

金属氧化物薄膜晶体管的激光退火

宁洪龙, 邓宇熹, 黄健朗, 罗子龙, 胡润东, 刘贤哲, 王一平, 邱天, 姚日晖, 彭俊彪

引用本文:

宁洪龙, 邓宇熹, 黄健朗, 等. 金属氧化物薄膜晶体管的激光退火[J]. 液晶与显示, 2020, 35(12): 1211–1221.

NING Hong-long, DENG Yu-xi, HUANG Jian-lang, et al. Laser annealing of metal oxide thin film transistor[J]. *Chinese Journal of Liquid Crystals and Displays*, 2020, 35(12): 1211–1221.

在线阅读 View online: <https://doi.org/10.37188/YJYXS20203512.1211>

您可能感兴趣的其他文章

Articles you may be interested in

激光对固态电解质金属氧化物薄膜晶体管性能的影响

Influence of laser irradiation on solid-electrolyte based metal-oxide thin film transistors performance

液晶与显示. 2020, 35(11): 1103–1109 <https://doi.org/10.37188/YJYXS20203511.1103>

磁控溅射法制备的 MoO_x 薄膜材料特性

Properties of MoO_x thin films prepared by magnetron sputtering

液晶与显示. 2020, 35(3): 211–218 <https://doi.org/10.3788/YJYXS20203503.0211>

高性能钆铝锌氧薄膜晶体管的制备

Fabrication of high performance Gadolinium-aluminum-zinc-oxide thin film transistors

液晶与显示. 2017, 32(5): 339–343 <https://doi.org/10.3788/YJYXS20173205.0339>

栅极坡度角对TFT器件制程的影响

Influence of gate profile on TFT manufacturing process

液晶与显示. 2020, 35(10): 1026–1035 <https://doi.org/10.37188/YJYXS20203510.1026>

未退火InGaZnO作为缓冲层的InGaZnO薄膜晶体管性能研究

Effects of using InGaZnO without annealing as buffer layer on the performance of InGaZnO thin film transistors

液晶与显示. 2015, 30(4): 602–607 <https://doi.org/10.3788/YJYXS20153004.0602>

文章编号:1007-2780(2020)12-1211-11

金属氧化物薄膜晶体管的激光退火

宁洪龙¹, 邓宇熹¹, 黄健朗¹, 罗子龙¹, 胡润东¹, 刘贤哲¹,王一平², 邱 天³, 姚日晖^{1*}, 彭俊彪¹

(1. 华南理工大学 发光材料与器件国家重点实验室, 高分子光电材料与器件研究所, 广东 广州 510641;

2. 南京航空航天大学 机械结构力学及控制国家重点实验室, 江苏 南京 210016;

3. 五邑大学 智能制造学部, 广东 江门 529000)

摘要:金属氧化物薄膜晶体管(MOTFT)具有较高的载流子迁移率($10 \sim 100 \text{ cm}^2/\text{V} \cdot \text{s}$),且薄膜均匀性好、制备温度低和可见光透明的优点,被认为是最有前途的新一代 TFT。激光退火因具有能量高、速度快、对衬底损伤小和退火范围可控的特点,相比传统热退火,更适用于柔性和大尺寸背板的制备。本文综述了有关金属氧化物薄膜及 MOTFT 激光退火的研究进展;详细讨论了激光退火中的关键参数;系统阐述了激光对金属氧化物薄膜的作用以及激光对 MOTFT 性能的影响。最后,总结了现在激光退火技术存在的问题以及发展方向。

关键词:激光退火技术;金属氧化物;薄膜晶体管;氧空位

中图分类号:TN249 **文献标识码:**A **doi:**10.37188/YJYXS20203512.1211

收稿日期:2020-06-17; **修订日期:**2020-08-18.

基金项目:国家重点研发计划(No.2016YFB0401504);国家自然科学基金(No.51771074, No.61574061);国家自然科学基金重大集成项目(No.U1601651);广东省基础与应用基础研究重大项目(No.2019B030302007);广州市科技计划项目(No.201904010344);中央高校基本科研业务费专项资金(No.2019MS012);季华实验室自主立项项目(No.X190221TF191);2019 年广东大学生科技创新培育专项资金(“攀登计划”专项资金: No.pdjh2019a0028, No. pdjh2019b0041);国家级大学生创新创业训练计划(No.201910561005, No.201910561007);华南理工大学百步梯攀登计划研究项目(No.j2tw201902475, No.j2tw201902203)

Supported by National Key R & D Program of China (No.2016YFB0401504); National Natural Science Foundation of China (No.51771074, No. 61574061); Major Integrated Projects of National Natural Science Foundation of China (No.U1601651); Guangdong Major Project of Basic and Applied Basic Research (No.2019B030302007); Science and Technology Project of Guangzhou (No.201904010344); Fundamental Research Funds for the Central Universities (No.2019MS012); Ji Hua Laboratory Scientific Research Project (X190221TF191); 2019 Guangdong University Student Science and Technology Innovation Special Fund (“Climbing Plan” Special Fund) (No.pdjh2019a0028, No.pdjh2019b0041); National College Students’ Innovation and Entrepreneurship Training Program (No.201910561005, No. 201910561007); South China University of Technology 100 Step Ladder Climbing Plan Research Project (No. j2tw201902475, No. j2tw201902203)

* 通信联系人, E-mail: yaorihui@scut.edu.cn

Laser annealing of metal oxide thin film transistor

NING Hong-long¹, DENG Yu-xi¹, HUANG Jian-lang¹, LUO Zi-long¹, HU Run-dong¹,
LIU Xian-zhe¹, WANG Yi-ping², QIU Tian³, YAO Ri-hui^{1*}, PENG Jun-biao¹

(1. *Luminescent Materials and Devices, South China University of Technology,
Guangzhou 510640, China;*

2. *State Key Laboratory of Mechanics and Control of Mechanical Structures,
Nanjing 510641, China;*

3. *Department of Intelligent Manufacturing, Wuyi University, Jiangmen 529020, China*)

Abstract: The metal oxide thin film transistor (MOTFT) has the advantages of high carrier mobility ($10 \sim 100 \text{ cm}^2/\text{V} \cdot \text{s}$), good thin film uniformity, low preparation temperature and transparent visible light. It is the most promising new generation TFT. Laser annealing has the characteristics of high energy, short time, low damage to the substrate and controllable processing range. According to the traditional thermal continuous, it is more suitable to produce flexible and large-size panels. The research progress of laser annealing discusses in detail the key parameters that affect the inversion effect in laser annealing; the effect of laser on metal oxide thin film and the effect of laser on the performance of MOTFT are systematically decomposed. Finally, the problems and development directions of current laser annealing technology are summarized.

