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Luminous TCAD Analysis of Transparent ITO Gate Recessed Channel MOSFET using Elliptical Lenslet

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***Abstract*—In this paper, we report the effect of luminous behaviour of transparent gate Recessed Channel MOSFET (RC-MOSFET).Aggressive scaling is associated with a number of higher order effects such as short channel effects, hot carrier effects and heating effect which significantly affect the device performance. The Ray trace method in MOSFET has emerged to be the ultimate solution. The proposed device has an elliptical lenslet above the RC MOSFET to focus the raytrace in to the transparent indium tin oxide (ITO) gate. The effect of illumination with the improved photogeneration rate, optical intensity, switching ratio and light absorption is studied. The work proves the effectiveness of transparent gate RC-MOSFET for higher efficiency, speed, ON current, reduction in power dissipation and better temperature stability. Luminous-3D RC-MOSFET is fully integrated with ATLAS and Device 3D.**

***Keywords* — DEVEDIT -3D, Illumination, ITO, Photogeneration, Ray Trace, RC-MOSFET.**

I. INTRODUCTION

In order to achieve high speed, low power dissipation and low noise, the device feature size is reduced. Short channel effect (SCE) degrades the controllability of drain current, which leads to degradation of the subthreshold slope and increase in subthreshold current [1]. As the device length is reduced to increase the speed of operation and the number of components per chip, the so-called short channel effect arises [3]. Recessed channel MOSFET is a promising device for suppressing SCEs, punch through and hot carrier effects. This is due to shallow junctions or even negative junctions in RC MOSFET which can be fabricated without any increase in the series resistance [1-3]. Thinning gate oxide and using shallow source/drain junctions are known to be effective ways of preventing SCEs.

In this paper luminous analysis is performed for Recessed channel MOSFET and conventional MOSFET for DC and AC under small signal condition of the incident frequency range of 600nm to 900nm [6]. Use of transparent ITO as a gate material has the advantage of minimal reflection of the gate surface so that most of the raytrace by an elliptical lens incident at the gate reach the channel region. The transparent ITO RC MOSFET shows the possibility to operate at relatively low temperature of 100 ^{0}C, due to the characteristics of downsizing and cost reduction in fabrication of integrated circuits [4]. Tin-doped ITO semimetal gate electrodes of the RC MOSFET is a solid solution of indium oxide (In_2O_3) and Tin oxide (SnO_2) material of 91:9 weight percent with a purity of 99.99% [5]. The advantage of ITO is that it possesses very high electrical conductivity and optical transparency in the visible region. The purpose of using ITO in Recessed channel MOSFET is to obtain stable film for large-area coatings with exceptionally low resistivity, improve switching ratio, which causes the decrease in device power consumption and high transmittance within the visible spectrum range [7].

While nanoscale MOSFET can do many things, but one thing it cannot do very well is to generate power at high frequencies. This is because as transistors become smaller, they tend to breakdown very easily with even a small amount of voltage or current. Up to now, all the research work has been focused on improving the photoresponse by implementing methods of enhancing the photocurrent such as use of transparent gate electrode [8] and channel material engineering [4]. Luminous3D analysis calculates the optical intensity and the photogeneration rate within the semiconductor device. It consistently solves drift diffusion or energy balance equations with photogeneration from an optical source for steady state, time domain and small signal analysis [9]. The light absorption and photogeneration effects of the reflection coefficients and the integrated loss due to absorption over the ray path are saved for each ray [15].

In luminous analysis, lenslets are not meshed for drift diffusion type analysis and is only used for raytracing. In elliptical lens, we specify the semi major axis, center and index. The light rays when pass through the lens converge on a single point. The single point to which the light rays are converging is called the focal point. The lens is used to specify lenslet characteristics used for light propagation analysis [15].

