An Investigation on the Comparative Sensor Performance of Polysilicon Nanowires with Single Crystal Silicon Nanowire

By

Anamika Shargen

Mehedi Hasan

&

Salim Sazzad

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Thesis Advisor   Department Chairperson

Dr. Mohammad Mojammel Al Hakim   Dr. MuhammedMazharul Islam

Department of Electrical & Electronic Engineering, East West University

Abstract

We study for the first time the effect of nanowire thickness and doping concentration on the electrical characteristics of single crystal and polycrystalline silicon nanowire biosensors. For nanowire thicknesses of 100 nm and 75 nm, a plausible sub-threshold slope around 100 mV/decade for a viable biosensor operation only achieve if doping concentration is 2×10^{16}/cm^3 or below both for single crystal and poly Si nanowires. For a 50nm nanowire thickness a relatively wide doping concentration range with a maximum doping up to 4×10^{17}/cm^3 choose for biosensor design while maintaining decent sub-threshold characteristics. The widest range of doping concentrations choose for 25nm and 10nm nanowire thickness with a maximum doping up to 10^{18}/cm^3 while maintaining a promising sub-threshold slope around 95 mV/decade for a viable biosensor design using single crystal and polycrystalline silicon nanowires. In general poly Si NW shows inferior characteristics than single crystal Si NW. However, for 10nm Si NW single crystal & poly Si NW show same sub-threshold slopes at all doping densities. Considering the fact that spacer etch process provides the cheapest & mass manufacturable platform for biosensor fabrication using poly Si material in comparison to the available single crystal platforms. It decides from this work that poly Si NW biosensor with Si thickness ≤ 10nm is the possible commercial route of sensor fabrication.

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First of all, we would like to thank our thesis supervisor Professor Dr. Mohammad Mojammel Al Hakim, Department of Electrical and Electronic Engineering of East West University (EWU), Dhaka, for his affectionate guidance and giving us the great opportunity to research on this interesting topic. Without his support we could not reach the current stage with this thesis. He continually provided us with invaluable knowledge throughout this research. We greatly appreciate his dedication and owe him lots of gratitude for guiding us with friendly behavior.

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Finally, we want to thank our family for support us as well as thank to all of our friends for their endless love and support.

Approval

The thesis title "An Investigation on the Comparative Sensor Performance of Polysilicon Nanowires with Single Crystal Silicon Nanowire" submitted by Mehedi Hasan (2013-2-80-061), Salim Sazzad (2013-2-80-063) and Anamika Shargen (2013-2-80-068) in the semester of Spring-2017, has been approved as satisfactory in partial fulfillment of the degree of the Bachelor of Science in Electrical and Electronic Engineering on April, 2017.

_____

Professor Dr. Mohammad Mojammel Al Hakim

Department of Electrical and Electronic Engineering

East West University, Dhaka 1212, Bangladesh

Department of Electrical & Electronic Engineering, East West University

Authorization

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Salim Sazzad

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Mehedi Hasan

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Anamika Shargen

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Chapter 1

Introduction

A nanowire is an extremely small structure, typically with diameters on the order of few nanometers up to 100nm. Silicon nanowire is one of the 1D nano-structures and has emerged as the promising sensing nanomaterial upon its unique mechanical, electrical and optical properties [1]. Due to its small size and large surface-to-volume ratio the depletion and accumulation of charge-carriers produced by specific binding of biological macromolecule on the surface affects the entire cross sectional conduction pathway, that's why NW devices give extraordinary sensitivity when compared to other transducers reported in the literature [2]. Si-NW chemical sensors operated as field-effect transistors (FET) are currently the most commonly used structures [3]. The application of silicon nanowire as a sensing nanomaterial for detection of biological and chemical species has gained attention due to its unique properties [4]. Though this advantage of nanowires has been used to sense ions, proteins, DNA and viruses, some important issues remain for mass commercialization. The appropriate choice of thickness, length, doping of nanowires and cost of fabrication are the outstanding issues has to be specified.

In general, the silicon nanowire nanofabrication toolbox consists of two techniques such as bottom-up approach and top-down approach. Generally, single crystal silicon nanowire is fabricated by using bottom-up technique. Bottom-up approach is a growth or synthesized technique of the Si NWs from bulk silicon wafers either metal catalyzed-assisted or metal catalyzed-free [4]. Bottom-up nano-fabrication is in principle simple and provides many high quality materials. In recent years, many researchers have successfully fabricated Si NWs using this approach in producing a large quantity of Si NWs [4]. In these techniques, suitable methods for accurate nanowire alignment are lacking, and electrical contact formation is problematic, making it difficult to construct functional device arrays [3].

Some expensive top-down technique is also exists for fabricating single crystal silicon nanowire which overcomes the shortcomings of bottom-up. Several groups used nano-patterning techniques such as deep-UV photolithography and electron beam lithography to fabricate silicon nanowires on silicon-on-insulator (SOI) substrate [6]. This has the advantage of CMOS compatibility. But the major disadvantage of this technique is the high cost associated with these advanced lithography techniques and expensive SOI wafers. Recently a low cost, top-down approach to nanowire fabrication has been reported that uses thin film technology and spacer etch technique [6-7]. This approach is particularly attractive because it produces nanowires with nano-scale dimensions using mature lithography in combination with standard deposition and spacer etch techniques that are widely available in industry. More importantly, this process can be used for glass or plastic substrates suitable for the realization of low cost disposable diagnostic kits. However, in this approach defined nanowires are usually amorphous and/ or polysilicon depending on the deposition and annealing conditions and hence, nanowire material usually composed of grain boundaries and defects which may also affect its electrical characteristics eventually affecting biosensor performance realized in these nanowires. So for there have been only a number of reports on poly silicon nanowires and there is no study comparing the performance of single crystal & poly crystalline silicon nanowire biosensors.

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In this study we first time perform a critical comparison of single crystal & poly crystalline Si NW's electrical performance to appraise in depth the achievable performance of poly Si NW biosensor in comparison to single crystal Si NW while poly Si platform has significant cost advantage. The effect of nanowire thickness and doping concentration on the electrical characteristics of both type silicon nanowires are investigated which also provides the proper combination of nanowire thickness and doping concentration to ensure the sensitive operation for both type of silicon. The electrical characteristics of a p-type silicon (single crystal and poly crystal) nanowire having a nanowire length 1μm is studied at various thicknesses and doping concentrations. 10nm, 25nm, 50nm, 75nm and 100nm thick nanowires with doping density varying from 10^{16}/cm^3 to 10^{18}/cm^3 are investigated.

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Chapter 2

Methodology

2.1 Device features and simulation models for single crystal silicon nanowire

The investigation on the sensitivity of Silicon nanowire for biosensor application were done with the help of numerical simulations using the software SILVACO Atlas device simulator [11], installed on the VLSI lab of East West University. A p-type silicon nanowire was created on 100nm oxide with a 500nm buried Si layer. A secondary gate (backgate) is made with 25nm Al beneath the buried Si layer. The gate oxide thickness was 2nm and a heavily doped poly-silicon layer was used as top gate material. In the silicon nanowire, two heavily doped regions on the two sides of the channel were employed to ensure ohmic contact on the source/drain regions. The gate doping was 10^{20}/cm^3 and the source/drain regions were also heavily doped with the doping density of 10^{20}/cm^3. Here, the gate doping was n-type whereas the drain and the channel doping was p-type. To contact source to drain and gate, aluminum electrode was chosen.
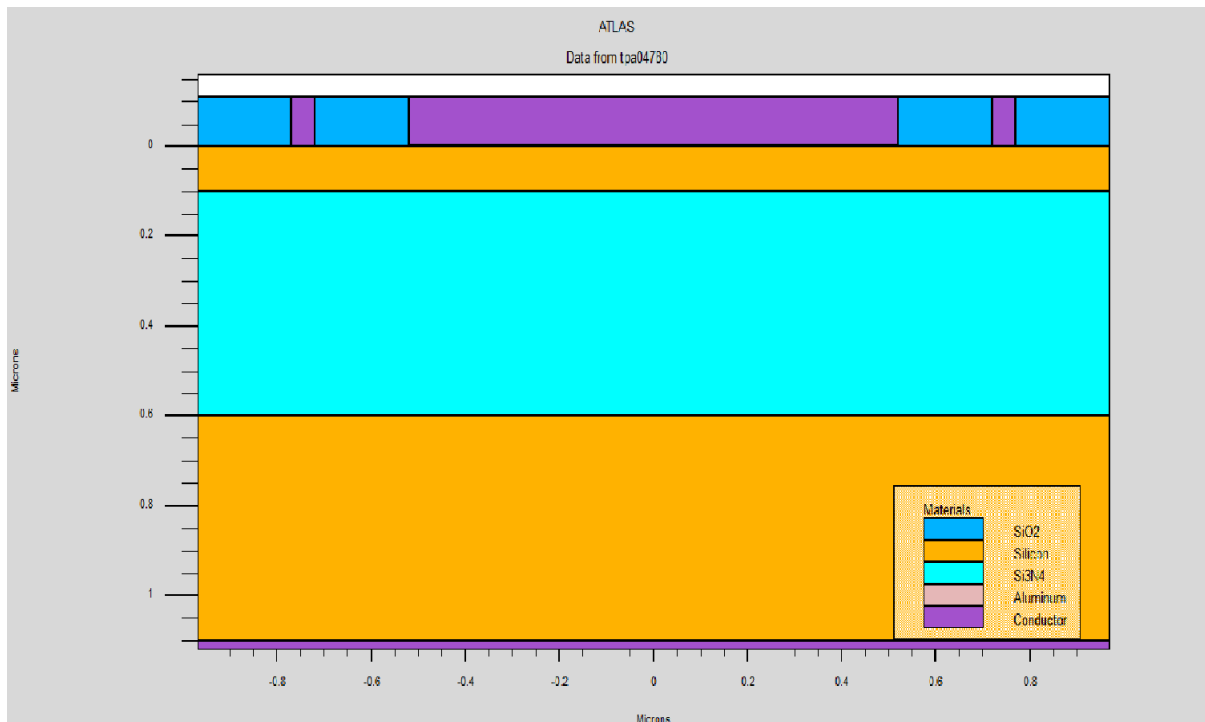
Figure 2.1: Schematic of the simulated p-type silicon nanowire.

In simulation our Si NW thickness were chosen at 100nm, 75nm, 50nm, 25nm and 10nm. Body doping of NW was also varied from 10^{16}/cm^3 to 10^{18}/cm^3 as Si-NW thickness 10nm quantum effect is neglected and a classical drift diffusion model is used to investigate Si-NW behavior. Fermi-Dirac (FERMI) carrier statistics model was used to account for certain properties of very highly doped (degenerate) materials. To accurately model carrier mobility in the constricted volume of NW Lombardi (CVT) model was used to take account temperature (T_L), perpendicular electric field ($E\perp$), parallel electric field (EII) and doping concentration (N) effects [11]. In the CVT model, the transverse field, doping dependent and temperature

dependent parts of the mobility are given by the three components that are combined using Mathiessen's rule.

These components are surface mobility limited by scattering with acoustic photons (μ_{AC}), the mobility limited by the surface roughness (μ_{SR}) and the mobility limited by scattering with optical intervalley photons (μ_b) are combined using Mathiessen's rule as follows [11]:

$$\mu_T^{-1} = \mu_{AC}^{-1} + \mu_b^{-1} + \mu_{SR}^{-1} \tag{2.1}$$

The first component, surface mobility limited by scattering with acoustic phonons equations [11]:

$$\mu_{AC.n} = \frac{BN.CVT}{E_\perp} + \frac{CN.CVT\ N^{\tau N.CVT}}{T_L E_\perp^{1/3}} \tag{2.2}$$

$$\mu_{AC.p} = \frac{BN.CVT}{E_\perp} + \frac{CN.CVT\ N^{\tau P.CVT}}{T_L E_\perp^{1/3}} \tag{2.3}$$

The equation parameters BN.CVT, BP.CVT, CN.CVT, CP.CVT, TAUN.CVT, and TAUP.CVT used for this simulation are shown in Table 2.1 [11].

The second component, μ_{sr} is the surface roughness factor and is given by [11]:

$$\mu_{sr} = \frac{DELN.CVT}{E_\perp^2} \tag{2.4}$$

$$\mu_{sr} = \frac{DELP.CVT}{E_\perp^2} \tag{2.5}$$

The equation parameters DELN.CVT and DELP.CVT used for this simulation are shown in Table 2.1 [11].

The third mobility component, the mobility limited by scattering with optical intervalley phonons is given by [11]:

$$\mu_{b,n} = MU0N.CVT\exp\left(\frac{-PCN.CVT}{N}\right) + \frac{\left[MUMAXN.CVT\left(\frac{T_L}{300}\right)^{-GAMN.CVT} - MU0N.CVT\right]}{1+\left(\frac{N}{CRN.CVT}\right)^{ALPHN.CVT}} - \frac{[-MU1N.CVT]}{1+\left(\frac{CSN.CVT}{N}\right)^{BETAN.CVT}} \tag{2.6}$$

$$\mu_{b,p} = MU0P.CVT\exp\left(\frac{-PCP.CVT}{N}\right) + \frac{\left[MUMAXP.CVT\left(\frac{T_L}{300}\right)^{-GAMP.CVT} - MU0P.CVT\right]}{1+\left(\frac{N}{CRP.CVT}\right)^{ALPHP.CVT}} - \frac{[-MU1P.CVT]}{1+\left(\frac{CSP.CVT}{N}\right)^{BETAP.CVT}} \tag{2.7}$$

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Table 2.1: Parameters for Equations 2.1 to 2.7

Statement	Parameter	Default	Units
MOBILITY	BN.CVT	4.75×10^7	cm/(a)
MOBILITY	BP.CVT	9.925×10^4	cm/(a)
MOBILITY	CN.CVT	1.74×10^5	
MOBILITY	BP.CVT	8.842×10^5	
MOBILITY	TAUN.CVT	0.125	
MOBILITY	TAUP.CVT	0.0317	
MOBILITY	GAMN.CVT	2.5	
MOBILITY	GAMP.CVT	2.2	
MOBILITY	MU0N.CVT	52.2	cm^2/(v-a)
MOBILITY	MU0P.CVT	44.9	cm^2/(v-a)
MOBILITY	MU1N.CVT	43.4	cm^2/(v-a)
MOBILITY	MU1P.CVT	29.0	cm^2/(v-a)
MOBILITY	MUMAXN.CVT	1417.0	cm^2/(v-a)
MOBILITY	MUMAXP.CVT	470.5	cm^2/(v-a)
MOBILITY	CRN.CVT	9.68×10^{14}	cm^{-3}
MOBILITY	CRP.CVT	2.23×10^{17}	cm^{-3}
MOBILITY	CSN.CVT	3.43×10^{20}	cm^{-3}
MOBILITY	CSP.CVT	6.10×10^{20}	cm^{-3}
MOBILITY	ALPHN.CVT	0.680	
MOBILITY	ALPHP.CVT	0.71	
MOBILITY	BETAN.CVT	2.00	
MOBILITY	BETAP.CVT	2.00	
MOBILITY	PCN.CVT	0.00	cm^{-3}
MOBILITY	PCP.CVT	0.23×10^{16}	cm^{-3}
MOBILITY	DELN.CVT	5.82×10^{14}	cm^{-3}

The model for carrier emission and absorption processes produced by Shockley-Read-Hall (SRH) is used to reflect the recombination phenomenon within the device. The electron and hole lifetimes $\tau_n \& \tau_p$ were modelled as concentration dependant. The equation is given by [11]:

$$R_{SRH} = \frac{pn - n_{ie}^2}{\tau_p \left[n + n_{ie} \exp\left(\frac{ETRAP}{kT_L}\right)\right] + \tau_n \left[p + n_{ie} \exp\left(\frac{-ETRAP}{kT_L}\right)\right]} \tag{2.8}$$

$$\tau_n = \frac{TAUN0}{1 + \left(\frac{N}{(NSRHN)}\right)} \tag{2.9}$$

$$\tau_p = \frac{TAUP0}{1 + \left(\frac{N}{(NSRHP)}\right)} \tag{2.10}$$

Here N is called the local (total) impurity concentration. The used parameters TAUN0, TAUP0, NSRHN and NSRHP are Table 2.2 [11]. This model was activated with the CONSRH parameter of the MODELS statement.

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Table 2.2: Default Parameter for equations 2.8 to 2.10

Statement	Parameter	Default	Units
METERIAL	TAUNO	1.0×10^{-7}	S
METERIAL	NSRHN	5.0×10^{16}	cm^{-3}
METERIAL	TAUPO	1.0×10^{-7}	S
METERIAL	NSRHP	5.0×10^{16}	cm^{-3}

To account bandgap narrowing effects, BGN model was used. These effects may be described by an analytic expression relating the variation in bandgap, ΔE_g, to the doping concentration, N. The expression used in ATLAS is from Slotboom and de Graaff [11]:

The used values for the parameters BGN.E, BGN.N and BGN.C are shown in Table 2.3 [11]:

Table 2.3: Default Parameters of Slotbooms Bandgap Narrowing Model foe equation 2.11

Statement	Parameter	Default	Units
METERIAL	BGN.E	9.0×10^{16}	V
METERIAL	BGN.N	1.0×10^{16}	cm^{-3}
METERIAL	BGN.C	0.5	-

2.2 Simulation models for poly silicon nanowire

The 2D coupled Poisson's drift-diffusion solver with Fermi-Dirac (FERMI) carrier statistics was also used to model carrier transport in poly silicon NW. The Shockley-Read-Hall model for carrier emission and absorption was used to reflect the recombination phenomena within the device. Moreover, the band gap narrowing (BGN) effects in the heavily doped source/drain regions were included by Slotboom and de Graaff's analytical BGN model. However, for mobility we used constant mobility model for poly silicon NWS simulation because TFT module in ATLAS is compatible with constant low field mobility model only. Use of other mobility model overwrites constant low field model and gives inaccurate results. Constant low field mobility model is independent of doping concentration, carrier densities and electric field. It does account for lattice scattering due to temperature according to:

$$\mu_{n0} = \text{MUN} \left(\frac{T_L}{300}\right)^{\text{-TMUN}} \qquad (3.1)$$

$$\mu_{p0} = \text{MUP} \left(\frac{T_L}{300}\right)^{\text{-TMUP}} \qquad (3.2)$$

Where T is the lattice temperature. The low field mobility parameters: MUN, MUP, TMUN and TMUP can be specified in the MOBILITY statement with the defaults as shown in Table 2.4.

Table 2.4: Default mobility model values for polysilicon

Statement	Parameter	Default	Unit
MOBILITY	MUN	1000	cm^2/V.s
MOBILITY	MUP	500	cm^2/V.s
MOBILITY	TMUN	1.5	-
MOBILITY	TMUP	1.5	-

However we have used MUN=14cm^2/V.s and MUP=6cm^2/V.s as experimentally extracted mobility of similar polysilicon nanowires were within the range of 6cm^2/V.s to 12cm^2/V.s considering variation of polysilicon nanowire width and height after fabrication.

Poly silicon is a disorder material which contains a large number of defects states within the band gap of the material and interface. The defect states as a combination of exponentially decaying band tail states and Gaussian distribution of mid gap states [11] shown in Figure 3.2. We therefore model the poly silicon using a continuum of trap states consist of both donor-like and acceptor-like states distribution across the energy band gap. The defect states as a combination of exponentially decaying band Tail states and Gaussian distribution of mid gap states are used with parameters previously used in the literature for successful modelling of poly silicon thin film transistor [12].
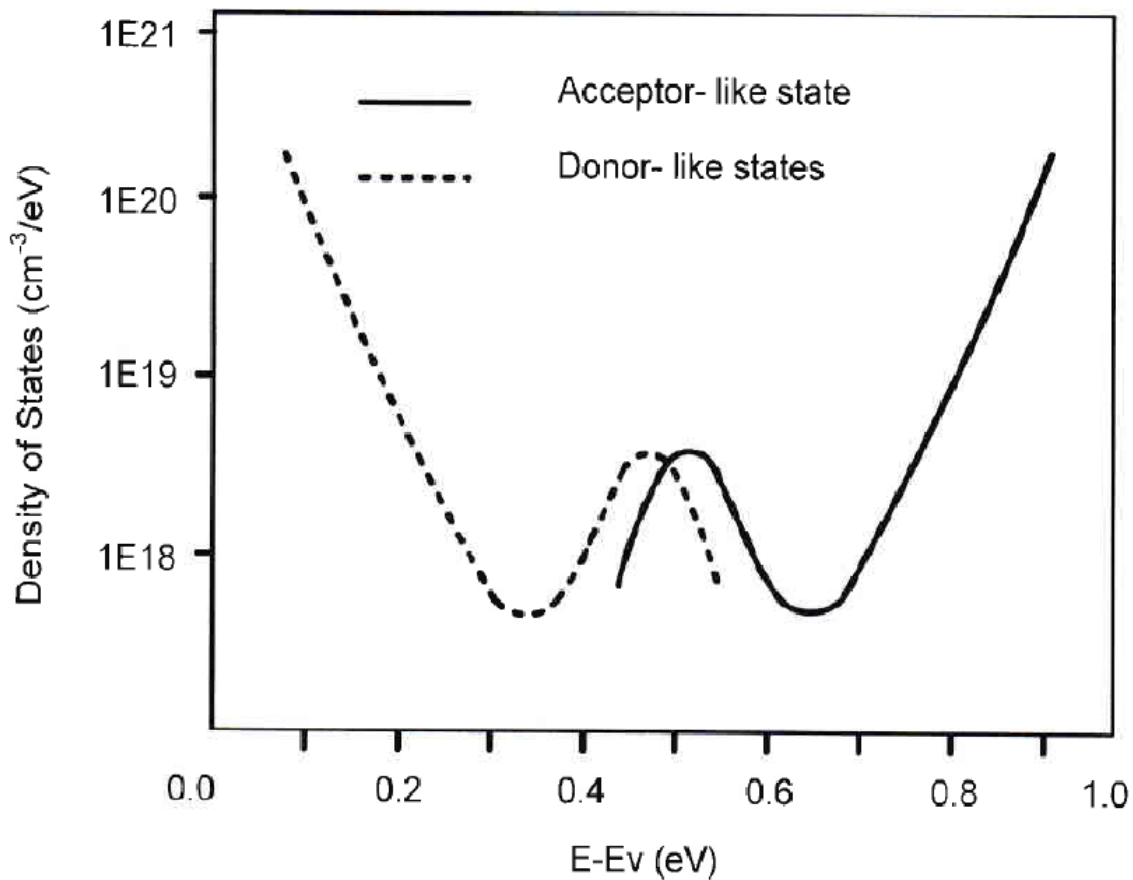
Figure 2.2: The distribution of acceptor and donor-like trap states across forbidden energy gap.

2.3 Simulation profile

Device simulation using SILVACO Atlas usually faces convergence problems and necessitates a long simulation run times. To avoid these problems, the simulation of silicon nanowire MOSFET has been divided into a few groups. At first, structure definition was performed. In this definition the simulation focused on creating the structure with a suitable mesh density. Regions and electrodes were defined as depicted in Figure 2.3. Finer nodes were assigned in critical areas, such as across the gate oxide to monitor channel activity and to get a better picture

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of the depletion layer and junction behavior near the source/drain boundaries. A coarser mesh was used elsewhere in order to reduce simulation run time.
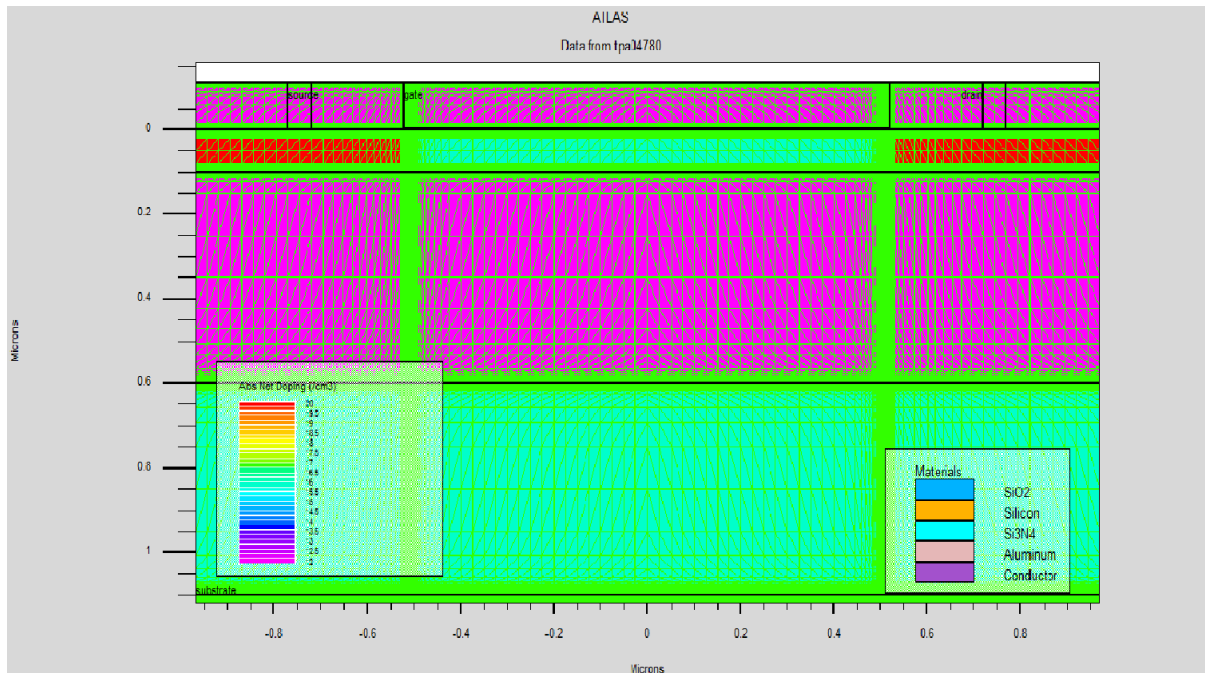
Figure 2.3: Cross-sectional view of p-type nanowire showing the mesh density used in this simulation

Once the structure and the mesh were found to be as desired, the simulation was performed with appropriate models as discussed in section 2.1 and numerical solving methods. The model was invoked by using the statements FERMI, CVT, CONSRH, BGN. The numerical solving methods GUMMEL, NEWTON were used to reduce the simulation run time, while keeping the accuracy of the simulation at an acceptable level.

