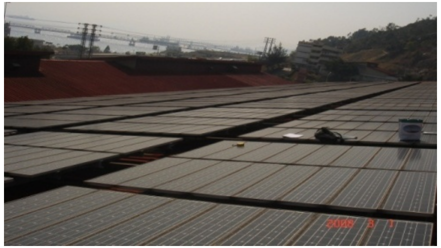
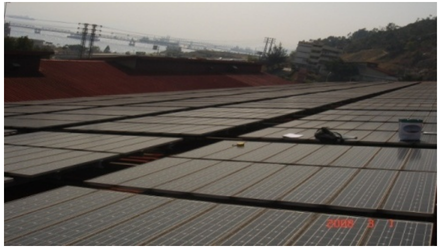
晶体硅光伏组件在服役过程中功率损失的理论计算与数值模拟研究

董 娴
顺德中山大学太阳能研究院

2018年12月· 威海

Theoretical calculation and numerical simulation of power loss in crystalline silicon PV modules based on fielded degradation



Xian Dong
ShunDe SYSU Institute for Solar Energy, Sun Yat-sen University

Dec 2018· Weihai

Outline

1. Background
2. Loss analysis for solar cells and module process
3. PoF based on fielded modules
4. Reliability prediction model

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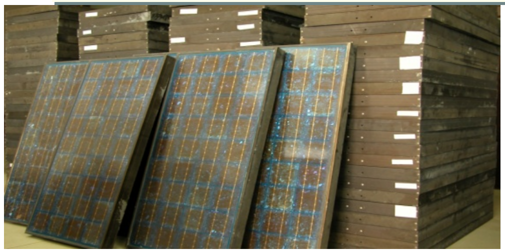
1. Background

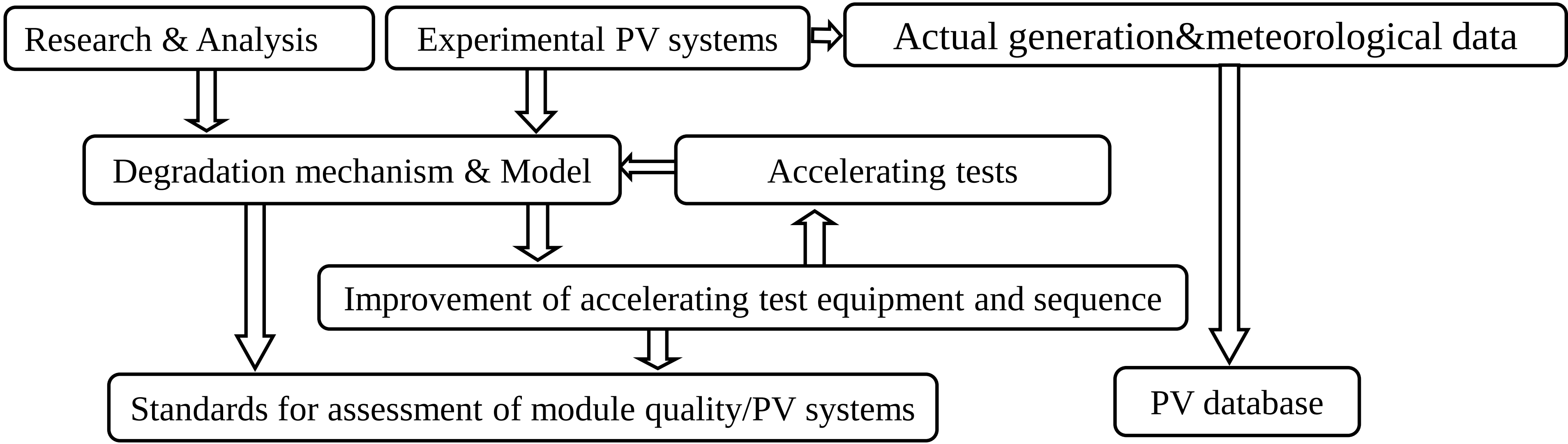
SYSU Solar



Collaboration platforms

- **State Key Laboratory of Optoelectronic Materials and Technologies**
- **South China Branch of NERCRE (National Engineering Research Center of Renewable Energy)**
- **Guangdong Provincial Key Laboratory of Photovoltaic Technologies**
- **Cooperation Base of CPVT (National Center of Supervision and Inspection on Solar Photovoltaic Products Quality) and Sun Yat-Sen University**
- **Key Laboratory of Solar Energy of Education Department, Guangdong Province**

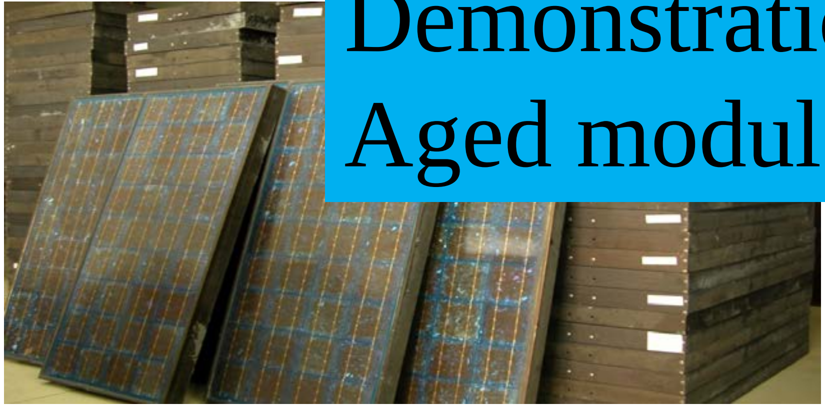
- **Reliability and Life-cycle of modules are key points for PV systems**
- **Precise prediction of output for modules and PV plants**
- **Scheme of quality assessment for PV modules and plants**

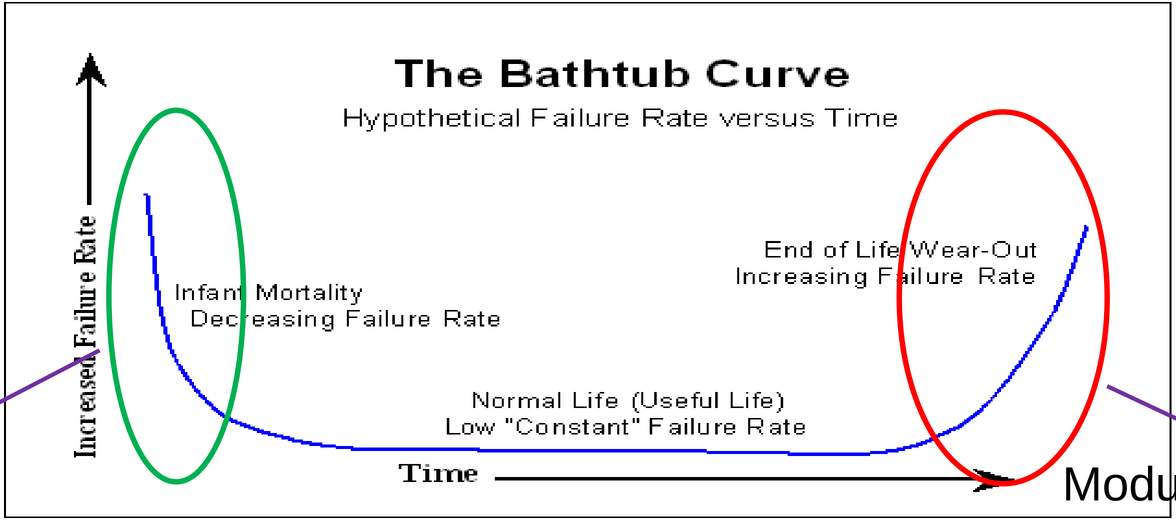


Demonstration bases 12

Demonstration systems 37

Aged modules 3000+





Solar cell
Production process

lifetime (t)

Module technology
Operation environment
Encapsulate material

Outline

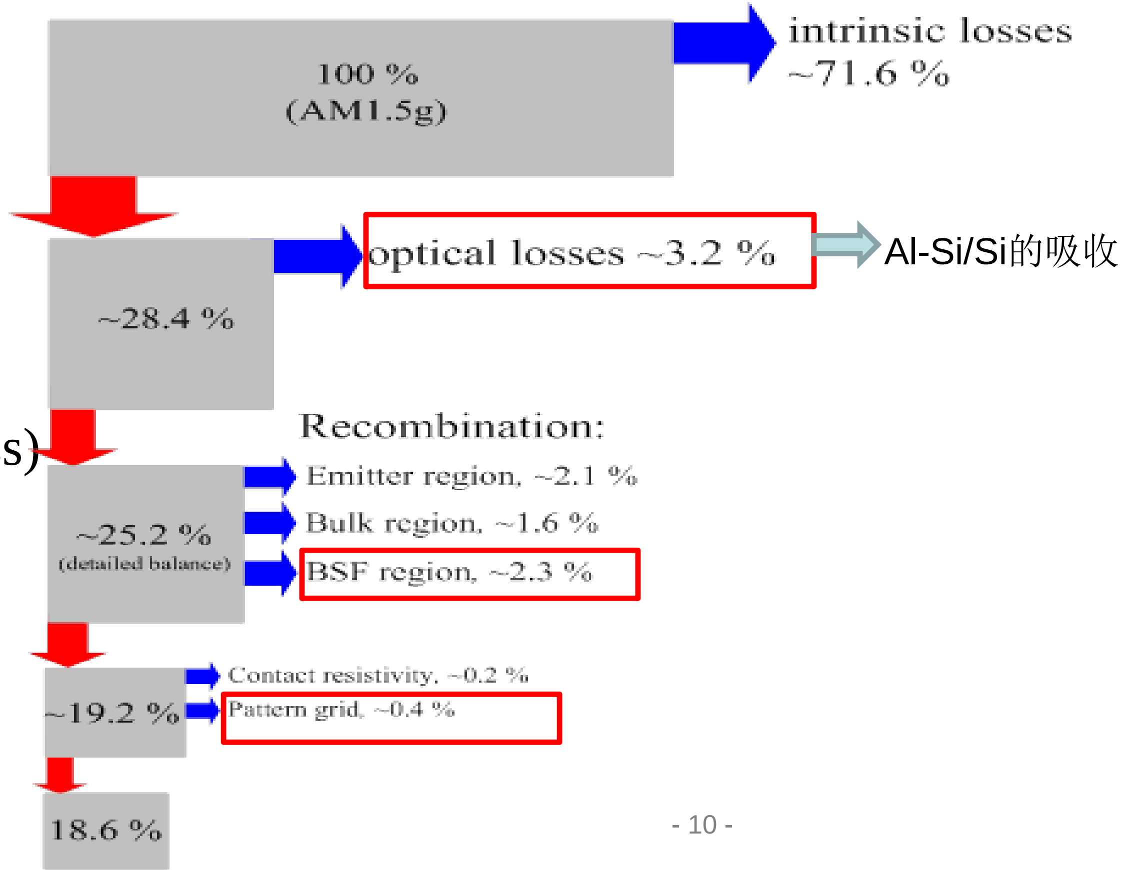
1. Background
2. **Loss analysis for solar cells and module process**
3. PoF based on fielded modules
4. Reliability prediction model

2.1 电池损失分析(Loss Analysis)：

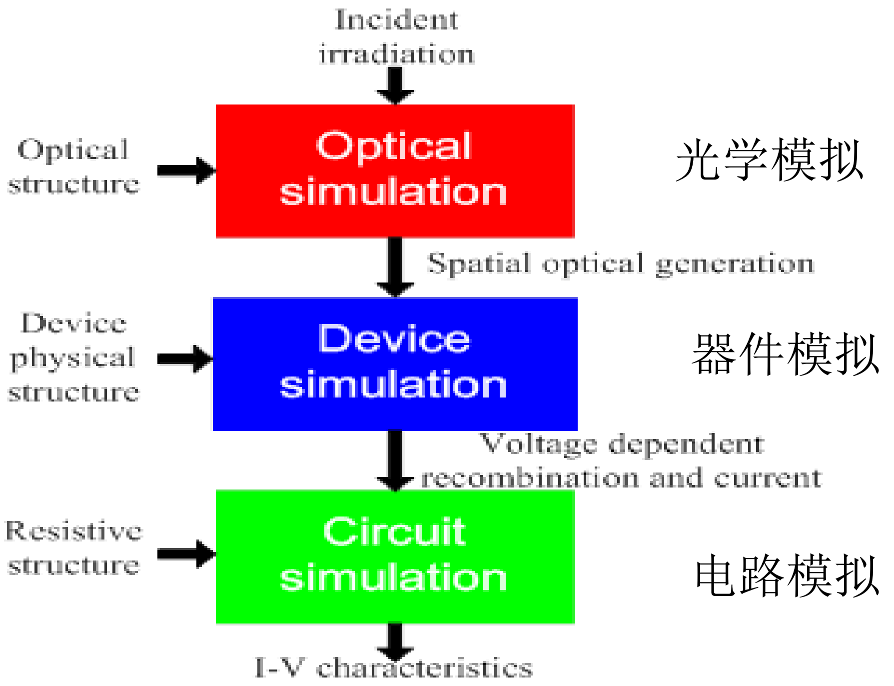
SYSU Solar

电池的主要损失来源：

- 光学损失 (optical loss)
- 复合损失 (recombination loss)
- 电阻损失 (resistive loss)

