Structural, magnetic, and electronic properties of Niₙ and Feₙ nanostructures \((n = 1–4)\) adsorbed on zigzag graphene nanoribbons

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Extensive ab initio density-functional calculations were performed to investigate the structural, magnetic, and electronic properties of systems comprising Niₙ and Feₙ nanostructures \((n = 1–4)\) adsorbed on hydrogen-passivated zigzag graphene nanoribbons (GNRs). Both Ni and Fe atoms were most strongly bound at GNR edge sites and neither altered whether the GNR was metallic or semiconducting. However, Niₙ nanostructures were more strongly bound than Feₙ nanostructures, and their atoms had much smaller spin magnetic moments; Niₙ/GNR systems, like the pristine GNR, always had lowest energy with antiparallel edge spins, whereas among Feₙ/GNR systems this was only found for one- or two-atom adstructures at subedge or near-subedge atop sites; and zigzag Ni₃ and Ni₄ chains placed at GNR hole sites retained close contact with the GNR upon relaxation, whereas the analogous Fe chains adopted geometries similar to those of free-standing Fe clusters, with one or more atoms lifted away from the GNR.

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I. INTRODUCTION

Identification of Kroto et al.1 of the truncated icosahedral structure of \(\text{C}_{60}\) in 1985 spurred intense research on the properties of fullerences and other all-carbon nanostructures, especially carbon nanotubes (CNTs)2,3 and the graphene sheet.4–9 The latter is a zero-gap two-dimensional semiconductor with striking properties of interest for nanoelectronics; in particular, it has extremely high carrier mobility due to the linear band dispersion around the Fermi point.5 CNTs, obtained conceptually by rolling up a strip of graphene sheet, are uniquely specified by their diameter and winding angle, which together determine not only their structure but also other properties, such as whether they behave electronically as conductors or semiconductors.3 A carbon nanostructure that has attracted considerable attention of late is the graphene nanoribbon (GNR), an (unrolled) graphene strip.10–31 Just as the structures and electronic properties of CNTs are determined by their diameter and winding angle, so those of GNRs are determined by their width and by the direction-dependent configuration of atoms along their long edges, which can range from zigzag (the edges run perpendicular to one of the bond directions) to armchair (the edges run parallel to one of the bond directions). In particular, zigzag GNRs with hydrogen-passivated edges, in which all the spins are the same along each edge, are metallic or semiconducting depending on whether the two edges have the same or opposite spins32 [the latter configuration, Ferro-F, is marginally more stable than the former, Ferro-F, in which antiferromagnetic (AFM) coupling between nearest neighbors is frustrated at the center of the ribbon].17,29

CNTs can be obtained with the catalytic aid of late transition metals (TMs), notably Ni,3,32–34 For this and other reasons, there has been considerable research on nanostructures composed of C and TM atoms. It is found, for example, that systems with early TMs differ markedly from those with late TMs. Thus early TMs do not catalyze CNT formation, and early 3\(d\) metals (Ti, V, and Cr) preferentially form “met-cars”35–41 (clusters with TMₙC₁₂ stoichiometry and remarkable stability), while late 3\(d\) metals (Co and Ni) do not.41 Knowledge of how TM-C interactions depend on where the TM atoms bind is of fundamental importance for understanding not only catalytic CNT growth, the mechanism of which is still controversial,33,42 but also the magnetic and other electronic properties of carbon nanostructures with adsorbed or embedded TM atoms. For example, GAUSSIAN03 calculations have predicted that the electron tunneling current in Ni-C₆₀-Ni is greater when the Ni atoms occupy hole sites than in the more stable structure43 in which they occupy bridge sites.45 Of course, non-TM atoms can also alter electronic properties: hydrogen-passivated zigzag GNRs with boron-doped ferromagnetically coupled edges have been shown theoretically to be semiconductors with spin-sensitive transmittance.24