To get convergence, a special bias point solving method was used. It was found that the simulation faced difficulty in solving the initial desired bias points i.e. ±1V, ±2V, ±3V, ±4V, ±5V for back gate voltage ±1V for drain voltage. Therefore, the initial gate bias was set to 0.005V and the next bias point was set to 0.05V, before finally setting the bias point to desired value.

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Chapter 3

Results and Discussion:
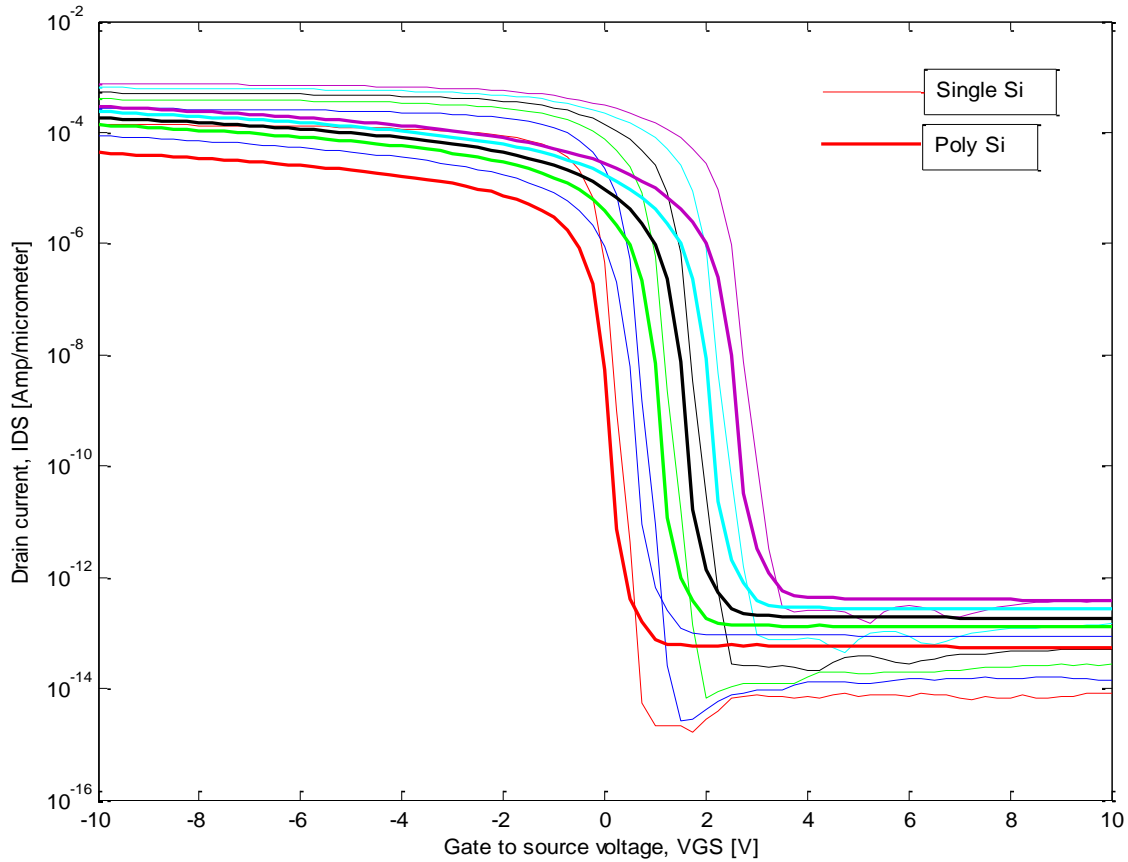
Figure 3.1: Sub-threshold characteristics of p-type Silicon nanowires with 10^{16}/cm^3 doping concentration at 100nm thickness; single crystal Si and poly crystal Si. The NWs have channel length of 1µm.

Figure 3.1 shows sub-threshold characteristics (I_{DS} vs V_{GS}) of p-type (single crystal and poly crystal) Si NWs for 100nm nanowire thickness. The length of the nanowire is 1µm and doping density is 10^{16}/cm^3. For single crystal Si in Figure 3.1, the sub-threshold slope is found to be 105mV/decade. The drive current of single crystal Si NW is found to be 1.23×10^{-4}A/µm at $V_{DS} = 0.5$V and $V_{GS} = -5$V. For poly Si NW sub threshold slope S is found to be 113mv/decade. The sub threshold slope of 1µm long 100nm thick poly Si NW is inferior to that of the single crystal Si NW. The drive current is also lower than single crystal Si NW with a value of 2.11×10^{-5}A/µm at $V_{DS} = 0.5$V and $V_{GS} = -5$V. Although the exhibited value of sub threshold slope is higher than ideal 60mV/decade; a sub-threshold swing around $\approx$100mv/decade is fair for using both poly Si and single crystal Si NW as sensors with slightly degraded performances for poly Si case.
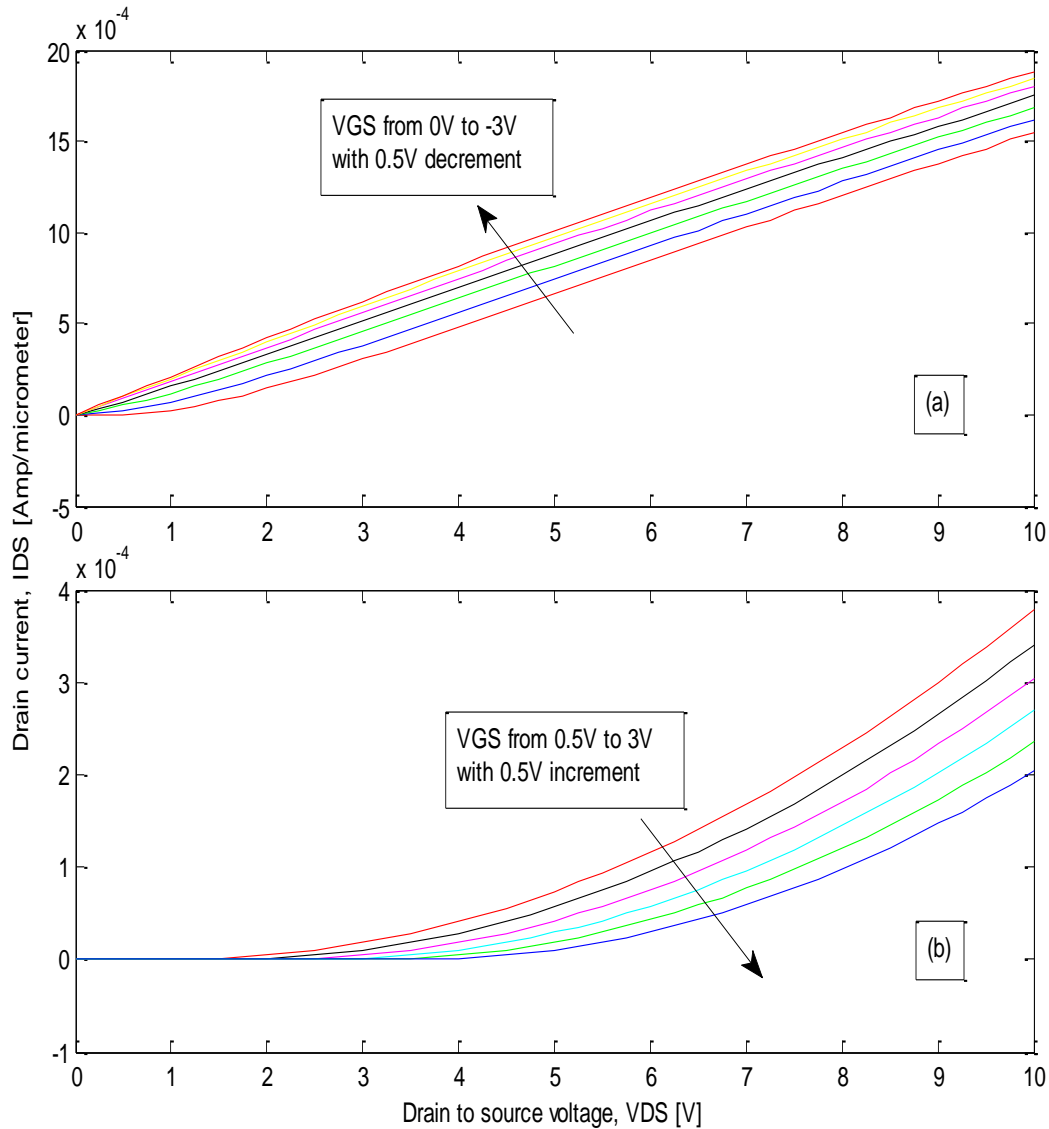
Figure 3.2: Output characteristics of p-type Silicon nanowires with 10^{16}/cm^3 doping concentration at 100nm thickness; (a) single crystal Si and (b) poly crystal Si. The NWs have channel length of 1μm.

Figure 3.2 shows output characteristics (I_{DS} vs. V_{DS}) of 1μm long p-type (single crystal and poly crystal) silicon nanowires for 100nm thickness while the doping density is 10^{16}/cm^3. For single crystal Si NW a typical non-linear characteristics is observed with insignificant conduction up to certain level of drain bias. With the application of negative V_{GS} this non-linear characteristics is reduced and drive current increases. The increase in drive current can be explained by the modulation of NW conduction due to strong hole accumulation upon application of negative V_{GS}. For poly Si NW the non-linearity of I_{DS}-V_{DS} characteristics is significantly increased. In particular the NWs drive current significantly lower and the NWs do not show significant conduction up to 2V of V_{DS} where is much higher that single crystal Si NW which has a value of 0.5V.

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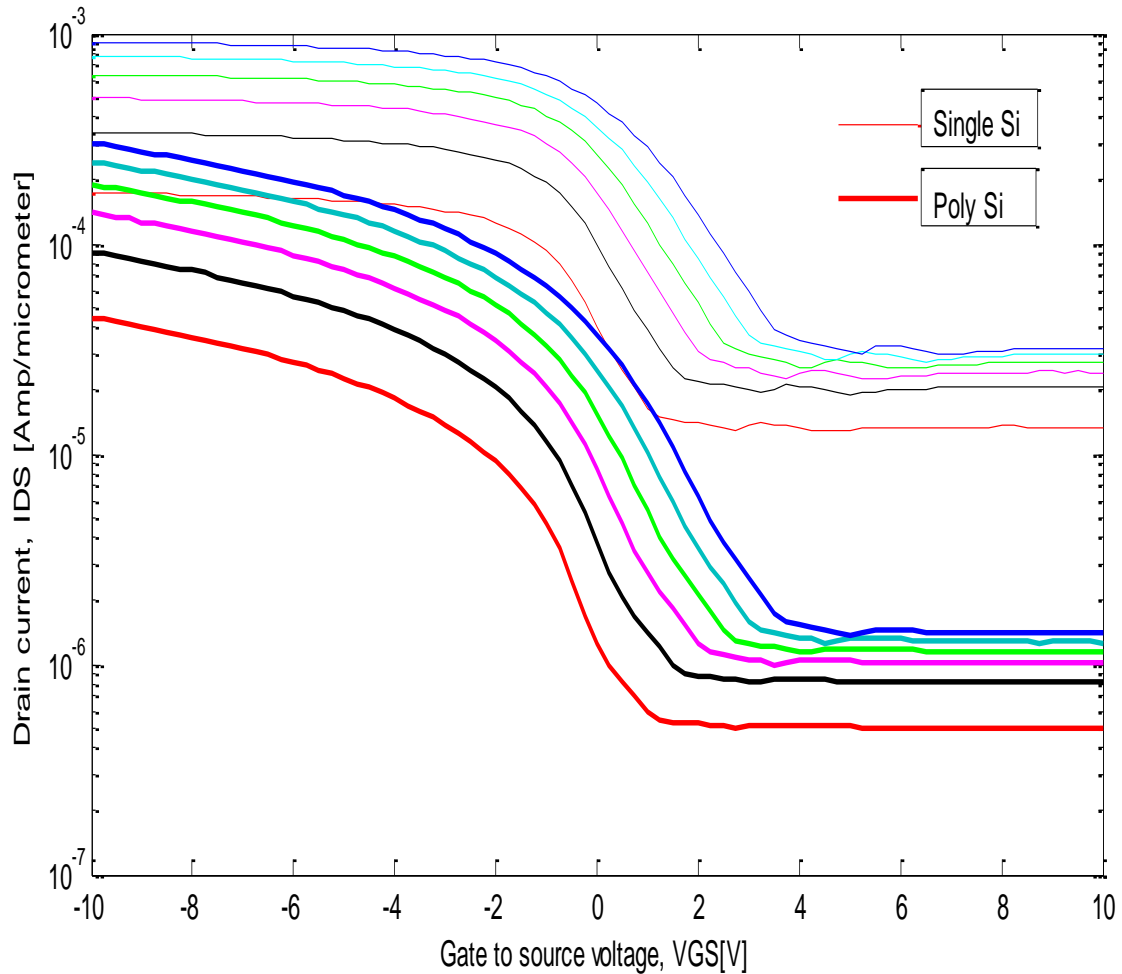
Figure3.3: Sub-threshold characteristics of p-type Silicon nanowires with $4\times10^{17}/cm^3$ doping concentration at 100nm thickness; single crystal Si and poly crystal Si. The NWs have channel length of 1μm.

Figure 3.3 shows sub-threshold characteristics (I_{DS} vs. V_{GS}) of p-type (single crystal and poly crystal) Si NWs for 100nm nanowire thickness. The length of the nanowire is 1μm and doping density is $4\times10^{17}/cm^3$. For single crystal Si in Figure 3.3, the sub-threshold slope is found to be 2420mV/decade. And for the poly crystal Si in Figure 3.3, the sub-threshold slope is found to be 2530mV/decade. These drastically inferior sub-threshold characteristics render 100nm thick single and poly-silicon nanowires with a doping density $4\times10^{17}/cm^3$ unsuitable for a viable biosensor operation. Although the sub-threshold slope of single crystal Si is lower than the poly crystal Si, both have very high values of slopes than the ideal value. This observation implies that both single and poly crystal Si nanowire cannot be used as sensor with a doping density of $4\times10^{17}/cm^3$. The drive current of single crystal Si NW is 1.6×10^{-4}A/μm at V_{GS}=-5V and V_{DS} = 0.5V. This current is again higher than poly Si NW which has a value of 2.27×10^{-5}A/μm at this is biasing condition.

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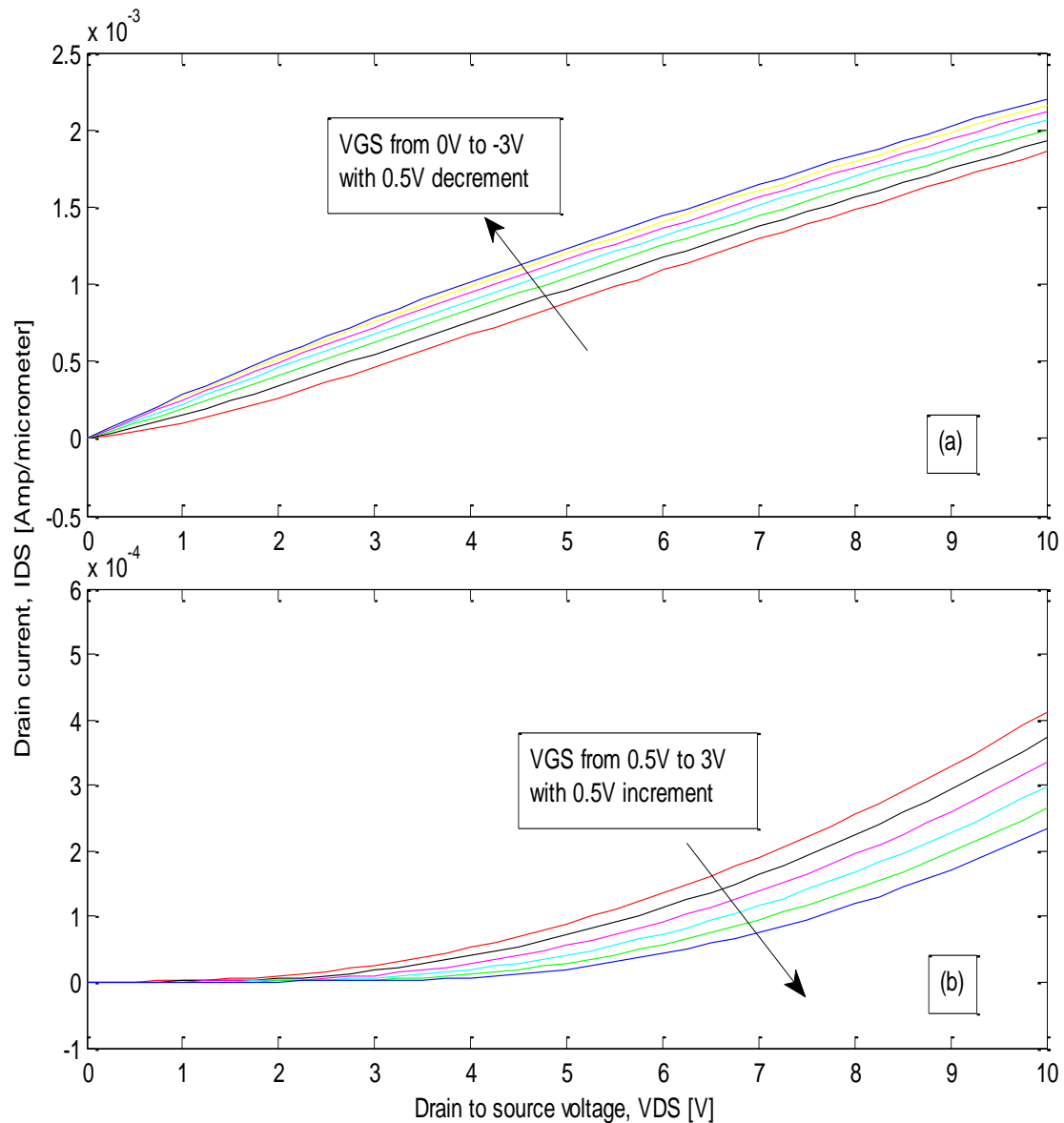
Figure 3.4: Output characteristics of p-type Silicon nanowires with $4\times10^{17}/cm^3$ doping concentration at 100nm thickness; (a) single crystal Si and (b) poly crystal Si. The NWs have channel length of 1µm.

Figure 3.4 shows output characteristics (I_{DS} vs. V_{DS}) of 1µm long p-type (single crystal and poly crystal) silicon nanowires for 100nm thickness while the doping density is $4\times10^{17}/cm^3$. For single crystal Si NW, the characteristics is more linear at this doping density in comparisons to the doping of $10^{16}/cm^3$ and the typical (Figure 3.2(a)) non-conduction region is also disappears. However, for poly Si NW the characteristics is still non-linear with an insignificant conduction up to a $V_{DS} = 2V$. The drive current of poly Si NW is inferior to single crystal Si NW. However both single crystal Si and poly Si NW at this doping exhibit higher drive current than $10^{16}/cm^3$ doping density (Figure 3.2).

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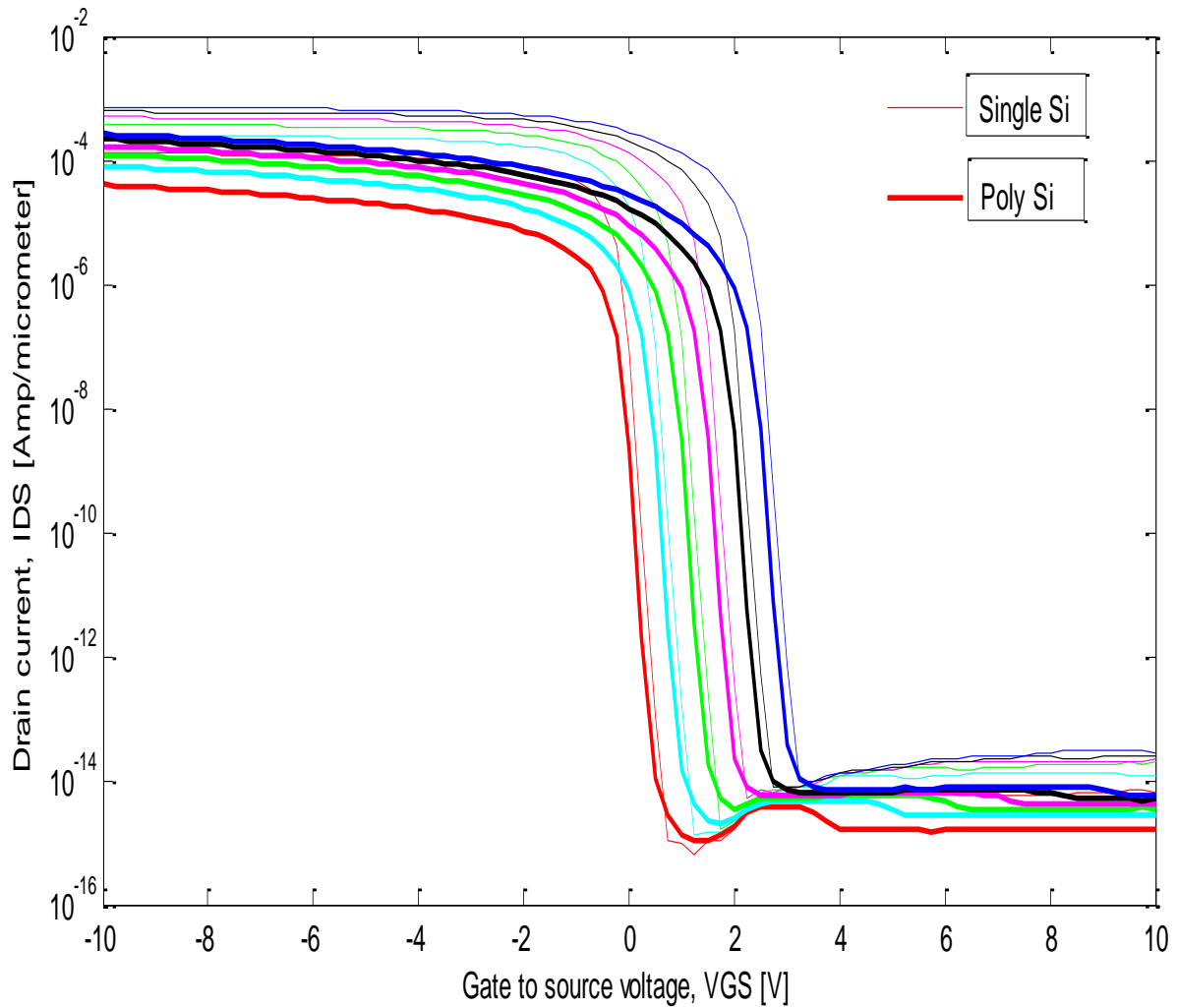
Figure 3.5: Sub-threshold characteristics of p-type Silicon nanowires with $10^{16}/cm^3$ doping concentration at 25nm thickness; single crystal Si and poly crystal Si. The NWs have channel length of 1µm.

