Abstract—Graphene nanoribbons (GNRs) are considered as a prospective interconnect material. A comprehensive conductance and delay analysis of GNR interconnects is presented in this paper. Using a simple tight-binding model and the linear response Landauer formula, the conductance model of GNR is derived. Several GNR structures are examined, and the conductance among them and other interconnect materials [e.g., copper (Cu), tungsten (W), and carbon nanotubes (CNTs)] is compared. The impact of different model parameters (i.e., bandgap, mean free path, Fermi level, and edge specularity) on the conductance is discussed. Both global and local GNR interconnect delays are analyzed using an RLC equivalent circuit model. Intercalation doping for multilayer GNRs is proposed, and it is shown that in order to match (or better) the performance of Cu or CNT bundles at either the global or local level, multiple zigzag-edged GNR layers along with proper intercalation doping must be used and near-specular nanoribbon edge should be achieved. However, intercalation-doped multilayer zigzag GNRs can have better performance than that of W, implying possible application as local interconnects in some cases. Thus, this paper identifies the on-chip interconnect domains where GNRs can be employed and provides valuable insights into the process technology development for GNR interconnects.

Index Terms—Armchair graphene nanoribbon (ac-GNR), carbon nanotube (CNT), conductance, delay modeling, graphene nanoribbon (GNR), intercalation doping, specularity, very large scale integration (VLSI) interconnects, zigzag GNR (zz-GNR).

I. INTRODUCTION

Graphene nanoribbons (GNRs) have been recently proposed as one of the potential candidate materials for both transistors [1] and interconnects [2]–[4]. GNRs are obtained by patterning graphene, which is a flat monolayer of carbon atoms tightly packed into a 2-D honeycomb lattice, and is a basic building block of carbon nanotubes (CNTs), GNRs, graphite, etc. [5], as shown in Fig. 1.

A. Basic Properties

Both GNRs and CNTs can conduct much larger current densities than Cu (a traditional interconnect material), due to their strong sp² hybridized bonds, and the absence of severe reliability problems that plague Cu, particularly for future interconnect geometries [7]–[11]. The thermal conductivities of GNRs and CNTs are also much larger than that of Cu [14]–[16]. Moreover, compared to Cu, both GNRs and CNTs have large carrier mean free paths (MFPs), which lead to large electrical conductance [18]–[20]. However, GNRs are believed to be more controllable from a fabrication point of view. This is due to the planar nature of graphene, which can be patterned using high-resolution lithography. The properties of GNRs, Cu, single-walled CNTs (SWCNTs), and multiwalled CNTs (MWCNTs), relevant to interconnect applications, are listed in Table I.
To comprehend the outstanding electrical and thermal properties of GNRs and CNTs, it is important to understand the electronic band structure of graphene. According to the tight-binding model [24], graphene is a semimetal or a zero-gap semiconductor, with a linear energy spectrum of \( E = \pm \hbar v \Delta k / 2 \pi \) near the Dirac points [Fig. 2(a)], where \( \Delta k \) is the distance from the Dirac points to any point in the \( k \) space, \( \hbar \) is Planck’s constant, \( v_f = \sqrt{3 \pi \gamma a / \hbar} = 10^6 \text{ m/s} \) is the Fermi velocity, where \( \gamma = 3 \text{ eV} \) is the overlap integral between nearest neighbor \( \pi \)-orbitals, and \( a = 0.246 \text{ nm} \) is the lattice constant [25]. Due to the linear energy dispersion near the Dirac points, the charge carriers in graphene mimic relativistic particles with constant magnitude of \( v_f \), which are called massless Dirac Fermions. Due to the limited width of GNRs, they are confined 1-D structures: wave function vanishes at two edges. Thus, the transverse wave vector in GNR is quantized with separation of \( \pi / w \) (\( w = i \lambda / 2 \) or \( k = i \pi / w \), where \( i \) is an integer, and \( \lambda \) is the wavelength), where \( w \) is the width of the GNR. As a result, armchair GNRs (ac-GNRs) [Fig. 2(b)] can be either metallic (the transverse wave vector with respect to the Dirac point, \( \Delta k_{\text{transverse}} = n \pi / w \), where \( n \) is an integer; note that when \( n = 0 \), \( \Delta k_{\text{transverse}} = 0 \), implying that the zeroth subbands pass through the Dirac points) or semiconducting \( \Delta k_{\text{transverse}} = (n + 1/3) \pi / w \) or \( \Delta k_{\text{transverse}} = (n - 1/3) \pi / w \), depending on the number \( N \) of hexagonal carbon rings across the width: metallic when \( N = 3m - 1 \) and semiconducting when \( N = 3m + 1 \) [Fig. 2(d) and (e)] [26]. In comparison, zigzag GNRs (zz-GNRs) are always metallic and independent of \( N \). However, the electronic states of zz-GNRs are more complicated. Particularly, the zz-GNRs have the “dispersionless band” or “zero-mode,” which originates from the edge states [26]–[28] [Fig. 2(f)]; almost flatband appears within the region of \( 2 \pi / 3 < |k_{\text{a}}| \leq \pi \). Note that for the same \( w \), the \( N \) of ac-GNRs is approximately \( \sqrt{3} \) times larger than the \( N \) of zz-GNRs due to the nature of the honeycomb lattice. It should also be noted that the band structure of the monolayer graphene can be strongly affected by the substrate (e.g., SiO\(_2\) substrate with O-termination and without H-passivation) [29]. It is assumed in this paper that the graphene is deposited onto a proper substrate so that the tight-binding model is valid. Furthermore, for the case of multilayer GNRs, the substrate has negligible impact on the layers that are above the first few layers.

