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CARRIER ACCUMULATION AND SPACE-CHARGE-LIMITED CURRENT FLOW IN FIELD-EFFECT TRANSISTORS*

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Abstract—This paper reports an investigation of devices fabricated by lateral diffusion techniques which have non-uniform doping profiles along the channel. The application of a two-dimensional numerical method to a device model representing these devices shows carrier accumulation in the conductive channel. The increase of carrier concentration with the increasing drain-to-source voltages is caused by the interaction of the source and the drain N^+-regions. This indicates the possibility of the space-charge-limited current which is a different conduction mechanism from that of the conventional devices. From the study of one-dimensional N^+–N–N^+ structures, the length-to-L_{DE} (extrinsic Debye length) ratio of the channel and the crossover voltage have been recognized as important parameters in realizing the space-charge-limited current. The drain characteristics of a device model with a small crossover voltage and a small length-to-L_{DE} ratio are obtained by a simple analysis. Triode-like characteristics are found for this model as expected.

Résumé—Cet exposé rapporte une étude de dispositifs fabriqués par des techniques de diffusion latérale qui ont des profilés de doping non uniformes au long du canal. L'application d'une méthode numérique bi-dimensionelle à un modèle de dispositif représentant ces dispositifs montre une accumulation de porteurs dans le canal conductif. L'accroissement de la concentration de porteurs avec l'augmentation de tensions du drain à la source est causée par l'interaction des régions N^+ de la source et du drain. Ceci indique la possibilité du courant limité de charge spatiale qui est un mécanisme de conduction différent de celui des dispositifs classiques. De l'étude de structures N^+–N–N^+ uni-dimensionelle le rapport de la longueur au L_{DE} (longueur Debye extrinsèque) du canal et la tension de croisement ont été reconnus comme paramètres importants dans la réalisation du courant limité de charge spatiale. Les caractéristiques d'écoulement d'un modèle de dispositif avec une faible tension de croisement et un faible rapport longueur à L_{DE} sont obtenues par analyse simple. Des caractéristiques genre triode sont trouvées pour ce modèle comme prévu.

Zusammenfassung—Die vorliegende Arbeit berichtet über Untersuchungen an Bauelementen, mit ungleichförmigem Dotierungsprofil, die durch eine laterale Diffusionstechnik hergestellt waren. Die Anwendung einer zweidimensionalen numerischen Methode auf ein Modell, das diese Bauelemente beschreibt, zeigt eine Trägeranreicherung im Leitungskanal. Die Zunahme der Trägerdichte mit wachsender Spannung zwischen Drain und Source wird durch eine Wechselwirkung zwischen den N^+-Gebieten der Drain- und Source-Bereiche bewirkt. Die Studie einer eindimensionalen N^+NN^+-Struktur zeigt, dass das Verhältnis der geometrischen Länge des Kanals zur Debye-Länge und die Überschneidespannung wichtige Parameter für das Auftreten des raumladungsbegrenzten Stromes sind. Die Drain-Charakteristick eines Modells mit kleiner Überschneidespannung und einem kleinen Längenverhältnis wird durch eine einfache Analyse erhalten. Erwartungsgemäss wird für das Modell eine Triodencharakteristik gefunden.

1. INTRODUCTION

IN A CONVENTIONAL junction FET, the current flow through the channel is controlled by a transverse electric field which is established by the reverse biased gate *P–N* junction.[1] According to the solution of Poisson's equation for a reverse biased *P–N* junction, the transverse electric field depletes carriers from the channel, thus increases the impedance of the channel. At the pinchoff voltage, all carriers are depleted from the channel

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and the drain current becomes saturated. As a result, pentode-like VI characteristics are realized.[1] Detailed two-dimensional calculation shows that, although complete depletion at pinchoff is inaccurate, the depletion of carriers is generally valid.[2]

In 1964, TESZNER and GICQUEL[3] reported their findings of some experimental devices with small length-to-width ratios fabricated by lateral diffusion techniques. Due to the fabrication process, the doping profiles of these devices are non-uniform along the channel. These devices have shown both pentode-like and triode-like characteristics. From the similarity with the space-charge-limited current, where the current is proportional to the square of the applied voltage, they suggested that the change in the drain characteristics is due to the joining of the two gate regions underneath the source region during the diffusion process. The device is then equivalent to a bipolar transistor operating beyond the punch-through point and the current is space-charge limited. ZULEEG[4] has developed this idea further and fabricated a device with N^+–N–P–N–N^+ structure which showed both the space-charge-limited operation and the bipolar operation.

Besides the experimental works of TESZNER and GICQUEL and ZULEEG, there are also some theoretical works about the insulated-gate FETs with triode characteristics. GEURST[5] has analyzed the insulated-gate FETs by choosing a symmetric device model where the current flows on the center line of the device. By using the theory of complex variables, the Laplace's equation is solved rigorously in the insulator gate region with the nonlinear boundary condition given along the center line. The solution gives a transcendental equation and the drain characteristics are obtained by finding the roots of the equation. NEUMARK and RITTNER[6,7] have noted that the transcendental equation has two sets of roots of physical interest and that the choice of a set of roots gives either the pentode-like or the triode-like characteristics. These analyses are purely mathematical and lack the physical understanding of the device operation.

The purpose of the present investigation can be divided into two parts. The first part is to find out whether carrier accumulation takes place or not in a junction FET by using a two-dimensional numerical calculation. This is accomplished by considering a silicon junction FET having non-uniform impurity distribution along the channel. The results demonstrate the carrier accumulation as a result of the interaction between the source and the drain. The second part of the investigation is concerned with the triode characteristics. The devices considered here have essentially the same geometrical structure as the conventional junction FETs. The study is based on the space-charge-limited (SCL) current for a one-dimensional N^+–N–N^+ structure made of silicon. The possibility and the criterion of obtaining the triode characteristics are investigated in terms of the parameters characterizing the device.

