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Transfer matrix model of multilayer graphene nanoribbon interconnects

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ABSTRACT

A general, algorithmic and exact transfer matrix model is presented for multilayer graphene nanoribbon (MLGNR) interconnects that is based on multi transmission line method (MTLM). In the proposed transfer matrix formulation the effect of Fermi level shift in GNR layers is considered. Also the capacitive and inductive coupling between the GNR layers is regarded in this matrix model. Moreover, in order to get the precise results, the block number parameter for distributed property of the interconnects is proposed for the first time. The straightforward, general and algorithmic format of the proposed matrix model causes it to be used for different technology nodes and length of the interconnects. Moreover any variation in the physical parameters can be involved simply in this formulation. Using this matrix model, one can examine different analytical prospects such as Nyquist, Bode, and Nichols stability criteria, zero and poles and step time responses for on-chip MLGNR interconnects, implemented for integrated circuit applications. Also this matrix model can be used in circuit simulators such as HSPICE in order to simulate the VLSI-ULSI circuits. As the couple of examples, we have extracted Nyquist diagrams and step time responses for 10 nm, 14 nm, and 22 nm technology nodes. The results show that relative stability of MLGNR interconnects increases with increasing technology node and interconnect length. The results demonstrate a considerable difference between the responses obtained using traditional MLGNR interconnect formulation and the exact proposed matrix model.

1. Introduction

Recent developments in science and technology of graphene nanoribbons (GNRs) have stimulated up major interest in GNR potential applications, particularly as interconnects and transistors [1–3]. In a high-quality sheet of graphene, carriers' mean free path (MFP) can be as long as $\lambda = 1$ μm, the thermal conductivity can be as large as 3–5 × 10^3 W/mK, and it is capable of conducting current densities as high as 10^8 A/cm^2 [4–7]. Moreover, its electrical conductivity is a linearly increasing function of temperature beyond $T = 300$ K [8–11]. The major advantage of GNR over CNT is its more straightforward fabrication processes [12,13]. These extraordinary properties have made GNR as a potential material for signal and power interconnects or transistors. Depending on its geometry, GNR can be either metallic or semiconducting that is suitable for interconnects and transistors respectively [14–18].

While each GNR has desirable material properties, it suffers from an intrinsic ballistic (quantum) resistance that is independent of GNR's length [15]. Such a high intrinsic resistance leads to excessive delay for interconnects applications. On the other hand, multilayer GNRs with reduced equivalent resistance have been physically demonstrated to be suitable media for interconnects [15].

Interconnects made of GNRs can potentially be used either as local, intermediate, or global forms [14–16]. Performance of local (on-chip) interconnects are vital to the analog ICs designed especially for radio frequency (RF) applications [19–20]. In other words, any instability such as possible high overshoots/undershoots or high frequency fluctuations in the output responses of on-chip interconnects used in a RF-IC can deteriorate the IC performance or its logic. In order to analyze the performance of GNRs designed for such on-chip applications, one needs to evaluate their stabilities and time domain responses precisely.

In recent years, most of the feasibility studies towards the use of GNRs as interconnects medium have been devoted to physical prospects [4–7], technological aspects [12,13] and some physical-based circuit modeling of GNRs [21–30].

In [22] the effect of electrostatic or chemical doping is included in order to increase charge density in graphene. In this paper the authors model the electrostatic doping in multilayer graphene interconnects by self-consistently solving Poisson's equation. However distributed nature of the interconnect is not considered completely in this model. In [24] propagation delay is found for different interconnect lengths and widths by using equivalent single-conductor (ESC) model for GNR interconnects. In the assumed ESC model the electrostatic and magnetic coupling between the graphene layers are not considered. Moreover

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tunneling between the adjacent graphene layers is not considered in this model. Also in [26] the authors have analyzed and compared the power, delay, and bandwidth performance of Cu and doped MLGNR using an equivalent single conductor model. The effect of rough edge defects of graphene ribbons has been included in this analysis. However scattering resistance in the graphene circuit model has included the edge roughness and there is no need to reconsider this effect again. In [27] the authors propose analytical time domain models for side contact and top contact MLGNR interconnects. They have used some physical insights about the transient behavior of these MLGNRs. This paper also has used ESC model in its analysis. In [30] an ESC model based on a finite-difference time-domain (FDTD) technique has been proposed. The performance of quasi-transverse electromagnetic model of interconnects has been analyzed for both voltage-mode signaling (VMS) and current-mode signaling (CMS) schemes. In this paper the interaction of the graphene layers with each other are not considered. Moreover all layers have been assumed to be same.

Briefly in the most of the aforementioned researches there are five important drawbacks:

- They have not used the accurate distributed circuit model and the distributed nature of the interconnect is not considered correctly.
- All of the graphene layers have been assumed to be same, while the outer layers have different physical parameters due to the screening effect.
- The exact coupling between the graphene layers is not considered. Between the layers there are magnetic and electrostatic coupling. Also between the adjacent layers there is tunneling effect.
- ESC model is not a suitable and exact model to analyze the MLGNR interconnects. MTL (Multi Transmission Line) model includes more details.
- There is not any algorithmic method to calculate a transfer function that can be used in Matrix based simulators like SPICE.

