Towards high performance a-IGZO thin film transistors and circuits

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Outline

- Introduction: why a-IGZO? and facing problems
- Selected results of a-IGZO TFTs and circuits:

1. carrier transport, interface, and reliability physics
2. several ways to improve device performance

- Summary

Market and industrial needs

大陆电子产品制造企业，一度饱受“缺屏之痛”，所需液晶面板很大比例依靠进口。海关统计数据显示，即使在2013年，大陆液晶面板进口额依然达到500亿美元以上，仅次于集成电路（2322亿美元）、石油（2196亿美元）和铁矿石（1057亿美元），排在第四位。

Future development needs

- 随着现在显示器向高分辨、低功耗、高速、大尺寸、3D的快速发展，对TFT的性能要求越来越高，要求TFT具有迁移率高、电流开关比大、开口率高、阈值电压漂移小、制备工艺相对廉价、容易大面积制备和集成的特点。
- System on panel (SOP)

Snapshot from “Minority report”

a-IGZO TFT的优势

a-Si:H TFT的局限：

- 具有较低的迁移率(<1cm^2/Vs)
- 低的光学透过率 (E_g~1.7 eV)
- 光稳定性差等缺点限制了其未来应用.

LTPS TFT的局限：

- 制作成本高，与a-Si TFT工艺兼容性低
- 均匀性差，实现大尺寸屏幕难度大

a-IGZO TFT的潜在优势：

1. 较高的沟道电子迁移率
2. 高的光学透过率 (E_g>3.0 eV)
3. 低的漏电流，低功耗
4. 低的制备温度，低成本

What is a-IGZO?

In_2O_3: Ga_2O_3: ZnO (IGZO)

Stable amorphous structure

→ Zn^{2+} as amorphous structure stability

tetrahedral coordination

High electron mobility

→ In^{3+} as electron pathway former

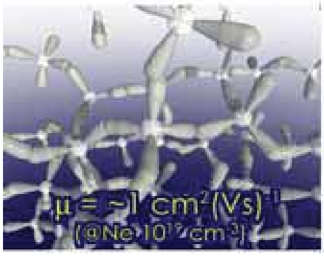
$(4d)^{10}(5s)^0$

Excellent controllability of carrier density

→ Ga^{3+} as carrier generation suppresser

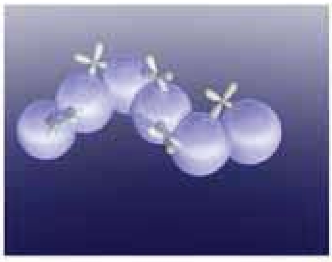
high ionic field strength

Amorphous state？



共价半导体 (如：a-Si)

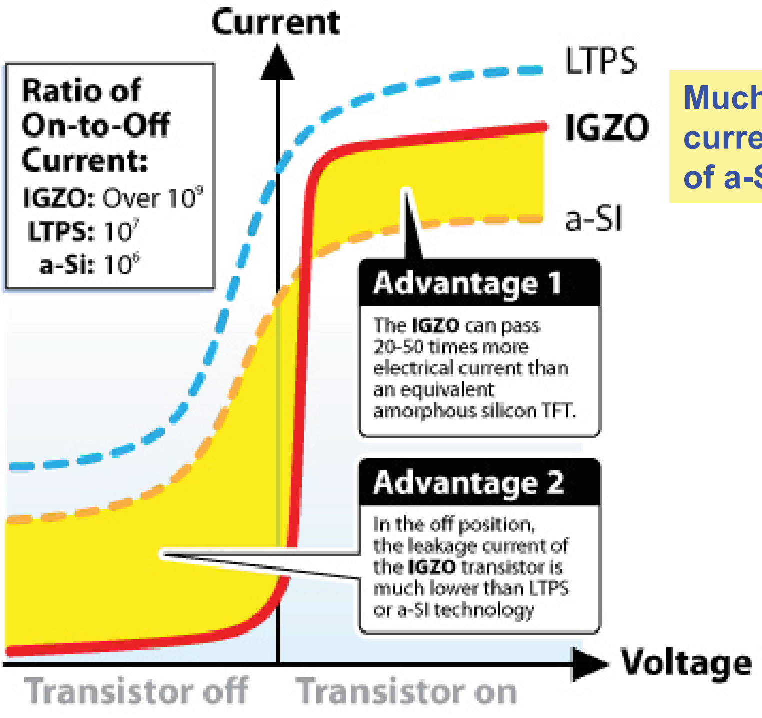
VS



离子半导体 (如：a-IGZO)

a-IGZO中金属的ns轨道交叠程度受晶格无序性的影响较小；因此，即使是非晶材料，仍然可以具有较高的迁移率。

Basic transfer I-V characteristics of IGZO TFTs



Ratio of On-to-Off Current:
IGZO: Over 10^9
LTPS: 10^7
a-Si: 10^6

Advantage 1

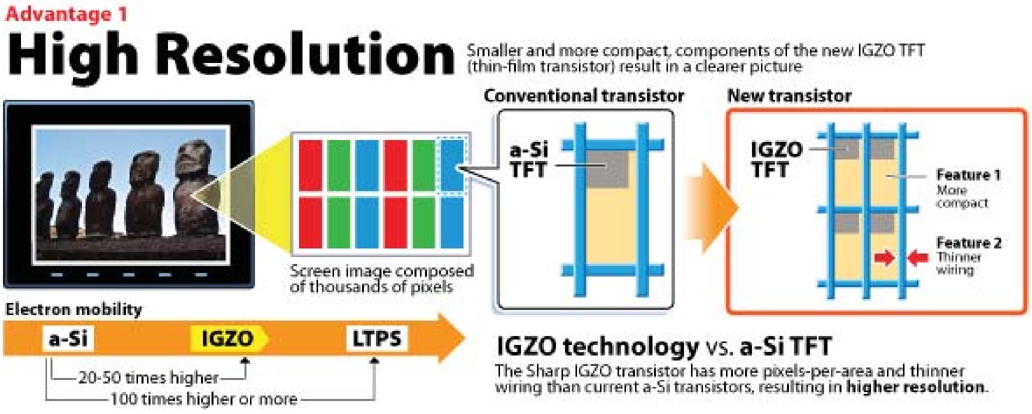
The **IGZO** can pass 20-50 times more electrical current than an equivalent amorphous silicon TFT.

