Analysis of the Lower and Upper Bounds of the Input of an NTC (Neural-Type Cell) Circuit

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***Abstract*—A neural-type cell (NTC) is an electronic circuit that produces pulse-coded signals by oscillating to mimic the behavior of a neuron. This paper mainly focuses on a certain type of NTC, analyzing the physical essence of the lower and upper bounds of input voltage that could support the oscillation of the circuit. The body effect of one of the transistors of the NTC is taken into consideration, which is neglected in previous researches. Then, a method of calculating the actual numerical values of the lower and upper bounds is presented, offering a more quantitative way to analyze this NTC. An NTC is built with TSMC 180nm technologies for numerical confirmation.**

Keywords—NTC, neural-type cell, pulse-coded signal, oscillation, input range, hysteresis

I. Introduction

The neural-type cell (NTC) was invented to imitate the behavior of neurons. One way of doing this is to realize the Hodgkin-Huxley equations [1] with electronic devices, which might involve a complex circuit. One other form of NTC [2] is invented by Kuklarni-Kohli and R. W. Newcomb later to bypass the intricacy of the Hodgkin-Huxley equations. The basic unit of this NTC is presented in [3], and a detailed analysis of the mechanism of this circuit is also offered in that paper. The oscillation of the circuit is mainly based on the intersections of the load line intersecting with the hysteresis line at the steep edge, causing the circuit to stay unstable. Reference [3] also enlarges on the hysteretic property of the NTC by bringing up a mathematical description of the hysteresis. The oscillation can also be supported from the perspective of semistate description [4]. Moreover, the oscillation of an NTC can only happen within a certain range of the input voltage, this phenomenon is revealed in [5], and a method of calculating the input voltage range is presented in that paper. However, the calculation is mainly based on a numerical approximation without taking the actual physical process into account, which makes this method lack universality. Until this stage, the NTC unit is composed of both MOSFETs and resistors. According to [6], such NTC might incur several limitations including a comparatively large size and a small range of input voltage to support oscillation. So, reference [6] provided an improved version of NTC – the all-MOS NTC, solving the two limitations listed above. The Hysteresis and the load line of an all-MOS NTC can be seen in Fig.1. The meanings of the variables marked in Fig.1 are shown in Fig.2.

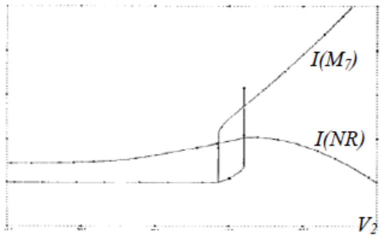

Fig. 1 The intersections and the hysteresis of an all-MOS NTC

Nevertheless, within all the previous work mentioned here, a theoretical explanation of the input voltage range of the NTC has never been given, especially for the all-MOS NTC which should be of more use in the future. This problem is tackled in this paper.

II. Analysis of the Physical Process of the NTC

Most of the previous work in this field analyzed the NTC by taking advantage of the hysteresis curve. However, due to the extreme nonlinearity of the circuit, the mathematical description [3] of this hysteresis is based on ideal assumptions. This way of description is sufficient for demonstrating the existence of the hysteresis, but not accurate enough to quantify the status of the circuit. Thus, the actual physical process should be focused on here. To make it easier for demonstration, an NTC composed of 180nm MOSFETs is used for simulation, and it is shown in Fig.2.

Besides using a smaller process node, other differences of this NTC from the one in [6] are the parameters of the MOSFETs and the capacitor, and they are listed here: W_1 = 7.8μm, L_1= 1.3μm, W_2 = 13μm, L_2 = 1.3μm, W_3 = 1.6μm, L_3