B. GNR Fabrication Methods

As mentioned earlier, the interest in GNRs is mainly due to their deemed patternability to produce metallic or semiconducting structures on demand. Various methods for fabricating GNRs are being pursued, but difficulties also exist in those methods. Carbon films have been demonstrated in dynamic random access memory trench capacitors using the chemical vapor deposition method [30], but the grown films are not single-crystal graphene films with ultrahigh electrical conductivity. Although thermal decomposition of single-crystal (0001) 6H-SiC or 4H-SiC can produce thin graphene films [31], [32], this approach requires single-crystal substrates and high temperatures, which is not suitable for interconnects due to the relatively low back-end thermal budget (~400 °C) in integrated circuit fabrication technologies. Graphene can also be mechanical exfoliated from graphite and deposited onto an insulating substrate [33], but this approach is uncontrollable for massive fabrication. In [22] (Fig. 3), graphene is segregated by dissolving carbon in a Ni substrate at high temperatures, covering with a silicone film, and then transferring to a desired substrate. The Ni substrate can be subsequently removed to allow GNR wire and contact formation through patterning. Similarly, graphene can be deposited onto copper (Cu) foils (which can be removed later) and transferred to insulating substrates [34]. While these approaches are more suitable for interconnect applications than the previous three approaches, they still require further investigation.

C. Fundamental Issues in GNRs and the Focus of This Paper

In addition to the fabrication challenges, several fundamental issues also exist in GNRs. First, GNRs have edge scattering, which reduces the effective MFP, while CNTs have no such issue. Second, while monolayer graphene has large MFP and conductivity, multilayer graphene turns to graphite and has much lower conductivity per layer due to intersheet electron hopping [35]. The interaction between layers also leads to a modification of the band structure (0.04 eV of band overlap is...
generated in neutral bulk graphite) [36]. In addition, zz-GNRs exhibit a nonzero bandgap [shown later in (17)] due to staggered sublattice potential from magnetic ordering once electron spin is considered [37], [38], which reduces the conductance. Hence, while various fabrication methods of GNRs are being pursued [2], [5], [22], [31]–[33], there is a critical need to evaluate the applicability of GNRs as very large scale integration (VLSI) interconnects and evaluate their performance in comparison to traditional metals (Cu and W) and CNTs. This will also provide guidance to the GNR interconnect fabrication processes.

In previous works [3], [4], the conductance of both metallic and semiconducting GNRs has been modeled and compared with Cu and SWCNTs. However, the assumption in [3] and [4] that ac-GNRs can be differentiated as metallic and semiconducting implies that \( N \) is fixed everywhere along the length (either \( N = 3m - 1 \) (metallic) or \( N = 3m, 3m + 1 \) (semiconducting), where \( m \) is an integer [3], [4]), which further implies very smooth (specular) edges of GNRs, and is against the complete diffusive edge assumption made in [3]. Although the above assumption is not against the complete specular-edge assumption in [4], theoretically, nanopatterning down to the accuracy of one atom is a formidable task from a practical point of view [26]. It should be noted that there are reports that graphene can be cut along certain crystallographic directions and potentially produce ac- or zz-GNRs with smooth edges using nanoparticles [39]. However, this approach is not controllable: neither the diameter of the particles (which determines the patterned slot width) nor the moving direction of the particles (which determines the patterned slot direction) can be accurately controlled.

Due to the high resistance of single graphene layers (discussed in Section III), it becomes necessary to use multiple graphene layers. Additionally, it has been shown that the conductivity of graphite can be enhanced by intercalation doping by exposure to dopant vapor (e.g., AsF\(_5\)) [40]–[42]. Recently, intercalation doping has been proposed to enhance the conductance of multilayer GNRs, and edge specularity effects for multilayer GNRs have been studied [43]. In this paper, details of both monolayer and multilayer GNRs are analyzed, and conductance as well as performance comparisons among GNRs, CNTs, Cu, and tungsten (W) are presented based on the interconnect geometry predicted in the International Technology Roadmap for Semiconductors (ITRS) 2007 [44] for both local and global level interconnects. An RLC delay model for GNR interconnects is also presented and used for comparative performance analysis.

