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Optical response of a metal-semiconductor field effect transistor in the presence of interface states and interfacial layer at the gate contact

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A simple analytical model on the electrical characteristics of a metal-semiconductor field effect transistor under optical illumination has been proposed by considering the inherent effects of interface states and interfacial layer at the gate-channel interface. The drain current of the device under optical illumination has been studied by treating optically generated carriers within the framework of a model that concerns arbitrary charge distribution in the channel region. It has been found that for a metal of relatively higher work function acting as the gate contact of the device, the drain current increases with increasing interface state density. An expression for the threshold voltage of the device has been derived and its dependence on the interface state density has been studied. It has been found that both the channel current and threshold voltage of the device increase appreciably under illuminated condition. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2956830]

I. INTRODUCTION

Metal-semiconductor field effect transistors (MESFETs) have been the subject of a number of investigations in recent years.[1–5] The optical sensitivity exhibited by these devices makes them attractive for application as optical field effect transistors.[6–11] The theoretical investigations in Refs. 7–9 and 11 assume an idealistic situation of an intimate gate contact. Though this assumption allows a great deal of mathematical simplification in the theoretical modeling of MESFETs, it leads to several constraints in interpreting the experimental results of practical MESFET structures. For instance, the temperature dependence of the threshold voltage of GaAs MESFET cannot be interpreted on the basis of a model suited for ideal MESFET structures having intimate metal-semiconductor contact at the gate. In fact, the presence of various nonidealities such as an interfacial oxide layer, interface fixed charges, and interface states at the gate contact makes the analysis of the electrical characteristics of such devices quite involved. The effect of the presence of the above nonidealities has been considered in our previous publications.[12,13] It has been shown that the temperature dependence of the threshold voltage can be adequately explained if such nonidealities are considered in the evaluation scheme. The main objective of the present work is to explore the optical response of a MESFET by developing a simple theoretical model applicable to devices having a thin interfacial insulating layer and interface states at the gate contact.

In Sec. II of the paper, an expression for the space charge density in the channel of the device has been derived when the device is illuminated by light of a given wavelength. The functional form for the dc channel current under the illumination has been derived in Sec. III. The relations connecting the depletion layer width with various optical parameters and the scheme for numerical evaluations of the dc channel current are presented in Sec. IV. An expression for the threshold voltage of the device has been derived in Sec. V. The important results of the study are discussed in Sec. VI.

II. CHANNEL SPACE CHARGE DENSITY

The physical structure and the energy band diagram at the gate-channel contact of a MESFET under illumination are shown in Figs. 1(a) and 1(b), respectively. In the figure, L represents the length of the channel, a is the channel thickness, V_d is the drain voltage, V_g is the gate voltage, V_l is the photovoltage developed across the gate-channel interface, ϕ_m is the work function of the metal, χ is the electron affinity of the semiconductor, δ is the thickness of the interfacial insulating layer, Δ is the potential drop across the interfacial layer, qV_n is the energy difference between the Fermi level and the conduction band bottom in the bulk, and other terms have their usual meaning.

The space charge density and the electric field in the channel of the device can be obtained using Poisson's equation

$$d^2\psi/dy^2 = -\rho/\varepsilon_s, \tag{1}$$

where the y-direction (positive downward relative to the surface) is perpendicular to the channel (the x-direction) with the origin located at the gate edge near the source end. Since the device is illuminated by light, the electron-hole pairs are generated in the semiconductor due to optical absorption. The excess electrons in the depletion region diffuse into the channel region leading to an increase in the electron concentration, while the holes add up with positively charged donors and modify the depletion layer space charge density. Now, for a photon flux ϕ, the excess carrier density may be given by $\phi\alpha\tau\exp(-\alpha y)$,[8] where α is the absorption coefficient of the material and τ is the lifetime of the carriers. Accordingly, the space charge density in the semiconductor