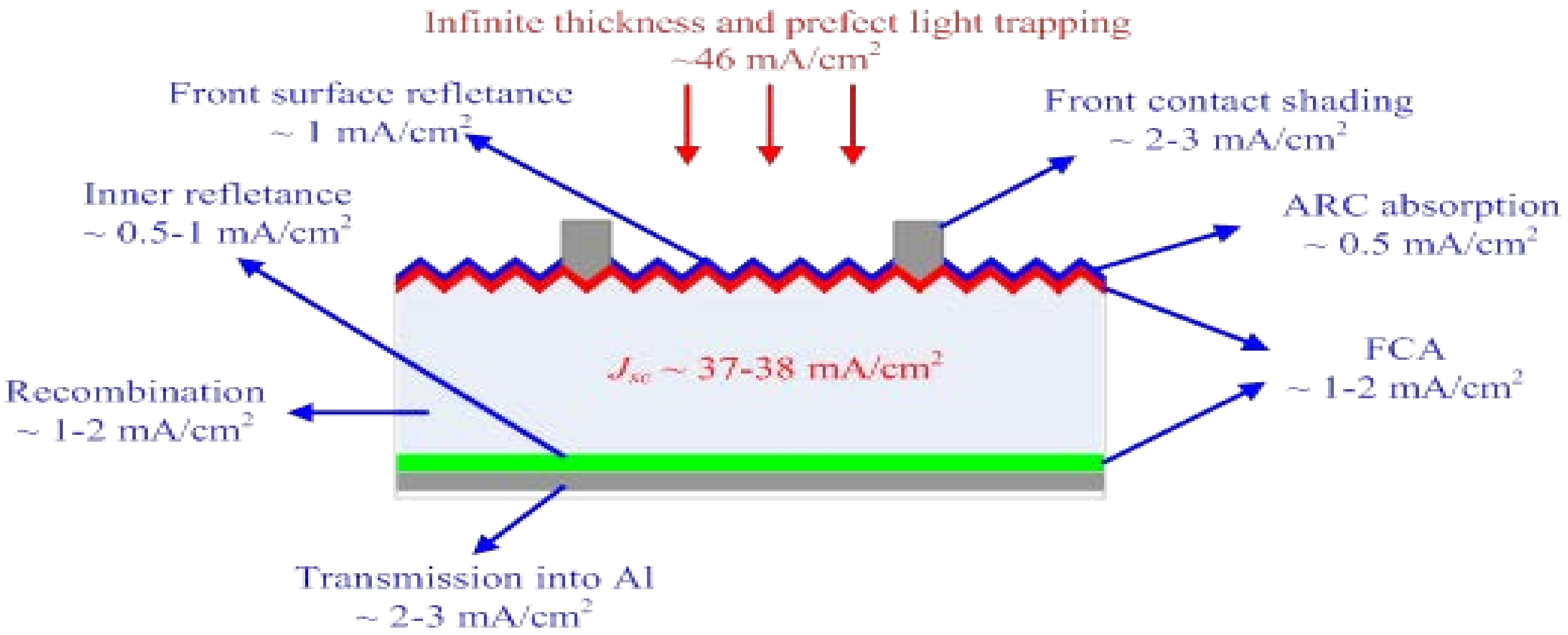


损失分析 – 全尺寸太阳电池数值模拟(full size)



基准模拟(Baseline)

完整的光学损失分布（考虑遮挡）：



- 常规电池的光学损失主要集中在背部Al吸收、前电极的遮挡和前表面反射

器件模拟 – 得到载流子浓度、复合电流密度空间分布 (Sentaurus)

扩散-漂移方程

$$\vec{J}_n = -q\mu_n n\nabla\psi + qD_n\nabla n,$$

$$\vec{J}_p = -q\mu_p p\nabla\psi + qD_p\nabla p$$

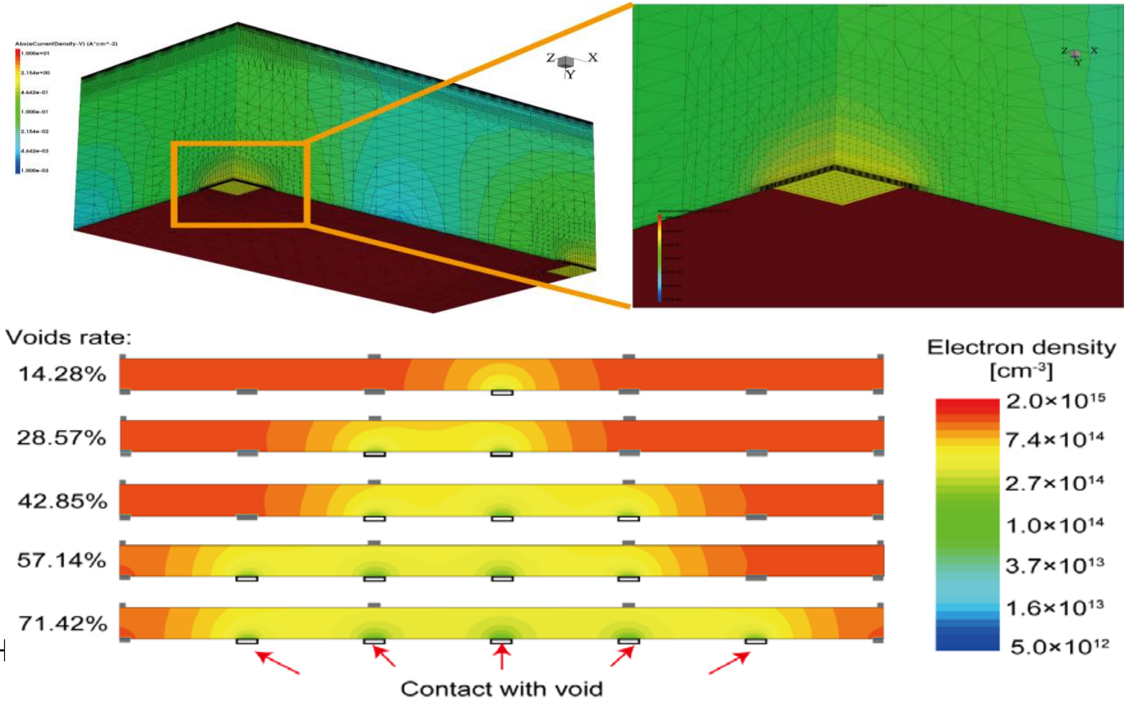
连续性方程

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla\cdot\vec{J}_n + G - R,$$

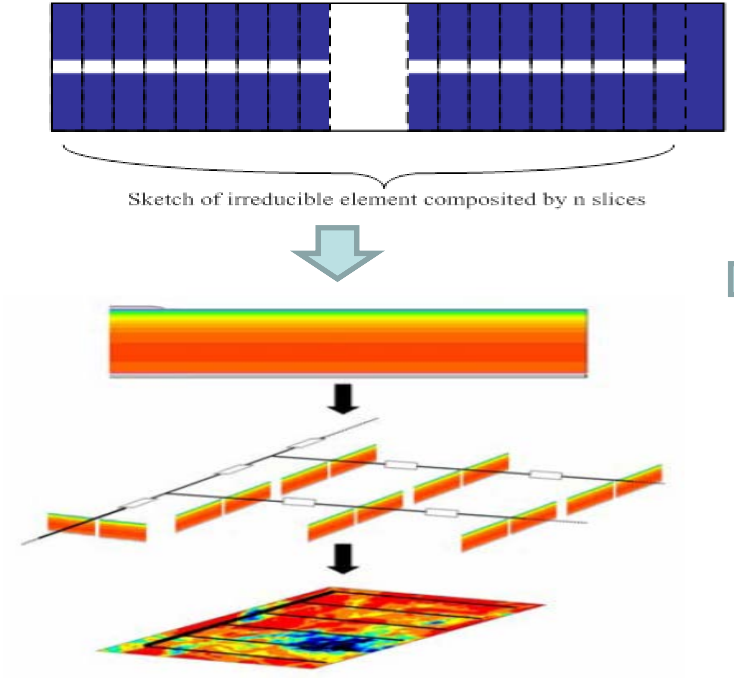
$$\frac{\partial p}{\partial t} = \frac{1}{q}\nabla\cdot\vec{J}_p + G - R$$

泊松方程

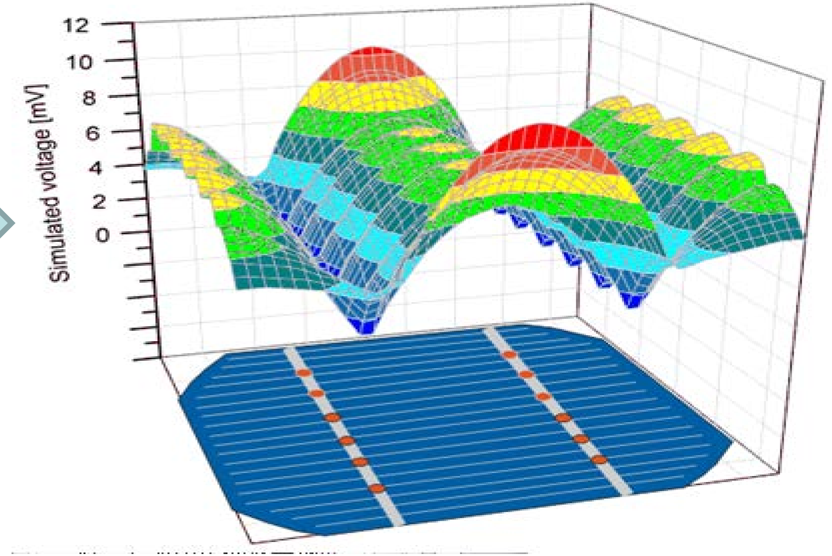
$$\nabla\cdot(\varepsilon\nabla\psi) = -q(p - n +$$



电路模拟(circuit simulation) – 得到压降分布以及电阻损失 (LTspice)



[1] Altermatt et al., 25th EUPVSEC

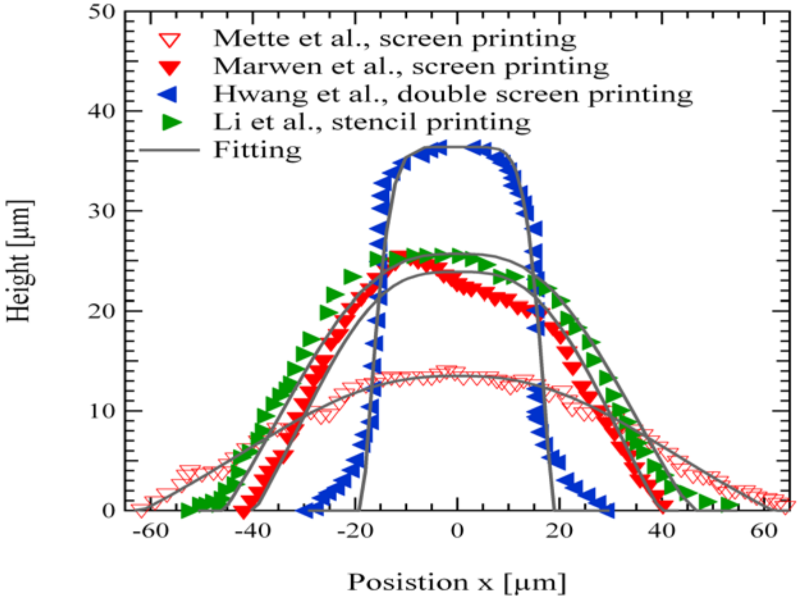


[2] Yang et al., PIP, 2012

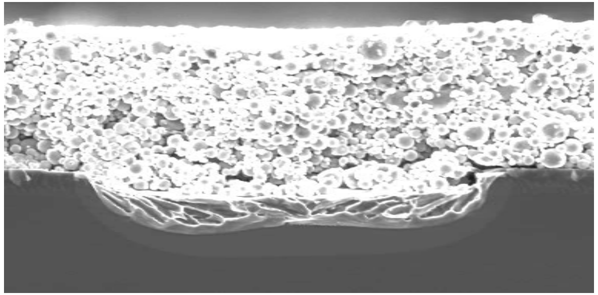
电阻损失(resistive loss)- 前电极分析(front electrode)

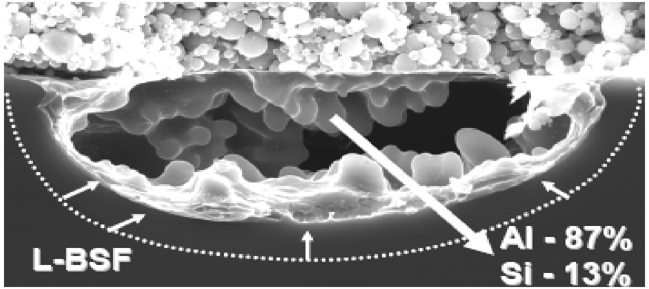
电池栅线横截面形状模型

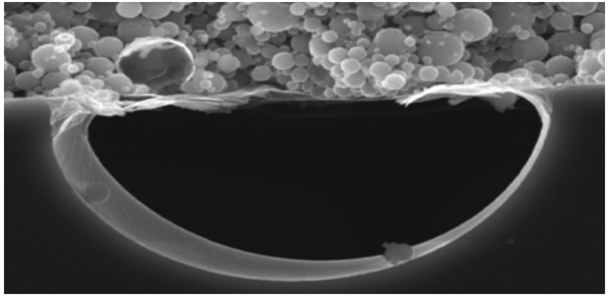
$$
\begin{cases}
h(x) = \left(\dfrac{k}{1+\left|\left(\dfrac{x}{W}\right)^{a}\right|} - 1\right)h_0, & 2\dfrac{h_0}{1+\left|\left(\dfrac{x}{W}\right)^{a}\right|} - h_0 > 0 \\[2ex]
h(x) = 0, & 2\dfrac{h_0}{1+\left|\left(\dfrac{x}{W}\right)^{a}\right|} - h_0 \le 0
\end{cases}
$$



