Recent commercialization has increased the research interest in transparent conducting oxides like indium tin oxide being implemented in display technologies and sensors. A wide range of values (4.2–5 eV) for the work function of ITO films are reported in literature. In this paper, we present an approach to extract the work function of indium tin oxide films from MOSFET devices. RF sputtered indium tin oxide is used as a transparent gate electrode to fabricate n-MOSFET. For the fabrication of the MOSFET, a four-level mask is used. Electrical characterization is performed on these MOSFET devices. We obtained work function value in the range between 4.62–4.81 eV using this technique.

**Experimental**

For fabrication of n-MOSFET transistor, p-type silicon (100) was used. The silicon wafer was cut into two equal pie shaped samples, each sample fits up to ten MOSFET devices on it. On these wafers, two identical sets of MOSFETs were fabricated under similar process conditions. One MOSFET had Al as gate contact and the other had ITO as gate contact electrode. These MOSFETs will be referred as MOSFET/Al and MOSFET/ITO henceforth. Al was used as source and drain (S/D) contacts for both kinds of devices. The wafers were chemically cleaned with standard procedure using acetone, methanol followed by deionized water. During MOSFET device fabrication, four levels of lithography masks were employed. Following is the brief outline of MOSFET device fabrication. Wet oxidation was performed to grow a layer of 4500 Å thick silicon dioxide. This was achieved at 1100 °C for 45 minutes through steam bubbler and nitrogen as carrier gas.

**Source and drain diffusion.**—The first level mask was used to create S/D wells with the help of negative photoresist (PR). After defining wells in the oxide layer, phosphorus was pre-deposited into silicon at 950 °C for 15 minutes followed by wet oxidation at 1100 °C for 20 minutes to form n-type S/D regions.

**Contact windows and metallization.**—The second level mask was used to create contact windows at S/D. Al film was thermally evaporated. Third level mask was used to pattern Al in such a way that it remains confined only to S/D contact regions. Al deposited on rest of the sample is etched away using Al etch solution (16 parts of phosphoric acid, 1-part nitric acid, 1-part acetic acid, 20 parts DI water).

**Gate electrode deposition.**—Lift-off process was used to develop Al and ITO as gate electrodes for MOSFETs. The photoresist was patterned using the fourth level mask. Al was thermally evaporated for the MOSFET/Al devices and patterned by removing the photoresist. ITO was RF sputter deposited on MOSFET/ITO devices using ITO target. The composition of target used was 90% In2O3 and 10% SnO2. ITO film thickness was measured to be 150 nm on MOSFET/ITO. Gate patterning of ITO was obtained by lift-off process by immersing...
the device in concentrated sulfuric acid (H₂SO₄) which dissolved the photoresist leaving ITO confined only to the gate region. Figure 1 shows cross section of the fabricated MOSFETs, one having Al gate electrode and the other with ITO gate electrode.

Results and Discussion

I-V Characteristics of both MOSFETs are shown in Figure 2. These were achieved using the Tektronix 576 curve tracer by measuring the drain current (I_d) against drain source voltage (V_ds) as function of different gate voltages (V_g). The threshold voltage for both the MOSFETs are found by the plotting $\sqrt{I_d}$ vs V_g characteristics as shown in Figure 3. The threshold voltage is extracted by extrapolating the linear part of curve. The threshold voltage for MOSFET with Al gate contact is given by the following equation:

$$V_{T(\text{Al})} = -\Phi_{\text{ms(Al)}} + 2\Phi_F - \frac{Q_i}{C_i} + \frac{Q_d}{C_i}$$

[1]

Where $\Phi_{\text{ms(Al)}}$ is the work function difference of Al/silicon interface. The Fermi potential, $\Phi_F$ is $0.88 \text{ eV}$ [8].

The threshold voltage for MOSFET with ITO gate contact is given by

$$V_{T(ITO)} = -\Phi_{\text{ms(ITO)}} + 2\Phi_F - \frac{Q_i}{C_i} + \frac{Q_d}{C_i}$$

[2]

Where $\Phi_{\text{ms(ITO)}}$ is the work function difference of ITO/silicon interface. The Fermi potential, $\Phi_F$ is $0.76 \text{ eV}$.