Advantage 2

In the off position, the leakage current of the **IGZO** transistor is much lower than LTPS or a-SI technology

Much higher on-current than that of a-Si TFTs

Extremely low leakage



Advantage 1

High Resolution

Smaller and more compact, components of the new IGZO TFT (thin-film transistor) result in a clearer picture

Screen image composed of thousands of pixels

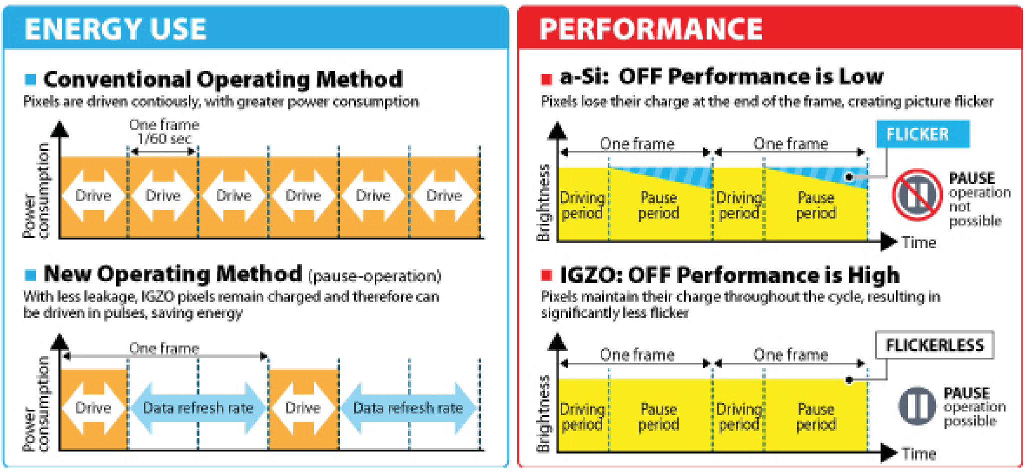
IGZO technology vs. **a-Si TFT**

The Sharp IGZO transistor has more pixels-per-area and thinner wiring than current a-Si transistors, resulting in **higher resolution**.

- **Since the electron mobility of IGZO is 30-50 times higher than that of a-Si, the on-current of IGZO TFTs is considerably higher. As a result, the IGZO transistor can be made smaller and the width of the signal line narrower.**
- **For LCD panels, the higher the resolution, the more difficult it is to achieve larger aperture ratio. But the IGZO technology enables high resolution while keeping aperture ratio large.**
- **Large aperture ratio is essential to retain brightness, or the body of the transistor would block too much light. It means less back-lighting is needed.**

Advantage 2

Less Power Consumption



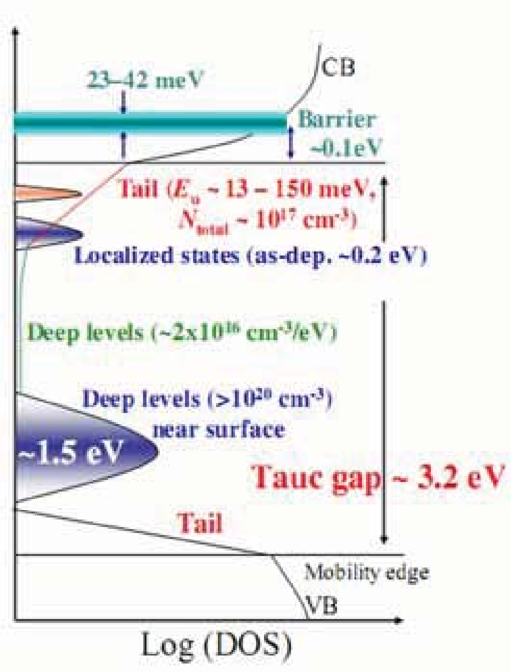
Most important advantage in my view!

- Currently, a panel needs to be refreshed or "driven" continually because leakage current causes the cell to discharge.
- Due to their ultra-low leakage, IGZO panels can retain their active state longer. It's then possible to save significant power by skipping drive cycles.

A comparative study reported in 2012

- Panel driving power is reduced by 62%;
- LED backlighting power is reduced by 50%;
- Approximately 56% less power is used in standard operation with an IGZO LCD as compared to an a-Si LCD. This will benefit hand-held and other battery-powered devices by dramatically extending battery life.

Facing problems in a-IGZO TFT development



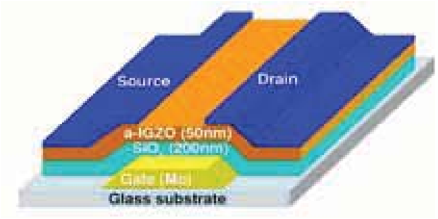
There are tons of defects in a-IGZO; the interface quality is also hard to control.

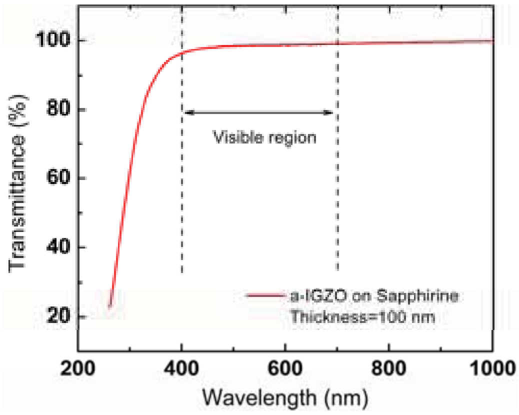
1. **Reliability is the biggest issue**, including performance shift under bias stress, under illumination, and under environmental aging.
2. **Further improving carrier mobility**. Can a-IGZO compete with LTPS for driving AMOLED?
3. **Flexible and fully transparent**

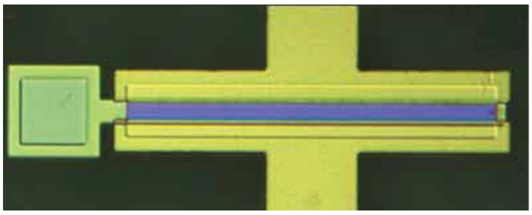
Development of a-IGZO TFTs at NJU

a-IGZO film deposition and device fabrication

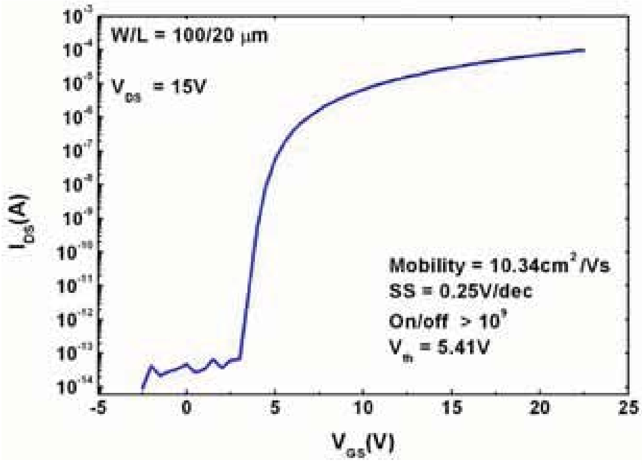
溅射采用的 InGaZnO 靶材原子比为 In:Ga:Zn为 2:2:1，所获得的a-IGZO薄膜在可见光波段平均具有98%以上的透过率。