背电极分析back electrode-空洞







SEM images from Elias Urrejola in 3rd workshop of metallization, 2011

Type 1:
薄BSF

Type 2:
空洞同时有BSF:

Type 3:
没有BSF

复合型空洞

电阻型空洞

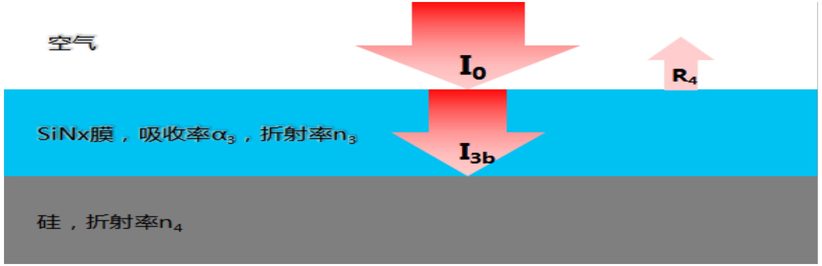
复合&电阻型空洞

2.2 Cell to Module loss analysis

CTM的主要损失来源：

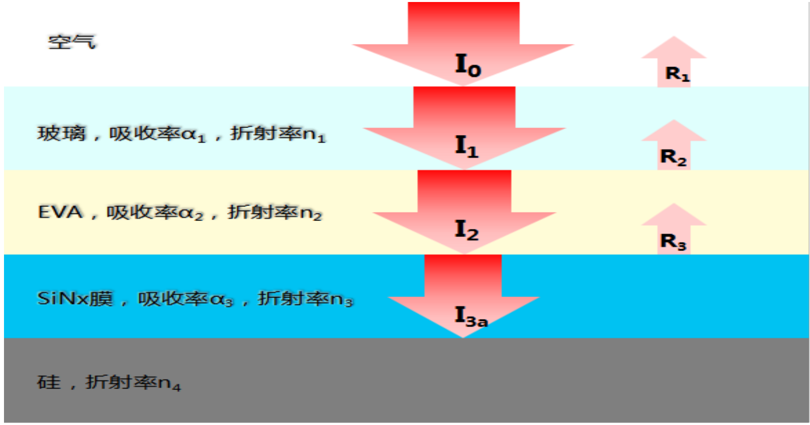
- 光学损失 (optical loss)
- 电阻损失 (resistive loss)

组件光学损失optical loss



组件封装前光学损失示意图

$$I_{3b}=I_0\cdot(1-R_4)$$



组件封装后光学损失示意图

$$I_{3a}=I_0\cdot(1-R_1)\cdot(1-\alpha_1)\cdot(1-R_2)\cdot(1-\alpha_2)\cdot(1-R_3)$$

在光线垂直入射的情况下，光线在**界面反射率R**由菲涅尔公式： $$R=\frac{(n_2-n_1)^2}{(n_2+n_1)^2}$$

太阳电池组件各材料光学参数*

	厚度（mm）	折射率n	吸收率α
空气	-	1.00	-
钢化玻璃	3	1.50	1.36%
EVA	0.45	1.48	1.61%
SiNx膜	-	2.10	-

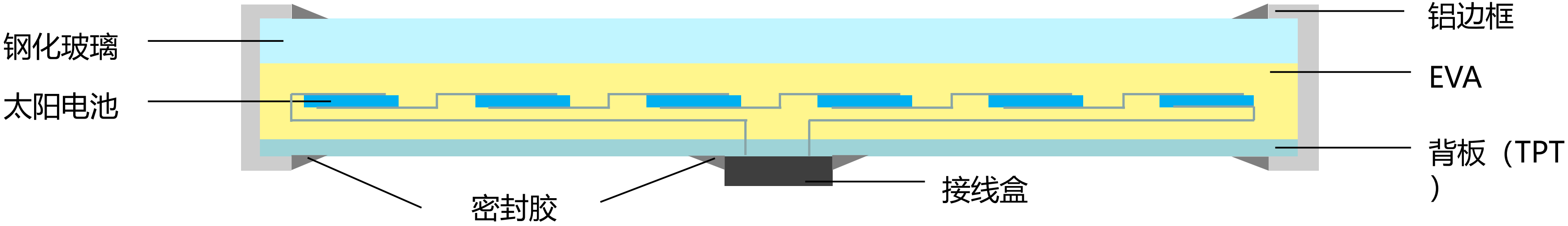
光学损失计算结果

	封装后	封装前	封装后光学增益
计算结果	$R_1=0.040$ $R_2=0.001$ $R_3=0.030$ $I_{3a}=0.904 \bullet I_0$	$R_4=0.126$ $I_{3b}=0.874 \bullet I_0$	$M=(I_{3a}-I_{3b})/I_{3b}$ $\approx$**3.42%**

在一定范围内，太阳电池的短路电流和光强成一个近似成正比的关系，也就是说，组件的短路电流会增加**3.42%**

*K. R. Mcintosh, J.N.Cotsell,et al. An optical comparison of silicone and EVA encapsulants for conventional silicon PV modules: A ray-tracking study[C]. 34th IEEE Photovoltaic specialist conference, p544-549, 7-12 June 2009,PA,USA

电学损失resistive loss



太阳电池组件截面图

电学损失主要包含五个部分：

1.互联条串联电阻造成的功率损失 P_1

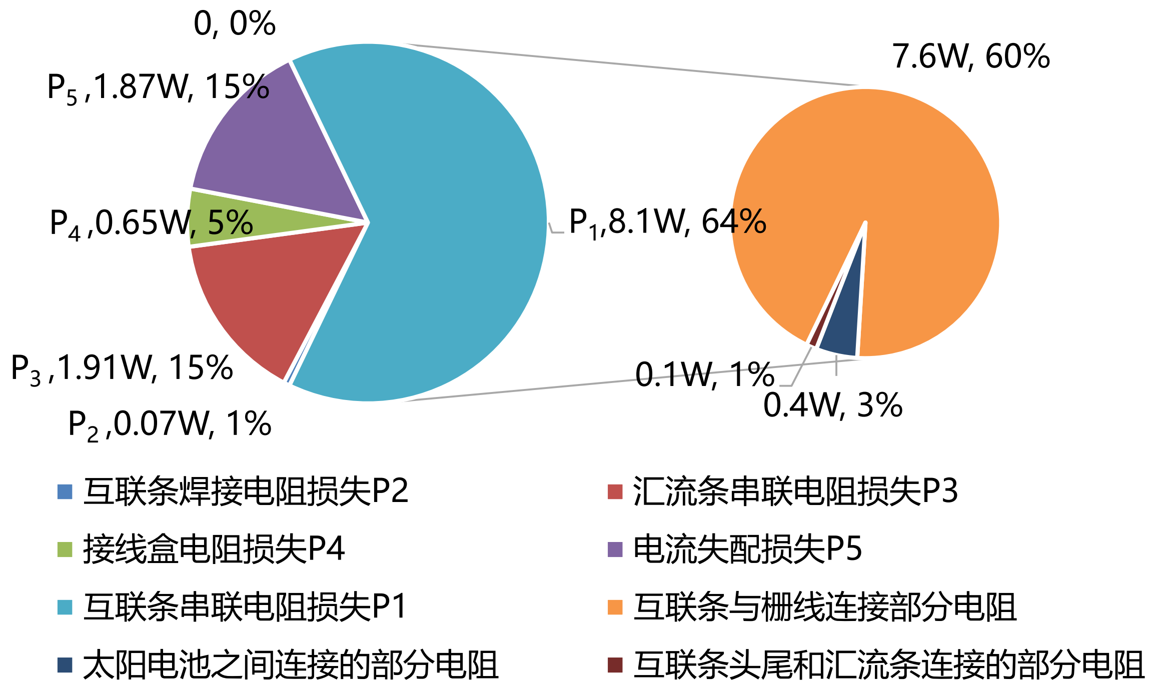
2.互联条焊接接触电阻造成的功率损失 P_2

3.汇流条串联电阻造成的功率损失 P_3

4.接线盒电阻造成的功率损失 P_4

5.太阳电池电流失配造成的功率损失 P_5

各项电学损失所占比例Loss proportion



Outline

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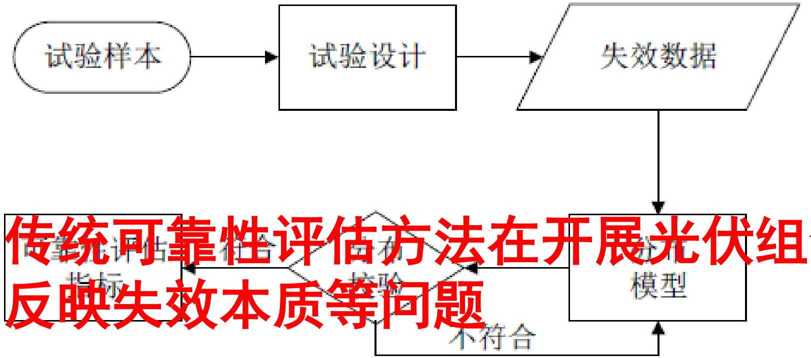
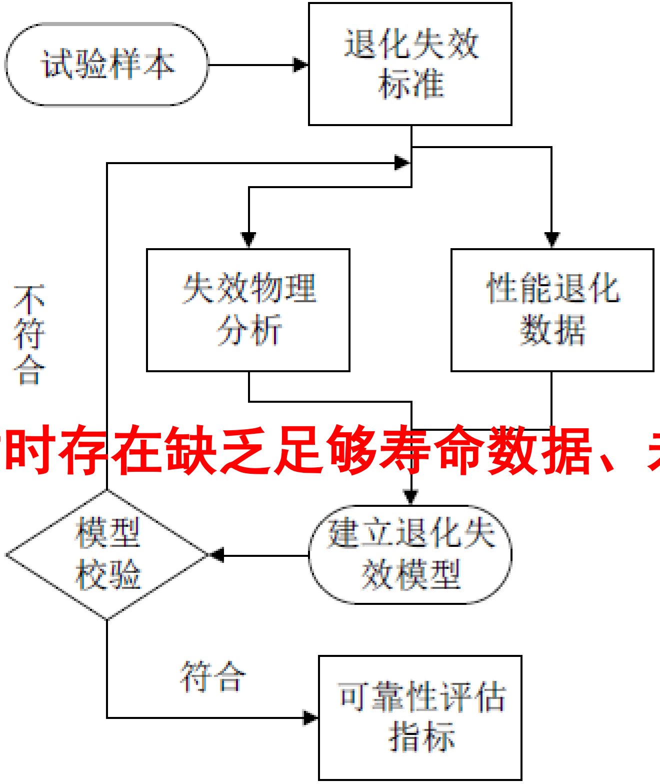
➢ 失效物理分析（Physics-of-Failure，PoF）



传统可靠性评估方法在开展光伏组件评估时存在缺乏足够寿命数据、未能反映失效本质等问题

传统可靠性评估方法典型程序



基于失效物理分析建模方法典型程序

产品的**可靠性（Reliability）**：在规定的时间内、产品完成规定功能的能力。

四个要素：
1）规定的时间（defined time);
2）规定的环境和使用条件（defined condition);
3）规定的任务和功能（defined task/function);
4）具体的可靠性指标（detailed index).