II. FUNDAMENTAL PHYSICS AND MODELS OF GNR CONDUCTANCE

The conductance of GNRs can be derived using the linear response (small voltage drop along the length) Landauer formula [45]: \( G_n \), the conductance of the \( n \)th conduction mode (with consideration of spin) in a single GNR layer, is expressed as

\[
G_n = 2q^2/h \cdot \int T_n(E)(-\partial f_0/\partial E)dE
\]

\[f_0(E) = (1 + \exp[(E - E_F)/k_BT])^{-1}\]  

(1)

where \( q \) is the elementary charge, \( T_n(E) \) is the transmission coefficient, \( f_0(E) \) is the Fermi–Dirac distribution function, \( E_F \) is the Fermi level, \( k_B \) is Boltzmann’s constant, and \( T \) is the temperature. The integration of (1) is from \( |E_n| \) to \( +\infty \) (for electrons) or from \( -\infty \) to \( -|E_n| \) (for holes), where \( E_n \) is the minimum (maximum) energy of the \( n \)th conduction (valence) subband. According to the simple tight-binding model (linear approximation near the Dirac point) [24], \( E_n \) of zz-GNRs can be expressed as [4]

\[E_n = 0 \quad \text{and} \quad |E_n| = (n+1/2) \cdot h v_F/2w \quad \text{for} \ n \neq 0\]  

(2)

where \( h \) is Planck’s constant, \( v_F = 10^6 \) m/s is the Fermi velocity, and \( w \) is the width of the GNR. Fig. 4(a) shows \( E_n \) as a function of the index \( n \) for a particular zz-GNR, with \( w = 30 \) nm. \( T_n(E) \) is determined by both edge scattering and scattering by defects and phonons. The edge scattering is schematically shown in Fig. 3(b), where \( cot \theta \) is the ratio of longitudinal (along the wire length) to transverse (across the wire width) velocities. \( \theta \) can be expressed as a function of \( E_n \) and the total energy \( E \) of an electron or hole, which is shown in (25) and (26) in Appendix. Fig. 4(c) shows \( \theta \big|_{E=E_F} \) (\( E_F = -0.21 \) eV, \( |E_n| \) from Fig. 4(a)).
Here, the term “1” is due to the quantum conductance, which can be ignored when $L \gg l_D$. Fig. 4(d) shows $LT_n(E_{\text{F}})$ as a function of $n$, assuming $L \gg l_D (= 1 \mu m)$. $G_n$ for both electrons and holes as a function of $n$ is shown in Fig. 4(e).

The total conductance of a single GNR layer (in units of S) can be calculated as

$$G_{\text{total}} = \sum_n G_n(\text{electrons}) + \sum_n G_n(\text{holes}).$$

Equation (4) is valid for zz-GNRs. However, this is not valid for a practical narrow ac-GNR with $\Delta E_n > \max\{k_B T, |E_{\text{F}}|\}$, which can be assumed to be neither metallic nor semiconducting due to the inability of patterning ac-GNRs with the width accuracy of one atom. The valid expression of conductance for ac-GNR with $\Delta E_n > \max\{k_B T, |E_{\text{F}}|\}$ requires further investigation, but is not discussed in this paper. For both zz-GNRs and ac-GNRs, when $\Delta E_n \ll \max\{k_B T, |E_{\text{F}}|\}$, the summation can be transformed to an integration form as follows:

$$G_{\text{total}} \approx \frac{2}{\Delta E_n} \left[ \int_0^\infty G_n(\text{electrons})dE_n + \int_{-\infty}^0 G_n(\text{holes})dE_n \right]$$

which can further be derived as

$$G_{\text{total}} = \frac{1}{L} \frac{2q^2}{h} \frac{2w^2}{\hbar v_f} \cdot 2k_B T \ln \left[ 2 \cosh \left( \frac{E_{\text{F}}}{2k_B T} \right) \right] \cdot \text{func}(w, l_D)$$

where

$$\text{func}(w, l_D) = \begin{cases} \pi w - 2l_D + 4\sqrt{w^2 - l_D^2} \cdot \text{arctanh}\left( \sqrt{\frac{l_D - w}{l_D + w}} \right), & l_D \geq w \\
\pi w - 2l_D - 4\sqrt{w^2 - l_D^2} \cdot \text{arctanh}\left( \sqrt{\frac{w - l_D}{w + l_D}} \right), & l_D < w \\
2\ln(l_D/w) + 2\ln 2 - 2 + \pi w/2, & l_D \gg w \\
\pi l_D/2 - 2l_D^2/3w^2, & l_D \ll w. \end{cases}$$

Note that the prefactor of 2 in (5) is from the degeneracy of $E_n = E_{n \pm 1}$. Detailed derivation of (6) is shown in Appendix. The 2-D sheet conductance in siemens square can be derived from (6) as

$$G_{\text{sheet}} = \lim_{w \to \infty} \frac{L}{w} G_{\text{total}} = \frac{2q^2}{h} \frac{\pi l_D}{\hbar v_f} \cdot 2k_B T \ln \left[ 2 \cosh \left( \frac{E_{\text{F}}}{2k_B T} \right) \right].$$

When $k_B T \ll |E_{\text{F}}|$, (7) reduces to [35, eq. (4)]

$$G_{\text{sheet}} = \frac{2q^2}{h} \frac{\pi l_D}{\hbar v_f} \cdot |E_{\text{F}}| = \frac{q^2}{h} \cdot l_D \cdot k_F$$

where $k_F$ is the wavenumber at the Fermi surface.

