Electromagnetic Compatibility Concepts at Nanoscale

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Abstract—**We present a new concept of nano electromagnetic compatibility (EMC) for nanoelectronics, based on the synthesis of the classical electrodynamics and quantum transport theory in nanostructures. We demonstrate that classical EMC concepts such as coupling, shielding, and impedance matching, should be reconsidered taking into account quantum correlations and tunneling, as well as spin-spin and dipole-dipole interactions. As a result equivalent circuits will contain additional elements of quantum nature, which significantly influence the EMC. The main concept is illustrated by the example of carbon nanotube based interconnects. We also briefly discuss the major challenges in nanoEMC and its future perspectives.**

Keywords - electromagnetic compatibility, spurious coupling, quantum effects, ballistic effects, nanoelectromagnetics

I. INTRODUCTION

The present-day stage of the development of electronics is characterized by intensive penetration of nanotechnologies into the production processes. As a result, new frequency ranges, from terahertz to optical, are actively explored for the information transmission and processing. The process is accompanied by the growth of the level of integration and the decrease of the operation power. It means that the EMC on the nanoscale is expected to become a complicated and acute problem in the nearest future. Although today it is too early to speak about the development and production of multicomponent and multifunctional nanoelectronic systems (currently we deal with the formation of the component basis of nanoelectronics[1]), such systems will appear very soon raising the nanoEMC problem to the full extend. We can conclude that the EMC basic principles, as applied to nanoelectronics, must be drastically modified with respect to their macroscopic counterparts. The main reasoning for that is that classical EMC is completely based on the macroscopic electrodynamics [1], while the operation of nanoscale electronic devices is strongly influenced by the quantum-mechanical effects due to the spatial confinement of the charge carrier motion. Present talk aims at the illustration of this statement. Certainly, here we give only a short qualitative introduction to the nanoEMC leaving the detailed fundamental analysis for the future. So, the main message of the present talk is to attract attention of the researchers from different areas, such as physics and technology of semiconductor nanostructures, micro- and nanoelectronics, electrical engineering, etc., to nanoEMC problem stimulating its analysis and practical use in the development of high-frequency nanoelectronic devices and systems.

Electromagnetic Compatibility allows a system to operate successfully, in spite of the unwanted electromagnetic couplings between its elements (assemblies, units, trace lines, etc.) and external interference [2-4]. The main EMC issues are the signal integrity, the coupling with environment, and the unwanted emissions.

On the macrolevel, electronic systems like on-board electronics, equipment cases, and printed circuit boards (PCBs) contain elements like RF modules, electronic devices, cables, and connectors, which interact according to the laws of classical electromagnetics. Therefore, the unwanted coupling is usually described by equivalent mutual capacitances and/or inductances between the elements. The EMC issues may also be related to the influence of the external electromagnetic fields or to non-ideal boundary conditions, like in the case of impedance mismatch [5,6].

It should be emphasized that at the macroscale the electronic systems and devices can be scaled down (to the order of 0.1 μm) following simple scaling rules, without any significant change in their performance. E.g., the capacitance

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and inductance for a simple line made of a conductor of radius *a* at a distance *d* from the ground plane depend on the *a/d* ratio, so they remain unchanged as long as the two dimensions are equally scaled down. Following this approach, the designers of Integrated Circuits (ICs) have successfully established scaling rules, and the EMC solutions have been successfully implemented for the scaled down systems.

However, it is no longer possible to rely on such approach below the submicron scale, because quantum phenomena have to be taken into account. For instance, the capacitances and inductances of nanocircuits contain additional components of the quantum nature, which do not explicitly depend on the geometrical parameters and, thus, do not follow the above-mentioned scaling rules.

On the nano-level, the size of nanostructures in one or more dimensions is comparable to the electron de Broglie wavelength at room temperature. Consequently, a number of quantum effects (electronic band structure, energy spectrum discretization, phonon spectra, ballistic charge propagation, few-body correlation effects, tunneling, resonant scattering, stress/strain, interface effects, etc.) have to be taken into account.

Such quantum effects give these nanoscale systems a behavior which usually is different from that observed at the macroscale, for instance, in terms of sensitivity of the electrical performance to frequency, size, and temperature change. Consequently, the classical EMC concepts like coupling, shielding, and matching, should be reconsidered, along with the classical solutions to such issues.