2. GRADED-CHANNEL DEVICES

Devices with small length-to-width ratios can be constructed by the lateral diffusion of the source N^+-region and the gate P^+-regions into the N-type epitaxial layer which is grown over the N^+ substrate.[3] Unlike the conventional JFETs where the impurity doping is graded perpendicular to the current flow,[8,10] the impurity distribution of these devices is non-uniform along the channel. As a result, the current flows parallel to the gradient of the impurity distribution.

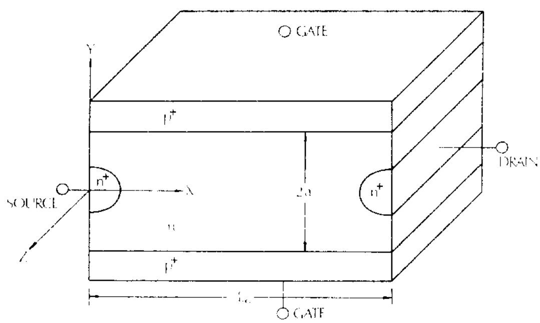

FIG. 1. Device model and co-ordinates.

Figure 1 shows the geometry of the device model with co-ordinates to be used later. For simplicity only N-channel devices will be considered. It is assumed that the P^+–N junctions at the gate are step junctions and that the doping profiles of the N^+–N junctions at the source and the drain contacts are described by complementary error functions. The gate P^+-regions are much more heavily doped than both N– and N^+-regions.

By assuming no variation along the Z-direction, the region of interest is a plane bounded by $X = 0$, $X = L_0$, $Y = a$, and $Y = -a$. The two N^+-regions are included in the analysis to obtain a relatively simple boundary condition. Furthermore, these N^+-regions are of primary importance in that the interaction of them makes the space-charge-limited current possible.

The specific device model shown has been chosen to avoid the complexity of mathematics while retaining the important features of the device characterization.

The normalized two-dimensional Poisson's equation and continuity equation can be written as[2]

$$\nabla^2\psi = -2\alpha[N(x,y) - n(x,y)] \qquad (1)$$

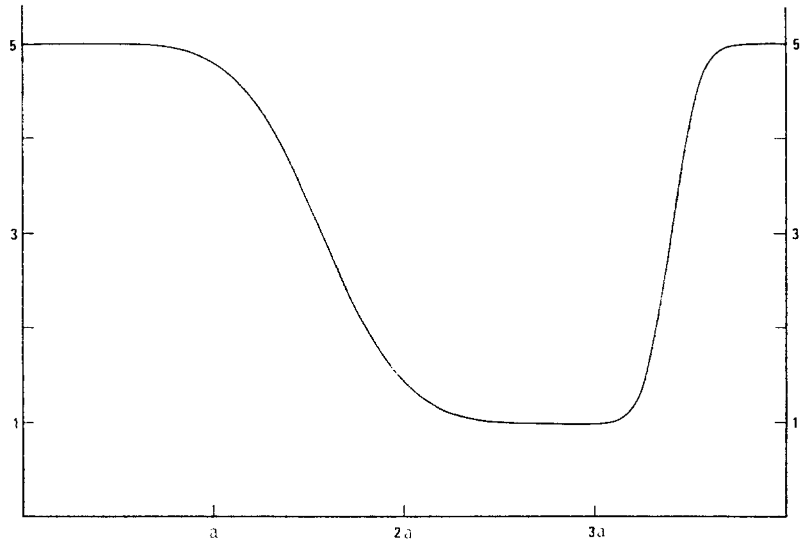

FIG. 2(a). Donor concentration on X-axis vs. x for the graded-channel device.

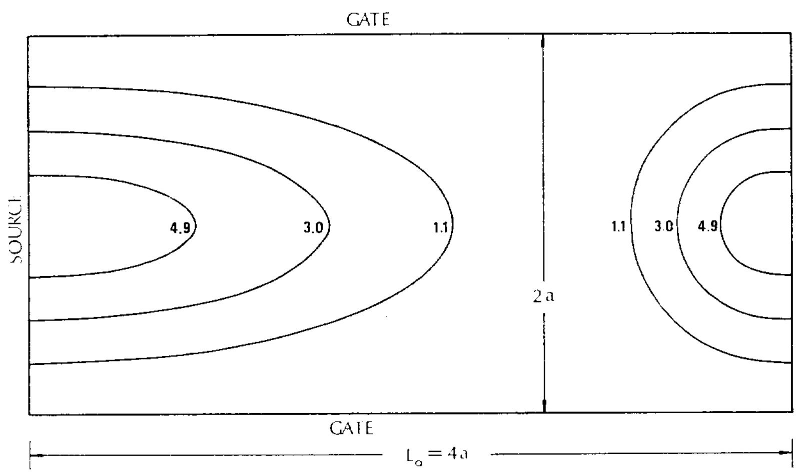

FIG. 2(b). Distribution of donor concentration for the graded-channel device. Donor concentration is normalized by $N_D = 10^{15}$ atoms/cm^3. $a = 1.31\ \mu$, $N_A = 10^{17}$ atoms/cm^3.

$$\nabla \cdot J_n = \nabla \cdot \left[-\frac{1}{\alpha} n(x,y)\mu_n \nabla \varphi_n \right] = 0 \quad (2)$$

$$n = e^{\psi - \varphi_n}. \quad (3)$$

The definitions of symbols in equations (1), (2), and (3) are listed in Table 1 with their normalizing constants. The numerical method has been reported in a previously published paper and will not be treated here.