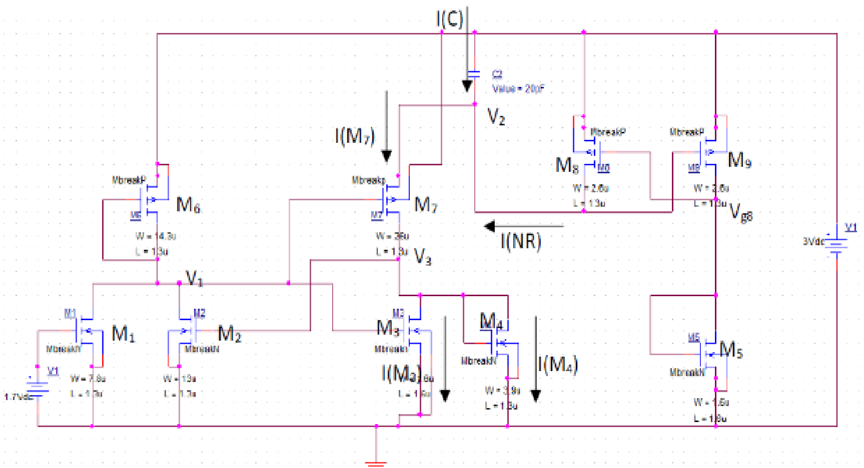

Fig. 2 A 180nm NTC used for simulation

= 1.6µm, W_4 = 3.9um, L_4 = 1.3µm, W_5 = 1.6µm, L_5 = 1.6µm, W_6 = 14.3µm, L_6 = 1.3µm, W_7 = 26µm, L_7 = 1.3µm, W_8 = 2.6µm, L_8 = 1.3µm, W_9= 2.6µm, L_9 = 1.3µm, k_p' = 32.95µA/V^2, k_n' = 134.00µA/V^2, V_{tn} = 0.3545V, V_{tp} = 0.4121V, C = 20pF. L_i and W_i stand for the length and width of the MOSFET with a subscript of *i;* k_p' and k_n' stand for the process transconductance parameters [7] of PMOS and NMOS; and V_{tp}, V_{tn} refers to the threshold voltage of PMOS and NMOS without body effect. All the threshold voltages in this paper are treated as positive numbers.

A brief description of the oscillating circuit is provided in [8]. However, the change of the threshold voltage of M_7 due to the body effect is not mentioned in that paper. It will be shown in the next part that the body effect plays an indispensable role in the oscillation cycle.

For convenience of explanation, the circuit is separated into several parts: 1) the input branch (M_1, M_2, and M_6); 2) the output branch (M_7, M_3, and M_4); 3) the nonlinear resistor (M_5, M_8, and M_9). The input is defined to be the gate-to-source voltage of M_1, and the output is defined as V_3, as is shown in Fig.2. Usually, when making use of the NTC, V_3 is treated as the output voltage. However, in this paper, V_2 deserves more attention as its changing pattern reveals more characteristics of this circuit.

Here is an expatiation of the oscillation process: There are two distinct phases in one cycle. The first phase (P_1) is when M_2 and M_4 are off, which means V_3 is less than V_{tn}, and the other one (P_2) refers to the opposite situation. The oscillation happens with the circuit endlessly jumping from one phase to the other.

In P_1, since V_3 is quite low, M_2 passes a tiny amount of current. The current through M_6, consequently, should also be smaller than in P_2. Thus, the voltage drop across the diode-connected transistor should also be smaller. V_1, as a result, is kept at a higher level, close enough to V_2, limiting the capability of M_7 to let-through current. The output branch is enduring a small amount of current, which means most of the current flowing from the nonlinear resistor will pass through the capacitor from the lower end to the higher end in Fig.2. (A more detailed discussion about the current will be provided in the last part of this section.) This will cause V_2 to rise, lowering the absolute value of the voltage drop between the body and the source of M_7. The body effect of this transistor will be mitigated, and its threshold voltage will drop. At the same time, as the $V_{sg}(M_7)$ rises due to the increase of V_2, the output branch starts to be injected an ascending amount of current through M_7.

As we mentioned, V_3, at this point, is lower than V_{tn}, which means it must be much lower than V_1, so M_3 is working in the triode region, while M_4 is off. This denotes that the current through the output branch mainly passes M_3. Meanwhile, the gate voltage of M_3, V_1, stays stable in this phase. So, when the current through the output branch increases, the drain voltage of M_3 will be raised. The moment V_{gs} of M_3 exceeds V_{tn} marks this NTC entering P_2.