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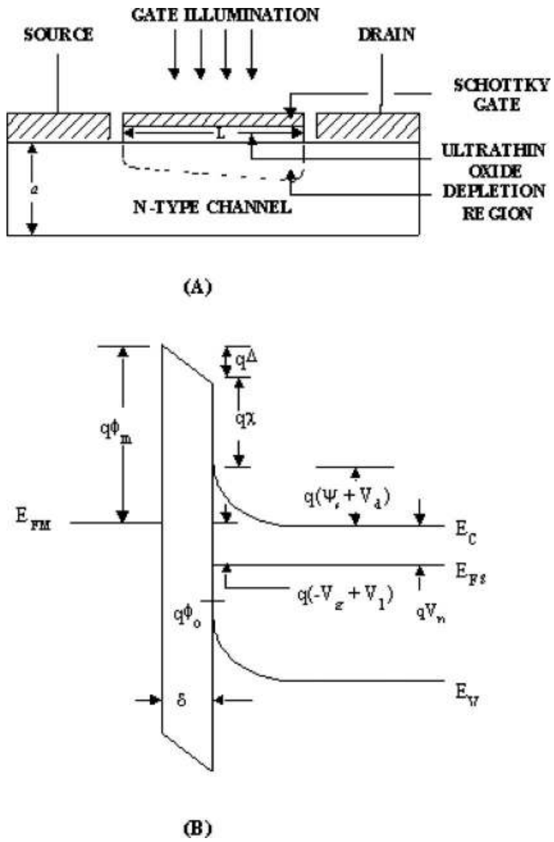

FIG. 1. Cross-sectional view of a MESFET (a) under optical illumination and (b) the corresponding energy band diagram at the gate-channel contact of the device.

would be the sum of the charge densities due to donor impurities and optically generated holes given by

$$\rho(y)=q(N_d+\phi\alpha\tau e^{-\alpha y}) \tag{2}$$

Equation (1) can be integrated in a manner described in Ref. 13, which yields

$$(d\psi/dy)^2/2=-\int_0^{\psi}[q(N_d+\phi\alpha\tau e^{-\alpha y})/\varepsilon_s]d\psi. \tag{3}$$

The second integral in the above equation has to be evaluated numerically since ψ is an implicit function of y. However, when the term $e^{-\alpha y}$ is not changing appreciably over the depletion region, it can be taken outside the integral, and Eq. (3) can be readily integrated with the sign convention[14] so that the surface potential would be negative for upward band bending. Using this approximation and considering the upper limit for the surface potential to be $\psi=-\psi_s$ at $y=0$, the electric field at the source end can be obtained by evaluating the integral in Eq. (3) as

$$E_s(y_1)=-d\psi/dy=-[(2qN_d\psi_s+2q\phi\alpha\tau e^{-\alpha y_1}\psi_s)/\varepsilon_s]^{1/2}, \tag{4}$$

where y_1 is the depletion layer width at the source end. Now, using the above expression for the electric field and applying the Gauss's law, one readily obtains the space charge at the source end as

$$Q_{\rm sc}(y_1)=-\varepsilon_sE_s(y_1)=(2q\varepsilon_sN_d\psi_s+2q\phi\alpha\tau\varepsilon_se^{-\alpha y_1}\psi_s)^{1/2}. \tag{5}$$

Similar expressions for the electric field and space charge density at the drain end can be derived as

$$E_s(y_2)=-\{(2qN_d(\psi_s+V_d)+2q\phi\alpha\tau e^{-\alpha y_2}(\psi_s+V_d))/\varepsilon_s\}^{1/2} \tag{6}$$

and

$$Q_{\rm sc}(y_2)=-\varepsilon_sE_s(y_2)=\{2q\varepsilon_sN_d(\psi_s+V_d)+2q\phi\alpha\tau\varepsilon_se^{-\alpha y_2}(\psi_s+V_d)\}^{1/2}, \tag{7}$$

where y_2 is the depletion layer width at the drain end.

The expression for the space charge density can also be obtained in another form by integrating Eq. (2) with y as

$$Q_{\rm sc}(h)=q\int_0^h(N_d+\phi\alpha\tau e^{-\alpha y})dy=qN_dh-q\phi\tau(e^{-\alpha h}-1), \tag{8}$$

where h is the depletion layer width at any point x along the channel. An equation can be established for the determination of h at any point x by writing the expression $Q_{\rm sc}$ in terms of h and equating the same with Eq. (8) as

$$qN_dh-q\phi\tau(e^{-\alpha h}-1)=[2q\varepsilon_s\{\psi_s+V(x)\}\{N_d+\phi\alpha\tau e^{-\alpha h}\}]^{1/2}. \tag{9}$$

