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Saturated velocity model of MESFET in the presence of non-uniform distribution of channel impurities and interface states at the gate contact

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A comparative analysis of the electrical properties of a metal-semiconductor field effect transistor operated in the region of electron velocity saturation has been studied for different types of impurity profiles and taking into consideration the effects of interface states and interfacial layer at the gate contact of the device. Particularly, the power law, exponential and Gaussian impurity profiles in the channel have been considered. The variations of space charge density and depletion layer width with drain voltage and interface state density for the above impurity profiles have been studied relative to that of uniform distribution of doping. The expressions for drain current for these doping profiles have been derived. The normalized current relative to that of uniform distribution of impurities has been studied as a function of drain voltage and interface state density for the respective doping profiles.

Keywords: Metal-semiconductor field effect transistor, Interface state distribution, Velocity saturation model, Non-uniform impurity profile

1 Introduction

Metal-semiconductor field effect transistors (MESFETs) operated under the application of high electric field across the drain has been modeled previously considering field dependent electron mobility[1-5]. As the applied electric field exceeds a critical value, the drift velocity of electrons tends to saturate. The drain current of the device under such circumstances can be described by velocity saturation model, originally proposed by Williams and Shaw[6]. The model assumes the depletion layer width of the device to be constant through out the channel. The effects of interface states and interfacial layer[7] at the gate contact have been considered and derived the *dc* current-voltage relation of a velocity saturated MESFET under average depletion layer width approximation and assuming a constant doping distribution in the channel region. It is,however,well known that under different processing conditions, the distribution of impurities in the channel may be non-uniform. Various works have already been carried out considering non-uniform doping distribution in the channel of the device. According to Williams and Shaw[6], the diffusion of dopants in to an epitaxial region produces an exponential decay of impurities across the epitaxial layer. The non-uniform channel doping has also been found in GaN epitaxial layer grown using MOVPE technique[8]. Abid *et al*[9]. have developed a theoretical model to calculate the gate to source capacitance of a MESFET considering an exponential decrease of dopants from the metal-semiconductor junction and a hi-lo-hi doping variation. A number of theoretical[10-14] studies have been made to describe the performance of an ion implanted MESFET considering Gaussian type distribution of impurities in the channel. The main objective of the present work is to extend our previous model[7] by taking into account different doping distribution in the channel region so that the domain of application of the model is extended to distributed impurities resulting from different processing techniques. In considering the above distributive defects, it will be assumed that the electric field applied across the channel is in excess of critical electric field to attain velocity saturation of carriers.

2 Interface State Model

The gate contact of a MESFET, unless specially fabricated, may have non idealities like interfacial layer, interface states and interfacial fix charges. The effects of these imperfections have been considered in many previous works[2,7,15-18]. In a number of occasions, the interface states density at the gate contact has been found to be energy dependent. The distribution of interface states density at Pt-*n*Si and Co-*n*Si contacts has been determined by applying a capacitance technique[19]. Pandey *et al*[20]. have applied the above capacitance technique to determine energy distribution of interface states at Al-*p*Si Schottky contact. The energy distribution of interface states is also found in a Si by X-ray photo-electron spectroscopy under applied bias[21] and in Schottky diodes on *n*-Ge and *n*-GaAs substrate[22]. Dhar *et al*[23]. have determined the distribution of interface state density for GaAs MESFET and AlGaAs/InGaAs pseudomorphic HEMT from ideality factor measurement. The nature of distribution of interface states with energy has been found to be exponential for an Al-nSi contact reported by Ayyildiz *et al*[24]. More generally, such a distribution can be expressed by a cosh-like function[15] given by:

$$D_{it}(E) = D_{ito}\left\{\exp\left(\frac{E-q\phi_0}{E_s}\right)+\exp\left(-\frac{E-q\phi_0}{E_s}\right)\right\} \quad \ldots(1)$$

where D_{it0} is the density of interface states at the minimum of the distribution, ϕ_0 the neutral level and E_s is an interface parameter. For acceptor-like states, the above distribution can be approximated as:

$$D_{it} = D_{it0}\exp\left(\frac{E-q\phi_0}{E_s}\right) \quad \ldots(2)$$

The relation in Eq. (2) has been applied earlier to calculate the interface states charge density for long channel[18] MESFET given by:

$$Q_{it} = -qD_{it0}E_s\left\{\exp\left(\frac{E_F-q\phi_0}{E_s}\right)-1\right\} \quad \ldots(3)$$

where E_F is the Fermi level of the semiconductor.

