

非晶硅薄膜厚度及特性对准分子激光晶化的影响

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摘要: **目的** 增加准分子激光晶化最优能量密度的工艺窗口以及提高晶化后多晶硅晶粒尺寸的均匀性, 并最终改善低温多晶硅薄膜晶体管 (Low Temperature Poly Silicon Thin Film Transistor, LTPS TFT) 的特性。**方法** 采用 PECVD 技术在玻璃基板上沉积不同厚度及折射率的非晶硅薄膜 (Amorphous Silicon Film)。利用高温退火炉脱氢后进行准分子激光退火 (Excimer Laser Annealing, ELA), 完成非晶硅到多晶硅的转变。通过扫描电镜、原子力显微镜对多晶硅晶粒尺寸以及表面粗糙度进行分析, 后续完成薄膜晶体管后利用 I-V 测试机台对器件特性进行测试。**结果** 随着非晶硅薄膜厚度的增加, 准分子激光晶化的最优能量密度 (Optimal Energy Density, OED) 以及工艺窗口 (OED Margin) 均增加, 当膜层厚度大于等于 47 nm 时, OED Margin 均为 25 mJ/cm²。当膜厚为 47 nm 时, 多晶硅晶粒尺寸均匀性为 0.64, 也处于较优的水平。非晶硅薄膜折射率为 4.5 时, 形成的多晶硅晶粒尺寸均匀性为 0.45, 远优于折射率为 4.38 时的多晶硅晶粒尺寸均匀性。折射率为 4.5 的非晶硅薄膜形成未掺杂的 LTPS TFT (PMOS) 迁移率为 120.6 cm²/(V·s), 阈值电压为 -1.4 V, 关态电流为 53 pA; 折射率为 4.38 时的迁移率为 112.4 cm²/(V·s), 阈值电压为 -2.0 V, 关态电流为 71 pA。**结论** 当非晶硅膜厚为 47 nm 时, 准分子激光晶化的 OED Margin 以及晶化后的多晶硅晶粒尺寸均处于较优的水平。另外, 提高非晶硅薄膜折射率同样有利于改善多晶硅晶粒尺寸均匀性以及薄膜晶体管转移特性。**关键词:** 非晶硅薄膜; 准分子激光晶化; 折射率; 薄膜晶体管器件特性
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Effects of Thickness and Characteristics of Amorphous Silicon Films on Excimer Laser Crystallization

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ABSTRACT: The work aims to improve optimal energy density process windows of excimer laser crystallization and enhance grain size uniformity of polycrystalline silicon, and finally improve characteristics of low temperature poly silicon thin film transistor (LTPS TFT). Amorphous silicon (a-Si) films of different thickness and refractive index were deposited on glass substrates by adopting PECVD technology. After dehydrogenation in high temperature annealing furnace, excimer laser annealing was performed to complete transition from amorphous silicon to polycrystalline silicon (P-Si). Grain size and surface roughness of polycrystalline silicon were analyzed with scanning electron microscope and atomic force microscope. After completion of thin-film transistors, I-V testing machine was used to test device characteristics. Both the optimum energy density (OED) and process window (OED margin) of excimer laser crystallization increased with the increase of amorphous silicon thin film thickness. When the film thickness was ≥ 47 nm, OED margin was 25 mJ/cm². Provided with film thickness of 47 nm, grain size

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uniformity was 0.64 and at optimal level. When refractive index of amorphous silicon film was 4.5, the grain size uniformity of polycrystalline silicon was 0.45, which was much superior to that of polycrystalline silicon grain with refractive index of 4.38. For un-doped LTPS TFT(PMOS) made from amorphous silicon film with refractive index of 4.5, mobility ratio was $120.6 \text{ cm}^2/(\text{V}\cdot\text{s})$, threshold voltage -1.4 V , and off-state current 53 pA ; for that made from amorphous silicon film with refractive index of 4.38, mobility ratio was $112.4 \text{ cm}^2/(\text{V}\cdot\text{s})$, threshold voltage -2.0 V , and off-state current 71 pA . Provided with amorphous silicon film thickness of 47 nm , OED margin of excimer laser crystallization and grain size uniformity of crystallized p-Si are both at superior level. In addition, improvement of refractive index of amorphous silicon film is also beneficial to enhancement of P-Si grain size uniformity and LTPS TFT transfer characteristics.