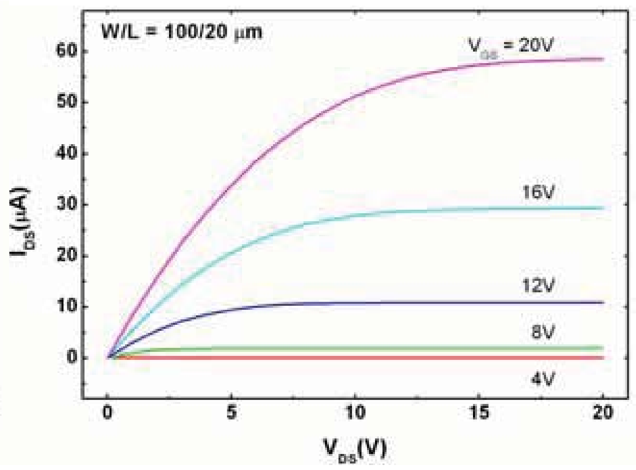






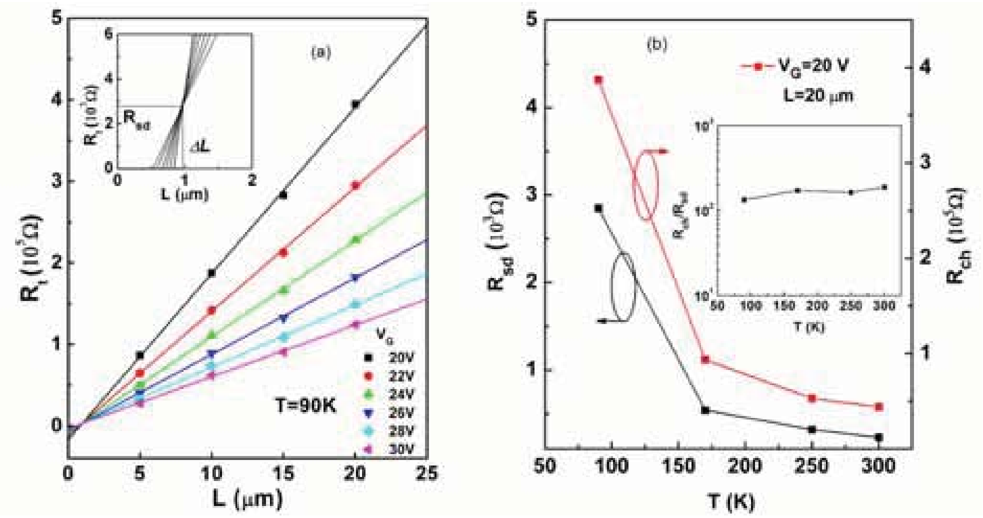
Typical DC parameters of the fabricated a-IGZO TFTs





- field effect mobility: 8-15 cm^2/Vs
- sub-threshold swing: 0.2-0.5 V/dec
- on/off current ratio： >10^9
- Threshold voltage：tunable and process dependent
- off-state leakage：<1 pA

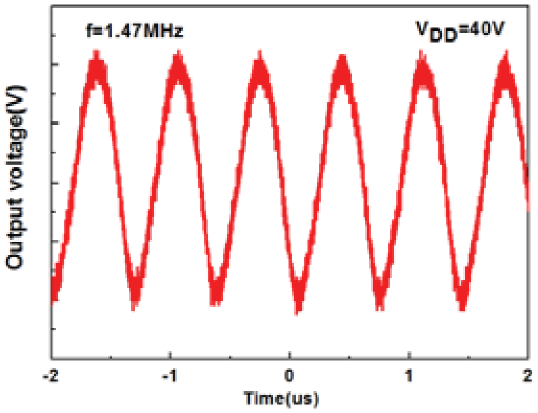
Low contact resistance of the a-IGZO TFTs

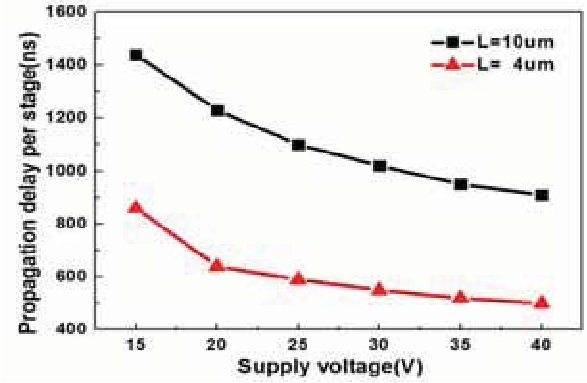


$$R_{\text{tot}} = \frac{V_{ds}}{I_{ds}} = R_{sd} + \frac{L - \Delta L}{\mu_{eff} C_{ox} W (V_{gs} - V_{th})}$$

Based on TLM measurement, the resistance of the Ti/Au-based source/drain contact is less than 1/100 of the channel resistance in the studied temperature range.

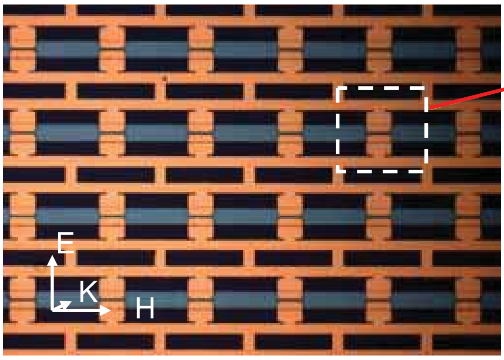
Seven-stage a-IGZO ring oscillator with Oscillation frequency over 1 MHz

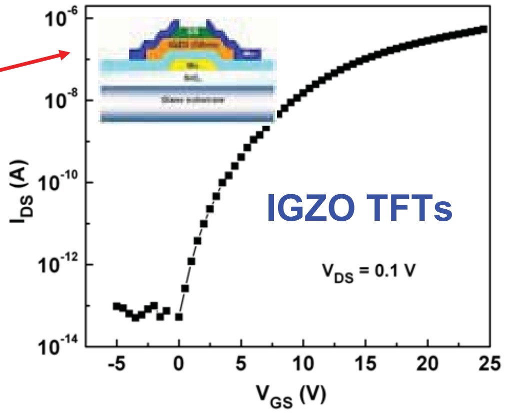


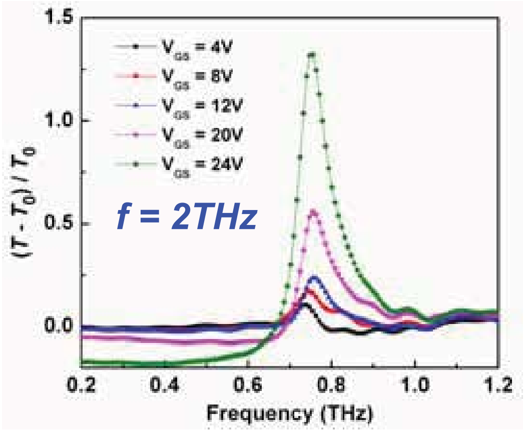


- **Ring oscillator is often used as a test vehicle to check how fast the device can operate in an integrated circuit.**
- **Comparatively, the first commercial CPU (Intel 4004) in history only has an operation frequency of 108 KHz.**