3 Evaluation of the Space Charge Density and Surface Potential

In a metal-semiconductor junction having non-uniform doping in the semiconductor side, the space charge density of the depletion layer[25] can be given by:

$$Q_{sc} = \int_0^h qN(y)dy \quad \ldots(4)$$

where q is the electronic charge, $N(y)$ the doping distribution and h is the depletion layer width at the gate contact. In the case of uniform distribution of doping, the space charge density can be obtained from Eq. (4) given by:

$$Q_{sc} = qN_d h \quad \ldots(5)$$

where N_d is the shallow doping density.

The semiconductor surface potential ψ_s at the gate contact can be obtained using the relation[6].

$$\psi_s = \frac{q}{\varepsilon_s}\int_0^h yN(y)dy \quad \ldots(6)$$

where ε_s is the permittivity of the semiconductor. When the doping is uniform, the surface potential becomes:

$$\psi_s = (qN_d h^2/2\varepsilon_s)^{1/2} \quad \ldots(7)$$

Eqs (4) and (6) can be applied to obtain Q_{sc} and ψ_s s a function of depletion layer widths y_1 and y_2 at the source (x = 0) and drain ($x = L$) ends, respectively. The functional forms for the above two quantities are presented in Table 1.

In order to compare the changes in the quantitative values of Q_{sc} with respect to uniform distribution of doping, we define a quantity Q_R, which represents a normalized value of dimensionless charge density relative to uniform space charge density. Similarly, the surface potential for the respective doping profile relative to uniform doping distribution, defined as ψ_R can be estimated.

4 Evaluation of the Drain Current

The drain current of a MESFET for an arbitrary doping variation in the channel[6] can be given by:

$$I_d = qv_s Z\int_h^a N(y)dy \quad \ldots(8)$$

where v_s is the saturated electron velocity, h the depletion layer width, L the channel length, a the channel depth and Z is the channel width.

Under average depletion layer approximation, the drain current[7] can be expressed as :

$$I_d = \frac{\int_{y_1}^{y_2}\{qv_s Z\int_h^a N(y)dy\}dh}{\int_{y_1}^{y_2} dh} \quad \ldots(9)$$

Table 1 — Expressions for surface potential and space charge density for different impurity profiles in the channel of a MESFET

Doping Profile $N(y)$	Surface Potential ψ_s	Space Charge Density Q_{sc}
Power law $N_d\left(\frac{y}{y_0}\right)^n$	Source end: $\frac{qN_d y_1^{n+2}}{\varepsilon_s (n+2) y_0^n}$ Drain end: $\frac{qN_d y_2^{n+2}}{\varepsilon_s (n+2) y_0^n}$	$qhN_d \frac{(h/y_0)^n}{(n+1)}$
Exponential: $N_d \exp(-\alpha y)$	Source end: $\frac{qN_d [1-\exp(-\alpha y_1)(\alpha y_1 + 1)]}{\varepsilon_s \alpha^2}$ Drain end: $\frac{qN_d [1-\exp(-\alpha y_2)(\alpha y_2 + 1)]}{\varepsilon_s \alpha^2}$	$qN_d\{1-\exp(-\alpha h)\}/\alpha$
Gaussian: $\frac{Q}{\sqrt{2\pi}\sigma}\exp\left\{-\frac{(y-R_p)^2}{2\sigma^2}\right\}$	Source end: $\frac{qQ\sigma}{\sqrt{2\pi}\varepsilon_s}\left[\exp\left\{-\frac{R_p{}^2}{2\sigma^2}\right\}-\exp\left\{-\frac{(y_1-R_p)^2}{2\sigma^2}\right\}\right]+\frac{QqR_p}{2\varepsilon_s}\left[erf\left(\frac{y_1-R_p}{\sqrt{2}\sigma}\right)+erf\left(\frac{R_p}{\sqrt{2}\sigma}\right)\right]$ Drain end: $\frac{qQ\sigma}{\sqrt{2\pi}\varepsilon_s}\left[\exp\left\{-\frac{R_p{}^2}{2\sigma^2}\right\}-\exp\left\{-\frac{(y_2-R_p)^2}{2\sigma^2}\right\}\right]+\frac{QqR_p}{2\varepsilon_s}\left[erf\left(\frac{y_2-R_p}{\sqrt{2}\sigma}\right)+erf\left(\frac{R_p}{\sqrt{2}\sigma}\right)\right]$	$\frac{qQ}{2}\left[erf\left(\frac{h-R_p}{\sqrt{2}\sigma}\right)+erf\left(\frac{R_p}{\sqrt{2}\sigma}\right)\right]$

