Enhancing breakdown voltage in amorphous zinc tin oxide Schottky diode

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Motivation

- Desire additive thin film amorphous oxide semiconductor (AOS) for future heterointegration
- Need rectifiers for energy harvesting, mixers, and power rectification **[Ref. 1]**

→ **Goal:** understand the breakdown mechanisms of AOS Schottky diodes

Introduction to Amorphous Oxide Semiconductors

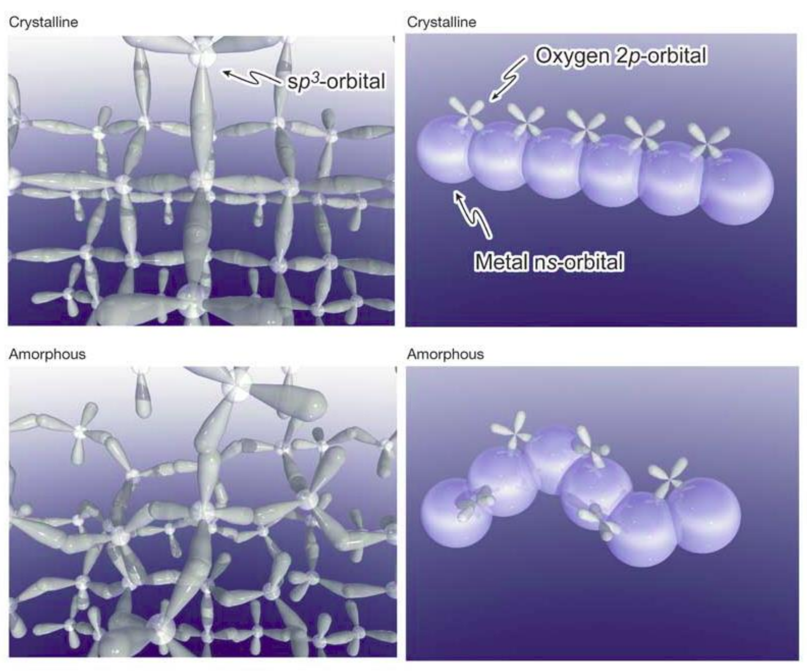


Image from ref. 2

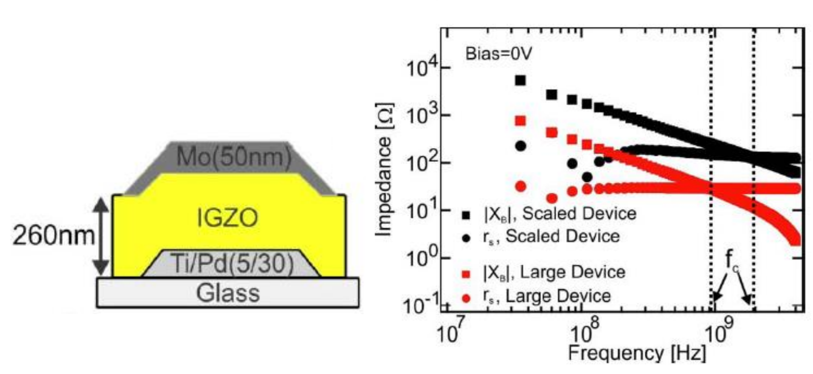
▸ Transparent amorphous oxide semiconductors

- Ionically-bonded oxides: spherical orbitals have large overlap regardless of bond angle; different than covalently-bonded Si, in which electron orbitals have strong directivity
- Use ternary or quaternary alloys of zinc oxide to create amorphous matrix.
- Alloys with $n > 4$ (In, Sn) create good electron conduction pathways.
- Amorphous morphology enables good uniformity at low deposition temperature