In the early stage of P_2, as M_2 is turned on to take in a large amount of current, the current through M_6 increases accordingly, bringing down V_1. As a result, on the one hand, the V_{sg} of M_7 increases to enable this transistor passing an increasing amount of current; on the other hand, the V_{sg} of M_3 drops, and M_3 refuses to absorb large current. These two factors force M_4 to soak in large current, further pumping up V_3 from V_{tn}. Then the current through M_2 gets increased again, bringing down V_1 … The NTC will move on with this tendency until next a few things happen.

Since $V_{sg}(M_7)$ is growing in P_2, the current through the transistor is also increasing. The current provided by the nonlinear resistor switches its way from the capacitor to the output branch. However, the output branch is asking for more current than the nonlinear resistor can give out. Consequently, the capacitor needs to provide current to the output branch. The current of the capacitor starts to flow from the upper end to the lower end, charging the capacitor, lowering V_2. The source-to-body voltage of M_7 will increase accordingly. The resultant increase of its threshold voltage will limit its capability to let-through large current. The tendency mentioned in the previous paragraph is curbed and reversed. At the end of P_2, the current through the output branch is a very small value, which makes the voltage drop across M_3 and M_4 no longer able to support M_2 and M_4 to be on. The NTC will now transit into P_1. A full cycle of the oscillation is completed.

There is one critical detail of the oscillation remaining undiscussed: What if the current provided by the nonlinear resistor is little when the current demand of the output branch is little (in P_1) and large in the opposite situation? There will not be enough fluctuation of current through the capacitor to change the source-to-body voltage of M_7 then. In fact, there is no such worry. Reference [6] mentioned that between the intersections of the load line and the hysteresis, the current of the nonlinear resistor is designed to go upwards when its input voltage (V_2) increases and go downward when V_2 decreases. During oscillation, when V_2 increases in P_1 to mitigate the body effect, the current from the nonlinear resistor will increase, and this increasing current mostly goes to the capacitor because the output branch is not able to take in large current, facilitating the rise of V_2. While in P_2, as the body effect gets intensified with the drop of V_2, the current from the nonlinear resistor decreases, urging the capacitor to give out more current, aggravating the body effect. The design of the NTC circuit is self-supportive.

To provide a clearer overview of the oscillation cycle, a cycle diagram is provided in Fig.3. The body effect and the change of V_3 are two critical factors of the dynamic behavior of this NTC.

III. CALCULATION OF THE LOWER AND UPPER BOUNDS OF NTC'S INPUT VOLTAGE

With the aforementioned analysis of the actual process of the oscillation, the calculation of the lower bound ($V_{in,low}$) and upper bound ($V_{in,high}$) of the input voltage of the NTC is ready

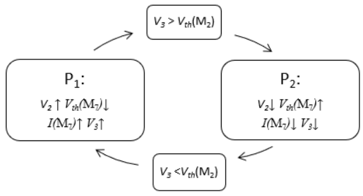

Fig. 3 The oscillation process of the NTC

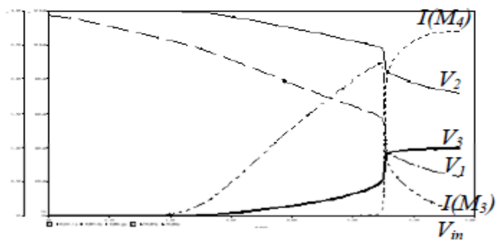

Fig. 4 The waveforms used to analyze the lower bound

to be presented. The NTC can oscillate only within this range. Before giving the calculation for both bounds, physical explanations on the existence of the bounds are to be provided.

A. The Calculation of the Lower Bound

The status of the NTC stepping across the lower bound as the input voltage increases is shown in Fig.4.

As shown in Fig.4, which is a result of a PSpice DC Sweep simulation, when V_{in} rises from 0V to around 1.1V, the circuit experiences a dramatic change. This signifies the start of oscillation. The dramatic change is caused by V_3 exceeding V_{tn}, which turns on M_2 and M_4, bringing down V_1 and transferring the current of output branch from M_3 to M_4. This will trigger the oscillation. Were it not for the existence of M_2 and M_4, the circuit will continue to change with the tendency that it follows before V_{in} reaches $V_{in,low}$.