A. Device Structure: Parameters And Simulation Approach

Analysis of Recessed channel MOSFET using Transparent ITO gate has been performed using the ATLAS and DEVEDIT 3D device simulator. Silvaco ATLAS advanced luminous 3D optical device simulator has been used to extract the device characteristics under illumination [16]. Fig 01(a) and Fig 01(b) shows the simulated device structure of the RC MOSFET and conventional MOSFET under illumination. The RC MOSFET uses a p-type substrate of concentration of 1×10^{16} cm^{-3}, source and drain regions have peak concentration of 1×10^{19} cm^{-3}. The channel threshold voltage of the fabricated structure extracted is 0.28V. All simulations were carried out at 300K and bias voltage V_{gs}=0.8V and V_{ds}=0.5V. We use a light source which ranges between 600nm to 900nm wavelength. The models used in the simulations of the RC MOSFET are Shockley–Read–Hall (SRH), Fermi Statistics (FERMI), AUGER, FLDMOB and Lombaerdi mobility model (CVT) for transverse field dependence. The CVT model sets general aim mobility ideal to include concentration, temperature, parallel field and transverse field effects [4]. The SRH model accounts for recombination/generation effects and uses fixed minority carrier lifetimes. Ray trace method has been used in simulator to solve photogeneration rate at each grid point. For the study of I-V characteristics, gate currents, transconductances (g_m) the impact ionization and hot-electron-injection models are used to provide an exact measure of hot-carrier-injection in short-channel devices [17].

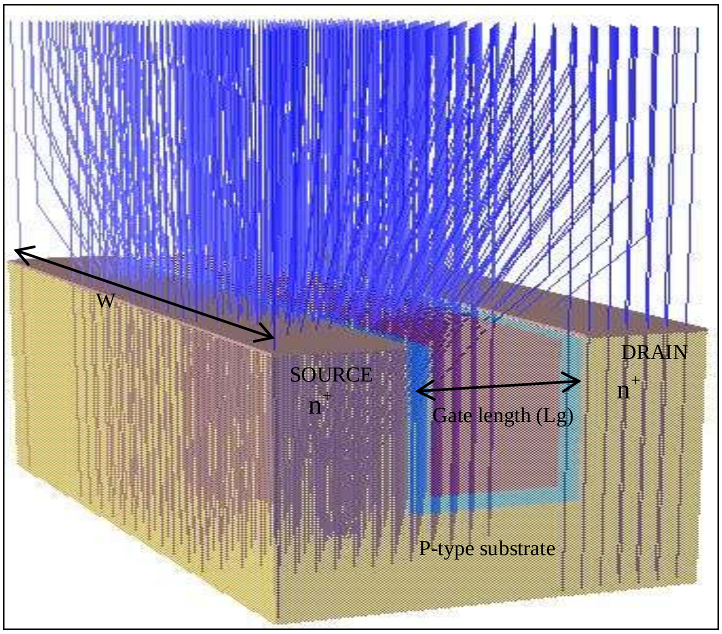

Fig. 01(a): Simulated Device structure of RC- MOSFET.

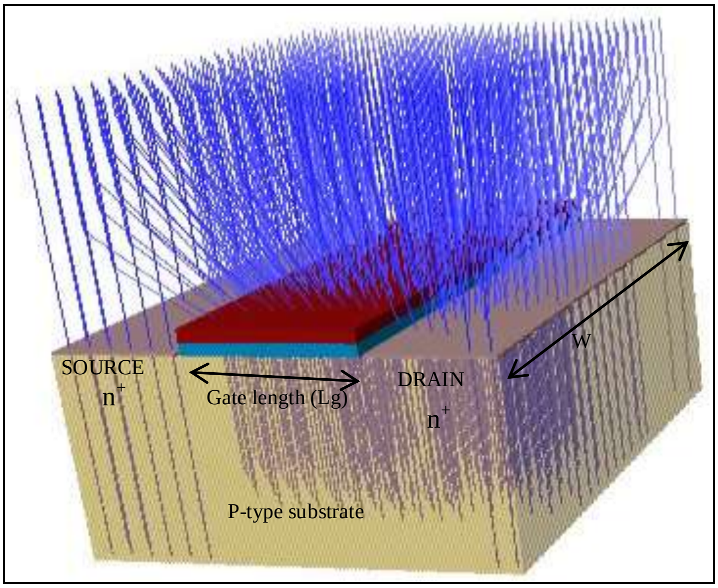

Fig. 01(b): Simulated Device structure Conventional MOSFET.

When light falls on elliptical lens, then the rays converge on a single point i.e. focal point on the surface of a transparent ITO gate and the photon whose energy is greater than that of the band-gap energy of the ITO material, are absorbed. This absorption excites an electron to leap into the valence band to the conduction band and as a result, a hole is left in the valence band. These electrons and holes behave as free particles and travel below intrinsic or extrinsic applied electric field [8]. There is continuous separation of electron–hole pairs due to the absorption of photons. The intensity of the incident light is directly proportional to the photocurrent. The aluminium electrodes in source and the drain side block the incident light. The real and imaginary values of refractive index for calculation of reflection coefficient at the transparent ITO Gate are taken from SOPRA database [19].