Ab initio calculations using SIESTA46 and TRANSANPA47 have shown that the most stable configuration of a hydrogen-passivated zigzag GNR with a single adsorbed Ni atom features the adatom at an edge site, that the adsorption process reduces the magnetic moments of both the Ni and its neighboring C atoms due to the hybridization of Ni 3\(d\) orbitals with C 2\(p\) orbitals, and that the electronic transmittance along the GNR is, as in the case of B-doped zigzag GNRs,24 spin dependent.29 To contribute to a better understanding of the behavior of TM/GNR systems, in the work described here we performed SIESTA calculations to compare the structural, magnetic, and electronic behaviors of Niₙ and Feₙ structures \((n = 1–4)\) that were supported on hydrogen-passivated zigzag GNRs. The Niₙ/GNR and Feₙ/GNR systems proved to differ significantly in many respects. The essential technical details of the method used are sketched in Sec. II, our results are discussed in Sec. III, and in Sec. IV we summarize our main conclusions.

II. DETAILS OF THE COMPUTATIONAL PROCEDURE

The computational method employed has been described in detail in Ref. 46. Briefly, it is a density-functional
theory (DFT) approach using numerical pseudoatomic orbitals as basis sets to solve the single-particle Kohn-Sham equations. For the exchange and correlation potential we used the Perdew-Burke-Ernzerhof form of the generalized gradient approximation (GGA).\textsuperscript{48} The atomic cores were described by nonlocal norm-conserving Troullier-Martins pseudopotentials\textsuperscript{49} factorized in the Kleinman-Bylander form.\textsuperscript{50} The pseudopotentials for Ni and Fe were generated using the valence configurations $4s^13d^9$ and $4s^13d^7$ and have been validated in previous work on Ni-C and Fe-C clusters.\textsuperscript{51–53} For both TM and C atoms, valence states were described using triple-$\zeta$ doubly polarized basis sets. The energy cutoff used to define the real-space grid for the numerical calculations involving the electron density was 250 Ry (in a few calculations performed as a check with a 500 Ry energy cutoff, the results were virtually the same as those obtained with the smaller cutoff). Using a conjugate gradient method,\textsuperscript{54} all the structures were fully relaxed, without any geometry or spin constraints, until the interatomic forces were smaller than 0.005 eV/Å.

Most calculations concerned a $9.83 \times 50 \times 10$ Å supercell containing four unit cells of a hydrogen-passivated (10,0) zigzag GNR (80 C atoms together with 8 H atoms saturating the dangling $\sigma$ bonds at the edges)\textsuperscript{55} together with Ni or Fe adatoms. Periodic boundary conditions were applied in all directions to make infinite copies of an endless adatom-spattered GNR 22.08 Å wide in the $y$ direction, with copies separated by 10 and 50 Å in the $z$ and $y$ directions, respectively. For the largest TM nanostructures, eight unit cells of GNR were included in the supercell as a check on accuracy. For some TM nanostructures, calculations were also performed in which the dangling $\sigma$ bonds were passivated with alternating H atoms and methylene groups,\textsuperscript{17} but the results were the same as with H-only passivation. A Monkhorst-Pack\textsuperscript{56} grid of $9 \times 1 \times 1$ $k$ points was used along the GNR growth direction ($x$ direction) for integration in the Brillouin zone; calculations performed with a $15 \times 1 \times 1$ grid gave virtually the same results.

III. RESULTS AND DISCUSSION

We started our calculations by reproducing known results for pristine hydrogen-passivated zigzag GNRs, i.e., zigzag GNRs with no TM atoms. We found the energy of Ferro-A to be just 0.014 eV/unit cell lower than that of Ferro-F. Note that Pisani et al.\textsuperscript{17} showed that although different exchange and correlation functionals can afford slightly different predictions of the magnetic configuration of GNRs, the qualitative features of the results are robust with respect to changes of functional. This should also hold for the results obtained in this paper for Ni$_n$/GNR and Fe$_n$/GNR systems.