在研究组件可靠性时，与其所处的工作工作时间的长短或非工作状态有关，应该把**对应的环境工作状态与经历时间**联系起来

光伏组件在其漫长的寿命中将承受很多环境影响

光照：太阳
Irradiation: Sun

温度：热，霜冻，昼夜循环
Temperature: Heat, Frost, Diurnal cycle

湿度
Humidity

机械应力：风，雪载荷，冰雹冲击
Mechanical stress: Wind, Snow load, Hail impact

水分：露水，雨水，霜
Moisture : Dew, Rain, Frost

大气：盐雾，灰尘，沙粒，污染、氧气
Air : Salt, Dust, Sand, Pollution， Oxygen

组件结构及典型区域划分 Module structure& Typical area

常规晶硅组件结构

典型区域

A 区 电池正面中央区域（热/光）heat+light

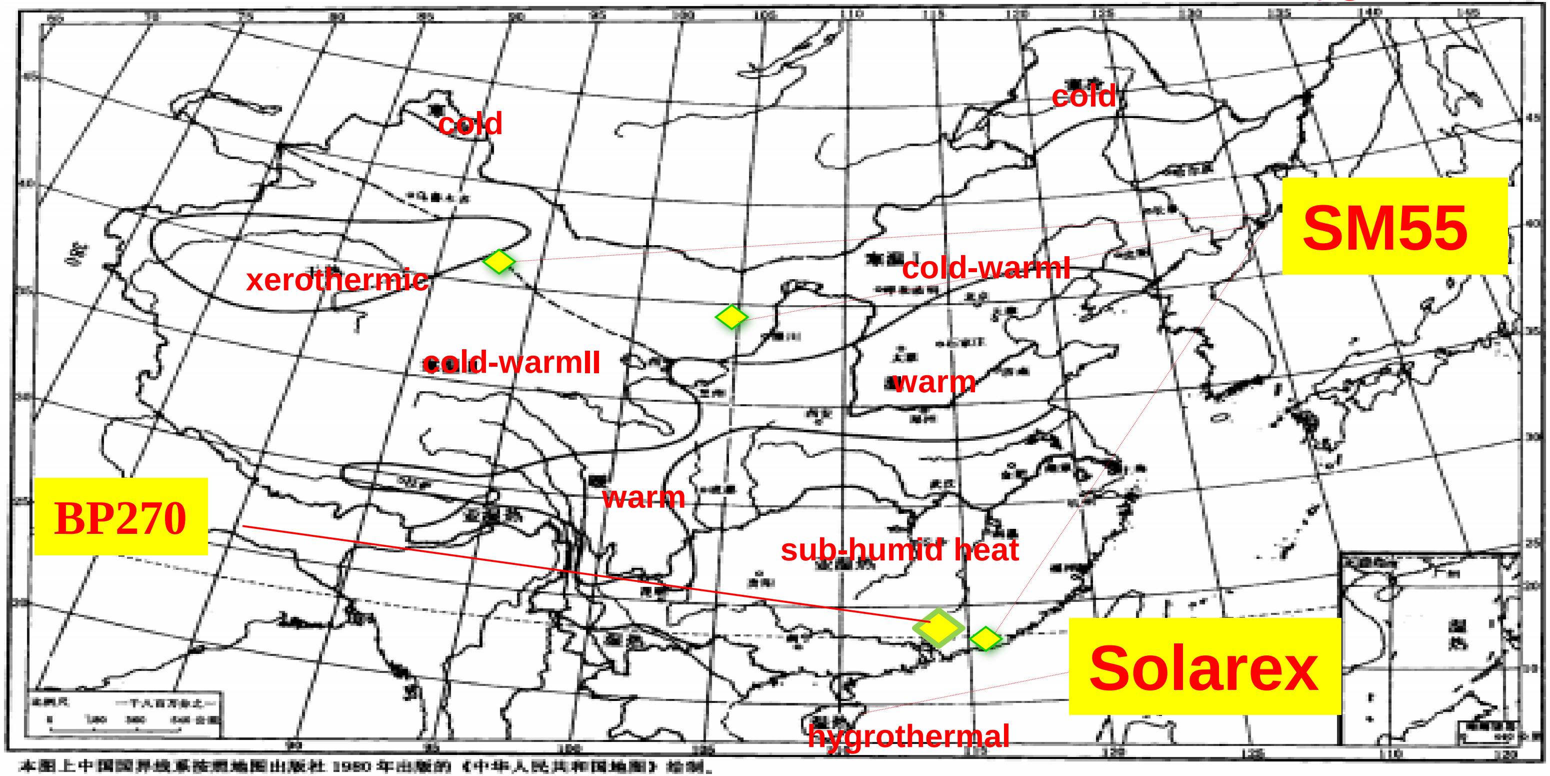
B区 电池正面边沿及间隙（光/水气）light+moisture

C区 电池背面中央区域（热/水汽）heat+moisture

D区 电池背面边沿区域（水汽）moisture

Distribution of 6 climates types in China

(cold- xerothermic - cold-warm - warm- sub-humid heat - hygrothermal)



(From: GB/T 4797.1-2005 Environmental conditions appearing in nature of electric and electronic products-Temperature and humidity)

SYSU Solar

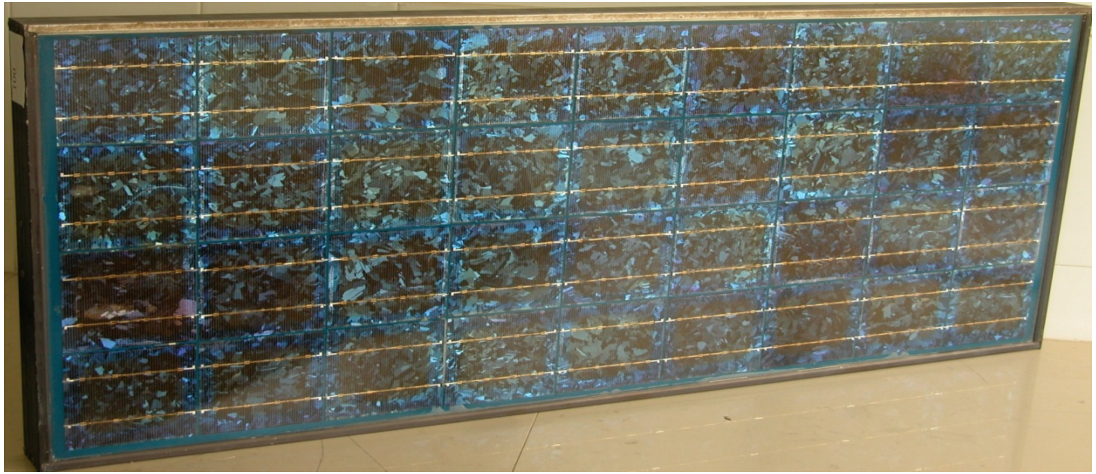
Degradation rate of modules from different climates(STC/rated value)

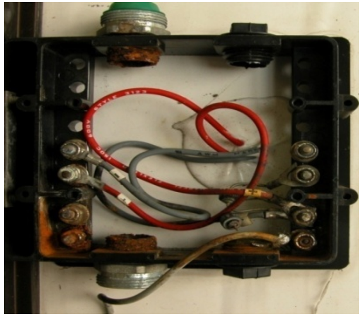
品牌	数量	测试时间	Pm	Im	Vm	Isc	Voc	FF
Solarex	144	2009	96	87.6	109.5	90.4	97.7	106.8
		2014	94.6	86.2	109.9	88.8	98.8	106.8
		2015	94.6	85.7	110.4	88.2	99.1	107.1
		2016	93.5	85.3	109.7	87.7	93.5	107.2
SM75	125（党河）	2015	92.8	96.5	96.0	87.0	99.3	96.4
	112（大风山）	2015	87.1	97.8	94.9	82.7	99.1	67.8
Siemens Solar	500	2014	75.1	88	85.2	92.4	97.6	83

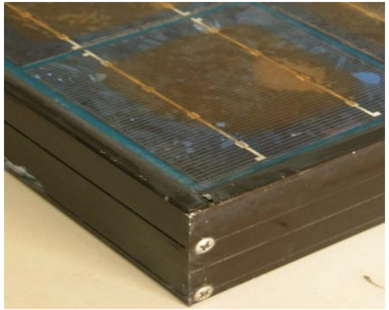
（注：Solarex组件于2009年被挑选其中功率较均匀的144块组件再次安装使用；西门子组件共2051块，目前挑选其中500块进行STC条件下的测试；SM75组件分别取党河125块大风山112块在STC条件下测试。）

不同运行环境下不同的衰减模式对组件功率的影响不同

Case1:Tracking degradation of Solarex modules







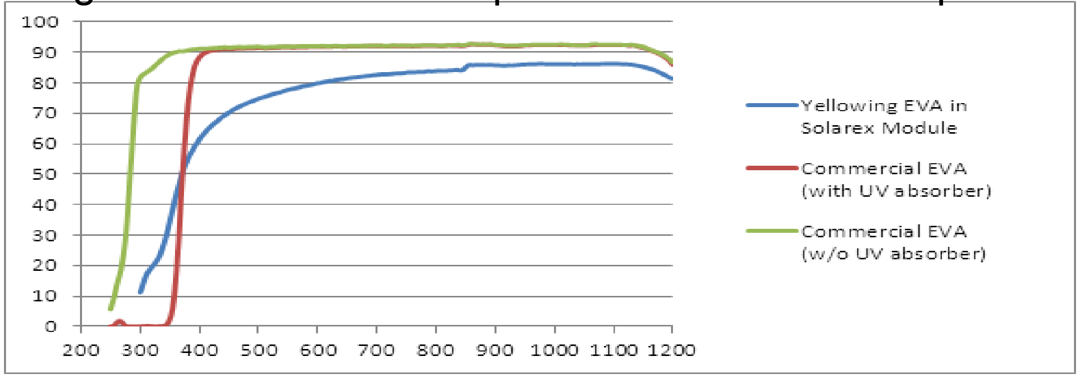
Poly module

- Glass: 3.2mm
- EVA
- laminated
- Backsheet: Tedlar only
- Solar cell: thckness 425μm,
  size 101×101mm
- Rated value：
  P=42.6Wp
  Voc=20.8V
  Isc=3.04A
  Vm=15.1V
  Im=2.82A

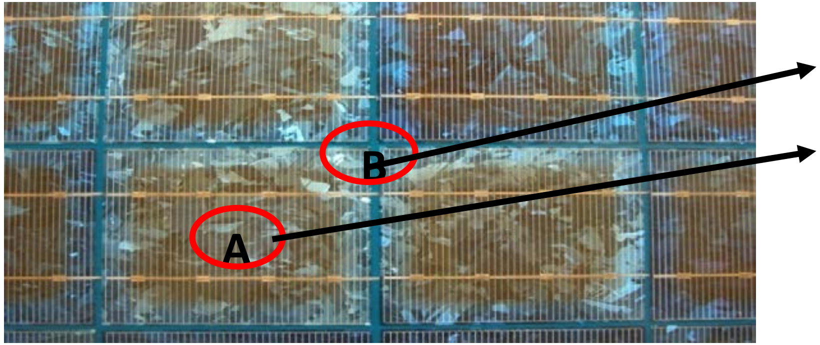
EVA Analysis

	method	reference	aged module
crosslinking-degree	exylene extraction	80-90	73 (marginal part)
light transmittance	ultraviolet spectrophotometer	91-93	<80
melting point	DSC	62-72	71
heat of solidification	DSC	5	0.54
VA content	TGA	28-33	33
PH	PH meter	5.69	5.09
yellowness index	colorimeter	0.9	11.5
tensile strength	Electronic Pull and Push Strength Caculator	18	3
breakage elongation		800	697
IR	IR spectrophotometer	-	acetic acid

Light transmittance comparison of surface encapsulant



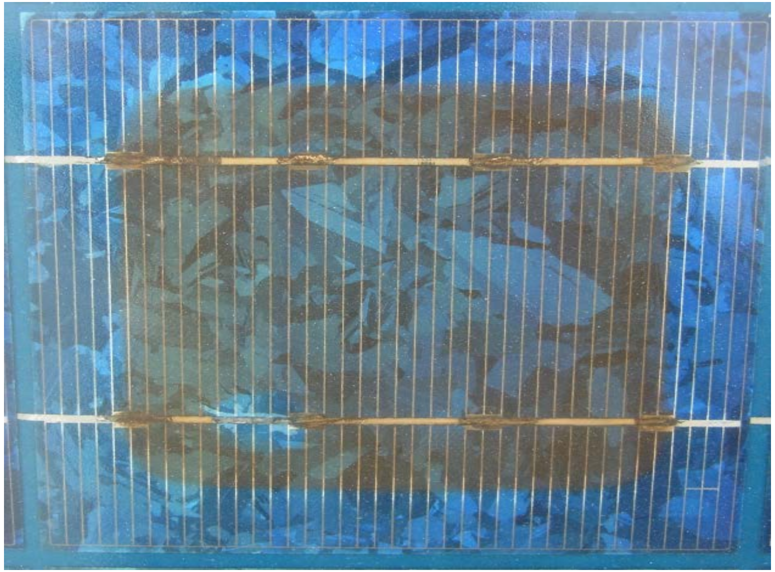
Crosslink degree of EVA from different parts in the module