In the next section, we formulate the main issues concerning the EMC modeling at the nanolevel, while suggesting a way to couple classical Maxwell equations to quantum mechanics. Section III deals with an example of application of this approach to EMC problems in interconnects. Finally, we briefly discuss major challenges of combining nanoscale physics with macroscopic electrodynamics and introduce the concept of nanoelectromagnetics.

II. NANOEMC MODELING

As pointed out above, the interaction between the elements in nanoEMC is not purely electromagnetic, since certain specifically quantum phenomena such as tunneling, spin-orbit interaction, and various many-body effects including dipole-dipole and spin-spin interactions, as well as Rabi waves start to play an essential role. The above mentioned quantum interactions lead to the appearance of multiparticle entangled states, which are proposed to be used for creating digital nanoelectronics (qubits of various types [7]). These interactions, which are considered to be essential to the operation of the prospective nanoelectronics devices, cannot be disregarded as parasitic factors defining characteristics of nanoEMC and have to be taken into account in any practical design. This is why a bridge between computational electrodynamics and quantum physics is needed. It is necessary to consider self-consistently the Maxwell equations and the quantum dynamic treatment of the charge carriers.

State-of-the-art achievements of molecular electronics allows utilization and manipulation of small collections atoms and molecules, such as semiconductor heterostructures, quantum wells, wires and dots [8-10], different forms of nanocarbon (spherical fullerenes, graphene [11], carbon nanotubes [12]), noble metal nanowires, organic macromolecules and organic polymers. The development of nanoelectronics stimulated a formation of nanoelectromagnetism [13, 14] – a novel branch of applied science related to the interaction of electromagnetic radiation with nanostructures and based on the synthesis of classical electrodynamics with quantum transport theory and quantum chemistry. For the latter, the most promising analysis tool appears to be the S-matrix approach based on the Landauer-Buttiker concept [15]. This self-consistent description results in a total S-matrix with a block-diagonal structure containing both free-fields and free electrons' sub-matrices, as well as field-electron interaction components.

This situation is different from the classical electron transport model (for instance Drude model for conductors), where charges are treated as atoms in a gas which undergoes a random thermal motion with an average thermal velocity and a field induced motion, characterized by the drift velocity. On the contrary, at the molecular or atomic scale a quantum mechanical description is needed, since the transport is characterized by the wave-like behavior of the electrons with possible tunneling. A Schrödinger/Maxwell model would take rigorously into account the quantum nature of the transport, but would easily lead to unaffordable numerical problems when increasing the number of carriers. Anyway, for a class of applications of great interest, a third approach can be followed, based on a *semi-classical transport model*. In this model, the electrons are regarded as classical particles moving with collisions in a spatially periodic potential, according to the Boltzmann transport equation. Electrons behave like particles that are unable to tunnel through barriers. In the collision events, the electrons can scatter inelastically, and so the kinetic energy of an incident particle is not conserved. This third approach may be applied, for instance, to model nano-interconnects, made of 1-D conductors (e.g., nanowires or carbon nanotubes) whose cross-section sizes are typically large enough (at least 1 nm in the quantum confined directions) to have local crystal structures [16, 17].

III. AN EXAMPLE OF NANOSCALE EMC MODELING: TRANSMISSION LINE MODEL FOR INTERCONNECTS

Conventional materials like copper are inadequate to meet the performance requirements for the interconnects which will wire the future integrated circuits made of nanotransistors with gate length equal or less than 10 nm. For instance, such interconnects will be required to sustain current densities on the order of MA/cm^2, leading to a volumetric heat production on the order of 10^3-10^4 W/mm^3. For this reason, new interconnect materials are proposed like metallic Nanowires (NWs), Carbon Nanotubes (CNTs) or Graphene Nanoribbons (GNRs). They can all be regarded as *one-dimensional* (1-D) materials, because of the negligible dimensions of the transverse cross section, compared to their lengths. The 1-D systems have two quantum confined directions, while still leaving one unconfined direction for the electrical conduction. Typical operating frequencies are supposed to be up to 0.1 THz. The above assumptions allow using the semi-classical approach described in the previous section, which leads to simple circuit models in the framework of the Transmission Line (TL) theory. For instance, let us consider the interconnects in Fig. 1, each made of a single conductor (CNT or NW in Fig. 1a, and GNR in Fig. 1b) above an infinite perfectly conducting ground. These interconnects may be described by the simple lossy TL model (Fig. 1c), with distributed R, L, and C elements and lumped terminal resistances which take into account the contact effects [17, 18].

