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A Field Effect Transistor Synthesized using Multiple Al-doped ZnO Nanorods

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Abstract
The different Al-doped ZnO nanorods and a SiO_2 gate insulator has been used to make nanorod field-effect transistors (FETs). The utilization of numerous nanorods gives higher on-current without significant declination in threshold voltage move and subthreshold inclines. It has been recorded that the on-current of the different ZnO nanorod FETs increases around directly with the quantity of nanorods, with on-current flows of roughly 1.8uA for each nanorod and little change in off-current roughly 4.2 pA. The subthreshold slopes and on–off current ratio of $5x10^2$ regularly enhance as the quantity of nanorods inside the channel is expanded, reflecting great consistency of properties from nanorod to nanorod. The electrical and optical properties were studied by using deposition parameters and the optimal conditions were defined. A comparison between conventional and Al-doped ZnO nanorods FETs shows that a conventional nanorod FET has a low conductivity in contrast with Al-doped ZnO nanorods FET. It has also been shown that temperature-dependent current-voltage relationship of single ZnO nanorod FETs affects the actuation energy of the drain current at gate voltages both above and below a certain limit.

Keywords: *Nanorod, transistor, ZnO, Al-dopant*

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INTRODUCTION
In recent years, transistors made up of nanobundles of single wall carbon nanotubes (SW-CNTs) [1] have replaced a Silicon thin film transistors (TFTs) and poly-Si TFTs [2] because those nano FETs have been widely used in microelectronic display devices, LEDs, laser diodes [3] and electron transport media for solar cells. These one of a kind nanostructures unambiguously show that ZnO most likely has the wealthiest group of nanostructures among all materials, both in structures also, in properties. The nanostructures could have novel applications in optoelectronics, sensors, transducers and biomedical sciences. Nanowires have the qualities of physical flexibility, transparency and electrical and mechanical properties. The test for accomplishing materials that are both electrically leading and optically straightforward is to comprehend the key material structure/property connections that control these properties so they might be decoupled with the end goal that the material holds straightforwardness while ending up electrically conductive [4]. They are widely used as nanobelts, nanosensors, nanoresonators, nanocantilevers and field effect transistors (FETs) [5]. ZnO nanowire transistor is the most suitable material having the quality of inherent flexibility. ZnO is a semiconductor having a large excitation binding energy (about 60 meV) and a widedirect band gap (about 3.37 eV). With these unique properties, ZnO has become one of the most important functional materials in terms of optical transparency and electrical conductivity. First report of ZnO nanowires in 2000 reveals the great attention on the study of 1-D ZnO nanowiresor nanorods [6] for their significance work in nanooptoelectronics. This great achievement brings nano-ZnO as the next most important nanomaterial after carbon nanotubes [7].

There was a challenge for the nanowire transistor devices to adjust the drive current capabilities of various devices. The technologies like a Si TFT or poly Si TFT that were used in display devices such as light emitting diodes (LEDs) and thin film transistor liquid crystal displays (TFT LCDs), have to be replaced by low power operation and low power consumption devices. The current drive per nanowire is limited and we require a large level of on-current, for that mobility clearly plays a role to increase the current driving capabilities of the nanowire to maximum. In order to achieve a large current, a large number of nanowires can be integrated within a single device. Since essential performance characteristics like on–off ratios and subthreshold slopes can be degraded by wire to wire variations, multi nanowire transistors can be developed and characterized to achieve the performance characteristics.

In this study, we have used multiple Al doped ZnO nanorods as the channel material and SiO_2 as insulating material to develop a nano FET. It has been shown that how on-current of the different ZnO nanorod FETs increases around directly with the quantity of nanorods andthe subthreshold slopes and on–off current ratio regularly enhance as the quantity of nanorods inside the channel is expanded, reflecting great consistency of properties from nanorod to nanorod. It has also been shown that how temperature-dependent current– voltage relationship of single ZnO nanorod FETs affects the actuation energy of the drain current at gate voltages both above and below a certain limit.