▸ Commercialized IGZO TFT

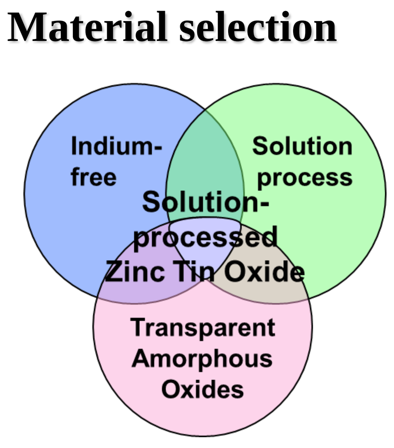
AU Optronics 65" 4kx2k UltraHD TV

▸ RF devices with IGZO



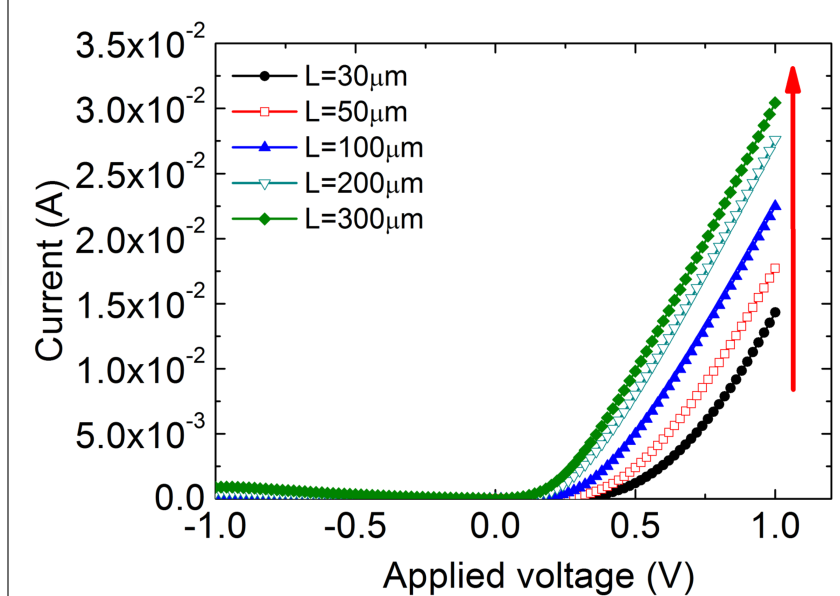
[Ref. 3]

▸ Material selection



Current measurements before and after breakdown (BD)

▸ Area-dependent current measurements before BD



- ➢ J_f of ~1000 A/cm², on/off ratio of > 100, n = 1.8 – 2.0, and Φ_B = 0.4 – 0.5 eV

$$J = J_s\left\{\exp\left[\frac{q(V - J\cdot A\cdot R_s)}{nk_BT}\right] - 1\right\}$$

- ➢ J_f follows thermionic emission theory with inhomogeneous barrier.

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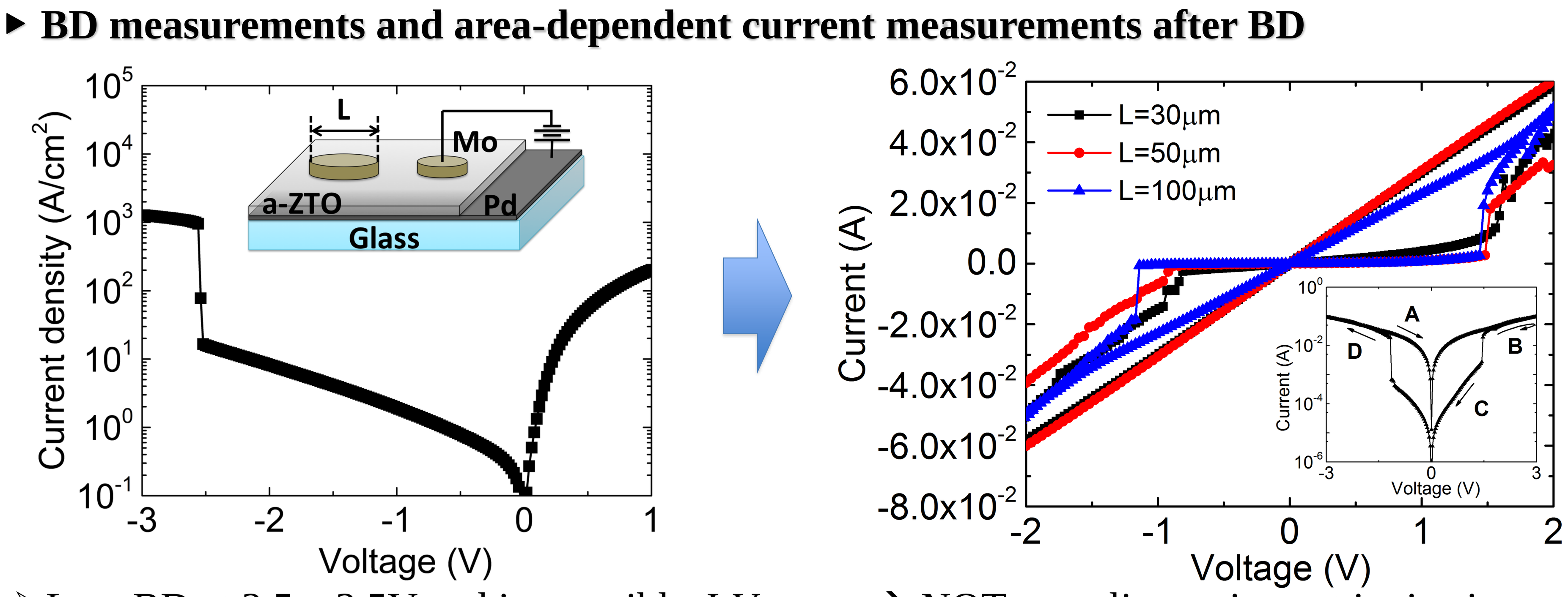
- ➢ I_f scales with respect to electrode area.

