

Freestanding n-Doped Graphene via Intercalation of Calcium and Magnesium into the Buffer Layer–SiC(0001) Interface

Jimmy C. Kotsakidis,* Antonija Grubišić-Čabo, Yuefeng Yin, Anton Tadich, Rachael L. Myers-Ward, Matthew DeJarld, Shojan P. Pavunny, Marc Currie, Kevin M. Daniels, Chang Liu, Mark T. Edmonds, Nikhil V. Medhekar, D. Kurt Gaskill, Amadeo L. Vázquez de Parga,* and Michael S. Fuhrer*



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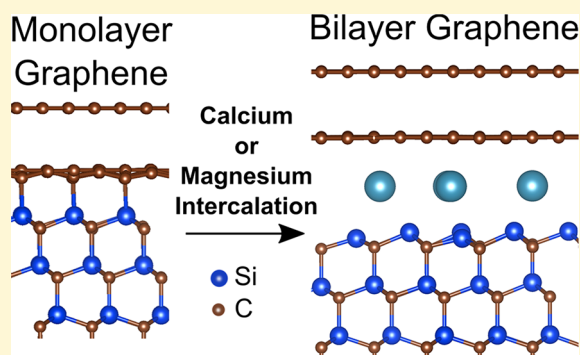


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ABSTRACT: The intercalation of epitaxial graphene on SiC(0001) with Ca has been studied extensively, yet precisely where the Ca resides remains elusive. Furthermore, the intercalation of Mg underneath epitaxial graphene on SiC(0001) has not been reported. Here, we use low energy electron diffraction, X-ray photoelectron spectroscopy, secondary electron cutoff photoemission, and scanning tunneling microscopy to elucidate the physical and electronic structures of both Ca- and Mg-intercalated epitaxial graphene on 6H-SiC(0001). We find that Ca intercalates underneath the buffer layer and bonds to the Si-terminated SiC surface, breaking the C–Si bonds of the buffer layer, i.e., “freestanding” the buffer layer to form Ca-intercalated quasi-freestanding bilayer graphene (Ca-QFSBLG). The situation is similar for the Mg-intercalation of epitaxial graphene on SiC(0001), where an ordered Mg-terminated reconstruction at the SiC surface is formed and Mg bonds to the Si-terminated SiC surface are found, resulting in Mg-intercalated quasi-freestanding bilayer graphene (Mg-QFSBLG). Ca-intercalation underneath the buffer layer has not been considered in previous studies of Ca-intercalated epitaxial graphene. Furthermore, we find no evidence that either Ca or Mg intercalates between graphene layers. However, we do find that both Ca-QFSBLG and Mg-QFSBLG exhibit very low work functions of 3.68 and 3.78 eV, respectively, indicating high n-type doping. Upon exposure to ambient conditions, we find Ca-QFSBLG degrades rapidly, whereas Mg-QFSBLG remains remarkably stable.



Graphene, the two-dimensional (2D) allotrope of carbon consisting of a network of hexagonally bonded carbon atoms,¹ possesses radically different properties than those of its bulk form (graphite), owing to its Dirac cone band structure at low energy.² In addition, considerable research has been conducted on the modification of graphene's properties via doping using techniques such as electrostatic gating,³ surface decoration,^{4,5} structure modification,⁶ and intercalation.⁷ Of these methods, intercalation (i.e., insertion of atomic or molecular species under or in between graphene layers) has proven a powerful method for achieving the highest doping levels in graphene.^{8–10} Thus, intercalation has enabled various investigations into the fundamental physics of superconductivity^{8,11,12} and many-body interactions^{8–10} as well as potential applications such as highly conductive and transparent electrodes¹³ and energy storage.¹⁴

Following the discovery of superconducting Ca-intercalated graphite (CaC₆)—which exhibits the highest superconducting transition temperature ($T_c = 11.5$ K) among the graphite intercalation compounds—intercalation of the alkaline-earth Ca has been of particular interest in attempts to achieve superconductivity¹² and extremely high doping in graphene.⁸

Superconductivity with a high T_c via conventional electron–phonon coupling¹⁵ or unconventional electron–electron coupling^{16,17} has been predicted in highly n-type doped graphene if the Fermi level (E_F) is shifted high into the conduction band near the Van Hove singularity. This scenario has analogies to the high- T_c cuprates, in which superconductivity is associated with the interaction between E_F and the Van Hove singularity.¹⁸ This physical scenario in graphene was first observed by McChesney et al.⁸ using submonolayer graphene on SiC(0001) intercalated with Ca (and the surface decorated with Ca and K), and it was subsequently suggested that the sample could exhibit superconductivity. More recently, the superconductivity of Ca-intercalated bilayer graphene was reported by Ichinokura et al.¹² with $T_c \approx 2$ K.

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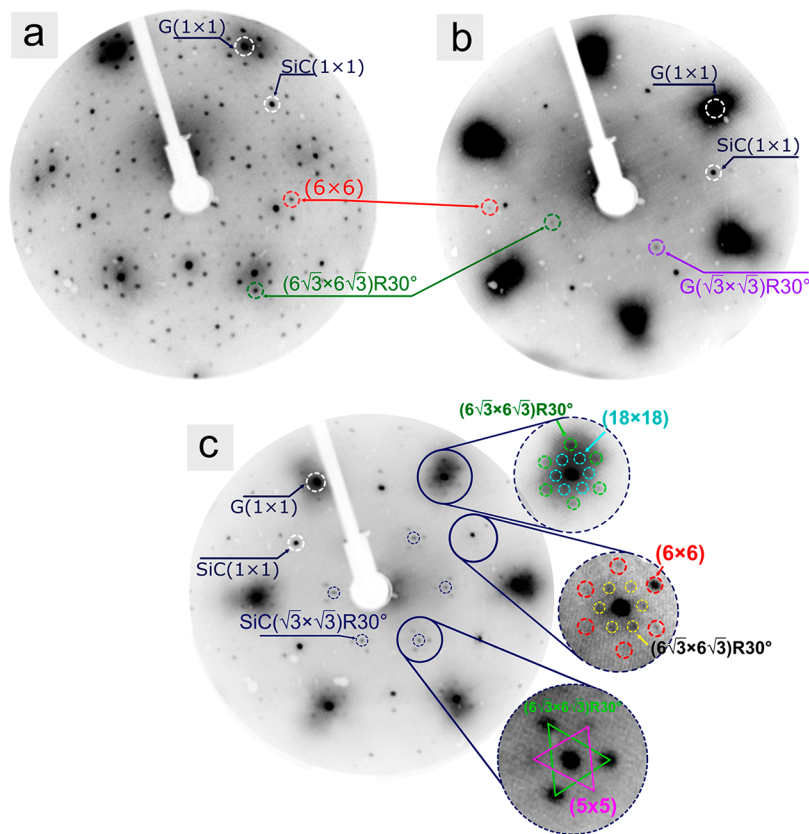


Figure 1. Low energy electron diffraction (LEED) patterns at electron energy of 100 eV. (a) Pristine epitaxial monolayer graphene on SiC(0001) (EMLG) showing graphene ($G(1 \times 1)$) and SiC ($SiC(1 \times 1)$) spots, as well as $(6\sqrt{3} \times 6\sqrt{3})R30^\circ$ and (6×6) spots arising from the buffer layer. (b) Ca-QFSBLG showing the emergence of $(\sqrt{3} \times \sqrt{3})R30^\circ$ spots with respect to the $G(1 \times 1)$ spots ($G(\sqrt{3} \times \sqrt{3})R30^\circ$). (c) Mg-QFSBLG with spots corresponding to a $(\sqrt{3} \times \sqrt{3})R30^\circ$ reconstruction relative to the $SiC(1 \times 1)$ spots ($SiC(\sqrt{3} \times \sqrt{3})R30^\circ$), along with (5×5) , (18×18) (around the $G(1 \times 1)$), and $(6\sqrt{3} \times 6\sqrt{3})R30^\circ$ (around the $SiC(1 \times 1)$) spots. In both Ca-QFSBLG (b) and Mg-QFSBLG (c) we observe the suppression of $(6\sqrt{3} \times 6\sqrt{3})R30^\circ/(6 \times 6)$ spots related to the buffer layer and increase in brightness of the $G(1 \times 1)$ with respect to the $SiC(1 \times 1)$ spots, as compared to pristine EMLG in (a).

The Ca-intercalation experiments performed to date have utilized large-area graphene on SiC,^{8,11,12,19–21} as it enables a wide range of surface probes such as scanning tunneling microscopy (STM), low energy electron diffraction (LEED), X-ray photoelectron spectroscopy (XPS), and angle resolved photoemission spectroscopy (ARPES). Graphene synthesis on SiC occurs via the sublimation of Si, where the remaining C naturally forms a hexagonal carbon network. This first layer of carbon is often termed the “zero layer” or “buffer layer”²² and is partially bonded to the topmost silicon on SiC(0001). Continued sublimation forms another buffer layer beneath the first, releasing the C–Si bonds of the original buffer layer, which then becomes monolayer graphene.

The structure of Ca-intercalated graphene on SiC is less clear, with disagreement regarding the location of the intercalated Ca. For instance, McChesney et al.⁸ implied the position of the Ca intercalant in their partial monolayer graphene was between the first graphene layer and the buffer layer. Kanetani et al.¹⁹ and Ichinokura et al.¹² studied the Ca-intercalated bilayer graphene on SiC(0001), and based on LEED and reflection high energy electron diffraction data concluded that Ca was intercalated between the first and second graphene layers. A correction to this interpretation was recently published by Endo et al.,²⁰ in which it was determined that the Ca intercalant position for bilayer graphene on SiC was between the buffer layer and the first graphene layer.