THEORETICAL METHODS AND COMPUTATIONAL TECHNIQUES

Al-doped ZnO nanorods showed hexagonal wurtzite structure. Wurtzite structure ZnO is shown in Figure 1. It is one of the most important II–VI group semiconductors with a direct and wide bandgap of 3.37 eV, large exciton binding energy of 60 meV and high optical gain of 300 cm^{-1} at room temperature. At room temperature, thermodynamically stable phase is wurtzite.

Figure 2 shows the SiO_2 based ZnO nanoFET in which ZnO nanorod has been grown using vapor transport method inside a tube furnace [8]. The material used to make ZnO nanorod was made up of a mixture of ZnO (99.999%), graphite carbon powder (99.9995%) and AlN (99.6%). A 60 nm thick thermally grown layer was used as a gate insulator on which an Al–doped multiple ZnOnonorod FET was fabricated. In our study, the average length and diameter of ZnO has been taken as 5 um and 300 nm. In the channel region, 20 nanorods has been used without overlapping between ZnO nanorods.Using semiconductor characterization systems, electrical measurements were performed. By using variable temperature probe station, variable temperature was measured. The temperature measured was in the step of 20K with a sweep from 300 K to 175 K. The turn-on voltages and average resistances were measured at room temperature (22℃) and at 50–120℃.

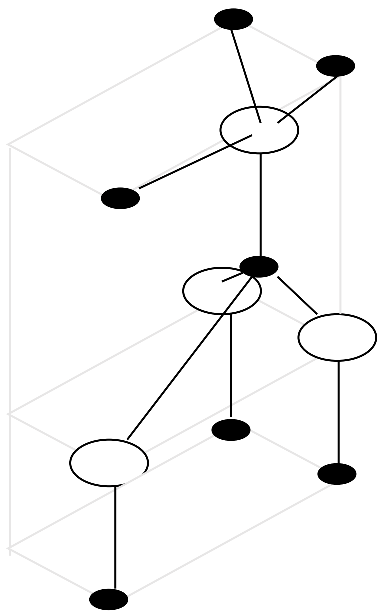

Fig. 1: *Wurtzite Structure of ZnO.*

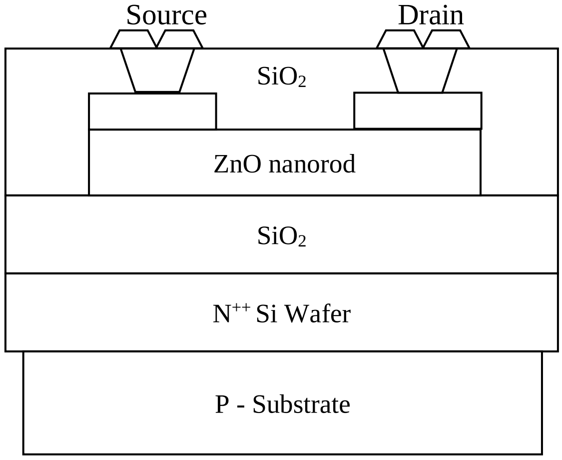

Fig. 2: *SiO_2 based ZnO nanoFET.*

RESULTS AND DISCUSSIONS

In Figure 2, we have seen that a ZnO nanorod has been used in a silicon based ZnO nanoFET, as a channel material. The drain current versus gate voltage characteristics of three ZnO FETs containing a single Al-doped nanorod each used in three transistors have been shown in fig. 3 along with its voltage and current data measured shown in Table 1, reveals that a single nanorod produces a small current. This characteristics is similar to the characteristics of an N type FET. Oxygen vacancies act as donors in ZnO, and may account for the n-channel behavior. For comparisons, we have studied undoped ZnO nanorod FET also and we concluded that undoped ZnO nanorod FET has a low conductivity (1nA) compared with Al-doped ZnOnanorods.(Table 2) (1 uA).We have measured the temperature-dependent, I_D - V_{DS} characteristics of a single ZnO nanorod FET at temperatures ranging from 300–200 K in 25K steps. The measured activation energies at three different gate biases (-1, 0, and 1 V) are 0.2, 0.1 and 0.07eV respectively. The activation energy is very low (0.07 to 0.2 eV) at gate voltages both above and below threshold (Tables 3, 4).