With the analysis of the lower bound presented above, calculation of the $V_{in,low}$ can be presented in this part. The situation where V_{in} is just below $V_{in,low}$ is focused on here. Since the NTC is still stable in this situation, there is no current flowing through the capacitor. Additionally, the current through M_4, $I(M_4)$, is negligible, since it is not comparable to the current through M_3, $I(M_3)$. Thus, we can get the equations that we need: the current from the nonlinear resistor $I(NR)$ equals $I(M_7)$ and $I(M_3)$.

First, $I(NR)$ is calculated. Because $I(M_5)$ must be the same as $I(M_9)$, we have:

$$\frac{1}{2}k'_p\left(\frac{W_9}{L_9}\right)\left(V_{dd}-V_2-V_{tp}\right)^2=\frac{1}{2}k'_n\left(\frac{W_5}{L_5}\right)\left(V_{g8}-V_{tn}\right)^2 \tag{1}$$

V_{g8} is the gate voltage of M_8. After a reorganization of (1), we can get that V_{g8} is a linear function of V_2:

$$V_{g8}=V_{tn}+\sqrt{\frac{k'_p}{k'_n}\left(\frac{W_9L_5}{W_5L_9}\right)}\left(V_{dd}-V_2-V_{tp}\right)=V_{g8}(V_2) \tag{2}$$

M_8 is now working in its triode region since V_2 hasn't dropped too much from V_{dd} according to Fig.4, the $V_{sd}(M_8)$ should be a small value. $I(NR)$ will be:

$$I(NR)=I_{sd}(M_8)=k'_p\left(\frac{W_8}{L_8}\right)\left[\left(V_{dd}-V_{g8}-V_{tp}\right)-\frac{1}{2}\left(V_{dd}-V_2\right)\right]\left(V_{dd}-V_2\right) \tag{3}$$

V_3 equals to V_{tn} at this moment, so $V_{sd}(M_7)$ should be large enough to make M_7 work in the saturation region. Hence, $I(M_7)$ can be represented as:

$$I(M_7)=\frac{1}{2}k'_p\left(\frac{W_7}{L_7}\right)\left[V_2-V_1-V_{tp}(V_2)\right]^2 \tag{4}$$

Here, V_{tp} is a function of V_2 because of the body effect.

Since $V_g(M_3)$, namely V_1, is high, and $V_d(M_3)$ is as low as V_{tn}, M_3 can be inferred to be working in the triode region at this point. So, $I(M_3)$ is:

$$I_{ds}(M_3)=k'_n\left(\frac{W_3}{L_3}\right)\left[(V_1-V_{tn})V_{tn}-\frac{1}{2}{V_{tn}}^2\right] \tag{5}$$

The left-hand sides of (3), (4) and (5) are the same value; a new variable is established to represent it -- I_{OB}. OB stands for 'output branch'.

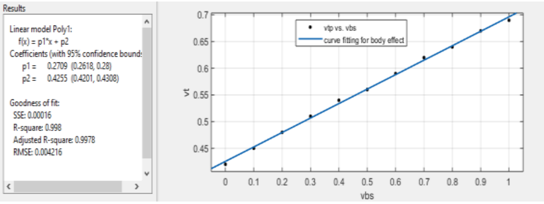

Fig. 5 The curve fitting session for the body effect

(3), (4) and (5) altogether constitute an equation set with three unknown variables: V_2, V_1, and I_{OB}. Solving this equation set can yield the value of these variables. Then we take V_1 into the next equation which indicates the equality of the current through M_6 and M_1 when M_2 is off:

$$\frac{1}{2}k'_p\left(\frac{W_6}{L_6}\right)\left(V_{dd}-V_1-V_{tp}\right)^2=\frac{1}{2}k'_n\left(\frac{W_1}{L_1}\right)\left(V_{in}-V_{tn}\right)^2 \tag{6}$$

(6) is an equation of V_{in}. The solution to it is $V_{in,low}$.