Subtracting Equation 2 from Equation 1 we get,

$$V_{T(\text{Al})} - V_{T(ITO)} = -\Phi_{\text{ms(AI)}} + \Phi_{\text{ms(ITO)}}$$

[3]

$$2.51 - 2.63 = - 0.88 + \Phi_{\text{ms(ITO)}}$$

$$\Phi_{\text{ms(ITO)}} = 0.76$$

$$\Phi_{\text{ms(ITO)}} - \Phi_s = 0.76$$

$$\Phi_{\text{ms(ITO)}} = 4.81 \text{ eV}$$

Figure 2. I_d - V_ds characteristics of (a) MOSFET/ITO and (b) MOSFET/Al.
Measurements were performed on several devices on both samples to find the work function of ITO. The work function of RF sputtered ITO film was found to be in the range of 4.62–4.81 eV for MOSFET based on ITO gate electrode. This fits in the wide range of ITO work function values reported in literature which is 4.2–5 eV.\textsuperscript{16–18} Figure 4 shows band diagram of ITO-silicon dioxide-silicon MOSFET structure. Hussain et al. have reported the work function of RF sputtered ITO in the range of 4.31 eV–4.81 eV using ultraviolet photoelectron spectroscopy (UPS).\textsuperscript{21} Du et al. have reported the work function of RF magnetron sputtered ITO in preparation of ITO/SiO\textsubscript{x}/n-Si solar cells at substrate temperature of 250°C is 4.99 eV using UPS.\textsuperscript{20} The work function of DC sputtered ITO film was reported as 4.68 eV using UPS.\textsuperscript{21} The work function of thermally evaporated ITO films is reported in the range 4.60–4.75 eV.\textsuperscript{15} The work function calculated using n-MOSFET device fits in the range of those reported by other work function extraction techniques. The reported technique can be implemented to extract the work function of ITO films used in metal/insulator/metal type devices, solar cells, OLEDs, OPVs and thin film transistors. Further, surface modification techniques can be used to fine tune the work function of ITO based organic optoelectronic devices to enhance the performance.\textsuperscript{1,22,23}

**Conclusions**

Work function of RF sputtered ITO films is obtained from electrical properties of MOSFET devices. ITO is used as transparent conducting gate electrode of MOSFET. n-MOSFETs were fabricated on silicon using a four-level mask. Two sets of MOSFETs were fabricated simultaneously on different silicon samples, one set having Al as gate electrode and the other had transparent conducting ITO as gate electrode metal. From the I-V characteristics of both MOSFETs, the work function of ITO was calculated to be in the range 4.62–4.81 eV.

