ohe N, Tsutsui K, Warabisako T, Saitoh T, *Sol. Energy Mater. Sol. Cells* **48**, 145–150 (1997).
41. Martinuzzi S *et al.*, *Mater. Sci. Eng., B* **71**, 229–232 (2000).
42. Wenham S, Green M, *Prog. Photovolt.* **4**, 3–33 (1996).
43. Schröter W, Kühnpafel R, *Appl. Phys. Lett.* **56**, 2207–2209 (1990).
44. Joshi S, Gösele U, Tan T, *J. Appl. Phys.* **77**, 3858–3863 (1995).
45. Sopori B *et al.*, *Sol. Energy Mater. Sol. Cells* **41/42** 159–169 (1996).
46. Waver P, Schmidt A, Wagemann H, *Proc. 14th Euro. Conf. Photovoltaic Solar Energy Conversion*, 2450–2453 (1997).
47. Green M, *Prog. Photovolt.* **8**, 443–450 (2000).
48. Schmidt J, Hezel R, *12th Workshop on Crystalline Si Solar Cell Materials and Processes*, National Renewable Energy Laboratory NREL/BK-520-32717, 64–71 (2002).
49. Zhao J, Wang A, Green M, *Prog. Photovolt.* **2**, 227–230 (1994).
50. Wenham S, *Prog. Photovolt.* **1**, 3–10 (1993).
51. Cuevas A, Russell D, *Prog. Photovolt.* **8**, 603–616 (2000).
52. Green M, *Silicon Solar Cells. Advanced Principles and Practice*, Chap. 10, Centre for Photovoltaic Devices and Systems, University of New South Wales, Sydney (1995).
53. Cuevas A, Sinton R, Swanson R, *Proc. 21st IEEE Photovoltaic Specialist Conf.*, 327–332 (1990).
54. Luque A, *Solar Cells and Optics for Photovoltaic Concentration*, Chap. 6, Adam Hilger Ltd, Bristol (1989).
55. Nijs J *et al.*, *IEEE Trans. Electron Devices* **46**, 1948–1969 (1999).
56. Moehlecke A, Zanesco I, Luque A, *Proc. 1st World CPEC* 1663–1666 (1994).
57. Glunz S, Knobloch J, Biro D, Wettling W, *Proc. 14th Euro. Conf. Photovoltaic Solar Energy Conversion*, 392–395 (1997).
58. Wenham S *et al.*, *Proc. 1st World CPEC*, 1278–1282 (1994).
59. Mulligan W *et al.*, *Proc. 28th IEEE Photovoltaic Specialist Conf.*, 158–163 (2000).
60. Zhao J, Wang A, Altermatt P, Zhang G, *Prog. Photovolt.* **8** 201–210 (2000).
61. Luque A, “Coupling Light to Solar Cells”, in Prince M (Ed), *Advances in Solar Energy* Vol. 8, 151–230, American Solar Energy Society, Boulder (1993).
62. Born M, Wolf E, *Principles of Optics*, 7th Edition, Chap. 1, Cambridge University Press, Cambridge, UK (1999).
63. Zhao J, Green M, *IEEE Trans. Electron Devices* **38**, 1925–1934 (1991).
64. Rodríguez J, Tobías I, Luque A, *Sol. Energy Mater. Sol. Cells* **45**, 241–253 (1997).
65. Green M, *Silicon Solar Cells. Advanced Principles and Practice*, Chap. 6, Centre for Photovoltaic Devices and Systems, University of New South Wales, Sydney (1995).
66. Moehlecke A, *Conceptos avanzados de tecnología para células solares con emisores p⁺ dopados con boro*, Chap. 5, Ph.D. thesis, Universidad Politécnica de Madrid, Madrid (1996).
67. Mi nano J, “Optical Confinement in Photovoltaics”, in Luque A, Araújo G (Eds), *Physical Limitations to Photovoltaic Energy Conversion*, 50–83, Adam Hilger Ltd, Bristol (1990).
68. Van Overstraeten R, Mertens R, *Physics, Technology and Use of Photovoltaics*, Chap. 4, Adam Hilger Ltd, Bristol (1986).
69. Hylton J *et al.*, *Prog. Photovolt.* **4**, 435–438 (1996).
70. Horzel J *et al.*, *Proc. 17th Euro. Conf. Photovoltaic Solar Energy Conversion*, 1367–1370 (2001).
71. Gandhi S, *VLSI Fabrication Principles*, Chap. 9, John Wiley & Sons, New York (1994).
72. Richards B, Cotter J, Honsberg C, Wenham S, *Proc. 28th IEEE Photovoltaic Specialist Conf.*, 375–378 (2000).
73. Nijs J *et al.*, *Proc. 1st World CPEC*, 1242–1249 (1994).
74. Ballif C, Huljić F, Hessler-Wyser A, Willeke G, “Nature of the Ag-Si Interface in Screen-Printed Contacts: A Detailed Transmission Electron Microscopy Study of Cross-Sectional Structures”, *Proc. 29th IEEE Photovoltaic Specialist Conf.* (New Orleans, 2002); in press.