Fig. 5 shows the resistances of monolayer GNRs of different widths, if $l_D = 1 \mu m$. It can be observed that the resistance difference between zz-GNRs and ac-GNRs is negligible.

Fig. 4. Modeling of zz-GNR ($E_0 = 0$) conductance: (a) Minimum (maximum) energy of the nth conduction (valence) subband. (b) Schematic view of edge scattering in GNRs and the definition of $\theta$. (c) $\theta$ for holes as a function of $n$ at $E = E_{\text{F}}$. (Note that $|E_{\pm 3}| > |E_{\text{F}}|$, which implies that $E = E_{\text{F}}$ is not allowed for $n = \pm 3$ and $|\theta|_{n = \pm 3, E = E_{\text{F}}} = \theta$. See also (26) in Appendix.) (d) Transmission coefficient $T_n(E)$ in unit length for holes as a function of $n$ at $E = E_{\text{F}}$. (e) Conductance in unit length for holes $G_{\text{total}}(E)$ can be obtained by using the Matthiessen’s rule, $T_n(E)$ can be obtained by

$$\frac{1}{T_n(E)} = 1 + \frac{L}{l_D \cos \theta} + \frac{L}{L/w \cos \theta} \approx \frac{L}{l_D \cos \theta} + \frac{L}{w \cos \theta}.$$
when GNR width is large enough, whereas the resistance of zz-GNRs is smaller than that of the corresponding ac-GNRs if \( w < 45 \) nm. However, as mentioned earlier, when the ac-GNR is narrow (which implies that \( \Delta w \) is smaller than that of the corresponding ac-GNRs when GNR width is large enough, whereas the resistance of monolayer GNR is much smaller than that predicted by (12), which is slightly greater than the bulk conductivity of Cu, with a hole volume concentration \( (n_p) \) of \( 4.6 \times 10^{20} \) cm\(^{-3}\).
The average layer spacing \( s = (s_1 + s_2)/2 \) between two adjacent graphene layers is 0.575 nm for stage-2 intercalated graphite, according to Fig. 7(b). Using the simplified tight-binding model, the relationship between \( E_F \) and hole density per layer \( (n_{p0} = n_E s) \) is expressed as

\[
n_{p0} = 4\pi(k_F/2\pi)^2 = 4\pi(E_F/h\nu_f)^2. \tag{13}
\]

For such type of intercalation-doped graphite, \( |E_F| = 0.60 \text{ eV} \) is obtained from (13), and \( l_D = 1.03 \mu m \) is obtained from (7). It should be noted that intercalated graphite with even larger conductivity \( (\sim 1(\mu\Omega \cdot \text{cm})^{-1}) \) has been reported in [42], however, this is not used in this work because of lack of data \( (l_D \text{ and } E_F \text{ cannot be obtained if carrier concentration is not known}) \). It should also be noted that using the band structure of graphene is a good approximation for the analysis of AsF_5-doped graphite due to the following two reasons: 1) interlayer interaction of AsF_5-doped graphite is suppressed as compared to neutral graphite (with band overlap of 0.04 eV between conduction and valence bands) and 2) \( E_F = -0.60 \text{ eV} \), which is far outside the band overlap region. For the undoped (neutral) graphite, the overlap of 0.04 eV is in the same order of \( k_B T \). This may induce some errors in the estimation of conductance but does not change the result qualitatively.

In addition to the GNRs, Cu, SWCNT bundles, and W are also discussed in this section for comparison. The geometry of the wires and the resistivity for Cu wire are obtained from the ITRS [44]. The resistance model for SWCNT bundles is derived in [48]: when one-third of the SWCNTs are metallic, the conductivity can be expressed as

\[
sigma(\text{SWCNT bundles}) \approx \frac{1}{3} \frac{4\pi l_D^2/h}{(D + s)^2 / \sqrt{3}/2} \tag{14}
\]

where \( s \) is minimum spacing between adjacent SWCNTs, and \( D \) is the diameter of SWCNTs. When \( s = 0.34 \text{ nm}, D = 1 \text{ nm} \) and \( l_D = 1 \mu \text{m} \) [48], \( \sigma(\text{SWCNT bundles}) = 0.33 \text{ (}\mu\Omega \cdot \text{cm})^{-1} \).