Following the above preliminaries, we performed extensive calculations on single-adatom Ni/GNR and Fe/GNR systems to investigate, as possible adsorption sites, the central hole site (CHS) of the GNR unit cell, a subcentral bridge site (SCBS), and a subedge “atop” site (SEAS) [see Figs. 1(a)–1(c)]. In each case, we also investigated magnetic behavior; magnetic differences between the Ni/GNR and Fe/ GNR systems were expected because the Fe atom has three unpaired $d$ electrons and the Ni atom has only one. Due to space limitations, we present here only part of our results for these and other Ni$_n$/GNR and Fe$_n$/GNR systems ($n=2–4$); for the remainder, see the supplementary material.\textsuperscript{57}
TABLE I. Nomenclature employed in this paper for Ni$_n$ adstructures ($n=1–4$) on a (10,0) GNR in Ferro-A and Ferro-F configurations, together with the absolute values of the adsorption energies, and the magnetic moments of the Ni atoms and of two C atoms at opposite edges of the ribbon. Names indicate initial geometries: CHS, central hole site; SCBS, subcentral bridge site; SEAS, subedge atom site; NHS, neighboring hole site; DD, double decker (one adatom atom another); NAS, neighboring atop site; 2SEAS, SEAS+SEAS; CHS-LC, linear chain starting at CHS; and CHS-ZZC, zigzag chain starting at CHS.

| $n$ | Name          | $E$ (eV) | $\mu_{Ni}$ (\(\mu_B\)) | $\mu_{C}$ (\(\mu_B\)) |
|-----|---------------|---------|--------------------------|------------------------|
|     |               | Ferro-A | Ferro-F                  | Ferro-A                | Ferro-F                |
| 1   | CHS           | 1.611   | 1.592                    | 0.00                   | −0.03                  |
|     | SCBS          | 1.297   | 1.276                    | −0.05                  | 0.10                   |
|     | SEAS          | 1.978   | 1.965                    | −0.51                  | 0.47                   |
| 2   | CHS+NAS       | 3.753   | 3.733                    | −0.012, 0.0            | −0.023, −0.026         |
|     | DD-CHS        | 3.977   | 3.902                    | −1.305, −0.653         | 1.287, 0.761           |
|     | SEAS+NAS      | 4.283   | 4.266                    | −0.42, −0.44           | 0.42, 0.36             |
|     | DD-SEAS       | 4.560   | 4.553                    | 1.173, 0.097           | 1.172, 0.11            |
|     | 2SEAS         | 4.705   | 4.689                    | −0.197, −0.763         | 0.169, 0.705           |
| 3   | CHS-LC        | 5.769   | 5.756                    | −0.01, −0.001, 0.009   | 0.002, −0.094, 0.002   |
|     | CHS-ZZC       | 5.843   | 5.827                    | −0.085, −0.013, 0.04   | 0.035, −0.012, −0.017  |
| 4   | CHS-LC        | 7.840   | 7.829                    | −0.010, −0.040, −0.009, 0.004 | 0.027, 0.100, 0.107, 0.048 |
|     | CHS-ZZC       | 9.751   | 9.699                    | −0.492, −0.598, 0.590, 0.481 | 0.473, 0.613, 0.579, 0.477 |

The entries for $n=1$ in Tables I and II list the predicted adsorption energies of Ni and Fe on Ferro-A and Ferro-F, together with the spin magnetic moments of the adatom and of the nearest C atoms of the two edges (for each $n$, magnetic moments were in fact calculated for all atoms in a band perpendicular to the $x$ direction that contained the adatoms). For both metals, the most stable structure featured the adatom at a Ferro-A SEAS, which in the case of Ni/GNR agrees with the results of Rigo et al.\textsuperscript{29} Unlike Rigo et al., however, we found that adsorption at an SCBS was also stable for Ni [Ni(SCBS)/Ferro-A being slightly more stable than Ni(SCBS)/Ferro-F] though not for Fe. This result for Ni is consistent with the stability of C$_{2p}$ with Ni adsorbed at bridge sites.\textsuperscript{44,45} When adsorption occurred at the CHS, Ni(CHS)/Ferro-A was again slightly more stable than Ni(CHS)/Ferro-F, but adsorption of Fe reversed the spin preference of the pristine GNR, Fe(CHS)/Ferro-F being more much stable than Fe(CHS)/Ferro-A. For all configura-