KEY WORDS: amorphous silicon films; excimer laser crystallization; refractive index; thin film transistor device characteristics

随着平板显示产业对于高分辨率、快响应速度、窄边框的需求越来越强烈,多晶硅薄膜晶体管目前引起了广泛的关注^[1]。相比于非晶硅,准分子激光晶化形成的多晶硅拥有较高载流子迁移率、较低的材料成本、较高的显示画面质量,因此近年来对于该领域的研究一直处于较活跃的状态^[2-5]。低温多晶硅作为有源层可以实现 LCD 及 OLED 显示,同时柔性 OLED 显示器也可以采用低温多晶硅薄膜晶体管作为背板,因此该技术提供了广阔的应用空间^[6]。准分子激光参数、激光晶化机理、预处理过程、非晶硅的厚度及质量,这些都会对多晶硅薄膜晶体管的特性有较大影响^[7-9]。早期有文献介绍^[10],不同的非晶硅薄膜厚度对于晶体管载流子迁移率有显著影响,但是对于 ELA 晶化的 OED Margin 的影响以及对多晶硅晶粒尺寸均匀性的影响未做详尽说明。另外,氢化非晶硅薄膜的折射率被认为与其膜层中 H 含量及微孔含量相关,即 H 含量及微孔含量减小,薄膜折射率随之增加^[11]。

本文研究了不同非晶硅厚度对于 ELA 结晶能量、工艺窗口以及多晶硅晶粒尺寸大小及均匀性的影响。同时,制备梯度折射率的非晶硅薄膜以研究准分子激光晶化的效果,高折射率的非晶硅薄膜有利于优先晶化形核。

1 实验方法

在玻璃基板上先沉积一定厚度的氮化硅和氧化硅复合膜层作为缓冲层,该缓冲层在 ELA 晶化时可以起到保温作用,有利于晶粒形核长大。随后,在 AKT-1600PX PECVD 设备上沉积非晶硅薄膜,气体源为 SiH_4 和 H_2 。折射率调整采用全因子 DOE 实验设计方法,具体沉积条件如表 1,温度调整范围为 $390\sim 430^\circ\text{C}$ 。不同非晶硅薄膜厚度通过调整沉积时间而获得,厚度范围 $40\sim 50 \text{ nm}$ 。薄膜厚度及折射率(n)采用 CompleteEASE 光谱椭偏仪测量。

非晶硅薄膜沉积后,基板放置于高温退火炉中进行去氢处理,退火条件为 $450^\circ\text{C}/90 \text{ min}$,保证各条件下非晶硅薄膜中氢含量低于 2%,以防止进行 ELA 时发生氢爆。

ELA 工艺采用 JSW 公司 LA370-N1-C7-D7 设备

表 1 非晶硅膜层折射率调整 DOE 实验
Tab.1 DOE experiment of refractive index adjustment of a-Si film

No.	H_2 Flow(sccm)	SiH_4 (sccm)	RF Power/W
1	1500	180	205
2	2400	260	110
3	600	260	300
4	2400	260	300
5	1500	180	205
6	2400	100	300
7	1500	180	205
8	1500	180	205
9	600	260	110
10	1500	180	205
11	2400	100	110
12	600	100	110
13	600	100	300

进行,激光源为 XeCl 气体,激光波长为 308 nm 。在整张玻璃基板进行激光扫描之前需要先进行能量密度(Energy Density, ED)条测试,优选 Mura 状况最优的能量密度(图 1)。结晶后多晶硅的晶粒大小及均匀性采用扫描电子显微镜进行评价,多晶硅表面粗糙度采用原子力显微镜进行评价。