▸ BD measurements and area-dependent current measurements after BD

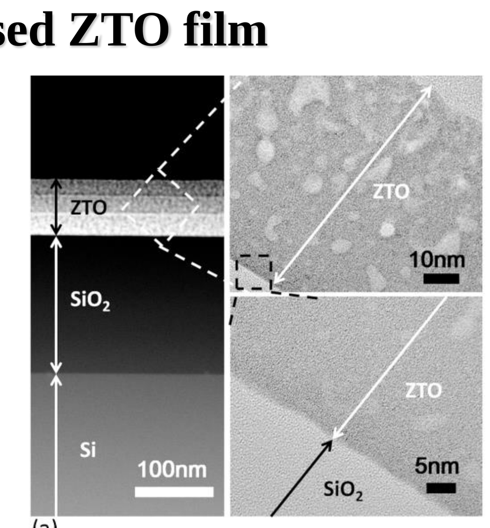


- ➢ Low BD at 2.5 – 3.5V and irreversible *J-V* curve → NOT tunneling or impact ionization
- ➢ After breakdown, the device shows symmetric, linear *J-V* curves, where their resistivity changes due to bias → *bipolar switching behavior*.
- ➢ After breakdown, I_f does not relate to electrode area → *conductive filament formation*

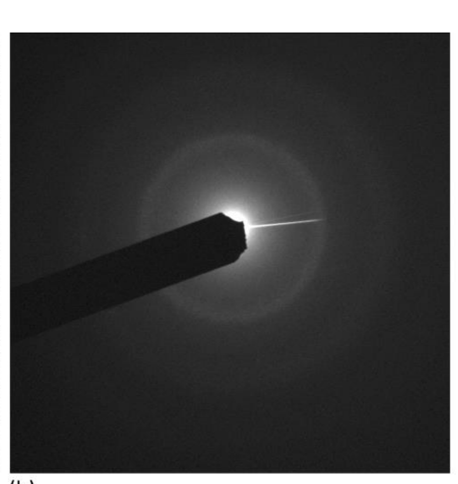
Device Fabrication

▸ Solution-processed ZTO film

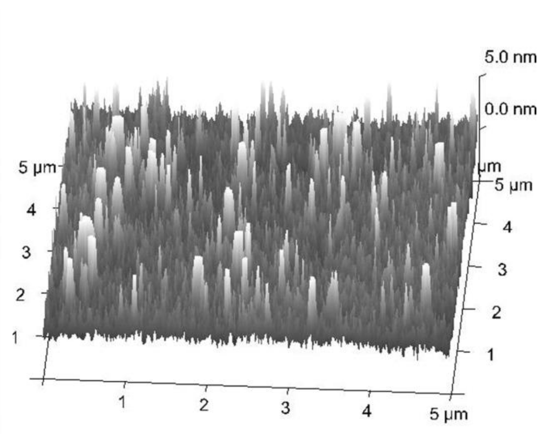
Zinc tin oxide solution
zinc acetate dihydrate and tin (II) acetate in 2-methoxyethanol and ethanolamine (stabilizer)



