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High performance ZnO nanowire field effect transistors with organic gate nanodielectrics: effects of metal contacts and ozone treatment

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Abstract

High performance ZnO nanowire field effect transistors (NW-FETs) were fabricated using a nanoscopic self-assembled organic gate insulator and characterized in terms of conventional device performance metrics. To optimize device performance and understand the effects of interface properties, devices were fabricated with both Al and Au/Ti source/drain contacts, and device electrical properties were characterized following annealing and ozone treatment. Ozone-treated single ZnO NW-FETs with Al contacts exhibited an on-current (I_{on}) of $\sim 4 \mu\text{A}$ at $0.9 V_{\text{gs}}$ and $1.0 V_{\text{ds}}$, a threshold voltage (V_{th}) of 0.2 V , a subthreshold slope (S) of $\sim 130 \text{ mV/decade}$, an on-off current ratio ($I_{\text{on}}/I_{\text{off}}$) of $\sim 10^7$, and a field effect mobility (μ_{eff}) of $\sim 1175 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. In addition, ozone-treated ZnO NW-FETs consistently retained the enhanced device performance metrics after SiO_2 passivation. A 2D device simulation was performed to explain the enhanced device performance in terms of changes in interfacial trap and fixed charge densities.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

ZnO is an II–VI group semiconductor with a wurtzite crystal structure, a direct and wide bandgap of 3.37 eV , a large exciton binding energy (60 meV for ZnO versus 28 meV for GaN) and high optical gain (300 cm^{-1} for ZnO versus 100 cm^{-1} GaN) at room temperature [1–3]. Wurtzitic ZnO has been widely used to demonstrate numerous applications including low voltage and short wavelength (green or green/blue) electro-optic devices such as light-emitting diodes and laser diodes, transparent ultraviolet (UV)-protection films, transparent conducting oxide materials, piezoelectric materials, electron-transport media for solar

cells, chemical sensors and photocatalysts [1–5]. Since the first report of ZnO nanowires [6], much attention has focused on studying one-dimensional ZnO materials such as nanowires [1, 6–10] or nanorods [11–15] from the standpoint of novel fundamental physical phenomena as well as novel nanotechnology. One important, but not well addressed, application of ZnO nanowires would be in thin film transistors to replace conventional poly-silicon thin film transistors (poly-TFTs). Even though poly-TFTs have been used to fabricate commercial display circuits, they lack transparency, mechanical flexibility, and compatibility with plastic substrates, all of which are required for developing future flexible displays. ZnO nanowire field effect transistors (NW-FETs) are attractive candidates for future flexible display

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Figure 1. Cross-sectional view of a SAND-based ZnO NW-FET with FE-SEM image in inset and structure of the SAND film.

products due to the flexibility and transparency of the nanowires. However, compared to poly-TFTs, most previously reported ZnO NW-FETs have shown relatively poor device performance in terms of conventional metrics such as on-current (I_{on}), on-off current ratio ($I_{on}:I_{off}$), subthreshold slope (S) and field effect mobility (μ_{eff}) [16]. We have recently reported that replacing the conventional SiO_2 dielectric with a self-assembled nanodielectric (SAND) provided ZnO NW-FETs with significantly higher $I_{on} \sim 2.5 \mu\text{A}$ at low gate and drain voltage and higher mobilities [17]. The S (~ 400 mV/decade) and $I_{on}:I_{off}$ ($\sim 10^4$) of those devices compared favourably with the reported values for other semiconductor nanowire transistors, but were not yet suitable for large-scale integration.

In order to develop ZnO NW-FETs with suitable performance for transparent and flexible electronics, it is important to investigate the effects of the nanowire interfaces, both along the body of the nanowire and at the contacts. Intrinsic (not intentionally doped) ZnO nanowires display an n-type behaviour due to oxygen vacancies and/or Zn interstitials that act as donors [16]. It has been experimentally shown that the conductivity of ZnO nanowires can be tuned by controlling oxygen vacancies on the surface or in the bulk, which is also believed to be a sensing mechanism for ZnO-based gas sensors [18]. It has been speculated that conduction through ZnO nanowires is surface-centred rather than bulk-centred because surface oxygen vacancies have a significant effect on electron transport through ZnO nanowires [19]. UV illumination, ozone treatment, and annealing in hydrogen or oxygen have been used to modulate ZnO thin film conductivity, mainly via desorption or adsorption of oxygen species from the surface [20, 21]. Another important issue to be addressed is the interface between source/drain metal contacts and ZnO nanowires. The presence of a Schottky barrier at the nanowire-metal interface usually leads to the reduction in I_{on} , and it has been suggested that a zero or even negative barrier height is desirable to maximize I_{on} in a given device configuration [22].