Applying Eqs (8) and (9), the expressions for drain current for different types of distributions profiles can be derived. For uniform[7] doping, Eq. (9) becomes:

$$I_d = qv_s ZN_d[a-(y_1+y_2)/2] \qquad \ldots(10)$$

The expression for drain current for power law, exponential and Gaussian types of doping profile are presented in Table 2. For the calculation of drain current, it is necessary that the values of the depletion layer widths y_1 and y_2 may be determined with the help of the charge neutrality condition at the gate contact[16-18] following the evaluation scheme on MESFET. The general form of the charge neutrality condition at the gate contact is given by:

$$\phi_m = \chi - \Psi_s - V_n - V_g - V_d = \frac{\delta}{\varepsilon_i}[Q_{sc} + Q_{it} + Q_f] \quad \ldots(11)$$

where ε_i is the permittivity of the insulating layer, ϕ_m the metal work function, χ the electron affinity of semiconductor, V_g the applied gate voltage, V_d the applied drain voltage, V_n the difference between Fermi level and the bottom of the conduction band in the bulk and δ is the thickness of the oxide layer.

From Eq. (11), the depletion layer widths can be numerically solved at the source and drain ends after substituting the expressions for Ψ_s and Q_{sc} from Table 1. The values of y_1 and y_2 so calculated can be substituted in the expressions for I_d in Table 2 to evaluate drain current for different doping profiles.

5 Discussion

The functional forms for the drain current derived within the domain of velocity saturation model and taking into account the non-uniform distribution of doping and interface states clearly suggest the role of different parameters controlling the shape of the distribution profile. These functional forms can be applied to realize the characteristic features of the devices involving unevenly distributed impurities. In all such cases, the evaluation scheme requires the application of charge neutrality condition of the system and the Gauss law at the gate contact.

We have particularly applied the above evaluation scheme to compare the performance of the devices having unevenly distributed impurities with that of uniformly doped devices with special reference to interface states effects. For the purpose of comparison, as already defined, a set of relative and

Table 2 — Expressions for drain current for different impurity profiles in the channel of a MESFET under velocity saturation

Doping Distribution	Expressions of Drain Current
Power Law	$I_d = \frac{qV_sZ}{(n+1)}\left[aN(a) - \frac{1}{(n+2)}\left\{\frac{y_2^2N(y_2) - y_1^2N(y_1)}{y_2 - y_1}\right\}\right]$
Exponential	$I_d = \frac{qV_sZ\{N(y_1) - N(y_2)\}}{\alpha^2(y_2 - y_1)} - \frac{qV_sZN(a)}{\alpha}$
Gaussian	$I_d = \frac{qV_sZQ}{2}\left[erf\left(\frac{a-R_p}{\sqrt{2}\sigma}\right) - \frac{\sqrt{2}\sigma}{(y_2-y_1)}\left\{\frac{y_2-R_p}{\sqrt{2}\sigma}erf\left(\frac{y_2-R_p}{\sqrt{2}\sigma}\right) + \frac{1}{\sqrt{\pi}}\exp\left[-\frac{(y_2-R_p)^2}{2\sigma^2}\right] - \left(\frac{y_1-R_p}{\sqrt{2}\sigma}\right)erf\left(\frac{y_1-R_p}{\sqrt{2}\sigma}\right) - \frac{1}{\sqrt{\pi}}\exp\left[-\frac{(y_1-R_p)^2}{2\sigma^2}\right]\right\}\right]$