The calcium intercalation of graphite^{23,24} and graphene^{8,12,19–21,25,26} has been extensively studied and can highly n-type dope these systems.⁸ On the other hand, the alkaline-earth magnesium has not been investigated as an intercalant in graphene on silicon carbide systems. Some reasons for this may be due to the well-known experimental knowledge that metallic magnesium does not intercalate graphite²⁷ and also may be exacerbated by magnesium’s well-known high vapor pressure.²⁸ More recent theoretical considerations have substantiated the difficulty of magnesium intercalation for a range of different materials (including graphite) and have implied that the difficulty of Mg intercalation is a result of its weak binding forces to the target substrate.²⁹ Thus, it is likely that for these reasons the intercalation of graphene on SiC with magnesium was not considered.

Despite these challenges, magnesium has been intercalated underneath graphene on Ni(111)³⁰ and between layers of a “graphite-like” material composed of boron carbon and nitrogen.³¹ Furthermore, magnesium intercalation for energy storage applications has long been sought after to replace lithium.³² But in this case, magnesium forms part of an electrolyte or organic molecule.^{33,34} As a rule, it has generally been understood that Mg intercalation of pure carbon systems is not possible, but the fact that intercalation of graphene on SiC(0001) systems can occur at the buffer layer–SiC(0001) interface³⁵ implies that the “traditional” rules of intercalation

from experiments with graphite in which the intercalant is inserted between graphite layers may not apply (as was the case with other substrates and modified materials^{30,31}).

In this communication, we present new findings on the intercalation structure of two alkaline-earth metals—Ca and Mg—via the intercalation of epitaxial monolayer graphene (EMLG) (and hydrogen intercalated “quasi-freestanding” bilayer graphene, “H-QFSBLG”—see [Supporting Information Section 1.3](#)) on 6H-SiC(0001). We show that Ca intercalates underneath the buffer layer of EMLG, bonding with the Si-terminated surface of the SiC(0001) and “quasi-freestanding” the buffer layer to create another graphene layer, i.e., forming quasi-freestanding bilayer graphene (QFSBLG) above the Ca–Si layer, which we term Ca-QFSBLG. The intercalated Ca forms a new ordered ($\sqrt{3} \times \sqrt{3}$)R30° interface reconstruction with respect to the graphene. The observations are supported by density functional theory (DFT) calculations, which show Ca under the buffer layer as the lowest energy configuration. In addition, we report for the first time on the intercalation of EMLG with Mg. Similar to Ca, Mg intercalates underneath the buffer layer of EMLG, bonding with the Si surface of SiC and freestanding the buffer layer to again form QFSBLG, which we term Mg-QFSBLG. Here, stronger Mg–Si interactions produce an ordered Mg-terminated ($\sqrt{3} \times \sqrt{3}$)R30° reconstruction with respect to the SiC rather than the graphene. As in the Ca-intercalation experiment, we find no evidence to suggest the formation of an Mg-carbide or intercalation of the Mg in between graphene layers. Both Ca- and Mg-intercalated systems result in the formation of bilayer graphene with exceptionally low work functions (3.68 and 3.78 eV, respectively). However, while the Ca-QFSBLG system is not air-stable, we find that the Mg-QFSBLG system shows remarkable stability to ambient conditions, with little change in photoemission spectra after ≈ 6 h of exposure to ambient conditions. Consequently, Mg intercalation could offer a possible route to highly electron doped, low work function, and air-stable graphene.

■ EXPERIMENTAL OVERVIEW

The EMLG samples were prepared using a previously described method (further details can be found in [Methods](#)).³⁶ The EMLG samples are majority monolayer, with inclusions of bilayer and trilayer regions. However, our conclusions are not affected by the number of graphene layers in the starting sample, as (1) the LEED and XPS analysis of the structure and chemistry at the intercalated buffer layer/SiC interface is insensitive to the number of graphene overlayers and (2) previous studies have shown that bilayer regions (step edges) of such samples do not include a buffer layer³⁷ and subsequent intercalation (with hydrogen) results in near-total conversion of the samples to QFSBLG.³⁸ Ca and Mg intercalation for XPS and LEED measurement was carried out at the Australian Synchrotron soft X-ray beamline end station under ultrahigh vacuum (UHV) conditions ($\approx 1 \times 10^{-10}$ mbar). Low temperature STM was carried out at Monash University on Ca-QFSBLG prepared in situ, under UHV ($\approx 1 \times 10^{-10}$ mbar). The Mg-QFSBLG sample analyzed with the STM was prepared by Mg intercalation at the Australian Synchrotron and then transferred in ambient air to the STM UHV chamber.

We have additionally studied Ca and Mg intercalation of H-QFSBLG, prepared using a previously described method (see [Methods](#) for details on growth).³⁸ We found no evidence for Mg intercalation of H-QFSBLG (see [Supporting Information Section 2.3](#)), but were able to intercalate Ca to transform H-

QFSBLG to Ca-QFSBLG, with substantially similar properties to Ca-QFSBLG formed from EMLG (discussed further in [Supporting Information Section 1.3](#)). Details of all experiments are found in [Methods](#).

■ RESULTS AND DISCUSSION

Low Energy Electron Diffraction (LEED) of Ca- and Mg-Intercalated EMLG on SiC(0001). [Figure 1](#) shows LEED images taken at an electron energy of 100 eV. [Figure 1a](#) shows a typical EMLG sample with graphene ($G(1 \times 1)$) and SiC ($SiC(1 \times 1)$) spots, as well as the expected ($6\sqrt{3} \times 6\sqrt{3}$)R30° and (6×6) spots which originate from the buffer layer–SiC interaction.³⁹ The Ca- and Mg-intercalated samples are shown in [Figure 1b,c](#), respectively, and share important features. First, the relative intensities of the SiC(1×1) to the $G(1 \times 1)$ spots after Ca- and Mg-intercalation are greatly reduced. This is in contrast to the similar intensities of the $G(1 \times 1)$ and SiC(1×1) spots in pristine EMLG prior to intercalation ([Figure 1a](#)). Second, the ($6\sqrt{3} \times 6\sqrt{3}$)R30° spots are strongly suppressed in both the Ca- and Mg-intercalated samples ([Figure 1b,c](#), respectively), when compared to pristine EMLG ([Figure 1a](#)). These observations are similar to the case of H-QFSBLG after H-intercalation of EMLG, which is known to decouple the buffer layer,⁴⁰ and, thus, suggests that the buffer layer of the EMLG is similarly decoupled after Ca/Mg-intercalation and transformed to QFSBLG (i.e., Ca/Mg-QFSBLG). Consequently, our LEED results present the first evidence that intercalation of Ca and Mg occurs between the SiC(0001) surface and the buffer layer, in disagreement with previous reports. We note that the weak ($6\sqrt{3} \times 6\sqrt{3}$)R30° spots after Ca/Mg-intercalation (seen in [Figures 1b,c](#)) are also observed after H-intercalation⁷ and likely result from incomplete (i.e., partial) intercalation.⁴¹

Furthermore, [Figure 1b](#) shows the emergence of ($\sqrt{3} \times \sqrt{3}$)R30° spots with respect to the $G(1 \times 1)$ spots after Ca-intercalation (which we label “ $G(\sqrt{3} \times \sqrt{3})R30^\circ$ ”). Previous Ca-intercalation studies¹⁹ also reported $G(\sqrt{3} \times \sqrt{3})R30^\circ$ spots and interpreted these as due to Ca atoms intercalating between the graphene layers. Yet the $G(\sqrt{3} \times \sqrt{3})R30^\circ$ spots are not definitive evidence for intercalation between the graphene layers, as their emergence has been observed after the intercalation of Yb in buffer-layer-only samples to form “quasi-freestanding” monolayer graphene on SiC.¹⁰ Thus, it is plausible that the $G(\sqrt{3} \times \sqrt{3})R30^\circ$ spots instead describe a Ca-QFSBLG structure. As we discuss further below, the prior interpretation is incorrect, and Ca (and Mg) indeed lie between the SiC(0001) surface and the buffer layer.

In contrast, the Mg-intercalated EMLG sample in [Figure 1c](#) shows the emergence of ($\sqrt{3} \times \sqrt{3}$)R30° spots with respect to the SiC(1×1) spots, not the $G(1 \times 1)$ spots (i.e., SiC($\sqrt{3} \times \sqrt{3}$)R30°). Such spots were observed by Stöhr et al.⁴² and Kim et al.⁴³ after intercalation of the buffer layer only on SiC with Bi and In, respectively, and by Xia et al.⁴⁴ after Si-intercalation of EMLG. The SiC($\sqrt{3} \times \sqrt{3}$)R30° spots have also been observed in the past with Si adatoms bonded via the dangling bonds of the Si surface of SiC.⁴⁵ Thus, the observation of these SiC($\sqrt{3} \times \sqrt{3}$)R30° spots strongly indicates that Mg has intercalated beneath the buffer layer, releasing the buffer layer–SiC bonds to create Mg-QFSBLG, in agreement with the disappearance of the ($6\sqrt{3} \times 6\sqrt{3}$)R30°/(6×6) and brightness increase in $G(1 \times 1)$ spots relative to the SiC(1×1) spots.