In this paper, we report a study of ZnO NW-FETs aimed at addressing these issues. Devices were fabricated using various contact metals in order to understand the effects of the contact interface on device properties. We also investigated the effects of ozone treatment on device performance in order to understand the effects of the nanowire-dielectric interface and the nanowire surfaces. For optimal contact

and ozone treatment conditions, we achieved significantly enhanced device performance for ZnO NW-FETs, in terms of I_{on} , $I_{on}:I_{off}$, S and μ_{eff} .

2. Fabrication and experimental details

Single ZnO NW-FETs were fabricated using a 15 nm thick SAND as the gate insulator, and Al source/drain contacts. Figure 1 shows the cross-section of the ZnO NW-FET along with the structure of the SAND film. In addition, ZnO NW-FETs with a 60 nm thick SiO_2 gate insulator were fabricated to test different metal contacts (Au/Ti or Al). The optimum metal contacts were then used when fabricating SAND-based ZnO NW-FETs. The fabricated device structure of these single ZnO-NW FETs was a typical back-gate configuration using a heavily doped n-type Si substrate ($\rho \sim 0.01 \Omega \text{ cm}$) as a common gate. The details of device fabrication procedures and SAND film properties can be found elsewhere [17, 23]. The SAND film ($t \sim 15$ nm) used in this study consists of three layer-by-layer self-assembled organic multilayers and has been successfully used for nanowire-based applications, demonstrating its high performance as a gate insulator ($C_i \sim 180 \text{ nF cm}^{-2}$, $E_{breakdown} \sim 7 \text{ MV cm}^{-1}$, and $I_{leakage} \sim 1 \times 10^{-8} \text{ A cm}^{-2}$ at 1 V) [17, 24]. The average diameter and length of the ZnO nanowires (Nanolab Inc.) from field emission scanning electron microscopy (FE-SEM) images were 120 nm and 5 μm respectively. The synthesis details and microstructural characterization of these ZnO nanowires can be found in [25].

Following device fabrication, ozone treatment (UV-ozone cleaner, UVO 42-220, Jelight Co. Ltd) was used to achieve the highest device performance in terms of I_{on} , $I_{on}:I_{off}$, S , and μ_{eff} . The controlled ozone condition was obtained by setting the oxygen of 50 ppm, UV wavelength of 184.9 nm and UV lamp power of 28 mW cm^{-2} @ 254 nm, and the exposing time was varied from 1 to 4 min. In addition, when the devices were exposed to ozone, they were shielded from UV light, which is known to desorb oxygen species from ZnO surfaces and to increase both I_{on} and off-current (I_{off}) by several orders of magnitude [26]. Typical annealing processes such as N_2 annealing and H_2 annealing were also considered. However, it was observed that N_2 annealing severely degrades the I_{on} of SiO_2 -based ZnO NW-FETs, and ZnO conductivity is known to increase upon H_2 annealing, usually inducing negative V_{th}

Figure 2. I_{ds} - V_{gs} characteristics ($V_{ds} = 0.1$ V) of representative ZnO NW-FETs with Al and Au/Ti contacts.

shifts in ZnO thin film transistors [27]. Overall, we find that ozone treatment provides facile control over the device performance metrics of ZnO NW-FETs, and a short ozone exposure with Al contacts is found to be optimum, whereas prolonged ozone exposures (>3 min) result in significant reduction of I_{on} . We also confirmed that the robust SAND gate dielectric is compatible with this ozone treatment. Finally, ZnO NW-FETs were passivated by depositing a 300 nm thick SiO_2 layer by e-beam evaporation (deposition rate = $0.5 \text{ \AA s}^{-1}$ at $\sim 5 \times 10^{-7}$ Torr). The current-voltage (I - V) characteristics of the devices were measured using a probe station with a HP 4156A semiconductor parameter analyser. The surface of the Al film was expected to oxidize during the ozone treatment, resulting in an oxide layer comparable to that observed by prolonged air exposure (6–16 $\text{\AA}$) [28]. Since the overall film was 140 nm thick, the contact-to-nanowire interface was expected to be unoxidized, so the primary effect on contact properties was expected to be somewhat increased difficulty in breaking through the surface oxide with the probe pads.

