Comments on “Negative capacitance effect in semiconductor devices”

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Comments on "Negative Capacitance Effect in Semiconductor Devices"

Jian-Guo Ma, Kiat Seng Yeo, and Manh Anh Do

Capacitors play a very important role in the modeling of semiconductor devices. Without a good understanding and accurate model for the capacitance characteristics, one cannot model devices very well. The conventional equivalent circuit models of devices, such as MOSFET's, MESFET's, HEMT's, and so on, are constructed mainly by using capacitors and resistors together with a voltage-controlled current-source. For fitting the measured terminal behaviors of a device, negative capacitances are often used. In the above paper,¹ the authors tried to interpret the negative capacitance (NC) phenomenon theoretically in physics. However, we find some points in the above paper are arguable.

A. Definitions of Capacitance

For small-signal approximation, the relation between ac terminal current I and ac terminal voltage V can be expressed for a general two-terminal network as

$$I = YV = (G + jB)V. \quad (1)$$

where Y is the terminal total admittance in the discussed terminal, G is its real part, and B is its imaginary part. Then, the authors defined their capacitance from (1) letting

$$B = \omega C \text{ or } C = B/\omega \quad (2)$$

where ω is the operation frequency.

From the circuit point of view, (1) defines only the relation between the terminal current I and the corresponding terminal voltage V . If B is **always positive**, it represents an effective capacitive effect and an effective capacitance can be defined as (2). Generally, because the two-terminal network is a black box, one has **NO** detailed information about the **internal circuit types** and the **types of the circuit elements**. For this general network, it is possible that B has positive or negative values. Fig. 1 shows a general equivalent circuit of a black box. Now

$$Y = \frac{1}{Z} = \frac{1}{R + jX} = \frac{R}{R^2 + X^2} - \frac{jX}{R^2 + X^2} \quad (3)$$

and $I = YV = (G + jB)V$ with

$$G = \frac{R}{R^2 + X^2} \quad B = \frac{-X}{R^2 + X^2}. \quad (4)$$

If Z of the black box is a pure capacitive element, then $R = 0$, and $X = -1/\omega C$. Now the terminal behavior of the black box is purely capacitive. However, if $Z = j\omega L$, that is a pure inductive element, now $X = \omega L$ and

$$B = -\frac{1}{\omega L}. \quad (5)$$

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¹M. Ershov, H. C. Liu, L. Li, M. Buchanan, Z. R. Wasilewski, and A. K. Jonscher, *IEEE Trans. Electron Devices*, vol. 45, pp. 2196–2206, Oct. 1998.

Fig. 1. Terminal behavior of an equivalent circuit.

Fig. 2. R , L , and C series-parallel circuit.

It is **negative B**! However, it is **not** a **NEGATIVE CAPACITOR** which would be

$$C = -\frac{1}{\omega^2 L} \quad (6)$$

according to their definition (2).

B. Equation (22)

If the equivalent circuit of the black box in Fig. 1 has the structure shown in Fig. 2, its effective terminal admittance can be expressed as

$$Y = \frac{(\omega C)^2 R_c}{1 + (\omega C R_c)^2} + \frac{R_L}{R_L^2 + (\omega L)^2} + j\omega \left[C_o + \frac{C}{1 + (\omega C R_c)^2} - \frac{L/R_L^2}{1 + (\omega L/R_L)^2} \right] = G + jB. \quad (7)$$

The imaginary part of (7) has the same form as (22) of the paper. Where the authors defined a capacitor $C(\omega)$ depending on the working frequency. The imaginary part of (7) now can be either positive or negative, it represents only the terminal relationship between the terminal current I and the related terminal voltage V .

From the circuit point of view, if B is positive, the effective terminal behavior is capacitive, and if it is negative, the effective terminal effect is **INDUCTIVE**, and it **DOESN'T** mean that there is any **NEGATIVE** capacitor in the circuit. It is obvious that the sign of B depends on the parameters of C_o , C , L , R_c , R_L , and the operation frequency.

By selecting suitable values of the parameters C_o , C , L , R_c , R_L , it is very easy to obtain curves of $(B/\omega) \sim f$ which are the same as Fig. 7 in the paper. In Fig. 2, if we choose $R_L = 0$, from (7) we have

$$B = \omega \left(C_o + \frac{C}{1 + (\omega C R_c)^2} - \frac{1}{\omega^2 L} \right). \quad (8)$$

Because the circuit in Fig. 2 is just a L-C-R resonance circuit with resonance frequency f_o , if $f > f_o$, B is positive, and if $f < f_o$, it is **NEGATIVE**. That can explain in the literature why the so-called NC occurs only at lower frequency and in high frequency there is no NC phenomena.

Actually, from the circuit theory point of view, if a circuit is inductive, its B is negative and if B is positive, it means that the

circuit is capacitive. If the terminal behavior of a circuit shows that its B is going from negative to positive (or from positive to negative), the circuit is just a resonance one. We **cannot conclude** that the circuit element of the circuit is capacitor or inductor. In other hands, we can not REALIZE a circuit with physical negative capacitor.

I. CONCLUSIONS

The definition of capacitor from $I = (G + jB) V$ used in the paper is not correct. Using an R-L-C resonance circuit we can interpret the so-called NC, that is just an inductive effect. Instead of using the conventional R-C equivalent circuit model for a diode, we should use R-C-L resonance circuit as the equivalent circuit for the diode.

Author's Reply

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Z. R. Wasilewski, and A. K. Jonscher

The comment by Ma *et al.* [1] raises important questions concerning circuit modeling of semiconductor devices displaying negative capacitance (NC) phenomenon. Representation of the device as an equivalent circuit allows efficient simulation at the circuit level. Parameters of the equivalent circuit are obtained by fitting the circuit characteristics to the experimental data. Circuit representation provide the means to mimic the device behavior, but it very often fails to explain this behavior, because the detailed information on physical

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processes is not available on this level. The purpose of our paper¹ was the analysis of the general physical mechanisms underlying the NC effect in semiconductor devices. We proposed a convenient and physically sound approach to NC treatment based on transient current analysis, and pointed out typical mistakes involved in NC interpretation. The issues of circuit modeling of devices with NC were beyond the scope of our paper.

From the viewpoint of the phase relationship between ac current and voltage, NC corresponds to inductive behavior, i.e., positive inductance (as well as positive capacitance is equivalent to negative inductance). Therefore, devices with NC can be represented by equivalent circuits containing inductances (for example, an equivalent circuit for the model of NC of our paper [Eqs. (21) and (22)] was presented by Ma *et al.* [1]). However, such representation does not explain NC effect from the viewpoint of physics. It cannot identify the microscopic mechanisms of NC, and cannot provide the guidelines for NC suppression or enhancement. Such information can be obtained only from the detailed physical analysis on the microscopic level.

The definition of capacitance in terms of admittance in our paper, criticized by Ma *et al.* [1], is widely accepted in physics and electrical engineering [2]. Probably, the term "capacitance" (or "NC") is not very suitable to describe the inductive device behavior. However, most of the semiconductor devices have positive capacitance, and the term "NC" was introduced to describe a very rare, unusual situations when imaginary part of admittance is negative [for convention $\delta I, \delta V \sim \exp(i\omega t)$].

It should be pointed out that the real device behavior can be much more complicated than that of equivalent circuit of [1] (Fig. 2). In particular, this circuit cannot describe $1/f$ behavior of NC in QWIP's, which spans over three decades at low frequency. Also, NC can occur at high frequencies, contrary to a statement of the comment [1], due to the parasitic inductance of the measurement setup [3], [4].

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