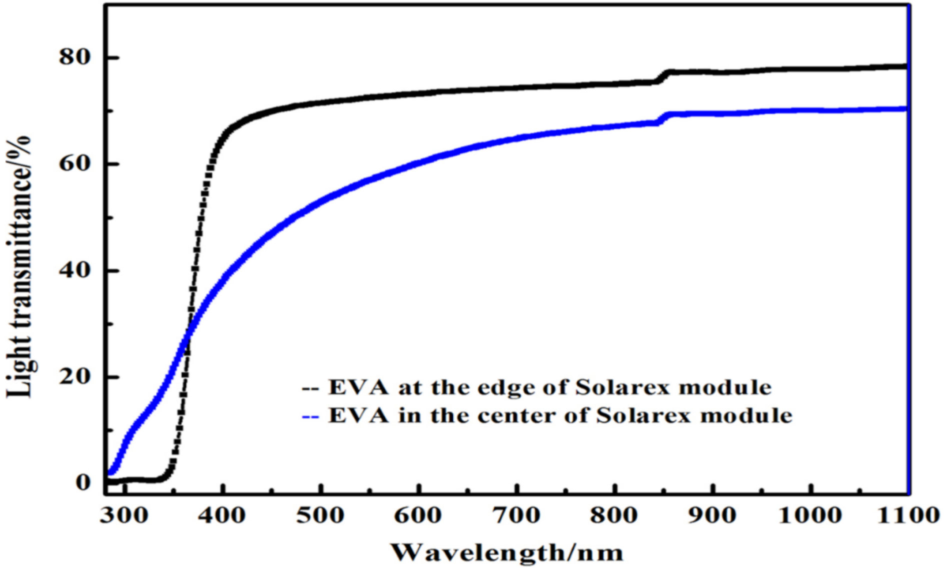


73.43%

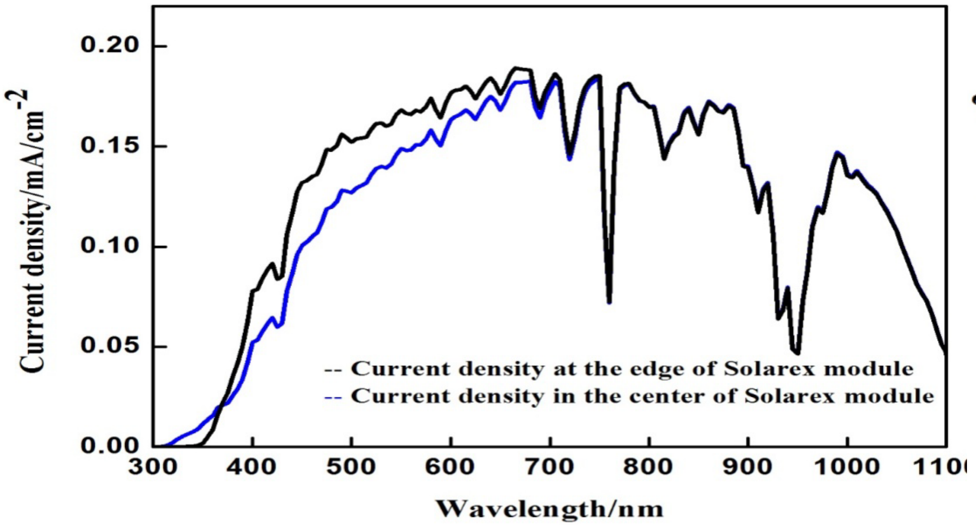
94.86%

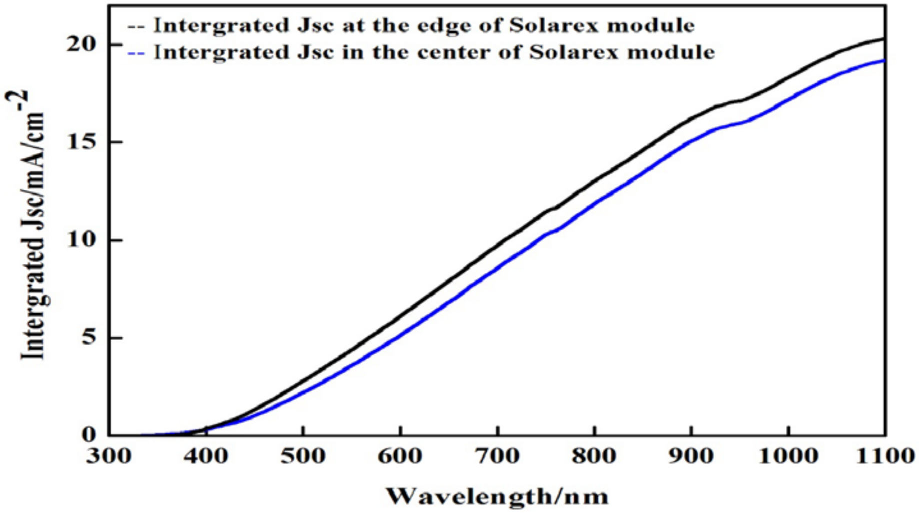
Solarex 组件电性能衰减分析



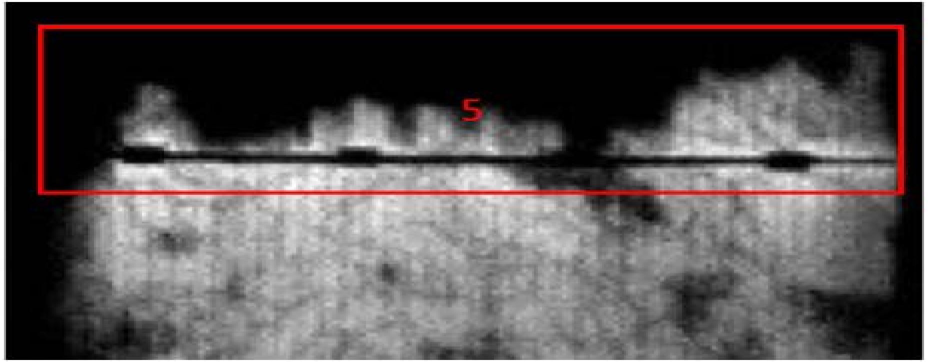


Solarex 组件电性能衰减分析





跟新的EVA相比，根据模拟计算结果发现，由于透光率下降导致的Solarex组件中边缘和中间EVA光生电流损失分别为10.12%和15.08%。而组件的Isc衰减率为14.3%，可见目前该批组件Isc的衰减主要来自EVA的光学损失。



Degradation mechanism:

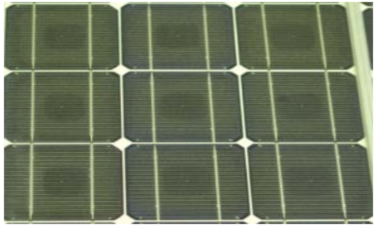
Optical loss

Yellowness of EVA

Electrical loss

Moistrue intrusion & micro crack

Case2:Compare of Siemens modules from different climates



Mono module

- Glass 3.2mm, EVA laminated
- Pruduce/installation time:1992-1998
- Back-sheet: Tedlar/PET/Tedlar
- Cell thickness 320μm, size 101×101mm
- Rated value： P = 55 Wp， Voc = 21.7 V，
  Isc = 3.45 A, Vm =17.4 V， Im = 3.15 A

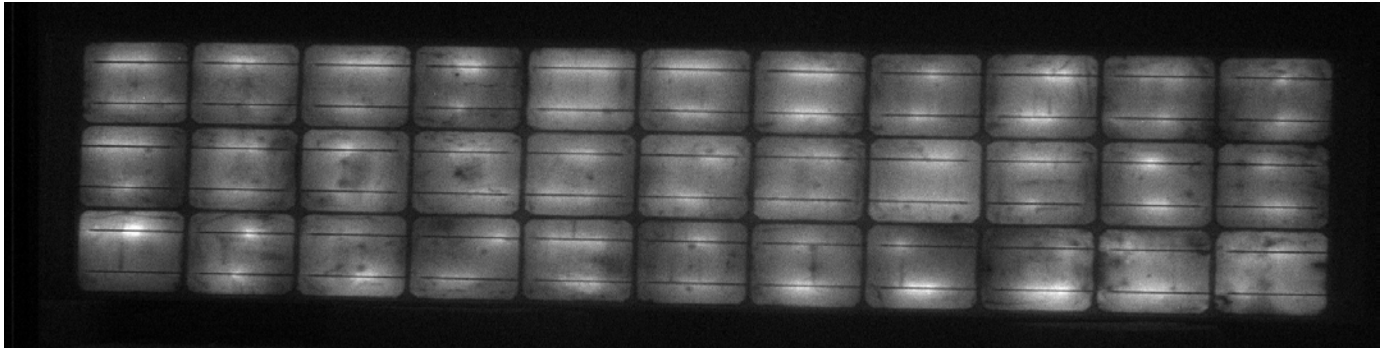
Degradation compare of modules from different climates(STC)

SM55	Age	Qty	Pm/W	Im/A	Vm/V	Isc/A	Voc/V	FF
Rated value			55	3.15	17.4	3.45	21.7	0.73
Storage		1	51.6	3.03	17.0	3.35	21.6	0.71
Shenzhen	20	500	41.3	2.77	14.8	3.19	21.2	0.61

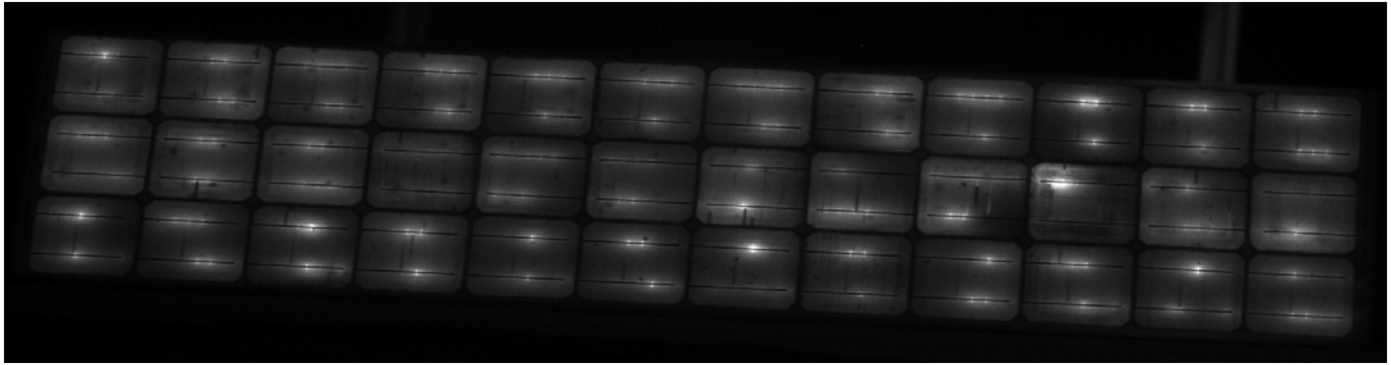
6% **25%** **7%** **13%**

M75	Age	Qty	Pm/W	Im/A	Vm/V	Isc/A	Voc/V	FF
Rated Value			48	3.02	15.9	3.35	19.8	0.72
Dunhang	23	61	44.6	2.92	15.3	3.25	19.7	0.70
Haixi	23	41	41.8	2.77	15.1	3.14	19.6	0.68

Relationship between degradation and climates/operation conditions

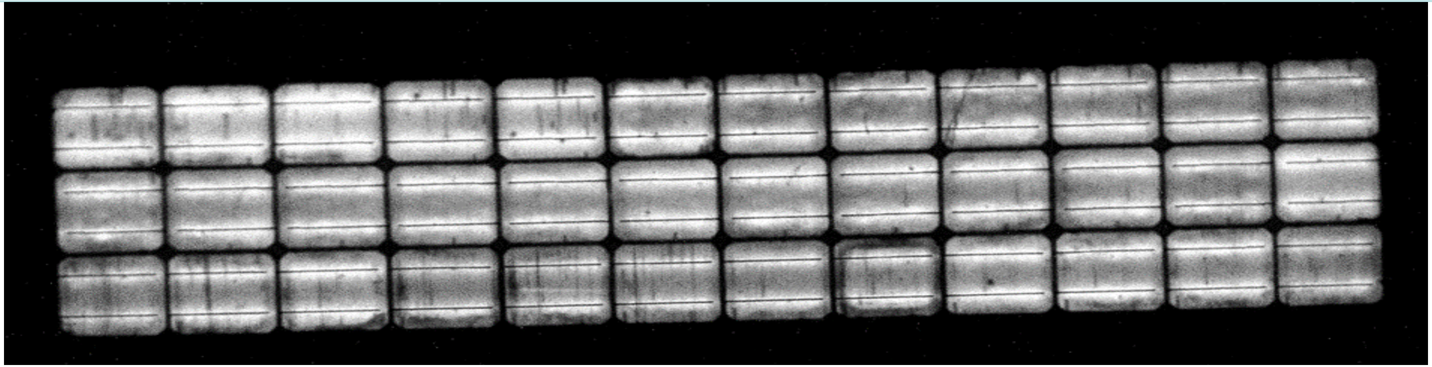


M75



SM55

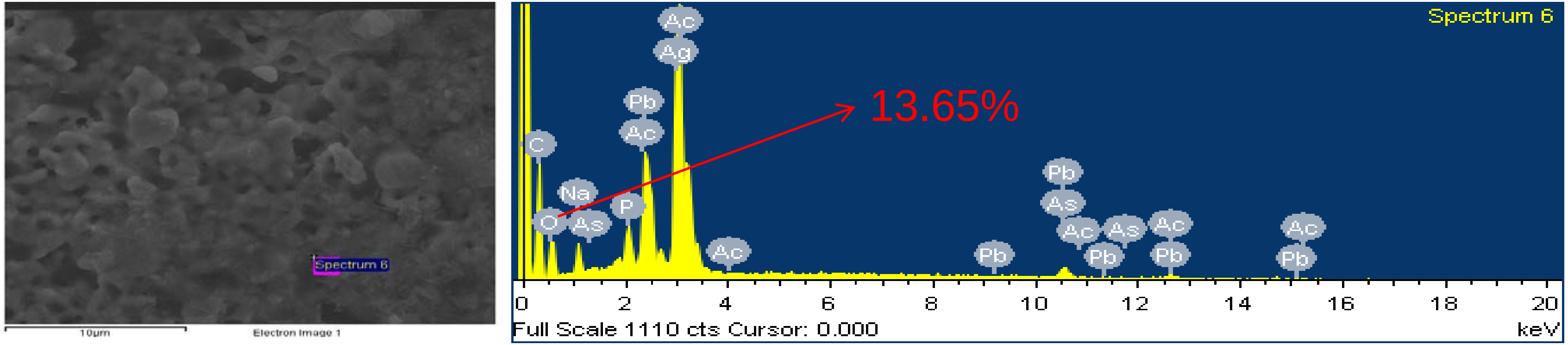
Why high series resistance?