Also visible in [Figure 1c](#) are extra spots concentric around both the $G(1 \times 1)$ and SiC(1×1) spots. These spots are shown more clearly in the magnified and enhanced views in the right

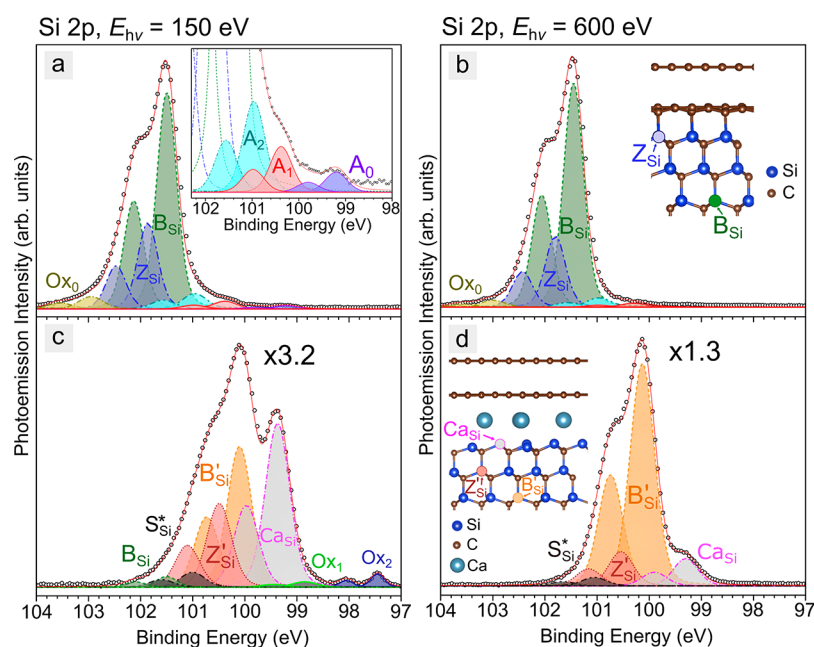


Figure 2. X-ray photoemission spectra showing the Si 2p core level of pristine epitaxial monolayer graphene on SiC(0001) (EMLG) and Ca-intercalated EMLG (Ca-QFSBLG) at two incident X-ray energies (E_{hv}): 150 eV (left, surface sensitive) and 600 eV (right, bulk substrate sensitive). (a, b) Pristine EMLG before intercalation showing all components. Component B_{Si} is the bulk component of SiC, whereas component Z_{Si} is a more surface SiC component. The approximate atom locations of components B_{Si} and Z_{Si} are shown in the inset of b. (c, d) EMLG after Ca-intercalation (Ca-QFSBLG) and new components B'_{Si} , Z'_{Si} , S^*_{Si} , and Ca_{Si} . Components Z_{Si} and B_{Si} have been shifted to lower binding energy and are now labeled Z'_{Si} and B'_{Si} , respectively. c has its y-scale magnified $\times 3.2$ from a, and d has its y-scale magnified $\times 1.3$ from b. The approximate atom positions of the components are shown in the inset of d; see text for further explanation of the components.

Table 1. Summary of the Fitting Parameters for the Major Components in Figure 2^a

EMLG, Si 2p		(a, b) pristine EMLG				(c, d) second Ca intercalation			
component	E_{hv} (eV)	E_B (eV) $2p_{3/2}$	E_B (eV) $2p_{1/2}$	RI	G_w (eV)	E_B (eV) $2p_{3/2}$	E_B (eV) $2p_{1/2}$	RI	G_w (eV)
B_{Si}	150	101.50	102.13	1	0.4	101.45	102.05	0.016	0.4
	600	101.45	102.06	1	0.4	-	-	-	-
Z_{Si}	150	101.86	102.47	0.40	0.4	-	-	-	-
	600	101.80	102.43	0.32	0.4	-	-	-	-
Ox_0	150	102.95	103.55	0.06	0.5	-	-	-	-
	600	102.95	103.55	0.03	0.5	-	-	-	-
B'_{Si}	150	-	-	-	-	100.11	100.74	0.24	0.5
	600	-	-	-	-	100.13	100.74	0.68	0.5
Z'_{Si}	150	-	-	-	-	100.51	101.13	0.12	0.5
	600	-	-	-	-	100.54	101.16	0.10	0.5
S^*_{Si}	150	-	-	-	-	101	101.63	0.02	0.5
	600	-	-	-	-	101.05	101.65	0.026	0.5
Ca_{Si}	150	-	-	-	-	99.37	99.97	0.24	0.5
	600	-	-	-	-	99.3	99.9	0.08	0.5
Ox_1	150	-	-	-	-	98.85	99.45	0.008	0.5
	600	-	-	-	-	-	-	-	-
Ox_2	150	-	-	-	-	97.45	98.05	0.02	0.25
	600	-	-	-	-	-	-	-	-

^aBoth the Si $2p_{3/2}$ and the $2p_{1/2}$ peak locations are given, as well as the relative intensity (RI) of the $2p_{3/2}$ peaks as referenced to the bulk SiC peak B_{Si} corresponding to pristine SiC prior to Ca intercalation. G_w refers to the Gaussian FWHM for the Voigt fit (which was fixed to one of two values, except for component Ox_2), whereas the Lorentzian FWHM (W_L) was kept constant at 0.1 eV in all fits. The dashes correspond to no observation.

inset of Figure 1c. In regards to the $G(1 \times 1)$ spots, the new concentric spots correspond to an (18×18) reconstruction, rotated 30° with respect to the $(6\sqrt{3} \times 6\sqrt{3})R30^\circ$ spots. Observation of the (18×18) spots is consistent with the expected expansion of the Moiré pattern from the interaction of graphene with SiC(0001) from $(6\sqrt{3} \times 6\sqrt{3})R30^\circ$ to (18×18) upon the $(\sqrt{3} \times \sqrt{3})R30^\circ$ reconstruction of the surface

(i.e., $(\sqrt{3} \times \sqrt{3})R30^\circ \times (6\sqrt{3} \times 6\sqrt{3})R30^\circ = (18 \times 18)$). These LEED spots have been observed previously after the intercalation of Pt underneath graphene on SiC(0001), and their appearance was attributed to the concurrent formation of a Pt-silicide.⁴⁶ Similarly, we observe the appearance of $(6\sqrt{3} \times 6\sqrt{3})R30^\circ$ spots around the SiC(1 \times 1) spots corresponding to the expansion of the (6×6) Moiré by the $(\sqrt{3} \times \sqrt{3})R30^\circ$

reconstruction. Also seen are (5×5) spots in Figure 1c, but these were not found to have significance regarding the Mg-intercalation structure.³⁹

LEED spot patterns have elucidated the overlaying symmetries resulting from Ca- and Mg-intercalation of EMLG and suggest that both Ca and Mg intercalate underneath the buffer layer to form Ca-QFSBLG and Mg-QFSBLG. Nonetheless, LEED alone cannot determine the chemistry occurring underneath the graphene, and so we turn to XPS. Below, we first discuss the Si 2p and then the C 1s XPS spectra of Ca-QFSBLG (discussion of the O 1s and Ca 2p core levels can be found in the Supporting Information, Section 1.5), before discussing the surface morphology of Ca-QFSBLG as imaged by STM and density functional theory calculations concerning the predicted structure of Ca-intercalated EMLG. This discussion will then be repeated for Mg-QFSBLG (without the theoretical consideration), which we will show shares many similarities with Ca-QFSBLG.

X-ray Photoelectron Spectroscopy of Ca-QFSBLG

Here we present and discuss the XPS results for the C 1s and Si 2p core levels for the same EMLG sample, the LEED of which is shown in Figure 1b. H-QFSBLG samples were also transformed to Ca-QFSBLG by the same intercalation method used for the EMLG samples and showed similar XPS spectral features—see Supporting Information Section 1.3 for details.

Figure 2 shows the Si 2p core level XPS spectra—photoemission intensity as a function of binding energy, E_B —before and after Ca-intercalation. In all XPS spectra, experimental data points are shown as open black circles, and the final fit is overlaid as a red line. Each Si 2p component is comprised of $2p_{3/2}$ and $2p_{1/2}$ peaks colored identically to avoid confusion, and we quote only E_B values corresponding to the $2p_{3/2}$ peak. Fit parameters of the major components are given in Table 1; the full set of fit parameters (which includes the omitted first intercalation step) can be found in Supporting Information Section 1.1.

Figure 2a,b shows the Si 2p core level spectra of pristine EMLG. The tunability of the synchrotron source allowed different X-ray energies ($E_{hv} = 150$ eV, 600 eV) to be used in order to determine the surface and bulk nature of the various components and aided in spectrum deconvolution. Pristine EMLG shows two major components: B_{Si} ($E_B = 101.47 \pm 0.05$ eV) corresponds to “bulk” SiC^{7,47,48} and Z_{Si} ($E_B = 101.83 \pm 0.05$ eV) to surface Si bonded to the C in the buffer layer/zero layer.^{7,43,49} Further discussion concerning the component Z_{Si} can be found in Supporting Information Section 1.2. (The components corresponding to compounds present in both the Si 2p and the C 1s XPS spectra are designated using the same label, with different subscript labels, in order to distinguish the specific core level; i.e., B_{Si} and B_C are the bulk SiC signals in the Si 2p and C 1s spectra, respectively). We note here that the E_B value was calculated by averaging all measured values (including the values from the omitted first intercalation which can be found in the Supporting Information Section 1.1)—see Methods for further details. The corresponding atomic positions for the major components of pristine EMLG are shown schematically in the inset of Figure 2b. These positions are approximately determined by a calculation of the relative intensity ratio, RI_R , discussed in detail in Methods. The RI_R is a qualitative measure of surface sensitivity, with an $RI_R > 1$ indicating that the component is more toward the surface (see Methods and Supporting Information Section 1.1), and was calculated using the relative intensity (RI) referenced to the well-known bulk

component B_{Si} (or B_C in the case of C 1s spectra, see below), following closely the conventions used in ref 49. For instance, the RI_R of component Z_{Si} is $1.25 [RI(150 \text{ eV})/RI(600 \text{ eV}) = 0.4/0.32 = 1.25]$ and implies a more surface origin for this component. Additional components— Ox_0 , A_0 , A_1 , and A_2 —are seen with intensities $<8\%$ relative to component B_{Si} and likely result from oxygen contamination (Ox_0) and silicon adatoms (A_0 , A_1 , A_2). These components, along with components Ox_1 and Ox_2 (which are thought to arise from differing Ca–Si stoichiometry), are in small concentration and, thus, are not significant for the determination of the general Ca-intercalated structure. We refer the reader to Supporting Information Sections 1.2 and 1.3 for further discussion of these features.

Figure 2c,d shows the Si 2p XPS spectra of Ca-QFSBLG formed by Ca-intercalation of the sample in Figure 2a,b. We show here only the final Ca-intercalation step. The results of the intermediate intercalation step, which do not affect the conclusions presented here, can be found in Supporting Information Section 1.2. Nonetheless, immediately apparent in Figure 2c,d is the complete change in spectrum shape—the bulk (B_{Si}) and surface bulk (Z_{Si}) components have all but disappeared and have been replaced by several components at lower binding energies.