75. Lenkeit B *et al.*, *Proc. 16th Euro. Conf. Photovoltaic Solar Energy Conversion*, 1332–1335 (2000).
76. Hoonstra J, de Moor H, Weeber A, Wyers P, *Proc. of the 16th Euro. Conf. Photovoltaic Solar Energy Conversion*, 1416–1419 (2000).
77. Bruton T *et al.*, *Proc. 14th EC Photovoltaic Specialist Conf.*, 11–19 (1997).
78. Tool C *et al.*, *Prog. Photovolt.* **10**, 279–291 (2002).
79. Martinelli G *et al.*, *Proc. 14th European Photovoltaic Solar Energy Conversion*, 778, 779 (1997).
80. Münzer K, Holdermann K, Schlosser R, Sterk S, *IEEE Trans. Electron Devices* **46**, 2055–2061 (1999).
81. Finck von Finckenstein B *et al.*, *Proc. 28th IEEE Photovoltaic Specialist Conf.*, 198–200 (2000).
82. King R, Mitchell K, Gee J, *Proc. 1st World CPEC*, 1291–1294 (1994).
83. Moschner J *et al.*, *Proc. of the 2nd World CPEC*, 1426–1429 (1998).
84. Nijs J *et al.*, *IEEE Trans. Electron Devices* **46**, 1948–1969 (1999).
85. Hilali M *et al.*, “Optimization of Self-Soping Ag Paste Firing to Achieve High Fill Factors on Screen-Printed Silicon Solar Cells with a 100 Ω /sq. Emitter” *Proc. of the 29th IEEE Photovoltaic Specialist Conf.*, (New Orleans, 2002); in press.
86. Sivonthaman S *et al.*, *Proc. 14th Euro. Conf. Photovoltaic Solar Energy Conversion*, 400–403 (1997).
87. Doshi P *et al.*, *Proc. 25th IEEE Photovoltaic Specialist Conf.*, 421–424 (1996).
88. Doshi P *et al.*, *Sol. Energy Mater. Sol. Cells* **41/42**, 31–39 (1996).
89. Biro D *et al.*, *Sol. Energy Mater. Sol. Cells* **74**, 35–41 (2002).
90. Périchaud I, Floret F, Martinuzzi S, *Proc. 23rd IEEE Photovoltaic Specialist Conf.*, 243–247 (1993).
91. Narasimha S, Rohatgi A, *IEEE Trans. Electron Devices* **45**, 1776–1782 (1998).
92. Macdonald D, Cuevas A, Ferraza F, *Solid-State Electron.* **43**, 575–581 (1999).
93. Gee J, Sopori B, *Proc. 26th IEEE Photovoltaic Specialist Conf.*, 155–158 (1997).
94. del Cañizo C, Tobías I, Lago R, Luque A, *J. Electrochem. Soc.* **149**, 522–525 (2002).
95. Gandhi S, *VLSI Fabrication Principles*, Chap. 8, John Wiley & Sons, New York (1994).
96. Johnson J, Hanoka J, Gregory J, *Proc. 18th Photovoltaic Specialist Conf.*, 1112–1115 (1985).
97. Sopori B, Deng X, Narayanan S, Roncin S, *Proc. 11th Euro. Conf. Photovoltaic Solar Energy Conversion*, 246–249 (1992).
98. Szulfcik J *et al.*, *Proc. 12th EC Photovoltaic Specialist Conf.*, 1018–1021 (1994).
99. Leguijt C *et al.*, *Sol. Energy Mater. Sol. Cells* **40**, 297–345 (1996).
100. Aberle A, Hezel R, *Prog. Photovolt.* **5**, 29–50 (1997).
101. Soppe W *et al.*, “On Combining Surface and Bulk Passivation of $\text{SiN}_x\text{:H}$ Layers for mc-Si Solar Cells”, *Proc. 29th IEEE Photovoltaic Specialist Conf.* (New Orleans, 2002); in press.