Numerical Confirmation

The NTC shown in Fig.2 is taken as an example for numerical confirmation.

First, a function is required to describe body effect. To simplify the calculation, a linear curve fitting is adopted to reveal the relationship between the threshold voltage and the source-to-body voltage (V_{sb}). The function is:

$$V_{tp}(M_7)=0.2709V_{sb}+0.4255 \tag{7}$$

As is shown in Fig.5, this linear function is accurate enough for the body effect of a 180nm PMOS.

By solving (3), (4) and (5), we can get two sets of real solutions: $V_{2,1}$=2.6011V, $I_{OB,1}$=53.6910 μA, and $V_{1,1}$=1.6639 V; the second set of solution is $V_{2,2}$= 2.2991V, $I_{OB,2}$=77.6132 μA, and $V_{1,2}$= 2.1690V. The second solution should be discarded because $V_{2,2}$ and $V_{1,2}$ are too close in this case, which means $V_{sg}(M_7)$ is too small for M_7 to provide $I_{OB,2}$. Taking $V_{1,1}$ into (6), the final solution for V_{in} can be given. The final result for $V_{in,low}$ is 0.9749V. With PSpice simulation, the actual results are: V_2 = 2.4346V, I_{OB} = 93.314 μA, V_1 = 1.4251V, and $V_{in,low}$= 1.1215V.

The inaccuracy of the calculation is mainly caused by the fact that the formula we have for the current of a 180 nm MOS working in the triode region is smaller than it should be. There are two ways of avoiding this: 1) use a more precise math model; 2) modify the formula we already have. In this example, the second method is adopted. (3) is simplified into:

$$I(NR)=k'_p\left(\frac{W_8}{L_8}\right)\left(V_{dd}-V_{tp}\right)\left(V_{dd}-V_2\right) \tag{8}$$

V_{g8} and (V_{dd}-V_2) are omitted to forcefully make the current value larger. And in effect, these two values are small enough to be neglected. This equation is also simplified into a linear one, palpably simplifying the calculation.

After solving the simplified equation set containing (8), (4) and (5); the new solution is: $V_{2,1}$ = 2.4688V, $I_{OB,1}$ = 90.2659 μA, $V_{1,1}$ = 1.3760V; and $V_{in,low}$ is 1.168V. This result is accurate enough.

B. The Calculation of the Upper Bound

As the input voltage increases when the NTC is oscillating, the amplitude of the oscillation will decrease, as is shown in Fig.6. This is because the hysteretic curve shown in Fig.1 shrinks and its two intersections with the load line are getting closer. The moment when the two intersections

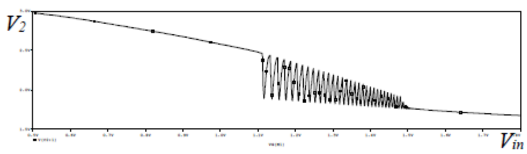

Fig. 6 The decreasing of the oscillation amplitude as the input voltage increases

converge to each other is when the oscillation totally dies away. The V_{in} in this situation is $V_{in.high}$.

To get $V_{in.high}$, it is necessary to describe the fading of the oscillation. Here is a way to accomplish this: two statuses are specified within every single oscillation cycle, and the V_2 of these two statuses, $V_{2,status1}$ and $V_{2,status2}$, should be functions of only V_{in}. When the two curves for the two functions intersect, the corresponding V_{in} denotes $V_{in,high}$.

The first status deserving attention can be depicted as: At the end of P_2, the body effect causes $V_{tp}(M_7)$ to be larger than $V_{sg}(M_7)$, limiting the amount of current passing through M_7. However, later, in P_1, as the capacitor discharges itself to a certain extent, there must be a moment when $V_{tp}(M_7)$ equals $V_{sg}(M_7)$. This is the first moment we focus on. According to the description here, we have:

$$V_1 = V_2 - (k_1(V_{dd}-V_2) + k_2) \tag{9}$$

$(k_1(V_{dd}\text{-}V_2)+k_2)$ is a linear approximation of the function, $V_{tp}(V_2)$. It has been proved to be accurate enough.