Table 1: *Gate Voltage (V) versus Drain Current, I_D (A) for Single Nanorod Each Used in Three ZnO nanoFETs.*

Gate Voltage (V)	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**
Drain Current (A) (FET 1)	$2x10^{-7}$	$1x10^{-7}$	$1.35x10^{-7}$	$1.55x10^{-7}$	$1.73x10^{-7}$	$1.76x10^{-7}$	$1.79x10^{-7}$	$1.82x10^{-6}$
Drain Current (A) (FET 2)	$2.5x10^{-7}$	$1x10^{-7}$	$1.35x10^{-7}$	$1.55x10^{-7}$	$1.65x10^{-7}$	$1.7x10^{-7}$	$1.75x10^{-7}$	$1.8x10^{-7}$
Drain Current (A) (FET 3)	$3x10^{-7}$	$1.05x10^{-7}$	$1.4x10^{-7}$	$1.6x10^{-7}$	$1.65x10^{-7}$	$1.72x10^{-7}$	$1.72x10^{-6}$	$1.75x10^{-6}$

Table 2: *Gate-source Voltage, V_{GS} versus Drain Current, I_D at Different Values of Drain-source voltage, V_{DS} for a ZnO FET Containing a Single Nanorod*

For V_{DS} = 0V		**For V_{DS} = 0.4V**		**For V_{DS} = 0.8V**		**For V_{DS} = 1.2V**		**For V_{DS} = 1.6V**		**For V_{DS} = 2V**		**For V_{DS} = 2.4V**	
V_{GS} (V)	**I_D(A)**	**V_{GS} (V)**	**I_D(A)**	**V_{GS} (V)**	**I_D (A)**	**V_{GS} (V)**	**I_D (A)**	**V_{GS} (V)**	**I_D(A)**	**V_{GS} (V)**	**I_D (A)**	**V_{GS} (V)**	**I_D(A)**
-1.5	0.00E+00	-1.5	8.00E-09	-1.5	3.00E-08	-1.5	4.00E-08	-1.5	4.40E-08	-1.5	4.50E-08	-1.5	4.70E-08
-1	0.00E+00	-1	1.00E-07	-1	1.65E-07	-1	2.00E-07	-1	2.35E-07	-1	2.50E-07	-1	2.60E-07
-0.5	0.00E+00	-0.5	1.80E-07	-0.5	3.50E-07	-0.5	4.50E-07	-0.5	5.00E-07	-0.5	5.40E-07	-0.5	5.60E-07
0	0.00E+00	0	2.80E-07	0	5.00E-07	0	6.50E-07	0	7.50E-07	0	8.20E-07	0	8.50E-07
0.5	0.00E+00	0.5	4.00E-07	0.5	7.00E-07	0.5	9.00E-07	0.5	1.03E-06	0.5	1.12E-06	0.5	1.18E-06
1	0.00E+00	1	5.30E-07	1	9.00E-07	1	1.15E-06	1	1.30E-06	1	1.42E-06	1	1.50E-06
1.5	0.00E+00	1.5	7.00E-07	1.5	1.10E-06	1.5	1.35E-06	1.5	1.55E-06	1.5	1.70E-06	1.5	1.80E-06

Table 3: *Gate-source Voltage, V_{GS} versus Drain Current, I_D at Different Values of Drain-source Voltage, V_{DS} for a ZnO FET Containing 10 Nanorods*