102. Ruby D, Wilbanks W, Fieddermann C, *IEEE 1st WPEC* 1335–1338 (1994).
103. Shirasawa K *et al.*, *Proc. 21st IEEE Photovoltaic Specialist Conf.*, 668–673 (1990).
104. Zhao J, Wang A, Campbell P, Green M, *IEEE Trans. Electron Devices* **46**, 1978–1983 (1999).
105. De Wolf S *et al.*, *Proc. 16th Euro. Conf. Photovoltaic Solar Energy Conversion*, 1521–1523 (2000).
106. Bilyalov R, Stalmans L, Schirone L, Lévy-Clement C, *IEEE Trans. Electron Devices* **46**, 2035–2040 (1999).
107. Spiegel M *et al.*, *Sol. Energy Mater. Solar Cells* **74**, 175–182 (2002).
108. Huster F *et al.*, *Proc. 28th IEEE Photovoltaic Specialist Conf.*, 1004–1007 (2000).
109. Joos W *et al.*, *Proc. 16th Euro. Conf. Photovoltaic Solar Energy Conversion*, 1169–1172 (2000).
110. Pirozzi L *et al.*, *Proc. 12th Euro. Conf. Photovoltaic Solar Energy Conversion*, 1025–1028 (1994).
111. Ruby D *et al.*, *Proc. of the 2nd World CPEC*, 39–42 (1998).

112. Inomata Y, Fukui K, Shirasawa K, *Sol. Energy Mater. Sol. Cells* **48**, 237–242 (1997).
113. Winderbaum S, Reinhold O, Yun F, *Sol. Energy Mater. Sol. Cells* **46**, 239–248 (1997).
114. Lüdemann R, Damiani B, Rohatgi A, Willeke G, *Proc. 17th Euro. Conf. Photovoltaic Solar Energy Conversion*, 1327–1330 (2001).
115. Macdonald D *et al.*, “Texturing Industrial Multicrystalline Silicon Solar Cells”, *ISES Solar World Congress* (2001).
116. Schmidt W, Woesten B, Kalejs J, *Prog. Photovolt.* **10**, 129–140 (2002).
117. Yelundur V, Rohatgi A, Jeong J, Hanoka J, *IEEE Trans. Electron Devices* **49**, 1405–1410 (2002).
118. Janoch R *et al.*, *Proc. IEEE 28th Photovoltaic Specialist Conf.*, 1403–1406 (2000).
119. Meier D *et al.*, *Sol. Energy Mater. Sol. Cells* **65**, 621–627 (2000).
120. Taguchi M *et al.*, *Prog. Photovolt.* **8**, 503–513 (2000).
121. Jordan D, Nagle J, *Prog. Photovolt.* **2**, 171–176 (1994).
122. Bruton T *et al.*, *Proc. 17th Euro. Conf. Photovoltaic Solar Energy Conversion*, 1282–1286 (2001).
123. Honsberg C *et al.*, *Proc. 14th Euro. Conf. Photovoltaic Solar Energy Conversion*, 146–149 (1997).
124. Wenham S, Green M, Watt M, *Applied Photovoltaics*, Chap. 5, Centre for Photovoltaic Devices and Systems, University of New South Wales, Sydney (1995).
125. Van Overstraeten R, Mertens R, *Physics, Technology and Use of Photovoltaics*, Chap. 8, Adam Hilger Ltd, Bristol (1986).
126. King D *et al.*, *Prog. Photovolt.* **8**, 241–256 (2000).
127. Czanderna A, Pern J, *Sol. Energy Mater. Sol. Cells* **43**, 101–181 (1996).
128. Galica J, Sherman N, *Proc. 28th IEEE Photovoltaic Specialist Conf.*, 30–35 (2000).
129. Schmidhuber H, Krannich K, *Proc. 17th Euro. Conf. Photovoltaic Solar Energy Conversion*, 662–663 (2001).
130. Ishikawa N *et al.*, *Proc. 2nd World CPEC*, 2501–2506 (1998).
131. Smith D, Gee J, *Proc. 16th Euro. Conf. Photovoltaic Solar Energy Conversion*, 1104–1107 (2000).
132. Parreta A, Sarno A, Schloppo R, Zingarelli M, *Proc. of the 14th EC Photovoltaic Specialist Conf.*, 242–246 (1997).
133. Herrmann W, Becker H, Wiesner W, *Proc. 14th Euro. Conf. Photovoltaic Solar Energy Conversion*, 224–228 (1997).
134. Appelbaum J, Segalov T, *Prog. Photovolt.* **7**, 113–128 (1999).
135. Zilles R, Lorenzo E, *Int. J. Sol. Energy* **13**, 121–133 (1993).
136. Herrmann W, Wiesner W, Vaaßen W, *Proc. 26th IEEE Photovoltaic Specialist Conf.*, 1129–1132 (1997).
137. Herrmann W, Adrian M, Wiesner W, *Proc. 2nd World CPEC*, 2357–2359 (1998).
138. Roche D, Outhred H, Kaye R, *Prog. Photovolt.* **3**, 115–127 (1995).
139. Hauselaer P, van den Bossche J, Frisson L, Poortmans J, *Proc. 17th Euro. Conf. Photovoltaic Solar Energy Conversion*, 642–645 (2001).
140. Green M, “Surface Texturing and Patterning in Solar Cells”, in Prince M (Ed), *Advances in Solar Energy*, Vol 8, 231–269, American Solar Energy Society, Boulder (1993).
141. Quintana M, King D, McMahon T, Osterwald C “Commonly Observed Degradation in Field-Aged Photovoltaic Modules”, *Proc. 29th IEEE Photovoltaic Specialist Conf.* (New Orleans, 2002); in press.
142. Wilshaw A, Bates J, Oldach R, *Proc. 16th Euro. Conf. Photovoltaic Solar Energy Conversion*, 795–797 (2000).
143. IEC Standard 61215, *Crystalline Silicon Terrestrial PV Modules – Design Qualification and Type Approval* (1993).