TABLE I: Design Parameters for Conventional MOSFET & RC-MOSFET device designs

Channel Length (L_G)	30nm
Device Width (W)	200nm
Groove Depth (d)	40nm
Source/Drain Junction Depth	30nm
Negative Junction Depth (NJD)	20nm
Substrate Doping (N_A)	1×10^{16} cm^{-3}
Source/Drain Doping (N_D^+)	1×10^{19} cm^{-3}
Physical Oxide Thickness (t_{ox})	5.0nm
Permittivity of SiO_2	$\varepsilon ox = 3.9$
Wavelength	600nm to 900nm
Gate to Source voltage (V_{GS})	0.8V
Drain to Source voltage(V_{DS})	0.55V
Work function(Φ) Conventional MOSFET	4.7eV
Work function(Φ) RC MOSFET	4.7eV
Dimension	100×80nm

1) Results And Discussion

In this paper, we compare transparent gate RC MOSFET and conventional MOSFET and demonstrated that the proposed device design possesses superior switching ratio in comparison to other devices. The present analysis is carried out for a channel length, L_g=30nm, wavelength=600nm angle=90^0,Theta=90^0,and thickness of oxide, t_{ox}= 5.0nm, work function Φ_{ITO}=4.7eV.

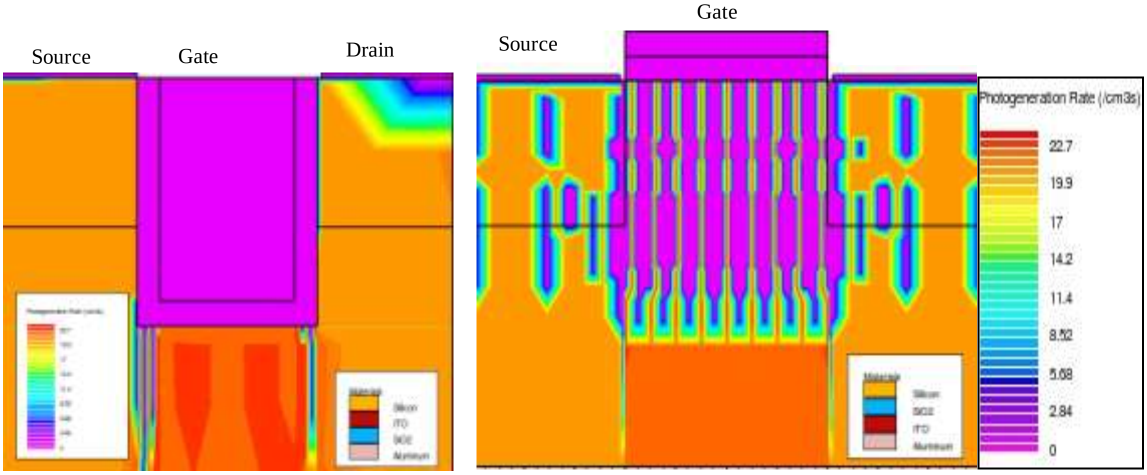

Fig. 02: Contour plot showing photogenerated carriers within the channel region of the incident radiation in RC and conventional MOSFET.

Fig.02: shows a contour plot of photogeneration rate along the channel length of RC and conventional MOSFET. Photogeneration or the photocurrent is the most important factor in luminous analysis. It is the process where mobile electron and holes are created due to absorption of electromagnetic radiation in the channel region. The photon has an enormous energy than the bandgap i.e hv > Eg [12]. Photogeneration rate is maximum in the channel region (Red colour) in RC-MOSFET as comparsion to conventional MOSFET. This is mainly due to ITO gate and moreover, the gate oxide is taken to be thin so that most of the incident radiation generates EHPs due to the absorption of incident photons in the channel region of RC-MOSFET [13].