Table 1

	Symbol	Normalization constant
Electro-static potential	ψ	kT/q
Electron quasi-Fermi level	φ_n	kT/q
Donor concentration	$N(x,y)$	N_D
Electron concentration	$n(x,y)$	N_D
Electron current density	J_n	$q\mu_{n0}N_DV_p/a$
Electron mobility	μ_n	μ_{n0}
Distance	x,y	a
Pinch-off voltage	$V_p = qN_Da^2/2\epsilon\epsilon_0$	
Low field electron mobility	μ_{n0}	
Donor concentration in N-region	N_D	
	$\alpha = qV_p/kT$	

The distribution of the donor concentration of the device model is shown in Fig. 2. The low doping level in N^+-regions has been chosen mainly for the simplicity of the numerical computation and reasonable computing time. More realistic values may be chosen at the cost of these factors. In the figure the donor concentration is normalized by $N_D = 10^{15}$ atoms/cm^3. Although the model chosen here is somewhat unrealistic due to the low doping level in the N^+-regions, the results are significantly different from that of conventional junction FETs and indicates the possibility of a SCL-triode which will be the subject of the next section.

In the numerical calculation, the mesh size has been chosen to be one third of the extrinsic Debye length in the N-region. This mesh size is equal to 0.745 times the extrinsic Debye length in the N^+-regions. The computation has been carried out on the IBM System 360/91. The program has been written in FORTRAN IV and compiled by the FORTRAN G compiler. When the mesh size is chosen as discussed above, the total memory requirement is approximately 250K bytes.

Figure 3 shows the drain characteristics of the device. In this figure and in Figs. 4–8, the applied bias voltages are normalized by $V_p - V_B$ where V_B is the built-in potential at the gate P–N

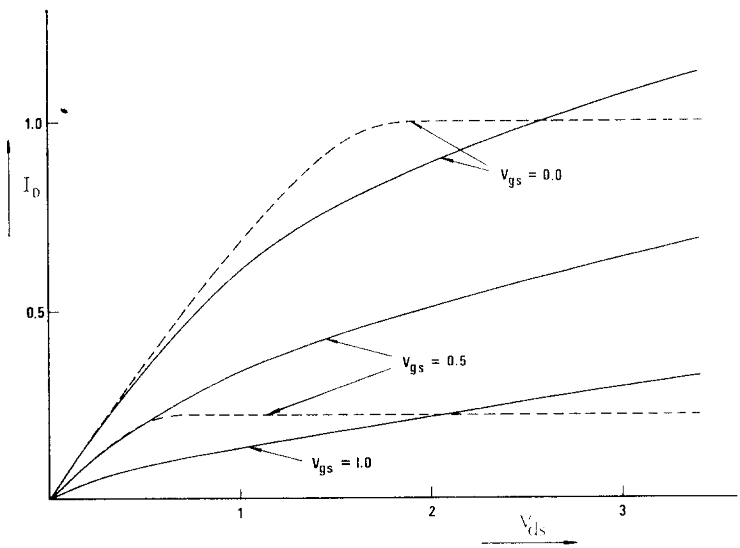

FIG. 3. Drain characteristics of the graded-channel device.

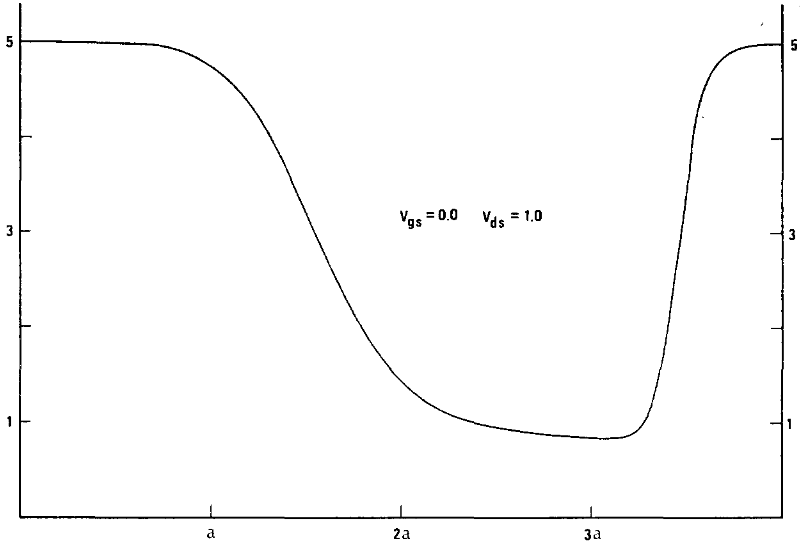

FIG. 4(a). Electron concentration on X-axis vs. x for the graded-channel device.

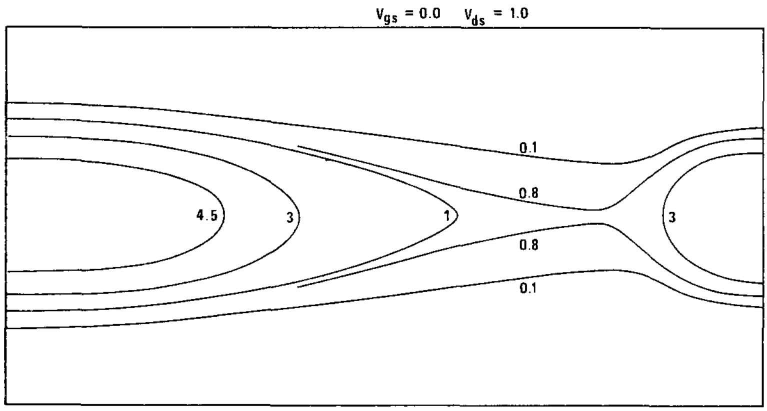

FIG. 4(b). Distribution of electron concentration for the graded-channel device.

junction. The polarities are equal to that of the normal operation of junction FETs. The dashed curves are the results of the gradual-channel approximation with $L/a = 0.794$ and include the effects of the source and the drain resistances. This value of L/a is obtained by defining L of the device as the length of the region where $N(x, 0) \leq 1.05$. Due to the low doping level in the N^+-regions the drain and the source resistance are large. The effects of these resistances are seen in the gradual-channel approximation as the shift of the saturation point to the right of the figure.

The comparison of Fig. 5 with 7 shows a considerably large change in the potential distribution in the source region with increasing drain voltage. This appears in the drain characteristics as the large differential drain conductance.[2] The maximum electric field in X-direction for $V_{gs} = 0$ and $V_{ds} = 3$ is 13.3 kV/cm and the drift velocity is not saturated. The field-dependent mobility, therefore, is not an important factor for the operation of the device up to the bias condition $V_{ds} = 3$.