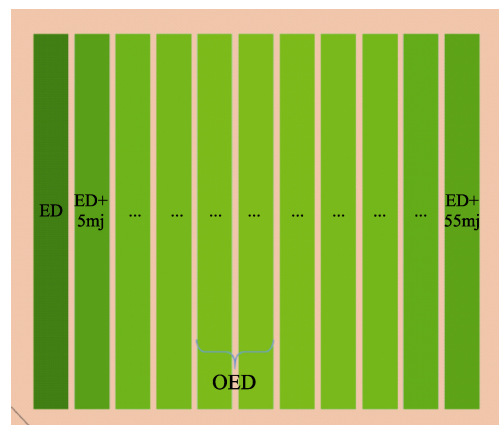


图 1 最优能量密度测试条

Fig.1 Optimum energy density test bar

2 结果及分析

2.1 非晶硅膜层厚度对 ELA 结晶能量及工艺窗口的影响

图 2 是在不同非晶硅薄膜厚度情况下 ELA 结晶最优能量密度及工艺窗口的变化趋势。由图 2 可以看出,随着非晶硅膜厚的增加,进行 ELA 扫描所需的能量也增加,这和 Paul van der Wilt 在文献中介绍的颇为一致。当非晶硅膜厚增加时,为保证非晶硅接近完全熔融状态,激光晶化的能量密度也会随之增加,二者几乎会呈现线性相关的关系^[12]。而膜层较薄时,激光能量稍有波动就会在多晶硅表面形成条纹状 Mura,因此膜厚增加对于 ELA 工艺窗口的提升是有益的。当膜厚范围为 47~50 nm 时,OED Margin 均为 25 mJ/cm²。

非晶硅的厚度同样对于结晶的晶粒尺寸大小及均匀性有显著影响(图 3—4),当膜层较薄时,多晶硅晶粒尺寸较小且晶粒尺寸均匀性较差,而膜层厚度超过一定范围时,晶粒尺寸均匀性也会变差,因此综合多晶硅晶粒尺寸大小及均匀性、OED Margin,优选非晶硅膜厚 47 nm 为最佳结晶膜厚,此时晶粒尺

寸为 350 nm,晶粒尺寸均匀性约 0.64 (Uniformity=(Max-Min)/(2·AVG))。

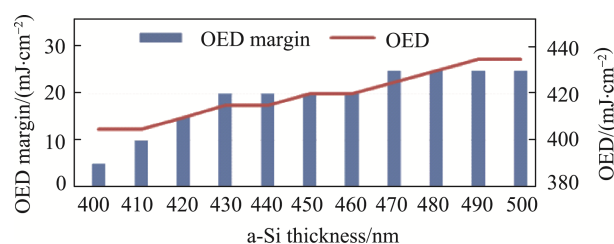


图 2 非晶硅厚度对 OED&OED Margin 影响
Fig.2 influence of a-Si thickness on OED&OED Margin

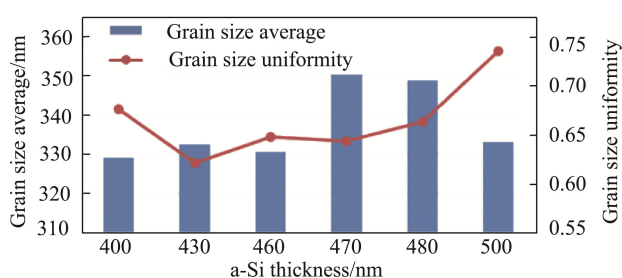


图 3 多晶硅晶粒尺寸及均匀性随非晶硅膜厚变化趋势
Fig.3 P-Si grain size and uniformity trend by a-Si thickness