At this moment, (6) is true. After a reorganization of this equation, V_1 becomes a linear function of V_{in}:

$$V_1 = -\sqrt{\frac{k_n'}{k_p'}\frac{W_1 L_6}{L_1 W_6}}(V_{in} - V_{tn}) + V_{dd} - V_{tp} \tag{10}$$

Getting rid of V_1 in (9) and (10), the function $V_{2,status1}(V_{in})$ can be obtained:

$$V_2 = \frac{-\sqrt{\frac{k_n' W_1 L_6}{k_p' L_1 W_6}}(V_{in}-V_{tn})+V_{dd}-V_{tp}+k_2+k_1 V_{dd}}{1-k_1} = V_{2,status1} \tag{11}$$

The second moment to focus on is: at the end of P_1, the current of the output branch increases to a level that makes V_3 equals V_{tn}. This scenario is very similar to the one focused on when calculating $V_{in,low}$, the only difference is that in this case, the current through the capacitor cannot be ignored. But (4), (5) and (6) can still be made use of, so is (10) which is another form of (6). Moreover, the current through M_7 and M_3 are still the same.

Thus, it is reasonable to construct another equation out of (4) and (5) and replace the V_1 in both sides of the equation with a function of V_{in}, which is given in (10). So, the curve for $V_{2,status2}(V_{in})$ can result:

$$k_p'\left(\frac{W_3}{L_3}\right)\left((V_1(V_{in}) - V_{tn})V_{tn} - \frac{1}{2}{V_{tn}}^2\right) = \frac{1}{2}k_p'\left(\frac{W_7}{L_7}\right)\left(V_{2,status2} - V_1(V_{in}) - V_{tp}\right)^2 \tag{12}$$

When $V_{2,status1}$ equals $V_{2,status2}$, we can combine (11) and (12) into one equation, the unknown variable being V_{in}. The solution of this equation is $V_{in,high}$. This equation, essentially, is just the same as replacing the right-hand side of (12) with zero. This is because (11) is depicting the scenario when the source-to-gate voltage and the threshold voltage of M_7 are the same, so the current through M_7 must be zero then, and the right-hand side of (12) is the formula for M_7's current.

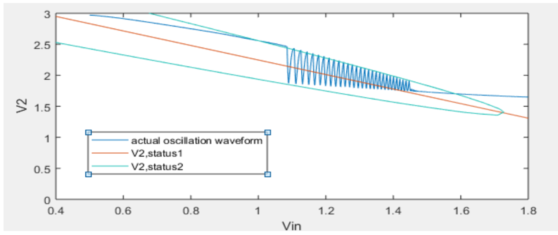

Fig. 7 The curves for equations (11), (12) and the oscillation itself

Numerical Confirmation

The 180nm NTC in Fig.2 is used again to verify the calculation method provided above. The curves for (11) and (12) are plotted together with the oscillation waveform in Fig.7. The solution for $V_{in,high}$ is 1.71V, while the actual value is around 1.64V. In fact, there is no absolute upper bound for the input voltage. Because, as the input voltage increases, the spike-like oscillation of the NTC will gradually transform into a type of irregular fluctuation.

As is shown in this picture, the two curves depict the fading of oscillation quite satisfyingly. There might be inaccuracy when the input voltage is quite close to the higher bound because of a sudden attenuation in the oscillatory amplitude. This is owing to the phase, P_1, which we select the two statuses from, does not exist in the strict sense when V_{in} is close to $V_{in,high}$. P_1 is defined as when M_2 and M_4 are completely shut down. But, apparently, as P_1 and P_2 gets extremely close to each other, there will be no such moment. However, this shouldn't nullify this calculating method as it aims at providing a quantitative insight into the fading of the oscillation instead of the ultimate numerical answer. If the latter is the only goal that we pursue, there is no way more convenient than just running a simulation to achieve this goal.

It should also be mentioned here that PSpice uses the BSIM model instead of an analytical one, which might account for the inaccuracy in the numerical result.

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