The resistivity model for W wire is adapted from [51] and [52], which is described by

\[
\rho = \rho_0 \left\{ \frac{1}{3} + \alpha + \frac{2}{3} - \frac{2}{3} \ln \left( \frac{1 + \alpha}{\alpha} \right) \right. \\
\left. + \frac{3}{8} C(1 - p) \frac{1 + AR l_D}{AR w} \right\} \tag{15}
\]

where

\[
\alpha = (l_D/d)R/(1 - R) \tag{16}
\]

\[\rho_0 = 8.7 \mu \Omega \cdot \text{cm} \text{ is the resistivity of the bulk material, } AR \text{ is the aspect ratio, } w \text{ is the wire width, } l_D = 33 \text{ nm is the MFP, } d = w/2 \text{ is the average distance between grain boundaries, } p = 0.3 \text{ is the specularity parameter, } R = 0.25 \text{ is the reflectivity coefficient at grain boundaries, and } C = 1.2 \text{ is an empirical parameter.}

The wire resistances of different types of both global and local interconnects are compared in Fig. 8. Beyond the 22-nm technology node, SWCNT bundles are the best, while all of the GNR structures are not better than Cu—for both global and local wires. However, an AsF_5-doped multilayer GNR is always better than W.

A zero bandgap of zz-GNRs is assumed in the above analysis. However, in reality, a bandgap is induced because of the staggered sublattice potential from magnetic ordering once electron spin is considered [37], [38]. The bandgap of zz-GNRs increases with decreasing wire width [the bandgap, in electronvolts, is 0.933/(\( w + 1.5 \))], with \( w \) in nanometers. In such a situation, (2) can be modified as

\[
E_0 = \frac{0.933}{2(w + 1.5)} |E_n| = \left( |n| + \frac{1}{2} \right) \frac{h\nu_f}{2w} \tag{17}
\]

If (26) in Appendix and (3) are still assumed to be valid for zeroth conduction modes, the total conductance should then be calculated directly from (4). The calculated results for both monolayer and multilayer GNRs are shown in Fig. 9. It is shown that the resistance of narrow width zz-GNRs becomes even worse after such consideration, particularly for the monolayer GNRs and neutral multilayer GNRs. This resistance change is primarily because of the edge scattering in the zeroth conduction mode, which is not an issue if \( E_0 \) is assumed to be zero.

Fig. 10 shows the conductance contour plots as a function of both \( l_D \) and \( E_F \) for both bulk graphite and 16.5-nm-wide (minimum global wire width for the 11-nm technology node) multilayer zz-GNRs. In the contour plots, the slopes of the
Fig. 9. Impact of the bandgap of zz-GNRs on resistance estimation of (a) long global wires and (b) $L = 1 \mu m$ local wires. $l_D$, $|E_F|$, specularity, and average layer spacing in monolayer GNRs and neutral and stage-2 AsF$_3$-doped multilayer GNRs are the same as in Fig. 8. The arrows indicate the resistance changes after consideration of the bandgap of zz-GNRs (smaller and bigger symbols indicate before and after such consideration, respectively).

Fig. 10. Conductance contours as a function of Fermi level $|E_F|$ and MFP $l_D$. Solid lines show the conductance per layer of 16.5-nm-wide (minimum global wire width in the 11-nm technology node) long global multilayer zz-GNR wires. Dashed lines show the sheet conductance per layer of bulk graphite. The "dot" on the lower left-hand side represents neutral graphite, while the "open triangles" represent the three stages of AsF$_3$ intercalation-doped graphite [50]. $p$ is assumed to be 0. The bandgap of zz-GNRs and the edge scattering of the zeroth conduction mode are considered.

Contour lines, $(\partial D / \partial |E_F|)_G$, indicate the importance of the two parameters, i.e., $l_D$ and $E_F$. We have

$$\frac{|E_F|}{G} \left( \frac{\partial G}{\partial |E_F|} \right)_{l_D} / \left( \frac{\partial D}{\partial |E_F|} \right)_{E_F} = \frac{|E_F|}{l_D} \left( \frac{\partial l_D}{\partial |E_F|} \right)_{G} \tag{18}$$

where $G$ is either the conductance per layer of $w = 16.5$ nm multilayer zz-GNRs or the sheet conductance per layer of graphite, and $(\partial z / \partial x)_0$ stands for the partial differential of $z$ to $x$ when maintaining a fixed $y$ for three correlated variables $x$, $y$, and $z$. Therefore, steeper contour lines indicate higher importance of $E_F$. Hence, the plots indicate that $l_D$ and $E_F$ are equally important for bulk graphite $l_D / (\partial l_D / \partial |E_F|) = -1$, but $E_F$ is more important if $l_D \gg w$ for very narrow zz-GNRs (contour lines are steeper). Note that this statement is contrary to that in [43], which is due to the consideration of the bandgap of zz-GNRs and the edge scattering of zeroth conduction mode in this paper: the edge scattering of zeroth conduction mode, which is independent of $l_D$ [refer to the third term in (3)], becomes the dominant factor in determining the conductance.

Complete diffusive edges are assumed in the above analysis, but the GNR conductance can be improved by improving the specularity $(p)$ of the edges. Recently, a backscattering probability of 0.2 [53], or equivalently, $p = 0.8$, has been achieved.