THz modulator with a-IGZO TFT-based metamaterial structure



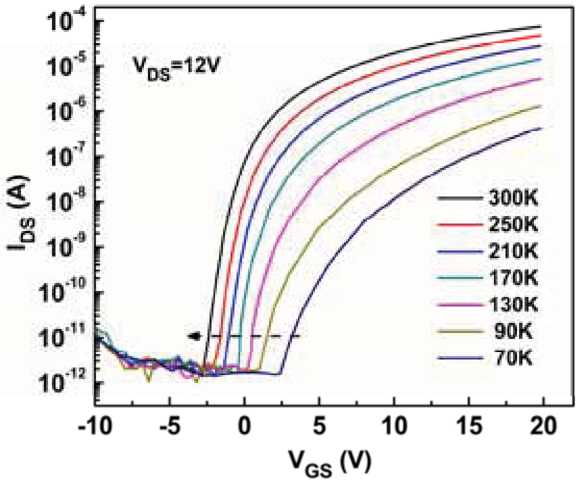


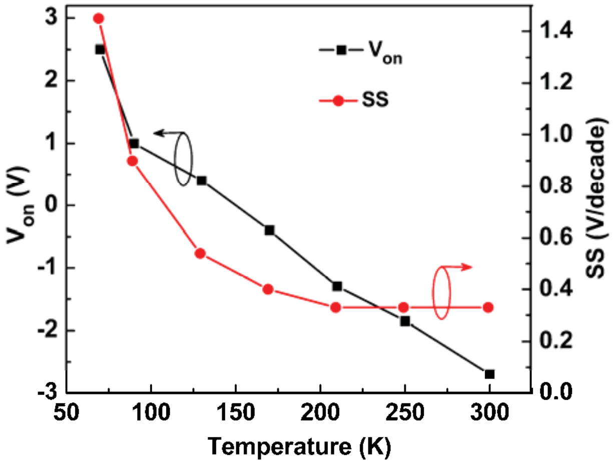


- **If the TFTs are all in off-state, metamaterial-based THz band-stop filter is formed; If the TFTs are in on-state, the filter is de-assembled.**
- **Clear modulation of 2 THz terahertz wave is realized.**

Carrier transport mechanism of a-IGZO TFTs

Temperature dependent I-V characterization

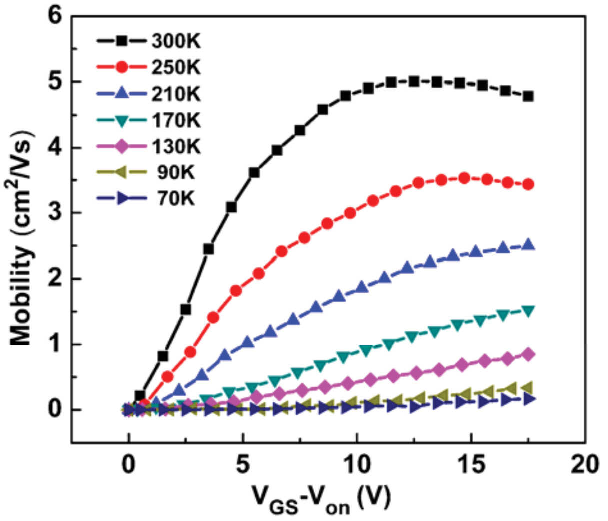


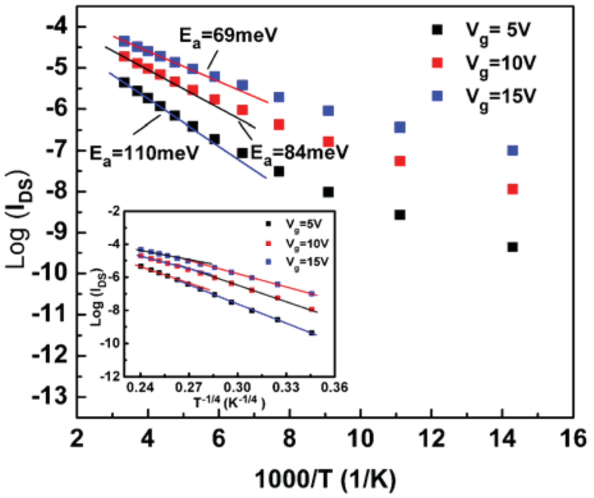


$$\Delta SS = \frac{\Delta N_t \ln(10)kT}{C_i}$$

The decrease of SS as a function of temperature indicates that the filling status of localized trapping states is changed. suggesting that the carrier transport properties of the TFT could change considerably under different temperature and biasing conditions

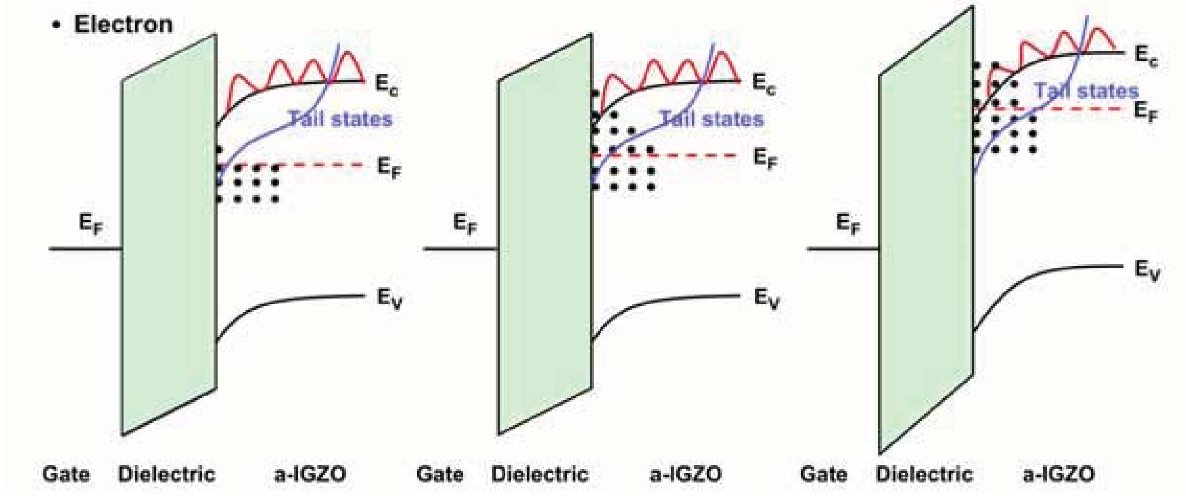
Temperature dependent mobility and conductance analysis





- **The large variation and complex variation trends of μ_{FE} again suggest that the carrier transport process within the TFT is likely governed by different transport mechanisms at different operation conditions.**
- **The temperature dependent channel conductance is tested by various transport models.**

Carrier transport models in a-IGZO TFTs

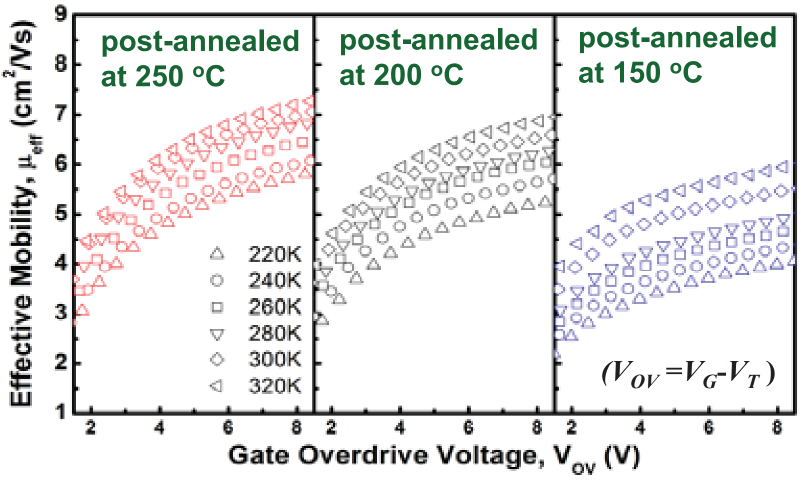


(a) Low T, low V_g (b) high T, relative low V_g (c) high T, high V_g

- In low temperature range, the dominant carrier transport mechanism is hopping between localized band-tail states; As temperature increases, multiple trapping and release plays a role in the whole carrier transport process; in high gate bias range when the Fermi level moves above the mobility edge, band transport with percolation conduction starts to dominate.