TABLE II. As for Table I but for Fe$_n$ adstructures ($n=1–4$). For Fe$_3$/Ferro-F and Fe$_4$/Ferro-F, we also include results for SEAS-ZZCs (ZZCs that started at a SEAS and continued toward the center of the GNR; see text).

| $n$ | Name          | $E$ (eV) | $\mu_{Fe}$ (\(\mu_B\)) | $\mu_{C}$ (\(\mu_B\)) |
|-----|---------------|---------|--------------------------|------------------------|
|     |               | Ferro-A | Ferro-F                  | Ferro-A                | Ferro-F                |
| 1   | CHS           | 0.074   | 0.607                    | −0.75                  | 2.27                   |
|     | SCBS          | Unstable|                         |                        |                       |
|     | SEAS          | 1.043   | 1.036                    | −3.08                  | 3.07                   |
| 2   | CHS+NAS       | 1.987   | 2.550                    | 3.037, −3.087          | 3.521, 3.191           |
|     | DD-CHS        | 2.955   | 2.974                    | −3.021, −3.288         | 3.013, 3.281           |
|     | SEAS+NAS      | 3.348   | 3.324                    | −3.396, −3.432         | 3.398, 3.422           |
|     | DD-SEAS       | 3.519   | 3.503                    | −2.410, −3.214         | 2.397, 3.206           |
|     | 2SEAS         | 3.571   | 3.542                    | −3.443, −3.438         | 3.448, 3.442           |
| 3   | CHS-LC        | 3.415   | 3.752                    | 3.402, −2.273, 3.398   | 2.828, 3.261, 2.79     |
|     | CHS-ZZC       | 4.734   | 5.524                    | −3.156, −0.084, 3.306  | 2.8, 3.017, 2.805      |
|     | SEAS-ZZC      | 6.180   |                         |                        | 2.933, 3.050, 2.970    |
| 4   | CHS-LC        | 4.712   | 5.064                    | −3.075, −3.459, 3.463, 2.990 | 3.509, 3.207, 3.130, 3.497 |
|     | CHS-ZZC       | 7.537   | 8.411                    | −2.700, −2.729, 2.941, 2.331 | 3.350, 2.871, 2.878, 3.302 |
|     | SEAS-ZZC      | 8.646   |                         |                        | 3.125, 3.302, 3.016, 3.342 |

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tions, the Fe/GNR was less stable than the Ni/GNR, a finding that was repeated for \( n = 2, 3, \) and 4 and which is in keeping with results for TM adsorption on graphene.\(^{58}\)

**Figures 1(a)–1(c)** show the spin density and magnetic moment results for Fe(CHS)/Ferro-F, Ni(SCBS)/Ferro-A, and Fe(SEAS)/Ferro-F, respectively, after full relaxation; the re-