Figure 3.5 shows sub-threshold characteristics (I_{DS} vs. V_{GS}) of p-type (single crystal and poly crystal) Si NWs for 25nm nanowire thickness. The length of the nanowire is 1µm and doping density is $10^{16}/cm^3$. For single crystal Si in Figure 3.5, the sub-threshold slope is found to be 86.1 mV/decade which is noticeably better than the 100nm thick single crystal Si NW at doping of $10^{16}/cm^3$. The drive current of single crystal Si NW is 1.14×10^{-4} A/µm at $V_{DS} = 0.5$V and $V_{GS} = -5$V which is lower than 100nm thick single crystal Si NW at this doping (Figure 3.1). For poly Si sub threshold slope is 103mV/decade which inferior than single crystal Si NW at this doping. However, poly Si NWs sub-threshold slope at 25nm thickness is found to be improved in comparison the 100nm thickness (Figure 3.1).

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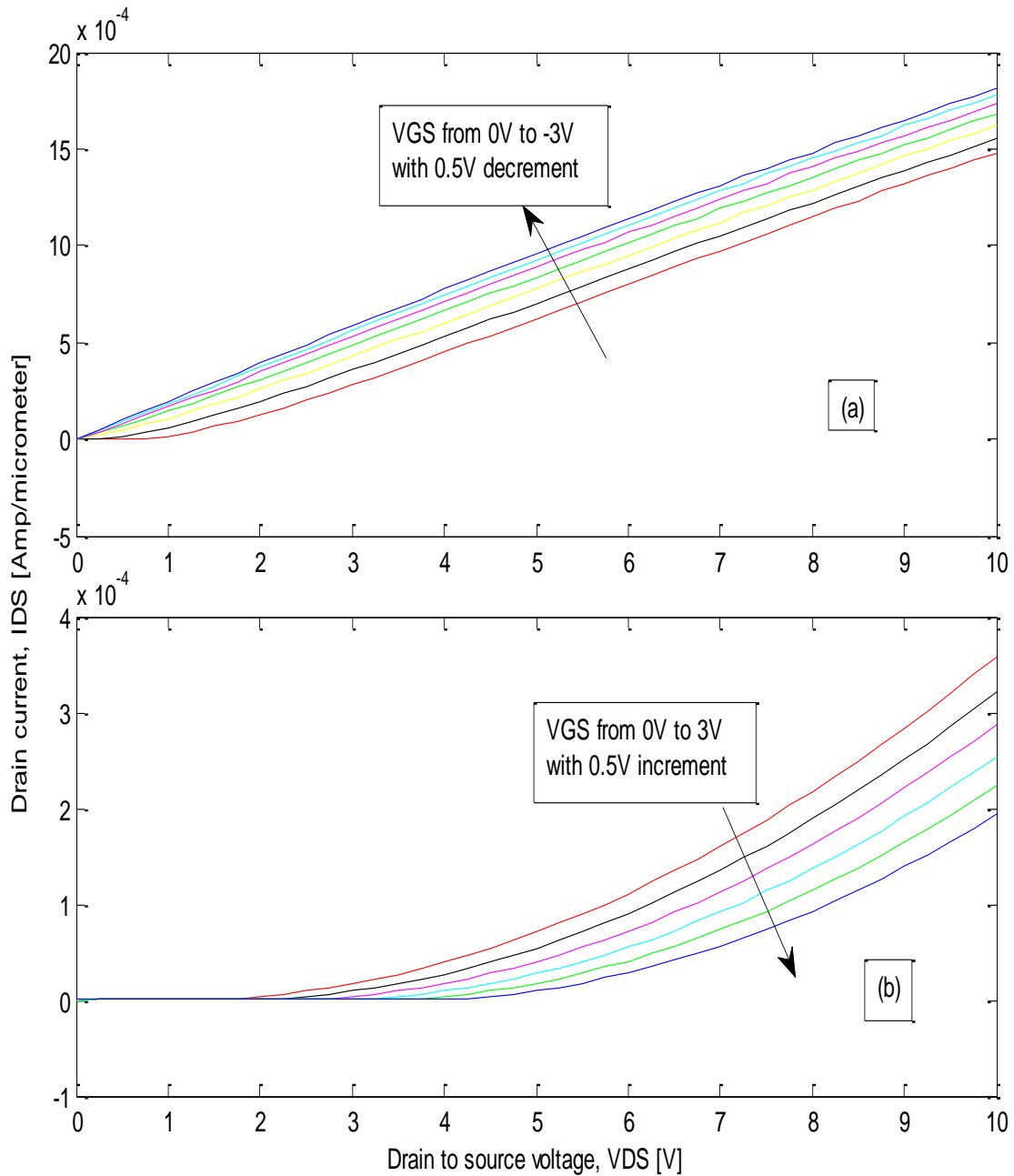
Figure 3.6: Output characteristics of p-type Silicon nanowires with $10^{16}/cm^3$ doping concentration at 25nm thickness; (a) single crystal Si and (b) poly crystal Si. The NWs have channel length of 1μm.

Figure 3.6: shows output characteristics (I_{DS} vs. V_{DS}) of 1μm long p-type (single crystal and poly crystal) silicon nanowires for 25nm thickness while the doping density is $10^{16}/cm^3$. For single crystal Si NW the output characteristics at 25nm thickness and $10^{16}/cm^3$ doping is similar to that of 100nm thick NW at this doping. However the drive current of poly Si NW at 25nm thickness is lower than 100nm thickness. For poly Si NW (Figure 3.6(b)) the characteristics is again more non-linear than single crystal Si NW which is similar to the observations of NW's output characteristics at doping $10^{16}/cm^3$ and 100nm thickness.

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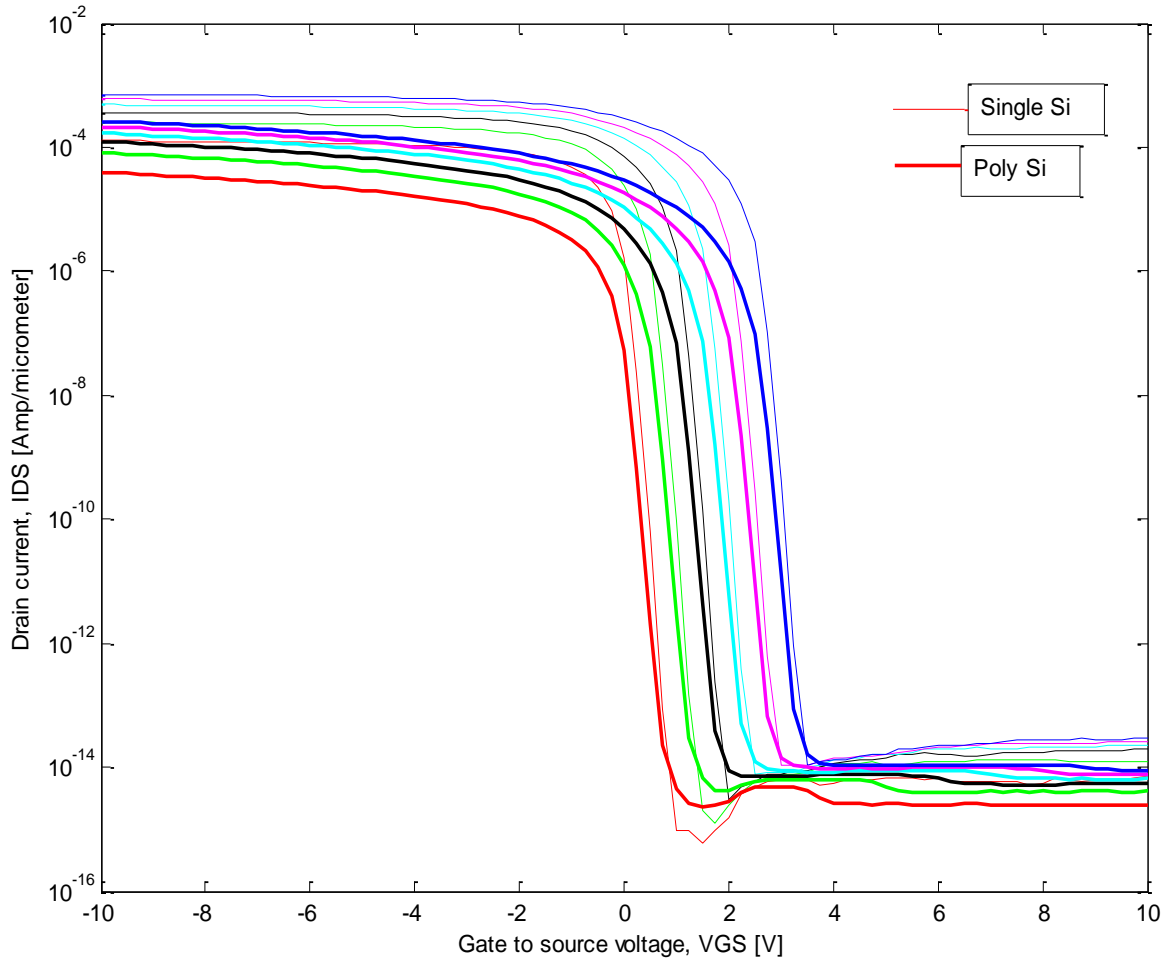
Figure 3.7: Sub-threshold characteristics of p-type Silicon nanowires with $4\times10^{17}/cm^3$ doping concentration at 25nm thickness; single crystal Si and poly crystal Si. The NWs have channel length of 1µm.

Figure 3.7 shows sub-threshold characteristics (I_{DS} vs. V_{GS}) of p-type (single crystal and poly crystal) Si NWs for 25nm nanowire thickness. The length of the nanowire is 1µm and doping density is $4\times10^{17}/cm^3$. A drastic change in the NW characteristics can be observed for 25nm thick Si NW at thus doping density in comparison to 100nm thick NW (Figure 3.3). While 100nm thick NW at doping of $4\times10^{17}/cm^3$ exhibited significantly unsuitable sub-threshold slope value offer sensor operation both single crystal poly Si NW at 25nm thickness exhibited significantly improved sub-threshold slope value at doping of $4\times10^{17}/cm^3$. The sub threshold slope of single crystal and poly crystal Si NWs are 97.9mV/decade and 118mV/decade respectively which is much better than 100nm thick NW's at this doping (Figure 3.3). It should also be noted that the drive current of poly/single crystal NWs at this doping is higher than $10^{16}/cm^3$ doping.

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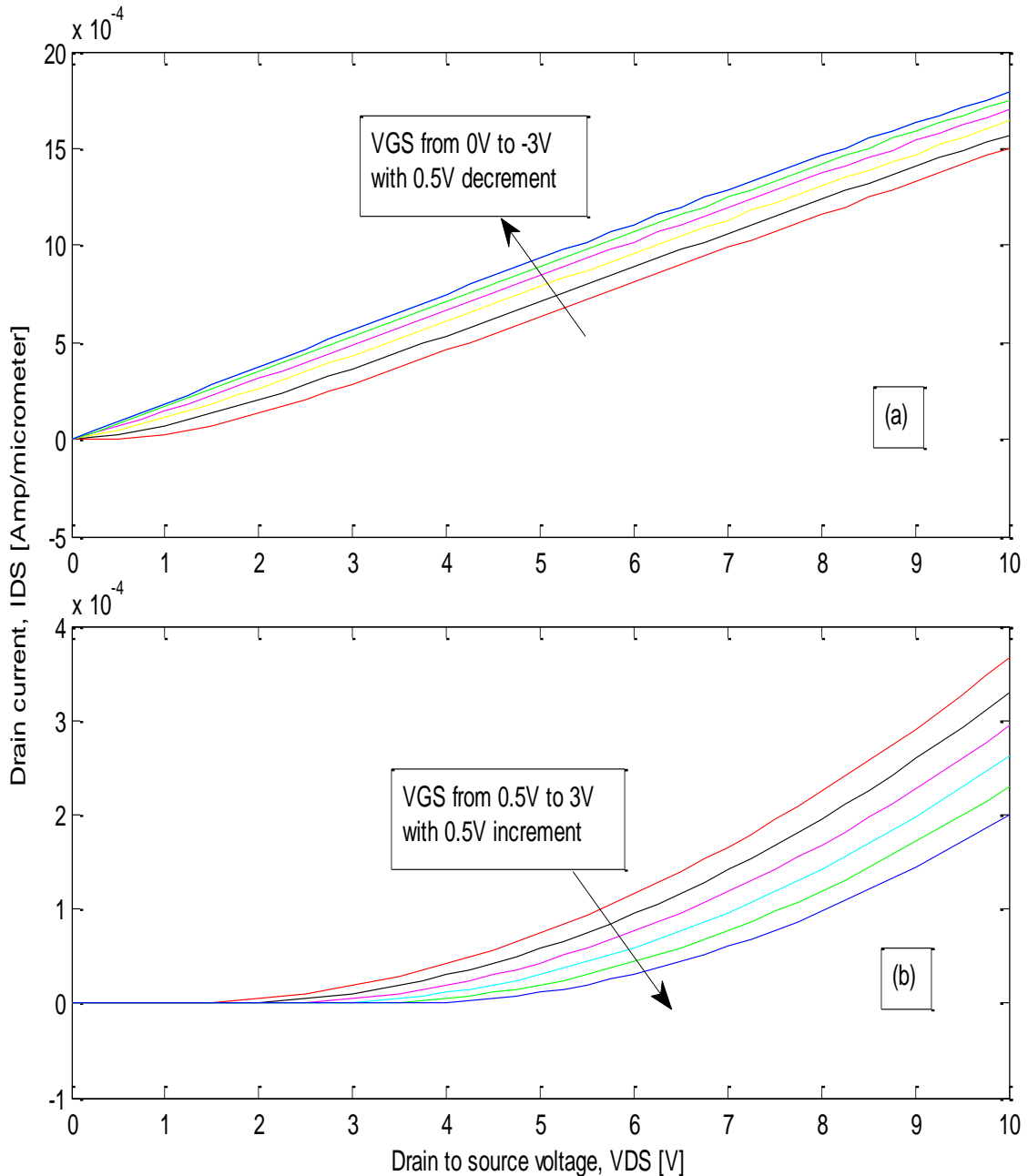
Figure 3.8: Output characteristics of p-type Silicon nanowires with $4\times10^{17}/cm^3$ doping concentration at 25nm thickness; (a) single crystal Si and (b) poly crystal Si. The NWs have channel length of 1µm.

Figure 3.8 shows output characteristics (I_{DS} vs. V_{DS}) of 1µm long p-type (single crystal and poly crystal) silicon nanowires for 25nm thickness while the doping density is $4\times10^{17}/cm^3$. The exhibited output characteristics are similar to the output characteristics observed previously for 100nm NW thickness at this doping. Except that the drive current is lower than 100nm thick NW's at this doping (Figure 3.4).

Department of Electrical & Electronic Engineering, East West University
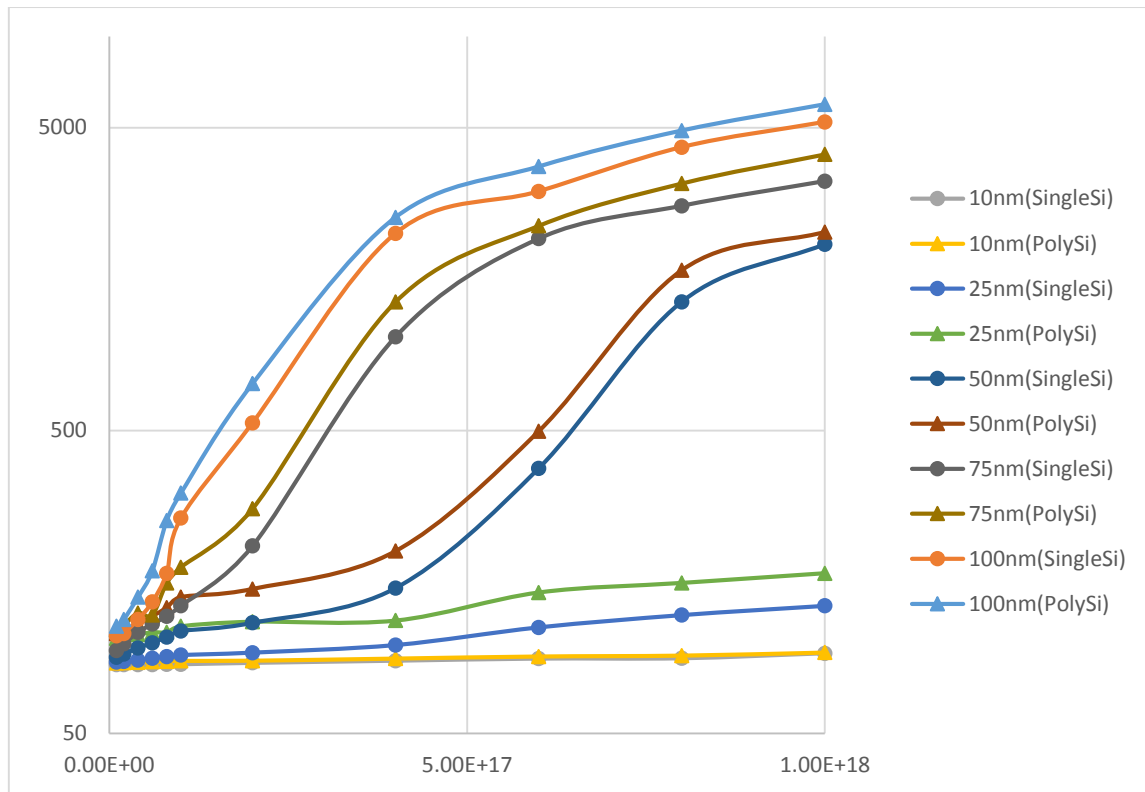
Figure 3.9: Sub-threshold slopes as a function of doping concentrations for different thicknesses of single crystal Silicon and poly crystal Silicon nanowires

Figure 3.9 summarizes the extracted values of sub-threshold slopes as a function of doping concentrations for different thicknesses & for single crystal Silicon / poly crystal Silicon nanowires. It can be seen that poly Si NW generally shows inferior characteristics than single crystal Si NW of all doping densities for NW thicknesses of 100, 75, 50 & 25nm which agrees well with general believe that poly Si NW will give inferior sensor performance than single crystal Si NW. However, for 10nm Si NW single crystal & poly Si NW show same sub-threshold slopes at all doping densities. Considering the fact that spacer etch process provides the cheapest & mass manufacturable platform for biosensor fabrication using poly Si material in comparison to the available single crystal platforms. It can be decided from this work that poly Si NW biosensor with Si thickness ≤ 10nm is the possible commercial route of sensor fabrication. Figure 3.9 also elucidates the proper combination of nanowire thickness and doping to ensure the sensitive operation of single crystal and polycrystalline silicon nanowire biosensors. For nanowire thickness of 100nm and 75nm, a severely degraded sub threshold slope can be observed when doping concentrations are above 10^{17} /cm^3 both for single crystal and poly Si nanowires. The polysilicon nanowires exhibit sub-threshold slopes of 5970mV/decade and 4080mV/decade respectively for 100nm and 75nm nanowire thickness at the doping concentration of 10^{18}/cm^3. A plausible sub-threshold slope of the single crystal Si NWs exhibit sub-threshold slopes of 5220mV/decade and 3330mV/decade respectively for 100nm and 75nm nanowire thickness at a doping concentration of 10^{18} /cm^3. A plausible sub-threshold slope around 100 mV/decade for a viable biosensor operation at these thickness can only be achieve if doping concentration is 2×10^{16}/cm^3 or below both for single crystal and poly silicon nanowires. For a 50nm nanowire thickness a relatively wide doping concentration range

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can be chosen for biosensor design while maintaining decent sub-threshold characteristics. In this thickness a doping up to 4×10^{17}/cm^3 with a sub-threshold slope around 100 mV/decade can be chosen. The widest range of doping concentrations can be chosen for 25nm and 10nm nanowire thickness with a maximum doping up to 10^{18}/cm^3 while maintaining a promising sub-threshold slope around 95mV/decade for a viable biosensor design using both single and polycrystalline silicon nanowires.

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Chapter 4

Conclusion

We have investigated the effect of nanowire thickness and doping concentration on the electrical characteristics of single crystal and polycrystalline silicon nanowire biosensors. For nanowire thicknesses of 100 nm and 75 nm, a plausible sub-threshold slope around 100 mV/decade for a viable biosensor operation can only be achieved if doping concentration is 2×10^{16}/cm^3 or below both for single crystal and poly Si nanowires. For a 50nm nanowire thickness a relatively wide doping concentration range with a maximum doping up to 4×10^{17}/cm^3 can be chosen for biosensor design while maintaining decent sub-threshold characteristics. The widest range of doping concentrations can be chosen for 25nm and 10nm nanowire thickness with a maximum doping up to 10^{18}/cm^3 while maintaining a promising sub-threshold slope around 95 mV/decade for a viable biosensor design using single crystal and polycrystalline silicon nanowires. In general poly Si NW shows inferior characteristics than single crystal Si NW. However, for 10nm Si NW single crystal & poly Si NW show same sub-threshold slopes at all doping densities. Considering the fact that spacer etch process provides the cheapest & mass manufacturable platform for biosensor fabrication using poly Si material in comparison to the available single crystal platforms. It can be decided from this work that poly Si NW biosensor with Si thickness ≤ 10nm is the possible commercial route of sensor fabrication.

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Chapter 5

Appendix A

Single Crystal Silicon Nanowire

1. **1e16/cm³**

NW thickness 10nm:

Fig.01: Ids vs Vds curves

Fig.02: Ids vs Vgs curves

NW thickness 25nm:

Fig.03: Ids vs Vds curves

Fig.04: Ids vs Vgs curves

NW thickness 50nm:

Fig.05: Ids vs Vds curves

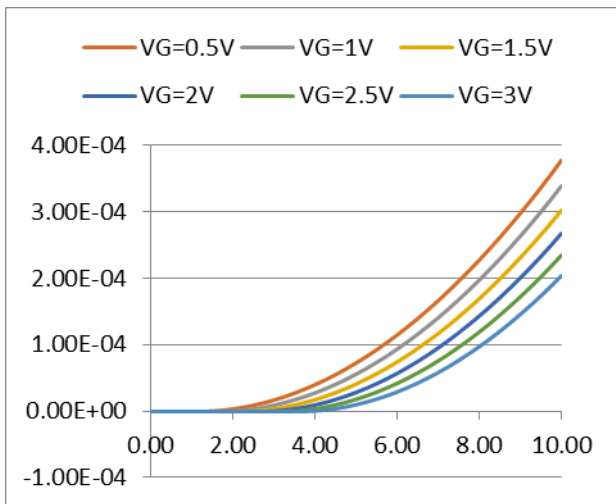Fig.06: Ids vs Vgs curves

NW thickness 75nm:

Fig.07: Ids vs Vds curves
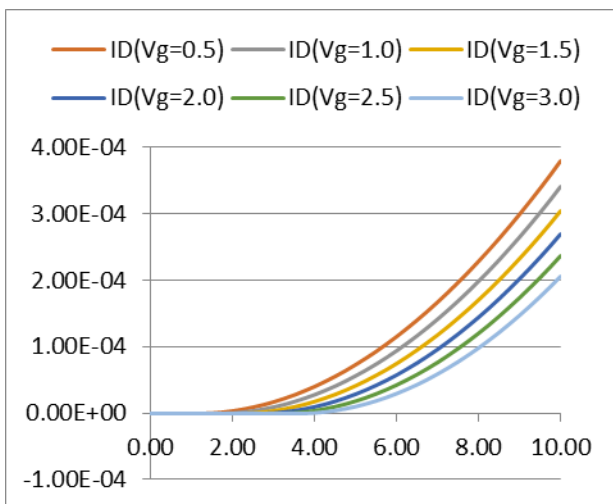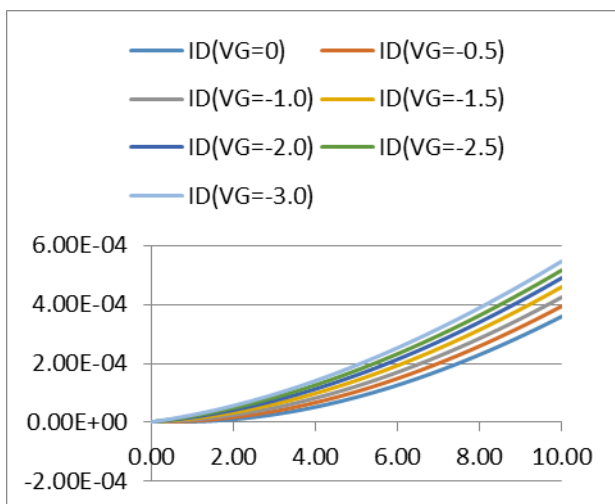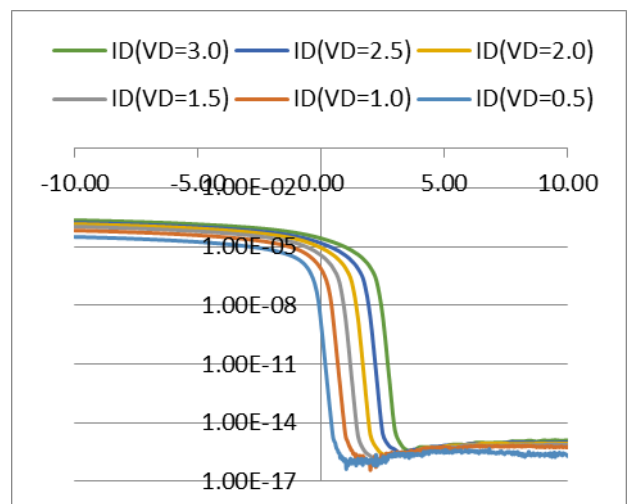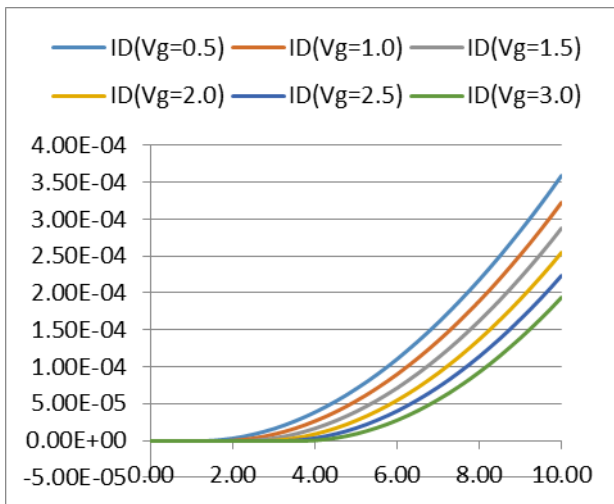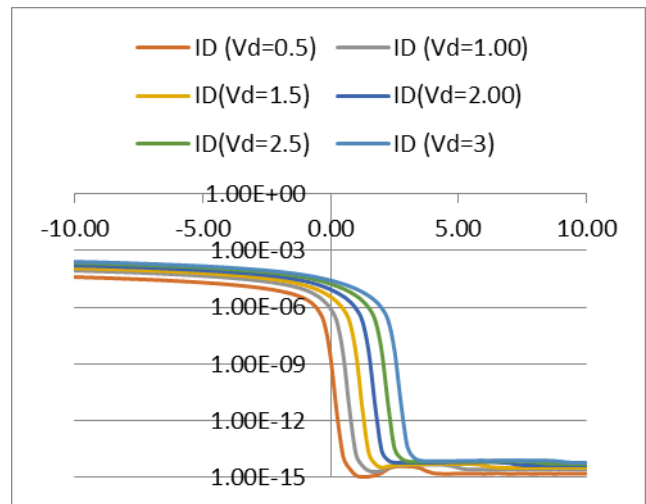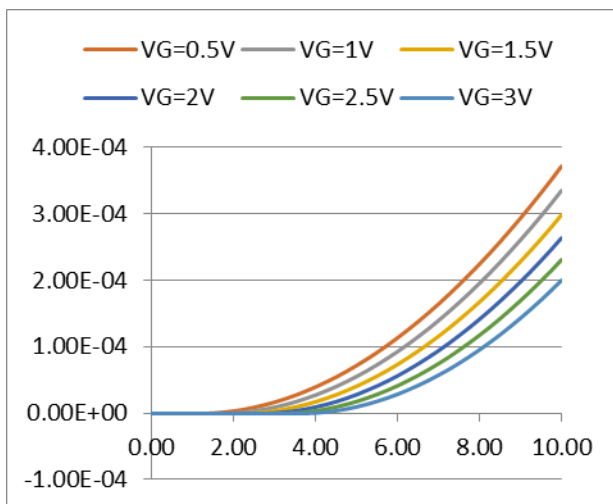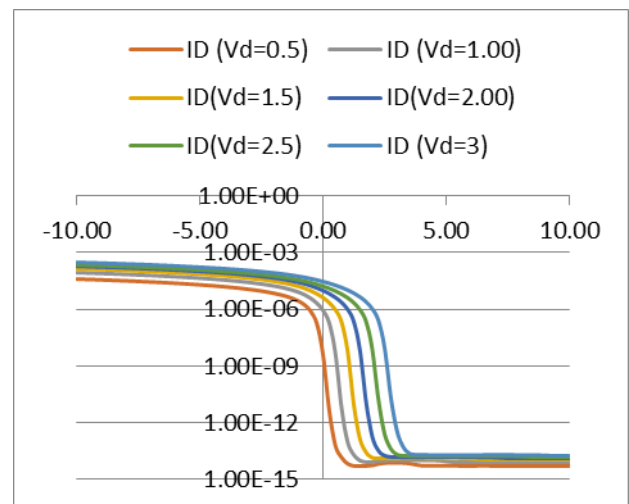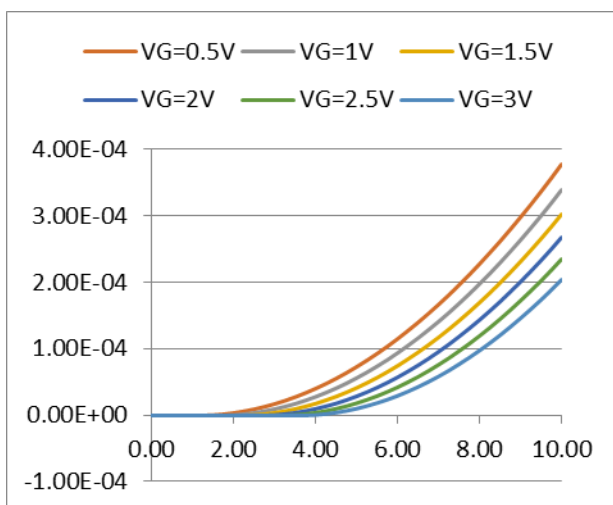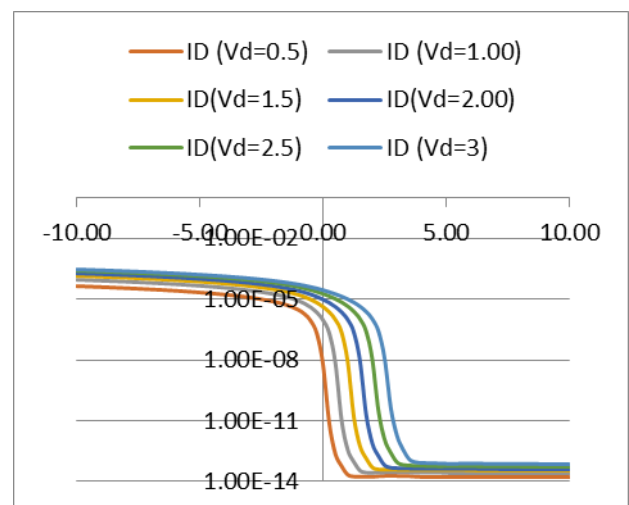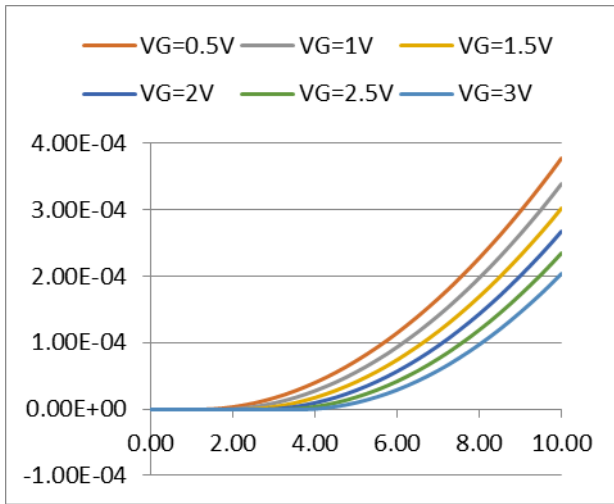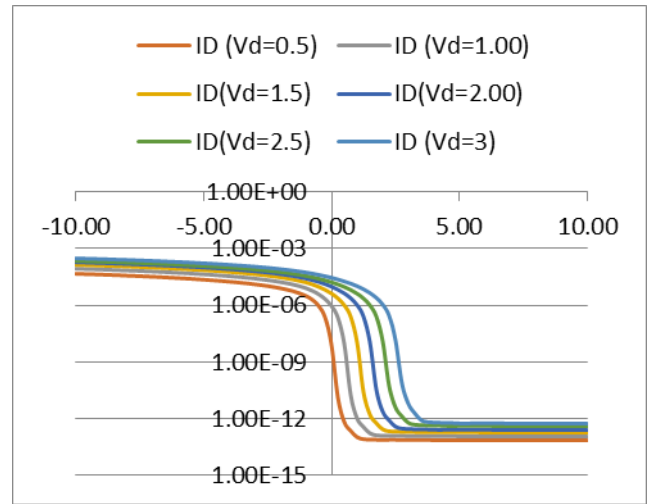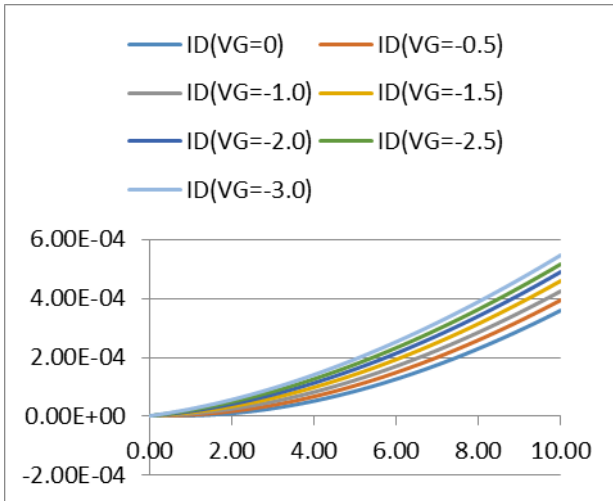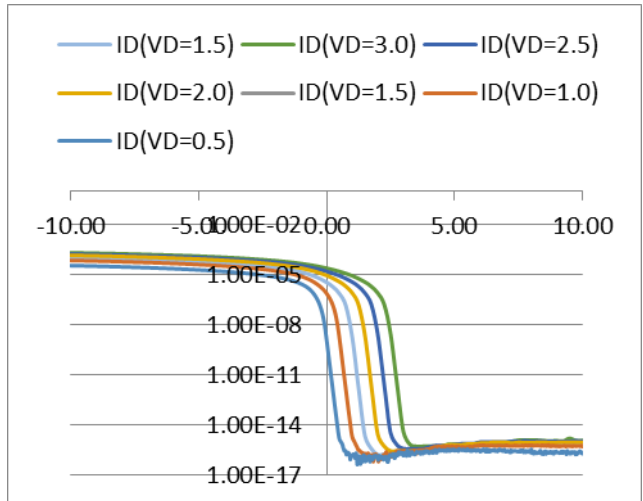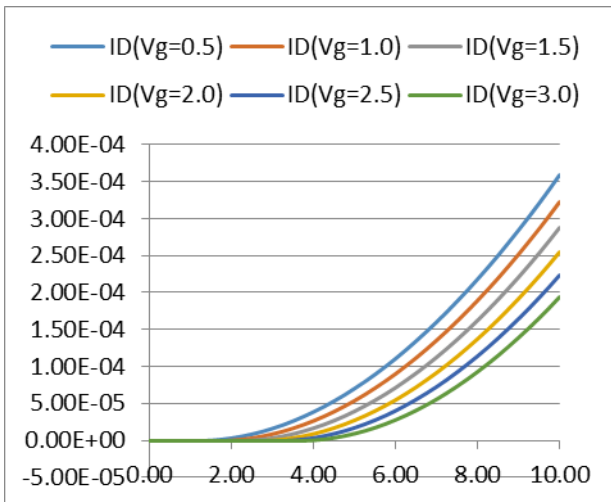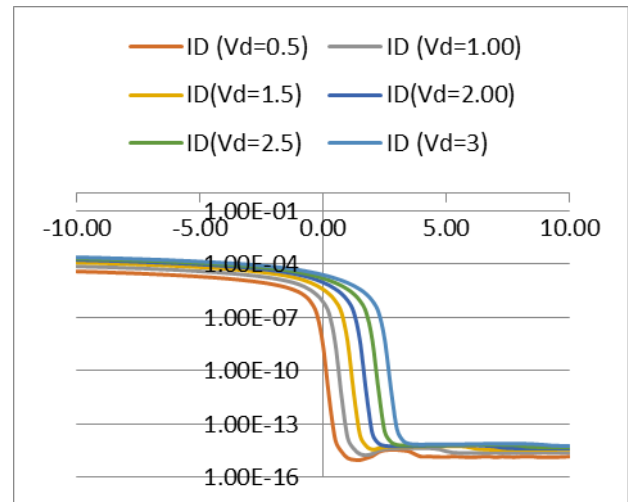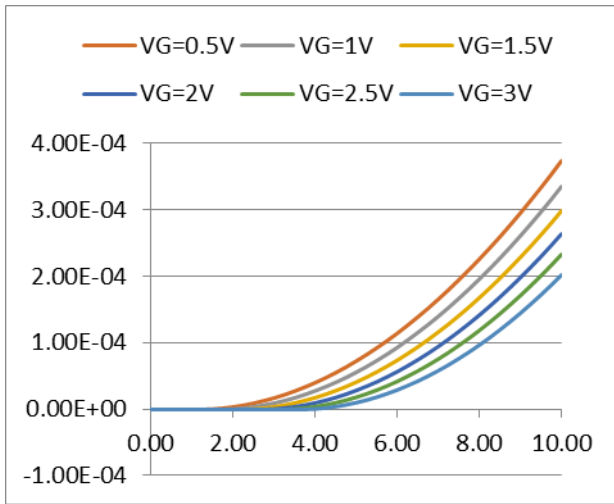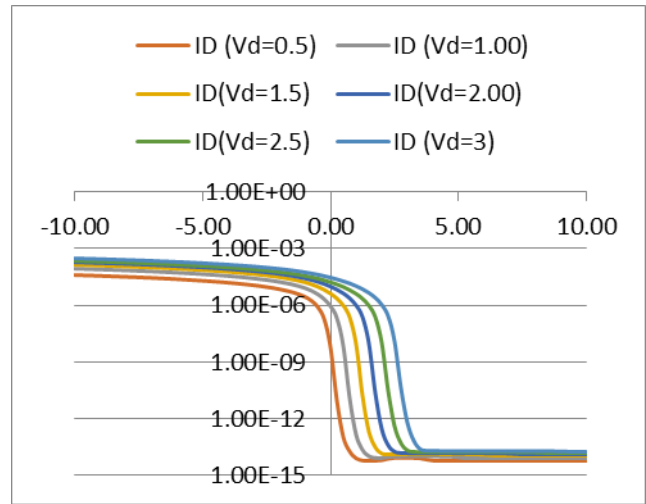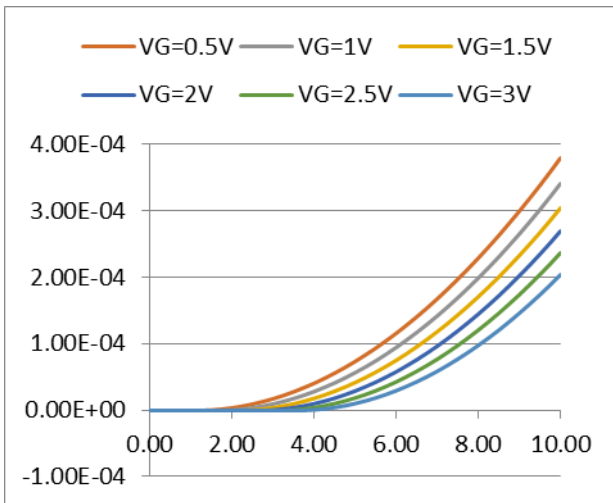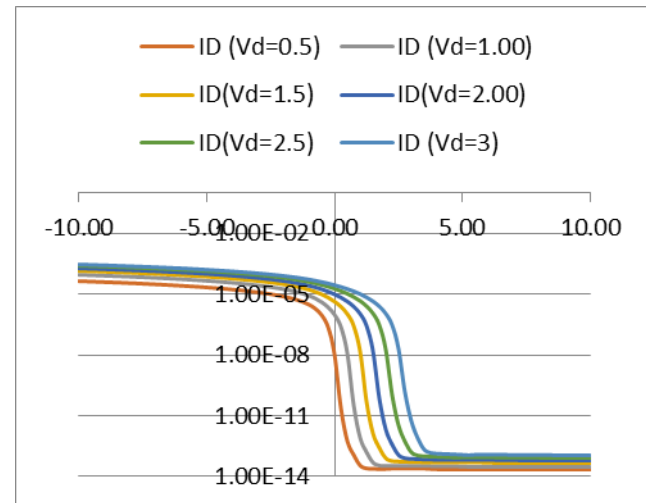

Fig.08: Ids vs Vgs curves

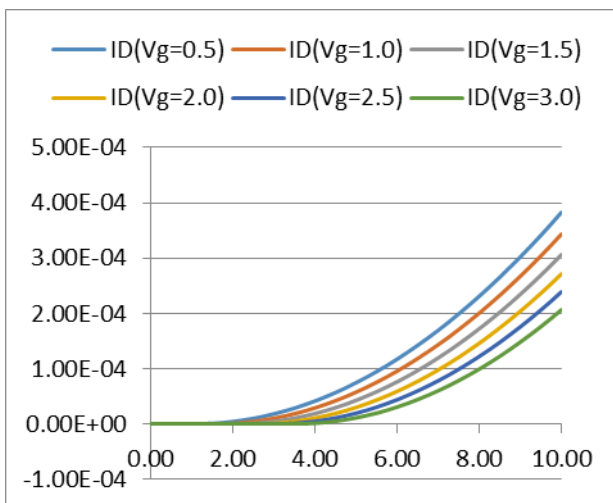**NW thickness 100nm:**

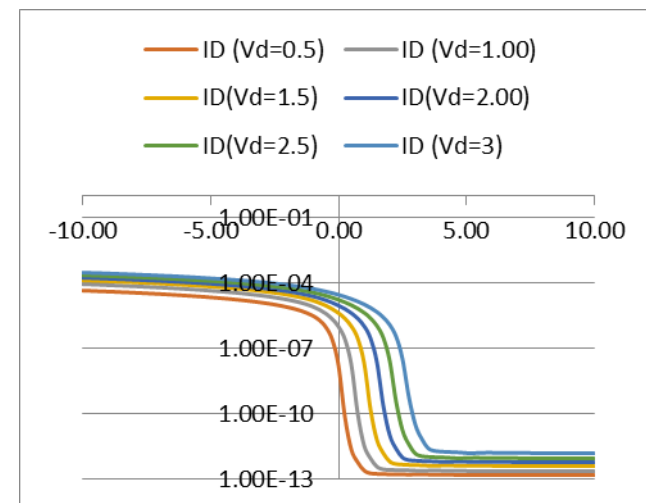Fig.09: Ids vs Vds curves

Fig.10: Ids vs Vgs curves
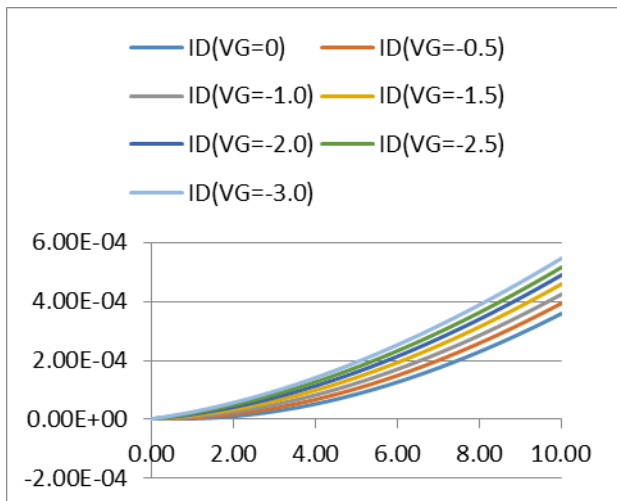
2. 2e16/cm^3

NW thickness 10nm:

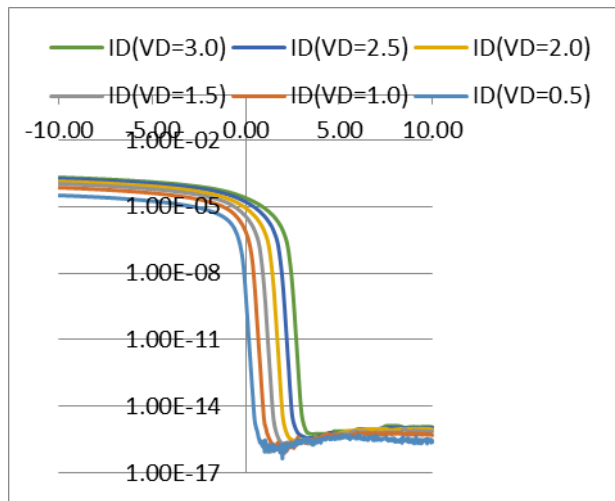Fig.11: Ids vs Vds curves

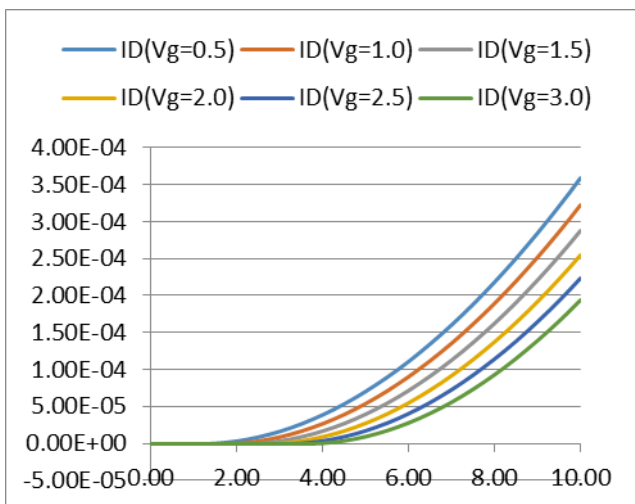Fig.12: Ids vs Vgs curves

NW thickness 25nm:

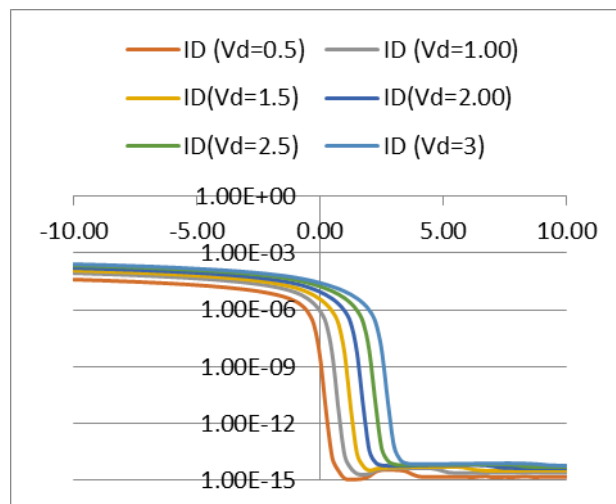Fig.13: Ids vs Vds curves

Fig.14: Ids vs Vgs curves

NW thickness 50nm:

Fig.15: Ids vs Vds curves

Fig.16: Ids vs Vgs curves

NW thickness 75nm:

Fig.17: Ids vs Vds curves

Fig.18: Ids vs Vgs curves

NW thickness 100nm:

Fig.19: Ids vs Vds curves

Fig.20: Ids vs Vgs curves

3. $4e16/cm^3$

NW thickness 10nm:

Fig.21: Ids vs Vds curves

Fig.22: Ids vs Vgs curves

NW thickness 25nm:

Fig.23: Ids vs Vds curves

Fig.24: Ids vs Vgs curves

NW thickness 50nm:

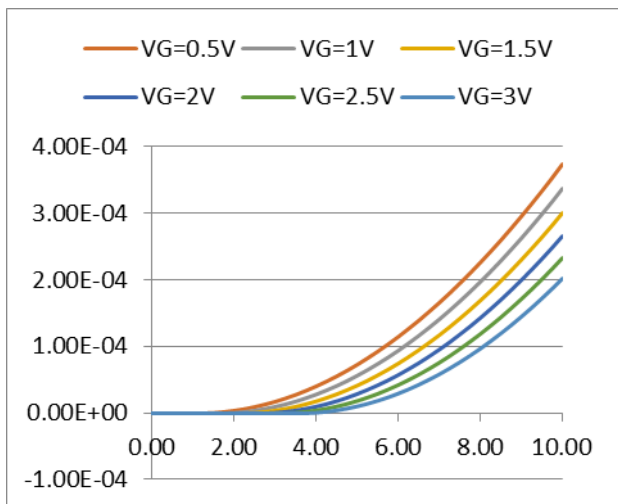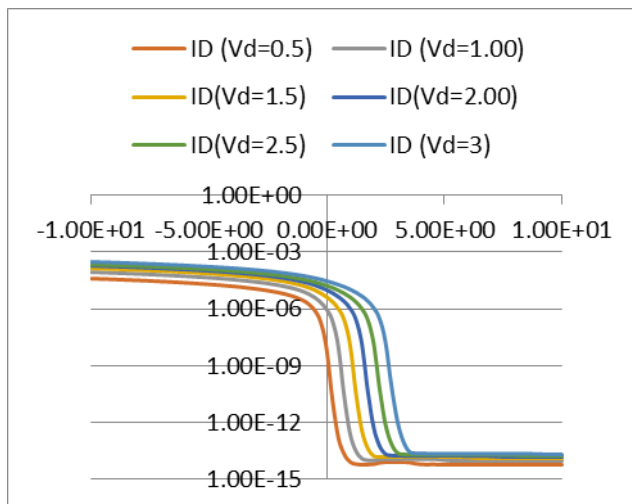Fig.25: Ids vs Vds curves