dimensionless quantities, e.g. the dimensionless space charge density (Q_R), depletion layer width (Y_R) and drain current of a device (I_R) for particular doping profile, (i.e., power law, exponential or Gaussian distribution) relative to uniform distribution of impurities, are evaluated. These quantities will eventually determine the relative merits and demerits of the devices having unevenly distributed impurities compared to uniformly doped devices. A particular value of Q_R will fix the value of dimensionless depletion layer width Y_R. Accordingly, the pinch off condition for a specific doping profile can be evaluated relative to the uniformly doped device. Figure 1 shows the variation of relative space charge densities (relative to uniform doping) for power law, exponential and Gaussian distribution with the drain voltage V_d. In all three cases, the relative space charge density is less than unity, signifying that the space charge densities for unevenly distributed impurities to be less compared to the space charge density of uniformly doped devices for the present set of distribution parameters.

Moreover, it is seen that the voltage dependence of Q_R for exponential and Gaussian distribution are just opposite to that of power law distribution. It is however noted that the relative space charge density is not much sensitive to interface states density, although the absolute value of said parameters gradually increases as the doping profile is changed from exponential to power law through the intermediate Gaussian distribution. The nature of variation of Q_R with interface state density is shown in the inset of Fig. 1.

The enhancement in the space charge density leads to an increase in the depletion layer width with voltage when the doping distribution is uniform. Figure 2 shows the variation of Y_R as a drain voltage. A comparative study of the calculated depletion layer

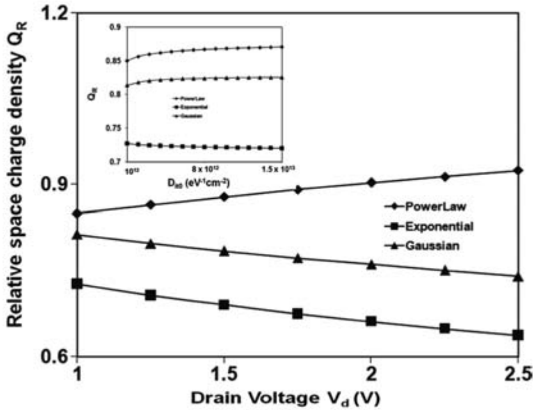

Fig. 1 — Variation of relative space charge density Q_R with drain voltage of a short channel MESFET for gate voltage V_g = 1 V. The channel depth and channel width are considered to be 5×10^{-5} cm and 10^{-5} cm, respectively. Other parametric values: $y_0 = 10^{-5}$ cm, n = 1, α = 50000 cm^{-1}, Q = 2.5×10^{12} cm^{-3}, $R_p = 10^{-5}$cm, $\sigma = 10^{-5}$ cm, T = 300 K, E_s = 0.5 eV, E_g = 3.4 eV, χ = 4.1 eV, ϕ_0 = 1 eV, ϕ_m = 5 eV, $D_{it0} = 10^{12}$ cm^{-2} eV^{-1}, $V_s = 2 \times 10^7$ cm/s and $N_d = 10^{17}$/cm^3.The variation of Q_R with interface state density is shown in the inset