The TL per-unit-length parameters are a combination of the classical parameters (electrostatic capacitance C_e and magnetostatic inductance L_m) and quantum ones:

$$R \approx \frac{\nu L_k}{1+C_e/C_q}, \quad L=\frac{L_k+L_m}{1+C_e/C_q}, \quad C=C_e, \qquad (1)$$

with ν being the collision frequency. Here, *kinetic inductance* L_k and quantum capacitance C_q [16, 17] strongly affect the electrical performance and thus the EMC behavior of such interconnects. For instance, typically $L_k/L_m \approx 10^3 \div 10^4$, and $C_e/C_q << 1$, which means that the propagation velocity is no longer given by $1/\sqrt{C_e L_m}=1/\sqrt{\varepsilon\mu}$, but is about $1/\sqrt{C_e L_k}$, that is about two orders of magnitude smaller. A negative consequence of this slowing down is the shift towards lower values of the resonance frequencies of such lines, which limits the frequency range where they can be practically used. Nevertheless, a positive consequence of the dominance of the kinetic inductance over the magnetic one is the low sensitivity of such interconnects to high-frequency effects like skin effect or proximity effects.

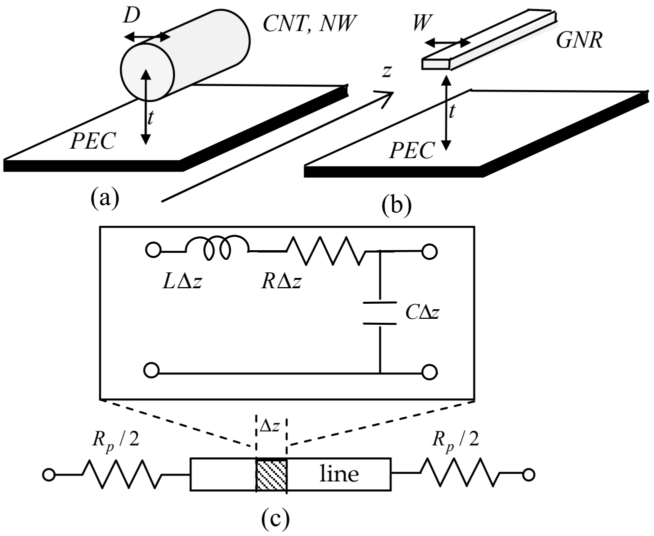

Fig. 1. A simple interconnect made by: (a) a NW or a CNT, and (b) by a GNR, above an ideal ground; (c) transmission line model.

This is due to the fact that L_k does not depend on frequency, whereas L_m starts to depend on frequency as the frequency increases, due to the modulation of the magnetic field penetration depth. Fig. 2 shows the distribution of the current density computed at 200 GHz in a wire made of conventional copper and in a bundle of multi-walled CNTs [19]. The current density for the CNT case is almost uniform, which mitigates not only many EMC problems (like the possible unwanted interaction with adjacent wires), but also the thermal problems related to the presence of non-uniform Joule heat production or hotspots.

