The electron transit time is not the ultimate responsible for the high-frequency noise: The frontier between electronics and electromagnetism

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I. INTRODUCTION

It is generally believed (and found in many textbooks[1–4]) that the electron transit time is the ultimate responsible for the high-frequency noise behaviour of the state-of-the-art ballistic electronic devices. In fact, the constant progress in high-frequency applications during the last 50 years has been based mainly on the idea of reducing the electron transit time[1–4], either by scaling their lengths or introducing materials with higher electron mobility. In this conference, we argue that the ultimate responsible of the high-frequency noise is not the electron transit time, but a new shorter time related to the duration of the current peak detected on a particular surface, say S, while the electron is crossing the device.

It is well-known that the electron movement inside the device generates a time-dependent electric field $\vec{E}(\vec{r}, t)$ on a particular surface S. Such time-dependent electric field implies a displacement current on S. This displacement current, which is present even when the electron is not crossing the device, determines the duration of the current peak[5–7]. The total current, which includes the particle current density, $\vec{J}(\vec{r}, t)$, gives:

$$i(t) = \int_S \vec{J}(\vec{r}, t) \cdot d\vec{s} + \int_S \epsilon(\vec{r}) \frac{\partial \vec{E}(\vec{r}, t)}{\partial t} \cdot d\vec{s}, \qquad (1)$$

where $\epsilon(\vec{r})$ is the inhomogeneous electric permittivity. In the definition of the duration of the current peak due to an electron travelling along the device, there are scenarios where the exact transit time of the electron is not at all a relevant parameter. In addition, we will show that a proper understanding of the relationship between the electron movement and the displacement current opens new unexplored possibilities for the manipulations of the high-frequency performance of electronic devices.

II. DISPLACEMENT CURRENT AND TRANSIT TIME

Ramo[6] and Shockley[7], in the 30's, were the pioneers in determining how the high-frequency performance of electronic devices is related to the electron dynamics inside the active region. They showed that an electron moving with velocity $\vec{v} = \{v_x, 0, 0\}$ between two (infinite) metallic plates separated by a distance L_x generates a current peak in one of the plates equal to $i(t) = -q \cdot v_x / L_x$ during $0 < t < \tau$, being q the (unsigned) electron charge. The time-integral of the current during $\tau = L_x/v_x$ gives the expected transmitted charge $-q$. In this particular case, the relevant time for the current is effectively the electron transit time $\tau = L_x/v_x$. *Can we envision other scenarios where the displacement current collected on a particular surface is not related to the electron transit time?* Below, we answer positively to this question.

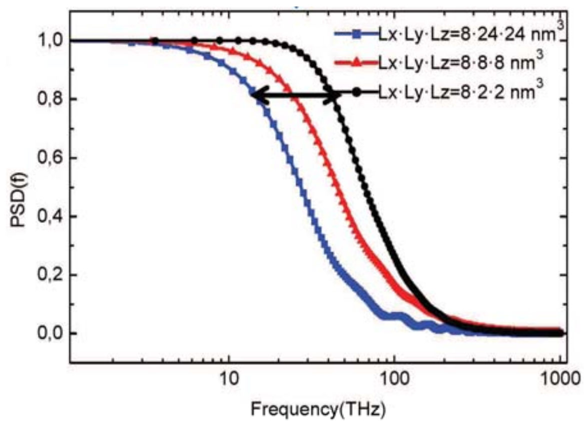

FIG. 1. *Power spectral density (PSD) of the current fluctuations (in arbitrary units) as a function of frequency for a GAA FET with different geometries (and identical channel length L_x) operating under DC conditions.*

To go beyond the previous Ramo-Shockley result is mandatory to deal with, at least, a three terminal device that ensures that the instantaneous current in the source is not equal to that in the drain, while still satisfying the instantaneous current conservation. For this reason, we consider the three terminal Gate-All-Around Field Effect Transistors (GAA FETs). In Fig. 1, we plot the power spectral density (PSD) of the current fluctuations for a particular GAA FETs. Numerical simulations for different geometries (L_x is the transport source-drain direction and L_y and L_z are the lateral directions) of this particular GAA FETs are shown in Fig. 1. We clearly see how the high-frequency cut-off frequency of current fluctuations is independent of the electron transit time $\tau = L_x/v_x$. A variation of an order of magnitude of the noise spectrum range can be achieved without changing the device active region $L_x = 8$ nm nor its (average) velocity v_x. For such particular FETs, the high-frequency performance can be improved without neither length scaling nor using materials with higher electron mobility[8].