3. Results and discussion

Figure 2 shows the measured drain current versus gate-source voltage (I_{ds} - V_{gs}) plots for representative devices with Al and Ti source/drain contacts. For these devices, the gate dielectric consisted of a 60 nm thick SiO_2 layer. As shown in figure 2, ZnO NW-FETs with Al source/drain contacts produce two orders of magnitude higher I_{on} than the device with Au/Ti source/drain contacts. The transconductance, $g_m = dI_{ds}/dV_{gs}$, of ZnO NW-FETs with Al and Au/Ti peak at $\sim 0.06 \text{ }\mu\text{S}$ (Al) and $\sim 0.001 \text{ }\mu\text{S}$ (Au/Ti), corresponding to field effect mobilities of $\sim 70 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ (Al) and $\sim 1.3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ (Au/Ti), respectively. Details of the μ_{eff} extraction procedure are described later.

On the basis of the comparable work functions of Al and Ti ($\Phi_{Al} = 4.28 \text{ eV}$ and $\Phi_{Ti} = 4.33 \text{ eV}$) [29], both Au/Ti and Al would be expected to form relatively good ohmic contacts to ZnO, which has an electron affinity, $\chi_{ZnO} = 4.29 \text{ eV}$ and an effective work function $\Phi_{ZnO} = 4.45 \text{ eV}$ for moderately doped n-type material [30]. However, there are two factors that determine the effective Schottky barrier height: (i) metal work function and (ii) wetting interactions between the metal

contacts and ZnO nanowires. Poor wetting is known to produce surface states at the metal-nanowire interface, inducing Fermi level pinning and resulting in different effective Schottky barrier heights, even when the work functions of two different metals are nearly identical [22]. It is proposed here that Ti has poor wetting interactions or different surface reactivity with ZnO and induces much higher surface states than Al as indicated by poor S ($>700 \text{ mV/decade}$).

In order to study the effect of nanowire surface states and dielectric interfaces, SAND-based ZnO NW-FETs with Al contacts were annealed in air at 130°C for 15 min and then exposed to ozone treatment. Figures 3(a) and (b) show the measured I_{ds} - V_{gs} plots for a representative device in the 'as-fabricated' state, after annealing, and after ozone treatment, on semi-logarithmic and linear scales, respectively. Annealing of the present ZnO NW-FETs resulted in an improved S (230 mV/decade), as shown in figure 3(a). Annealing at moderate temperatures has been shown to reduce fixed positive charges and interfacial trap densities in SAND films [23]. This effect probably accounts for the observed improvement in S . However, annealing in air also degraded the I_{on} by more than one order of magnitude. A prior report on polycrystalline ZnO thin films observed decreased conductivity upon annealing in air at higher temperatures, and attributed this effect to oxygen at grain boundaries, which can act as acceptors or other negatively charged states [20]. SnO_2 nanobelt FETs also exhibit decreased conductivity along with a positive V_{th} shift upon a 200°C air anneal, and this effect was attributed to negatively charged oxygen adsorbed on the SnO_2 surface [31]. Although the SAND dielectric did not allow higher temperature anneals, SiO_2 -based ZnO NW-FETs were annealed at 250 and 340°C which resulted in significant reductions in the conductivity of the ZnO NW ($I_{on} \sim 50 \text{ pA}$). It is possible that the surface of the ZnO NW adsorbed oxygen species during the anneal, resulting in a deep depletion region. During the photolithography process, the devices were exposed to $\sim 120^\circ\text{C}$. However, it is expected that the ZnO NWs were not significantly oxidized during this process since they were covered by photoresist, and therefore not in direct contact with air. Ozone treatments for 1 or 2 min following the 130°C anneal resulted in significant device performance enhancements with complete I_{on} recovery. Compared to as-fabricated devices, the S was reduced from 400 to 130 mV/decade along with improvement in the $I_{on}:I_{off}$ ($\sim 10^7$), and a shift in the threshold voltage (V_{th}) from -0.4 to 0.2 V , which enables enhancement-mode device operation with low operating voltage (V_{ds} and V_{gs}). The drain current versus drain-source voltage (I_{ds} - V_{ds}) characteristics (figure 3(c)) of an ozone-treated single ZnO NW-FET illustrate these improvements, displaying $I_{on} \sim 4 \text{ }\mu\text{A}$ at $0.9 \text{ }V_{gs}$ and $1.0 \text{ }V_{ds}$ with enhancement-mode operation. The g_m (figure 3(d)) peaks at $\sim 1.5 \text{ }\mu\text{S}$. Although g_m is expected to depend strongly on the device geometry (dielectric constant, dielectric thickness and gate length), the observed g_m compares favourably with previous ZnO NW-FET reports. Although one study observed a g_m of $3.06 \text{ }\mu\text{S}$ [32], most prior reports show much lower values [33, 34]. Figure 4 shows the measured I_{ds} - V_{gs} relationships for thirteen ZnO NW-FETs which had comparable post-ozone properties. These devices exhibit average values of $S \sim 150 \text{ mV/decade}$, $I_{on}:I_{off} \sim 10^6$ and