The specularity effect can be modeled by multiplying the term $L/w \cot \theta$ (term of edge scattering) in (3) by $(1 - p)$, i.e.,

$$\frac{1}{T_n(E)} = 1 + \frac{L}{l_D \cos \theta} + \frac{L(1 - p)}{w \cot \theta} \approx \frac{L}{l_D \cos \theta} + \frac{L(1 - p)}{w \cot \theta} \tag{19}$$

It can be observed in Fig. 11 that the conductance of zz-GNR can be improved significantly if the edges change from completely diffuse $(p = 0)$ to completely specular $(p = 1)$. However, even for $p = 1$, monolayer and neutral multilayer GNRs are not better than Cu. Furthermore, only if $p$ is very close to 1 can the AsF$_3$-doped multilayer zz-GNRs be better than Cu.

For local interconnects, where wire length can be comparable to or smaller than $l_D$, the quantum contact resistance cannot be ignored. Similar to CNTs, the quantum contact resistance for GNRs is $\hbar/2q^2$ for each conduction mode. The per unit length wire resistances as a function of length of different structures are shown in Fig. 12. It should be noted that the quantum contact resistance is the lower limit of contact resistance in CNT/GNR interconnects. In reality, the situation could even be worse because of the imperfect contact resistance, which is fabrication technology dependent.
IV. RLC DELAY MODEL FOR GNR INTERCONNECTS

In addition to the resistance, the capacitance and inductance are also important to the propagation delay. Similar to the CNTs [8], the distributed capacitance of GNRs contains both the electrostatic and quantum capacitances, while the distributed inductance contains both the magnetic and kinetic inductances. The distributed RLC equivalent circuit for GNRs is shown in Fig. 13. $R_Q$ is the quantum contact resistance defined as

$$R_Q = \frac{\hbar}{2q^2} N_{\text{ch}} N_{\text{layer}}$$

where $N_{\text{ch}}$ is the number of conducting channels (modes) in one layer, $N_{\text{layer}}$ is the number of GNR layers, $r = r_{\text{one layer}}/N_{\text{layer}}$ is the distributed scattering resistance, $C_Q$ and $C_E$ are the quantum and electrostatic capacitance, respectively, and $l_K$ and $l_M$ are the kinetic and magnetic inductance, respectively. $C_Q$ can be expressed as

$$C_Q = N_{\text{layer}} N_{\text{ch}} 4q^2/h v_f.$$  

$l_K$ can be expressed as

$$l_K = \frac{(h/4q^2 v_f)/N_{\text{layer}} N_{\text{ch}}}.\,$$

where $v_f$ is the Fermi velocity. $N_{\text{ch}}$ can be expressed as

$$N_{\text{ch}} = N_{\text{ch,electron}} + N_{\text{ch,hole}}$$ 

$$= \sum_n \left[ 1 + \text{exp} \left( \frac{E_n,\text{electron} - E_F}{k_B T} \right) \right]^{-1}$$

$$+ \sum_n \left[ 1 + \text{exp} \left( \frac{E_F - E_n,\text{hole}}{k_B T} \right) \right]^{-1}.$$  

where $E_n,\text{electron}$ ($E_n,\text{hole}$) is the minimum (maximum) energy of the $n$th conduction (valence) subband. Generally, the kinetic inductance in monolayer GNRs is much larger than the magnetic inductance, while that is not always the case in multilayer GNRs. On the other hand, the quantum capacitance in multilayer GNRs is much larger than the electrostatic capacitance, while that is not always the case in monolayer GNRs.

V. PERFORMANCE COMPARISON OF GNRs WITH OTHER MATERIALS

The delay of both global and local interconnects in the 11-nm technology node are analyzed based on the distributed RLC model in Fig. 13. The quantum capacitances and kinetic inductances are obtained from (21) and (22), while electrostatic capacitances and magnetic inductances are obtained from the predictive technology model [54]. Simulations were implemented using HSPICE. The driver equivalent resistance and capacitance are obtained from the 11-nm technology node (ITRS 2007) [44].

Fig. 14 shows the comparison with respect to Cu global interconnects. The performance of monolayer zz-GNR and neutral multilayer zz-GNR is much worse than Cu, even if a complete specular edge is assumed. The multilayer zz-GNR can match or become better than Cu only if it is intercalation (AsF$_5$) doped and if it has very specular edges ($p > 0.8$). The AsF$_5$-doped multilayer zz-GNRs can even be better than SWCNT bundles if $p = 1$ is achieved. However, for more
practical edge specularity, i.e., $p = 0.2 - 0.6$, GNRs cannot match the performance of Cu or that of SWCNT bundles (even for metallic fraction = 1/3) at the global level. It is worth noting that for global interconnects, MWCNT bundles are better than SWCNT bundles (for metallic fraction = 1/3) [48], which implies that GNRs cannot match the performance of MWCNT bundles.