At the source end, the above equation can be written as

$$qN_dy_1-q\phi\tau(e^{-\alpha y_1}-1)=[2q\varepsilon_s\psi_s(N_d+\phi\alpha\tau e^{-\alpha y_1})]^{1/2}. \tag{10}$$

Equation (10) enables one to calculate y_1 for known values of ψ_s and other system parameters. Similarly, an equation involving the depletion layer width at the drain end can be derived by replacing h by y_2 in Eq. (9) as

$$qN_dy_2-q\phi\tau(e^{-\alpha y_2}-1)=\{2q\varepsilon_sN_d(\psi_s+V_d)+2q\varepsilon_s\phi\alpha\tau e^{-\alpha y_2}(\psi_s+V_d)\}^{1/2}, \tag{11}$$

where V_d is the drain voltage.

III. THE CHANNEL CURRENT: FUNCTIONAL FORM

Since the charge density in Eq. (2) is no longer a uniform distribution in the presence of an external illumination, the evaluation of the channel current of the device on the basis of our previous approach[12,13] for uniform doping distribution does not apply here. A general approach for estimating the drain current for an arbitrary charge distribution has been discussed by Sze.[14] The same approach has been adopted in the present case, and an expression for the drain current has been derived as

$$I_d=(2Z\mu/\in_sL)\int_{y_1}^{y_2}\{Q(a)-Q(h)\}h\rho(h)dh, \tag{12}$$

where

$$Q(a) = \int_0^a q(N_d + \phi\alpha\tau e^{-\alpha y})dy = qN_d a - q\phi\tau(e^{-\alpha a} - 1), \tag{13}$$

$$Q(h) = \int_0^h q(N_d + \phi\alpha\tau e^{-\alpha y})dy = qN_d h - q\phi\tau(e^{-\alpha h} - 1) \tag{14}$$

are the quantities modified in the presence of optical illumination. Now, with the help of Eqs. (12)–(14), an expression for the drain current can be obtained as

$$I_d = 2\mu Z[\ Q(a)(I_1 + I_2) - q^2 N_d^2 I_3 + q^2 N_d \phi\tau I_4 - q^2 N_d \phi\tau\alpha I_5 + q^2\phi^2\tau^2\alpha I_6)]/\varepsilon_s L, \tag{15}$$

where

$$I_1 = (y_2^2 - y_1^2)/2,$$

$$I_2 = -[y_2 e^{-\alpha y_2} - y_1 e^{-\alpha y_1} + (e^{-\alpha y_2} - e^{-\alpha y_1})/\alpha]/\alpha,$$

$$I_3 = (y_2^3 - y_1^3)/3,$$

$$I_4 = I_2 - I_1,$$

$$I_5 = -[y_2^2 e^{-\alpha y_2} - y_1^2 e^{-\alpha y_1} - 2I_2]/\alpha,$$

$$I_6 = -[y_2 e^{-2\alpha y_2} - y_1 e^{-2\alpha y_1} + (e^{-2\alpha y_2} - e^{-2\alpha y_1})/2\alpha]/2\alpha - I_2.$$

The channel current given by Eq. (15) can be calculated as a function of drain and gate voltages if the depletion layer widths y_1 and y_2 are explicitly known as functions of drain and gate voltages, respectively.

IV. EVALUATION OF THE DEPLETION LAYER WIDTH AND THE CHANNEL CURRENT

Since an interfacial layer is considered, the method of evaluation of the depletion layer widths y_1 and y_2 is similar to that of Schottky contacts having interfacial imperfection such as interfacial layer, interface states, and fixed charges.[12,13] The evaluation procedure requires consideration of the energy band diagram, Gauss's law, and the charge neutrality condition at the gate-channel contact. Following our previous approach in the above references, we find correlations between various system parameters of a nonideal MESFET structure given by

$$\Phi_m - \chi - \Psi_s + V_g - V_l - V_n = \delta\{Q_{sc}(y_1) + Q_{it1} + Q_f\}/\varepsilon_i \tag{16}$$

at the source end and

$$\Phi_m - \chi - \Psi_s + V_d + V_g - V_l - V_n = \delta\{Q_{sc}(y_2) + Q_{it2} + Q_f\}/\varepsilon_i \tag{17}$$

at the drain end. In the above two equations Q_f is the insulator fixed charge density, and Q_{it1} and Q_{it2} that represent the interface trapped charge densities at the source and drain ends, respectively, can be estimated using appropriate interface state model[15,16] as