For V_{DS} = 0V		**For V_{DS} = 0.4V**		**For V_{DS} = 0.8V**		**For V_{DS} = 1.2V**		**For V_{DS} = 1.6V**		**For V_{DS} = 2V**		**For V_{DS} = 2.4V**	
V_{GS} (V)	**I_D (A)**	**V_{GS} (V)**	**I_D (A)**	**V_{GS} (V)**	**I_D (A)**	**V_{GS} (V)**	**I_D (A)**	**V_{GS} (V)**	**I_D (A)**	**V_{GS} (V)**	**I_D (A)**	**V_{GS} (V)**	**I_D (A)**
-1.5	0.00E+00	-1.5	8.00E-08	-1.5	3.00E-07	-1.5	4.00E-07	-1.5	3.50E-07	-1.5	4.50E-07	-1.5	4.00E-07
-1	0.00E+00	-1	1.00E-06	-1	1.65E-06	-1	2.00E-06	-1	2.35E-06	-1	2.50E-06	-1	2.60E-06
-0.5	0.00E+00	-0.5	1.80E-06	-0.5	3.50E-06	-0.5	4.50E-06	-0.5	5.00E-06	-0.5	5.40E-06	-0.5	5.60E-06
0	0.00E+00	0	2.80E-06	0	5.00E-06	0	6.50E-06	0	7.50E-06	0	8.20E-06	0	8.50E-06
0.5	0.00E+00	0.5	4.00E-06	0.5	7.00E-06	0.5	9.00E-06	0.5	1.03E-05	0.5	1.12E-05	0.5	1.18E-05
1	0.00E+00	1	5.30E-06	1	9.00E-06	1	1.15E-05	1	1.30E-05	1	1.42E-05	1	1.50E-05
1.5	0.00E+00	1.5	7.00E-06	1.5	1.10E-05	1.5	1.35E-05	1.5	1.55E-05	1.5	1.70E-05	1.5	1.80E-05