Transfer function derivation and stability analysis of MLGNR and CNT bundle interconnects with assuming them as a single transmission line (STL) have been done by Nasiri et al. using 4th order Pade's approximations [31] and Fathi et al. using 4–6th order Pade's approximations [32,33] respectively. Their mathematical derivations are very tedious and the results have not enough accuracy because the distributed nature of the interconnect is not treated precisely with only 4th and 6th order transfer function. Also the coupling between GNR layers and Fermi level shift or dielectric surface charge effects are not considered in their derivations. In fact, there is not any exact, general, algorithmic, and yet simple formulation for transfer matrix of MLGNR interconnects. So one cannot examine precisely different analytical prospects such as Nyquist, Bode, and Nichols stability criteria, zero and poles, step time responses, and etc. for on-chip MLGNR interconnects, implemented for integrated circuit applications.

In this paper we have two important goals. At first, we present an exact matrix model for MLGNR interconnects based on multi transmission line method (MTLM) that can be used in anywhere. Fermi level shift for different GNR layers because of dielectric surface charge effects is considered in this formulation. Also the capacitive and inductive coupling between GNR layers is involved in this formulation. Importantly the block number parameter for distributed circuit portion of the interconnects is proposed for the first time so that the distributed nature of the interconnects implied exactly. Another important feature of the proposed matrix model is its straightforward, general and algorithmic format. It can be used for different technology nodes and length of the interconnects. Moreover any variation in the physical parameters can be involved simply in this matrix model. Also it can be used in circuit simulators such as HSPICE - that are based on matrix calculation - in order to simulate the VLSI-ULSI circuits.

Secondly, we have used the proposed matrix model for analyzing Nyquist stability criterion and step time response for on-chip MLGNR interconnects as a couple of examples. We have examined the model parameters for 10 nm, 14 nm, and 22 nm technology nodes in GNR interconnects. Also the effect of increasing MLGNR interconnects length on Nyquist stability and step time-responses are investigated. The large difference between the responses of the traditional formulations and proposed matrix model is illustrated to emphasis the importance of this research.

2. General model

2.1. Model structure

Fig. 1 illustrates a schematic representation of MLGNR interconnect of length *l*, width *W*, and height *H*. It consists of *N* identical GNRs of equally spaced layers (*d*). The interconnect spacing from the ground plane equals *y*. The total number of GNRs, ν, equals to H/d.

For convenience, layers of a given MLGNR are labeled by positive integers (i.e., $i = 1, 2, 3, \ldots, \nu$).

2.2. Model parameters

In order to obtain the number of conducting channels in each GNR, one can add up contributions from all electrons in all n_C conduction sub-bands and all holes in all n_V valence sub-bands [23,31]. It is important to note that the effect of charges accumulated at the substrate surfaces causes the Fermi level shift. The Fermi level shift decreases exponentially as the layer is away from the substrate, and becomes negligible after the fifth layer [34]. For the *i-th* ≤ 4 layer, the Fermi level, E_F, decays by $e^{-\delta i/\beta}$, where $\delta = 0.34$ nm and $\beta = 0.387$ nm [34]. So for *i-th*

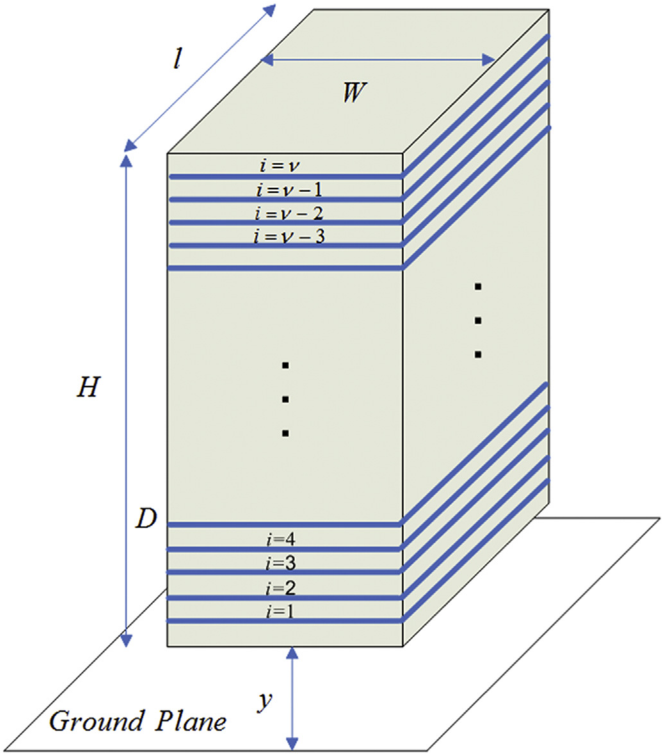

Fig. 1. Schematic representation of a MLGNR interconnect of dimension $l \times W \times H$, consisting ν identical MLGNRs of equally spaced layers (d). The layers $i = 1$ to 4 and $i = \nu$-3 to ν see the ionized impurity of the substrate.

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