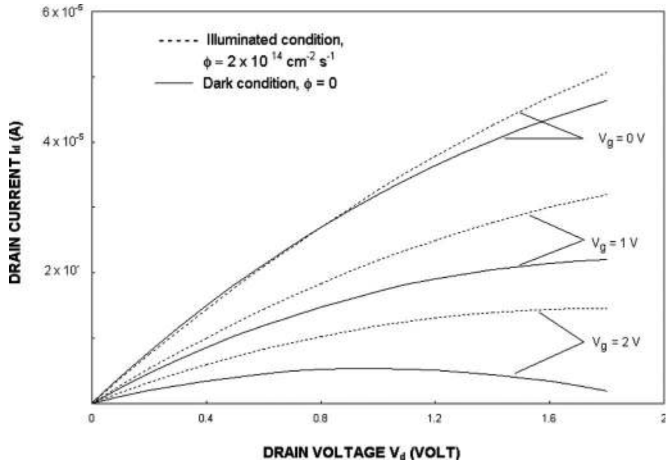

FIG. 2. The channel current vs drain voltage characteristics of a silicon MESFET for different values of gate voltage under dark and illuminated conditions. The continuous line curves represent the characteristics under dark condition. The dashed line curves represent the characteristics under illumination. Parametric values: E_g=1.12 eV, ϕ_m=5.2 eV, χ=4.05 eV, ϕ_0=0.3 eV, $N_d=5\times10^{15}$ cm^{-3}, $N_f=10^{11}$ cm^{-2}, $\delta=10^{-7}$ cm, ε_l=8.854 $\times10^{-14}$ F cm^{-1}, $D_{it}=10^{11}$ cm^{-2} eV^{-1}, $Z=10^{-4}$ cm, $A=10^{-4}$ cm^2, μ =1500 cm^2 V^{-1} s^{-1}, $L=3\times10^{-4}$ cm, $\tau=5\times10^{-4}$ s, $\Phi=2\times10^{14}$ cm^{-2} s^{-1}, $\alpha=10^5$ cm^{-1}, and T=300 K.

$$Q_{it1} = -q^2 D_{it}(E_g - \phi_o - \Psi_s - V_n), \tag{18}$$

$$Q_{it2} = -q^2 D_{it}(E_g - \phi_o - \Psi_s - V_d - V_n), \tag{19}$$

where ϕ_0 is the neutral level. Equations (16) and (17) can be written in more explicit forms by using Eqs. (5), (7), (18), and (19) as

$$\Phi_m - \chi - \Psi_s + V_g - V_l - V_n = \delta[\{2q\varepsilon_s\psi_s(N_d + \phi\alpha\tau e^{-\alpha y_1})\}^{1/2} - q^2 D_{it}(E_g - \phi_o - \Psi_s - V_n) + Q_f]/\varepsilon_i \tag{20}$$

and

$$\Phi_m - \chi - \Psi_s - V_d + V_g - V_l - V_n = \delta[\{2q\varepsilon_s(N_d + \phi\alpha\tau e^{-\alpha y_2})(\psi_s + V_d)\}^{1/2} - q^2 D_{it}(E_g - \phi_o - \Psi_s - V_d - V_n) + Q_f]/\varepsilon_i, \tag{21}$$

The values of y_1 and y_2 can be solved numerically as a function of V_d using Eqs. (10), (11), (20), and (21) for different values of V_g, D_{it}, and ϕ and may be substituted in Eq. (15) to obtain the channel current. However, it may be mentioned here that the photovoltage developed across the gate-channel interface drives a photocurrent to the gate leading to a leakage of photocarriers. Such a loss of photocarriers reduces the drain current of the device under optical illumination. Therefore, to get a maximum effect of illumination on the channel current, one may seek the photovoltage to be negligibly small. Such a condition has been examined in order to compare the dc channel characteristics of the device under the dark and illuminated conditions. The results are illustrated in Figs. 2–4 for silicon MESFET.