Cross-sectional TEM



SAED of *a*-ZTO

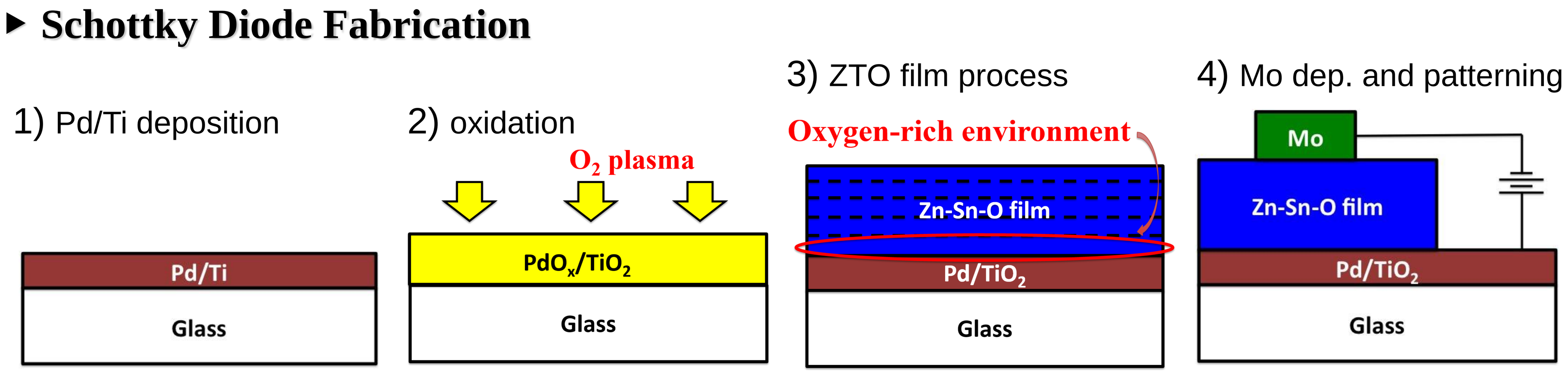


Surface AFM of *a*-ZTO

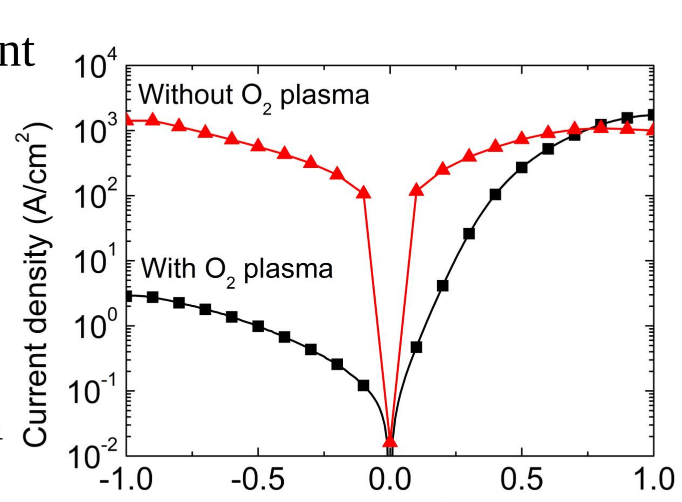
- ➢ Solution-processed ZTO film is amorphous, non-porous, and smooth
  - ✓ TEM and Selected Area Electron Diffraction (SAED) of amorphous ZTO
  - ✓ AFM R_q = 1.5 nm

[Ref. 4]