Component Ca_{Si} is highly surface-like, with an $RI_R = 4$. It is substantially shifted relative to component B_{Si} (and Z_{Si}) of pristine EMLG by $\Delta E_B = 2.18 \pm 0.11$ eV, suggesting a significant chemical change at the Si surface. Its binding energy of $E_B = 99.29 \pm 0.06$ eV is similar to that of a Ca-silicide.^{50,51} This is strong evidence for a Ca–Si bonding environment at the SiC surface underneath the graphene and buffer layer, and is in contrast with previous reports that Ca intercalates between the graphene layers,^{12,19} or between the buffer layer and the first graphene layer.^{8,20}

In fact, many previous reports on the intercalation of alkalis,^{52–54} transition metals,^{46,55,56} rare earths,^{9,10,57} and other elements^{49,58–60} have reported intercalation underneath the buffer layer (see ref 35 for a brief review of intercalation of graphene on SiC). Furthermore, many prior studies on the intercalation of graphene on SiC have specifically reported the formation of silicide-like compounds,^{46,56,60,61} and thus, it is not surprising that we observe a surface Si component matching closely in binding energy with that of a Ca-silicide. The observation of a Ca–Si interaction implies disruption of the Si–C bonds on the SiC(0001) surface with the C-rich buffer layer and is supported by the LEED intensity suppression of the ($6\sqrt{3} \times 6\sqrt{3}$)R30° spots (which arise from the buffer layer) and an increase in the intensity of the $G(1 \times 1)$ spots relative to the $SiC(1 \times 1)$ spots which indicates decoupling of the buffer layer (see Figure 1b). Both XPS and LEED observations are consistent with the formation of a Ca–Si compound and a new graphene layer.

Two other major peak components in Figure 2c,d include components B'_{Si} and Z'_{Si} located at binding energies of $E_B = 100.07 \pm 0.05$ eV and $E_B = 100.48 \pm 0.07$ eV, respectively. These new components are shifted equally to lower binding energies relative to B_{Si} and Z_{Si} by -1.40 ± 0.10 eV ($B_{Si} \rightarrow B'_{Si}$) and -1.35 ± 0.12 eV ($Z_{Si} \rightarrow Z'_{Si}$) and are separated equally in binding energies; 0.36 ± 0.1 eV ($Z_{Si} \rightarrow B_{Si}$) and $0.41 \text{ eV} \pm 0.12$ eV ($Z_{Si} \rightarrow B'_{Si}$) to within error. The RI_R of these components suggests that B'_{Si} ($RI_R = 0.35$) is in the bulk, while Z'_{Si} ($RI_R = 1.1$) is closer to the surface. This situation is illustrated with the atomic model inset in Figure 2d and further supports that components B_{Si} (Z_{Si}) and B'_{Si} (Z'_{Si}) are simply binding energy-

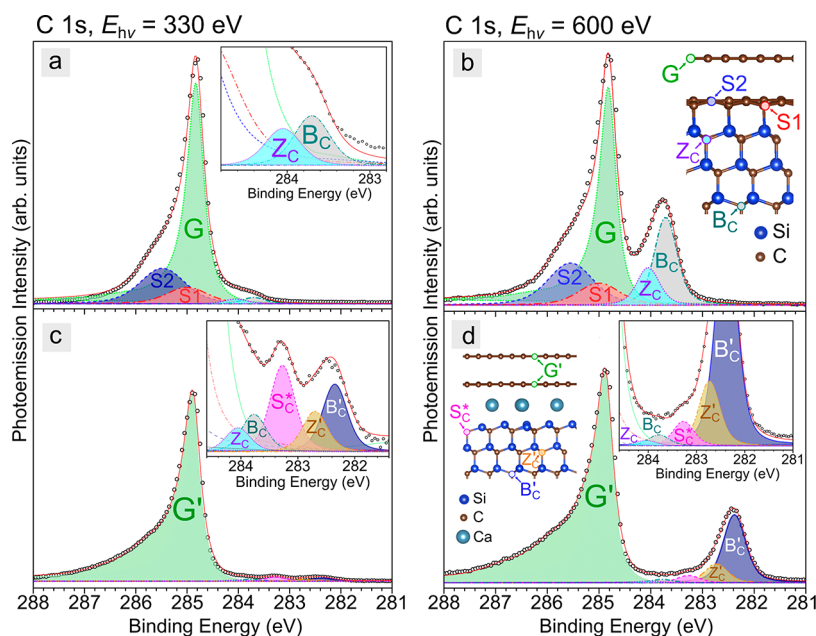


Figure 3. X-ray photoemission spectra showing the C 1s core level of pristine epitaxial monolayer graphene on SiC(0001) (EMLG) and Ca-intercalated EMLG (Ca-QFSBLG) at two X-ray energies, $E_{hv} = 330$ eV (left, surface sensitive) and $E_{hv} = 600$ eV (right, bulk substrate sensitive). (a, b) Pristine EMLG before Ca-intercalation showing deconvoluted components G (graphene), S1/S2 (carbon in the buffer layer), and Z_C/B_C (surface/bulk SiC). The SiC components at lower binding energy are more clearly seen in the magnified view of the inset of Figure 3a. The approximate atomic location of these components is shown in the inset of b (see text for details). (c, d) Ca-QFSBLG showing component G' (doped graphene). Three additional SiC components have emerged, S_C^* , Z'_C , and B'_C , related to the changed SiC conditions due to formation of a Ca–Si compound between SiC and the buffer layer. The SiC components at lower binding energy are magnified in the right insets. The approximate atom locations for the new components are shown in the left inset of d.

Table 2. Summary of the Fitting Parameters for the Major Components in Figure 3^a

EMLG, C 1s		(a, b) pristine EMLG			(c, d) second Ca intercalation		
component	E_{hv} (eV)	E_B (eV)	RI	Q/W_L or W_G/W_L (eV)	E_B (eV)	RI	Q/W_L or W_G/W_L (eV)
S2	330	285.48	5.63	0.8/0.4			
	600	285.55	0.48	0.8/0.4			
S1	330	285.00	2.62	0.7/0.4			
	600	285.00	0.25	0.7/0.4			
G	330	284.83	35.0	12/0.2			
	600	284.82	2.47	9/0.2			
G'	330				284.89	26.75	9/0.2
	600				284.88	2.09	9/0.2
Z_C	330	284.05	0.75	0.4/0.2	284.05	0.18	0.4/0.2
	600	284.05	0.43	0.4/0.2	284.05	0.02	0.4/0.2
Z'_C	330				282.70	0.31	0.4/0.2
	600				282.73	0.22	0.4/0.2
B_C	330	283.7	1	0.4/0.2	283.77	0.29	0.4/0.2
	600	283.71	1	0.4/0.2	283.78	0.04	0.4/0.2
B'_C	330				282.35	0.52	0.4/0.2
	600				282.38	0.77	0.4/0.2
S_C^*	330				283.27	0.66	0.4/0.2
	600				283.27	0.08	0.4/0.2

^aThe binding energy location (E_B) is stated, as well as the relative intensity (RI) of the 1s peaks as referenced to the bulk SiC peak B_C corresponding to pristine SiC prior to Ca-intercalation. Q refers to the asymmetry parameter of the graphene, which was fit using a Breit–Wigner–Fano (BWF) function. W_G refers to the gaussian FWHM for the Voigt fit, whereas the Lorentzian FWHM (W_L) was kept constant at 0.2 eV in all fits except for the buffer layer components S1 and S2.

shifted equivalents of each other. The shift to lower binding energy of the SiC components is typically observed in the intercalation of graphene on silicon carbide systems and is caused by significant band bending upon intercalant insertion beneath the buffer layer.^{7,46,49,58,59,62–64}

Figure 3 (component fit parameters shown in Table 2) shows the C 1s core level XPS spectra before and after Ca-intercalation of the same EMLG sample as Figure 1b (and Figure 2). An E_{hv} of 330 and 600 eV was used to characterize the surface and bulk components, respectively. Figure 3a,b shows the pristine EMLG sample prior to intercalation, consisting of five components.