Key words: laser annealing; metal oxide; thin film transistor; oxygen vacancy

1 引言

2019 年,曲面屏和全面屏席卷了显示市场,成为电子显示行业的最大热点之一。低温、低成本及大尺寸的柔性显示背板制备技术受到了广泛关注。薄膜晶体管(Thin Film Transistor, TFT)作为像素中的开关元器件^[1],是显示产业的基础技术和核心技术。其中,MOTFT 具有迁移率较高($10 \sim 100 \text{ cm}^2/\text{V} \cdot \text{s}$)、工艺简单、低温制备工艺、低成本、高透明、非晶结构,优异的大面积均匀性等优点,符合于大尺寸、柔性等未来显示制备方向的需求^[2-3]。在 MOTFT 的制备中,一般需要通过后退火工艺对器件进行性能提升和稳定化。激光退火瞬间产生热效应,使薄膜获得与热退火相同的热效应。而区别于传统热退火,激光退火有处理速度快、热积累少和散热快的优点。而激光退火的短热驱动时间还能减少衬底杂质向薄膜的扩散^[4]。同时,激光退火是自上而下的工艺,会在薄膜中形成温度梯度^[5],薄膜表面温度高,衬底温度低,有效减少了退火对衬底的损伤。因此,激

光退火工艺更适用于大尺寸、柔性显示背板的制备。

本文综述了 MOTFT 激光退火工艺的关键参数,并从薄膜到器件系统介绍了 MOTFT 激光退火的研究现状,分析了激光对金属氧化物薄膜及 MOTFT 的作用机理,最后总结了现在激光退火工艺技术存在的问题并展望了金属氧化物薄膜和 MOTFT 激光退火的发展前景。

2 激光退火对薄膜的作用

激光照射金属氧化物薄膜后,被激发的载流子会依次发生 4 个过程:(1)载流子激发;(2)热弛豫;(3)载流子复合;(4)热效应和结构效应^[6]。图 1 为经过激光激发后固体中各种电子和晶格效应的发生时间,每个绿色条代表 $10^{17} \sim 10^{22} \text{ cm}^{-3}$ 载流子密度下特征时间的大概范围。这 4 个效应会在激光退火过程中同时存在,其发生机理取决于退火激光的波长、能量密度、脉冲宽度等参数^[7],下面将具体介绍这些影响因素的作用。

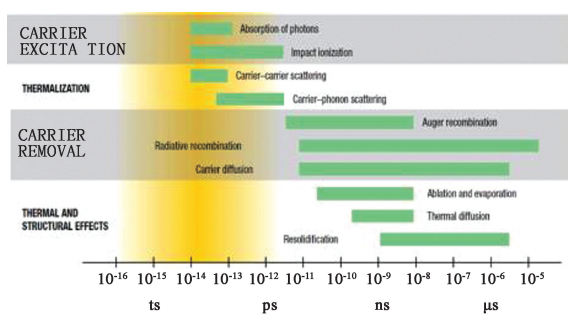


图 1 激光激发后固体中各种电子和晶格效应的发生时间^[6]

Fig.1 Action mechanism of laser processing film: Time scales of various electrons and lattice effects in solids after laser excitation^[6].

2.1 激光波长

根据比尔-兰伯特定律,激光的辐射强度在薄膜内部衰减^[8-9],其衰减规律如公式(1):

$$I(z) = I_0 e^{-\alpha z}, \quad (1)$$

其中: I_0 是经过反射损耗后薄膜表面以下的激光强度, $I(z)$ 是薄膜表面下深度为 z 的激光强度, α 是薄膜的吸收系数。一定波长的激光对薄膜的穿透深度与吸收系数有关^[10],如公式(2)所示:

$$\delta = \frac{1}{\alpha} = \frac{\lambda}{4\pi k_e}, \quad (2)$$

其中: δ 是穿透厚度, k_e 是消光系数。激光对金属氧化物薄膜的穿透厚度如图 2 所示,比较不同波长的激光对金属氧化物膜($\approx 1 \sim 10 \mu\text{m}$)的光穿透厚度: λ 为激光波长, A 为吸收系数, δ 是光

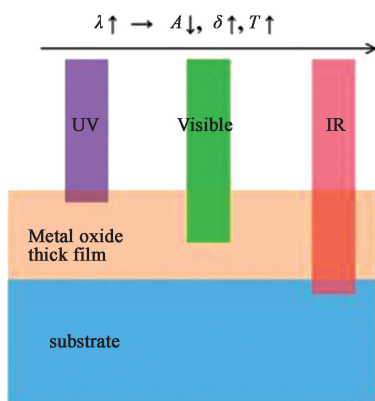


图 2 不同波长激光在金属氧化物半导体膜的光穿透深度^[7]

Fig.2 Penetration depth of laser light with different wavelengths on the metal oxide semiconductor film^[7]

穿透厚度, T 是光透射率。紫外激光对金属氧化物薄膜穿透厚度较浅^[7,11-12],适用于较薄的薄膜($<300 \text{ nm}$)退火。Haribabu Palneedi 等人采用 560 nm 的激光退火 $4 \mu\text{m}$ 的可见光半透明 Pb (Zr,Ti) O_3 薄膜,发现激光会对薄膜中间层进行直接加热,表面和底层通过热扩散间接加热,不会对衬底造成损伤^[13]。C.S.Sandu 等人发现,193 nm 和 248 nm 激光对 SnO_2 薄膜穿透厚度不同(分别为 66 nm 和 148 nm),导致了不同的晶化效果,193 nm 激光照射后薄膜有更明显的结晶梯度^[14]。

2.2 激光能量密度

激光的能量密度是脉冲激光退火的关键参数。一定能量密度的激光能诱导薄膜表面粒子产生热运动,从而修复薄膜表面缺陷,使薄膜表面致密化^[15-16],达到阈值能量密度的激光还能诱导薄膜重结晶和非晶薄膜的晶粒生长^[17-18],修复薄膜晶界缺陷,填补内部孔洞和微裂纹。Chien-Yie Tsay 等人发现,能量密度 $350 \text{ mJ}/\text{cm}^2$ 的激光均能消除 IGZO 和 IZO 薄膜中的有机物,使其获得均匀平整的表面^[19-20],同时两种薄膜均保持非晶态。激光退火还能通过对薄膜表面的快速蒸发作用,改善薄膜表面形貌,使薄膜获得更平整的表面^[21-23]。Ya-Hui Yang 和 W. M. Tsang 发现,激光退火能诱导薄膜的晶粒生长,能减少薄膜内部缺陷和晶界对光的散射,从而提高薄膜透射率^[24-25]。一定能量密度的激光对薄膜产生的热效应能通过模拟仿真进行研究,邵景珍等人利用有限元法模拟了 KrF 准分子激光辐照 ZnO 薄膜的热效应,给出了激光辐照后 ZnO 薄膜的热流密度随时间变化的曲线,并计算了薄膜的熔融阈值和熔融深度^[26]。