**PDOS (states/eV)**

**E-\(E_F\) (eV)**

**FIG. 2.** (Color online) Ni and Fe PDOSs of TM(CHS)/Ferro-A and TM(SEAS)/Ferro-A (TM=Ni,Fe). The PDOS delta functions have been replaced by Gaussian functions of finite breadth.
remaining results are included in the supplementary material. At the CHS, the magnetic moment of the Ni atom in Ni/CHS/Ferro-A was zero due to hybridization between the Ni 3d and nearest-neighbor C 2p orbitals, although in the less stable Ni/CHS/Ferro-F it had a small magnetic moment with AFM coupling to the edge C atoms. By contrast, the Fe atom had an appreciable magnetic moment in both Fe/CHS/Ferro-A and Fe/CHS/Ferro-F [see Table I and Fig. 1(a)], with ferromagnetic (FM) coupling to the edge C atoms in the latter. The energetic disadvantage of Fe/CHS/Ferro-A would seem to be due to the Fe atom not being able to couple ferromagnetically to both edges; of course, no such frustration can occur in Ni/CHS/Ferro-A, in which the magnetic moment of the Ni atom is zero. At an SCBS, an Ni adatom had a slightly larger magnetic moment than at the CHS due to a lesser degree of hybridization and coupled ferromagnetically to the nearest edge in both Ni(SCBS)/Ferro-A and Ni(SCBS)/Ferro-F [see Table I and Fig. 1(b)]; however, both these structures were less stable than their CHS analogs. The most stable single-adatom configurations featured the Ni or Fe atoms at SEAS, and in both cases Ferro-A was just marginally more stable than Ferro-F. The magnetic moments of Ni in Ni(SEAS)/Ferro-A and Ni(SEAS)/Ferro-F, 0.51 \( \mu_B \) and 0.47 \( \mu_B \), respectively, are in keeping with the values predicted by Rigo et al., 0.53 \( \mu_B \) and 0.47 \( \mu_B \). The stronger magnetic character of Fe is reflected by magnetic moments of 3.08 \( \mu_B \) in Fe(SEAS)/Ferro-A and 3.07 \( \mu_B \) in Fe(SEAS)/Ferro-F [see Table II and Fig. 1(c)].

Figure 2 shows the projected density of states (PDOS) of Ni and Fe atoms adsorbed on Ferro-A at the CHS and at a SEAS. At the CHS, the Ni PDOS below the Fermi level \( E_F \) is composed of \( d \)-type states resulting from hybridization between the 3d orbitals of the Ni adatom and the nearest-neighbor C 2p orbitals, which lowers the lower limit of the effective \( d \) band to approximately 4 eV below \( E_F \). Equal spin-up and spin-down densities give a zero spin magnetic moment. At the SEAS, there are unoccupied spin-down...
$d$-type states in an energy range of about 0–2 eV above $E_F$, in consonance with the nonzero spin magnetic moment of the Ni adatom at this position. Moreover, the unoccupied $p$ orbitals are now delocalized $\pi'$ orbitals. When the adatom is Fe at the CHS, delocalized unoccupied $\pi'$ orbitals are accompanied by significant unoccupied spin-up and spin-down $d$-type state densities around 0.8 and 0.0 eV above $E_F$, respectively, while at the SEAS the two main $d$-type peaks of the spin-up and spin-down densities are located within windows about 2 eV wide around 2.4 and 0 eV below $E_F$, respectively.

The five two-adatom configurations investigated had adatoms at the CHS and at a neighboring hole site closer to one of the edges of the ribbon (CHS+NHS), at a SEAS and a neighboring atop site closer to the center of the ribbon (SEAS+NAS), at two neighboring SEAS (2SEAS), at a single SEAS, in a double-decker configuration with one of the two adatoms atop the other (DD-SEAS), and in a similar double-decker configuration at the CHS (DD-CHS). These last two configurations were included to allow comparison with the finding of Johll et al.\(^{58}\) that TM dimers on graphene bind most stably in DD-CHS-like configurations. Tables I and II list postrelaxation energies and the spin magnetic moments of adatoms and edge carbons, and Figs. 3(a) and 3(b) show spin density and magnetic moment results for Fe$_2$(CHS+NHS)/Ferro-F and Fe$_2$(SEAS+NAS)/Ferro-F (the remainder are included in the supplementary material\(^{57}\)).