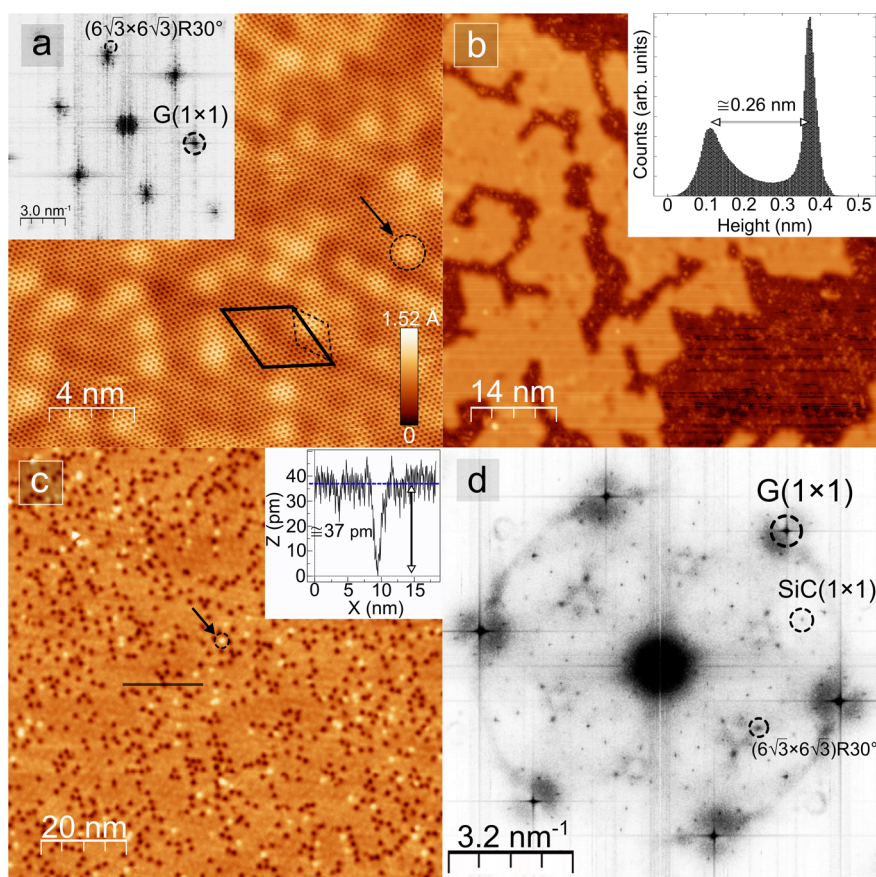


Figure 4. Scanning tunneling microscopy (STM) images of pristine epitaxial monolayer graphene (EMLG) before and after Ca-intercalation. (a) Pristine EMLG (1 V, 200 pA, 77 K) showing atomic resolution, along with real space $(6\sqrt{3} \times 6\sqrt{3})R30^\circ$ (solid line) and (6×6) (dashed line) quasi-periodicities (Moiré). The bright spots correspond to silicon adatom features (dotted circle, arrow). Inset shows the fast Fourier transform (FFT) of the same image showing $G(1 \times 1)$ graphene spots with a measured lattice parameter of ≈ 0.25 nm and $(6\sqrt{3} \times 6\sqrt{3})R30^\circ$ spots around $G(1 \times 1)$ spots. (b) First Ca-intercalation step (0.12 V, 300 pA, 4.6 K) showing formation of raised areas (Ca-QFSBLG). The height difference between these raised areas and the unintercalated graphene is 0.26 ± 0.01 nm (see inset). (c) After the second Ca-intercalation, Ca-QFSBLG formed on entire terraces (0.1 V, 400 pA, 4.6 K). Arrow and dotted circle show the postintercalation bright spot feature (different from the bright spot in a—see text). Inset shows a topographic line scan across one of the dark spots in the image, denoted by the solid black line. (d) FFT of c showing underlying symmetry of the Ca-QFSBLG surface and graphene ($G(1 \times 1)$), SiC ($\text{SiC}(1 \times 1)$), and $(6\sqrt{3} \times 6\sqrt{3})R30^\circ$ spots.

Component G located at $E_B = 284.83 \pm 0.05$ eV corresponds to graphene, in agreement with prior reports.⁶⁵ All graphene-related peaks were fit using a Breit–Wigner–Fano line shape,⁶⁶ instead of the often used Doniach–Šunjić line shape,^{67,68} as the BWF line shape was found to more accurately describe our data (see Supporting Information Sections 1.1 and 1.3 for further details).

Components S1 ($RI_R = 10.48$) and S2 ($RI_R = 11.73$) are due to Si–C bonds from the buffer layer to the underlying SiC and C–C bonds in the buffer layer, respectively,^{7,65} and have an intensity ratio of $S2:S1 \approx 2:1$, in agreement with previous findings.⁶⁵ Additionally, two components at lower binding energy are resolved—components Z_C and B_C . These components are related to the carbon in the SiC surface and bulk, respectively. Component B_C at $E_B = 283.73 \pm 0.05$ eV ($RI_R = 1$, used as the RI reference) represents the well-known EMLG bulk component of SiC and agrees well in binding energy with prior measurements.^{47,65} We also find evidence for a surface-like component, Z_C , related to the carbon in SiC at $E_B = 284.05 \pm 0.05$ eV ($RI_R = 1.74$)—particularly evident from the asymmetry of the SiC peak in Figure 3b. Component Z_C has been fitted in previous reports in order to explain the different bonding environment of carbon toward the surface of the SiC.^{43,49} The

shift of Z_C relative to B_C of $\Delta E_B = 0.32 \pm 0.1$ eV is in agreement with the shift observed in the Si 2p spectra (Z_{Si} to B_{Si}) and suggests a similar chemical environment for these components. The inset in Figure 3a shows components Z_C and B_C more clearly at $E_{hv} = 150$ eV, and the inset of Figure 3b shows the approximate location of all the components in an atomic model.

Figure 3c,d shows the C 1s core level XPS spectra for the same sample after Ca-intercalation. It is immediately apparent that components S1 and S2 are no longer present, implying the absence (or near elimination of) bonding between the SiC and buffer layer. Moreover, although significantly suppressed in intensity, components B_C and Z_C are still present in the Ca-intercalated spectra. This is in agreement with the Si 2p core level spectra in Figure 2c,d (which showed the presence of component B_{Si}) and LEED (Figure 1b) suggesting partial intercalation, similar to that observed with hydrogen intercalation.⁴¹

The graphene peak, now labeled G' , located at $E_B = 284.88 \pm 0.05$ eV ($RI_R \approx 13$), is not shifted significantly (within measurement error) with respect to the original EMLG graphene component G ($E_B = 284.83 \pm 0.05$ eV), although from prior Ca-intercalation experiments,^{8,12} we expect significant n-type doping of the graphene. We do on the other hand

observe significant changes in the line shape of the graphene component, which is significantly broadened and more asymmetric. This increase in asymmetry of the G' peak is predicted to arise in highly doped graphene due to 2D plasmon losses^{69,70} (see Supporting Information Sections 1.2 and 1.4 and Methods for details on G' peak fitting) and suggests that the (n-type, as we shall soon discover) doping level of the graphene has increased significantly.

Nonetheless, we observe that the bulk component B_C and the associated surface component of the bulk, Z_C, have been shifted to lower binding energy—labeled as components B'_C ($E_B = 282.33 \pm 0.05$ eV, $RI_R \approx 0.72$) and Z'_C ($E_B = 282.70 \pm 0.05$ eV, $RI_R \approx 1.34$). The respective shifts in E_B are -1.40 ± 0.1 eV (B_C → B'_C), -1.35 ± 0.1 eV (Z_C → Z'_C), with a separation between components of 0.32 ± 0.1 eV (Z_C → B_C) and 0.37 ± 0.1 eV (Z'_C → B'_C). These shifts are in good agreement with the shifts in E_B for the analogous Si 2p components in the preceding discussion and, thus, give confidence in our assignment of components B'_C/B'_{Si} and Z'_C/Z'_{Si} as the shifted components B_C/B_{Si} and Z_C/Z_{Si} brought about by band bending effects induced by the creation of a Ca–Si layer on the SiC(0001) surface. Approximate atom locations are shown in the atomic model inset of Figure 3d.

An additional component, which we label S_C^{*}, is evident in the Ca-intercalated spectra, located at $E_B = 283.26 \pm 0.05$ eV and shifted from component B_C by 0.47 ± 0.1 eV. An analogous component was observed in the Si 2p core level spectrum (Figure 2c,d), S_C^{*} at $E_B = 101.01 \pm 0.05$ eV, shifted to higher binding energy from component B_{Si} by 0.47 ± 0.1 eV. This equivalence in binding energy shift across both core levels suggests that these components are from the same SiC compound. The E_B value of component S_C^{*} agrees well with substoichiometric values of SiC.⁷¹ Indeed, judging from Figure 3c,d, we see that S_C^{*} ($RI_R = 8.25$) is a surface component (hence the “S” assignment) and thus could be a result of SiC unreacted with Ca, yielding a C-rich SiC compound residing at the surface (and, thus, partly explaining the relatively smaller, $RI_R \approx 1$, in the Si 2p core level). Further discussion of component S_C^{*} can be found in Supporting Information Section 1.2.

In summary, the Si 2p and C 1s core level spectra have yielded strong evidence for (1) a Ca–Si interaction at the surface of the SiC(0001) and (2) the elimination of buffer layer–SiC bonding. The formation of a Ca–Si compound is also supported by the Ca 2p spectra which can be found in Supporting Information Section 1.5. Coupled with the LEED results of Figure 1b, we conclude that Ca intercalates between the buffer layer and SiC(0001), bonding with the silicon at the SiC(0001) surface, disrupting the buffer layer–SiC bonding and converting the buffer layer into a new graphene layer.

Low Temperature Scanning Tunneling Microscopy of Ca-QFSBLG. Figure 4a shows an STM image of pristine EMLG prior to Ca-intercalation and transformation to Ca-QFSBLG. Apparent is the atomic resolution and Moiré pattern of the underlying buffer layer showing the $(6\sqrt{3} \times 6\sqrt{3})R30^\circ$ and associated (6×6) periodicity as expected.^{39,72,73} The inset in Figure 4a shows the fast Fourier transform (FFT) of the STM image. The graphene spots, labeled G(1 × 1), yield a lattice parameter of 0.253 ± 0.005 nm, in reasonable agreement with the lattice parameter of graphene (0.246 nm). In addition, we observe the $(6\sqrt{3} \times 6\sqrt{3})R30^\circ$ spots around the G(1 × 1) spots, in agreement with the pristine LEED images in Figure 1a. Another feature in Figure 4a is the bright spots (circled in Figure 4a) scattered randomly on the surface of the EMLG. These bright spots have been previously observed and have been

attributed to silicon adatoms on the surface of the SiC.⁷⁴ This is further strengthened by our interpretation that the spectral components A₀, A₁, and A₂, observed in the Si 2p photoemission spectra of pristine EMLG (Figure 2a,b), as corresponding to Si adatoms (see Supporting Information Section 1.2). Further STM data on the bright spots, including atomic resolution and height measurement, is presented in Supporting Information Section 1.6.

Figure 4b shows the same sample (from Figure 4a) after partial Ca intercalation as imaged with the STM at 0.12 V, 300 pA (see Supporting Information Section 1.6 for further details on Ca deposition). What is immediately apparent is that the surface is now covered by a network of raised “islanded” areas which no longer show the long-wavelength $(6\sqrt{3} \times 6\sqrt{3})R30^\circ$ modulation associated with the buffer layer. This observation is consistent with previous alkali^{52,53} and hydrogen⁷⁵ intercalation studies of graphene on SiC and indicates the formation of a freestanding structure. This observation is also consistent with the LEED data in Figure 1 and with the XPS data in Figures 2 and 3 which imply that the Si–C bonds that define the buffer layer are largely eliminated via the suppression of the $(6\sqrt{3} \times 6\sqrt{3})R30^\circ/(6 \times 6)$ spots and formation of a Ca–Si compound (component Ca_{Si})/elimination of components S1 and S2, respectively. The height of the newly formed feature is $\approx 0.26 \pm 0.01$ nm as judged by a histogram of heights from the STM image shown in the inset of Figure 4b. This is in agreement with the displacement measured by Fiori et al.⁵³ after the intercalation of Li atoms underneath the buffer layer and also agrees with the theoretical height increase for Ca-QFSBLG (see below).