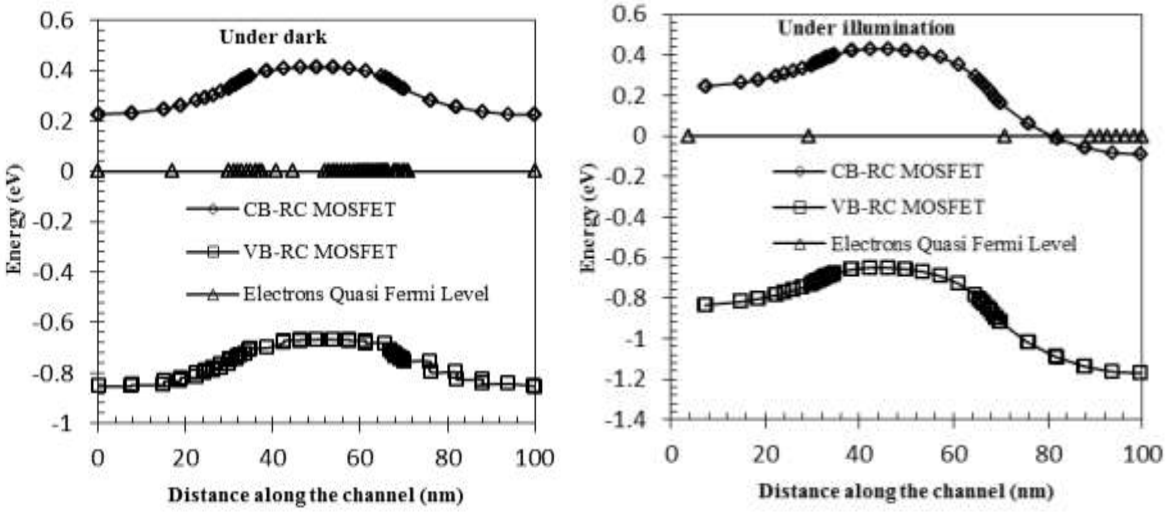

Fig. 03: Conduction band energy and Valence band energy variation along the channel at Electron Quasi Fermi Level at zero bias Under dark and under illumination for RC-MOSFET.

Fig. :03 shows the variation of conduction band and valence band with electron quasi Fermi level along the channel length of RC MOSFET examined under dark and illuminated conditions & it is mainly due to electron quasi Fermi level which lies within the valence band and conduction band at source and drain region. It helps to analyze the motion of the carriers i.e. carriers always flow from the source to drain. In normal operation of n-channel MOSFET, free electrons move from source to drain, but the current direction is from drain to source. Since the hole current is negligible everywhere, it is assumed that the electron quasi Fermi energy (level) is constant where hole concentration is significant. Under illumination, the free carriers are increased so that thermalisation happens so fast that the carriers relax to the conduction band edge long before they reach the contacts [11]. Hence, it is the thermalised carriers that determine the quasi-Fermi levels.

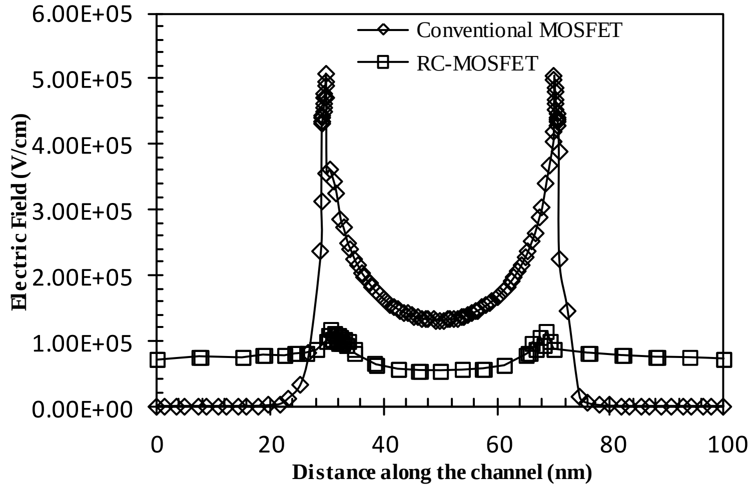

Fig. 04: Electric field variation along the channel for Conventional MOSFET and RC-MOSFET at L_G=30 nm, V_{ds}=0.5 V, V_{gs}=0.8 V, t_{ox}=5nm and wavelength=650nm.