For local interconnects (Fig. 15), the performance of AsF$_5$-doped multilayer zz-GNRs can either match or be better than that of Cu, only if it has very specular edges ($p > 0.8$). The AsF$_5$-doped multilayer zz-GNRs can be slightly better than SWCNT bundles if $p = 1$ is achieved. The monolayer zz-GNRs are worse than Cu for most cases, even if complete specular edge is achieved, although it can be better than Cu in some special cases (minimum driver size and several micrometer wire lengths) due to their smaller capacitance. The neutral multilayer GNRs are not even better than W, even if complete specular edge is achieved. However, the AsF$_5$-doped multilayer zz-GNRs are better than W in most cases, which suggest possible application of zz-GNRs as local interconnects.

The overall results are summarized in Table II. In general, until the very end of the roadmap (11-nm technology node), GNRs are not better than Cu, unless some special technology improvements are achieved: multilayer zz-GNR with proper intercalation doping and very specular edges.

### APPENDIX

Equation (6) can be derived from (5) as follows:

$$
\int_{0}^{\infty} G_n(\text{electrons}) dE_n = \int_{0}^{\infty} \frac{2q^2}{\hbar} dE_n \int_{E_n}^{\infty} T_n(E) \left(-\frac{\partial f_0}{\partial E}\right) dE
$$

$$
= \frac{2q^2}{\hbar} \int_{0}^{\infty} \left(-\frac{\partial f_0}{\partial E}\right) dE \int_{E_n}^{\infty} T_n(E) dE_n
$$

$$
= \frac{2q^2}{\hbar} \int_{0}^{\infty} E \left(-\frac{\partial f_0}{\partial E}\right) dE \int_{0}^{\infty} \frac{1}{E} T_n(E) dE_n
$$

$$
\text{(24)}
$$

where

$$
|E_n| = hv_f |k_y| \quad |E| = hv_f \sqrt{k_x^2 + k_y^2}
$$

$$
\text{(25)}
$$

### VI. Conclusion

In this paper, GNRs have been analyzed from fundamental physics to their industrial prospects as VLSI interconnects. Monolayer, neutral multilayer, and intercalation-doped multilayer zz-GNR interconnects are analyzed from both conductance and propagation delay perspectives. The conductance of GNRs, which were analytically derived using a simple tight-binding method and the Landauer formalism, accounted for edge scattering of the zeroth conduction modes and small bandgap in narrow zz-GNRs. A comparative analysis (with other interconnect materials: Cu, CNTs, and W) was carried out for interconnect geometries until the very end of ITRS 2007 (11-nm technology node). The analysis reveals that although GNRs appear to have some fabrication advantages over CNTs (for horizontal interconnects) in order for them to match (or better) the performance of Cu or that of CNT bundles at both the global and local levels, some special technology improvements must be achieved. More specifically, it is shown that proper intercalation doping and very specular edges ($p > 0.8$) are necessary to make multilayer zz-GNR interconnects comparable to or better than Cu or CNT interconnects at either the global or local level. On the other hand, intercalation-doped multilayer zz-GNRs at the local level can have better performance than that of tungsten (even for $p = 0$), implying possible application as local interconnects in some cases.

### TABLE II

PERFORMANCE COMPARISON OF DIFFERENT MATERIALS WITH RESPECT TO Cu AT THE 11-nm TECHNOLOGY NODE OF ITRS 2007

<table>
<thead>
<tr>
<th>Interconnect Material</th>
<th>Global</th>
<th>Local</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten (W)</td>
<td>-</td>
<td>worse</td>
</tr>
<tr>
<td>SWCNT ($D$=1nm, 1/3 metallic)</td>
<td>better</td>
<td>better</td>
</tr>
<tr>
<td>MWCNT</td>
<td>much better [48]</td>
<td>worse [48]</td>
</tr>
<tr>
<td>Mono-layer GNR ($p$=1)</td>
<td>much worse</td>
<td>worse</td>
</tr>
<tr>
<td>Neutral multi-layer GNR ($p$=1)</td>
<td>much worse</td>
<td>worse</td>
</tr>
<tr>
<td>AsF$_5$ doped multi-layer GNR ($p$=0)</td>
<td>worse</td>
<td>worse</td>
</tr>
<tr>
<td>AsF$_5$ doped multi-layer GNR ($p$=0.8)</td>
<td>comparable</td>
<td>comparable</td>
</tr>
<tr>
<td>AsF$_5$ doped multi-layer GNR ($p$=1)</td>
<td>much better</td>
<td>better</td>
</tr>
</tbody>
</table>
where $k_x$ and $k_y$ are the wave vector components along and across the GNR, respectively, and

$$|\tan \theta| = \left| \frac{k_y}{k_x} \right|, \quad |\sin \theta| = |E_n/E|.$$  \hspace{1cm} (26)