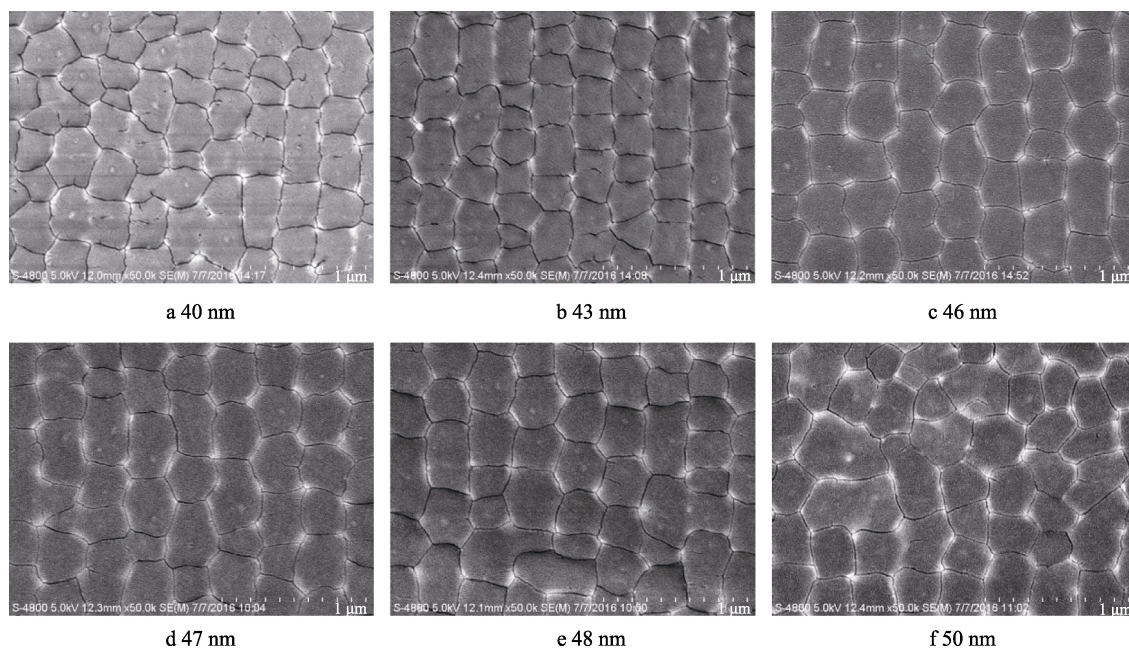


图 4 不同厚度非晶硅膜层结晶后状态
Fig.4 crystalline state of different a-Si thickness

2.2 非晶硅薄膜折射率对准分子激光晶化的影响

图 5 是不同 PECVD 沉积工艺条件下折射率的变

化规律,可以看出随着 SiH₄ 流量的增加,折射率呈现先增加后减小的趋势。这是因为在一定范围内, SiH₄ 流量增加,膜层中 H 含量减小,因此折射率增加;而超出一定范围后,过高的 SiH₄ 流量也会导致

沉积速率迅速增加,此时膜层中会形成众多的微孔,从而导致非晶硅折射率减小。同样, H_2 流量增加导致非晶硅膜层中 H 含量增加,从趋势图中也可以看出折射率随之减小。折射率随着沉积温度及沉积功率的变化呈现相反的趋势,沉积温度升高,非晶硅膜层更加致密,因此折射率也增加,并且在各沉积工艺参数中,温度的影响最为显著^[13]。

不同折射率的非晶硅薄膜晶化后,晶粒尺寸均匀性变化趋势如图 6—7 所示,从图中可以明显地看出,随着折射率的增加,多晶硅晶粒尺寸的均匀性也随之改善。这是由于折射率较高时,激光在非晶硅膜层中经过的路径较长,可以保证充分的融化结晶,同时高折射率下的非晶硅薄膜微孔含量较低,因此晶化后多晶硅的晶粒尺寸均匀性及表面粗糙度均处于较优水平。