Fig. 04: shows the variation of the electric field, along the channel from source to drain side for RC-MOSFET and conventional MOSFET. It can be seen that there is an appreciable increase in the electric field near the source side as compared to drain side in RC MOSFET. It clearly shows that electron velocity near the source is improved, thereby improving the carrier injected into the channel. This is mainly due to the photocurrent available at 650nm wavelength of the incident light because maximum light is reaching the channel region in RC MOSFET.

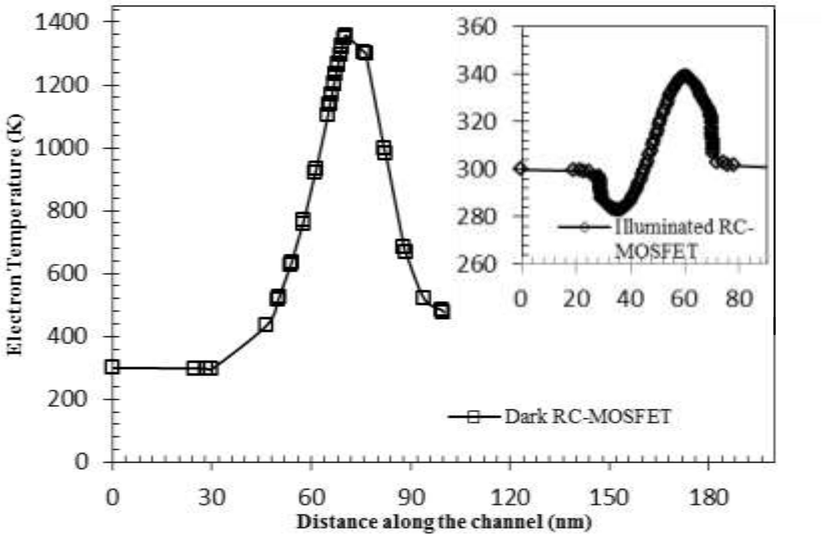

Fig. 05: Electron temperature variation along the channel for wavelength= 650nm in dark and illumination RC-MOSFET.

Fig. 05: shows the variation of electron temperature along the channel length from source to drain under dark and illumination RC MOSFET. As is clear from the results, an appreciable reduction in electron temperature for illuminated RC MOSFET at the drain side is observed. This is because incident radiation results in a large amount of photon-generated electron hole pair in the depletion layer. Indium tin oxide has a low electrical resistivity, high optical transparency of visible light and exhibits metallic character of high conductivity, so it is directly dependent upon temperature [18]. When the carrier concentration increases, mobility decreases and hence, the increase in electron temperature is less in an illuminated RC MOSFET as compared to under dark condition.

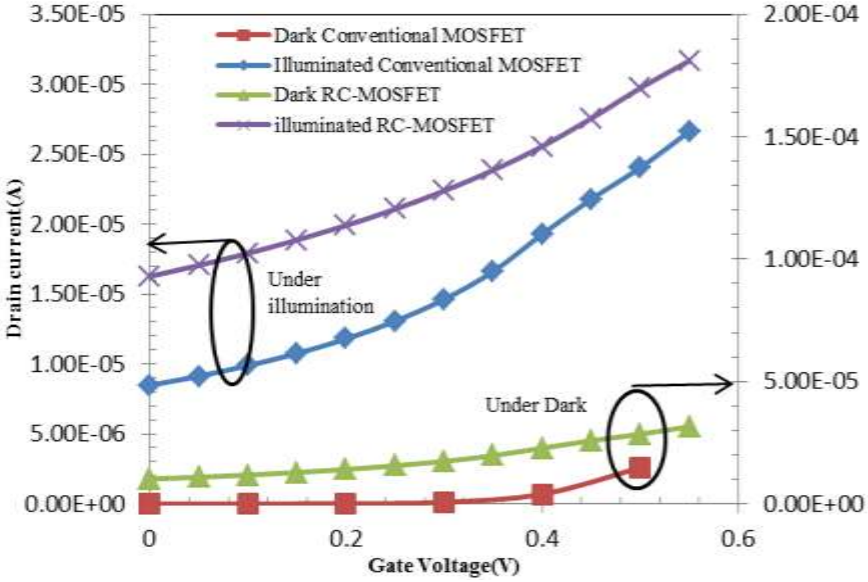

Fig. 06: Drain current Vs Gate Voltage for V_{DS}= 0.5 V in under illumination and dark RC-MOSFET & Conventional MOSFET.