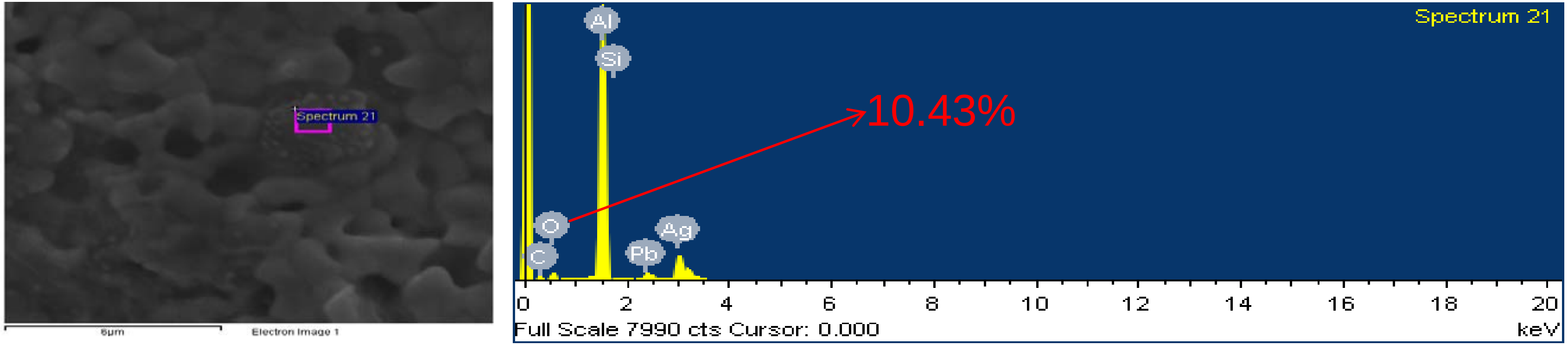
SM55 Storage indoor

Structrue of electron connection in front surface and back surface

SYSU Solar

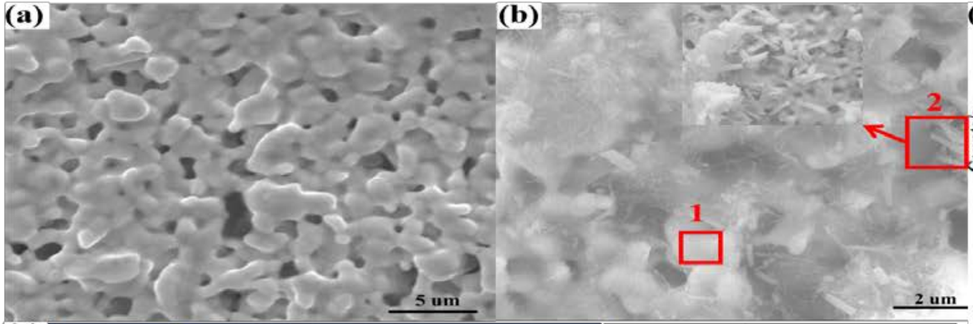


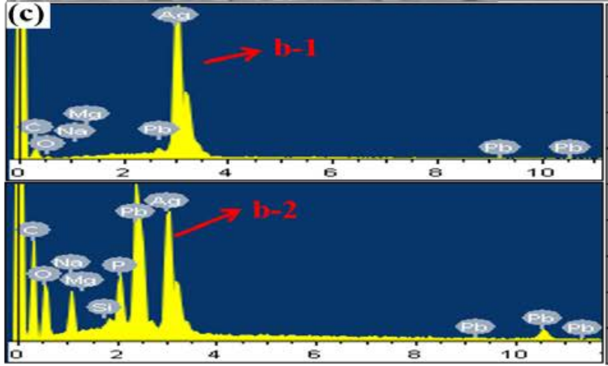
Ag fingers on the front surface of solar cell



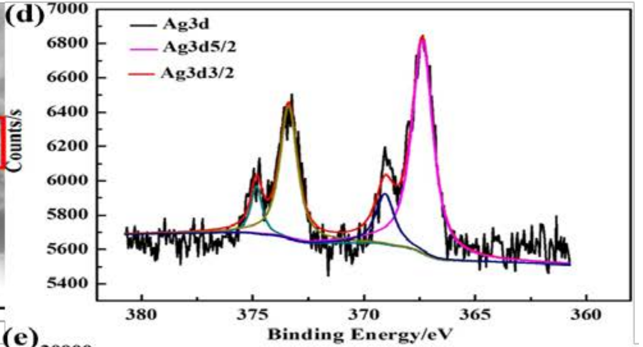
Fingers on the back surface of solar cell

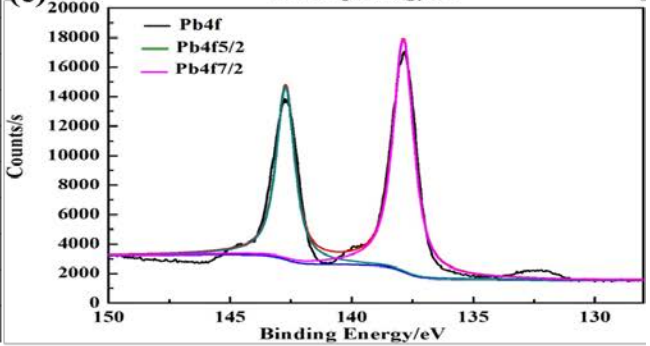
SM55 组件电性能衰减分析



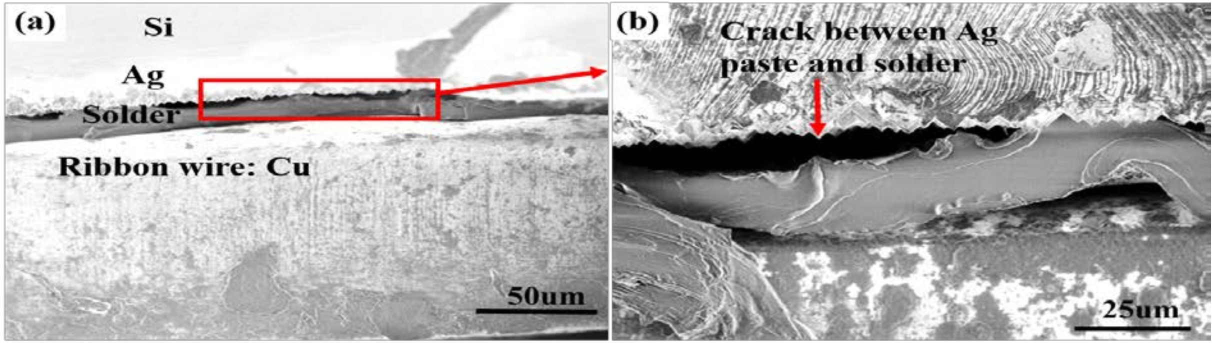


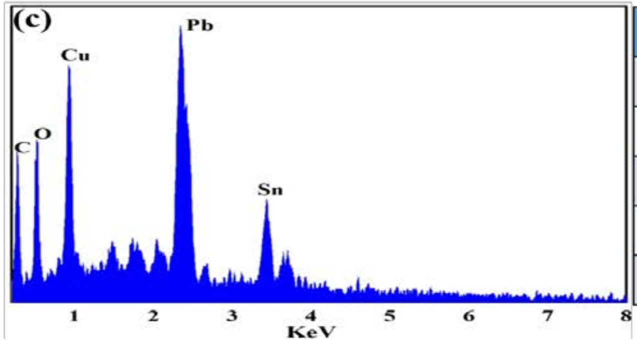
Element	Weight %	
	1	2
C	4.71	26.4
O	4.03	18.1
Ag	89.59	23.0
Pb	0.97	25.1
Na	0.47	3.97
Mg	0.24	0.16
P		2.98
Si		0.2





SM55 组件电性能衰减分析





Element	Wt%	Atomic%
Pb	41.06	9.61
Cu	20.29	15.49
Sn	19.58	8.00
O	10.07	30.53
C	9.00	36.37

Degradation mechanism:

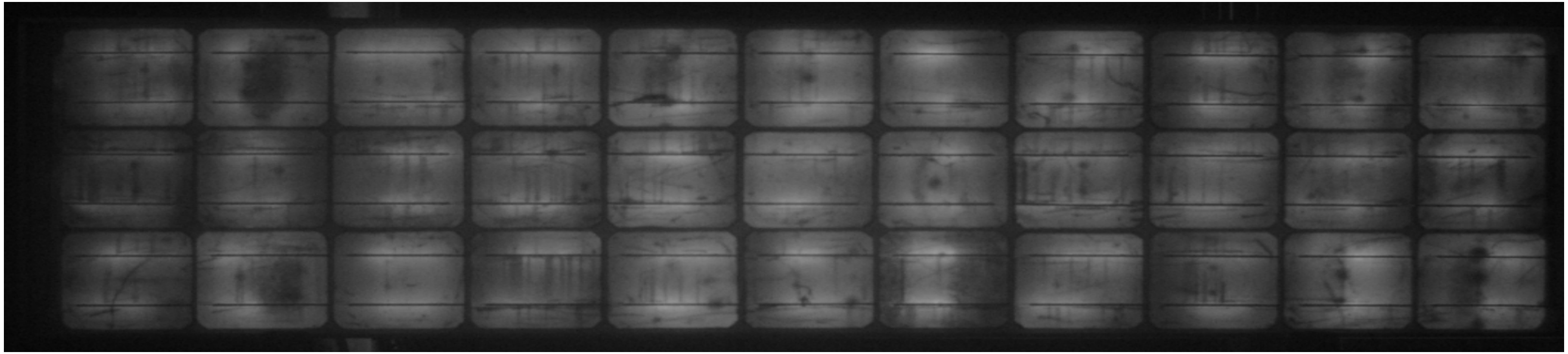
Bad contact between solar cell and ribbon

↑

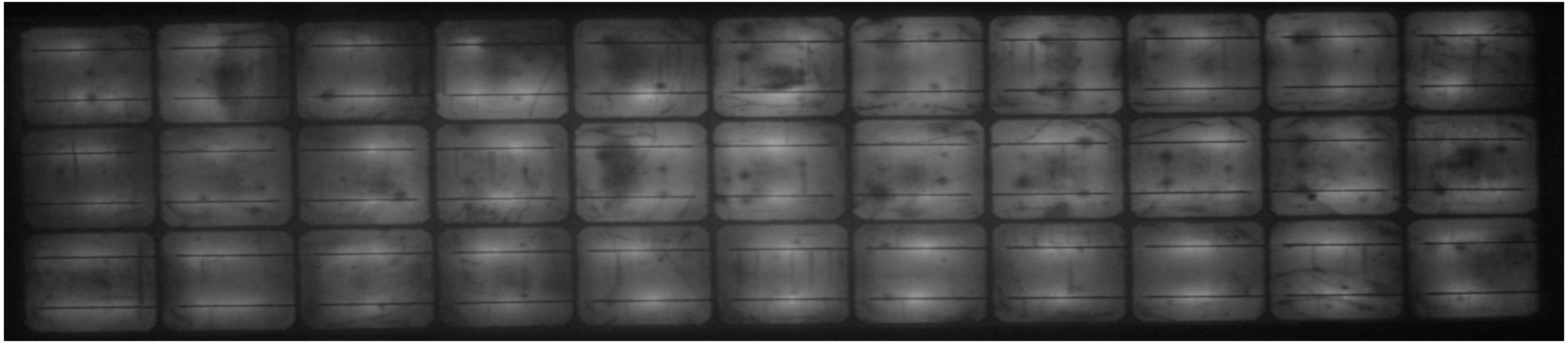
Al/Ag paste/produce process/severe climate

M75组件电性能衰减情况

大风山



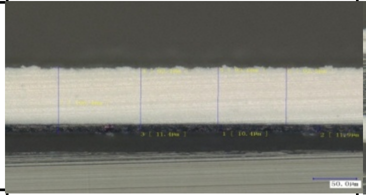
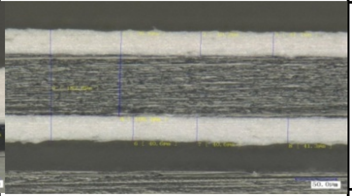
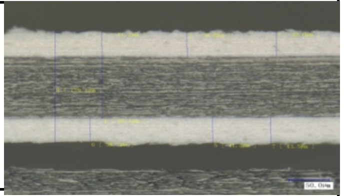
党河