2.3 激光功率

激光的功率是连续激光退火的关键参数。与激光能量密度相似,激光退火所产生的热效应与激光功率的大小相关。李代林等人利用有限元法研究了连续激光作用下的 TiO_2 薄膜的三维温度场分布,发现 TiO_2 温度场与激光功率有关,结合实验分析了激光功率对 TiO_2 薄膜表面形貌、晶相和颜色状态的影响,研究表明,激光功率为 6 W、光斑半径为 3 mm 的连续激光辐照 TiO_2 薄膜 10 s 后获得的最优处理效果^[27]。

2.4 脉冲宽度

金属氧化物的热传递主要通过声子热运动进

行,而电子-声子的耦合放热时间 τ_{e-q} 与激光脉冲宽度 τ_p 有关^[28-30]。当 $\tau_p > \tau_{e-q}$ 时,主要发生热力学过程,激光诱导薄膜宏观温度的升高;当 $\tau_p < \tau_{e-q}$ 时,主要发生非热力学过程,光子能量在晶格振动前被电子吸收,从而使固体表面瞬间升温,这种极端非平衡态会产生高温、高压和高密度的等离子体,薄膜表面产生超快非热融解和激光烧蚀等现象,从而影响薄膜表面形貌。

而激光处理薄膜的损伤阈值也与脉冲宽度有关,Wolfe 给出了损伤阈值与脉宽的关系式:

$$D_{th} = 7 \cdot t_p^{0.35}, \quad (3)$$

其中: D_{th} 是损伤阈值, t_p 是脉宽。因此,损伤阈值是随着脉宽的增大而增大的。但脉冲宽度对薄膜的作用并不都呈现上述关系。根据多光子吸收模型的机理解释,当 $E_g \ll h\omega$ 时,损伤阈值与脉冲宽度无关;当 $E_g \gg h\omega$ 时,损伤阈值与脉冲宽度呈线性关系^[31]。

2.5 重复频率

重复频率是脉冲激光退火的时间参数,影响着退火过程中热积累和热传递的过程^[32]。重复频率与激光平均功率的关系如公式(4)所示:

$$P_M = E_p \times f_{pulse}, \quad (4)$$

其中: P_M 是激光平均功率, E_p 是脉冲能量, f_{pulse} 是脉冲重复频率。当重复退火激光频率过低,会因快速热扩散使退火区的热效应不足^[33]。而 Buerle D 等人发现,高重复频率激光会在辐照区形成颗粒屏蔽效应^[34],从而影响下一次脉冲对薄膜表面的热效应。

2.6 退火气氛

由于空气中的激光退火引入的氧缺陷会增加薄膜带尾态密度,影响 TFT 性能,这种缺陷往往难以通过钝化技术进行修复,因此激光退火通常采用真空或惰性气氛环境,从而减少空气中水分和氧气等对薄膜性能的影响^[35-37]。而气氛的种类和压强等会影响薄膜激光退火后的表面形貌、颗粒大小,从而影响薄膜的光学性能^[38]。其中,高热导率气体会因为激光诱导的热碰撞而迅速冷却,减少热效应的产生,从而降低薄膜的表面粗糙度和晶粒大小^[39-41]。一般在热导率高的气氛下退火,薄膜的表面更平整,晶粒尺寸更小。

3 激光退火对 MOTFT 的作用

激光退火对 MOTFT 沟道层的载流子激发

后,所产生的效应会改变薄膜的表面形貌、化学成分和晶格结构等,从而影响其器件性能,主要体现在迁移率、阈值电压(V_{th})、亚阈值摆幅(SS)等性能的改善。

3.1 表面形貌改善对 TFT 性能影响

由于薄膜表面缺陷多、不平整而导致 TFT 的界面缺陷多、层间接触电阻大等问题会显著影响 TFT 的性能,因此在 TFT 制备过程中对沟道层表面形貌的优化尤为重要。由于激光退火是一种由上至下的工艺,热效应的形成一般从薄膜表面开始进行,因此激光退火对薄膜表面的作用是显著的,激光退火对 TFT 层间界面缺陷的修复与表面形貌优化的过程相似。利用这一点可以通过激光退火提高 TFT 器件性能。

研究表明,沟道层薄膜表面形貌的改善与层间界面缺陷的修复有利于改善 TFT 迁移率、亚阈值摆幅等性能^[42-44]。图 3 为经过激光退火改善表面形貌后 TFT 的性能变化。Hau-Yuan Huang 等人发现,在 300 mJ/cm^2 能量密度激光退火后 IGZO-

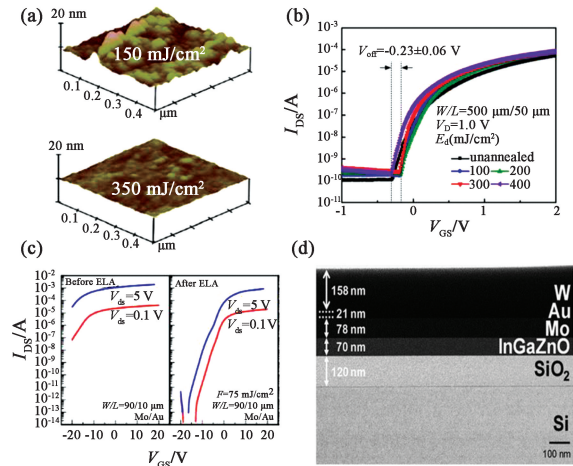


图 3 (a)IGZO 薄膜的 SPM 图^[20]; (b)不同能量密度激光退火的 IGZO-TFT 的 $I_{DS}-V_{GS}$ 特性曲线^[44]; (c)KrF 激光退火的 Mo/Au 电极 TFT 输出特性曲线; (d)激光退火后 Au/Mo/IGZO/SiO₂/Si 叠层的 STEM 横截面图像^[48]。

Fig.3 (a) SPM images of surfaces of IGZO thin films^[20]; (b) $I_{DS}-V_{GS}$ characteristics of InGaZnO TFT without and with ELA of different energy densities values^[44]; (c) Transfer characteristics for TFT with Mo/Au electrode after KrF ELA; (d) STEM cross-section image of the Au/Mo/IGZO/SiO₂/Si stack after KrF ELA^[48].

