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Comments on the Theory of Negative Resistance of FET Devices

莊晴光，蔡　中 Ching-Kuang Tzuan and Chun Tsai

Department of Electronics Engineering, N.C.T.U.

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ABSTRACT — A theory of negative differential resistance proposed originally for JFET is extended and discussed for the results of MISFET devices to determine both peak point and valley point in the I-V curves.

Recently, several papers [1-5] are dealing with a negative differential resistance characteristics from an FET device with some kind of internal feedback. Since the feedback circuit is built in the device, a general theory to predict whether the feedback is sufficient to generate the property of negative resistance is needed. A method, proposed by Mizuno, Kano, Takagi, and Teramoto [6], can used to derive a critical equation for the prediction of JFET negative resistance devices. In this short note, comments are given and discussed when a similar method is applied to the MISFET devices

For a general theory, the feedback condition is implicitly expressed as

$$V_{GS}=f(V_{DS}) \tag{1}$$

where V_{DS} is the drain-source voltage and V_{GS} the gate-source voltage. Therefore, from simple mathematical knowledge, if the drain current, I_{DS}, has a maximum point, the following conditions should be satisfied:

$$\frac{dI_{DS}}{dV_{DS}}=0 \tag{2}$$

$$\frac{d^2I_{DS}}{dV_{DS}{}^2}<0 \tag{3}$$

Since the negative differential resistance has been observed in MISFET devices both in non-saturation region [7] and saturation region [3], both two cases have to be treated.

The usual expressions of drain current in the non-saturation and the saturation regions are given by the following two equations [8], respectively:

$$I_{DS}=K\{(V_{GS}-V_T)V_{DS}-\frac{V_{DS}{}^2}{2}\} \tag{4}$$

$$I_{DS}=\frac{KL}{2(L-\Delta L)}\{(V_{GS}-V_T)^2\} \tag{5}$$

where

K: a constant, negative for p-channel and positive for n-channel,

L: the channel length,

ΔL: the channel shortening length which is equal to $[A(V_{DS}-V_{GS}+V_T)]^{\frac{1}{2}}$, where A is a constant, (positive for n-channel and negative for p-channel)

V_T: the threshold voltage.

In the above equations, a constant value of V_T is assumed, and the modulation of channel length by the spreading of the drain depletion region is included. For simplicity, the other factors which may affect the current beyond pinch-off are neglected. Applying conditions of Eq. (2) and (3) for both cases, we have:

1. Non-saturation case

$$\frac{dI_{DS}}{dV_{DS}} = K\{V_{DS}f' + (V_{GS}-V_T) - V_{DS}\} \tag{6}$$

$$= 0$$

or

$$f'_p = 1 - \frac{V_{GSp}-V_T}{V_{DSp}} \tag{7}$$

and

$$\frac{d^2I_{DS}}{dV_{DS}^2} = K\{V_{DS}f'' + 2f' - 1\} \tag{8}$$

$$< 0$$

or

$$f''_p < \frac{1-2f'_p}{(\pm V_{DSp})} \tag{9}$$

2. Saturation case

$$\frac{dI_{DS}}{dV_{DS}} = \frac{KL(V_{GS}-V_T)}{4\,\Delta L(L-\Delta L)^2}\{f'[4\,\Delta L(L-\Delta L) - A(V_{GS}-V_T)] + A(V_{GS}-V_T)\} \tag{10}$$

$$= 0$$

or

$$f'_p = \frac{A(V_{GSp}-V_T)}{A(V_{GSp}-V_T) - 4\,\Delta L_p(L-\Delta L_p)} \tag{11}$$

and

$$\frac{d^2I_{DS}}{dV_{DS}^2} = \frac{KL(V_{GS}-V_T)}{2\,\Delta L(1-\Delta L)}\{f''[\frac{4\,\Delta L(L-\Delta L) - A(V_{GS}-V_T)}{2(L-\Delta L)}] + \frac{A^2(V_{GS}-V_T)(6\,\Delta L-4L)}{4\,\Delta L(L-\Delta L) - A(V_{GS}-V_T)}\} \tag{12}$$

$$<0$$

or

$$f''_p < (\pm) 8\, A f'_p (L - \Delta L_p)(2L - 3\,\Delta L_p) \qquad (13)$$

where f' and f" are the first and second derivatives of Eq. (1) with respect to V_{DS}, respectively. The subscript "p" represents the peak point or the maximum point, and the upper sign is used for n-channel and the lower sign for p-channel. It can be seen from Eq. (9) and Eq. (13) that , as long as f' is negative and f" is less than or equal to zero, there definitely exists a peak point, and followed with a negative derivative region in the I-V curve. However, this kind of argument is only for the circuit in which there is no other current path from drain to source except the surface channel of the MIS device. Therefore, the theory developed so far can not explain the results in the article of Lehovec and Ruleeg [3]. In their results, there is also a minimum point, or valley point in the I-V curves. Therefore, two sets of conditions should be used. For the peak point, the Eq. (2) and (3) is used except the I_{DS} should be replaced by the total currents of all paths. For the valley point, the conditions are the same if we change the sign of the second equation.

The method of Mizuno et al has been discussed for MISFET devices and extended to determine both the peak point and the valley point. If there is only one current path from drain to source as those devices made by JFET [2], there exists a single peak point. If there are several pathes, then there may also exist a valley point when the current through the other pathes gradually increasing while the current through the channel is decreasing and turning the I-V curve up again.

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