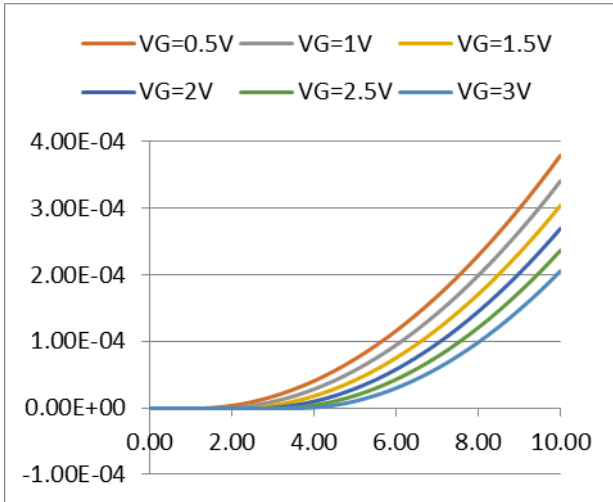Fig.26: Ids vs Vgs curves

NW thickness 75nm:

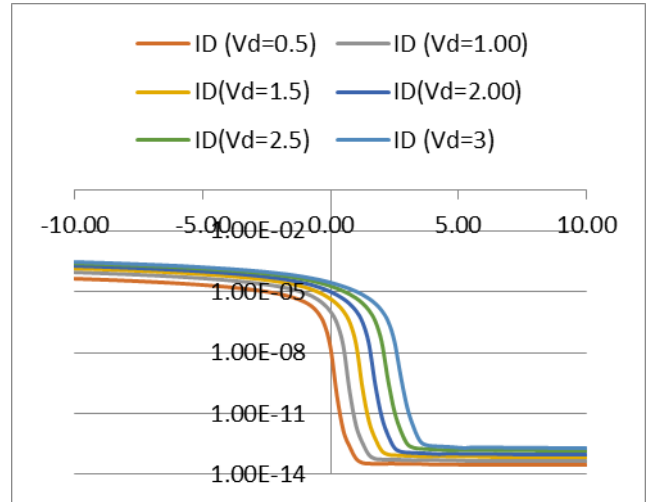Fig.27: Ids vs Vds curves

Fig.28: Ids vs Vgs curves
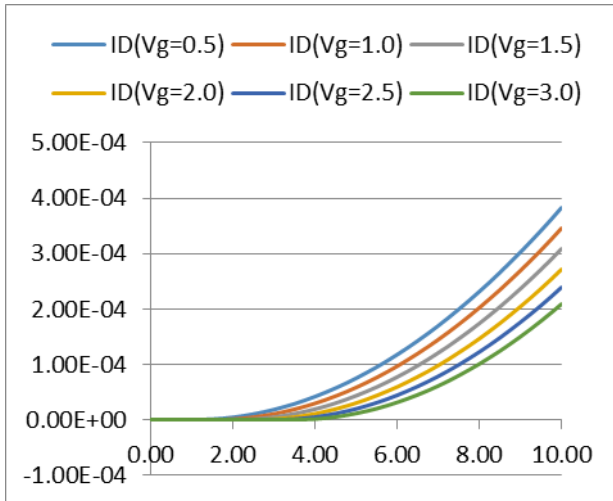
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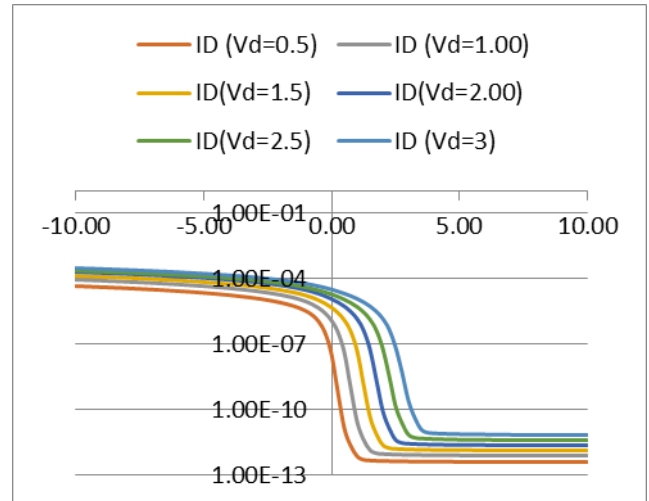

Fig.29: Ids vs Vds curves

Fig.30: Ids vs Vgs curves

4. 6e16/cm^3

NW thickness 10nm:

Fig.31: Ids vs Vds curves

Fig.32: Ids vs Vgs curves

NW thickness 25nm:

Fig.33: Ids vs Vds curves

Fig.34: Ids vs Vgs curves

NW thickness 50nm:

Fig.35: Ids vs Vds curves

Fig.36: Ids vs Vgs curves

NW thickness 75nm:

Fig.37: Ids vs Vds curves

Fig.38: Ids vs Vgs curves

NW thickness 100nm:

Fig.39: Ids vs Vds curves

Fig.40: Ids vs Vgs curves

5. 8e16/cm^3
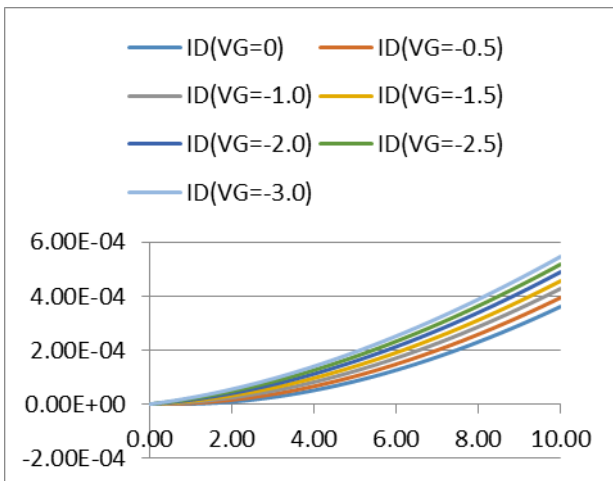
NW thickness 10nm:

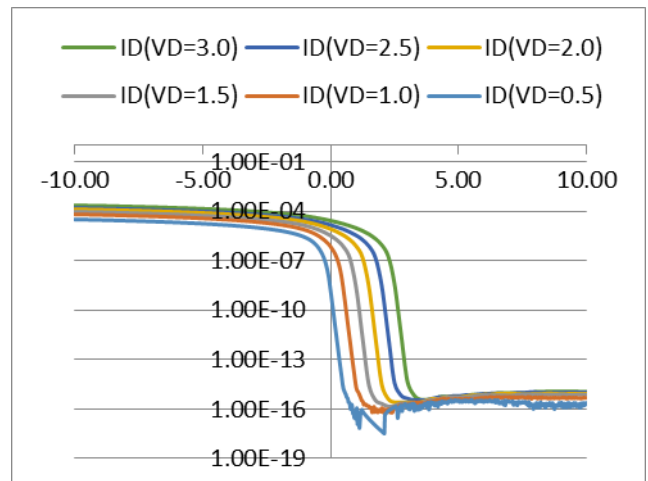
Fig.41: Ids vs Vds curves

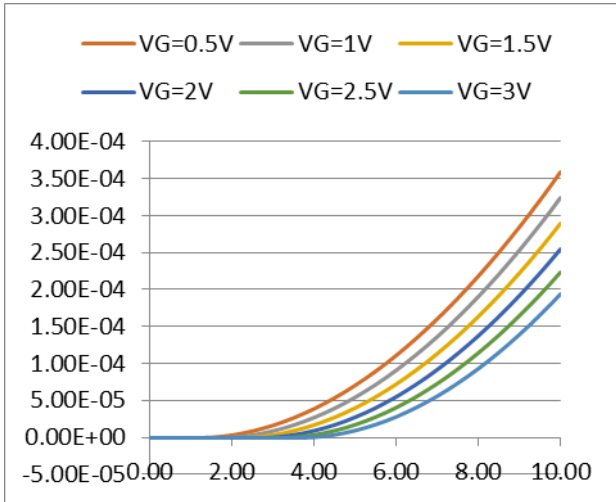Fig.42: Ids vs Vgs curves

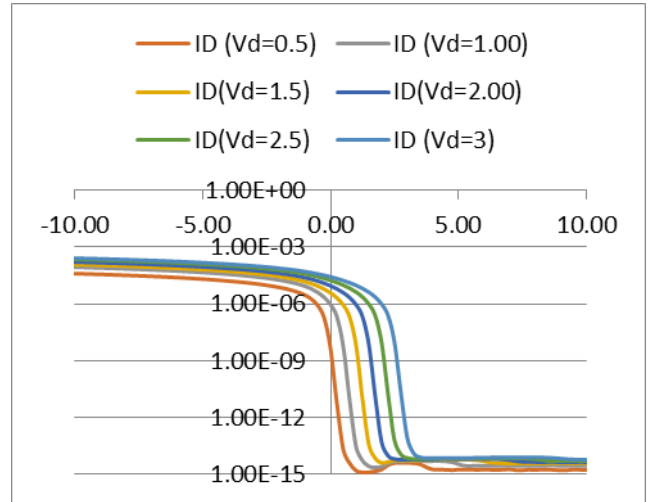### NW thickness 25nm:

Fig.43: Ids vs Vds curves

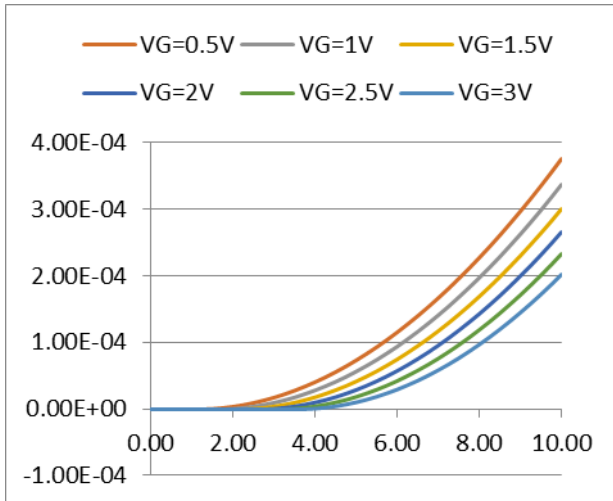Fig.44: Ids vs Vgs curves

NW thickness 50nm:
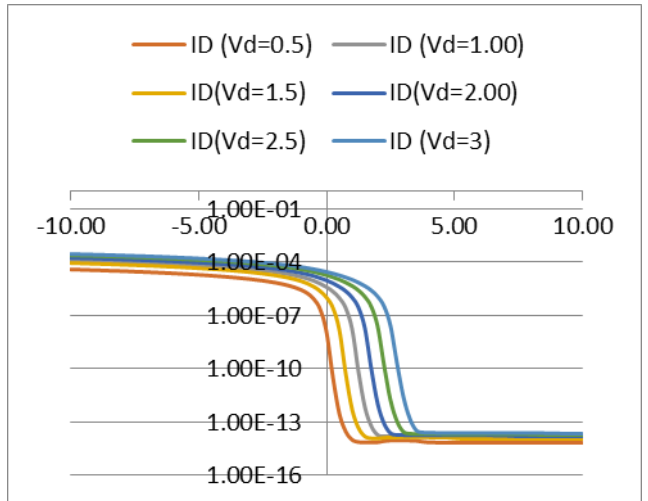

Fig.45: Ids vs Vds curves

Fig.46: Ids vs Vgs curves

NW thickness 75nm:

Fig.47: Ids vs Vds curves

Fig.48: Ids vs Vgs curves

NW thickness 100nm:

Fig.49: Ids vs Vds curves

Fig.50: Ids vs Vgs curves

6. 1e17/cm^3

NW thickness 10nm:

Fig.51: Ids vs Vds curves

Fig.52: Ids vs Vgs curves

NW thickness 25nm:

Fig.53: Ids vs Vds curves

Fig.54: Ids vs Vgs curves

NW thickness 50nm:

Fig.55: Ids vs Vds curves

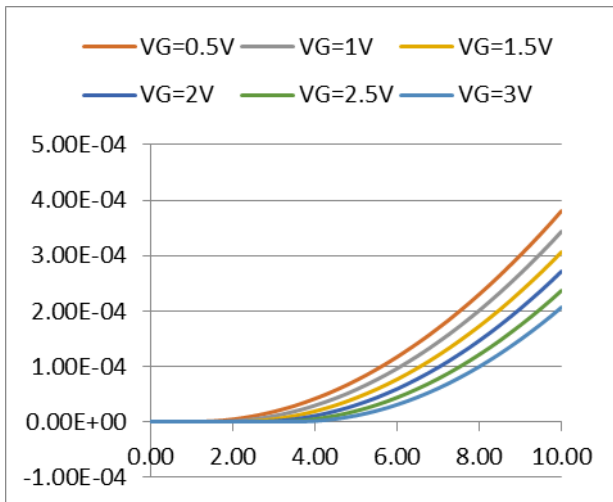Fig.56: Ids vs Vgs curves

NW thickness 75nm:

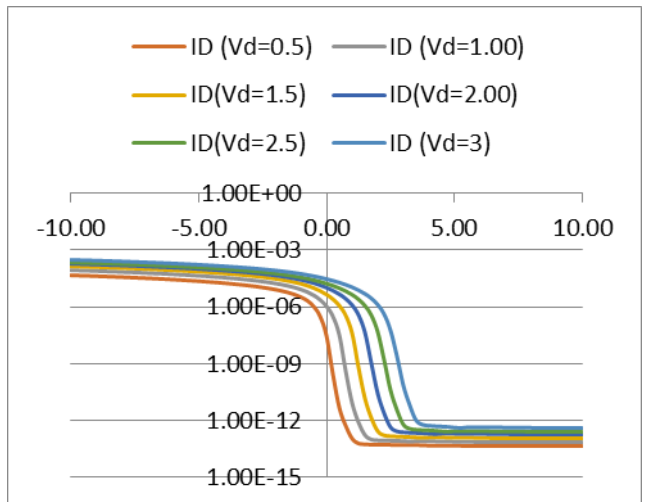Fig.57: Ids vs Vds curves

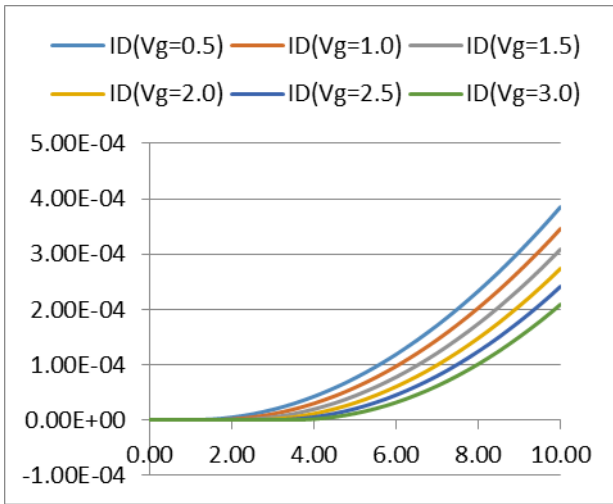Fig.58: Ids vs Vgs curves

NW thickness 100nm:
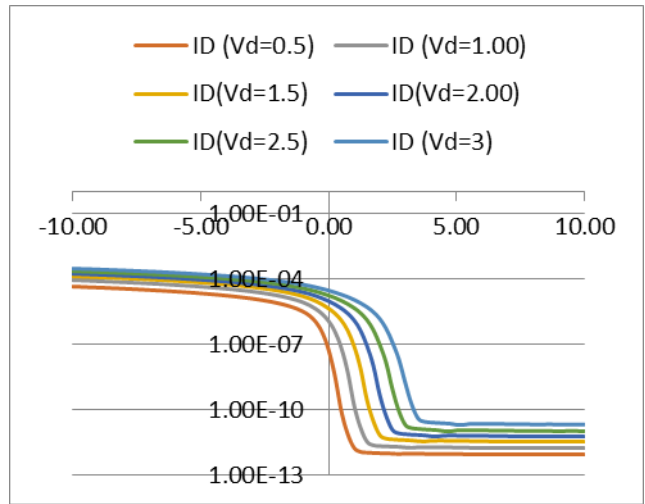

Fig.59: Ids vs Vds curves

Fig.60: Ids vs Vgs curves
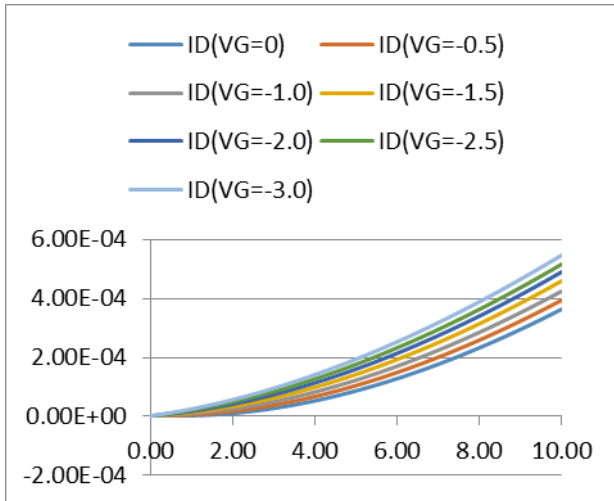
7. 2e17/cm^3

NW thickness 10nm:

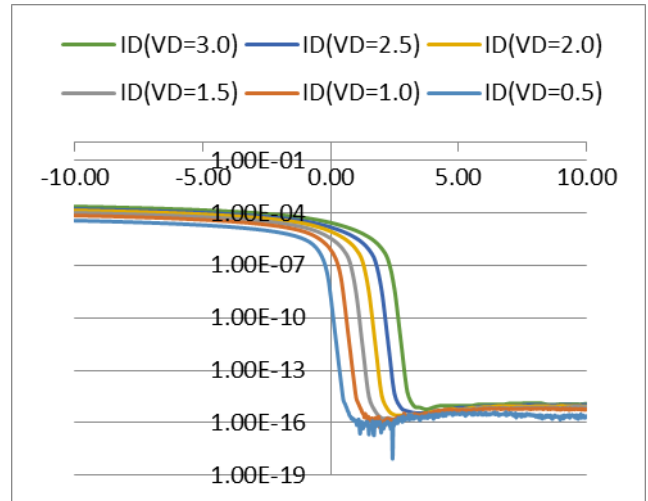Fig.61: Ids vs Vds curves

Fig.62: Ids vs Vgs curves

NW thickness 25nm:

Fig.63: Ids vs Vds curves

Fig.64: Ids vs Vgs curves

NW thickness 50nm:

Fig.65: Ids vs Vds curves

Fig.66: Ids vs Vgs curves

NW thickness 75nm:

Fig.67: Ids vs Vds curves

Fig.68: Ids vs Vgs curves

NW thickness 100nm:

Fig.69: Ids vs Vds curves

Fig.70: Ids vs Vgs curves

8. 4e17/cm^3

NW thickness 10nm:

Fig.71: Ids vs Vds curves

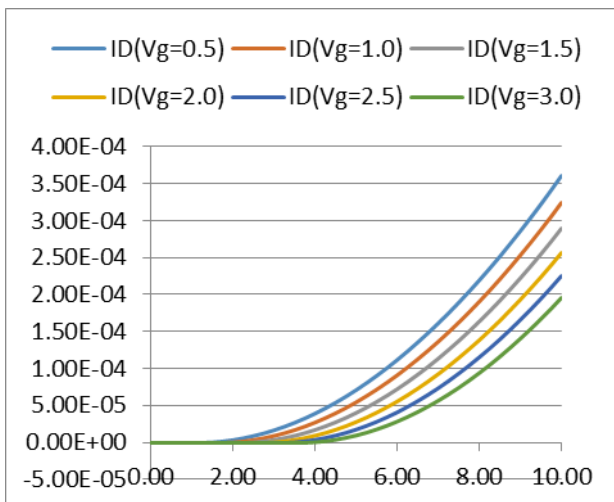Fig.72: Ids vs Vgs curves

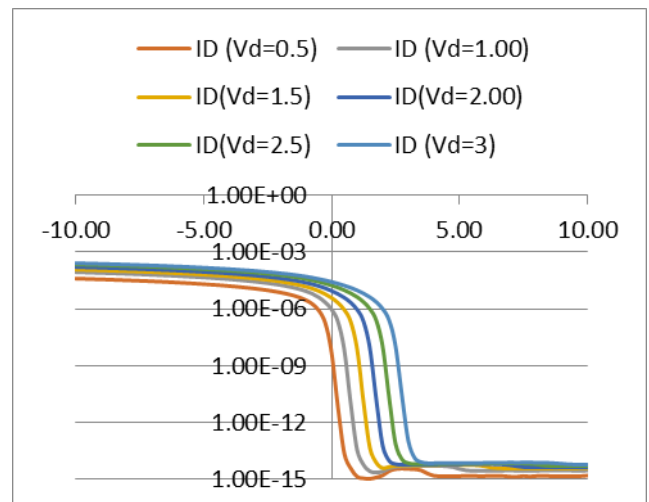**NW thickness 25nm:**

Fig.73: Ids vs Vds curves

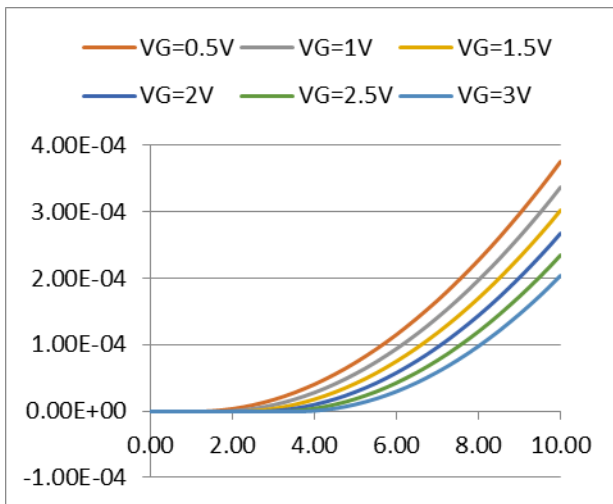Fig.74: Ids vs Vgs curves

NW thickness 50nm:
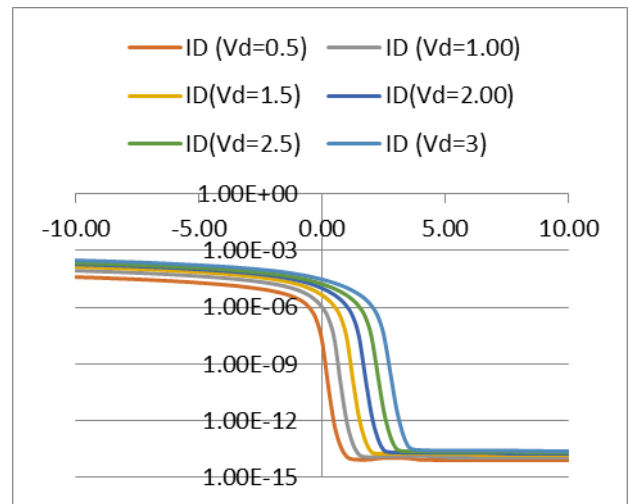

Fig.75: Ids vs Vds curves

Fig.76: Ids vs Vgs curves
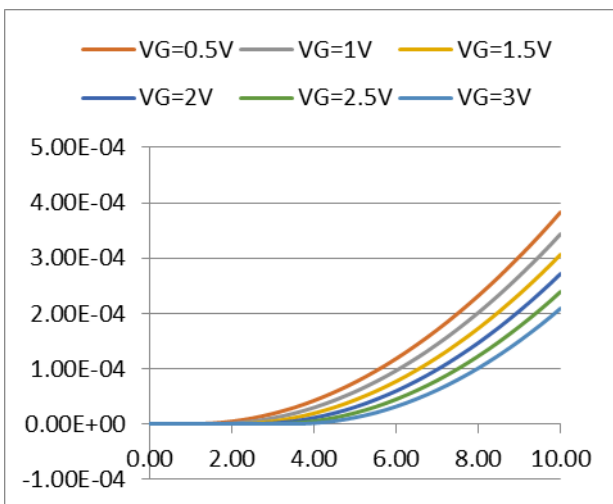
NW thickness 50nm:
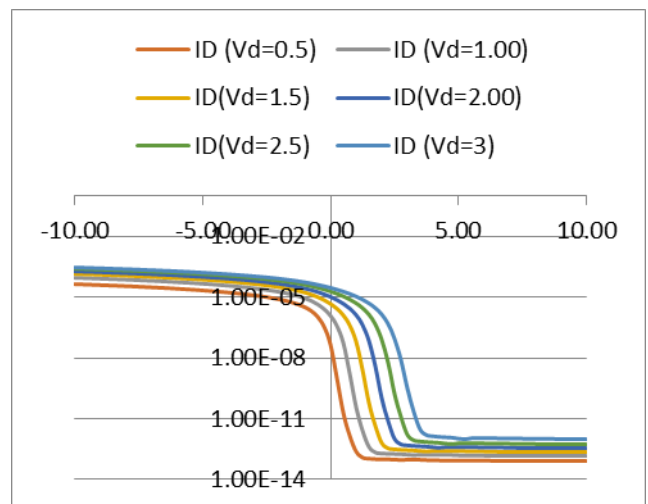