▸ Schottky Diode Fabrication

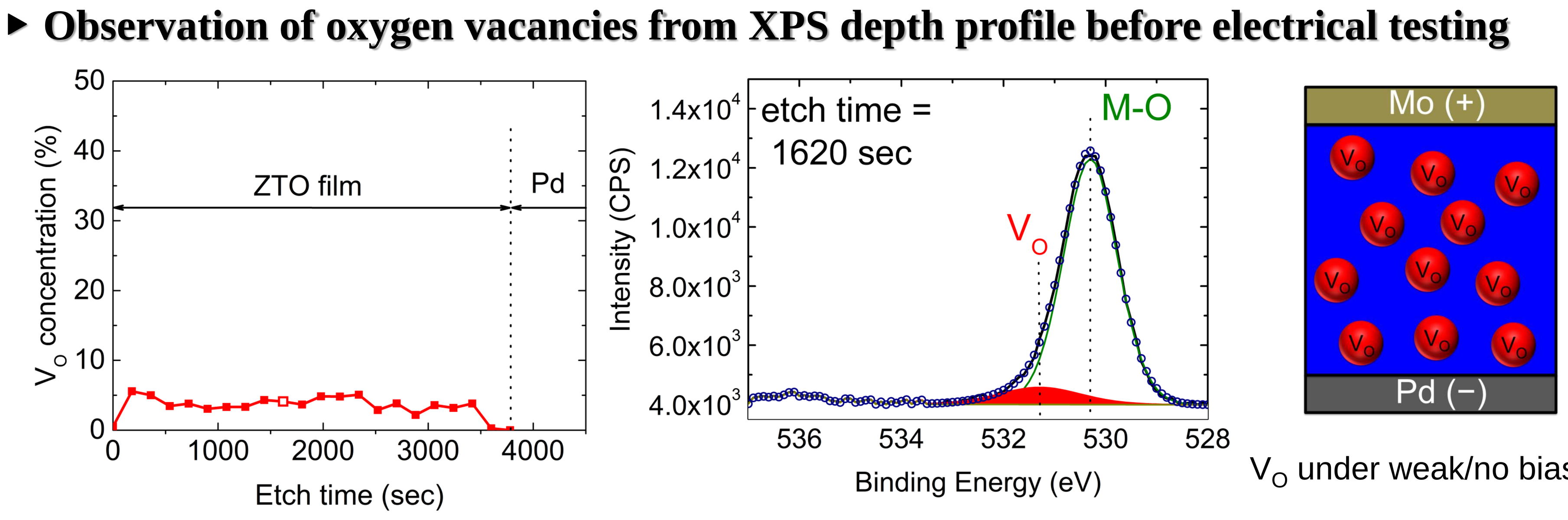


- ➢ Schottky (Ti/Pd) evaporation and oxygen plasma treatment
  - ✓ Reduce oxygen vacancies for rectifying contact **[Ref. 5]**
- ➢ ZTO solution process multi-layer deposition and pattern
  - ✓ Deposit five layers for 120nm-thick ZTO film
- ➢ Ohmic contact (Mo) sputter and liftoff
  - ✓ Low Mo-ZTO contact resistance, $R_C \times W$ = 8.7 Ω-cm **[Ref. 6]**



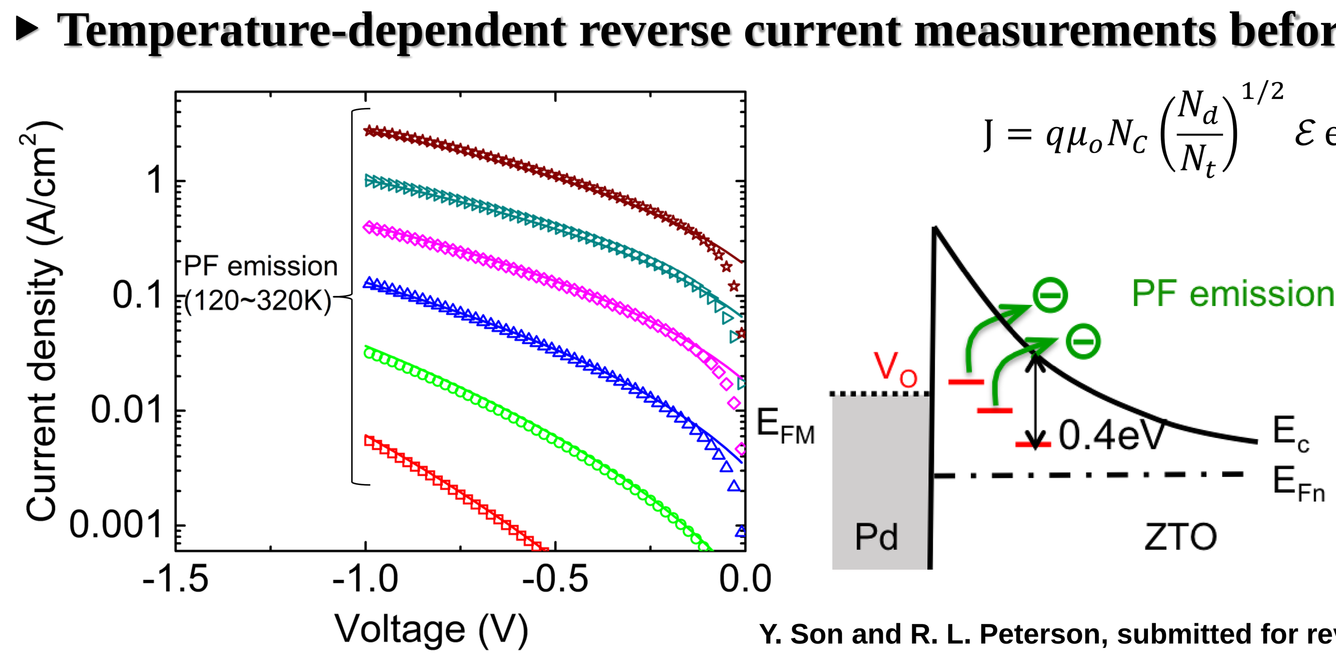
The role of oxygen vacancies (V_O)