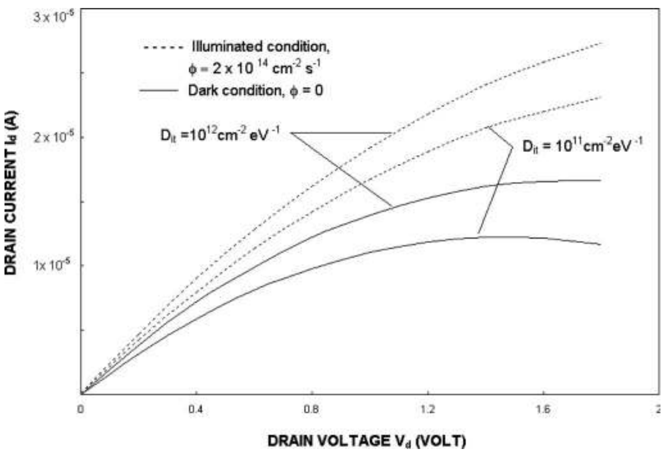

FIG. 3. The channel current vs drain voltage characteristics of a silicon MESFET for different values of interface state density under dark and illuminated conditions. The values of the parameters are the same as in Fig. 2.

V. THRESHOLD VOLTAGE

The threshold voltage of the device under illumination is the gate voltage for which the channel current just approaches zero, i.e., when $y_2=a$. An expression for the threshold voltage can be readily derived from Eq. (21) as

$$V_{\rm th} = \Phi_m - \chi - (\Psi_s + V_d)|_{y_2=a} + V_g - V_n - V_l - \delta[q\{N_d a - \phi\tau(e^{-\alpha a} - 1)\} - qD_{\rm it}(E_g - \phi_o - \Psi_s - V_d - V_n) + Q_f]/\varepsilon_i. \tag{22}$$

It is apparent from the above equation that to have a complete mathematical form for the threshold voltage, the functional form for the term $(\Psi_s+V_d)|_{y_2=a}$ is to be derived. An expression for this term can be derived by substituting $y_2=a$ in Eq. (11) given by

$$(\psi_s + V_d)|_{y_2=a} = \frac{\{q[N_d a - \phi\tau(e^{-\alpha a} - 1)]\}^2}{2q\varepsilon_s(N_d + \phi\alpha\tau e^{-\alpha a})}. \tag{23}$$

With the help of Eqs. (22) and (23), one readily obtains

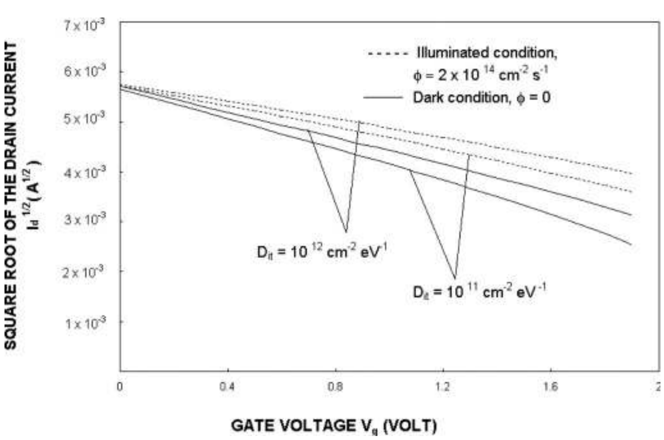

FIG. 4. The square root of the channel current vs gate voltage plots of a silicon MESFET for different values of interface state density under dark and illuminated conditions. The values of the parameters are same as in Fig. 2.