Solid-state Electronics, 86, 41, 2013

Mobility degradation mechanism in band transport region



$$\mu_{eff}^{-1} = \mu_C^{-1} + \mu_{PH}^{-1} + \mu_{SR}^{-1} = \kappa T^{-1} + \lambda T^{1.75} + \eta$$

- Coulomb scattering weakens at higher carrier density (proportional to V_{OV}) due to the enhanced screening effect, while phonon scattering follows the opposite trend because of the increased electron-phonon interaction.
- Coulomb scattering would also reduce while phonon scattering would strengthen at higher temperatures

→ **Coulomb scattering**

Interface properties and interface improving technique of a-IGZO TFTs

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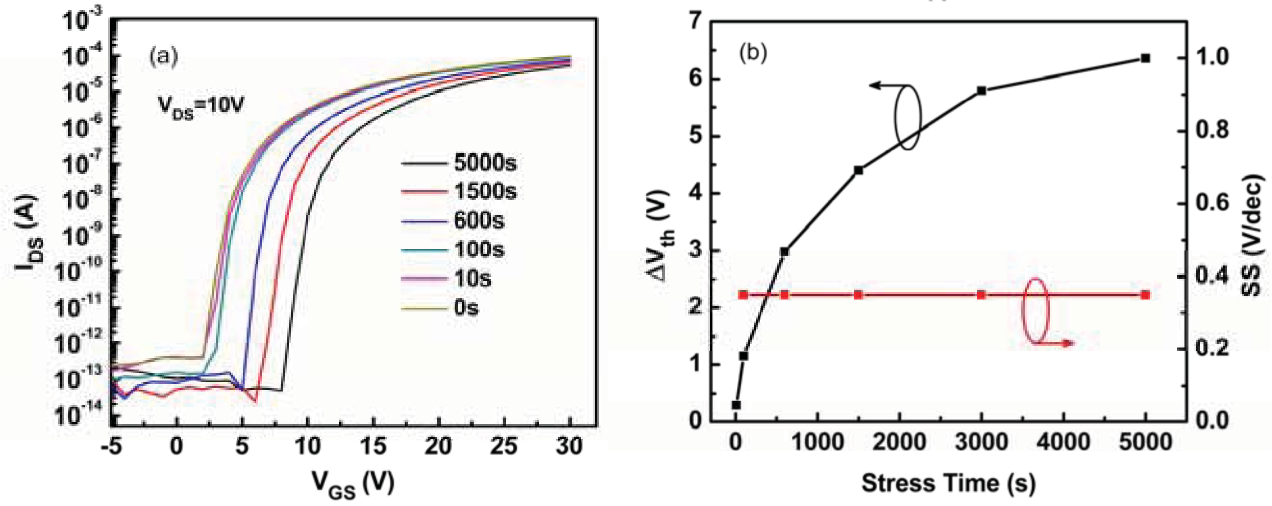
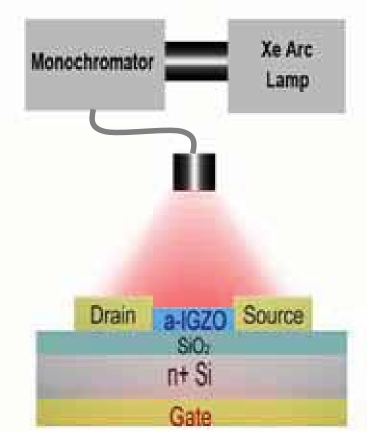
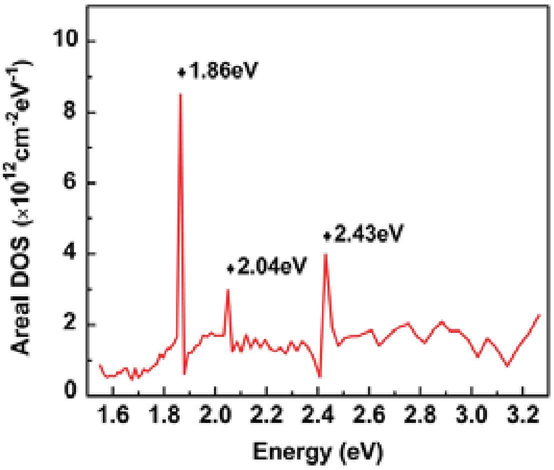
Interface-related reliability issue of a-IGZO TFTs

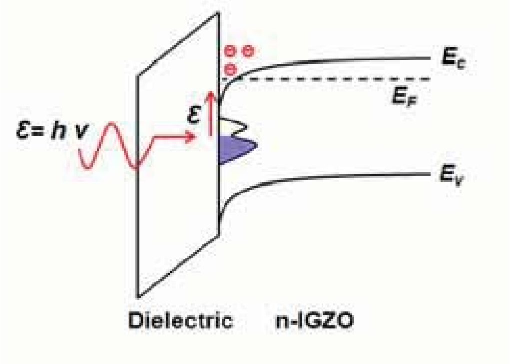


- Under positive gate bias stress, V_{th} shifts towards positive direction due to carrier trapping at interface states.
- Since there is no change for SS and μ_{FE} in our case, new defect generation mechanism could be excluded.

Photo-excited charge-collection spectroscopy (PECCS)

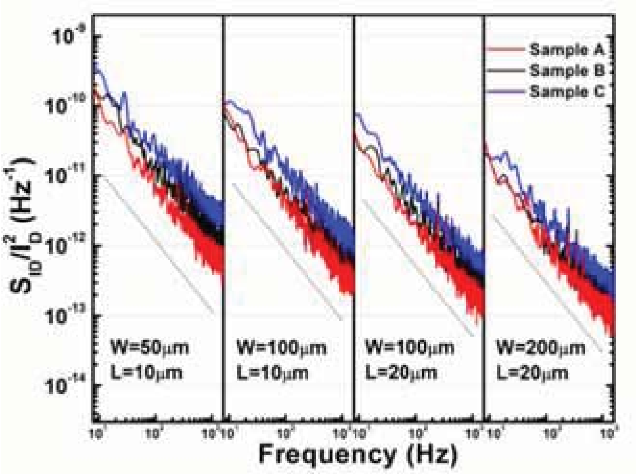


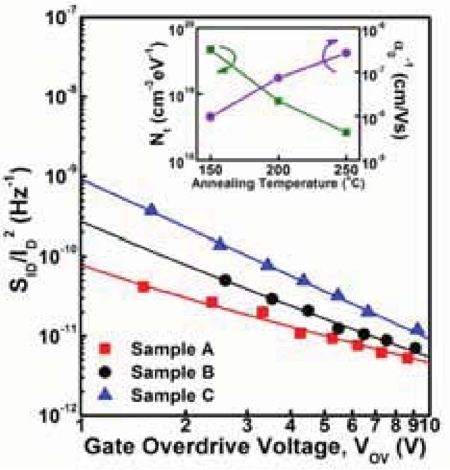




- High density interfacial trap states of more than ~10^{12} $cm^{-2}eV^{-1}$ at certain energy levels is revealed by PECCS.
- The DOS peaks matched well with the theoretical deep electron trap energy levels in bulk ZnO.