We consider now the same device operating under AC conditions. The conventional small-signal admittance parameter model for the GAA FETs is drawn in Fig. 2. We compute numerical simulations of the gate and drain transients currents $i_1(t) = i_G(t) - i_G^{DC}(t)$

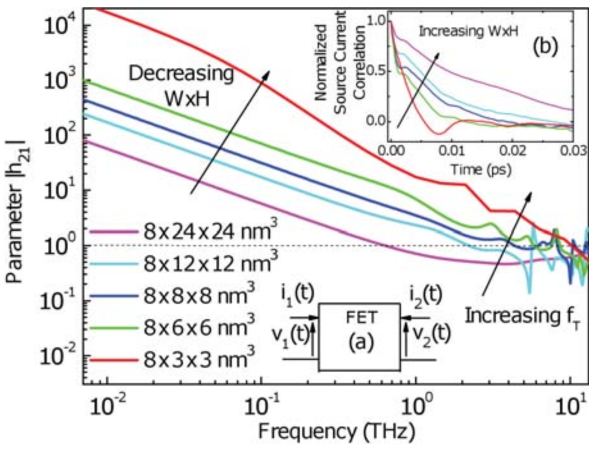

FIG. 2. *h_{21} parameters as a function of frequency for the volume $L_x \times L_y(W) \times L_z(H)$. (a) Two-port (admittance) small-signal circuit. (b) Source current autocorrelation with DC bias. The FET with larger lateral area does not satisfy the single band quantum wire requirement, but it is included to show the tendency of the results.*

and $i_2(t) = i_D(t) - i_D^{DC}(t)$, being $i_G^{DC}(t)$ and $i_D^{DC}(t)$ the DC value before the voltage step. A Fourier transform of $i_1(t)$ and $i_2(t)$ directly provides the small-signal admittance parameters $Y_{2,1}(f)$ and $Y_{1,1}(f)$. The intrinsic cut-off frequency, f_T, can be computed then as $|h_{2,1}(f_T)| = |Y_{2,1}(f_T)/Y_{1,1}(f_T)| = 1$. To see clearly the effect of the cross section area, we have presented the intrinsic cut-off frequencies in Fig. 2. We notice that for the same longitudinal length L_x, the cut-off frequency increases from $f_T = 0.62\, THz$ up to $f_T = 10.20\, THz$ when the later area is scaled down, as seen in Fig. 2. These results confirm that the geometry of the GAA FETs (for a fixed L_x) has a relevant role in their high-frequency behaviour. In order to confirm the role of the current pulse on the results, we present the correlations of the source current with DC bias for the previous FETs. The results in Fig. 2(b) clearly show that the larger the lateral area is, the wider the current temporal pulse[9].

III. WHERE IS THE FRONTIER BETWEEN ELECTRONICS AND ELECTROMAGNETISM?

In this conference we present an original strategy to optimize radio-frequency (or digital) performance of GAA FETs by modifying their lateral areas, without L_x scaling or mobility improvement. The ultimate reason of such improvement is that the transit time $\tau = L_x/v_x$ is no longer a limiting high-frequency factor for those GAA FETs where the lateral dimensions L_y, L_z are similar or smaller than their length L_x. A time shorter than $\tau = L_x/v_x$ controls their intrinsic signal and noise high-frequency performance.

The proper understanding of the relationship between the electron movement and the displacement current opens new unexplored possibilities for the influence on high-frequency electronic devices. Traditionally, electronics is based on the manipulation of the particle current (first term in Eq. (1)), while partially neglecting the displacement current (second term of Eq. (1)). On the contrary, electromagnetism is based on the manipulation of the displacement current due to variations of the electric (and magnetic) fields at scenarios where the particle current becomes practically irrelevant. For dimensions shorter than $L_x = 0.1\mu m$, the electromagnetic vector potential can be reasonably neglected at frequencies lower than around 100 THz. As a consequence, a new type of electronic devices, in the frontier between electronics and electromagnetism, is envisioned by controlling the shape of the displacement current (i.e. electric field) instead of the particle current (i.e. the electron charge).

ACKNOWLEDGMENTS

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