TFT 的迁移率由 $4.7 \text{ cm}^2/\text{V} \cdot \text{s}$ 上升到 $17.8 \text{ cm}^2/\text{V} \cdot \text{s}$, SS 由 0.1 V/dec 下降到 0.075 V/dec ^[45]。Cihai Chen 等人发现,通过激光诱导致密化可修复沟道和介电层之间的缺陷,从而优化 TFT 性能,且性能随激光能量密度上升 ($41 \sim 99 \text{ mJ/cm}^2$) 而提高,如 IZO-TFT 的迁移率由 $2.8 \text{ cm}^2/\text{V} \cdot \text{s}$ 上升到 $9.0 \text{ cm}^2/\text{V} \cdot \text{s}$, SS 由 0.9 V/dec 下降到 0.62 V/dec , 阈值电压负飘,由 1.4 V 变为 -2.5 V ^[46-47]。Juan Paolo S. Bermundo 等人发现,一定能量密度的激光退火能有效改善沟道表面形貌及修复界面缺陷,从而有效调节 IGZO-TFT 的阈值电压^[48]。

3.2 化学成分变化对 TFT 性能影响

对于 MOTFT 而言,沟道成分中氧空位的含量是研究重点。如图 4 所示,激光诱导形成的氧空位主要有两个过程:一是通过对化学键的解离从而形成的氧空位^[49-51],因此能实现单光子激发的紫外激光更容易破坏金属氧化物离子键的静电平衡,诱导形成氧空位^[52-54],在本课题组的掺硅氧化锡(STO)薄膜激光退火研究中也发现类似规律^[55]。二是热效应导致氧原子的热运动形成

的氧空位,这种效应产生的氧空位会随退火气氛中氧气的含量而变化。激光诱导产生的光辅助缩合及致密化反应能形成更纯的金属氧化物晶格结构,在金属氧化物晶格中形成的氧空位能更好地促进载流子的传输^[46,56-58]。由公式(5)可知^[59]:

$$\text{O}_0^x = \frac{1}{2} \text{O}_{2(g)} + \text{V}_\text{O}^\bullet + 2e^-, \quad (5)$$

其中: O_0^x 是晶格氧, $\text{V}_\text{O}^\bullet$ 是氧空位, e^- 是电子。因此氧空位的形成往往伴随电子的产生,从而提高了金属氧化物薄膜的载流子浓度。氧空位含量的增加使高浓度载流子能在导带附近形成电子传输路径,从而提高 TFT 器件迁移率,降低阈值电压^[45,60-63]。

而氧空位浓度太高可能会给 TFT 性能带来负面影响。激光退火也可以通过减少沟道氧空位来提高 TFT 性能^[64-65]。Cranton W M 等人则发现,通过激光退火能同时降低 AZO 薄膜的氧空位的含量和晶粒处吸附氧的含量,从而优化薄膜晶格结构,使薄膜获得更优的电学性能^[66],进而提高 TFT 的性能。这是因为,晶界处吸氧缺陷

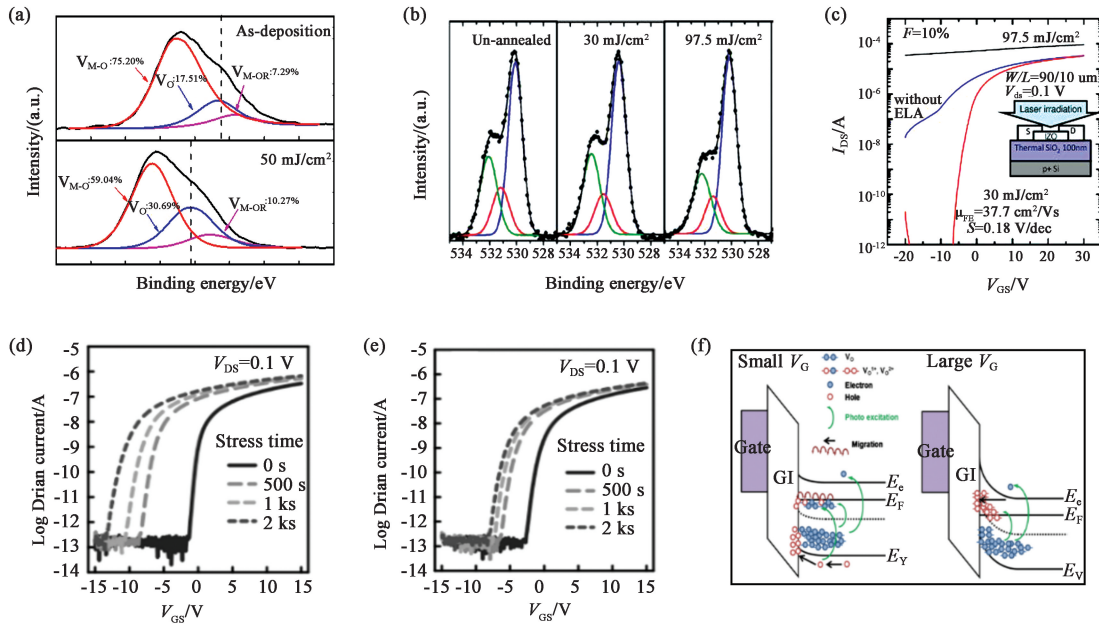


图 4 (a)激光退火前后 a-STO 薄膜的 XPS 图谱^[55]; (b)和(c)分别是 IZO 薄膜 XPS 图谱^[65]和 ELA 前后的 IZO-TFT 的转移特性曲线^[66]; IGZO 薄膜 XPS 图谱; (d)和(e)分别是蓝色激光退火前后 a-IGZO-TFT 的 NBIS 图^[72]; (f)不同负偏应力对应的失稳机理示意图^[70]。

Fig.4 (a) XPS spectra of a-STO films before and after laser annealing^[55]; (b) and (c) are the XPS spectra of IZO thin film^[65] and transfer characteristic curve of IZO-TFT before and after ELA^[66]; (d) and (e) are the NBIS diagrams of a-IGZO-TFT before and after blue laser annealing^[72]; (f) Schematic diagram of instability mechanism corresponding to different negative bias stresses^[70].