▸ Observation of oxygen vacancies from XPS depth profile before electrical testing



V_O under weak/no bias

▸ Temperature-dependent reverse current measurements before BD



$$J = q\mu_o N_c\left(\frac{N_d}{N_t}\right)^{1/2}\mathcal{E}\exp\left[\frac{-(\Phi_t + \Phi_d - q\sqrt{q\mathcal{E}/\pi\epsilon_r\epsilon_o})}{2kT}\right]$$

- ➢ Energy level of deep donors contributing to Poole-Frenkel emission agrees with known V_O in *a*-ZTO **[Ref. 7,8]**

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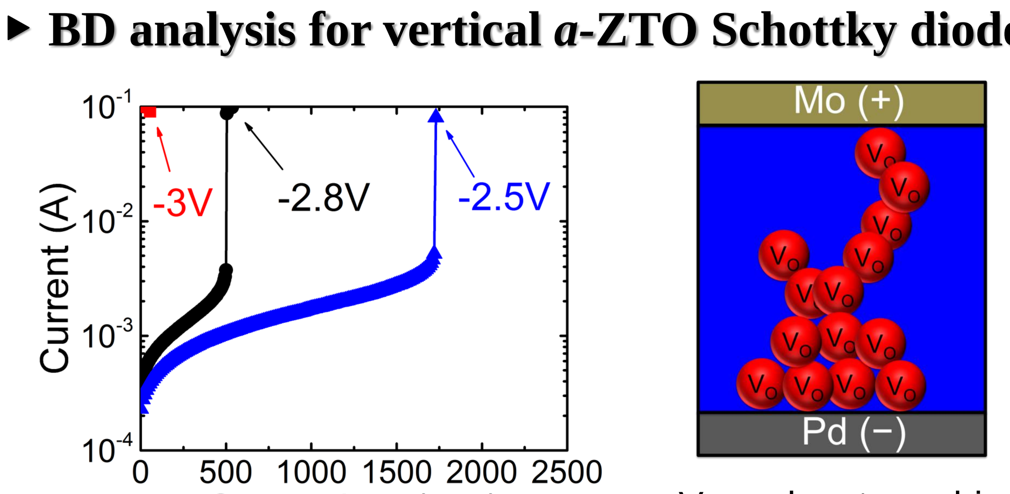
▸ BD analysis for vertical *a*-ZTO Schottky diode (Bias stress test)



V_O under strong bias

- ➢ V_O is known to migrate under high field and form a *conductive filament* in amorphous oxide resistive memory devices. **[Ref. 9]**
- ➢ BD is attributed to the same physical phenomenon in our AOS Schottky diodes

Conclusions

- ➢ First analysis of breakdown mechanism on thin-film vertical AOS Schottky diode.
- ➢ The BD mechanism in our solution-processed Pd:Zn-Sn-O Schottky diodes is not due to impact ionization or tunneling, but rather due to forming behavior by oxygen ion migration.
- ➢ Prior to BD, V_O that are evenly distributed in AOS film lead to high leakage current via Poole-Frenkel emission.

References

[1] A. Chasin *et al.*, in *Tech. Dig. Intl. Electron Dev. Mtg. (IEDM)* (Washington, DC, 2013), pp. 292–295. [2] K. Nomura *et al.*, *Nature*. **432**, 488–492 (2004). [3] A. Chasin *et al.*, *IEEE Trans. Electron Devices*. **60**, 3407–3412 (2013). [4] W. Hu, R. L. Peterson, *J. Mater. Res.* **27**, 2286–2292 (2012). [5] Y. Son, J. Li, R. L. Peterson, *ACS Appl. Mater. Interfaces*. **8**, 23801–23809 (2016). [6] W. Hu, R. L. Peterson, *Appl. Phys. Lett.* **104**, 192105 (2014). [7] W. Körner, C. Elsässer, *Thin Solid Films*. **555**, 81–86 (2014). [8] P. T. Erslev *et al.*, *Appl. Phys. Lett.* **95**, 192115 (2009). [9] Y. Yang, W. Lu, *Nanoscale*. **5**, 10076 (2013).

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