Figure 4c shows an STM image of the same sample after another intercalation step, imaged at 0.1 V and 400 pA. Imaging the sample became increasingly challenging after each intercalation step due to the difficulty of removing excess Ca, which formed clusters on the graphene surface. A method for the removal of excess Ca on the surface using the STM tip was developed and resulted in atomically clean surfaces (see Supporting Information Section 1.6 for details). Nonetheless, Figure 4c shows that, after the second intercalation, entire terraces now lack the $(6\sqrt{3} \times 6\sqrt{3})R30^\circ$ modulation; we again interpret these as Ca-intercalated (i.e., Ca-QFSBLG) regions.

Figure 4d shows the FFT of the surface in Figure 4c and elucidates the underlying symmetry of the surface. Here we can see graphene spots (G(1 × 1)), SiC spots (SiC(1 × 1)), and the $(6\sqrt{3} \times 6\sqrt{3})R30^\circ$ symmetry that still exists, in agreement with the LEED from Figure 1. Notably, however, unlike the LEED results which showed $(\sqrt{3} \times \sqrt{3})R30^\circ$ spots with respect to the G(1 × 1) spots, Figure 4d shows no evidence of the $G(\sqrt{3} \times \sqrt{3})R30^\circ$ symmetry. This provides strong evidence that the graphene bilayer created by Ca-intercalation is not itself intercalated with Ca to form CaC₆/C₆CaC₆,¹⁹ which has a unit cell that is $(\sqrt{3} \times \sqrt{3})R30^\circ$ with respect to the graphene. Thus, we conclude that Ca intercalation has formed quasi-freestanding bilayer graphene (i.e., Ca-QFSBLG), separated from the SiC surface by a Ca layer which has interacted strongly with the Si on the SiC(0001) surface. The $(\sqrt{3} \times \sqrt{3})R30^\circ$ spots observed in LEED indicate that the Ca underneath the QFSBLG is indeed in registry with the graphene; however, the STM measurements show that the perturbation of the $(\sqrt{3} \times \sqrt{3})R30^\circ$ Ca layer on the bilayer graphene unit is small.

The Ca-intercalated graphene areas in Figure 4b,c are different in appearance to the pristine EMLG starting sample in Figure 4a and contain “dark” and “bright” spots (different

from the “bright” spots attributed to Si adatoms prior to Ca-intercalation) on the surface (these spots are particularly evident on the uniform terrace in Figure 4c but can also be seen in the partially intercalated “island” areas in Figure 4b). The dark spots (which are not holes—see Supporting Information Section 1.6) have a height variation of <40 pm (see Figure 4c, inset) and, thus, are likely not due to the buffer layer corrugation which is ≈ 60 pm⁷³—in agreement with the height variation of similar features measured with STM after H-intercalation of graphene on SiC.⁴¹ In fact, similar “dark” features have been observed using STM after alkali,^{52,53} indium,⁴³ and hydrogen⁴¹ intercalation of graphene on silicon carbide. The observation of these features is, thus, intercalant *independent* and points to a universal underlying mechanism involving the SiC surface. In the case of H-intercalation, Murata et al.⁴¹ attributed these features to hydrogen vacancies, with a measured density ranging from $\approx 10^{11}$ to 10^{13} cm⁻² depending on the intercalation temperature used. Here we find that our dark spot density of $\approx 9 \times 10^{12}$ cm⁻² is within this range and agrees favorably with the dark spot density found after hydrogen intercalation.⁴¹ The density of the silicon adatoms (bright spots in Figure 4a) is on the order of 10^{13} cm⁻² for our measured data, whereas Rutter et al.⁷⁴ observed Si adatom densities on the order of 10^{14} cm⁻², in rough agreement with our numbers. Thus, we tentatively propose that the dark spots are Ca vacancies that are tied to Si adatom locations on the surface of the SiC. As for the postintercalation bright spots (arrow in Figure 4c), the height variation does not exceed ≈ 30 pm (see Supporting Information Section 1.6), and the density is $\approx 1 \times 10^{12}$ cm⁻², in approximate agreement with prior measurements on H-intercalated graphene on SiC.⁴¹ We note here that the postintercalation bright spots we observe after Ca-intercalation are likely not the same bright spots that were initially attributed to silicon adatom defects in the STM micrograph of pristine EMLG in Figure 4a. Previous reports have attributed these bright spots to defects⁴¹ or protrusions from intercalants bonded to the underlying graphene, rather than the SiC surface.⁷⁶ Since we do not observe electron scattering (i.e. standing waves) emanating from the postintercalation bright spots,^{77,78} our observations suggest the latter. Thus, we tentatively attribute these bright spots to excess metallic Ca that may be present on top of the underlying Ca-silicide. For further information on these postintercalation bright spot features, we refer the reader to Supporting Information Section 1.6. We mention here briefly that the STM of Ca-intercalated graphene has been previously conducted,^{19,21,25} but the bright and dark spot features shown in Figure 4b,c were not (to our best knowledge) reported.

The STM has elucidated the surface structure of Ca-intercalated EMLG on SiC(0001). In summation, we have found that Ca-QFSBLG has formed upon intercalation of Ca via elimination of EMLG's Moiré pattern and that no Ca-intercalation between the graphene layers occurred—consistent with our LEED (Figure 1b) and XPS (Figures 2 and 3) results.

Density Functional Theory of Ca-Intercalated Graphene on SiC(0001). Our results strongly imply that Ca-intercalation of EMLG occurs between the buffer layer and SiC(0001) surface to form Ca-QFSBLG and not between the buffer layer and graphene (or between graphene layers). To better understand this, we utilize DFT to investigate the energetics of Ca-intercalation.

Figure 5 shows schematics of the two structures modeled using DFT. Figure 5a,b shows side and top views of the first modeled structure, corresponding to Ca-QFSBLG, i.e., Ca

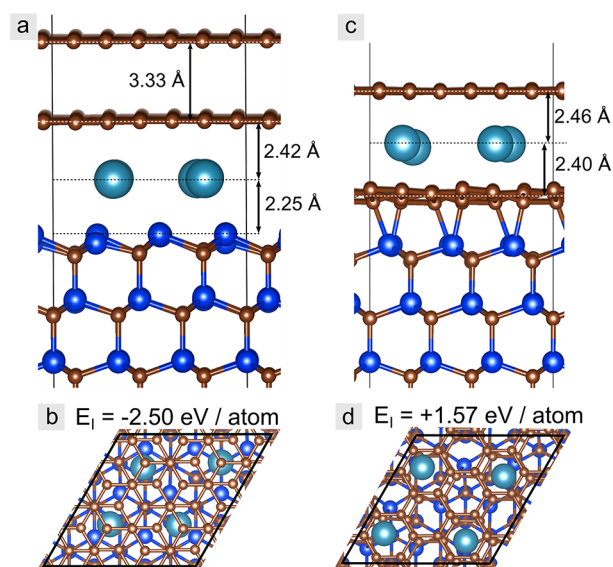


Figure 5. Atomic models (dark blue = Si, brown = C, light blue = Ca) of Ca-intercalated monolayer graphene on SiC(0001), showing the two possible intercalation regimes. (a) Side view of Ca-QFSBLG showing vertical distances and (b) top down view of Ca-QFSBLG showing the unit cell and approximate $(\sqrt{3} \times \sqrt{3})R30^\circ$ coordination of the Ca with respect to the graphene. The energy required for intercalation is $E_I = -2.50$ eV/atom (energetically favorable). (c) Side view of Ca intercalated between the first graphene layer and the buffer layer (SiC/Buffer/Ca/Graphene) showing distances and (d) top down view of Ca intercalated between the first graphene layer and the buffer layer showing the unit cell. In the case of (SiC/Buffer/Ca/Graphene) the coordination of the Ca was slightly larger than $(\sqrt{3} \times \sqrt{3})R30^\circ$. The energy required for intercalation is $E_I = +1.57$ eV/atom (not energetically favorable).

intercalated between the buffer layer–SiC interface to produce bilayer graphene from EMLG (SiC/Ca/Graphene/Graphene). The former buffer layer is raised to lie 0.467 nm above the surface Si atoms, a change in height (Δh), compared to pristine EMLG, of approximately 0.26 nm (using the known value for buffer layer–Si distance of 0.21 nm),⁷⁹ in excellent agreement with our experimentally measured value of $\Delta h = 0.26 \pm 0.01$ nm from STM. Figure 5c,d shows a second modeled structure, corresponding to Ca instead intercalated between the first graphene layer and the buffer layer (SiC/Buffer Layer/Ca/Graphene), a model that has been, up until now, thought to describe Ca-intercalation.²⁰ Using this model, the insertion of Ca gives a Δh of 0.153 nm when compared with pristine EMLG, which is not in agreement with our STM measurements (see Figure 4b, inset). The energy, E_I , required to intercalate Ca was calculated (see Methods) yielding $E_I = -2.50$ and $+1.57$ eV/atom for Ca intercalated underneath the buffer layer and Ca intercalated between the first graphene layer and the buffer layer, respectively. Here, a negative value indicates the process is energetically favorable. Thus, DFT supports our experimental finding that the favored intercalation site for the Ca is between the SiC and the buffer layer.