The most interesting result of the device is

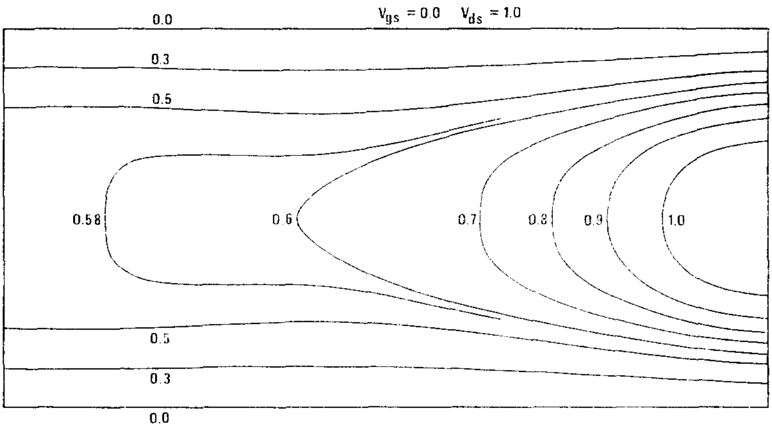

FIG. 5. Potential distribution for the graded-channel device.

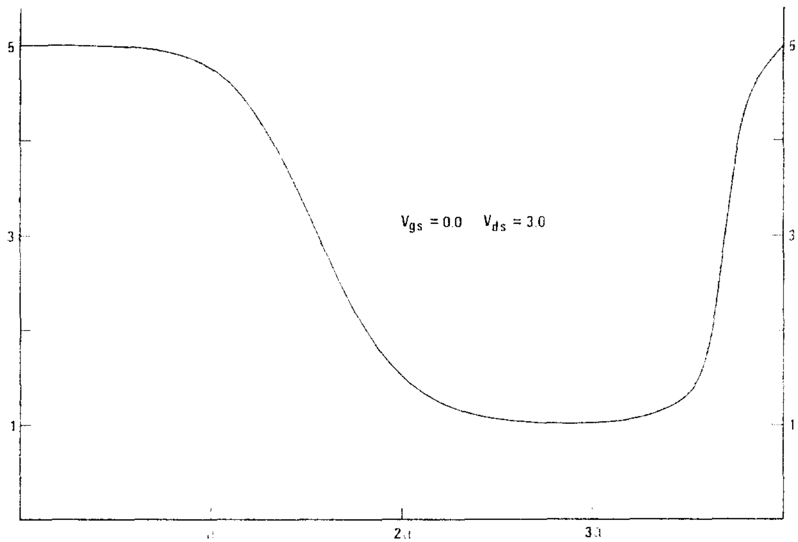

FIG. 6(a). Electron concentration on X-axis vs. x for the graded-channel device.

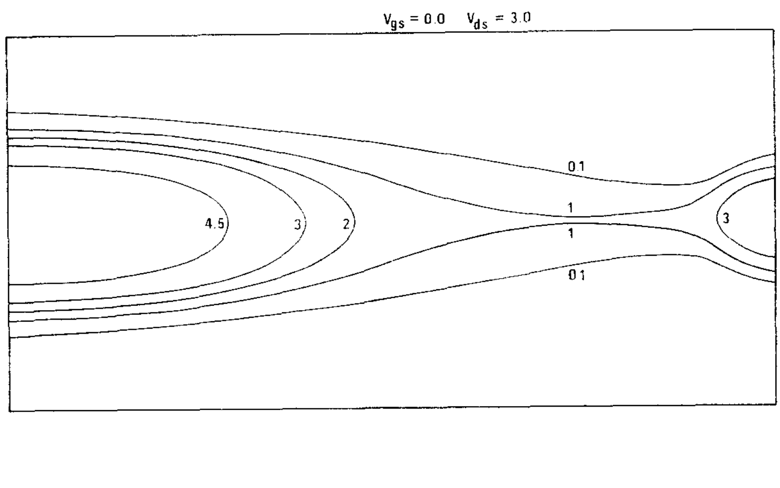

FIG. 6(b). Distribution of electron concentration for the graded-channel device.

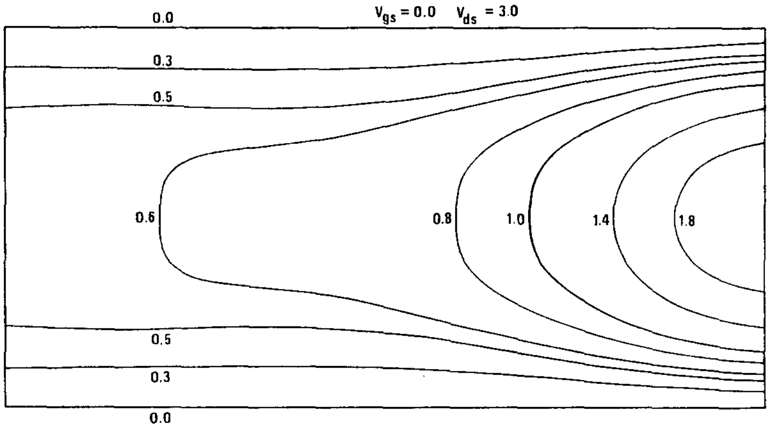

FIG. 7. Potential distribution for the graded-channel device.

the variation of the electron distribution with the bias voltages. From Table 2, we see that for small drain voltages, the electron concentration in the conductive channel decreases with increasing drain voltages while for large drain voltages it increases with increasing drain voltages. In Figs. 4 and 6, we also see that the distribution of the electron concentration is similar to that of the short device in Ref. 2 for small drain voltages while it is significantly different for large drain voltages. The accumulation of the free carriers with increasing drain voltages can be seen most clearly in Fig. 8 which shows the electron concentration on X-axis for two different drain voltages with a fixed gate voltage. It can be concluded from these observations that a new current conduction mechanism is in operation for large drain voltages, i.e. the SCL current