Figure 3. Measured characteristics for a representative SAND-based ZnO NW-FET with Al contacts: (a) I_{ds} – V_{gs} characteristics ($V_{ds} = 0.1$ V) showing curves for as-fabricated device, and for various annealing/ozone treatments. (b) Linear I_{ds} – V_{gs} for various conditions. Upon 2 min ozone treatment, V_{th} was shifted from -0.4 to 0.2 V as indicated by the black arrow. (c) I_{ds} – V_{ds} characteristic after 2 min ozone treatment. (d) g_m and μ_{eff} at $V_{ds} = 0.1$ V after 2 min ozone treatment.

Figure 4. I_{ds} – V_{gs} characteristics ($V_{ds} = 0.1$ V) of thirteen ZnO NW-FETs after 2 min ozone treatment.

$\mu_{eff} \sim 687 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ after 2 min ozone treatment. The ozone treatment probably modifies the charge state or removes a portion of the adsorbed oxygen from the nanowire surface which would reduce the negative surface charge, and may also remove other contaminants. Additional ozone treatment beyond 2 min results in degradation of the I_{on} and g_m . Both as-fabricated and ozone-treated ZnO NW-FETs were passivated by depositing a 300 nm thick SiO_2 layer by e-beam evaporation. Ozone-treated ZnO NW-FETs consistently retain the enhanced performance metrics even after passivation.

Typically, carrier mobility is considered to be a metric of transistor performance that is relatively independent of geometry. However, extraction of μ_{eff} in NW-FETs requires a significantly different procedure than that in conventional transistors. In metal–oxide–semiconductor FETs (MOSFETs)

or other thin film transistors, it is generally possible to independently determine the mobility and carrier concentration versus gate bias using techniques such as Hall effect and conductivity measurements. However, in NW-FETs, it is typically not possible to extract the channel carrier concentration through a direct measurement, due to the lack of the extended lateral geometry required for Hall measurements and the relatively large parasitic capacitances, which typically dominate capacitance–voltage measurements. The mobility of NW-FETs is typically calculated from measured I – V characteristics of the transistors, along with a capacitance estimated from the geometry and dielectric properties of the materials. Therefore, the combination of the cylinder-on-plate capacitance model (equation (1)) and the MOSFET model (equation (2)) was employed to calculate mobility [35].

$$C_i = \frac{2\pi\epsilon_0 k_{eff} L}{\cosh^{-1}(1 + t_{ox}/r)} \quad (1)$$

$$\mu = \frac{dI_{ds}}{dV_{gs}} \times \frac{L^2}{C_i} \times \frac{1}{V_{ds}} \quad (2)$$

where $k_{eff} \sim 3.0$ is the effective dielectric constant of SAND, $L \sim 2 \mu\text{m}$ is the channel length, and $r = 60 \text{ nm}$ is the radius of the ZnO NW. Note that equation (1) is exact for the case of two perfect electric conductors (a cylinder and an infinite plane) embedded in a uniform ideal dielectric. In the case of a NW-FET, equation (1) does not reflect the exact charge versus voltage relationships in the semiconductor regions or the effects of bulk/interfacial charge in the insulator.