"border trap" information revealed by 1/f noise analysis

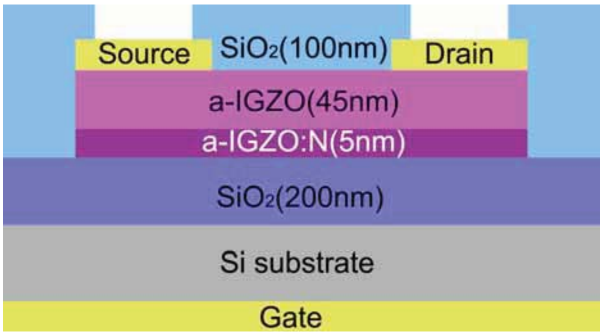


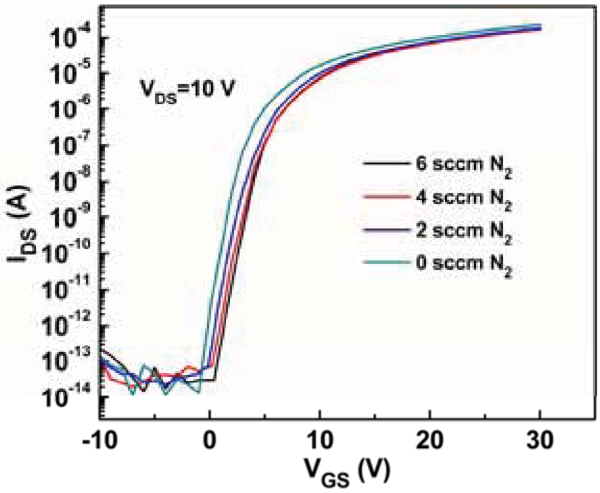


Sample A, B and C are post-annealed at 250, 200, and 150 °C for 1 h, respectively.

- The extracted "border trap" density within the range of 14~19 Å of the gate oxide ranges from 10^{18} to 10^{20} $cm^{-3}eV^{-1}$.
- The LFN results suggest that annealing at higher temperature has a more remarkable effect on removing "border traps" than traps closer to the channel/dielectric interface.

Enhanced bias stress stability of a-IGZO TFTs by inserting an ultra-thin InGaZnO:N interfacial layer

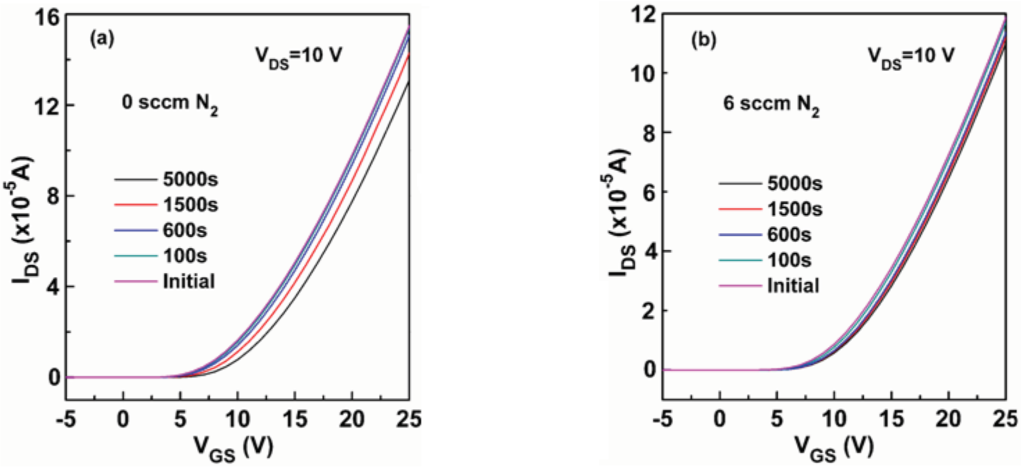




- **During the InGaZnO:N sputtering deposition, the Ar and O_2 flow rates are fixed at 36 sccm and 6 sccm respectively, while the N_2 flow rate is selected to set between 0 and 6 sccm.**

Appl. Phys. Lett. 102, 193505, 2013

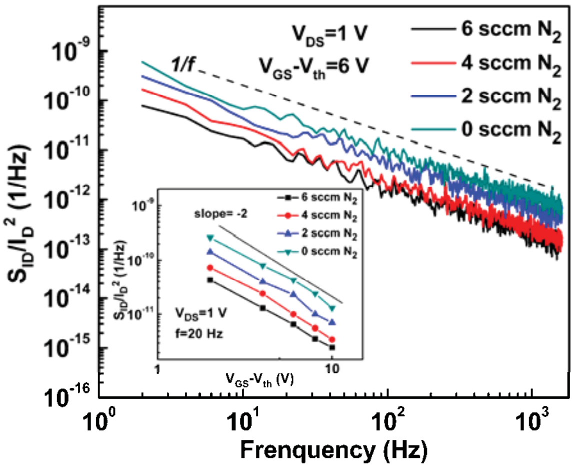
The TFT is stressed at a high gate voltage of 20 V for a total time up to 5000 s while keeping both its source and drain electrodes grounded.



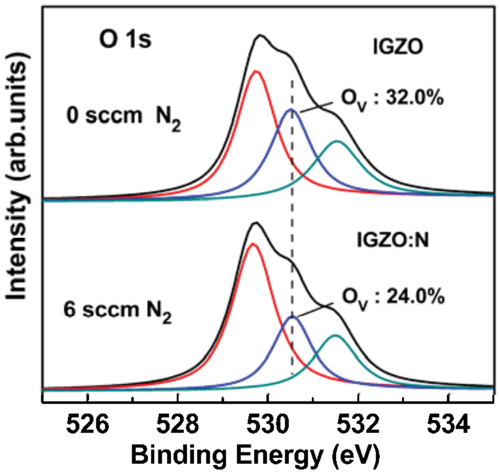
N_2 (sccm)	V_{th} (V)	μ_{FE} (cm²/Vs)	SS (V/dec)	$I_{on/off}$	ΔV_{th} (V)
0	3.5	8.6	0.53	$>10^9$	2.2
2	4.5	8.5	0.53	$>10^9$	1.1
4	5.0	8.4	0.55	$>10^9$	0.8
6	5.2	8.6	0.55	$>10^9$	0.7

The new device shows enhanced bias stress stability with significantly reduced threshold voltage drift under positive gate bias stress.