In all five Ni pair configurations, the Ferro-A configuration of the GNR was slightly more stable than the Ferro-F configuration. In the CHS+NHS configuration, both Ni atoms behaved similarly to single Ni atoms at the CHS, with zero or very small magnetic moments; in the SEAS+NAS configuration, both Fe atoms had magnetic moments of about 3.4$\mu_B$ regardless of the GNR configuration, and in the 2SEAS configuration (the most stable), both always had magnetic moments of about 3.44$\mu_B$. The magnetic moments of the two adatoms in the double-decker configurations were much more similar than in the case of Ni, but differed more than in the other configurations (by 0.8$\mu_B$ in DD-SEAS).

Note that in DD-CHS configuration, both Ni$_2$/Ferro-F and Fe$_2$/Ferro-F had adsorption energies and magnetic moments similar to those reported for a double-decker configuration at a hole site of graphene: 3.58 eV, 1.29$\mu_B$ and 0.73$\mu_B$ for Ni, and 3.0 eV, 3.48$\mu_B$ and 2.76$\mu_B$ for Fe.\(^{58}\)

The three- and four-adatom configurations investigated were, before relaxation, linear and zigzag chains (LCs and ZZCs) with an atom at the CHS and the other atoms at neighboring hole sites or (for Fe ZZCs) an atom at a SEAS and the other atoms at atop sites nearer the center of the GNR [see Figs. 4(a), 4(b), and 5 and the supplementary material\(^{57}\)]. Ferromagnetically coupled ZZCs are the most stable configurations of free-standing Ni and Fe chains of infinite length.\(^{60}\) Note that, in view of the preference of Fe and Ni dimers for the 2SEAS configuration, none of the three- or four-adatom structures studied is likely to be the ground state structure for that number of adatoms. It seems probable that the adatoms of the ground state structures all occupy SEASs, and for a study of such structures to prevent interactions between the adstructure and its images in neighboring supercells it would be necessary to use a supercell much larger than four unit cells. The structures we were able to examine in the present study nevertheless enable comparison between LCs and ZZCs and between Fe ZZCs in more central and more lateral locations, as well as comparison of Fe with Ni. Tables I and II list postrelaxation energies and spin magnetic moments, and Figs. 4(a), 4(b), and 5 show spin densities and magnetic moments across the GNR for Fe$_2$(CHS+NHS)/Ferro-A there is FM coupling between the CHS atom and one edge, and AFM coupling between this atom and the other edge, between the NHS atom and its nearest edge, and between the two Fe atoms. In the SEAS+NAS configuration, both Fe atoms had magnetic moments of about 3.4$\mu_B$ regardless of the GNR configuration, and in the 2SEAS configuration (the most stable), both always had magnetic moments of about 3.44$\mu_B$. The magnetic moments of the two adatoms in the double-decker configurations were much more similar than in the case of Ni, but differed more than in the other configurations (by 0.8$\mu_B$ in DD-SEAS).

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The three- and four-adatom configurations investigated were, before relaxation, linear and zigzag chains (LCs and ZZCs) with an atom at the CHS and the other atoms at neighboring hole sites or (for Fe ZZCs) an atom at a SEAS and the other atoms at atop sites nearer the center of the GNR [see Figs. 4(a), 4(b), and 5 and the supplementary material\(^{57}\)]. Ferromagnetically coupled ZZCs are the most stable configurations of free-standing Ni and Fe chains of infinite length.\(^{60}\) Note that, in view of the preference of Fe and Ni dimers for the 2SEAS configuration, none of the three- or four-adatom structures studied is likely to be the ground state structure for that number of adatoms. It seems probable that the adatoms of the ground state structures all occupy SEASs, and for a study of such structures to prevent interactions between the adstructure and its images in neighboring supercells it would be necessary to use a supercell much larger than four unit cells. The structures we were able to examine in the present study nevertheless enable comparison between LCs and ZZCs and between Fe ZZCs in more central and more lateral locations, as well as comparison of Fe with Ni. Tables I and II list postrelaxation energies and spin magnetic moments, and Figs. 4(a), 4(b), and 5 show spin densities and magnetic moments across the GNR for
The geometries of Ni\(_3\) and Ni\(_4\) CHS-LCs and of Ni\(_3\) CHS-ZZCs were hardly altered by relaxation, but in Ni\(_4\) CHS-ZZCs the Ni atoms moved to bridge sites defining a rhom-

**FIG. 6.** (Color online) Ni and Fe PDOS of Ni\(_n\) (CHS-ZZC)/Ferro-A and Fe\(_n\) (CHS-ZZC)/Ferro-F (n=3,4) after full relaxation. The PDOS delta functions have been replaced by Gaussian functions of finite breadth.