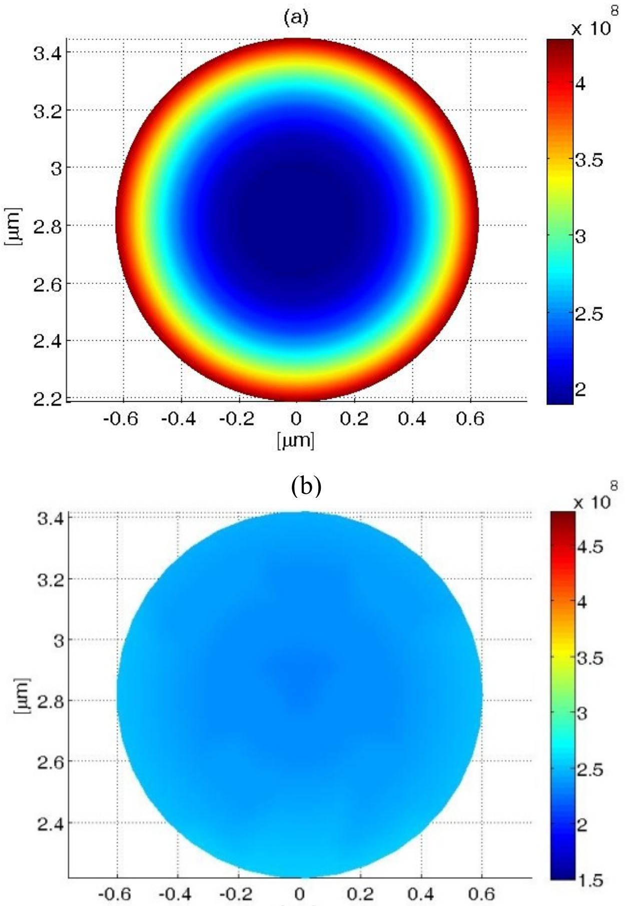

Fig. 2. Distribution of the current density (in MA/cm^2) in the cross section of a wire with a diameter of 1.2 μm at 200 GHz made of (a) copper and (b) a bundle of multi-walled CNTs.

IV. CONCLUSIONS AND PERSPECTIVE WORK

This paper summarizes the proposed general concept of nanoEMC, in which classical EMC issues are deeply changed due to the presence of quantum phenomena. The first examples of modeling nanoEMC problems are given, but many challenging problems are open and require further work.

Some of such challenges are related to the computational burden. The circuits containing nanoscale components have a giant level of integration on the order of 10^7-10^8 elements. The presence of many parasitic cross-links (the number of which significantly exceeds the number of system elements) is a major challenger for any realistic noise estimates. Despite the possibility of the element clustering, mathematical modeling of these cross-links (in the way similar to the macroscopic systems' modeling [2,5,6]) presents significant computational challenges.

Another example of challenging problem is the correct definition and modeling of the nanoscale coupling. In classical macroscale EMC, the crosstalk is modeled in terms of the currents and voltages induced in a given electronic device by all neighboring elements. Due to the weakness of the interactions, the partial currents responsible for the influence from the different elements are added. These currents and voltages are connected with each other by cross-conductances (or mutual capacitances and inductances). This approach is no longer valid in the nanoEMC. A single surface plasmon quantum does not induce current and voltage, but transfers power to the neighboring elements. Indeed, the observed voltages and currents are proportional to the expectation values of the creation and annihilation operators $<a^{\pm}>$, which are zero for a single Fock state, whereas the energy is proportional to $<a^{+}a^{-}>$ which is not zero since $<a^{+}a^{-}> \neq <a^{+}><a^{-}>$). The interaction of mesoscopic quantum objects is based on the theory of open systems [20]. This theory has various formulations, whose central point is usually a concept of reservoir [20]. However, this concept seems to be unsuitable for the nanoEMC, since the reservoir is assumed to influence the system, whereas the system is assumed to have no influence on the reservoir, which is not the case for the nanoEMC where the inter-element interactions represent the most essential issue. In our opinion, this issue can be resolved by using the theory of general susceptibility [21]. Its applicability is restricted by the relatively weak interaction limit; however, this is the most practically interesting limit in the nanoEMC. In this limit, the essential role is played by the spatial and temporal correlators of the first and second orders. The frequency spectra of cross-integrations are calculated as Fourier transforms of corresponding correlators [22]. These spectra are expressed through the cross-susceptibility, via the Kubo formula [22].

A third challenge in the nanoEMC is the introduction of generalized susceptibilities of various nanoelectronic elements and the derivation of efficient computational algorithms, such as for instance the fast integral equation based techniques [23]. The use of generalized susceptibilities to represent the complex conductivities of lumped circuits is well-known [24]. More recently [25], it was shown that radiation pattern of quantum antennas can also be expressed in term of generalized susceptibilities. We propose to use them for interconnects, waveguides, resonators, etc. It should be noted that the generalized susceptibilities of nanostructured elements of various types belong to the general class of physical quantities called kinetic coefficients, which obey general Onsager symmetry rules [24]. This helps to identify immediately a range of effects that are important for the nanoEMC, like the quantum nonreciprocity [25] which does not have any classical analogs.

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