It should be noted that our DFT results closely match the conclusions of Sandin et al.⁵² (which used Na as the intercalant) but disagree with a recent publication by Zhang et al.²¹ concerning Ca-intercalation. Sandin et al.⁵² concluded that a (SiC/Na/Graphene/Graphene) structure accurately describes Na-intercalation by comparing experimentally measured and theoretically calculated work function shifts. Zhang et al.²¹ used

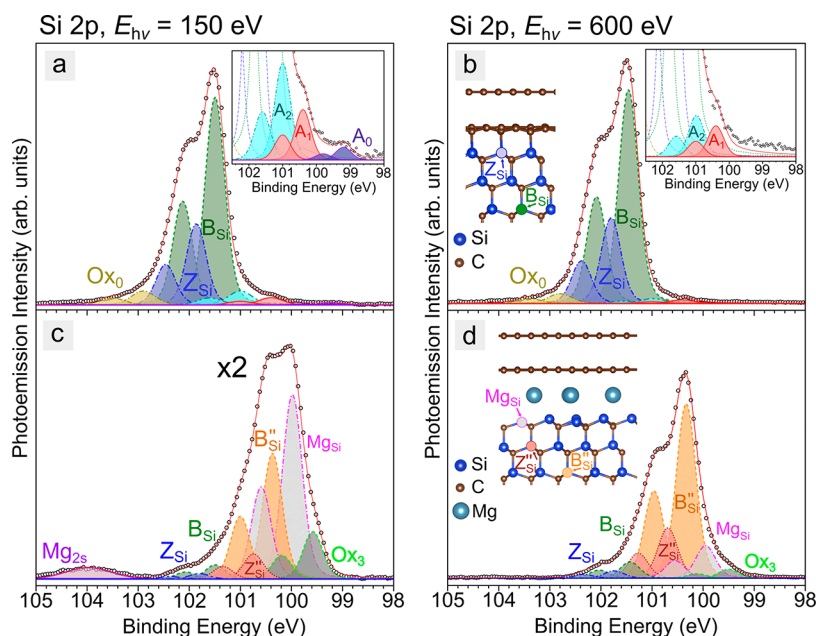


Figure 6. X-ray photoemission spectra showing the Si 2p core level of pristine epitaxial monolayer graphene on SiC(0001) (EMLG) and Mg-intercalated EMLG (Mg-QFSBLG) at X-ray energies $E_{hv} = 150$ eV (left, surface sensitive) and $E_{hv} = 600$ eV (right, bulk sensitive). (a, b) Pristine EMLG showing deconvolution of spectra into components (see main text for details). Right hand side insets in a and b show the magnified view of the lower binding energy components, and the left hand side inset in b shows the atomic model and approximate location of the EMLG spectral components. (c, d) After Mg-intercalation, Mg-QFSBLG is formed. Spectra are deconvolved into components (see main text for details). Left hand side inset in d shows atomic model and approximate location of Mg-QFSBLG spectral components.

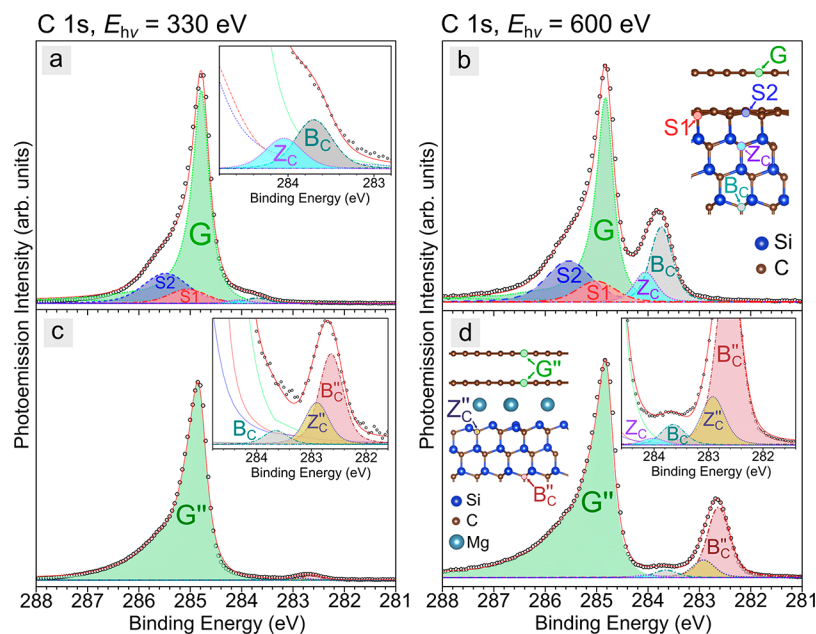


Figure 7. X-ray photoemission spectra for the C 1s core level of pristine epitaxial monolayer graphene on SiC(0001) (EMLG) and Mg-intercalated EMLG (Mg-QFSBLG) at X-ray energies of $E_{hv} = 330$ eV (left, surface sensitive) and $E_{hv} = 600$ eV (right, bulk sensitive). (a, b) Pristine EMLG prior to Mg-intercalation showing the graphene (G), buffer layer (S1, S2), and SiC (Z_C , B_C) components. Inset in a shows the magnified view of the Z_C and B_C components. Inset in b shows the approximate location of all the components with respect to an atomic model of EMLG. (c, d) After Mg-intercalation and the formation of Mg-QFSBLG showing new components, G'' (doped graphene), B'_C (shifted bulk SiC component), and Z'_C (shifted “surface” SiC component). Components Z_C and B_C are still present as the sample was only partially intercalated. Right hand side insets in c and d show a magnified view of components B'_C and Z'_C . Left hand side inset in d shows the approximate location of components B'_C and Z'_C .

STM and DFT calculations to find that low concentrations of Ca could intercalate in a “metastable” configuration underneath the buffer layer, although (SiC/buffer layer/Ca/Graphene) and (SiC/buffer layer/Graphene/Ca/Graphene) structures were found to be more energetically favorable—in stark disagreement

with our findings which suggest that the (SiC/Ca/Graphene/Graphene) structure is most stable. Furthermore, the change in height after intercalation in ref 21 was experimentally measured as 0.283 nm (theoretically calculated as 0.29 nm), and this

Table 3. Summary of the Fitting Parameters for the Major Components in Figure 6^a

EMLG, Si 2p		(a, b) pristine EMLG				(c, d) second Mg intercalation			
component	E_{hv} (eV)	E_B (eV) 2p _{3/2}	E_B (eV) 2p _{1/2}	RI	W_G (eV)	E_B (eV) 2p _{3/2}	E_B (eV) 2p _{1/2}	RI	W_G (eV)
Ox _o	150	102.90	103.50	0.068	0.5				
	600	102.80	103.40	0.046	0.5				
Z _{Si}	150	101.86	102.46	0.392	0.4	101.80	102.38	0.014	0.4
	600	101.80	102.38	0.401	0.4	101.74	102.34	0.035	0.4
B _{Si}	150	101.50	102.13	1	0.4	101.49	102.07	0.034	0.4
	600	101.46	102.09	1	0.4	101.43	102.03	0.076	0.4
B _{Si} ^{''}	150					100.37	101.0	0.304	0.4
	600					100.33	100.96	0.817	0.4
Z _{Si} ^{''}	150					100.74	101.34	0.061	0.4
	600					100.69	101.27	0.235	0.4
Mg _{Si}	150					99.98	100.59	0.446	0.4
	600					99.95	100.55	0.152	0.4
Ox ₃	150					99.58	100.19	0.115	0.4
	600					99.50	100.12	0.042	0.4
Mg _{2s}	150					103.97	n/a	n/a	1
	600					-	n/a	n/a	-

^aBoth 2p_{3/2} and 2p_{1/2} are stated, as well as the relative intensity (RI) of the 2p_{3/2} peaks as referenced to the bulk SiC peak B_{Si} corresponding to pristine SiC prior to Mg intercalation. W_G refers to the Gaussian FWHM for the Voigt fit (which was fixed to one of two values), whereas the Lorentzian FWHM (W_L) was kept constant at 0.1 eV in all fits. Component Mg_{2s} is not a 2p core level (see text). Dashes correspond to no observation; n/a = not applicable.

Table 4. Summary of the Fit Parameters of the Major Components in Figure 7^a

EMLG, C 1s		(a, b) pristine EMLG			(c, d) second Mg intercalation		
component	E_{hv} (eV)	E_B (eV)	RI	Q/W_L or W_G/W_L (eV)	E_B	RI	Q/W_L or W_G/W_L (eV)
S2	330	285.48	5.563	0.8/0.4			
	600	285.54	0.550	0.8/0.4			
S1	330	285.05	2.636	0.7/0.3			
	600	285.005	0.281	0.7/0.3			
G	330	284.787	39.31	12/0.2			
	600	284.830	2.723	12/0.2			
G ^{''}	330				284.836	36.66	12/0.2
	600				284.822	2.898	9/0.2
Z _C	330	284.05	0.625	0.4/0.2	-	-	-
	600	284.05	0.400	0.4/0.2	284.02	0.033	0.4/0.2
Z _C ^{''}	330				282.90	0.375	0.4/0.2
	600				282.92	0.233	0.4/0.2
B _C	330	283.70	1	0.4/0.2	283.65	0.125	0.4/0.2
	600	283.74	1	0.4/0.2	283.65	0.100	0.4/0.2
B _C ^{''}	330				282.64	0.900	0.4/0.2
	600				282.63	0.933	0.4/0.2

^aThe binding energy location (E_B) is stated, as well as the relative intensity (RI) of the 1s peaks as referenced to the bulk SiC peak B_C corresponding to pristine SiC prior to Mg intercalation. Q refers to the asymmetry parameter of the graphene (which was fit using a BWF function). W_G refers to the Gaussian FWHM for the Voigt fit, whereas the Lorentzian FWHM (W_L) was kept constant at 0.2 eV in all fits except those for for buffer layer components S1 and S2. Dashes correspond to no observation.

disagrees with both of our experimental and theoretical results presented here.