Fig 06: shows the variation of drain current with respect to gate voltage V_G varying from 0 to 0.8V with V_D=0.5 V in dark and under illumination. It is evident from the figure that there is an increase in drain current under illumination as compared to the dark condition. It is due to more electron hole pair generation in the depletion region and the effective threshold voltage reduces under illumination [10]. It clearly shows that RC MOSFET is a better photo-sensing device because it has lower dark current and enhanced photo sensitivity due to its better gate controllability. This higher effective gate bias enhances the device conductivity and consequently the drain current increases.

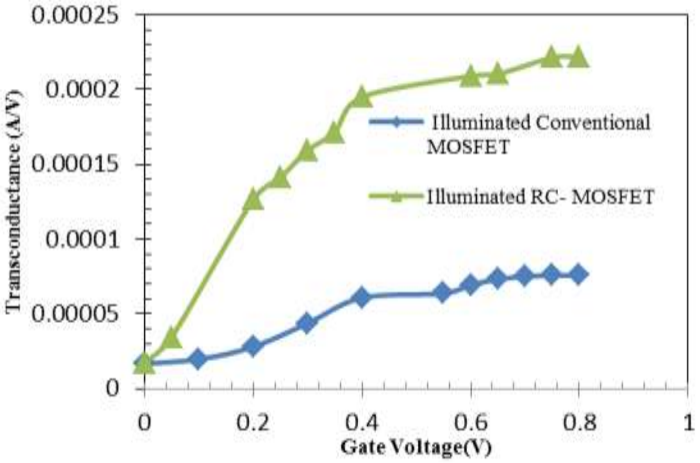

Fig. 07: Transconductance Vs Gate Voltage for V_{DS}= 0.5V in under illumination RC-MOSFET & Conventional MOSFET.

Fig. 07: shows the variation of transconductance with respect to drain voltage under varying gate voltage from 0V to 0.8V. The drain current is low until the device goes in the inversion layer. Due to this, the change in gate transconductance in RC MOSFET is seen at higher gate voltage as shown in figure. It is evident from the figure that the transconductance curve reaches a top and then remains constant in the saturation region. This is due to the effect of V_{GS} on enhanced electron mobility. The transconductance is use in integrated circuit design as it decides power dissipation and transition frequency. A substantial rise in transition frequency can contribute towards an increase in drain current and hence improvement in transconductance [14].

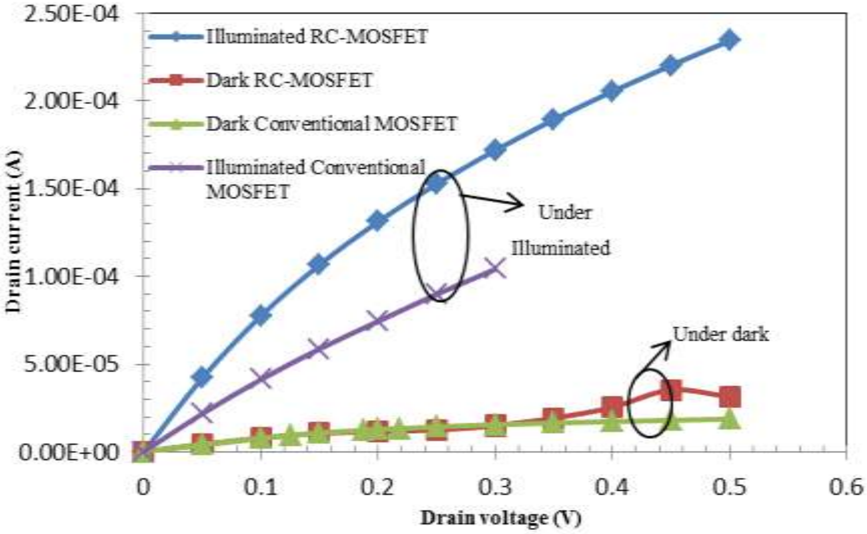

Fig. 08: Drain current Vs Drain Voltage for V_{GS}= 0.5V in under illumination RC-MOSFET & Conventional MOSFET.

Fig. 08: shows the variation of drain current with respect to drain voltage V_D varying from 0V to 0.8V with V_{GS}=0.5 V in dark and under illumination. It can be seen that the effective threshold voltage reduces because of optical radiation due to photo voltage created across the gate terminal. It is due to higher magnitude of photogenerated current than the dark current that effective gate control and subthreshold characteristics enhance [16].