Using the measured g_m (figure 3(d)) and equations (1), (2), an μ_{eff} can be estimated for the NW-FETs. For ozone-treated single ZnO NW-FETs, the calculated μ_{eff} is $\sim 1175 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, which is larger than typically reported

Figure 5. (a) and (b) Cross-sectional views of a depletion-mode ZnO NW-FET and the band diagrams in (c) horizontal (A–A') and (d) vertical (B–B') cross-sections of both as-fabricated (solid lines) and ozone-treated (dotted lines) ZnO NW-FETs. Φ_{B1} and Φ_{B2} are electron barrier heights that correspond to the bulk nanowire regions in as-fabricated and ozone-treated devices respectively, and the arrows in the band diagrams represent the direction of band bending after 2 min ozone treatment.

values for ZnO NW-FETs [33, 34, 36, 37] and ideal single-crystal ZnO bulk mobility ($\sim 200 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$) [29], although one study has stated mobilities in the range of 1200–4120 $\text{cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ [32]. While the origin of these high mobilities is currently unresolved, the SAND dielectric has been observed to provide high performance in a number of channel materials [17, 24], so the SAND appears to provide a high quality interface. It is also likely that the highly crystalline nature of the ZnO nanowires is partially responsible, considering that the low mobility of polycrystalline ZnO films is due to scattering at the intergrain regions and/or tunnelling through intergrain barriers [19].

The enhanced device performance metrics of ozone-treated ZnO NW-FETs can be explained by considering negative fixed charges on ZnO nanowire surfaces and interfacial traps at the SAND–ZnO NW interface along with band diagrams. Figure 5 shows the cross-section of the device structure and band diagrams corresponding to as-fabricated and ozone-treated devices. The band diagrams were generated by a 2D device simulator (MEDICI), which will be explained in detail in the following paragraph. The relative band line-up with the contacts corresponds to the work function parameters discussed earlier (A–A'). In figures 5(c) and (d), the solid and dashed lines represent the band diagrams of as-fabricated and ozone-treated devices, respectively, and the indicated electron barrier height (Φ_B) corresponds to a cross-section through the bulk of the nanowire. To verify the band diagram of 2 min ozone-treated ZnO NW-FETs experimentally, temperature-dependent I_{ds} – V_{ds} characteristics of 2 min ozone-treated devices were measured at different gate biases ($V_g = -1, 0$

and 1 V) with temperatures varying from 350 to 150 K in 50 K steps. The activation energy (E_a) values ($V_{ds} = 1 \text{ V}$) extracted from an Arrhenius plot ($\log I$ versus $1/T$) at $V_g = -1, 0$ and 1 V were 0.16, 0.08 and 0.05 eV, respectively. The observation of $E_a < 3 \text{ kT}$ for biases above V_{th} indicates a small Φ_B for carrier injection into nanowire channels. On the basis of this behaviour, it appears that contact effects do not dominate the temperature-dependent behaviour, and that the measured E_a values correspond to the Φ_B illustrated in figure 5. This would imply either that the semiconductor barrier at the metal contact is small (as illustrated in figure 5) or that a higher but very thin barrier, which would allow tunnelling, exists at the contacts. According to the simulation, the Φ_B increases upon ozone treatment as indicated by the arrows in the band diagrams. On the other hand, the negative V_{th} observed in as-fabricated devices indicates that a negative gate bias ($\sim -0.4 \text{ V}$) must be applied in order to turn off body current through undepleted regions (B–B'). The negligible V_{th} shift upon annealing in air indicates that the centre portion of ZnO nanowires remains undepleted, whereas the positive V_{th} ($\sim 0.2 \text{ V}$) of the ozone-treated devices implies that the body current path through undepleted regions was removed upon ozone treatment.

It has been reported that negative oxygen species adsorbed on the ZnO surfaces form depletion regions that decrease the conductivity [18]. In the case of other metal oxide nanowires (e.g. SnO_2), the effects of heating and oxygen exposure have been explained using an oxygen surface binding model in which an unbound layer of Sn at the surface causes a layer of shallow donors [38]. On the basis of this model, it was claimed that a surface bound oxygen monolayer removes the shallow donors and fully depletes 10–100 nm diameter nanowires due to the absence of the shallow donor states and the negative charge of the oxygen, which can be viewed as a source of negative fixed charges. The previous studies on nanowires have utilized heating in controlled ambients to vary the oxygen binding. The ozone treatment used in the current study is expected to modify the amount of absorbed oxygen on the surface compared to ambient levels, and may result in different binding characteristics.