的降低能减少陷阱能级密度及降低晶粒间电子传输的势垒^[67-68]。Seonghyun Jin 等人发现,电子-空穴对会影响 TFT 的光照负偏压稳定性(NBIS),他们通过 445 nm 激光退火,减少了 IGZO 中的氧空位,从而减少了沟道处电子-空穴对含量,提高了 IGZO-TFT 的光照负偏压稳定性^[69-72]。此外,氧空位的形成还会降低金属氧化物薄膜的热导率^[73-74],会影响多次脉冲照射对薄膜的热效应。

3.3 晶格结构改善对 TFT 性能影响

激光退火诱导重结晶能使薄膜形成亚稳缺陷结构,可减小导带底附近的带尾态密度,从而提高 TFT 迁移率和降低阈值电压^[75-76]。激光诱导薄膜重结晶还能减少缺陷能级对载流子的捕获和晶界对载流子的散射,使薄膜电导率升高,电阻率下

降^[77-78],从而提高 TFT 的开态电流,提高 TFT 的迁移率和开关比^[24,79-80]。

但激光退火诱导晶粒生长也可能对 TFT 性能造成负面影响。Mitsuru Nakata 等人发现,激光诱导 IGZO 薄膜结晶后,载流子浓度过高,导致沟道耗尽层太宽,难以形成夹断,使 IGZO-TFT 关态电流(I_{off})太高,开关比($I_{\text{on}}/I_{\text{off}}$)降低^[81]。另一方面,激光诱导结晶可能会引起沟道的体积膨胀,造成 TFT 的漏电流增加,Fuminobu Hamano 等人通过激光退火后的附加激光辐照工艺减少了这种膨胀效应,降低了器件的漏电流^[82]。因此,需要激光退火合理地调控载流子浓度,才能提高 TFT 的性能。表 1 总结了合适的激光退火工艺对金属氧化物 TFT 性能改善的例子。

表 1 激光退火的金属氧化物 TFT 性能
Tab.1 Performance of laser annealed metal oxide TFT

TFT	Laser annealing parameters	Mobility/ ($\text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$)	V_{th}/V	$I_{\text{on}}/I_{\text{off}}$	SS/ ($\text{V} \cdot \text{Dec}^{-1}$)	References
IGZO-TFT	248 nm, 300 mJ/cm ²	17.8	-0.19	3.5×10^5	0.075	[45]
IGZO-TFT	248 nm, 80 mJ/cm ²	18.0	1.70			[48]
IGZO-TFT	308 nm, 170 mJ/cm ²	15.6	0.50		0.13	[77]
IGZO-TFT	355 nm, 740 mJ	7.65		2.88×10^6		[25]
IZO-TFT	800 nm, 99 mJ/cm ²	9.0	-2.50	5.7×10^6	0.62	[46]
IZO-TFT	30 mJ/cm ²	37.70		$\approx 10^7$	0.18	[65]
In ₂ O ₃ -TFT	248 nm, 300 mJ/cm ² 10pluses	6~10.0	Close to 0	$>10^5$		[63]
ZnO-TFT	355 nm, 925 mJ	0.50		4.7×10^5		[25]
ZnO-TFT	355 nm, 740 mJ	0.49				[76]

4 结 论

激光退火的优良特性已经被广泛认识,在过去的研究中,激光退火对金属氧化物薄膜和金属氧化物薄膜晶体管性能的改善表现出优良的前景。针对金属氧化物薄膜及其 TFT,现在已经研究出一系列的激光退火工艺优化方案,有效地提高了 TFT 的性能。但是激光退火技术依然存在一些问题,如:(1)退火工艺参数较复杂,导致退火过程的调控比较困难;(2)激光退火中,大多数讨

论对薄膜的热效应,激光光子对金属氧化物半导体薄膜作用的讨论较少,需要进一步研究;(3)由于高能量激光会对薄膜表面造成一定程度损伤,影响其对薄膜表面形貌的改善,具体表现在激光退火对 TFT 亚阈值摆幅的优化不如热退火。最近的研究中,有通过附加退火步骤、器件老化和制备新型结构 TFT 等方法来优化 TFT 的激光退火工艺,丰富了激光退火技术的优化方案。因此,激光退火技术使高性能柔性、大尺寸显示背板的制备拥有更多可能性,对推动柔性、大尺寸显示发展具有重要意义。

参 考 文 献:

- [1] 钟云肖,谢宇,周尚雄,等.溶液法氧化物薄膜晶体管的印刷制备[J].液晶与显示,2017,32(6):443-454.
ZHONG Y X, XIE Y, ZHOU S X, *et al.* Oxide semiconductor thin film transistor device print fabrication based on solution method [J]. *Chinese Journal of Liquid Crystals and Displays*, 2017, 32(6): 443-454. (in Chinese)
- [2] 王磊,徐苗,兰林锋,等.金属氧化物 TFT 驱动 AMOLED 显示研究进展[J].中国科学:化学,2013,43(11):1383-1397.
WANG L, XU M, LAN L F, *et al.* Research progress of active matrix organic light emitting diode (AMOLED) displays driven by metal oxide thin film transistors (TFT) [J]. *Scientia Sinica Chimica*, 2013, 43(11): 1383-1397. (in Chinese)
- [3] 刘贤哲.掺硅氧化锡薄膜晶体管的研究[D].广州:华南理工大学,2017.
LIU X Z. Study of Si doping tin oxide thin film transistors [D]. Guangzhou: South China University of Technology, 2017. (in Chinese)
- [4] KWON J Y, JEONG J K. Recent progress in high performance and reliable n-type transition metal oxide-based thin film transistors [J]. *Semiconductor Science and Technology*, 2015, 30(2): 024002.
- [5] KHAN A F, MEHMOOD M, ASLAM M, *et al.* Characteristics of electron beam evaporated nanocrystalline SnO₂ thin films annealed in air [J]. *Applied Surface Science*, 2010, 256(7): 2252-2258.
- [6] SUNDARAM S K, MAZUR E. Inducing and probing non-thermal transitions in semiconductors using femtosecond laser pulses [J]. *Nature Materials*, 2002, 1(4): 217-224.
- [7] PALNEEDI H, PARK J H, MAURYA D, *et al.* Laser irradiation of metal oxide films and nanostructures: applications and advances [J]. *Advanced Materials*, 2018, 30(14): 1705148.
- [8] BUELER D. *Laser Processing and Chemistry* [M]. Berlin: Springer, 2011.
- [9] DAHOTRE N B, HARIMKAR S P. *Laser Fabrication and Machining of Materials* [M]. New York: Springer, 2008.
- [10] KIM H, GILMORE C M, PIQU A, *et al.* Electrical, optical, and structural properties of indium-tin-oxide thin films for organic light-emitting devices [J]. *Journal of Applied Physics*, 1999, 86(11): 6451-6461.
- [11] PALNEEDI H, MAURYA D, KIM G Y, *et al.* Unleashing the full potential of magnetoelectric coupling in film heterostructures [J]. *Advanced Materials*, 2017, 29(10): 1605688.
- [12] ALLEMANN I B, GOLDBERG D J. *Basics in Dermatological Laser Applications* [M]. Basel: Karger, 2011.
- [13] PALNEEDI H, MAURYA D, KIM G Y, *et al.* Enhanced off-resonance magnetoelectric response in laser annealed PZT thick film grown on magnetostrictive amorphous metal substrate [J]. *Applied Physics Letters*, 2015, 107(1): 012904.
- [14] SANDU C S, TEODORESCU V S, GHICA C, *et al.* Densification and crystallization of SnO₂:Sb sol-gel films using excimer laser annealing [J]. *Applied Surface Science*, 2003, 208-209: 382-387.
- [15] CHOI I, JEONG H Y, JUNG D Y, *et al.* Laser-induced solid-phase doped graphene [J]. *ACS Nano*, 2014, 8(8): 7671-7677.
- [16] JOE D J, KIM S, PARK J H, *et al.* Laser-material interactions for flexible applications [J]. *Advanced Materials*, 2017, 29(26): 1606586.
- [17] 吴乐琦.半导体的激光退火[J].发光学报,1980(5):59-66.
WU L Q. Laser annealing of semiconductors[J]. *Chinese Journal of Luminescence*, 1980(5):59-66. (in Chinese)
- [18] YOUNG R T, NARAYAN J, CHRISTIE W H, *et al.* Semiconductor processing with excimer lasers [J]. *AIP Conference Proceedings*, 1983, 100(1): 266-278.
- [19] TSAY C Y, HUANG T T. Improvement of physical properties of IGZO thin films prepared by excimer laser annealing of sol-gel derived precursor films [J]. *Materials Chemistry and Physics*, 2013, 140(1): 365-372.
- [20] TSAY C Y, HUANG T T. Characterization of low-temperature solution-processed indium-zinc oxide semiconductor thin films by KrF excimer laser annealing [J]. *Ceramics International*, 2014, 40(6): 8287-8292.
- [21] BAYATI M R, JOSHI S, MOLAEI R, *et al.* Ultrafast switching in wetting properties of TiO₂/YSZ/Si(001) epi-

- taxial heterostructures induced by laser irradiation [J]. *Journal of Applied Physics*, 2013, 113(6): 063706.
- [22] CHEN M F, LIN K M, HO Y S. Laser annealing process of ITO thin films using beam shaping technology [J]. *Optics and Lasers in Engineering*, 2012, 50(3): 491-495.
- [23] MOLAEI R, BAYATI M R, ALIPOUR H M, *et al.* Nanosecond laser switching of surface wettability and epitaxial integration of c-axis ZnO thin films with Si(111) substrates [J]. *Journal of Physics: Condensed Matter*, 2013, 26(1): 015004.
- [24] YANG Y H, YANG S S, CHOU K S. Performance improvements of IGZO and ZnO thin-film transistors by laser-irradiation treatment [J]. *Journal of the Society for Information Display*, 2011, 19(3): 247-252.
- [25] TSANG W M, WONG F L, FUNG M K, *et al.* Transparent conducting aluminum-doped zinc oxide thin film prepared by sol-gel process followed by laser irradiation treatment [J]. *Thin Solid Films*, 2008, 517(2): 891-895.
- [26] 邵景珍, 王玺, 胡红涛, 等. 氧化锌薄膜的准分子激光退火热效应模拟分析[J]. 激光与光电子学进展, 2017, 54(6): 061401.
- SHAO J Z, WANG X, HU H T, *et al.* Thermal effect simulation analysis on excimer laser annealing of zinc oxide thin films [J]. *Laser & Optoelectronics Progress*, 2017, 54(6): 061401. (in Chinese)
- [27] 李代林, 杨丹, 崔纪琨, 等. 连续激光辐照下的 TiO₂ 薄膜热传导性质[J]. 中国光学, 2019, 12(3): 628-637.
- LI D L, YANG D, CUI J K, *et al.* Heat conduction properties of TiO₂ films irradiated by a continuous laser [J]. *Chinese Optics*, 2019, 12(3): 628-637. (in Chinese)
- [28] STAMPFLI P, BENNEMANN K H. Dynamical theory of the laser-induced lattice instability of silicon [J]. *Physical Review B*, 1992, 46(17): 10686.
- [29] VON DER LINDE D, SOKOLOWSKI-TINTEN K, BIALKOWSKI J. Laser-solid interaction in the femtosecond time regime [J]. *Applied Surface Science*, 1997, 109-110: 1-10.
- [30] GOLDMAN J R, PRYBYLA J A. Ultrafast dynamics of laser-excited electron distributions in silicon [J]. *Physical Review Letters*, 1994, 72(9): 1364-1367.
- [31] 刘强. 高损伤阈值介质膜层的制备及其研究[D]. 成都: 四川大学, 2004.
- LIU Q. Preparation and research on dielectric films with high damage threshold [D]. Chengdu: Sichuan University, 2004. (in Chinese)
- [32] SUTTMANN O, MOALEM A, KLING R, *et al.* Drilling, cutting, welding, marking and microforming [M]//SUGIOKA K, MEUNIER M, PIQU A. *Laser Precision Microfabrication*. Berlin Heidelberg: Springer, 2010: 311-335.
- [33] MAJUMDAR J D, MANNA I. Introduction to laser assisted fabrication of materials [M]//MAJUMDAR J D, MANNA I. *Laser-Assisted Fabrication of Materials*. Berlin Heidelberg: Springer, 2013: 1-67.
- [34] BUERLE D. Material transformations, laser cleaning [M]//BUERLE D. *Laser Processing and Chemistry*. Berlin Heidelberg: Springer, 2011: 535-559.
- [35] PADMANABHAM G, SHANMUGARAJAN B. Laser-based joining of metallic and non-metallic materials [M]//MAJUMDAR J D, MANNA I. *Laser-Assisted Fabrication of Materials*. Berlin Heidelberg: Springer, 2013: 159-220.
- [36] VOUTSAS A T, MARMORSTEIN A M, SOLANKI R. The impact of annealing ambient on the performance of excimer-laser-annealed polysilicon thin-film transistors [J]. *Journal of the Electrochemical Society*, 1999, 146(9): 3500.
- [37] SUGA K, CHIDA M, MISHIMA Y, *et al.* The effect of a laser annealing ambient on the morphology and TFT performance of poly-Si films [J]. *SID Symposium Digest of Technical Papers*, 2000, 31(1): 534-537.
- [38] CRACIUN V, BOYD I W, CRACIUN D, *et al.* Vacuum ultraviolet annealing of hydroxyapatite films grown by pulsed laser deposition [J]. *Journal of Applied Physics*, 1999, 85(12): 8410-8414.
- [39] MARINE W, PATRONE L, LUKYANCHUK B, *et al.* Strategy of nanocluster and nanostructure synthesis by conventional pulsed laser ablation [J]. *Applied Surface Science*, 2000, 154-155: 345-352.
- [40] MARMORSTEIN A, VOUTSAS A T, SOLANKI R. A systematic study and optimization of parameters affecting grain size and surface roughness in excimer laser annealed polysilicon thin films [J]. *Journal of*