Fig.77: Ids vs Vds curves
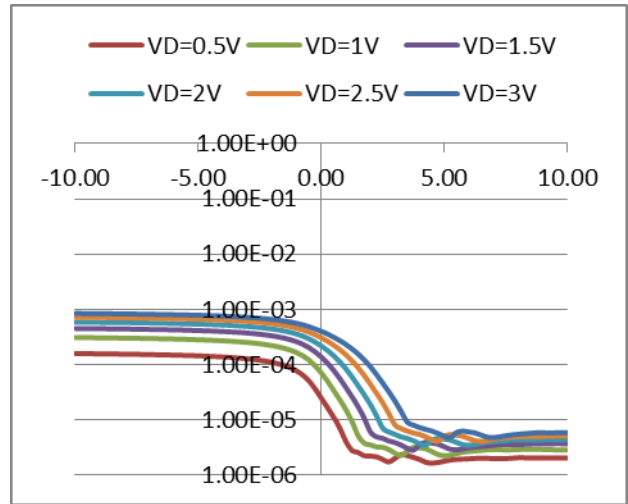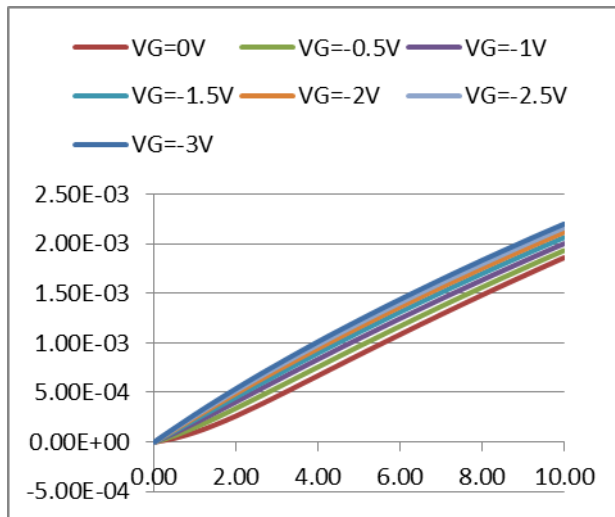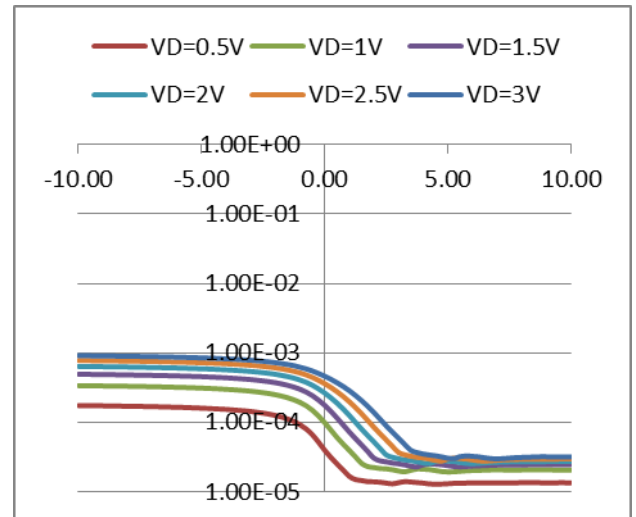
Fig.78: Ids vs Vgs curves

NW thickness 100nm

Fig.79: Ids vs Vds curves

Fig.80: Ids vs Vgs curves

9. 6e17/cm^3
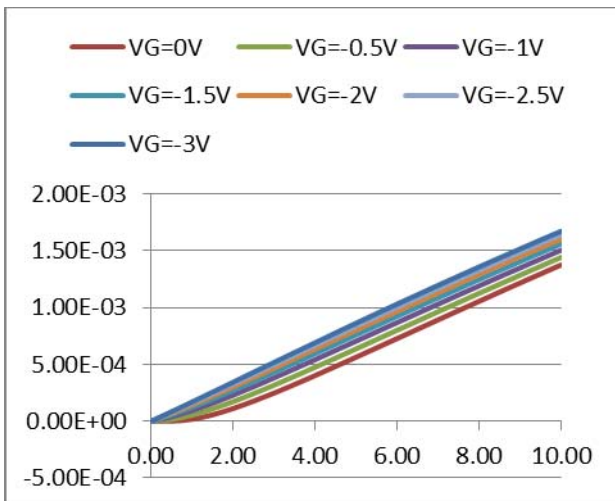
NW thickness 10nm:

Fig.81: Ids vs Vds curves
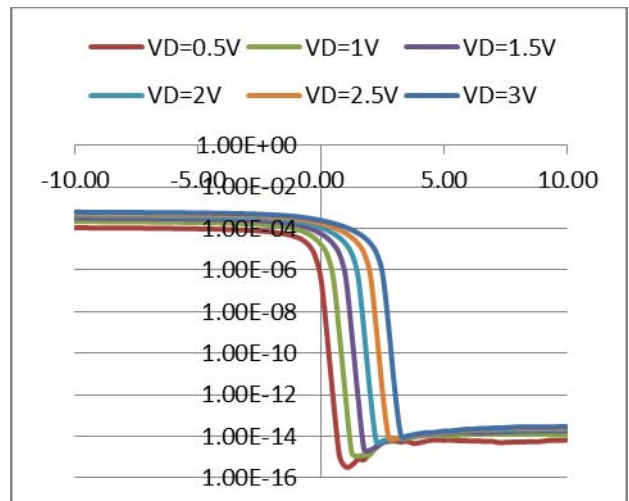
Fig.82: Ids vs Vgs curves
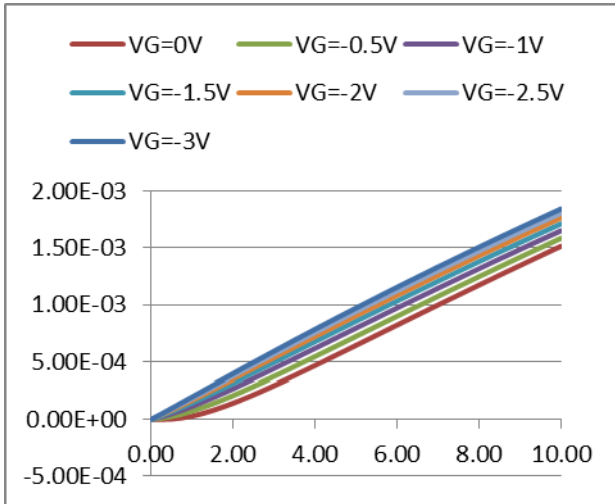
NW thickness 25nm:

Fig.83: Ids vs Vds curves
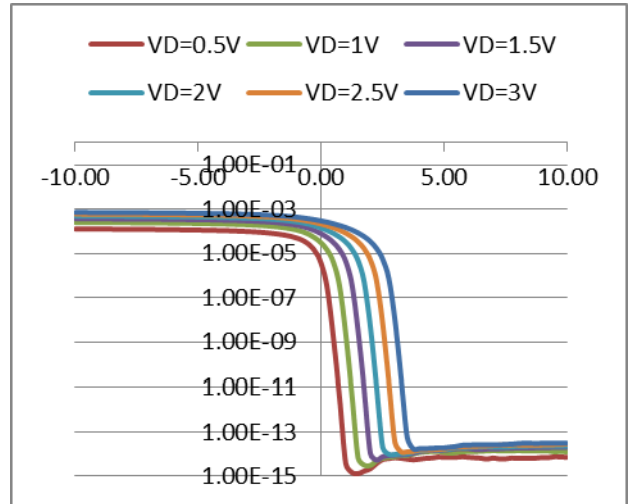
Fig.84: Ids vs Vgs curves
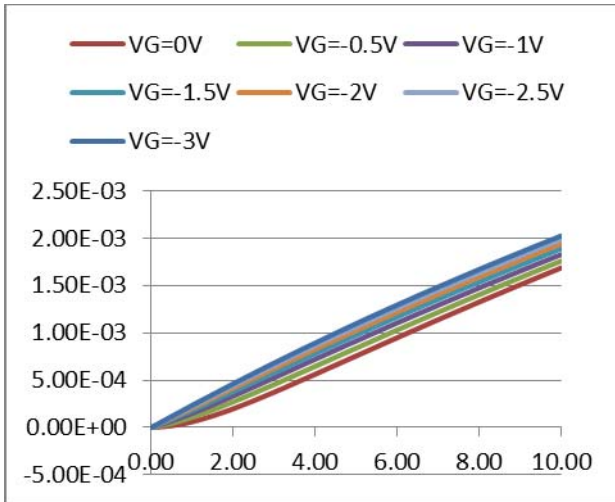
NW thickness 50nm:

Fig.85: Ids vs Vds curves
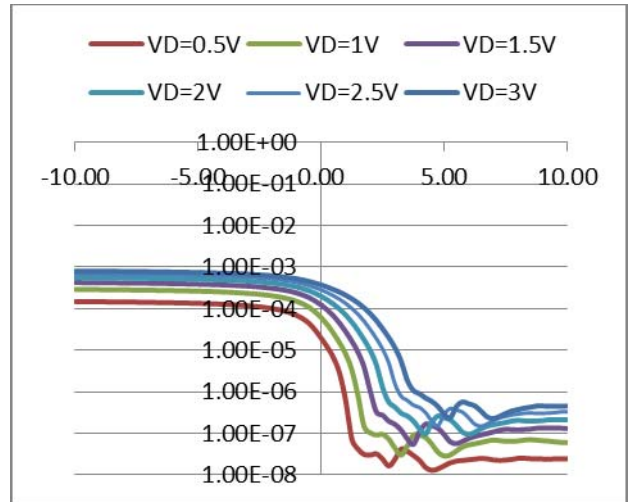
Fig.86: Ids vs Vgs curves
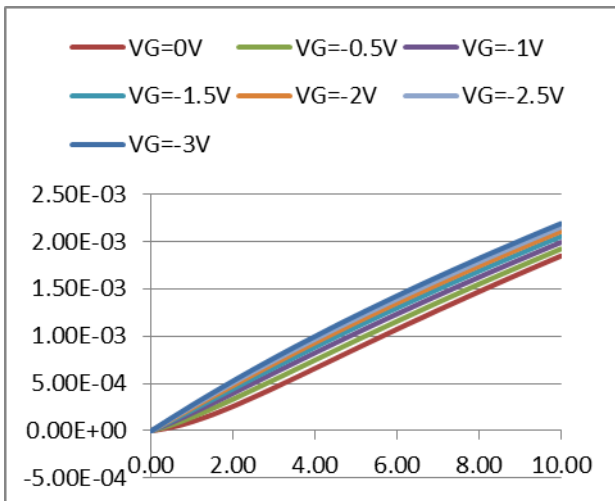
NW thickness 75nm:

Fig.87: Ids vs Vds curves
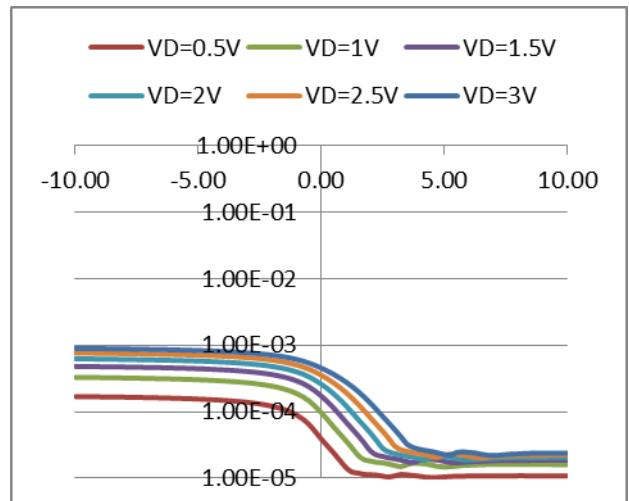
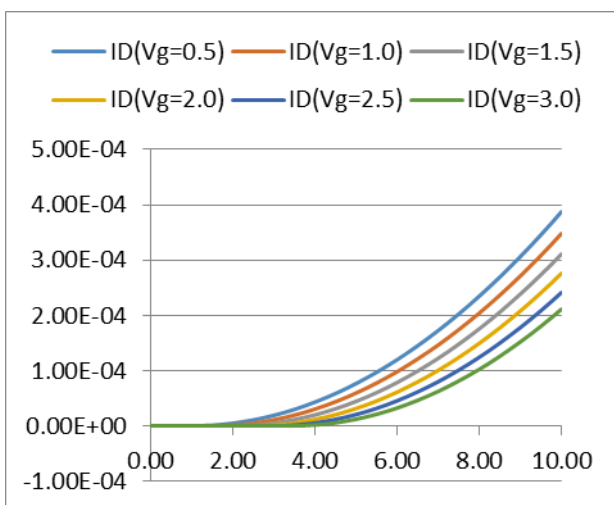Fig.88: Ids vs Vgs curves

NW thickness 100nm:
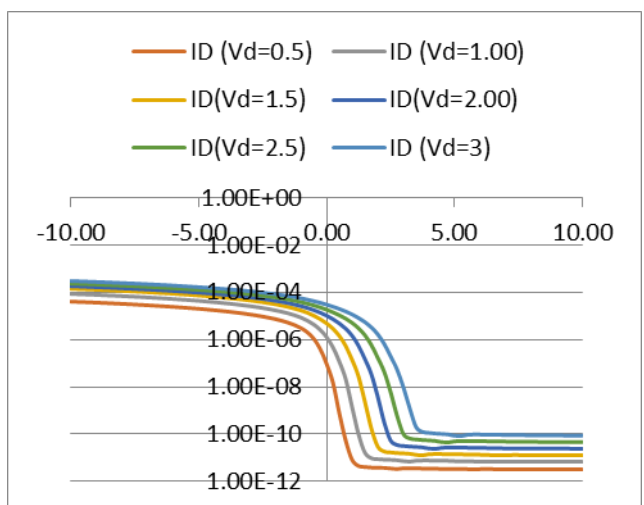

Fig.89: Ids vs Vds curves

Fig.90: Ids vs Vgs curves

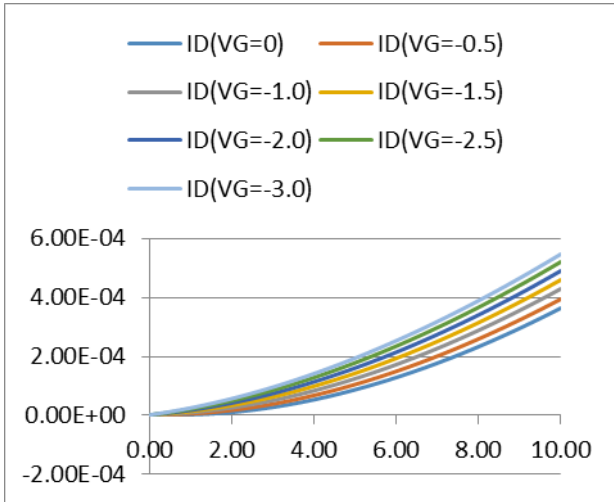**10. 8e17/cm^3**

NW thickness 10nm:

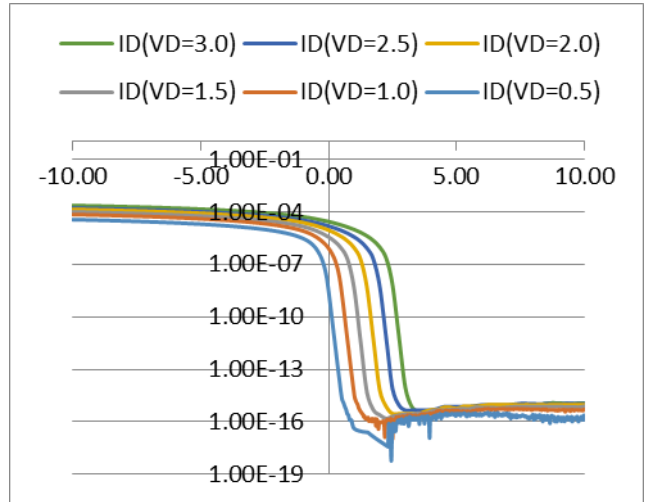Fig.91: Ids vs Vds curves

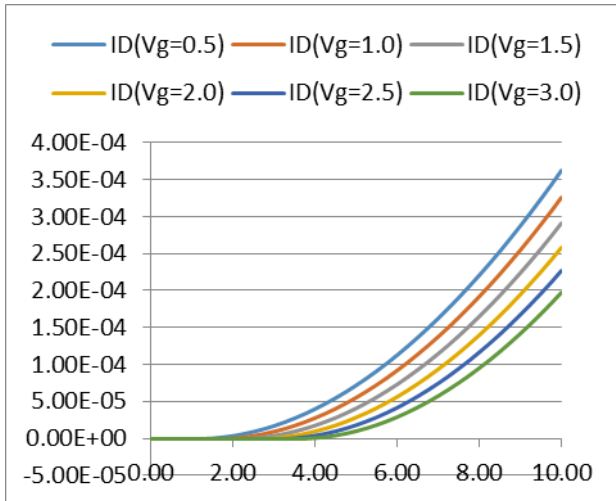Fig.92: Ids vs Vgs curves

NW thickness 25nm:
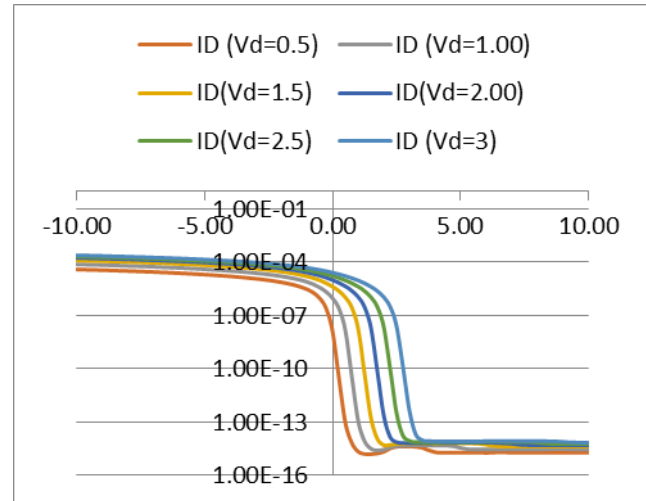

Fig.93: Ids vs Vds curves

Fig.94: Ids vs Vgs curves

NW thickness 50nm:

Fig.95: Ids vs Vds curves

Fig.96: Ids vs Vgs curves

NW thickness 75nm:

Fig.97: Ids vs Vds curves

Fig.98: Ids vs Vgs curves
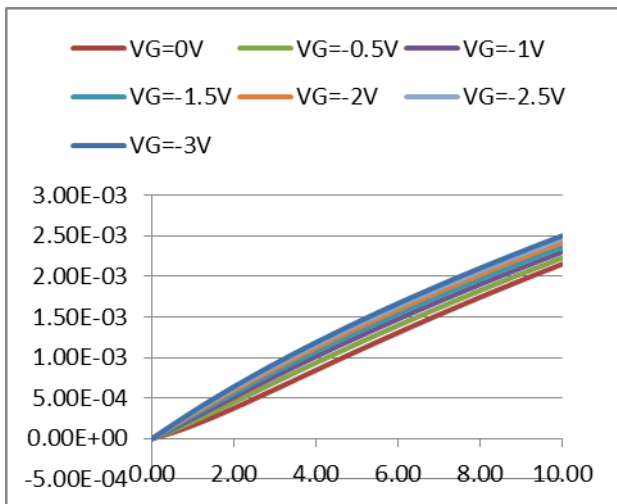
NW thickness 100nm:

Fig.99: Ids vs Vds curves
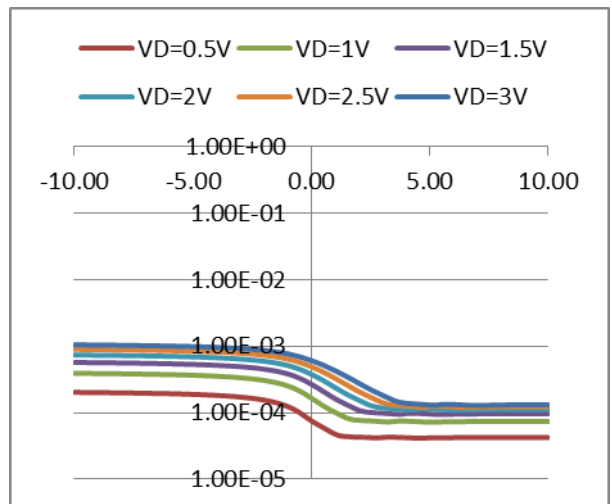
Fig.100: Ids vs Vgs curves

11. 1e18/cm³

NW thickness 10nm:

Fig.101: Ids vs Vds curves

Fig.102: Ids vs Vgs curves

NW thickness 25nm:

Fig.103: Ids vs Vds curves

Fig.104: Ids vs Vgs curves

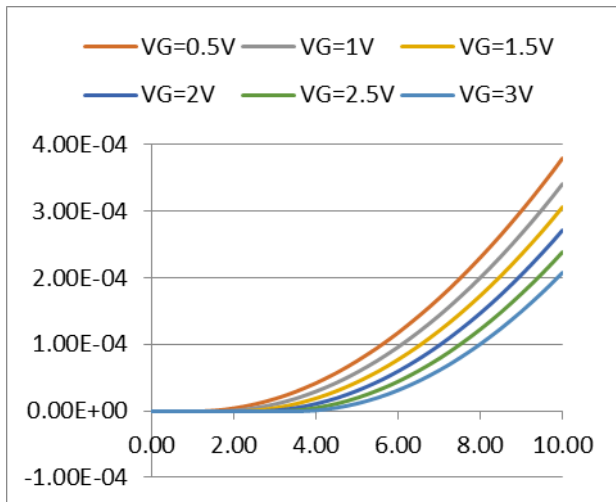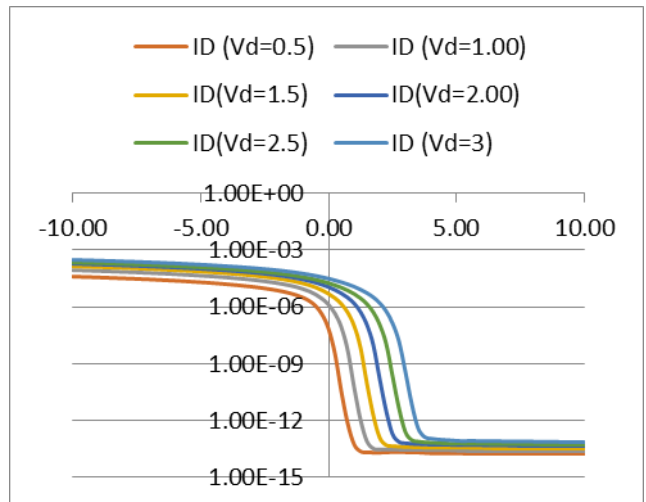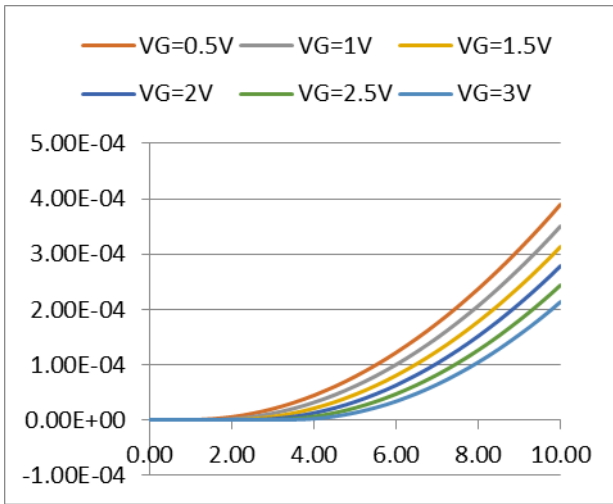**NW thickness 50nm:**