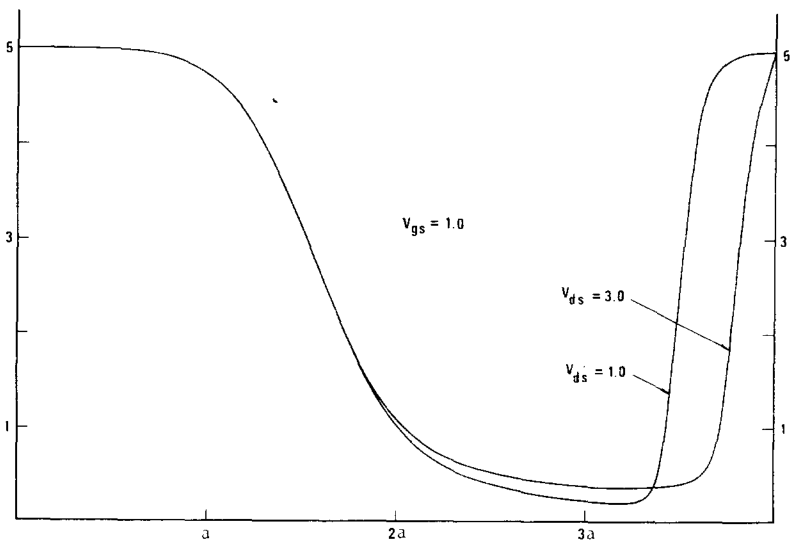

FIG. 8. Electron concentration on X-axis vs. x for the graded-channel device showing the carrier accumulation in the channel with increasing drain voltages.

Table 2. Minimum of normalized electron concentration on X-axis for various bias conditions

V_{ds} \ V_{gs}	0.0	0.5	1.0
0.1	0.9194	0.7011	0.2706
1.0	0.8217	0.5280	0.2096
2.0	0.9160	0.6188	0.2958
3.0	1.0160	0.7185	0.3754

starts to build up. Because of the low doping level of the source N^+-region and the gradual transition from the source N^+-region to the N-region, however, the SCL current is not dominant for this device. This is also seen in the drain characteristics. If the SCL current were dominant, the drain current would be proportional to the square of the drain voltage which gives the triode characteristics. The drain characteristics shown in Fig. 3 are the result of the competition of two different physical mechanisms: the normal field-effect transistor operation where the free carrier concentration in the conductive channel decreases with increasing drain voltages and the SCL current where it increases with increasing drain voltages. Previously, the large differential drain conductance was attributed to the large change of the potential distribution in the source region. This, however, is due to the increase of the electron concentration in the channel.

The ratio of the length of the N-region to the extrinsic Debye length, L/L_{DE}, is about 8 for this device. If the N^+-N junction at the source is abrupt and L/L_{DE} is decreased, the drain and the source N^+-regions will interact with each other and the SCL current can easily be realized. A device satisfying the above conditions will be considered in the next section.

3. SPACE-CHARGE-LIMITED TRIODES

In Section 2, it has been demonstrated that the interaction of the source and the drain N^+-regions gives the SCL current. This SCL current is similar to that observed by GREGORY and JORDAN[11] in their P^+–P–P^+ structure. The SCL triode considered in this paper is based on the SCL current of the one-dimensional N^+–N–N^+ structure which is analyzed in the first part of this section. In the second part, the effect of the gate P–N junction is combined with the results of the first part to obtain the triode-like characteristics.

One-dimensional N^+–N–N^+ Structure

The SCL current can be realized in either N^+–P–N^+ or N^+–N–N^+ structure. The former is equivalent to a bipolar transistor with floating base operating beyond punch-through. This structure forms the basis of ZULEEG's SCL triode[4] and is relatively well understood.[12] In this section, the N^+–N–N^+ structure is discussed including the effect of the fixed space charge of the residual donor concentration and the field-dependent mobility.

Figure 9 shows the model of this structure. The doping profiles in the N- and the N^+-regions are constant and the N^+–N junctions are step junctions. The size of the N^+-regions is large enough to have the thermal equilibrium condition

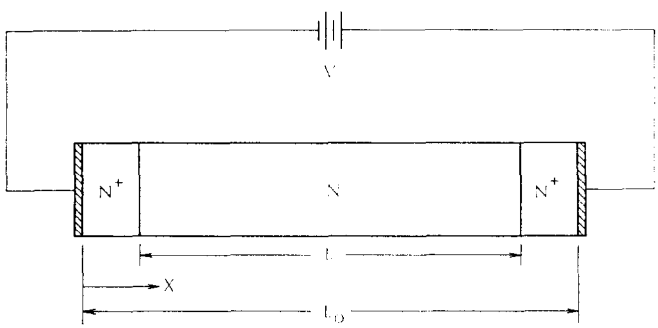

FIG. 9. One-dimensional N^+–N–N^+ structure.

at $X = 0$ and $X = L_0$. According to GREGORY and JORDAN,[11] the crossover between the Ohmic and Child's law regions occurs when the applied bias voltage is approximately equal to the crossover voltage, V_Ω.