LFN analysis

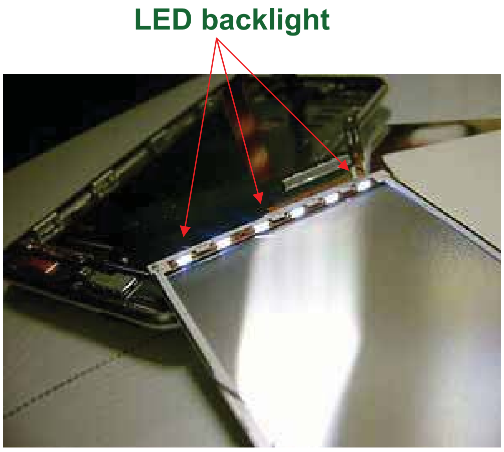


XPS analysis



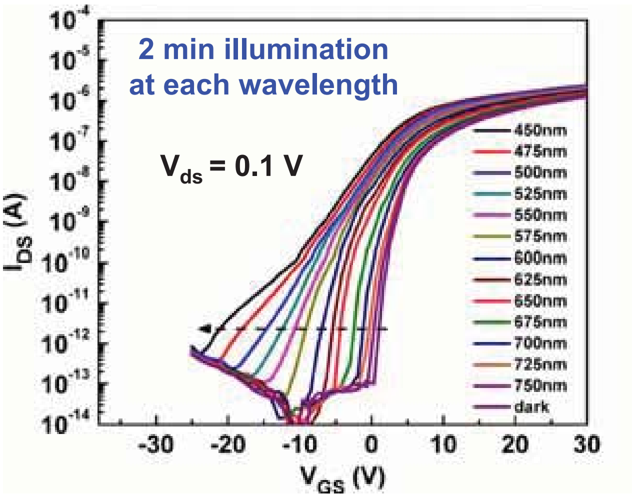
- Low-frequency noise measurement indicates that the interface quality of the a-IGZO TFTs is improved, which agrees with the enhanced bias stress stability.
- Based on XPS analysis, the concentration of oxygen vacancies within the a-IGZO:N layer is suppressed due to the formation of N-Ga bonds, which may explain the decrease of interface trap states upon nitrogen doping.

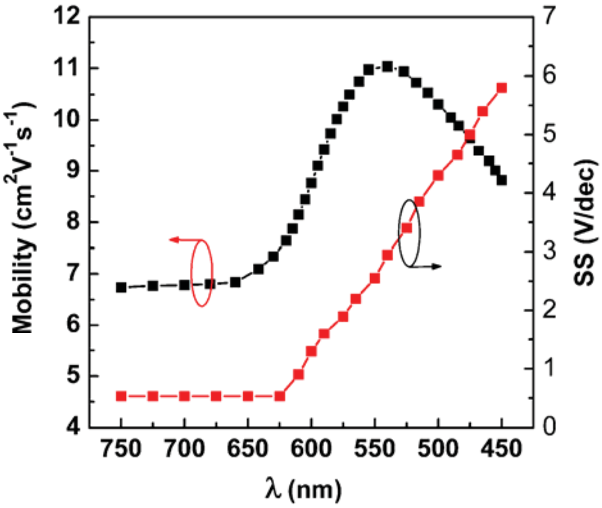
Performance shift of a-IGZO TFTs under illumination



- Because the TFTs are inevitably exposed to visible light emitted by the underlying backlight unit in AMLCD panels or the self-emitting radiation in AMOLED panels, the susceptibility of oxide TFTs with respect to illumination must be minimized.
- The instability of a-IGZO TFTs under NBIS has been reported to be induced by two main mechanisms: photo generation of ionized oxygen vacancies and trapping of photogenerated hole carriers at the channel/insulator interface.

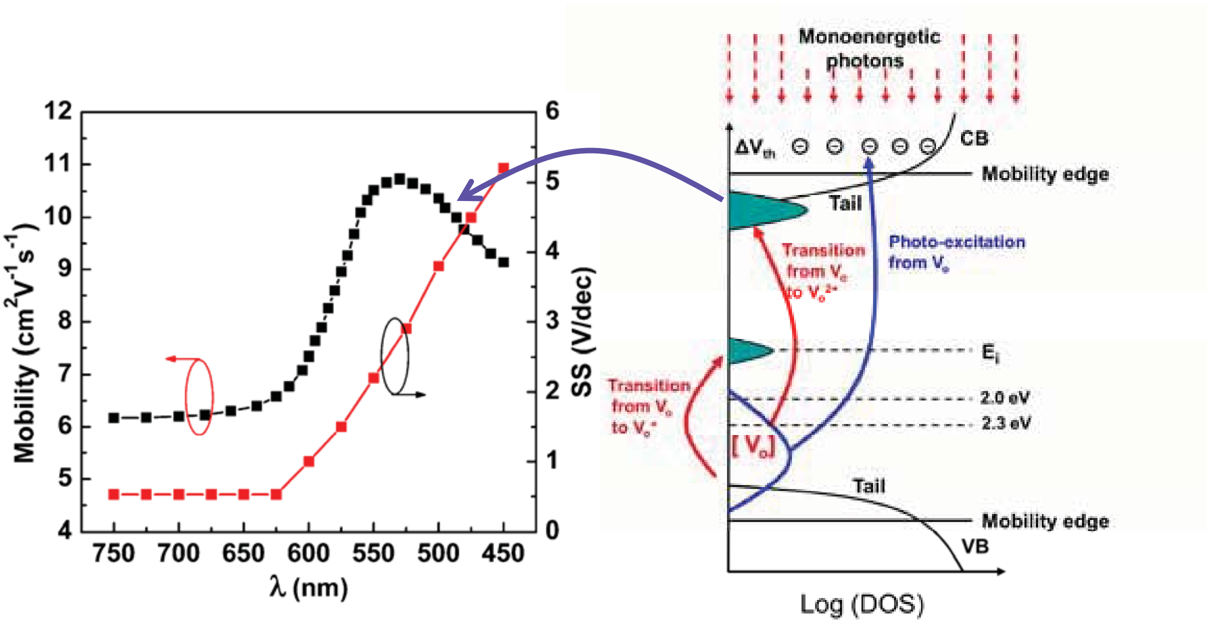
Electrical instability of a-IGZO TFTs thin film under monochromatic light illumination





- An increase of the SS is observed when the illumination wavelength is below 625 nm (~2.0 eV), The SS degradation is accompanied by a simultaneous increase of μ_{FE}) of the TFT, which then decreases at even shorter wavelength beyond 540 nm (~2.3 eV).
- However, the above variation can recover after a few minutes under dark.

The purposed physical model for performance degradation

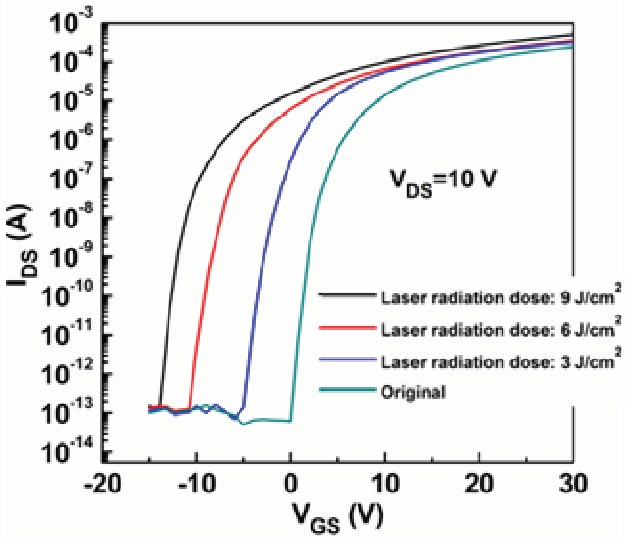


The variation of SS and μ $_{FE}$ is explained by a physical model based on generation of singly ionized Vo+ and double ionized Vo2+ within the a-IGZO active layer by high energy photons, which would form trap states near the mid-gap and the conduction band edge respectively.

Appl. Phys. Lett. 100, 243505, 2012

How to utilize the light-induced instability ?

