Microelectronics Journal 78 (2018) 101–113

Contents lists available at ScienceDirect

Microelectronics Journal

journal homepage: www.elsevier.com/locate/mejo

Bandwidth expanding technology for dynamic crosstalk aware single-walled and multi-walled carbon nanotube bundle interconnects

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ARTICLE INFO

Keywords:
Carbon nanotube
Dynamic crosstalk
Inductive peaking technology
Frequency response
3-dB bandwidth
Step response

ABSTRACT

In view of scarce bandwidth resources, an inductive peaking technology is used to expand 3-dB bandwidth of the coupled single-walled and multi-walled carbon nanotube bundle interconnects, which take the dynamic crosstalk into account. Based on decoupling technique and ABCD parameter matrix approach, the transfer function of the decoupled victim line at global level of 14 nm technology node is derived to analyze and compare the bandwidth performance under different length, diameter, temperature and load resistance conditions. It is obvious that 3-dB bandwidth can be effectively expanded by adding peaking inductance to the load irrespective of phase-mode. However, the bandwidth will remain nearly unchanged once the adding inductance reaches a certain extent. Furthermore, the overshoot and undershoot in the step response will be caused with the further increase of the peaking inductance. On the other hand, it is shown that the value of 3-dB bandwidth at out-of-phase mode is much smaller than that at in-phase mode under the same condition.

1. Introduction

As the feature size continues to scale down, the conventional copper material based interconnects in VLSI circuits will suffer from serious reliability problems, such as the increasing resistivity, electro-migration and current capacity issues [1,2]. In view of so many limitations, it is extremely significant to explore an emerging material to realize next generation on-chip interconnects. As soon as carbon nanotubes (CNTs) were discovered, they aroused a great deal of research interest in nanometer regime because of their unique mechanical, electrical and thermal properties [3,4]. Depending on different chiralities, CNTs can be either metallic or semiconducting [5]. However, only the metallic CNTs play a major role in an interconnect. CNTs can be classified as single-walled CNT (SWCNT) and multi-walled CNT (MWCNT) based on the rolled up graphene structure [6]. Compared with copper material, CNTs have several micrometer long mean free path (MFP) and lower resistivity. Moreover, CNTs can carry a higher current density of the order of 10^{10} A/cm^2 without any damage [7,8].

So far, a number of significant investigations of CNT interconnects have been done. The equivalent circuit of a CNT was firstly established based on the Lüttinger liquid theory [9,10]. However, CNT bundle is more preferred in the practical interconnect application due to larger intrinsic resistance of an isolated CNT. Then the transmission line model of CNT bundle interconnect was proposed to describe the electrical propagation characteristic [11,12]. In addition, the performance of CNT interconnect has been widely reported. Based on the ABCD parameter matrix approach, Fathi and Zhao et al. investigated the step response, delay and relative stability of CNT interconnects [13,14]. Nevertheless, the existing coupling noise in practical CNT bundle interconnects can not be ignored due to the technology scaling. Moreover, with the increasing clock frequency, inductive crosstalk becomes more and more important and hence needs to be taken into consideration [15]. Kumar et al. analyzed the effects of the functional and dynamic crosstalks on the transient response and delay [16]. Also, the thermal variations caused by the temperature in the integrated circuit have a considerable influence on the performance of CNT interconnect. Singh and Raj proposed the temperature-dependent model of SWCNT and MWCNT bundle interconnect at nanoscaled technology nodes [17]. At the same time, the effects of temperature on signal delay, power dissipation and power delay product were estimated.

At present, most discussions about CNT interconnects focus on the performance in the time domain. In addition, the frequency domain characteristics are also vital factors in integrated circuit design. 3-dB bandwidth that represents the capability of data transmitting plays a key role in the performance of the circuit. Majumder and Alam et al. proposed the closed-form expression of 3-dB bandwidth by using a

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https://doi.org/10.1016/j.mejo.2018.05.015
Received 16 January 2018; Received in revised form 23 April 2018; Accepted 25 May 2018

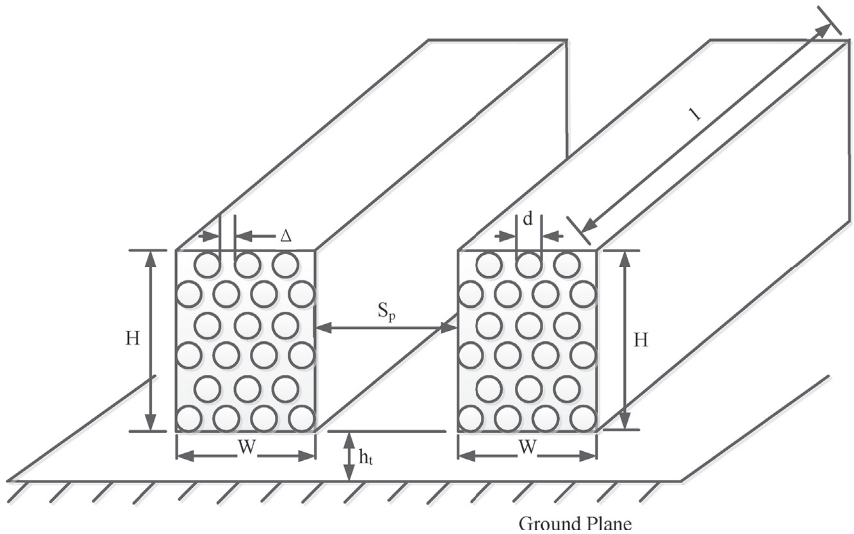

Fig. 1. The geometry of two coupled SWCNT bundle interconnects above the ground plane.