Therefore, one of the integrals in (24) can be evaluated as

$$\int_0^\pi \frac{E}{E} T_n(E) dE_n \approx \int_0^{\pi/2} \left( \frac{1}{|D \cos \theta| + \frac{1}{w \cot \theta}} \right)^{-1} \cos \theta \, d\theta = \frac{1}{2L} w \cdot \text{func}(w, l_D)$$  \hspace{1cm} (27)

where $\text{func}(w, l_D)$ is given in (6b), i.e.,

$$\text{func}(w, l_D) = \left\{ \begin{array}{ll}
\frac{\pi w - 2l_D}{l_D} + 4\sqrt{\frac{w}{l_D} - \frac{w^2}{l_D}} \cdot \text{arctanh} \left( \frac{l_D - w}{l_D + w} \right), & l_D \geq w \\
\frac{\pi w - 2l_D}{l_D} - 4\sqrt{\frac{w}{l_D} - \frac{w^2}{l_D}} \cdot \text{arctanh} \left( \frac{l_D - w}{l_D + w} \right), & l_D < w \approx \frac{2\ln \left(\frac{l_D}{w} + 2\ln \left(\frac{l_D}{2w} - 2 + \pi w/l_D, \right) \right)}{\pi l_D/2w - 2l_D^2/3w^2}, & l_D \gg w, l_D \ll w.
\end{array} \right.$$  

Note that the integration is from 0 to $\pi/2$ rather than $-\pi/2$ to $\pi/2$ because the degeneracy prefactor of $E_n = E_{-n}$ is already included in (5). The other integral in (24) can be evaluated as

$$\int_0^{\pi \hbar} \frac{-\partial f_0}{\partial E} dE = \int_0^\infty \frac{-E}{\partial E} \left(\frac{1}{1 + \exp \left(\frac{E - E_F}{k_BT}\right)}\right) dE = \int_0^\infty \frac{E}{4k_BT \cos^2 \left(\frac{E - E_F}{2k_BT}\right)} dE = k_BT \ln \left[1 + \exp \left(\frac{E}{k_BT}\right)\right].$$  \hspace{1cm} (28)

Therefore,

$$\int G_n(\text{electrons}) dE_n = \left(2q^2/h\right) \cdot k_BT \ln \left[1 + \exp \left(\frac{E_F}{k_BT}\right)\right] \cdot \frac{1}{2L} w \cdot \text{func}(w, l_D).$$  \hspace{1cm} (29)

Similarly

$$\int G_n(\text{holes}) dE_n = \left(2q^2/h\right) \cdot k_BT \ln \left[1 + \exp \left(-\frac{E_F}{k_BT}\right)\right] \cdot \frac{1}{2L} w \cdot \text{func}(w, l_D).$$  \hspace{1cm} (30)

From (5) and if $\Delta E_n = \hbar v_f/2w$, we get

$$G_{\text{total}} \approx \frac{2}{\Delta E_n} \int_0^{\infty} G_n(\text{electrons}) dE_n + \int_0^{-\infty} G_n(\text{holes}) dE_n = \frac{1}{2L} \frac{2q^2}{\hbar} \frac{2w^2}{\hbar v_f} \cdot k_BT \ln \left[2\cosh \left(\frac{E_F}{2k_BT}\right)\right] \cdot \text{func}(w, l_D)$$  \hspace{1cm} (31)

which is the same as (6).
Kaustav Banerjee (S’92–M’99–SM’03) received the Ph.D. degree in electrical engineering and computer sciences from the University of California, Berkeley, in 1999.

In July 2002, he joined the Faculty of the Department of Electrical and Computer Engineering, University of California, Santa Barbara, where he has been a Full Professor since 2007. He is also an affiliated faculty at the California NanoSystems Institute (CNSI) at UCSB. From 1999 to 2001, he was a Research Associate with the Center for Integrated Systems, Stanford University, Stanford, CA. From February to August 2002, he was a Visiting Faculty with the Circuit Research Laboratories, Intel, Hillsboro, OR. He has also held summer/visiting positions at Texas Instruments Incorporated, Dallas, from 1993 to 1997, and the Swiss Federal Institute of Technology, Lausanne, Switzerland, in 2001. His research has been chronicled in over 170 journal and refereed international conference papers and in two book chapters on 3-D ICs. He is also a coeditor of the book *Emerging Nanoelectronics: Life With and After CMOS* (Springer, 2004). His current research interests include nanometer-scale issues in VLSI as well as circuits and systems issues in emerging nanoelectronics. He is also involved in exploring the design and fabrication of various nanomaterials for ultra energy-efficient electronics and energy harvesting/storage applications.

Prof. Banerjee received a number of awards in recognition of his work, including the Best Paper Award at the Design Automation Conference in 2001, the ACM SIGDA Outstanding New Faculty Award in 2004, the IEEE Micro Top Picks Award in 2006, and the IBM Faculty Award in 2008. He has served on the Technical Program Committees of several leading IEEE and ACM conferences, including the IEEE International Electron Devices Meeting, the Design Automation Conference, the International Conference on Computer Aided Design, and the International Reliability Physics Symposium. From 2005 to 2008, he served as a member of the Nanotechnology Committee of the IEEE Electron Devices Society. He has also served on the Organizing Committee of the International Symposium on Quality Electronic Design at various positions, including Technical Program Chair in 2002 and General Chair in 2005. Currently, he serves as a Distinguished Lecturer of the IEEE Electron Devices Society.