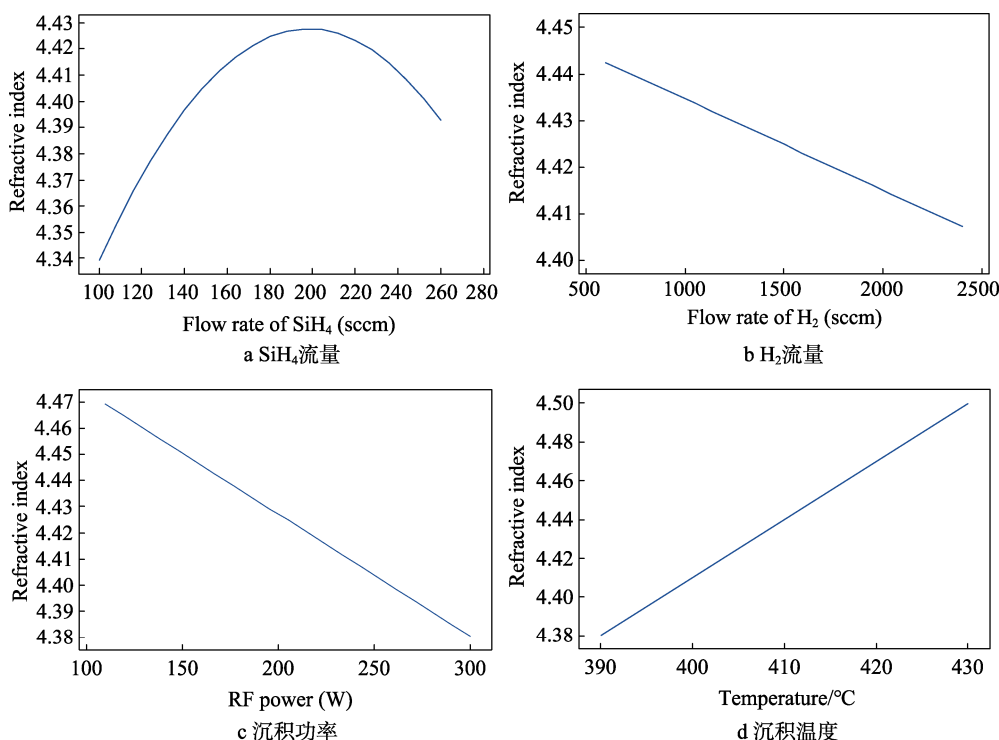


图 5 PECVD 沉积工艺与非晶硅折射率关系

Fig.5 Relationship between PECVD deposition process and refractive index of a-Si: (a) SiH₄ flow, (b) H₂ flow, (c) deposition power, (d) deposition temperature

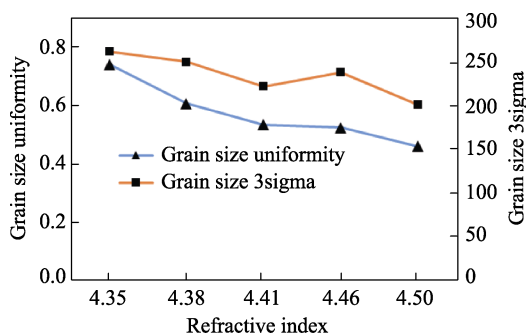


图 6 不同非晶硅折射率下多晶硅晶粒尺寸均匀性变化趋势

Fig.6 P-Si grain size uniformity trend by different refractive index of a-Si film

折射率为 4.38 及 4.50 的非晶硅薄膜晶化后(见图 8)分别完成薄膜晶体管制备, TFT 转移特性曲线以及主要特性数值见图 9 及表 2。高折射率非晶硅薄

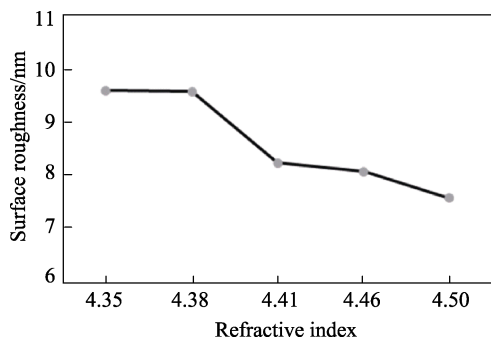


图 7 不同非晶硅折射率下多晶硅表面粗糙度变化趋势

Fig.7 P-Si surface roughness trend by different refractive index of a-Si film

膜晶化后,多晶硅拥有更好的晶粒尺寸均匀性以及更少的晶体缺陷,因此载流子通过相同长度的沟道会穿过更少的晶界及“陷阱”,这种情况下 TFT 也拥有较优的转移特性——较高的电子迁移率、更易开启的阈值电压以及较低的反态电流^[14-15]。