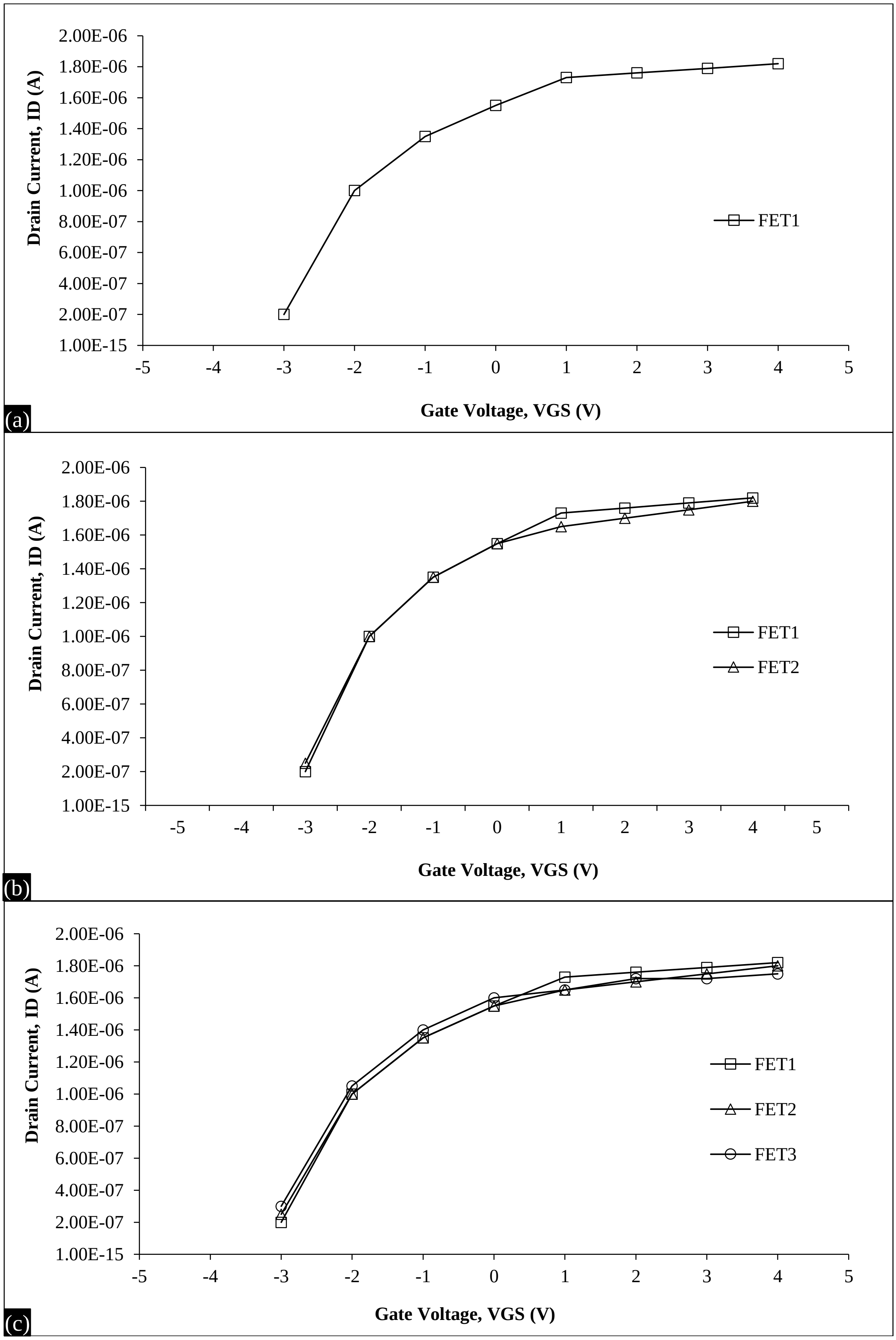

Fig. 3: *Drain Current versus Gate-source Voltage (I_D -V_{GS}) for (a) a Single ZnO Nanorod FET (b) Two Single ZnO FETs (c) Three Single ZnO Nanorod FETs*