simplified second-order approximation of the transfer function [18,19]. For any system, the higher the bandwidth is, the less time it takes to transmit a certain number of datas [20]. However, in nanometer regime, some factors bound to the technology may result in serious bandwidth problems. Especially for global interconnect, the bandwidth significantly drops due to the longer length [21]. Thus, rare bandwidth resources in high speed and high data rate transmission systems need to be efficiently used. Given this situation, how to expand the bandwidth has been considered as an important issue, which deserves to be discussed in the practical application. However, to the best of our knowledge, till date few researches have focused on the bandwidth expanding method for CNT interconnects considering crosstalk. In Ref. [22], inductive peaking technology was used to enhance 3-dB bandwidth of SWCNT bundle interconnect without considering the impacts of other interconnects. However, due to the technology scaling, crosstalk will be a major concern and cannot be avoided in future nano integrated circuits. Especially, when fabricated at smaller technology nodes, CNT interconnects will suffer from the unwanted crosstalk because of the electromagnetic coupling between two or several neighboring interconnects. Therefore, more work in the area still needs to be done. In view of the concept of inductive peaking [23,24], this paper presents the modeling of the coupled SWCNT and MWCNT bundle interconnects considering dynamic crosstalk neglected in the previous work to expand the bandwidth.

The novel contributions are evaluated below:

(1) As one of basic techniques for expanding bandwidth, when inductive peaking technology is used to enhance 3-dB bandwidth of SWCNT bundle interconnects, the dynamic crosstalk from the nearby signal line is taken into account, including the in-phase crosstalk and out-of-phase crosstalk.
(2) Besides SWCNT bundle interconnects, this paper also investigates the effects of the inductive peaking technology on the bandwidth of MWCNT bundle interconnects.
(3) Compared with two line coupling, multiple line structure all exists in practical applications. Thus this paper also takes three line coupled interconnects into consideration.

The remainder of this paper is organized as follows. Section 2 establishes the equivalent circuit model of the coupled SWCNT and MWCNT bundle interconnects using inductive peaking technology. In Section 3, the analytical expression of transfer function at different phase-modes is derived by using decoupling technique and ABCD parameter matrix method, which is used to obtain the implicit function of 3-dB bandwidth. The results and discussions under different conditions are presented in section 4. At last, the paper draws a conclusion in section 5.

2. Proposed model

2.1. SWCNT bundle interconnects

As depicted in Fig. 1, a pair of coupled SWCNT bundle interconnects in parallel of space S_p are placed above the ground plane at a same distance h_t. Both interconnects have the same width W, length l and height H. In this figure, Δ is the distance between two neighboring isolated SWCNTs, which is considered as Van der Wall's gap of 0.34 nm [25]. d is the tube diameter. The total number of metallic nanotubes (N_{CNT}) for a bundle interconnect is primarily dependent on the physical parameters W, H, d and Δ, which can be expressed as [26],

$$N_{CNT} = P_m(N_W N_H - [N_H/2]) \tag{1}$$

$$N_W = \left[\frac{W-d}{d+\Delta}\right] + 1 \tag{2}$$

$$N_H = \left[\frac{2(H-d)}{\sqrt{3}(d+\Delta)}\right] + 1 \tag{3}$$

where, N_W and N_H represent the number of SWCNT in horizontal and vertical directions, respectively. P_m is the metallic CNT percentage in the bundle. $[\cdot]$ means that only the integer part for a decimal is considered.

Based on the transmission line theory, Fig. 2 presents the equivalent circuit of two line coupled SWCNT bundle interconnects, which are driven by the same drivers with output resistance R_{tr} and capacitance C_{out}. In practice, as it has different equivalent resistance and capacitance values for linear and saturation regions of operation of MOS transistors, appropriation of nonlinear CMOS driver gate as resistive and capacitive elements gives rises to an inaccurate output. The practical CMOS driver which is characterized by Alpha-power law and nth power law model has been used for the accurate modeling of interconnect [27–30]. Here, in order to analyze the bandwidth enhancement performance, we need to obtain the analytical transfer function of interconnects. However, considering the complexity of practical CMOS driver, we still approximate it as lumped resistance and capacitance. In the middle of the model, the circuit mainly consists of the lumped and distributed elements. In general, the load is modeled as a capacitance in most papers. For the sake