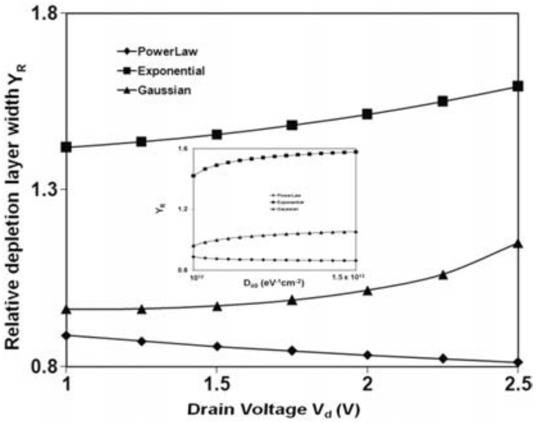

Fig. 2 — Variation of relative depletion layer width, Y_R with drain voltage for a gate voltage 1V. The parametric values are the same as those in Fig. 1. The variation of Y_R with interface state density is shown in the inset

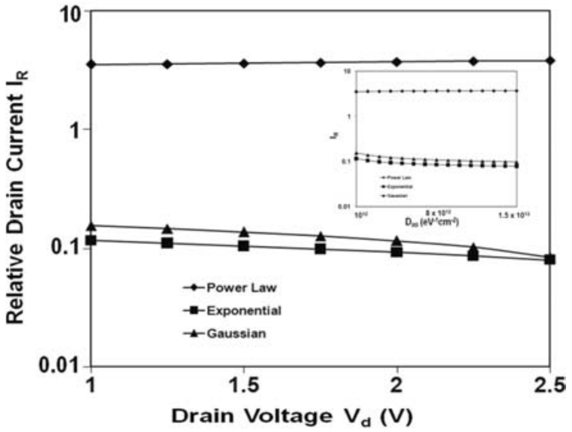

Fig. 3 — Variation of relative drain current, I_R with drain voltage for a gate bias 1V. The parametric values are the same as those in Fig. 1. The variation of I_R with interface state density is shown in the inset

width for power law, exponential and Gaussian distribution reveals Y_R values for exponential doping to be much larger compared to the remaining two other distributions, namely, the power law and Gaussian distribution. Much enhancement in the value of depletion layer width for exponential distribution ensures the drain current of the device to be smaller compared to other two cases. This also suggests possible reduction in the value of pinch off voltage of the device having exponential distribution of impurities. The nature of variation of Y_R has been found to be increasing with drain voltage, while a reverse trend has been found for power law distribution. Similar to the case of space charge density, the dependence of Y_R has been found to be insensitive with respect to interface states density. However, it is seen that Y_R versus D_{it} curves shifts upward as the distribution profile is changed from power law to exponential type distribution. Such a dependence is shown in the inset of Fig. 2.

The drain characteristics of device are shown in Fig. 3 for exponential, power law and Gaussian doping distribution. It is seen from Fig. 3 that the relative drain current I_R gradually decreases with the drain voltage for Gaussian and exponential doping whereas, for power law doping, the I_R increases with drain voltage. The value of I_R has been found to be much larger for power law doping compared to Gaussian and exponential doping. Thus, for application of a MESFET as a high power device, the power law doping is more suitable compared to other two types of doping distribution.

However, MESFETs having exponentially doped channel may be suitable for low power switching application. The variation of I_R with interface states for different impurity profiles have been shown in the inset of Fig. 3. It is seen that I_R decreases with interface state density for Gaussian and exponential doping, whereas, it is relatively unchanged for power law doping when the interface state density is large. The saturation of I_R for high values of interface density signifies surface pinning effect as a consequence of pinning of neutral level with the Fermi level of the semiconductor.

6 Conclusions

The space charge density has been evaluated in the channel of a short channel MESFET operated in the region of velocity saturation by adopting a scheme that considers interface states and interfacial layer at the gate contact of the device. The evaluation procedure has been carried out considering the charge neutrality condition of the system, Gauss's law and potential drop across the interfacial layer. The scheme has been applied taking into account different types of channel doping profiles. The depletion layer widths at the source and drain ends obtained using this evaluation scheme has been used to calculate the drain current of the device from the expressions derived for the respective doping profiles. The results are compared with that of uniformly doped MESFET structure on the basis of relative space charge density, depletion layer width and the channel current of the device.

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