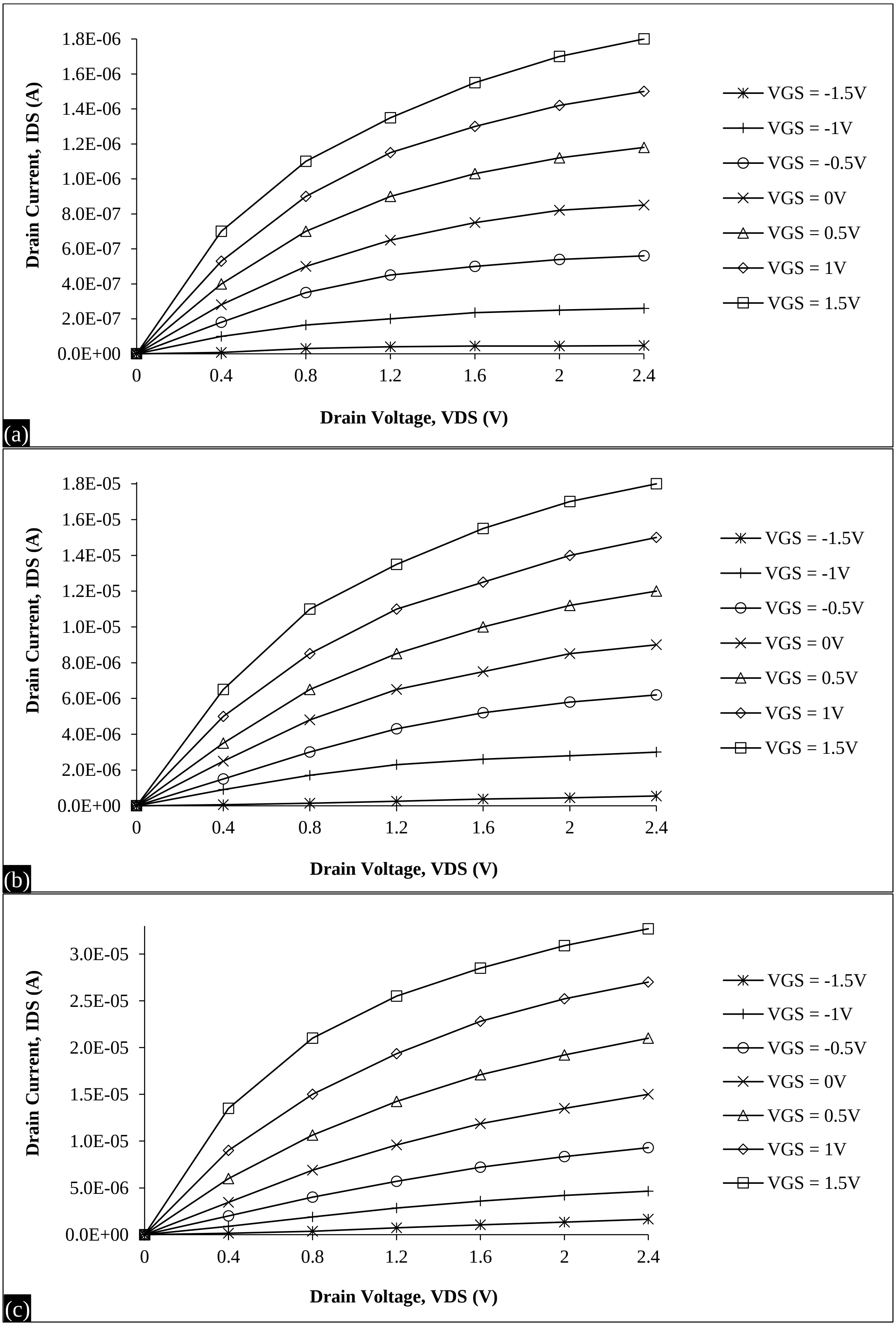

Fig. 4: *Drain-Source Voltage, V_{DS} versus Drain Current, I_D characteristics (V_{DS}-I_D) of (a) ZnO Nanorod FET Containing a Single Nanorod, (b) ZnO Nanorod FET Containing 10 Nanorods, and (c) ZnO Nanorod FET Containing 20 Nanorods.*

Table 4: *Gate-source Voltage, V_{GS} versus Drain Current, I_D at Different Values of Drain-source Voltage, V_{DS} for a ZnO FET containing 20 Nanorods.*

For V_{DS} = 0V		For V_{DS} = 0.4V		For V_{DS} = 0.8V		For V_{DS} = 1.2V		For V_{DS} = 1.6V		For V_{DS} = 2V		For V_{DS} = 2.4V	
V_{GS} (V)	I_D (A)	V_{GS} (V)	I_D (A)	V_{GS} (V)	I_D (A)	V_{GS} (V)	I_D (A)	V_{GS} (V)	I_D (A)	V_{GS} (V)	I_D (A)	V_{GS} (V)	I_D (A)
-1.5	0.00E+00	-1.5	1.50E-07	-1.5	3.75E-07	-1.5	7.20E-07	-1.5	1.05E-06	-1.5	1.35E-06	-1.5	1.65E-06
-1	0.00E+00	-1	9.00E-07	-1	1.90E-06	-1	2.85E-06	-1	3.60E-06	-1	4.20E-06	-1	4.65E-06
-0.5	0.00E+00	-0.5	2.00E-06	-0.5	4.00E-06	-0.5	5.70E-06	-0.5	7.20E-06	-0.5	8.34E-06	-0.5	9.30E-06
0	0.00E+00	0	3.45E-06	0	6.90E-06	0	9.60E-06	0	1.19E-05	0	1.35E-05	0	1.50E-05
0.5	0.00E+00	0.5	6.00E-06	0.5	1.07E-05	0.5	1.43E-05	0.5	1.71E-05	0.5	1.92E-05	0.5	2.10E-05
1	0.00E+00	1	9.00E-06	1	1.50E-05	1	1.94E-05	1	2.28E-05	1	2.52E-05	1	2.70E-05
1.5	0.00E+00	1.5	1.35E-05	1.5	2.10E-05	1.5	2.55E-05	1.5	2.85E-05	1.5	3.09E-05	1.5	3.27E-05