$$V_\Omega = \frac{qN_D L^2}{2\epsilon\epsilon_0} \qquad (4)$$

where N_D is the donor concentration in the N-region and L is the length of the N-region. The equations describing the structure are the one-dimensional forms of equations (1) and (2):

$$\frac{d^2\psi}{dx^2} = -2\beta\left(N(x) - e^{\psi - \varphi_n}\right) \qquad (5)$$

$$J = \frac{J_0}{\beta} e^{\psi - \varphi_n} \mu_n \frac{d\varphi_n}{dx} = \text{constant} \qquad (6)$$

where J is the current density and

$$\beta = \frac{qV_\Omega}{kT}$$

$$J_0 = -q\mu_{n0} N_D V_\Omega / L.$$

The linear dimension, x, is normalized by L. All other symbols have the same meaning and the same normalizing constant as in equations (1) and (2). Integration of equation (6) gives

$$e^{-\varphi_n(x)} = e^{-\varphi_n(l_0)} + \beta \frac{J}{J_0} \int_x^{l_0} e^{-\psi} \mu_n^{-1} dx \qquad (7)$$

where $l_0 = (L_0/L)$. Putting $x = 0$ in equation (7), we have

$$J = \frac{J_0}{\beta} \frac{e^{-\varphi_n(0)} - e^{-\varphi_n(l_0)}}{\int_0^{l_0} e^{-\psi} \mu_n^{-1} dx}. \qquad (8)$$

The boundary conditions for equation (5) are obtained from the applied bias voltage and the thermal equilibrium condition at $X = 0$ and $X = L_0$.

$$\psi(0) = \varphi_n(0) + \ln \frac{N^+{}_D}{N_D} \qquad (9)$$

$$\psi(l_0) = \varphi_n(l_0) + \ln \frac{N^+{}_D}{N_D} \qquad (10)$$

$$\varphi_n(l_0) - \varphi_n(0) = \beta \frac{V}{V_\Omega} \qquad (11)$$

where $N^+{}_D$ is the donor concentration in the N^+-regions and V is applied bias voltage.

By applying the method developed by GUMMEL,[13] equations (5), (7) and (8) are solved numerically with the boundary conditions given by equations (9)–(11). The parameters of the particular structure considered here are

$$N_D = 10^{13} \text{ atoms/cm}^3$$
$$N^+{}_D = 5 \times 10^{17} \text{ atoms/cm}^3$$
$$L = 8.285\,\mu$$
$$\beta = 20$$
$$V_\Omega = 0.517 \text{ V}.$$

The length of the N-region, L, is 6.32 times the extrinsic Debye length of that region. Since a small deviation from the thermal equilibrium condition is damped out in about $3L_{DE}$, L is small enough for the two N^+-regions to interact with each other. The size of the N^+-regions is 0.148 μ and is about 25 times the extrinsic Debye length of that region. Therefore, the thermal equilibrium condition is satisfied at the contacts. Because the problem is one-dimensional, different mesh sizes in N- and N^+-regions can be used without much difficulty. The mesh sizes are chosen such that the ratios of the mesh size to the extrinsic Debye length are 0.0253 in the N-region and 0.632 in the N^+-regions.

When the mobility is assumed to be a constant and when the fixed space charge due to the donor impurities is neglected, an approximate analysis[14] gives the SCL current as

$$J = \frac{9}{16} J_0 \left(\frac{V}{V_\Omega}\right)^2 \qquad V >> V_\Omega. \qquad (12)$$

If the electron concentration in the N-region is assumed to be equal to the donor concentration for small bias voltages the current in the Ohmic region is

$$J = J_0 \left(\frac{V}{V_\Omega}\right) \qquad V << V_\Omega. \qquad (13)$$

Figure 10 shows the computed I–V characteristic. The current densities given by equations (12)

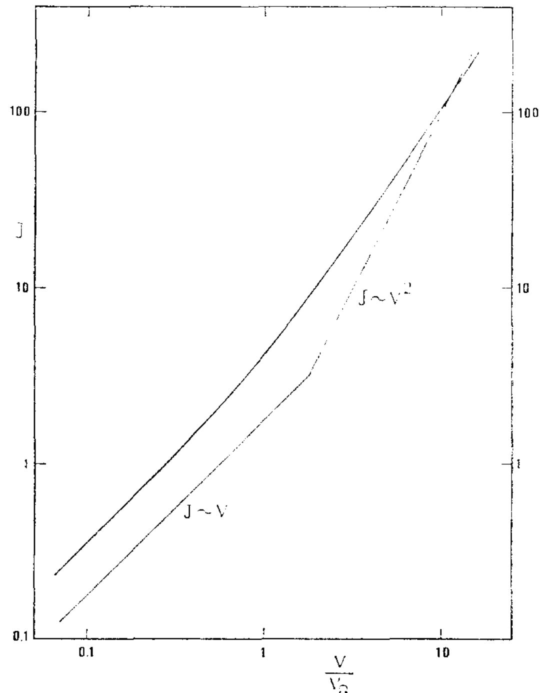

FIG. 10. I–V characteristics of the N^+–N–N^+ structure.

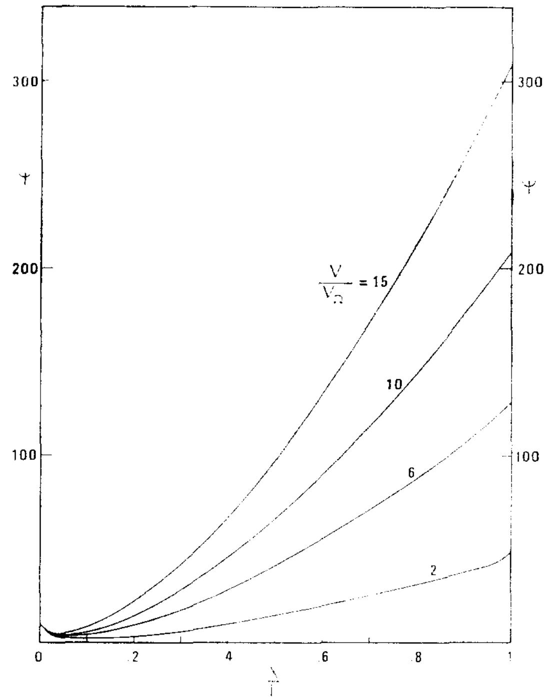

FIG. 11. Electro-static potential vs. X for the N^+–N–N^+ structure.

and (13) are also shown in the figure by two straight lines. In the figure, the current density is normalized by $9J_0/16$. Due to the factor 9/16, the two straight lines intersect each other when the applied voltage is greater than the crossover voltage. The larger current of the computed result in the linear region is due to the interaction of the two N^+-regions, which gives greater electron concentration than the donor concentration for the zero bias voltage. DENDA and NICOLET[12] have shown that for the three cases of thermal, tepid, and hot charge carriers the asymptotic dependences of the I–V characteristics are power laws of V^2, $V^{3/2}$, and V, respectively. For the model considered here, the electric field at the point where the electron concentration is minimum is 15.77 kV/cm when $V = 15\ V_\Omega$. Therefore, the electric field is in the tepid region for most of the N-region and the rate of increase of the current with increasing voltage is smaller than V^2.