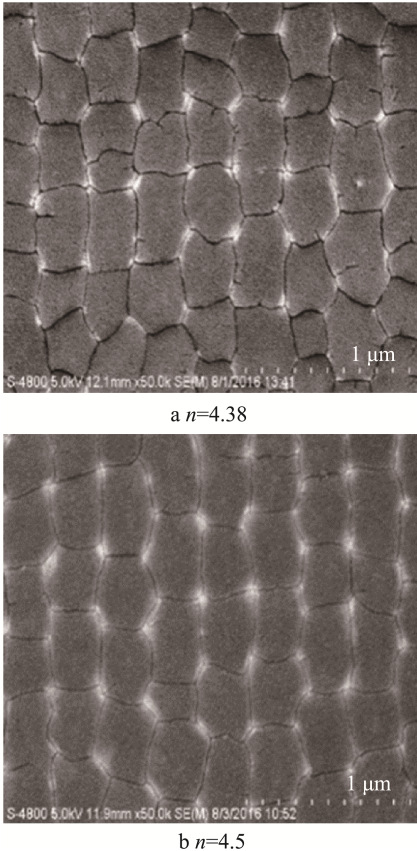


图 8 非晶硅薄膜折射率 $n=4.38$ 及 $n=4.50$ 时结晶状态
Fig.8 Crystallization state of a-Si film with refractive index of $n=4.38$ & 4.5

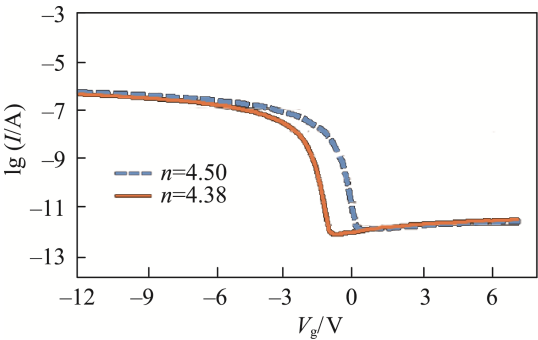


图 9 非晶硅薄膜折射率 $n=4.38$ 及 $n=4.50$ 时 LTPS TFT 转移特性曲线 ($W/L=3/26\ \mu\text{m}$, $V_d=-0.1\ \text{V}$)
Fig.9 LTPS TFT transfer characteristic curves of a-Si film with refractive index $n=4.38$ & 4.5 , where $W/L=3/26\ \mu\text{m}$, $V_d=-0.1\ \text{V}$

表 2 不同折射率的非晶硅形成的 LTPS TFT 的转移特性
Tab.2 Transfer properties of LTPS TFT formed by a-Si with different refractive index

n	Mobility $/(\text{cm}^2\cdot\text{V}^{-1}\cdot\text{s}^{-1})$	Threshold voltage/V	Off-state cur- rent/pA
4.38	111.2	-2.2	71
4.50	120.6	-1.4	53

3 结论

- 1) 随着非晶硅薄膜厚度的增加, 激光晶化的最佳能量也增加, 并且膜层厚度在 47~50 nm 范围内, OED Margin 可以达到 25 mJ/cm²。
- 2) 多晶硅晶粒尺寸均匀性随膜厚增加呈现先降低后升高的趋势, 当非晶硅膜厚为 43 nm 时, 多晶硅晶粒尺寸均匀性最优, 但是结合 OED Margin, 优选膜厚为 47 nm 的非晶硅薄膜, 此时晶粒尺寸为 350 nm, 晶粒尺寸均匀性为 0.65。
- 3) 升高 PECVD 沉积温度可以显著提高非晶硅薄膜的折射率, 高折射率非晶硅薄膜晶化后, 多晶硅晶粒尺寸均匀性及表面粗糙度均处于较优水平。 $n=4.5$ 时, 多晶硅晶粒尺寸均匀性为 0.45, 表面粗糙度为 7.6 nm。
- 4) 高折射率非晶硅薄膜晶化后形成薄膜晶体管, 其拥有较高的电子迁移率、更易开启的阈值电压及较低的反态电流。

参考文献:

[1] CHOI M, KIM S H, HUH J M, et al. Advanced ELA for Large-sized AMOLED Displays[J]. SID, 2014(4): 13-16.