**References**

1. H. Kim, C. Gilmore, A. Pique, J. Horwitz, H. Mattoussi, H. Murata et al., “Electrical, optical, and structural properties of indium-tin-oxide thin films for organic light-emitting devices,” *Journal of Applied Physics*, 86, 6451 (1999).
2. C. W. Tang and S. A. Van Slyke, “Organic electroluminescent diodes,” *Applied physics letters*, 51, 913 (1987).
3. C. W. Tang, “Two-layer organic photovoltaic cell,” *Applied Physics Letters*, 48, 183 (1986).
4. K. Sugiyama, H. Iishi, Y. Ouchi, and K. Seki, “Dependence of indium-tin-oxide work function on surface cleaning method as studied by ultraviolet and X-ray photoelectron spectroscopies,” *Journal of Applied Physics*, 87, 295 (2000).
5. J. Burroughes, D. Bradley, A. Brown, R. Marks, K. Mackay, R. Friend et al., “Light-emitting diodes based on conjugated polymers,” *nature*, 347, 539 (1990).
6. J. Kim, M. Granstrom, R. Friend, N. Johansson, W. Salaneck, R. Daik et al., “Indium-tin-oxide treatments for single- and double-layer polymeric light-emitting diodes: The relation between the anode physical, chemical, and morphological properties and the device performance,” *Journal of Applied Physics*, 84, 6859 (1998).
7. P. J. Hotchkins, S. C. Jones, S. A. Panigagua, A. Sharma, B. Kippelen, N. R. Armstrong et al., “The modification of indium tin oxide with phosphonic acids: mechanism of binding, tuning of surface properties, and potential for use in organic electronic applications,” *Accounts of chemical research*, 45, 337 (2011).
8. Y. Park, V. Choong, Y. Gao, B. R. Hsieh, and C. W. Tang, “Work function of indium tin oxide transparent conductor measured by photoelectron spectroscopy,” *Applied Physics Letters*, 68, 2699 (1996).
9. C. Herring and M. Nichols, “Thermionic emission,” *Reviews of Modern Physics*, 21, 185 (1949).
10. M. Kiziroglou, L. A. Zhukov, P. De Groot, and C. De Groot, “Thermionic field emission at electrodeposited Ni–Si Schottky barriers,” *Solid-State Electronics*, 52, 1032 (2008).
11. M. Meerbom, B. Lägel, A. Cascio, B. Doran, and R. Schlaf, “Direct comparison of photoemission spectroscopy and in situ Kelvin probe work function measurements on indium tin oxide films,” *Journal of electron spectroscopy and related phenomena*, 152, 12 (2006).
12. B. G. Streetman and S. Banerjee, *Solid electronic devices*, 2: Prentice-Hall Englewood Cliffs, NJ (1995).
13. W. Beadle, *Quick reference manual for silicon integrated circuit technology*, John Wiley & Sons, (1985).
14. J. Shewchun, J. Dubow, C. Wilmsen, R. Singh, D. Burk, and J. Wager, “The operation of the semiconductor-insulator-semiconductor solar cell: Experiment,” *Journal of Applied Physics*, 50, 2832 (1979).
15. N. Balasubramanian and A. Subrahmanyam, “Studies on evaporated indium tin oxide (ITO)/silicon junctions and an estimation of ITO work function,” *Journal of The Electrochemical Society*, **138**, 322 (1991).
16. J. Shewchun, J. Dubow, A. Myszkowski, and R. Singh, “The operation of the semiconductor-insulator-semiconductor (SIS) solar cell: Theory,” *Journal of Applied Physics*, **49**, 855 (1978).
17. W. Thompson and R. Anderson, “Electrical and photovoltaic characteristics of indium-tin oxide/silicon heterojunctions,” *Solid-State Electronics*, **21**, 603 (1978).
18. C. Pan and T. Ma, “Work function of In₂O₃ film as determined from internal photoemission,” *Applied Physics Letters*, **37**, 714 (1980).
19. S. Q. Hussain, W.-K. Oh, S. Ahn, A. H. T. Le, S. Kim, Y. Lee et al., “RF magnetron sputtered indium tin oxide films with high transmittance and work function for a-Si:H/c-Si heterojunction solar cells,” *Vacuum*, **101**, 18 (2014).
20. H. Du, J. Yang, Y. Li, F. Xu, J. Xu, and Z. Ma, “Preparation of ITO/SiOₓ/n-Si solar cells with non-decline potential field and hole tunneling by magnetron sputtering,” *Applied Physics Letters*, **106**, 093508 (2015).
21. J.-J. Ho, C.-Y. Chen, R. Y. Hsiao, and G. L. Ho, “The Work Function Improvement on Indium–Tin–Oxide Epitaxial Layers by Doping Treatment for Organic Light-Emitting Device Applications,” *The Journal of Physical Chemistry C*, **111**, 8372 (2007).
22. C. Ganzorig, K.-J. Kwak, K. Yagi, and M. Fujihira, “Fine tuning work function of indium tin oxide by surface molecular design: Enhanced hole injection in organic electroluminescent devices,” *Applied Physics Letters*, **79**, 272 (2001).
23. J. S. Kim, J. H. Park, J. H. Lee, J. Jo, D.-Y. Kim, and K. Cho, “Control of the electrode work function and active layer morphology via surface modification of indium tin oxide for high efficiency organic photovoltaics,” *Applied Physics Letters*, **91**, 112111 (2007).