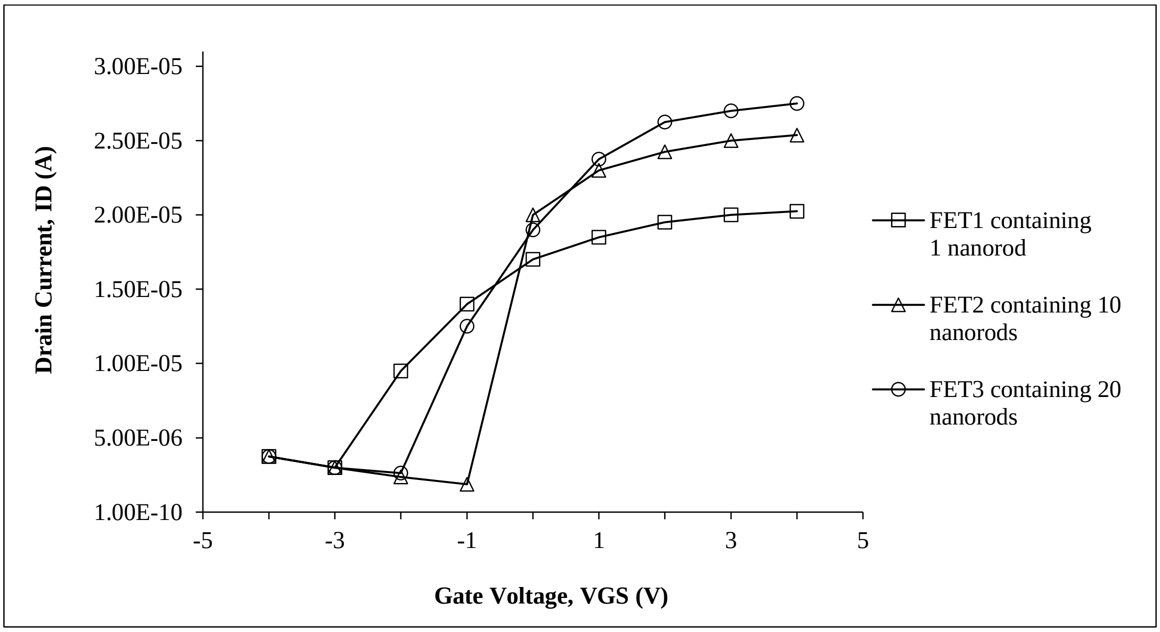

Fig. 5: *Gate-source Voltage, V_{GS} versus Drain Current, I_D (V_{GS} - I_D) for ZnO FET Containing 1, 10 and 20 Nanorods.*