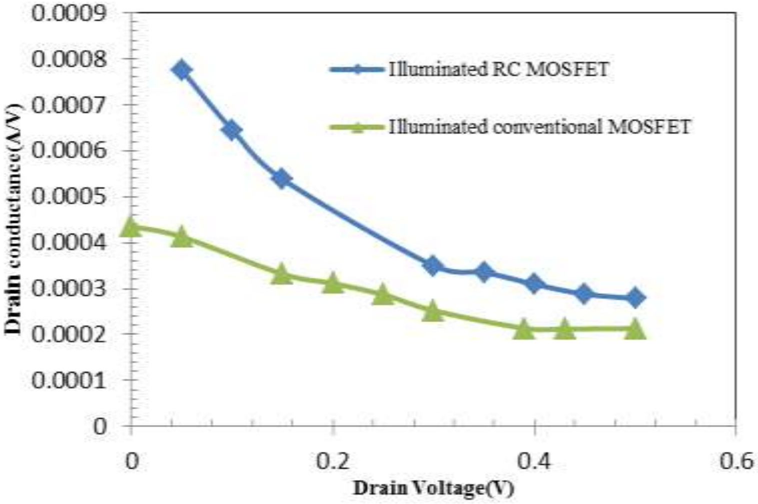

Fig. 09: Drain Conductance Vs Drain Voltage for V_{GS}= 0.8 in under illumination RC & conventional MOSFET.

Fig. 09: shows the variation of drain conductance with respect to drain voltage with V_D varying from 0V to 0.5V and V_G=0.8 in under illumination. This shows the drain conductance is constant with increasing drain voltage. As it is clear from the figure that output drain conductance is proportional to the drain current, and drain current is constant in saturation region of the RC and conventional MOSFET at higher drain voltage. So the drain conductance remains constant in saturation region under illumination RC and conventional MOSFET.

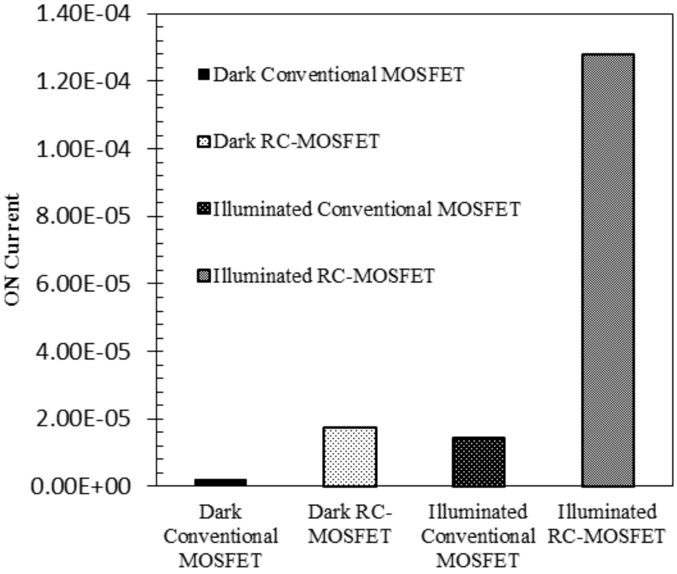

Fig. 10: ON Current for RC-MOSFET and conventional MOSFET under dark and illuminated at L_G=30 nm.

Fig. 10: shows high ON current in illuminated RC-MOSFET in comparison to dark RC and conventional MOSFET which favours pertinence in switching applications as compared to conventional MOSFET. In ITO, indium oxide (In_2O_3) and Tin oxide (SnO_2) contributes many free electrons which increases the electrical conductivity and decreases the resistivity [18]. As a result, the electron velocity near the source side is higher in an illuminated RC MOSFET which magnifies the source carrier injected into the channel Hence it improved the transconductance, low power dissipation and current driving capability in illuminated RC MOSFET.

CONCLUSION

Luminous analysis of the transparent RC MOSFET has been studied using silvaco TCAD software. In this paper, we emphasize our focus on transparent ITO gate RC MOSFET for improved switching ratio, transconductance and reduction in power dissipation. The high photogeneration rate is attributed to improved transmittance of the transparent ITO gate RC MOSFET compared to conventional MOSFET. The work thus presents a transparent RC MOSFET design as a promising solution for high-performance optical applications in the visible range of wavelength.

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