Fe\(_3\) (CHS-ZZC)/Ferro-F, Fe\(_4\) (CHS-ZZC)/Ferro-F, and Fe\(_4\) (SEAS-ZZC)/Ferro-F, respectively; for other results, see the supplementary material.\(^{57}\)
Fe₄ CHS-ZZC Ferro-F

Ni₂ SEAS-NAS Ferro-A

Fe₂ SEAS-NAS Ferro-A

Ni₃ CHS-ZZC Ferro-A

Fe₄ CHS-ZZC Ferro-F

FIG. 7. (Color online) Electronic band structures of (a) Ni₂(SEAS-NAS)/Ferro-A and Ni₃(CHS-ZZC)/Ferro-A and (b) Fe₂(SEAS-NAS)/Ferro-A and Fe₄(CHS-ZZC)/Ferro-F. Continuous red lines correspond to spin-up bands; dashed blue lines correspond to spin-down bands.

boid corresponding approximately to a graphene unit cell. CHS-ZZCs were more stable than CHS-LCs, and, in keeping with the results for Ni/GNR and Ni₂/GNR, Ferro-A was more stable than Ferro-F.

Like their Ni analogs, Fe₃ and Fe₄ CHS-LCs retained their structures upon relaxation, and like their centrally located Fe and Fe₂ homologs were more stable as Ferro-F than as Ferro-A. Ferro-F was also the more stable GNR configuration in Fe₃ and Fe₄ ZZCs, but the Fe atoms of these ZZCs adopted geometries that were similar to the triangle and tetrahedron of free-standing Fe₂ and Fe₄ clusters, with one or more atoms separated from the GNR. For example, the bond lengths in Fe₃(CHS-ZZC)/Ferro-F [Fig. 4(a)] were 2.27, 2.28, and 2.30 Å, and its atomic spin magnetic moments were 2.8μ₉, 3.0μ₉, and 2.8μ₉ (Table II; cf. 2.12, 2.40, and 2.40 Å and 3.14μ₉, 3.15μ₉, and 3.70μ₉ for free-standing Fe₃ as predicted by SIESTA/GGA calculations); the bond lengths and atomic spin magnetic moments of Fe₄(CHS-ZZC)/Ferro-F [Fig. 4(b)] were 2.35, 2.35, 2.36, 2.38, 2.39, and 2.52 Å and 3.35μ₉, 2.87μ₉, 2.88μ₉, and 3.30μ₉, respectively [Table II; cf. 4×2.31 and 2×2.66 Å and (4×3.50)μ₉ for free-standing Fe₃]. Similar distortions were observed in Fe₃(SEAS-ZZC)/Ferro-F and Fe₄(SEAS-ZZC)/Ferro-F (Fig. 5), which were more stable than their CHS-ZZC and CHS-LC analogs and had atomic spin magnetic moments even closer to those of the free-standing clusters. Thus the geometries of the most stable Fe₃/GNR and Fe₄/GNR structures that were investigated were not imposed by the planar geometry of the GNR but by those of the free Fe clusters, which underlines the weakness of the Fe-GNR interactions in comparison with the Fe-Fe interaction. That the atomic spin magnetic moments are so much larger in the Fe nanostructures than in their Ni analogs is attributable to the former, but not the latter, having a large excess of spin-down d-type states above Eₚ, as is illustrated in Fig. 6 by the cases of Ni₃(CHS-ZZC)/Ferro-A and Fe₄(CHS-ZZC)/Ferro-F (n=3, 4).