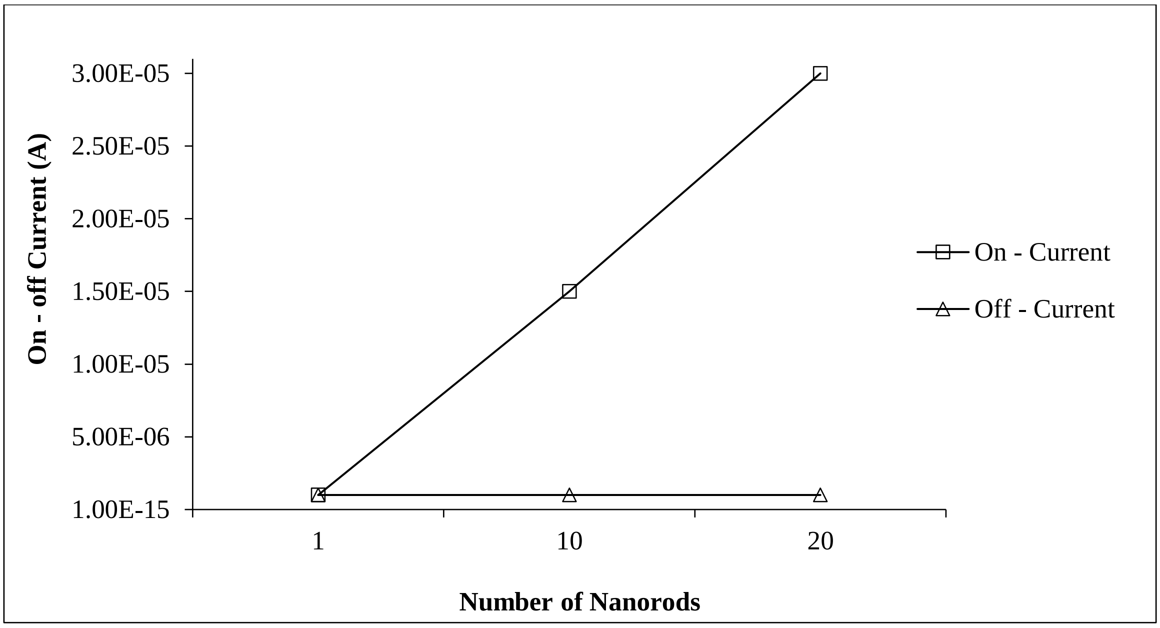

Fig. 6: *On–Off Current versus Number of Nanorods used in ZnO FETs.*

Table 5: *Gate-source Voltage, V_{GS} Versus Drain Current, I_D (V_{GS} - I_D) for ZnO FET containing Different Number of Nanorods.*

For a single nanorod		**For 10 nanorods**		**For 20 nanorods**	
V_{GS} (V)	**I_D (A)**	**V_{GS} (V)**	**I_D (A)**	**V_{GS} (V)**	**I_D (A)**
-4	3.75E-06	-4	3.75E-06	-4	3.75E-06
-3	3.00E-06	-3	3.00E-06	-3	3.00E-06
-2	9.50E-06	-2	2.38E-06	-2	2.63E-06
-1	1.40E-06	-1	1.88E-06	-1	1.25E-05
0	1.70E-06	0	2.00E-05	0	1.90E-05
1	1.85E-06	1	2.30E-05	1	2.38E-05
2	1.95E-06	2	2.43E-05	2	2.63E-05
3	2.00E-06	3	2.50E-05	3	2.70E-05
4	2.03E-06	4	2.54E-05	4	2.75E-05

Figure 4 (a,b,c) shows the drain – source voltage versus drain current (V_{DS} -I_D) characteristics. Figure 4a, 4b and 4c shows the characteristics of ZnO FET containing 1, 10 and 20 nanorods respectively. The drain current, I_D is approximately 1.8 uA, 18 uA and 30 uA for single nanorod ZnO FET, 10 nanorod ZnO FET and 20 nanorod ZnO FET respectively at V_{DS} = 2.4 V and V_{GS} = 1.5 V as may be seen from fig. 4a, 4b and 4c respectively. Figure 5 shows the gate-source voltage, V_{GS} versus drain current, I_D (V_{GS} -I_D) characteristics for ZnO FET containing 1, 10 and 20 nanorods (Table 5).

Figure 6 shows the on–off current level versus number of nanorods used in ZnO FETs. It can be seen from Figure 6 that the off current is in the range of approximately 10 picoampere and remains constant. The on-current increases with the increase in number of nanorods present in ZnO FET which can be seen from Figure 6.

CONCLUSION

Al-doped different ZnO nanorod FETs with SiO_2 as an insulting material were exhibited to accomplish higher on-currents without significant downgrade in on–off proportion, in threshold voltage shifts, or in subthreshold inclines. Al doping gives more strong conduction as compared to undoped devices. This is the effect of Al doping that Al substitution for O would bring about acceptor doping. The current level can be increased by increasing the number of nanorods in ZnO FETs even at low voltage operations. These outcomes show that the low on-current deficiencies of nanorod devices can be remedied by utilizing multiple ZnO nanorod FET devices. This quality of multiple ZnO nanorod FETs can be as driving capabilities for display applications. Moreover, silicon based single ZnO nanorod FETs, at various temperatures (300–180 K, 25 K venture) along with current–voltage (I–V) characteristics, demonstrate low actuation energies, low barrier infusion from the contacts to the channel.

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