The distribution of the electro-static potential in the N-region is shown in Fig. 11 for various bias voltages. In this figure and in Figs. 12 and 13 the origin of the X-axis is shifted to the metallurgical junction of the left N^+–N junction. The slight decrease of the potential near $X = 0$ is due to the built-in potential of the N^+–N junction.

Figure 12 shows the electron concentration in the N-region for several bias conditions. The increase of the electron concentration with increasing bias voltages is clearly seen. It is also to be noted that the electron density tends to become constant with increasing bias voltages. This is due to the field dependent mobility and when the drift velocity is completely saturated, the electron density should be a constant. This is confirmed by considering another N^+–N–N^+ structure which has the same crossover voltage but has a smaller length ($L = 2.62\,\mu$). Figure 13 shows the electron density and the electric field when $V = 15\ V_\Omega$. It is clearly seen in this figure that the electron density is constant when the electric field is greater than about 25 kV/cm. The

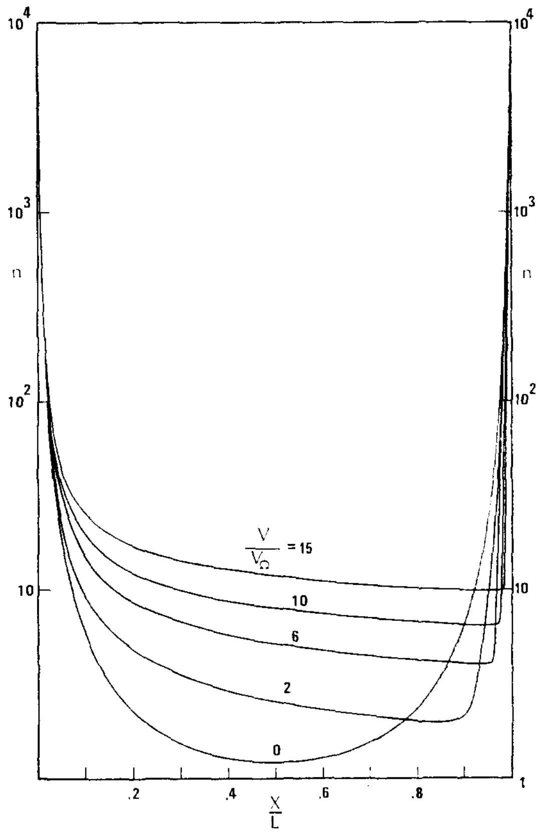

FIG. 12. Electron concentration vs. X for the N^+–N–N^+ structure.

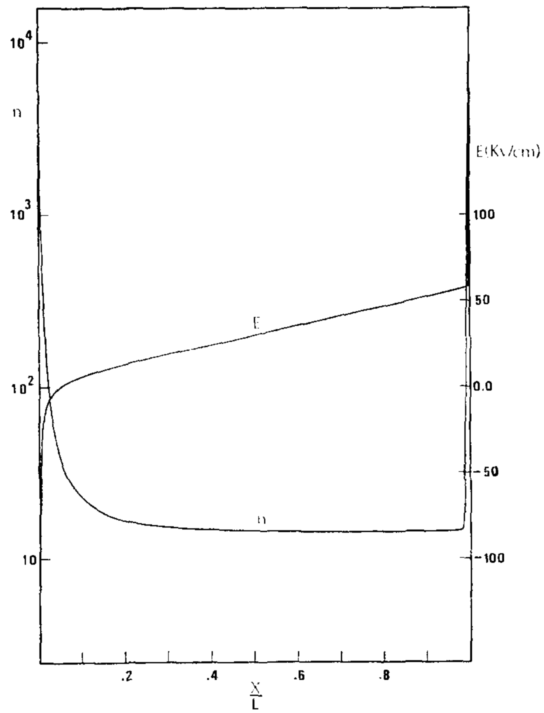

FIG. 13. Electron concentration and electric field for the N^+–N–N^+ structure with a small L.

current has been found to increase more slowly for this structure than for the one considered before. This is in agreement with the asymptotic dependence of the SCL current for hot charge carriers.

Triode characteristics

We consider a symmetric device in which the N^+–N–N^+ structure discussed previously is sandwiched between two heavily doped P^+ gate regions. Let the width of the structure be $2a$. This device will be called the 'SCL triode'. The geometrical structure of this device is essentially the same as a conventional junction FET with pentode-like characteristics. The important difference is the L/L_{DE} ratio of the N-region. For the long and the short device considered in reference 2, L/L_{DE} is 80 and 20 respectively. Therefore, the two N^+-regions do not interact with each other and the N^+–N junctions are simple Ohmic junctions. On the other hand, L/L_{DE} for the SCL triode is only about 6 and the SCL current flow can easily be realized.

The correct description of this device should be based on a two-dimensional analysis similar to those for the conventional junction FETs.[2] Due to the high doping level of the N^+-regions, however, the numerical method becomes extremely complicated. Instead of solving the pertinent equations exactly, an approximate but simple analysis is presented here which can give the general behavior of the external drain characteristics.