— V_{th} modulation by UV laser treatment

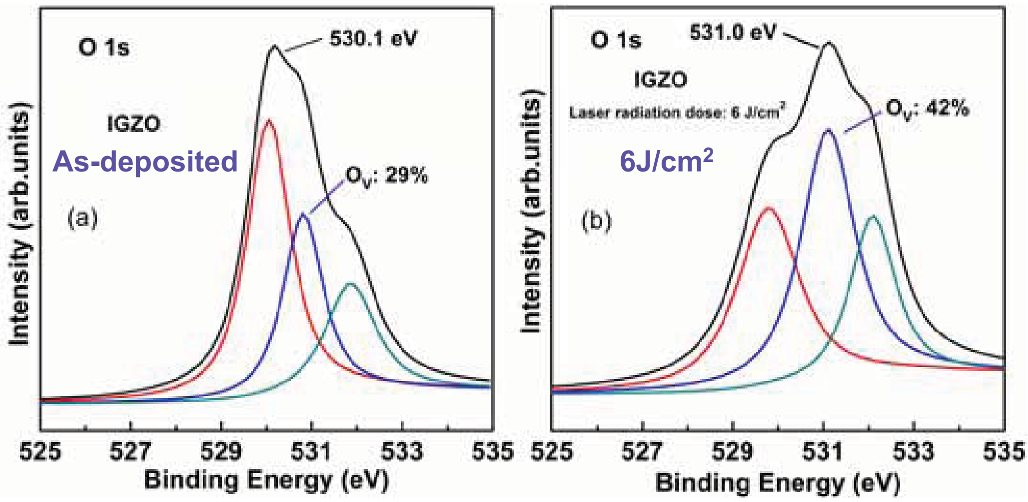


Laser radiation dose (J/cm^2)	V_{th} (V)	μ_{FE} (cm^2/Vs)	SS (V/dec)	$I_{on/off}$
0	5.0	10.0	0.37	>10^9
3	0.0	11.2	0.37	>10^9
6	-4.0	11.8	0.37	>10^9
9	-7.0	12.5	0.37	>10^9

Annealing condition: a 325 nm HeCd laser beam is reduced into a ~10 um-diameter laser spot with calibrated power density of ~200 mW/cm^2.

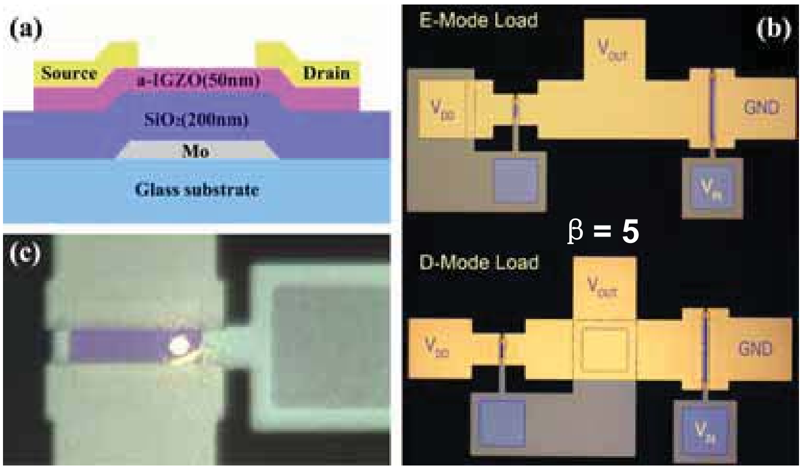
- By applying a special UV laser annealing technique, the V_{th} of the load TFT could be tuned from positive to negative gate voltage, changing a E-mode TFT into a D-mode TFT.
- This effect is permanent !

XPS analysis of the UV laser annealed a-IGZO films



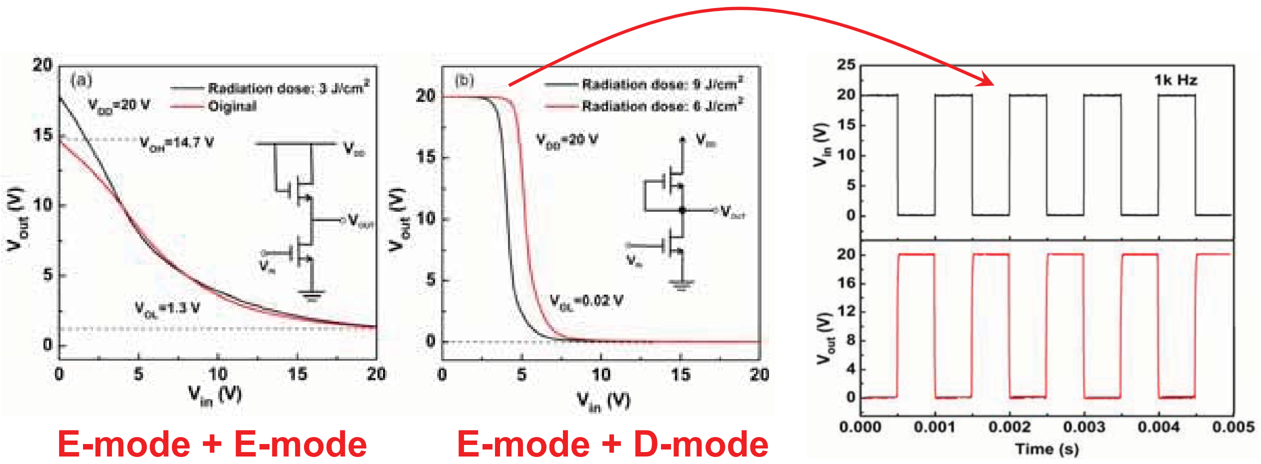
- Based on XPS analyses, the negative V_{th} shift can be attributed to the increase of oxygen vacancy concentration within the device channel upon laser annealing.
- The increase of oxygen vacancies is likely caused by breaking the weak chemical bonds upon laser irradiation.

Full-Swing a-IGZO Inverter With a Depletion Load Induced by Laser Annealing



- As mature p-type oxide with good electrical properties is not readily available, until recently most logic circuits based on oxide TFTs have been implemented with only n-type TFTs.
- To improve the performance of inverters, two n-channel a-IGZO TFTs with distinctly different threshold voltage (V_{th}) are highly desired.

Nearly 100% full swing is achieved



E-mode + E-mode

E-mode + D-mode

- The output voltage gain ($-dV_{out}/dV_{in}$) are −1.5 and −20.5 V/V for the enhancement load inverter (untreated) and the depletion load inverter (annealed with radiation dose of 9 J/cm^2) respectively, while their output swing range are 1.3-14.7 V and 0.02-20 V respectively.
- The laser-treated inverter with depletion load also demonstrates good dynamic performance with its rise and fall time both ~1.0 us.

IEEE EDL, in press

Summary

1. Wide bandgap amorphous oxide semiconductors are very attractive for next generation display applications due to their various benign physical properties.
2. The carrier transport mechanisms, interface properties, electrical instability under bias stress and illumination of a-IGZO TFTs are preliminarily studied.
3. Several proto-type a-IGZO TFTs or structures fabricated by using new processing techniques are demonstrated successfully. In particular, the developed laser annealing technique is highly flexible to modify individual device performance and is promising for re-functionizing a-IGZO TFT-based logic circuits.

Compared with Si-based TFTs, there are much more unknowns in oxide-based TFTs, which is still a very young field !

Thank you

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