[2] CHEN B W, CHANG T C, HUNG Y J. Surface Engineering of Polycrystalline Silicon for Long-term Mechanical Stress Endurance Enhancement in Flexible Low Temperature Poly-Si Thin-film Transistors[J]. ACS Appl Mater Interfaces, 2017, 9(13): 11942-11949.

[3] KEUM C M, KIM J K, MOON S J, et al. Low-temperature Poly-silicon Thin-film Transistor Developed without Ion Doping[J]. Journal of Information Display, 2014, 15(3): 135-138.

[4] MI Y U, JEONG K S, YUN H J. Investigation of the Instability of Low-temperature Poly-silicon Thin Film Transistors under a Negative Bias Temperature Stress[J]. Dissertations & Theses Gradworks, 2013, 9(1): 13-16.

[5] LEE S W, NAM D H, YOON J M, et al. Improvement of Gate Oxide Integrity in Low Temperature Poly Silicon TFT[J]. MRS Online Proceedings Library, 2003, 762: 569-576.

[6] 岳致富, 吴勇, 李喜峰, 等. 柔性低温多晶硅薄膜晶体管的弯曲稳定性[J]. 发光学报, 2017, 38(9): 1205-1209. YUE Zhi-fu, WU Yong, LI Xi-feng, et al. Bending Stability of Flexible Low Temperature Poly-silicon Thin-film Transistors[J]. Chinese Journal of Luminescence, 2017, 38(9): 1205-1209.

[7] BROTHERTON S D, MCCULLOCH D J, GOWERS J P, et al. Film Thickness Effects in Laser Crystallised Poly-Si TFTs[J]. IDW, 1996, 63: 21-25.

- [8] TENG T H, HUANG C Y, CHANG T K, et al. Degradation of Passivated and Non-passivated N-channel Low-temperature Polycrystalline Silicon TFTs Prepared by Excimer Laser Processing[J]. Solid-State Electronics, 2002, 46: 1079-1083.
- [9] CHERN H N, LEE C L, LEI T F. The Effects of H_2 - O_2 -Plasma Treatment on the Characteristics of Polysilicon Thin-film Transistors[J]. IEEE Transactions on Electron Devices, 1993, 40(12): 2301-2306.
- [10] HATANO M, SHIBA T. Late-News Paper: Selectively Enlarging Laser Crystallization Technology for High and Uniform Performance Poly-Si TFTs[J]. SID, 2002(2): 158-161.
- [11] WEBMAN I, JORTNER J, COHEN M H. Theory of Optical and Microwave Properties of Microscopically Inhomogeneous Materials[J]. Phys Rev B, 1977, 15(12): 5712-5723.
- [12] WILT P V D. Formation of Crystalline-Silicon Islands for Thin-film Transistors by Excimer-laser-induced Lateral Growth[D]. Netherlands: Delft University of Technology, 2003.
- [13] 李世彬, 吴志明, 朱魁鹏, 等. 衬底温度对用 RF-PECVD 法制备的非晶硅薄膜光学性能影响[J]. 物理化学学报, 2007, 23(8): 1252-1256.
LI Shi-bin, WU Zhi-ming, ZHU Kui-peng, et al. Effect of Substrate Temperature on the Optical Properties of a-Si:H Film by RE-PECVD[J]. Acta Physico-Chimica Sinica, 2007, 23(8): 1252-1256.
- [14] CHOI M, KIM S, HUH J M, et al. Advanced ELA for Large-sized AMOLED Displays[J]. SID, 2014(2): 13-16.
- [15] KIMURA M, TAYA J, NAKASHIMA A. Comparison of Transistor Characteristics between Excimer-laser and Solid-phase Crystallized Poly-Si Thin-film Transistors[J]. Solid-state Electronics, 2012, 72: 52-55..