To quantitatively estimate the effect of ozone treatment, MEDICI was used to simulate the I – V characteristics of a transistor with the same material parameters and layer thicknesses as the ZnO NW-FET, but using a rectangular geometry. The simulated device structure, with cross-section shown in figure 6(a), used a channel thickness equal to the nanowire diameter (120 nm) in the ZnO NW-FET, and an effective width (W_{eff}) which was adjusted to provide the correct I_{on} . The doping density of ZnO was set to $5 \times 10^{15} \text{ cm}^{-3}$, and the SAND film was modelled as a 15 nm thick SiO_2 layer with a dielectric constant of 3. For simulations using a μ_{eff} of $1175 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, W_{eff} was approximately 100 nm, as expected for a rectangular approximation to a cylindrical conductor. In order to account for surface charge effects, a fixed negative charge density (Q_F) is placed at the top and bottom interfaces of the channel, and a voltage-variable interfacial trap density (Q_{IT}) is placed at the SAND–ZnO interface. As shown in figure 6(b), a series of simulations with different values of Q_{IT} and Q_F were performed to fit the experimental I_{ds} – V_{gs} data from both as-fabricated (square dots) and 2 min ozone-treated (triangle dots) devices. The

Figure 6. (a) ZnO NW-FET structure set-up for MEDICI simulations, using rectangular geometry to approximate nanowire channel. (b) I_{ds} - V_{gs} relationships from (i) experimental data for as-fabricated (squares) and 2 min ozone-treated (triangles) devices and (ii) MEDICI simulations with parameters corresponding to 'best-fit' curves for the two cases (dashed and dotted lines). The fitting parameters are Q_{IT} and Q_F , as defined in the text.

dashed and dotted lines in figure 6(b) represent simulations with approximate 'best-fit' values to the as-fabricated and ozone-treated data, respectively. The as-fabricated device data can be modelled using $Q_{IT} = 4 \times 10^{12} \text{ cm}^{-2}$ and $Q_F = -5 \times 10^{10} \text{ cm}^{-2}$ while the data following ozone treatment correspond to $Q_{IT} = 2 \times 10^{12} \text{ cm}^{-2}$ and $Q_F = -3 \times 10^{11} \text{ cm}^{-2}$. The band diagrams shown in figure 5(d) were obtained from the MEDICI simulations using these parameters. Note that the surface charge concentrations, along with the relatively modest doping level, lead to a partial depletion of the nanowire bulk. In addition to the improved gating efficiency associated with the reduction in Q_{IT} , the fixed charge in the ozone-treated devices makes it easier to deplete the body of the transistor, and thus contributes to the improvements in subthreshold characteristics. The decrease in I_{on} following the 130 °C anneal cannot be explained simply by changes in surface charge or interface state density. The effect could be explained by a decrease in channel mobility, which may correspond to increased scattering caused by the relatively large density of surface states.

The shift of Q_F is consistent with prior reports of negative surface charges corresponding to oxygen species on the surface of metal oxides. The reduction in magnitude of Q_{IT} appears to be the primary mechanism responsible for the improvement in S observed following ozone treatment. The relative insensitivity of the ozone-treated devices to subsequent

vacuum processing and passivation indicates that the surface bound species are relatively stable.

4. Conclusion

In summary, single ZnO NW-FETs were fabricated using SAND as a gate dielectric, and the effects of metal contacts and ozone treatments were investigated. Outstanding device performance metrics were obtained by applying ozone treatment to ZnO NW-FETs with Al source/drain contacts, demonstrating enhancement-mode ZnO NW-FETs operating at sub-1V with exceptionally high I_{on} and $I_{on}:I_{off}$. Multiple ZnO NW-TFTs are expected to produce driving current comparable to that of poly-TFTs. With the excellent optical transparency and mechanical flexibility of ZnO nanowires, present reported enhancements in device performance metrics make ZnO NW-FETs a viable technology for the realization of low power flexible display circuits.

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