- Applied Physics*, 1997, 82(9): 4303-4309.
- [41] PEREIRA A, CROS A, DELAPORTE P, *et al.* Surface nanostructuring of metals by laser irradiation; effects of pulse duration, wavelength and gas atmosphere [J]. *Applied Physics A*, 2004, 79(4/6): 1433-1437.
- [42] KAMIYA T, NOMURA K, HOSONO H. Present status of amorphous In-Ga-Zn-O thin-film transistors [J]. *Science and Technology of Advanced Materials*, 2010, 11(4): 044305.
- [43] JEONG J H, YANG H W, PARK J S, *et al.* Origin of subthreshold swing improvement in amorphous indium gallium zinc oxide transistors [J]. *Electrochemical and Solid State Letters*, 2008, 11(6): H157-H159.
- [44] KIMURA M, KAMIYA T, NAKANISHI T, *et al.* Intrinsic carrier mobility in amorphous In-Ga-Zn-O thin-film transistors determined by combined field-effect technique [J]. *Applied Physics Letters*, 2010, 96(26): 262105.
- [45] HUANG H Y, WANG S J, WU C H, *et al.* Improvement of electrical performance of InGaZnO/HfSiO TFTs with 248-nm excimer laser annealing [J]. *Electronic Materials Letters*, 2014, 10(5): 899-902.
- [46] CHEN C H, CHEN G X, YANG H H, *et al.* Solution-processed metal oxide arrays using femtosecond laser ablation and annealing for thin-film transistors [J]. *Journal of Materials Chemistry C*, 2017, 5(36): 9273-9280.
- [47] CHEN C H, YANG H H, YANG Q, *et al.* Low-temperature solution-processed flexible metal oxide thin-film transistors via laser annealing [J]. *Journal of Physics D: Applied Physics*, 2019, 52(38): 385105.
- [48] BERMUNDO J P S, ISHIKAWA Y, FUJII M N, *et al.* H and Au diffusion in high mobility a-InGaZnO thin-film transistors via low temperature KrF excimer laser annealing [J]. *Applied Physics Letters*, 2017, 110(13): 133503.
- [49] SHARMA S D, SINGH D, SAINI K K, *et al.* Sol-gel-derived super-hydrophilic nickel doped TiO₂ film as active photo-catalyst [J]. *Applied Catalysis A: General*, 2006, 314(1): 40-46.
- [50] BAYATI M R, JOSHI S, MOLAEI R, *et al.* Ultrafast switching in wetting properties of TiO₂/YSZ/Si(001) epitaxial heterostructures induced by laser irradiation [J]. *Journal of Applied Physics*, 2013, 113(6): 063706.
- [51] 郭德成, 蒋晓东, 黄进, 等. 紫外脉冲激光退火发次对 KDP 晶体抗损伤性能的影响 [J]. *物理学报*, 2013, 62(14): 147803.
- GUO D C, JIANG X D, HUANG J, *et al.* Effect of raster scan number on damage resistance of KDP crystal irradiated by ultraviolet pulse laser [J]. *Acta Physica Sinica*, 2013, 62(14): 147803. (in Chinese)
- [52] MEZHENNY S, MAKSYMОВYCH P, THOMPSON T L, *et al.* STM studies of defect production on the TiO₂ (110)-(1×1) and TiO₂ (110)-(1×2) surfaces induced by UV irradiation [J]. *Chemical Physics Letters*, 2003, 369(1/2): 152-158.
- [53] FERNANDES R M, AP E F. Subject index [J]. *Applied Surface Science*, 2000, 168(1/4): 359-372.
- [54] CRACIUN V, CRACIUN D, CHEN Z, *et al.* Room temperature growth of indium tin oxide thin films by ultraviolet-assisted pulsed laser deposition [J]. *Applied Surface Science*, 2000, 168(1/4): 118-122.
- [55] DENG Y X, LIU X Z, YUAN W J, *et al.* Effect of deep UV laser treatment on silicon-doped Tin oxide thin film [J]. *Journal of the Society for Information Display*, 2020, 28(2): 194-203.
- [56] KIM M G, KIM H S, HA Y G, *et al.* High-performance solution-processed amorphous zinc indium tin oxide thin-film transistors [J]. *Journal of the American Chemical Society*, 2010, 132(30): 10352-10364.
- [57] JEONG S, HA Y G, MOON J, *et al.* Role of gallium doping in dramatically lowering amorphous-oxide processing temperatures for solution-derived indium zinc oxide thin-film transistors [J]. *Advanced Materials*, 2010, 22(12): 1346-1350.
- [58] DELLIS S, ISAKOV I, KALFAGIANNIS N, *et al.* Rapid laser-induced photochemical conversion of sol-gel precursors to In₂O₃ layers and their application in thin-film transistors [J]. *Journal of Materials Chemistry C*, 2017, 5(15): 3673-3677.
- [59] LIN Y H, LIU Y S, LIN Y C, *et al.* Decoupling free-carriers contributions from oxygen-vacancy and cation-substitution in extrinsic conducting oxides [J]. *Journal of Applied Physics*, 2013, 113(3): 1471-1477.
- [60] SOCRATOUS J, BANGER K K, VAYNZOF Y, *et al.* Electronic structure of low-temperature solution-processed amorphous metal oxide semiconductors for thin-film transistor applications [J]. *Advanced Functional Materials*, 2015, 25(12): 1873-1885.