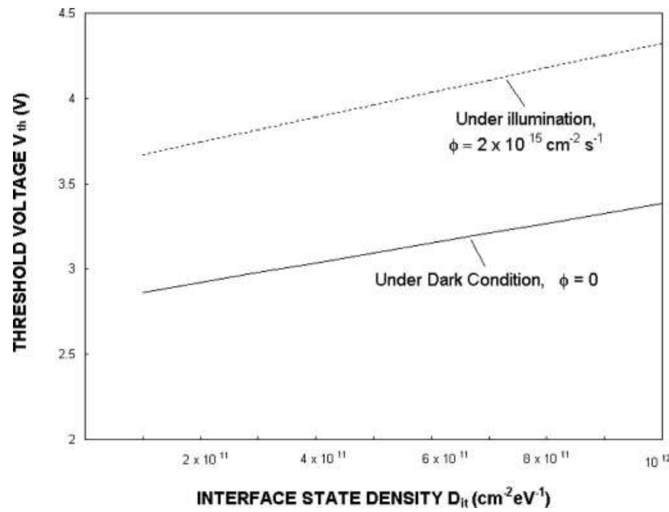

FIG. 5. Variation of the threshold voltage of a silicon MESFET as a function of interface state density under dark and illuminated conditions. The value of the photon flux has been considered to be $\Phi=10^{15}$ cm^{-2} s^{-1}. The values of the remaining parameters are same as used in Fig. 2.

$$V_{\rm th} = -[V_{bi} - V_{T1}^2/V_{T2} - V_l + \delta C_2 V_{T1}/\varepsilon_i]/C_2, \tag{24}$$

where $V_{T1}=q\{N_d a-\phi\tau(e^{-\alpha a}-1)\}$, $V_{T2}=2q\varepsilon_s(N_d+\phi\alpha\tau e^{-\alpha a})$, and $C_2=\varepsilon_i/(\varepsilon_i+q^2\delta D_{\rm it})$. The threshold voltage $V_{\rm th}$ is calculated using Eq. (24) for silicon MESFET for different values of interface state density assuming V_l to be negligibly small. The results are illustrated in Fig. 5.

VI. DISCUSSION

The analytical expression for the drain current derived in Sec. III [Eq. (15)] is a function of optically controllable parameters such as α, ϕ, y_1, and y_2. The parameters y_1 and y_2 are light sensitive through the surface potential Ψ_s. Accordingly, the channel current varies when the device is illuminated by light of appropriate wavelength. Figure 2 shows the I_d-V_d characteristics of silicon MESFET for different values of V_g under illuminated and dark conditions. The extent to which the channel current is changed under illuminated condition can be easily understood by comparing the dark characteristics for a particular value of the gate voltage V_g. As evident from the figure, the channel current exhibits usual variation with respect to drain and gate voltages under dark condition, but when the device is illuminated, the current increases significantly. Such an increase in the current is due to optically generated carriers in the channel region.

The effects of interface states on the channel current under dark and illuminated conditions are shown in Fig. 3. The I_d-V_d plots are generated considering the values of interface state density to be 10^{11} and 10^{12} cm^{-2} eV^{-1}, respectively. It is seen from these characteristics that under the dark condition (represented by continuous line curves), the channel current of the device increases with interface state density $D_{\rm it}$. The enhancement in the channel current is caused by a decrease in the depletion layer width with interface state density. Such a decrease in the value of the depletion layer width with $D_{\rm it}$ can be explained on the basis of interface pinning effect caused by high density of interface states at metal-semiconductor interface at the gate. The metal considered in the present case ensures high barrier for a low value of interface state density, e.g., $D_{it}=10^{11}$ cm^{-2} eV^{-1}. As the value of D_{it} is increased to 10^{12} cm^{-2} eV^{-1}, the interface pinning effect pushes the Fermi level downward to align with the neutral level. This reduces the surface potential and depletion layer width and, hence, an increase in the channel current of the device. The effect of illumination (represented by the dashed line curves) results to an appreciable upward shift of the I_d-V_d curves in Fig. 3. It may be mentioned here that the light sensitivity of the device increases with the value of the photon flux ϕ. The higher the value of ϕ, the better would be the performance of the device under optical illumination.

The $\sqrt{I_d}$ vs V_g characteristics of the device under dark and illuminated conditions are shown in Fig. 4. The above characteristics are in general linear in V_g for ideal devices, and the intercept on the V_g axis of these characteristics yields the value of the threshold voltage V_{th}. However, in the present case of a nonideal silicon MESFET, a change in the slope in these plots has been noted when the device is illuminated by light. This suggests an enhancement of the threshold voltage of the device under illumination. The extent to which the threshold voltage V_{th} is influenced by interface state density under dark and illuminated conditions is illustrated in Fig. 5. The upward shift of the V_{th} vs D_{it} plot under illumination suggests enhancement of the threshold voltage. By changing the value of D_{it}, a gradual increase in the value of V_{th} has been found.

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