Suppose the SCL triode has a relatively small length-to-width ratio ($L/a \sim 1$). Due to the small L/a ratio and the strong interaction of the N^+-regions, the drain current is determined mainly by the current density of the N^+–N–N^+ structure with the gate junction controlling the width of the conductive channel. Let $2b$ be the width of this channel. Then, the drain current per unit length in the Z-direction can be written as

$$I_D = 2J_{\text{SCL}}(V_{ds})\bar{b}(V_{ds},V_{gs}) \quad (14)$$

where J_{SCL} is the magnitude of the current density obtained in the previous section and $\bar{b}$ is an average of b. V_{ds} and V_{gs} in equation (14) and in the rest of this section are the magnitudes of the unnormalized drain-to-source and the gate-to-source voltages. In evaluating $\bar{b}$, one should note that a larger potential is required to deplete the increased carrier concentration in the conductive channel. This can be taken care of by introducing

$$V'_p = nV_p. \quad (15)$$

Here n is the normalized electron concentration in the conductive channel and V_p is the pinch-off voltage of the device. By using the results of a one-dimensional analysis with V_p replaced by V'_p, one obtains

$$\bar{b} = a\left(1-\sqrt{\frac{V}{V'_p}}\right) \quad (16)$$

where V is the potential drop across the space-charge region. Let

$$V_{pc} = n\left(\frac{L_0}{2}\right)V_p. \quad (17)$$

A reasonable estimate of $\bar{b}$ can be obtained by using V_{pc} for V'_p and $V_{gs}+V_B$ for V in equation (16).

$$b \simeq a\left(1-\sqrt{\frac{V_{gs}+V_B}{V_{pc}}}\right). \quad (18)$$

The triode characteristics shown in Fig. 14 are the result of applying equations (14) and (18) to a device with $L/a = 1$. The doping level of the gate P^+-regions is $N_A = 10^{20}$ atoms/cm^3. The drain current for the bias conditions such that $V_{gs}+V_B \geq V_{pc}$ is taken to be zero.

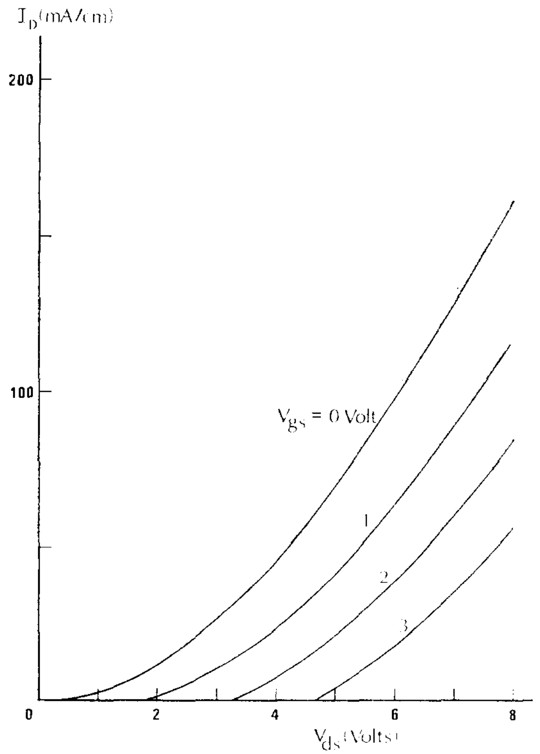

Fig. 14. Drain characteristics of the SCL triode.

4. COMPARISON OF THE DRAIN CHARACTERISTICS OF VARIOUS FIELD-EFFECT TRANSISTORS

The important parameters characterizing a junction FET are

L/a = length-to-width ratio

V_p = pinch-off voltage $= \dfrac{qN_D}{2\epsilon\epsilon_0}a^2$

V_Ω = crossover voltage $= \dfrac{qN_D}{2\epsilon\epsilon_0}L^2$

L_{DE} = extrinsic Debye length of the channel

$$= \sqrt{\left(\frac{\epsilon\epsilon_0 kT}{q^2N_D}\right)}$$

$$\alpha = qV_p/kT$$

$$\beta = qV_\Omega/kT.$$

These parameters are related as

$$\frac{a}{L_{DE}} = \sqrt{(2\alpha)}$$

$$\frac{L}{L_{DE}} = \sqrt{(2\beta)}$$

$$\frac{V_\Omega}{V_p} = \frac{\beta}{\alpha} = \left(\frac{L}{a}\right)^2.$$

Depending on the choice of these parameters and the bias voltages both pentode-like and triode-like drain characteristics can be obtained. The long device considered in Ref. 2 has good pentode-like characteristics. The values of the parameters for this device are

$$L/a = 8$$
$$V_p = 1.293 \text{ V}$$
$$V_\Omega = 83.75 \text{ V}$$
$$\alpha = 50$$
$$\beta = 3200.$$

The applied bias voltages are less than 5 V. Therefore, the N^+–N–N^+ (source-channel-drain) structure is operating in the Ohmic region. On the other hand, the SCL triode considered in this section has

$$L/a = 1$$
$$V_p = V_\Omega = 0.517 \text{ V}$$
$$\alpha = \beta = 20$$

and the applied bias voltages are less than 10 V. Since the drain-to-source voltages are well above the crossover voltage, the drain current is space-charge-limited.

From the above comparison, it is clear that one can design a field-effect device having pentode- or triode-like characteristics by choosing the parameters appropriately. A combined characteristics, pentode-like for small drain voltages and triode-like for large drain voltages, will also be possible because the two characteristics are obtained with the same device configuration.

5. CONCLUSION

A two-dimensional analysis of a device model of a junction FET with non-uniform doping profile along the channel shows carrier accumulation in the conductive channel indicating the possibility of the space-charge-limited current. This is a different conduction mechanism from that of the conventional junction FETs where the carriers are depleted from the channel. From the study of one-dimensional N^+–N–N^+ structures, the L/L_{DE} ratio and the crossover voltage have been recognized as important parameters in realizing the space-charge-limited current. The drain characteristics of a device model with a small crossover voltage and a small L/L_{DE} ratio are obtained by a simple analysis. Triode-like characteristics have been found for this model as expected.

In conclusion, this study shows that both triode-like and pentode-like characteristics can be obtained in junction FETs by an appropriate design of the device geometry and the doping profile.

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