Fig.105: Ids vs Vds curves

Fig.106: Ids vs Vgs curves

NW thickness 75nm:

Fig.107: Ids vs Vds curves

Fig.108: Ids vs Vgs curves

NW thickness 75nm:

Fig.109: Ids vs Vds curves
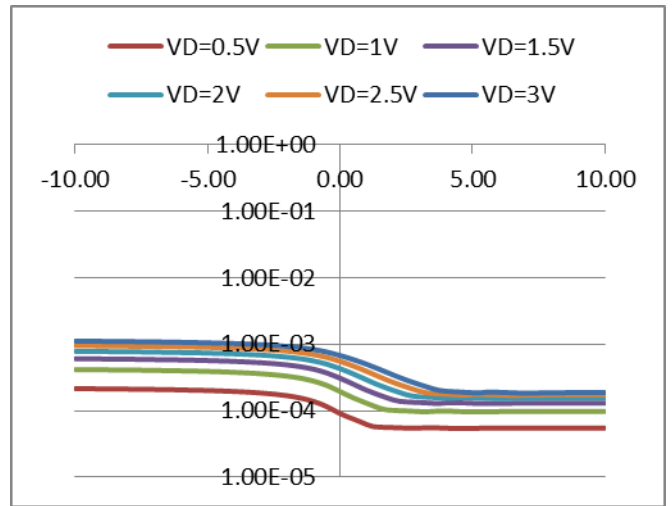
Fig.110: Ids vs Vgs curves

Appendix B

Poly Silicon Nanowire

1. 1e16/cm^3

NW thickness 10nm:

Fig.01: Ids vs Vds curves

Fig.02: Ids vs Vgs curves

NW thickness 25nm:

Fig.03: Ids vs Vds curves

Fig.04: Ids vs Vgs curves

NW thickness 50nm:

Fig.05: Ids vs Vds curves

Fig.06: Ids vs Vgs curves

NW thickness 75nm:

Fig.07: Ids vs Vds curves

Fig.08: Ids vs Vgs curves

NW thickness 100nm:

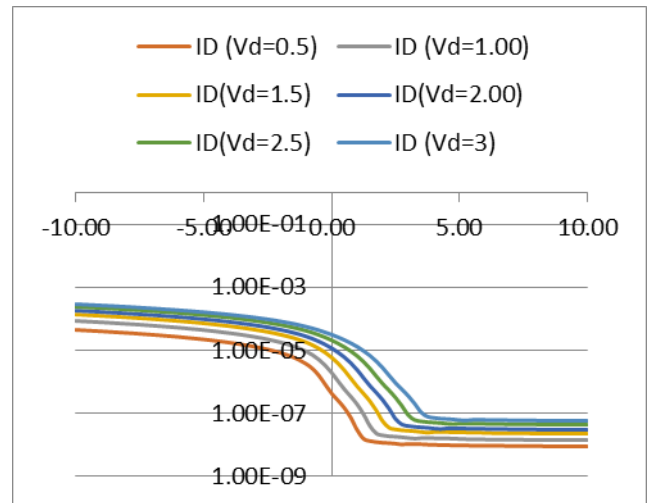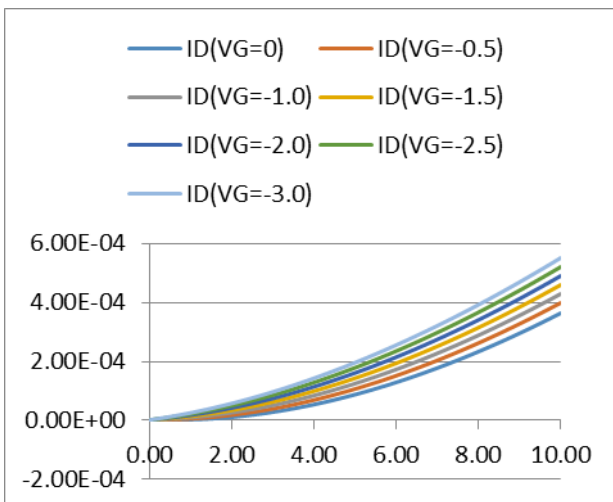

Fig.09: Ids vs Vds curves

Fig.10: Ids vs Vgs curves

2. $2e16/cm^3$

NW thickness 10nm:
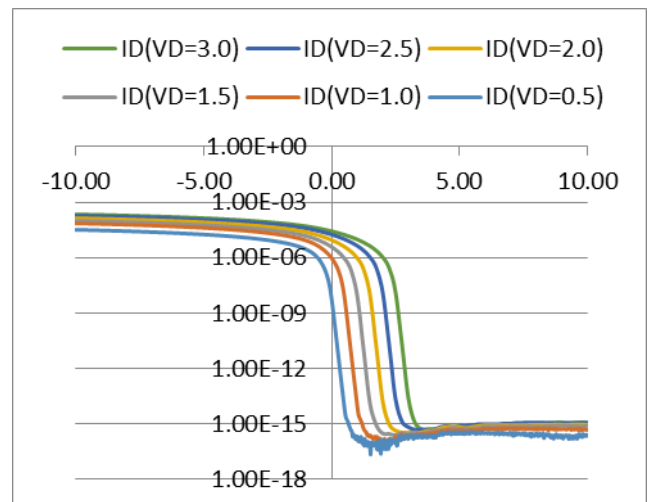

Fig.11: Ids vs Vds curves

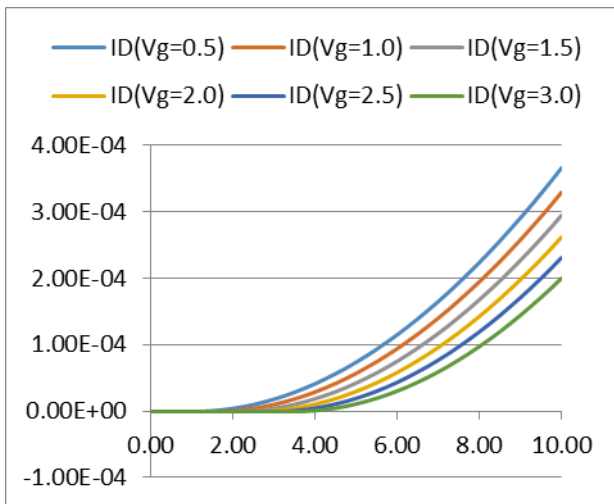Fig.12: Ids vs Vgs curves

NW thickness 25nm:

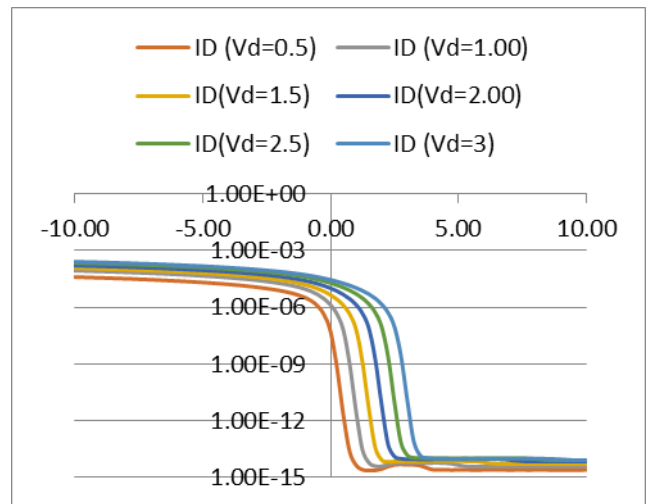Fig.13: Ids vs Vds curves

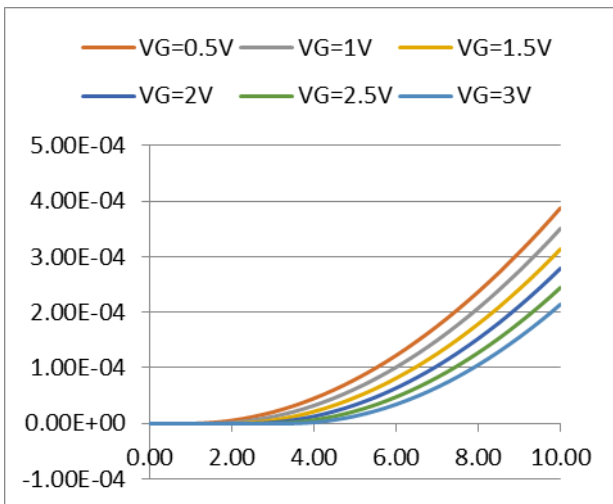Fig.14: Ids vs Vgs curves

NW thickness 50nm:

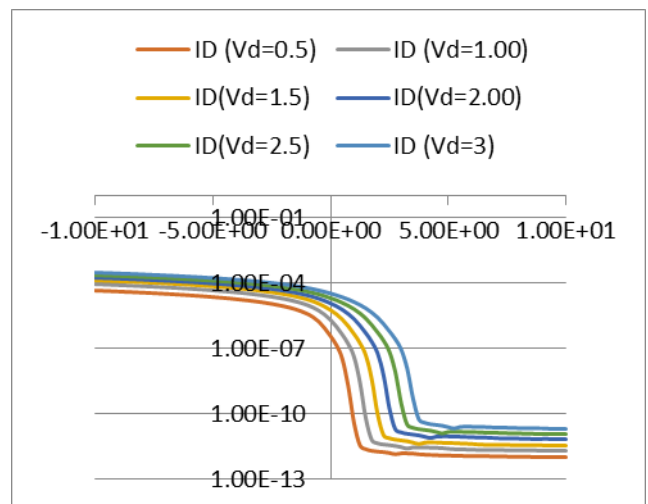Fig.15: Ids vs Vds curves

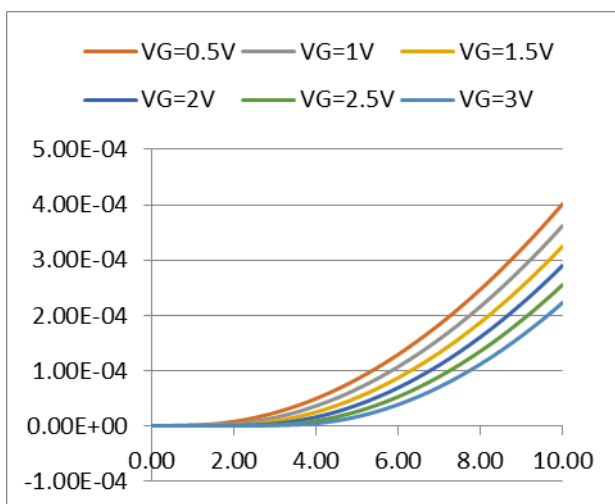Fig.16: Ids vs Vgs curves

NW thickness 75nm:

Fig.17: Ids vs Vds curves

Fig.18: Ids vs Vgs curves

NW thickness 100nm:

Fig.19: Ids vs Vds curves

Fig.20: Ids vs Vgs curves

3. 4e16/cm^3

NW thickness 10nm:

Fig.21: Ids vs Vds curves

Fig.22: Ids vs Vgs curves

NW thickness 25nm:

Fig.23: Ids vs Vds curves

Fig.24: Ids vs Vgs curves

NW thickness 50nm:

Fig.25: Ids vs Vds curves

Fig.26: Ids vs Vgs curves

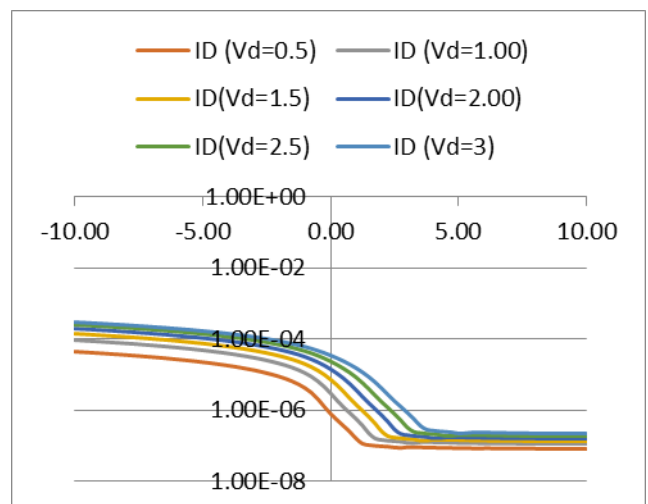**NW thickness 75nm:**

Fig.27: Ids vs Vds curves

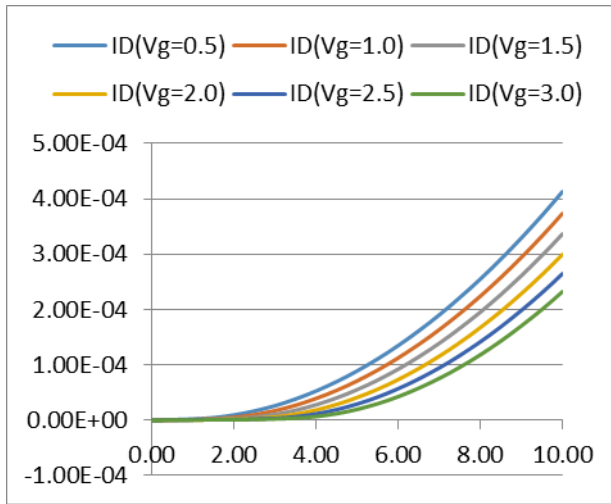Fig.28: Ids vs Vgs curves

NW thickness 100nm:
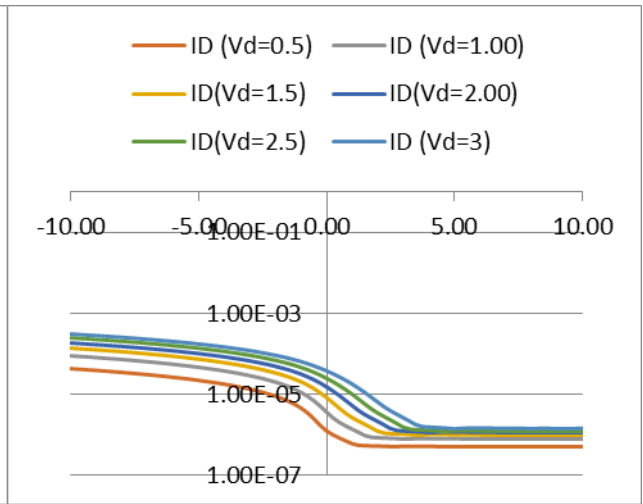
Fig.29: Ids vs Vds curves

Fig.30: Ids vs Vgs curves

4. 6e16/cm^3

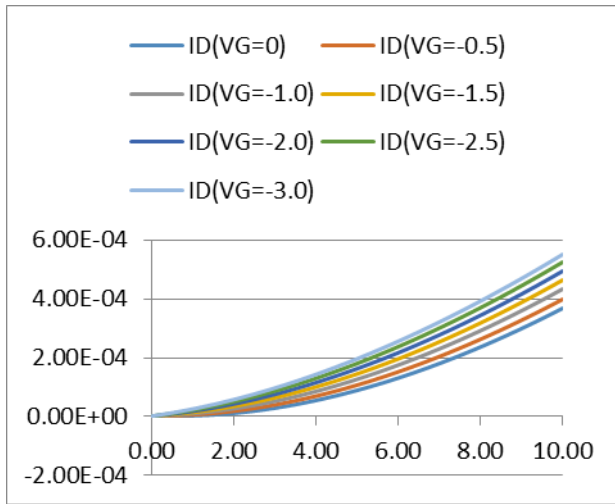**NW thickness 10nm:**

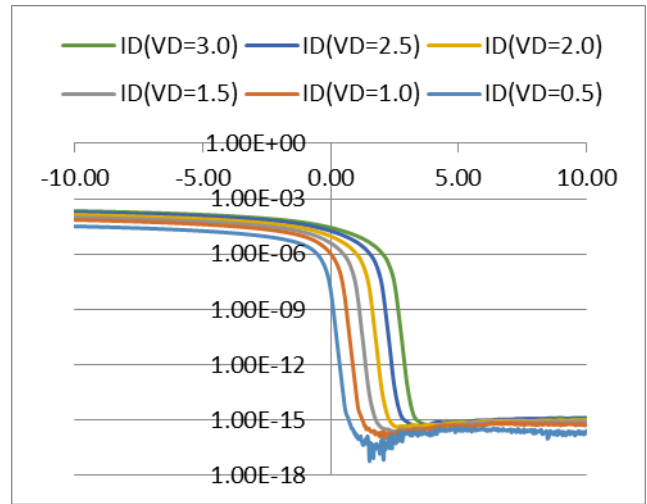Fig.31: Ids vs Vds curves

Fig.32: Ids vs Vgs curves

NW thickness 25nm:

Fig.33: Ids vs Vds curves

Fig.34: Ids vs Vgs curves

NW thickness 50nm:

Fig.35: Ids vs Vds curves

Fig.36: Ids vs Vgs curves

NW thickness 75nm:

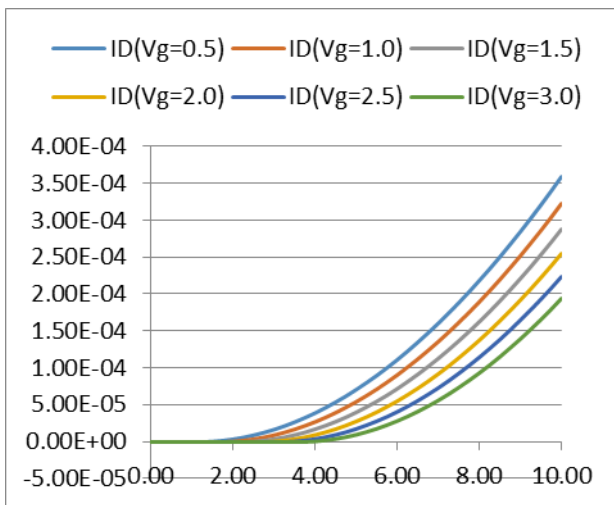Fig.37: Ids vs Vds curves

Fig.38: Ids vs Vgs curves

NW thickness 100nm:

Fig.39: Ids vs Vds curves

Fig.40: Ids vs Vgs curves

5. 8e16/cm^3

NW thickness 10nm:

Fig.41: Ids vs Vds curves

Fig.42: Ids vs Vgs curves

NW thickness 25nm:

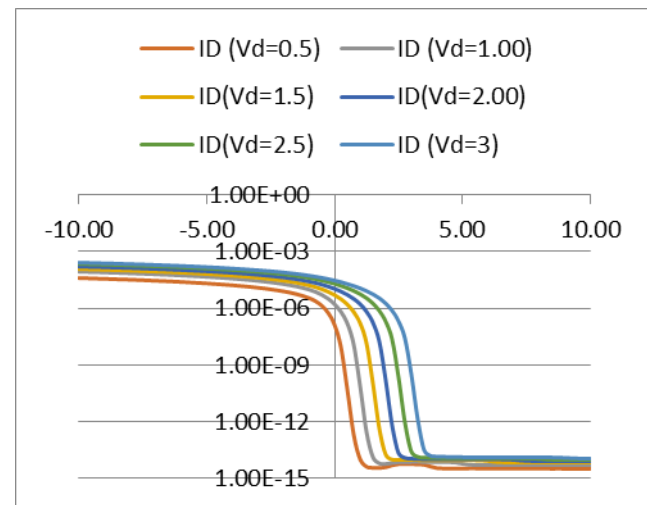
Fig.43: Ids vs Vds curves

Fig.44: Ids vs Vgs curves

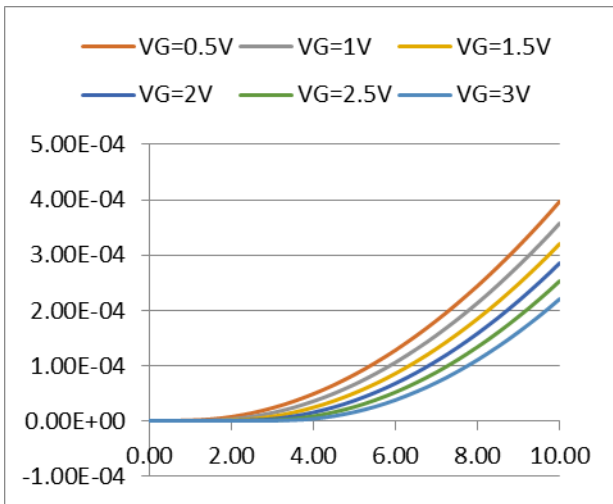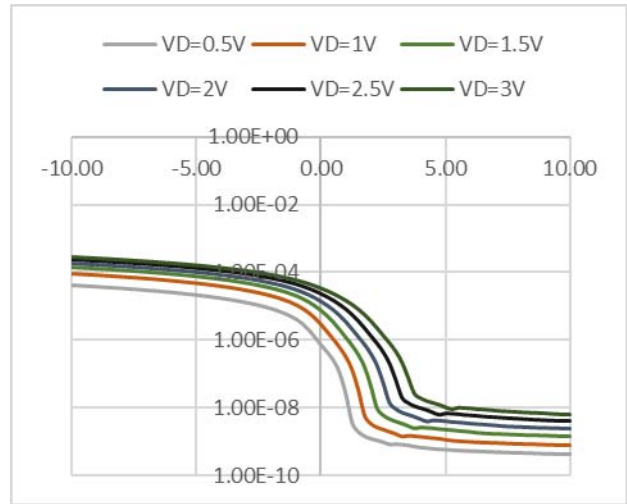**NW thickness 50nm:**

Fig.45: Ids vs Vds curves

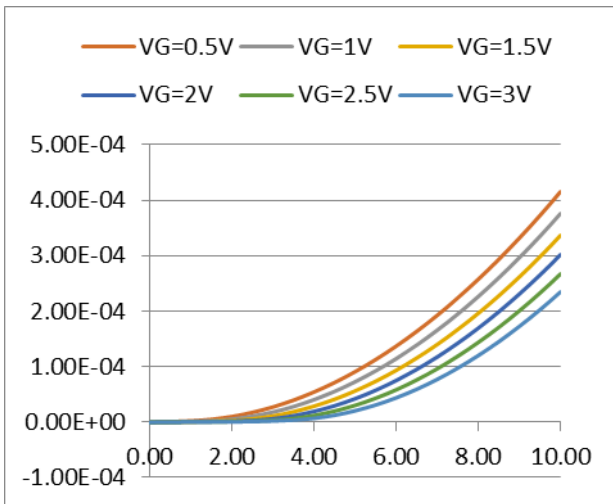Fig.46: Ids vs Vgs curves

NW thickness 75nm:
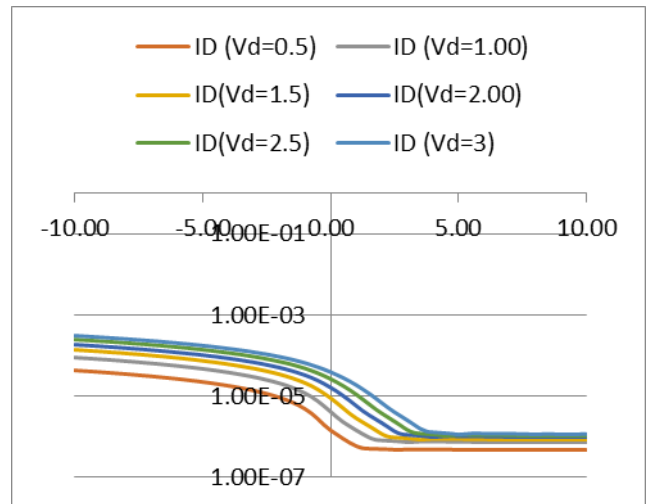

Fig.47: Ids vs Vds curves

Fig.48: Ids vs Vgs curve
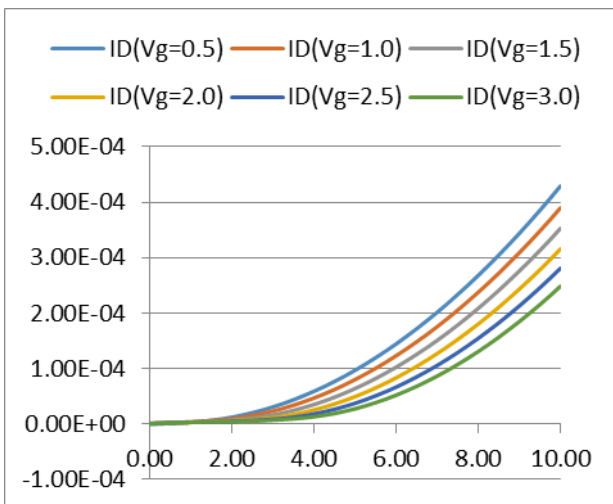
NW thickness 100nm:

Fig.49: Ids vs Vds curves

Fig.50: Ids vs Vgs curves

6. 1e17/cm^3

NW thickness 10nm:

Fig.51: Ids vs Vds curves

Fig.52: Ids vs Vgs curves

NW thickness 25nm:

Fig.53: Ids vs Vds curves
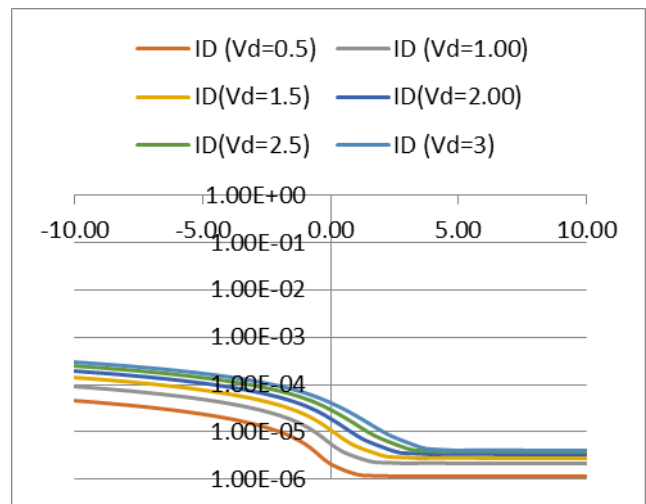

Fig.54: Ids vs Vgs curves

NW thickness 50nm:

Fig.55: Ids vs Vds curves

Fig.56: Ids vs Vgs curves

NW thickness 75nm:

Fig.57: Ids vs Vds curves

Fig.58: Ids vs Vgs curves

NW thickness 100nm:

Fig.59: Ids vs Vds curves

Fig.60: Ids vs Vgs curves
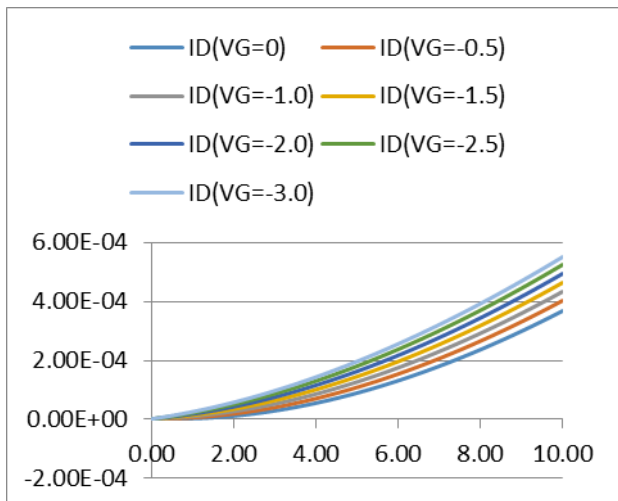
7.   2e17/cm^3

NW thickness 10nm:
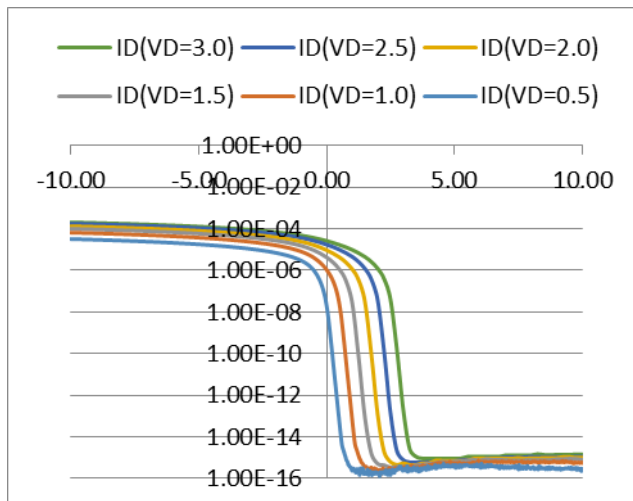

Fig.61: Ids vs Vds curves

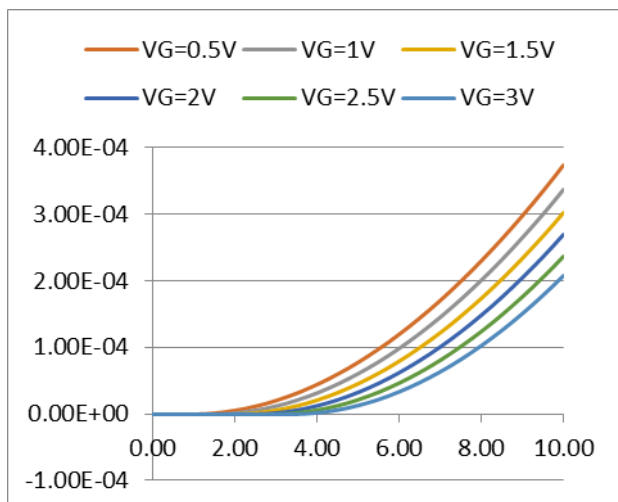Fig.62: Ids vs Vgs curves

NW thickness 25nm:

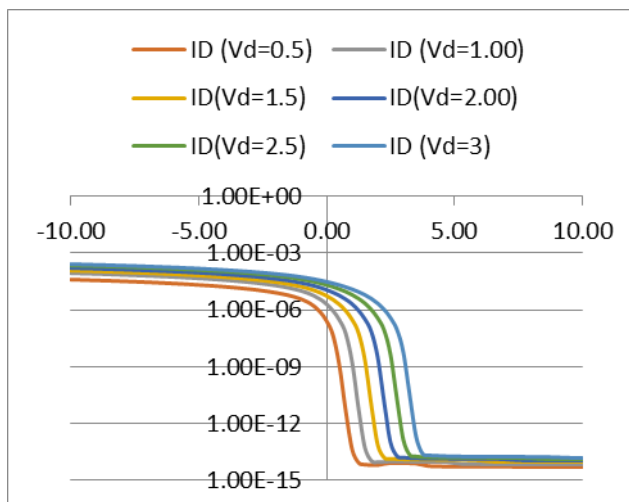Fig.63: Ids vs Vds curves

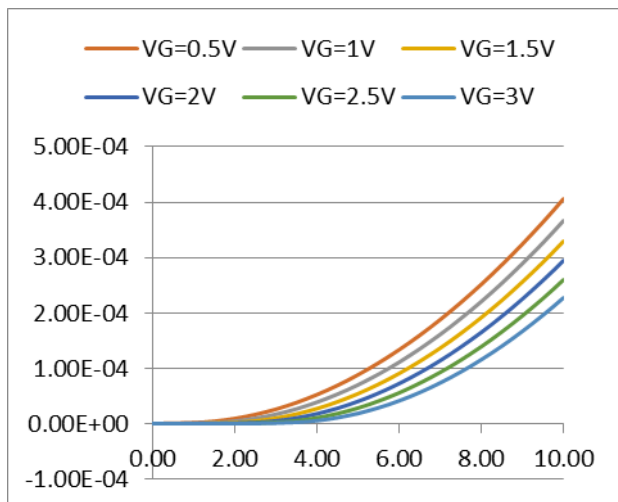Fig.64: Ids vs Vgs curves

NW thickness 50nm:

Fig.65: Ids vs Vds curves

Fig.66: Ids vs Vgs curves

NW thickness 75nm:

Fig.67: Ids vs Vds curves

Fig.68: Ids vs Vgs curve

NW thickness 100nm:

Fig.69: Ids vs Vds curves

Fig.70: Ids vs Vgs curves

8. 4e17/cm^3

NW thickness 10nm:

Fig.71: Ids vs Vds curves

Fig.72: Ids vs Vgs curves

NW thickness 25nm:

Fig.73: Ids vs Vds curves

Fig.74: Ids vs Vgs curves

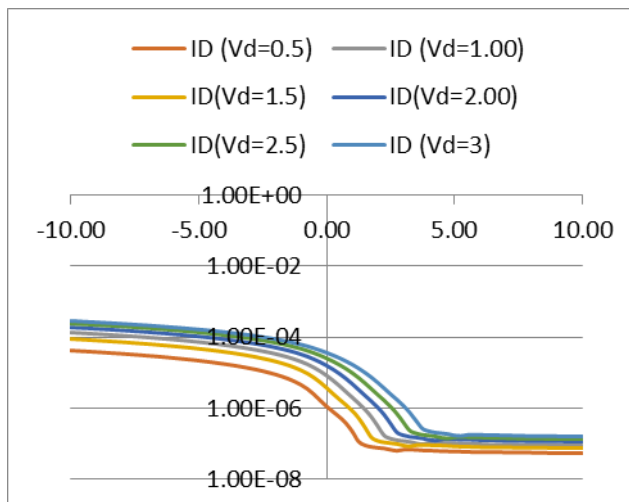**NW thickness 50nm:**

Fig.75: Ids vs Vds curves

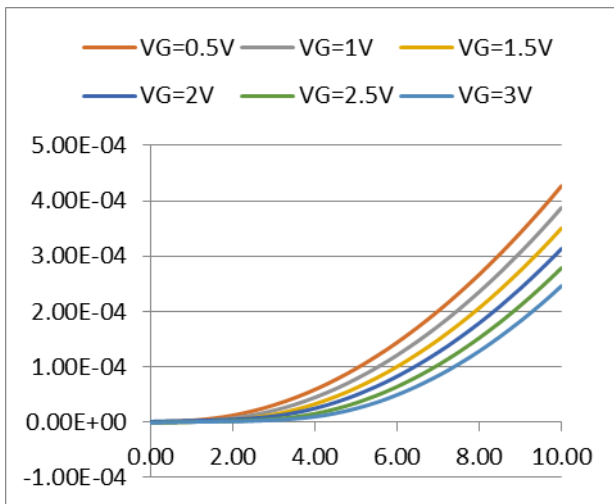Fig.76: Ids vs Vgs curves

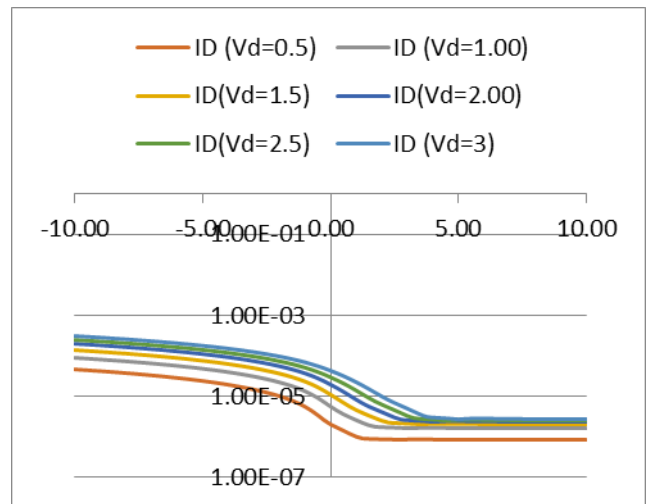**NW thickness 75nm:**

Fig.77: Ids vs Vds curves

Fig.78: Ids vs Vgs curves
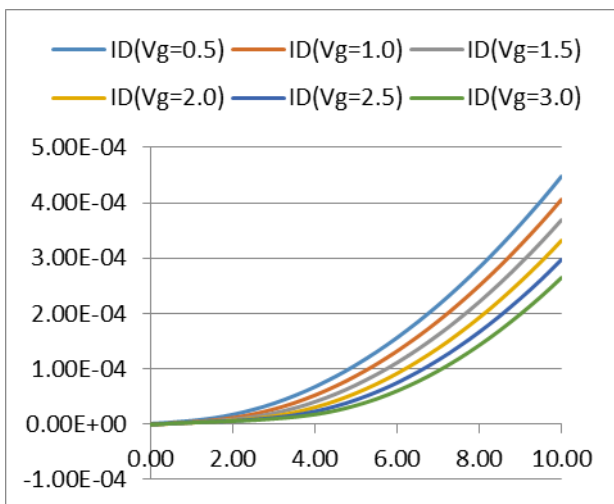
NW thickness 100nm:
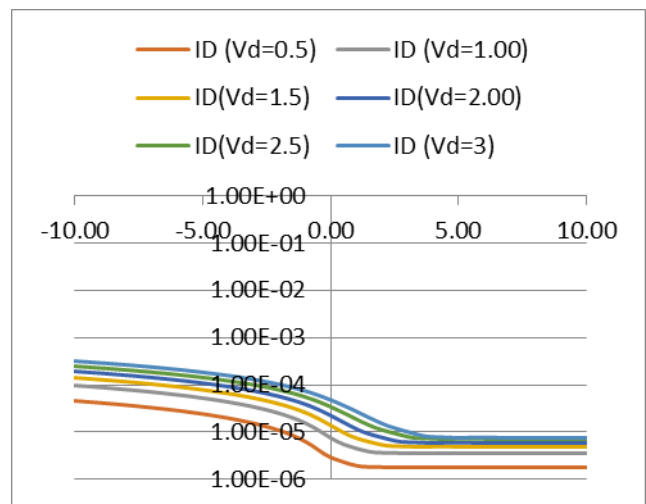

Fig.79: Ids vs Vds curves

Fig.80: Ids vs Vgs curves
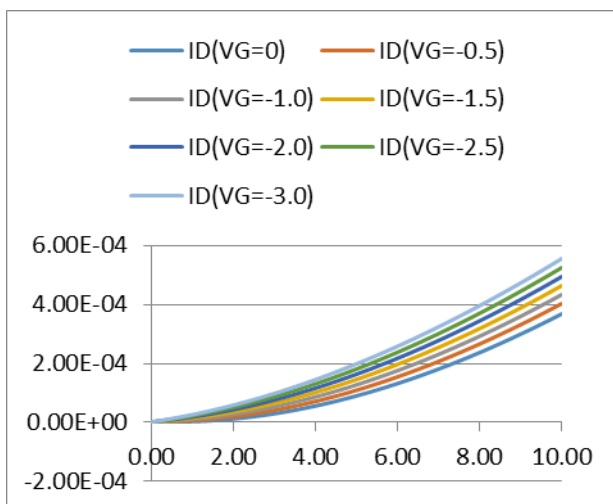
9. 6e17/cm³

NW thickness 10nm:

Fig.81: Ids vs Vds curves

Fig.82: Ids vs Vgs curves

NW thickness 25m:

Fig.83: Ids vs Vds curves

Fig.84: Ids vs Vgs curves

NW thickness 50m:

Fig.85: Ids vs Vds curves

Fig.86: Ids vs Vgs curves

NW thickness 75m:

Fig.87: Ids vs Vds curves

Fig.88: Ids vs Vgs curves

NW thickness 100m:

Fig.89: Ids vs Vds curves

Fig.90: Ids vs Vgs curves

10. 8e17/cm^3

NW thickness 10nm:

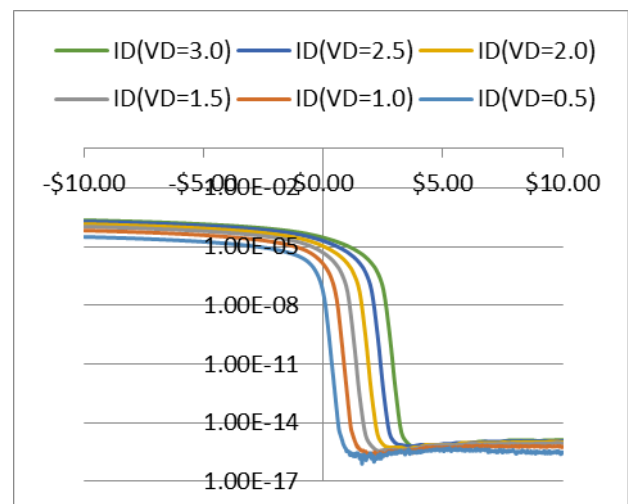Fig.91: Ids vs Vds curves

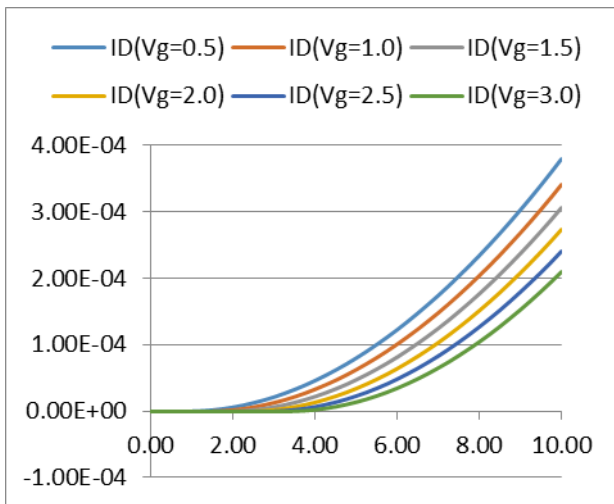Fig.92: Ids vs Vgs curves

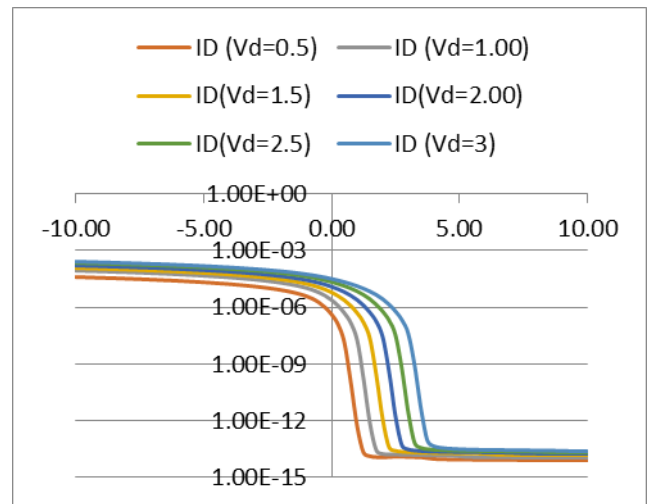**NW thickness 25nm:**

Fig.93: Ids vs Vds curves

Fig.94: Ids vs Vgs curves
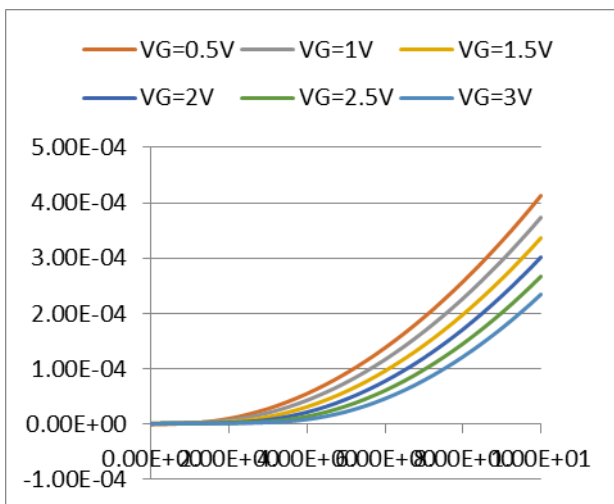
NW thickness 50nm:
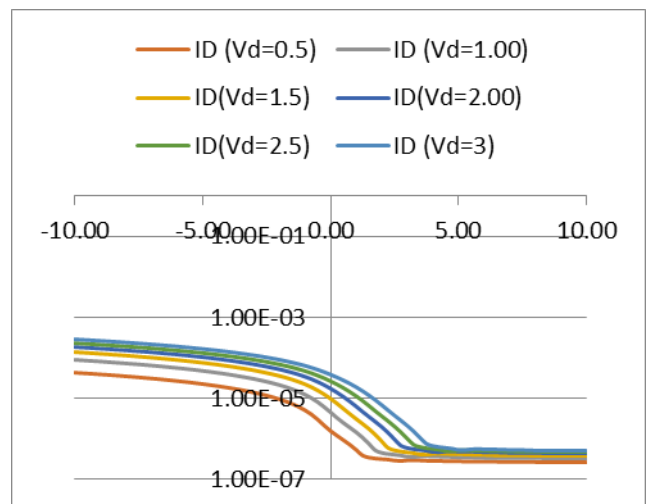

Fig.95: Ids vs Vds curves

Fig.96: Ids vs Vgs curves
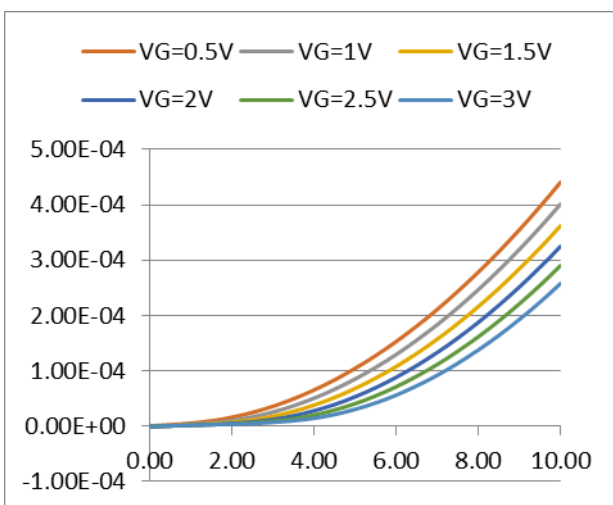
NW thickness 75nm:

Fig.97: Ids vs Vds curves

Fig.98: Ids vs Vgs curves

NW thickness 100nm:

Fig.99: Ids vs Vds curves

Fig.100: Ids vs Vgs curves

11. 1e18/cm^3

NW thickness 10nm:

Fig.101: Ids vs Vds curves

Fig.102: Ids vs Vgs curves

NW thickness 25nm:

Fig.103: Ids vs Vds curves

Fig.104: Ids vs Vgs curves

NW thickness 50nm:

Fig.105: Ids vs Vds curves

Fig.106: Ids vs Vgs curves

NW thickness 75nm:

Fig.107: Ids vs Vds curves

Fig.108: Ids vs Vgs curves

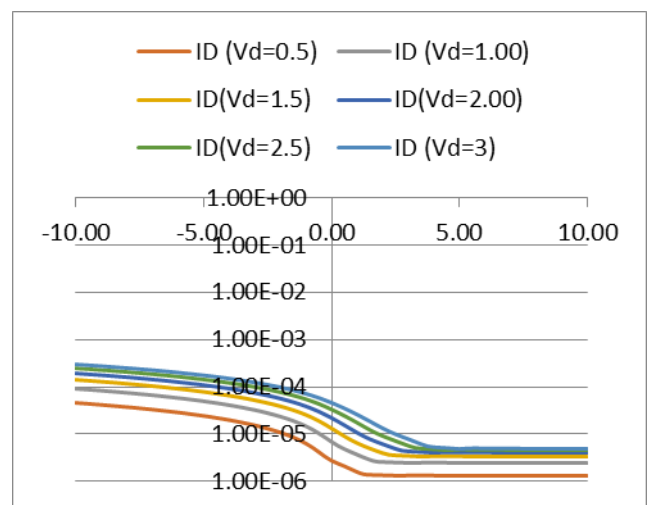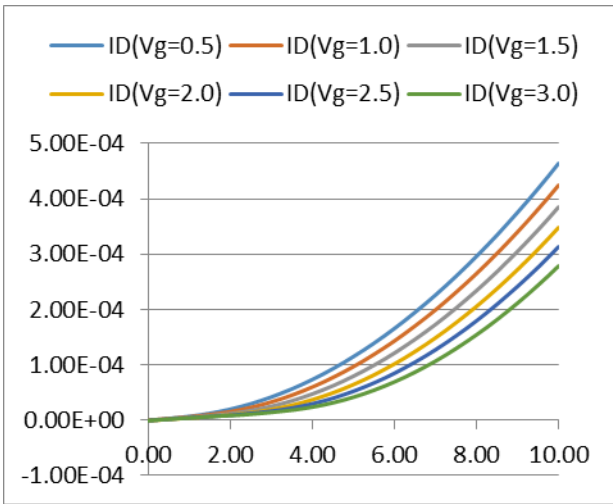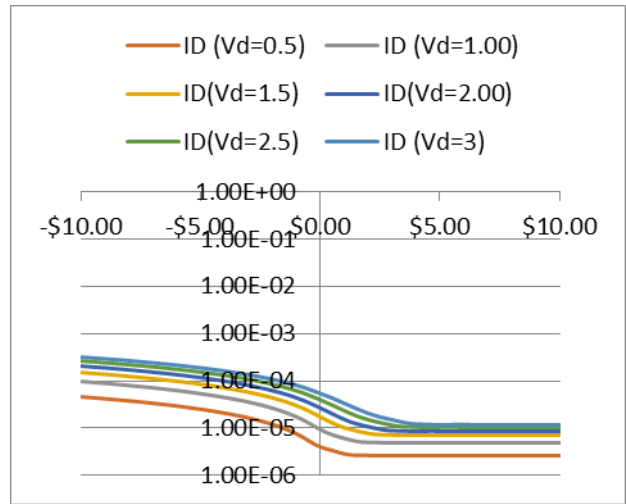**NW thickness 100nm:**

Fig.109: Ids vs Vds curves

Fig. 110 : Ids vs Vgs curves