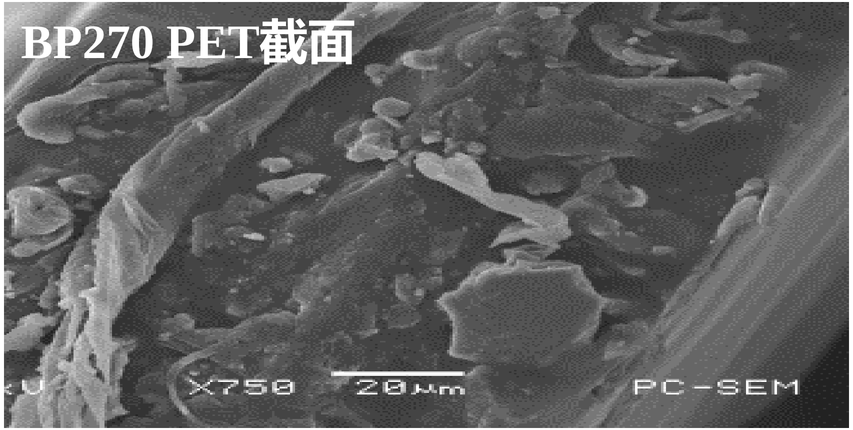


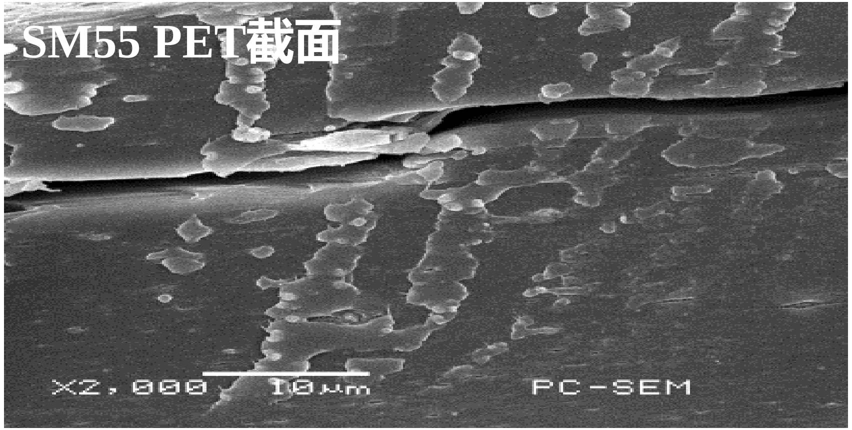
风载荷的影响较大，导致电池产生裂纹较多，串联电阻变大导致填充因子衰减严重

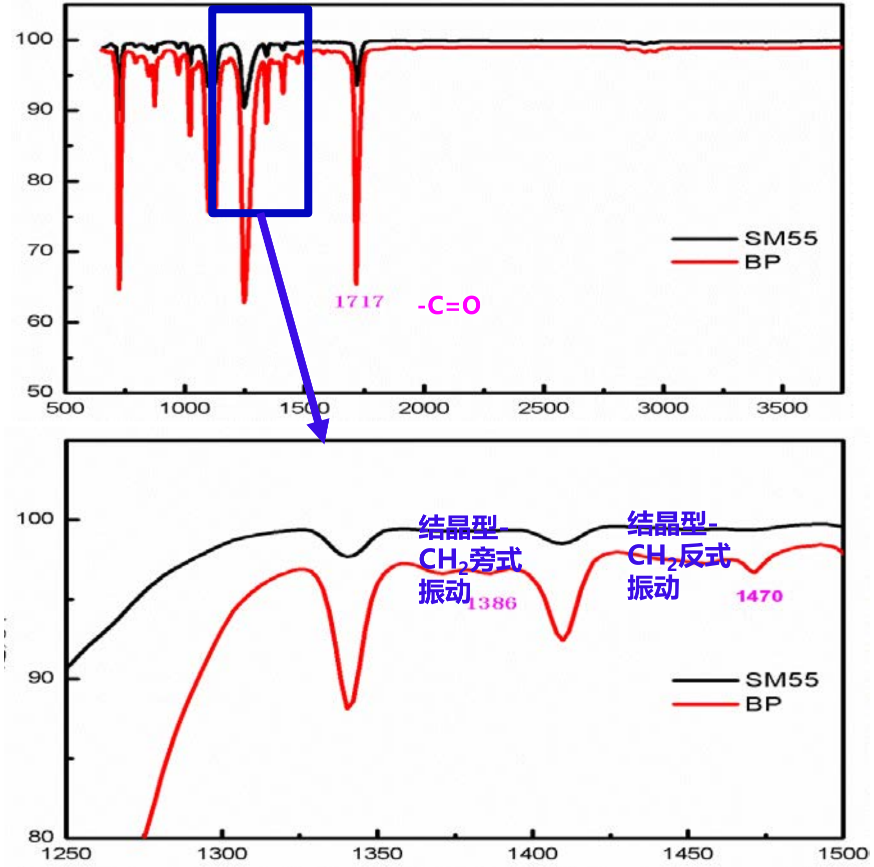
Back-sheet analysis

Solarex/BP270/SM55组件背板性能测试

测试项目		Solarex	BP270	SM55
水蒸气透过率 （gm/[m^2-day]）		8.21	3.98	3.64
整体厚度（um）		108	177	174
氟膜厚度（um）		96.8	40.3	40.5
背板结构				
拉伸强度（纵向/横向）Mpa	MD	46.52	93.52	95.06
	TD	73.18	110.65	127.59
断裂伸长率（纵向/横向）%	MD	184.45	165.45	178.4
	TD	122.92	116.34	80.56
击穿电压（kV）		6.66	15.66	15.83
体积电阻率		$1.964*10^{16}$	$1.266*10^{16}$	$1.364*10^{16}$


BP270 PET截面
X750
20μm
PC-SEM

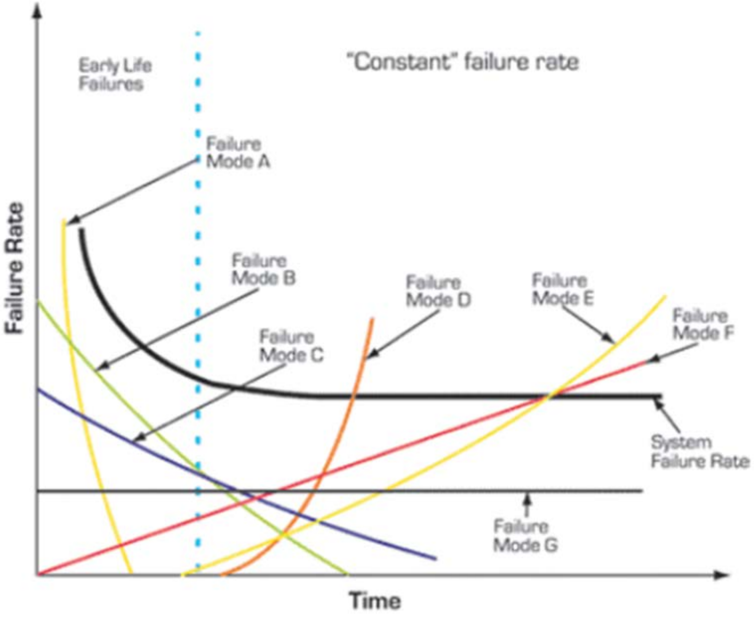

SM55 PET截面
X2,000
10μm
PC-SEM


100
90
80
70
60
50
500
1000
1500
2000
2500
3000
3500
SM55
BP
1717
-C=O
100
90
80
1250
1300
1350
1400
1450
1500
结晶型-
CH2旁式
振动
1386
结晶型-
CH2反式
振动
1470
SM55
BP

Outline

1. Background
2. Loss analysis for solar cells and module process
3. PoF based on fielded modules
4. **Reliability prediction model**

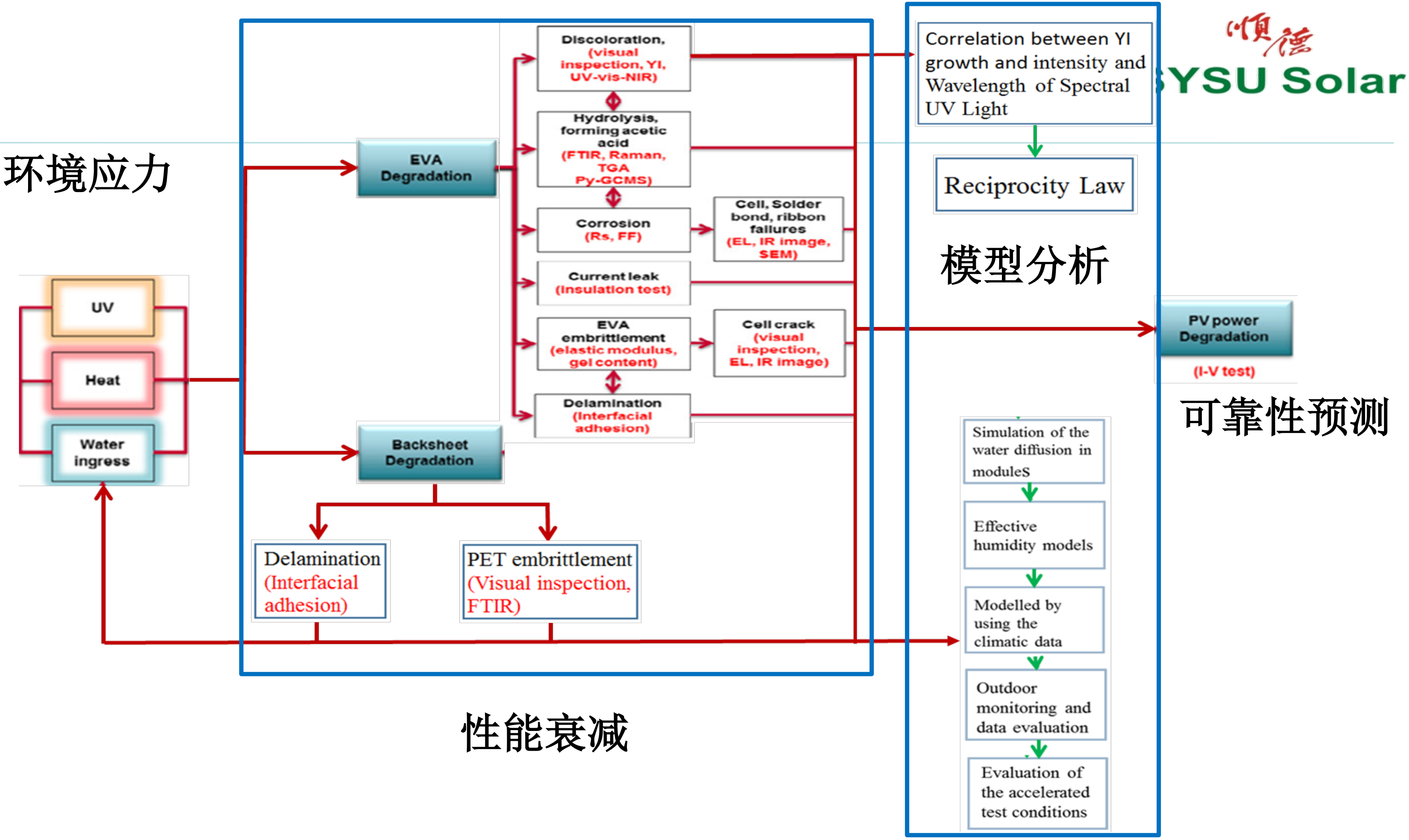
失效机理	故障位置	故障模式	相关应力	环境测试	模型
紫外线变色反应	EVA封装	低光效	T，强度，频率	温度中紫外线暴露	Arrhenius Exp (-Ea/kT)
脱粘	前表面	断电	ΔT, H, ΔH	湿热 温度循环	Coffin-Manson $N = C(\gamma)^n$
脱粘	后表面	传热差	ΔT, H, ΔH	湿热 温度循环	Coffin-Manson $N = C(\gamma)^n$
腐蚀	前表面互联	开路 增加阻力	M, ΔV, T, impurities	杂质 温度，通电，湿热	Eyring $(V)^n(RH)^n e^{-Ea/kT}$
疲劳解体	背板薄板	破裂	ΔT, ΔH	湿热 温度循环	Coffin-Manson $N = C(\gamma)^n$
断裂	玻璃	破裂	机械载荷	机械载荷	Paris Law $N=C(\Delta K)^n$
疲劳	封边	破裂 空洞	ΔT,ΔH	湿热 温度循环	Coffin-Manson $N = C(\gamma)^n$
金属分离	焊接	空洞	金属间	通电 温度 老化	Eyring (Black) $J^n e^{-Ea/kT}$
疲劳	焊接或电池连接	断连	ΔT, ΔV	温度环路供电	Coffin-Manson $N = C(\gamma)^n$



在组件的加速老化试验中引入合适的环境应力加速模型，可以更精确的模拟实际环境条件，从而利用加速试验分析组件的长期可靠性预估组件的使用寿命。

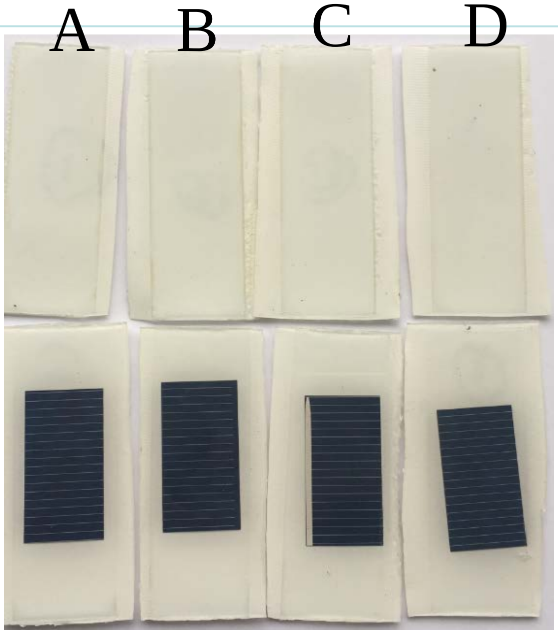
真实环境下，影响组件失效的环境应力不同，组件出现失效的时间不同

Olivier Haillant，Solar Energy Materials & Solar Cells 95 (2011) 1284–1292


环境应力
UV
Heat
Water ingress
EVA Degradation
Backsheet Degradation
Discoloration, (visual inspection, YI, UV-vis-NIR)
Hydrolysis, forming acetic acid (FTIR, Raman, TGA Py-GCMS)
Corrosion (Rs, FF)
Cell, Solder bond, ribbon failures (EL, IR image, SEM)
Current leak (Insulation test)
EVA embrittlement (elastic modulus, gel content)
Cell crack (visual inspection, EL, IR image)
Delamination (Interfacial adhesion)
Delamination (Interfacial adhesion)
PET embrittlement (Visual inspection, FTIR)
性能衰减
Correlation between YI growth and intensity and Wavelength of Spectral UV Light
Reciprocity Law
模型分析
Simulation of the water diffusion in moduleS
Effective humidity models
Modelled by using the climatic data
Outdoor monitoring and data evaluation
Evaluation of the accelerated test conditions
PV power Degradation
(I-V test)
可靠性预测