As was indicated in Sec. I, the carbon atoms of each edge of a hydrogen-passivated zigzag GNR all have the same spin, and the GNR is metallic or semiconducting depending on whether the spins at the two edges are parallel (Ferro-F) or antiparallel (Ferro-A). In both cases, there are flat energy bands near Eₚ that correspond to the π and π' orbitals of the edge atoms. After computing the electronic band structure of Ni/GNR systems with the Ni atom at various different adsorption sites, Rigo et al. reported that the electronic character of the GNR is not altered by adsorption of a single Ni atom, although its presence does perturb the energy bands. In this study we found that the same holds when two, three, or four Ni or Fe atoms are adsorbed, at least when the initial adsorption configurations are as in this study, as is shown in Figs. 7(a) and 7(b) for the cases...
of $\text{Ni}_2(\text{SEAS}+\text{NAS})$/Ferro-A, $\text{Ni}_4(\text{CHS-ZZC})$/Ferro-A, $\text{Fe}_2(\text{SEAS}+\text{NAS})$/Ferro-A, and $\text{Fe}_4(\text{CHS-ZZC})$/Ferro-F. Note that, as is expected given the computed PDOS [see Fig. 6 for the cases of $\text{Ni}_4(\text{CHS-ZZC})$/Ferro-A and $\text{Fe}_4(\text{CHS-ZZC})$/Ferro-F], the $\text{Fe}_n$/GNR systems show more splitting indicative of interaction between spin-up and spin-down bands and that the flat sections of the energy bands near $E_F$ in $\text{Ni}_n$/Ferro-A configurations extend to higher wave numbers as the number of adatoms increases, at the same time slightly reducing the gap between the states above and below $E_F$.

**IV. SUMMARY AND CONCLUSIONS**

In this work, using the computational package SIESTA\textsuperscript{46} with standard nonlocal norm-conserving pseudopotentials\textsuperscript{49} and the GGA to exchange and correlation,\textsuperscript{48} we performed extensive ab initio DFT calculations to investigate the structural, magnetic, and electronic properties of $\text{Ni}_n$ and $\text{Fe}_n$ nanostructures ($n=1-4$) that were adsorbed on hydrogen-passivated (10,0) zigzag GNRs. $\text{Ni}_n$ clusters were more strongly bound than $\text{Fe}_n$ clusters, and their atoms had much smaller spin magnetic moments. The difference in binding energies also explains why zigzag $\text{Ni}_2$ and $\text{Ni}_4$ chains placed at GNR hole sites retained close contact with the GNR upon relaxation, whereas the analogous Fe chains adopted geometries similar to those of free-standing Fe clusters, with one or more atoms lifted away from the GNR. An extensive study of adsorbed dimers shows that although, for both $\text{Ni}_2$ and $\text{Fe}_2$, the perpendicular DD-CHS and DD-SEAS configurations are, respectively, more stable than the epitaxial CHS+ NHS and SEAS+NAS configurations, the most stable configurations of the dimers are those with the two atoms at adjoining SEAs. Like the pristine GNR, $\text{Ni}_n$/GNR systems were more stable in Ferro-A than in Ferro-F configuration, whereas among $\text{Fe}_n$/GNR systems this was only found for one- or two-atom adstructures at subedge or near-subedge atop sites. The conductivity type of the GNR (metallic in Ferro-F configuration, semiconducting in Ferro-A configuration) was unaltered by adsorption of up to four Ni or Fe atoms.

The results presented in this paper show that, as in other TM/all-carbon systems,\textsuperscript{3,32-41,51-53} the structural, magnetic, and electronic properties of TM/GNR systems depend to a large extent on the nature of the TM atom. Accordingly, further simulations, as well as theoretical and experimental work, will be necessary for satisfactory understanding of the behavior of TM/GNR systems in general.

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