- [61] HUANG H, HU H L, ZHU J G, *et al.* Inkjet-printed In-Ga-Zn oxide thin-film transistors with laser spike annealing [J]. *Journal of Electronic Materials*, 2017, 46(7): 4497-4502.
- [62] HWANG S, LEE J H, WOO C H, *et al.* Effect of annealing temperature on the electrical performances of solution-processed InGaZnO thin film transistors [J]. *Thin Solid Films*, 2011, 519(15): 5146-5149.
- [63] HUANG X M, WU C F, LU H, *et al.* Large-swing a-IGZO inverter with a depletion load induced by laser annealing [J]. *IEEE Electron Device Letters*, 2014, 35(10): 1034-1036.
- [64] FUJII M N, ISHIKAWA Y, ISHIHARA R, *et al.* Nano-crystallization in ZnO-doped In₂O₃ thin films via excimer laser annealing for thin-film transistors [J]. *AIP Advances*, 2016, 6(6): 065216.
- [65] FUJII M, ISHIKAWA Y, ISHIHARA R, *et al.* Low temperature high-mobility InZnO thin-film transistors fabricated by excimer laser annealing [J]. *Applied Physics Letters*, 2013, 102(12): 122107.
- [66] EL HAMALI S O, CRANTON W M, KALFAGIANNIS N, *et al.* Enhanced electrical and optical properties of room temperature deposited aluminium doped zinc oxide (AZO) thin films by excimer laser annealing [J]. *Optics and Lasers in Engineering*, 2016, 80: 45-51.
- [67] NIAN Q, ZHANG M Y, SCHWARTZ B D, *et al.* Ultraviolet laser crystallized ZnO : Al films on sapphire with high Hall mobility for simultaneous enhancement of conductivity and transparency [J]. *Applied Physics Letters*, 2014, 104(20): 201907.
- [68] HAGENDORFER H, LIENAU K, NISHIWAKI S, *et al.* Highly transparent and conductive ZnO : Al thin films from a low temperature aqueous solution approach [J]. *Advanced Materials*, 2014, 26(4): 632-636.
- [69] TAKECHI K, NAKATA M, EGUCHI T, *et al.* Comparison of ultraviolet photo-field effects between hydrogenated amorphous silicon and amorphous InGaZnO₄ thin-film transistors [J]. *Japanese Journal of Applied Physics*, 2009, 48(1R): 010203.
- [70] OH H, YOON S M, RYU M K, *et al.* Transition of dominant instability mechanism depending on negative gate bias under illumination in amorphous In-Ga-Zn-O thin film transistor [J]. *Applied Physics Letters*, 2011, 98(3): 033504.
- [71] MIGLIORATO P, DELWAR HOSSAIN CHOWDHURY M, GWANG UM J, *et al.* Light/negative bias stress instabilities in indium gallium zinc oxide thin film transistors explained by creation of a double donor [J]. *Applied Physics Letters*, 2012, 101(12): 123502.
- [72] JIN S, LEE S, LEE E, *et al.* P-154L: late-news poster: stability enhancement of oxide TFTs by blue laser annealing [J]. *SID Symposium Digest of Technical Papers*, 2015, 46(1): 1228-1230.
- [73] OLORUNYOLEMI T, BIRNBOIM A, CARMEL Y, *et al.* Thermal conductivity of zinc oxide: from green to sintered state [J]. *Journal of the American Ceramic Society*, 2002, 85(5): 1249-1253.
- [74] LUCKYANOVA M N, CHEN D, MA W, *et al.* Thermal conductivity control by oxygen defect concentration modification in reducible oxides: the case of Pr_{0.1}Ce_{0.9}O_{2.8} thin films [J]. *Applied Physics Letters*, 2014, 104(6): 061911.
- [75] CHUNG C Y, ZHU B, AST D G, *et al.* High mobility amorphous InGaZnO₄ thin film transistors formed by CO₂ laser spike annealing [J]. *Applied Physics Letters*, 2015, 106(12): 123506.
- [76] YANG Y H, YANG S S, CHOU K S. Laser-irradiated zinc oxide thin-film transistors fabricated by solution processing [J]. *Journal of the Society for Information Display*, 2010, 18(10): 745-748.
- [77] NAKATA M, TAKECHI K, YAMAGUCHI S, *et al.* Effects of excimer laser annealing on InGaZnO₄ thin-film transistors having different active-layer thicknesses compared with those on polycrystalline silicon [J]. *Japanese Journal of Applied Physics*, 2009, 48(11R): 115505.
- [78] TSUCHIYA T, YAMAGUCHI F, MORIMOTO I, *et al.* Microstructure control of low-resistivity tin-doped indium oxide films grown by photoreaction of nanoparticles using a KrF excimer laser at room temperature [J]. *Applied Physics A*, 2010, 99(4): 745-749.
- [79] NAKATA M, TAKECHI K, AZUMA K, *et al.* Improvement of InGaZnO₄ thin film transistors characteristics utilizing excimer laser annealing [J]. *Applied Physics Express*, 2009, 2(2): 021102.
- [80] PARSHINA L S, NOVODVORSKY O A, KHRAMOVA O D, *et al.* Laser annealing of thin ITO films on flexible organic substrates [J]. *Semiconductors*, 2019, 53(2): 160-164.

- [81] NAKATA M, TAKECHI K, EGUCHI T, *et al.* Flexible high-performance amorphous InGaZnO₄ thin-film transistors utilizing excimer laser annealing [J]. *Japanese Journal of Applied Physics*, 2009, 48(8R): 081607.
- [82] HAMANO F, MIZUTANI A, IMOKAWA K, *et al.* Surface flattening of poly-Si thin films by laser annealing and electrical properties of LTPS-TFTs [C]//*Proceedings of SPIE 11268, Laser-based Micro- and Nanoprocessing XIV*. San Francisco: SPIE, 2020: 11268.

作者简介:



宁洪龙(1971—),男,湖南株洲人,博士,教授,2004年于清华大学获博士学位,主要从事新型信息显示材料与器件系统集成研究。E-mail: ninghl@scut.edu.cn



姚日晖(1981—),男,湖南涟源人,博士,副教授,2008年于中山大学获得博士学位,主要从事光电材料与器件领域的教学、科研工作。E-mail: yaorihui@scut.edu.cn