模型验证：户外实验样品VS室内加速测试

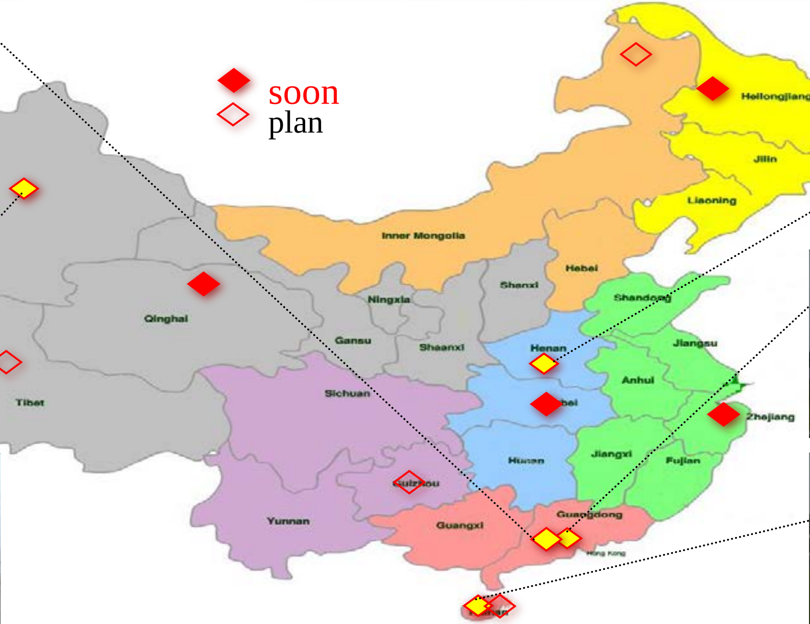
SYSU Solar



Re-installation of Siemens modules

SYSU Solar

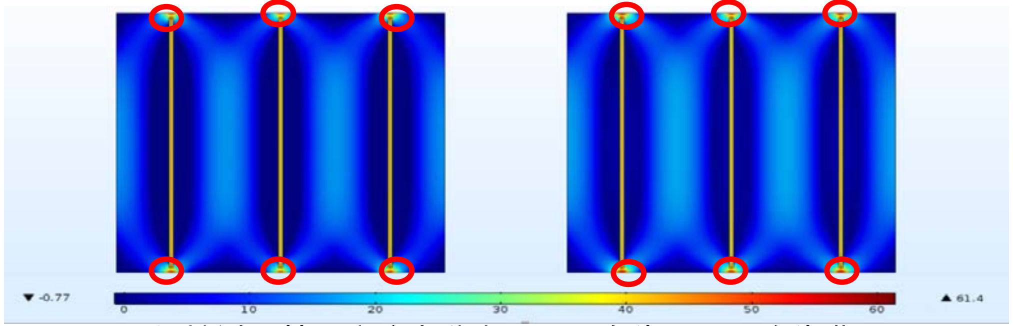
- Modules of the same batch worked in different climates were studied.
- 13 PV systems would be re-installed with these 17-year-old modules in typical climate locations.



马来西亚新增1组……

组件隐裂原因数值模拟分析Simulation analysis for cracks

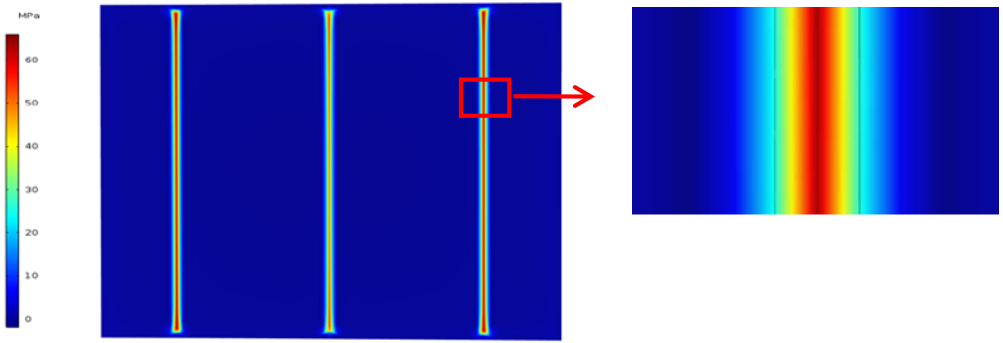
➢ 焊接过程热应力数值模拟分析(Thermal stress)



焊接过程第一主应力分布云图（左为正面，右为背面）

模拟结果表明热应力主要集中在焊带端部位置，而实际很多隐裂裂纹都集中在该位置，说明焊接过程热应力会增加产生裂纹产生的几率

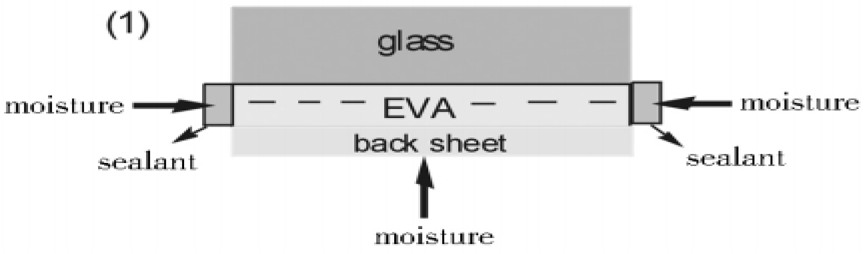
➢ 层压过程热应力数值模拟分析(Thermal stress)

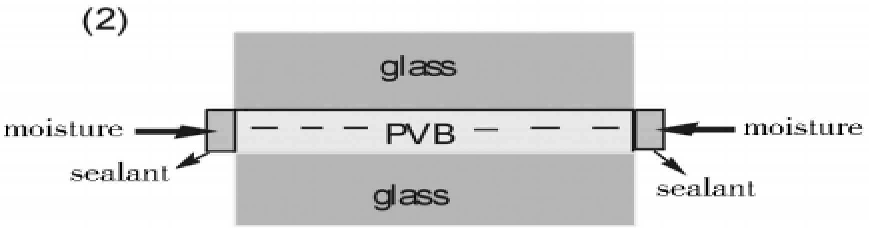


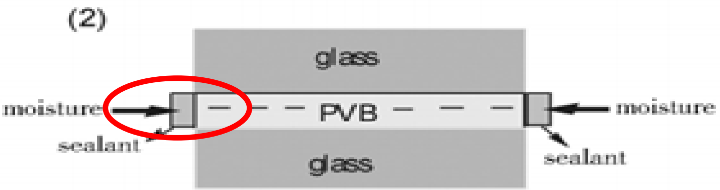
层压过程太阳电池第一主应力分布云图

模拟结果表明热应力主要集中在焊带及其附近位置，层压后，由于硅、EVA和焊带的热膨胀系数不同，该位置到较大应力，此处易产生裂纹。

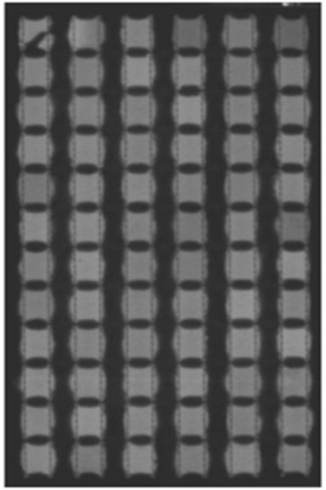
水汽透过模型Water vapor permeation theoretical model

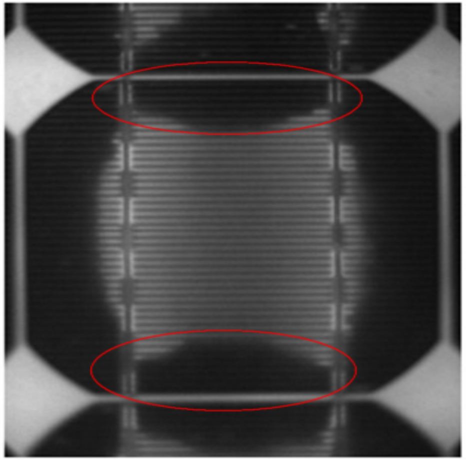




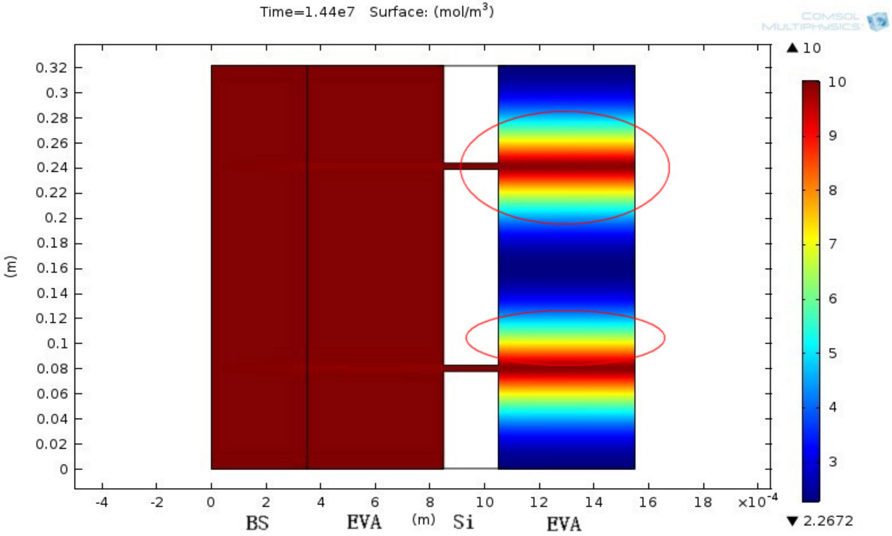


传统光伏组件和双玻组件水汽透过示意图





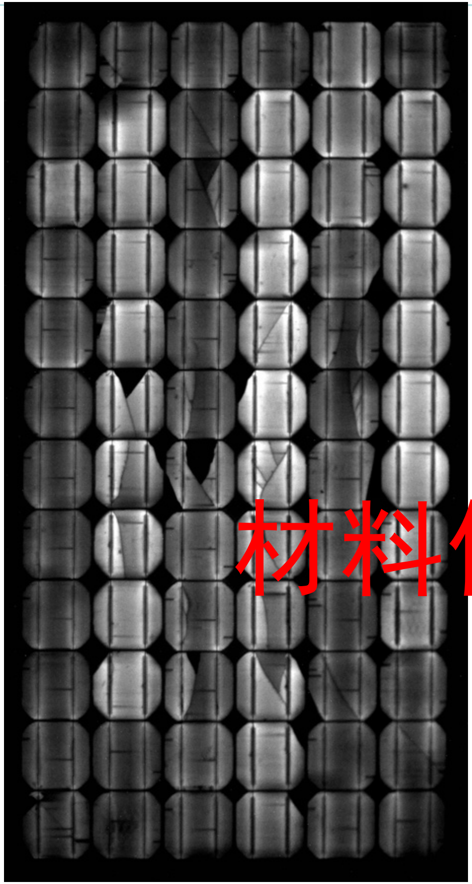
VS

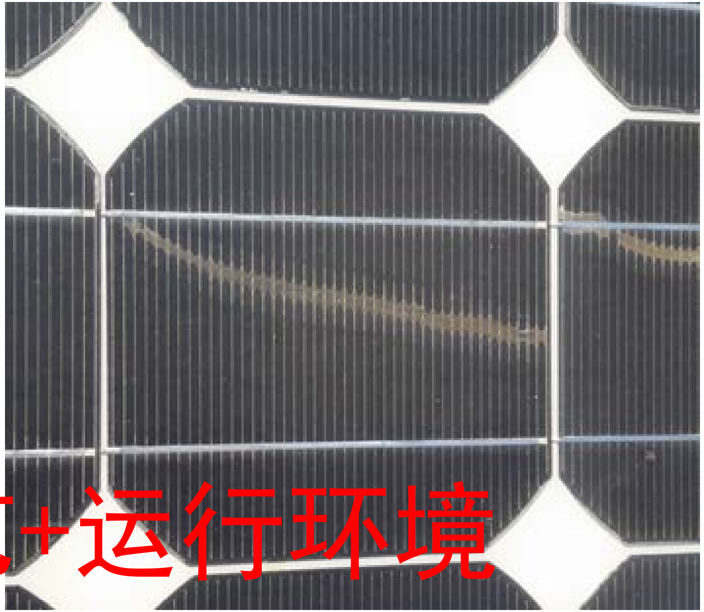


4000小时 EL图

4000小时 Comsol模拟图

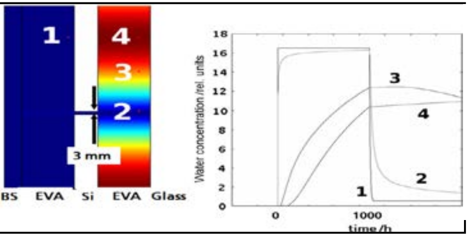
硅片表面变暗的区域和蒸汽浓度高的区域基本一致

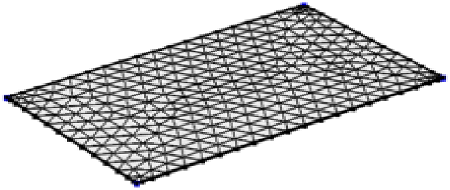


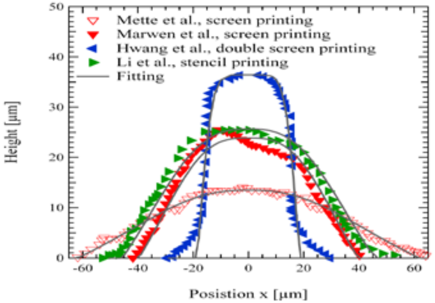


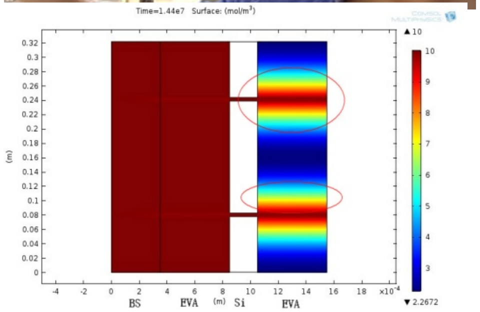
材料信息+生产工艺+运行环境

Thanks！









欢迎指正与交流！

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18929971580
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