X-ray Photoelectron Spectroscopy of Mg-QFSBLG. As in the Ca-intercalation case in the above sections, here we will focus on the Si 2p and C 1s core levels shown in Figures 6 and 7, respectively (O 1s and Mg 2p core levels can be found in Supporting Information Section 2.4). All relevant parameters for the component fits can be found in Table 3 (Si 2p) and Table 4 (C 1s). We shall note that the XPS results presented here, as in the Ca-intercalation case, are from the same sample analyzed initially with LEED (Figure 1c). Figure 6a,b shows the Si 2p core level of pristine EMLG sample prior to Mg-intercalation and are almost identical to the spectra obtained for the pristine EMLG

sample prior to Ca-intercalation in Figure 2a,b. Again, the RI's (and thus RI_R's) are referenced to the bulk of the SiC, components B_{Si}/B_C, and we retain the same nomenclature as in Figure 2a,b. All component binding energy locations and fit details can be found in the Supporting Information, Tables S10–S12, and since these components have not significantly changed, we refer the reader to the Supporting Information and preceding discussion of Figure 2a,b.

Figure 6 shows the Si 2p core level spectra before (Figure 6a,b) and after (Figure 6c,d) Mg-intercalation, showing drastic changes upon intercalation. We discuss again only the main components of the spectra and leave the discussion of nonessential components to the Supporting Information (see

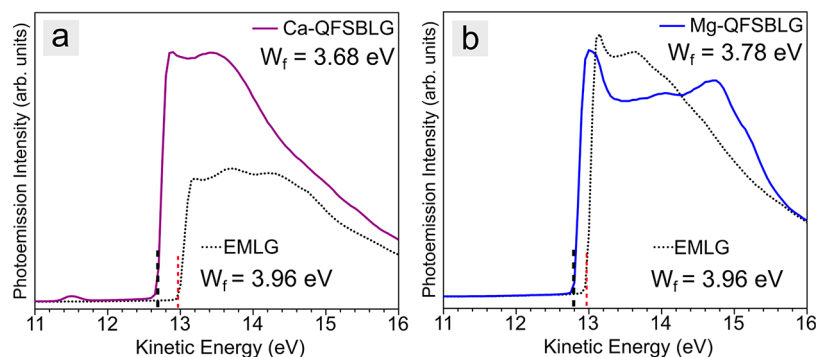


Figure 8. Secondary electron cutoff (SECO) photoemission measurements of pristine epitaxial monolayer graphene on SiC (EMLG) before and after Ca- and Mg-intercalation to form quasi-freestanding bilayer graphene on SiC (Ca-QFSBLG/Mg-QFSBLG). (a) Pristine EMLG (dotted line) and Ca-QFSBLG (solid purple line) showing work functions (W_f) of 3.96 and 3.68 eV, respectively. (b) Clean EMLG (dotted line) and Mg-QFSBLG (solid blue line) showing W_f of 3.96 and 3.78 eV, respectively.

Section 2.2). As we shall soon discover, the changes we observe in the XPS spectra amount to the creation of Mg-QFSBLG, and the XPS spectra are similar to the Ca-QFSBLG sample (with the exception that Mg could not displace the hydrogen in H-QFSBLG; see Supporting Information Section 2.3).

For instance, component Mg_{Si} located at $E_B = 99.94 \pm 0.05$ eV ($RI_R \approx 2.9$) matches closely in binding energy to an Mg-silicide compound.^{51,80,81} We rule out this component arising from an oxide (i.e., from the reaction of Mg with any underlying silicon oxide to form a silicate⁸²), since silicon oxides reside at higher binding energy. Thus, our XPS results imply that our Mg deposition and annealing procedure has intercalated Mg between the buffer layer–SiC interface, producing an Mg–Si compound closely resembling an Mg-silicide and decoupling the buffer layer to form another graphene layer—similar to the Ca-intercalation case. This result complements the LEED results in Figure 1c and is also supported by Raman mapping spectroscopy data (see Supporting Information Section 2.5).

We also see the appearance of component Mg_{2s} at $E_B = 103.94 \pm 0.05$ eV. A similar component has been observed in previous XPS studies of magnesium silicide formation on Si(111) and Si(100), though its origin is controversial.^{80,83} The observation of a higher binding energy component in the Si 2p core level spectrum after Mg_2Si formation on Si(100) was attributed to plasmon losses from Mg 2s electrons.⁸³ However, in our experiment there is no observable Mg metal on the surface after the second Mg-intercalation (see the Mg 2p core level in Supporting Information Figure S23a,b), and thus, component Mg_{2s} cannot be caused by metallic plasmon losses. In the case of Mg_2Si on Si(111), the higher binding energy component in the Si 2p spectrum ($E_B \approx 104$ eV, in agreement with our measurements) was attributed to satellite peaks from Mg 2s emission.⁸⁰ Satellite features can also (in addition to plasmons) be caused by polychromatic light and shake-up features. Since our experiment uses monochromatic light, we tentatively attribute this peak to a shake-up feature. Furthermore, component Mg_{2s} disappears into the signal noise level when $E_{hv} = 600$ eV, strongly implying that this component resides near the surface (i.e., is associated with the formation of the Mg-silicide). Further work is needed to confirm the origin of this feature, but its association with magnesium silicide formation lends support to our conclusion that Mg has intercalated at the buffer layer–SiC interface to interact with Si.

Figure 7a,b shows the pristine EMLG C 1s core level spectra, which are almost identical in nature to those of the Ca-

intercalation case in Figure 3a,b. Since the spectrum in Figure 7a,b is almost identical to that of Figure 3a,b, we refer the reader to the preceding discussion of Figure 3a,b and Supporting Information Sections 1.2 and 2.2 for further details.

As has been stated, the Mg-intercalation shown in Figure 6c,d shares similar features to the Ca-intercalation experiment. Upon comparison of Figure 7c,d with Figure 3c,d, we observe a similar change in shape and lack of peak shift of the graphene component G, now labeled G'', which we attribute to plasmonic effects due to high doping^{69,70} (see Supporting Information Section 1.4) and a reduction of the buffer layer contribution. Additionally, we observe that the new components B''_{Si}/B''_C and Z''_{Si}/Z''_C arise after intercalation in the Si 2p and C 1s core level spectra, respectively. These components are analogous to the shifted bulk (B''_{Si}/B''_C) and subsurface (Z''_{Si}/Z''_C) SiC components in Ca-QFSBLG (see Figures 2c,d and 3c,d), which arise from surface band bending caused by formation of an Mg layer underneath the buffer layer (analogous to Ca as in Figures 2 and 3). The shift of SiC components toward lower binding energy due to band bending at the SiC surface has been observed in many other graphene on SiC intercalation experiments.^{7,46,49,58,59,62–64} The relative shifts in binding energies among components B_{Si}/B_C , Z_{Si}/Z_C , B''_{Si}/Z''_C , and Z''_{Si}/Z''_C can be found in Supporting Information Section 2.2 and further supports our assignment of these components.

After analysis of the C 1s and Si 2p XPS spectra, we find remarkable similarities between Ca- and Mg-intercalated graphene. In the case of Mg intercalation, we find (as in the Ca-intercalation case): (1) formation of an Mg–Si compound underneath the buffer layer at the SiC(0001) surface and (2) the disappearance or diminishment of the buffer layer contribution in the Mg-intercalated C 1s spectra. These conclusions are further strengthened by the LEED results in Figure 1c, and we conclude here that Mg intercalated between the buffer layer and SiC(0001), interacting strongly with the SiC surface and disrupting the buffer layer–SiC bonding to convert the buffer layer into a new graphene layer (Mg-QFSBLG).

Work Function Measurements of Ca- and Mg-QFSBLG.

As noted above, we did not observe significant shifts in the binding energy of the graphene C 1s components upon either Ca- or Mg-intercalation. However, the shift in binding energy of the graphene component is not directly proportional to the shift in the Fermi level (E_F).^{70,84} The significant asymmetric broadening of the graphene C 1s component does suggest significant doping of the graphene, which would be expected

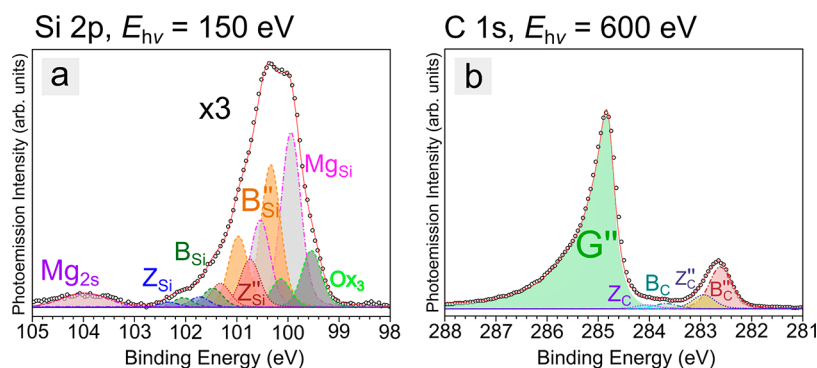


Figure 9. X-ray photoemission spectra showing the Si 2p and C 1s core levels of Mg-QFSBLG after ≈ 6 h of ambient air exposure (and after annealing in UHV) at X-ray energies of $E_{\text{hv}} = 150$ and 600 eV, respectively. (a) Si 2p core level, y-scale magnified $\times 3$ from Figure 6a. (b) C 1s core level. Component labels in a are the same as in Figure 6c,d, and labels in b are the same as in Figure 7c,d. Component Mg_{Si} (and O_{X_3}) in a has decreased in intensity relative to the other components causing the overall spectrum to change shape from Figure 6c,d. Component B_{C}' has not shifted in binding energy.

upon intercalation of an electron donor such as Ca or Mg.⁸ A comparison between our experimentally measured C 1s data and the calculated line shape of highly doped graphene can be found in Supporting Information Section 1.4 and shows that the line shape of our data closely matches bilayer graphene doped with at least one layer at 10^{14} carriers cm^{-2} . To gain further experimental insight into the changes in doping upon intercalation, the work function (W_{f}) was measured using the secondary electron cutoff (SECO) photoemission technique, shown in Figure 8.

Figure 8a shows the W_{f} of pristine EMLG and Ca-intercalated graphene, i.e., Ca-QFSBLG (a -9 V potential was applied to the samples; see Methods). Our measured value for the W_{f} of pristine EMLG ($W_{\text{f}} = 3.96 \pm 0.05$ eV) is in approximate agreement with prior values.⁸⁵ After Ca-intercalation to form Ca-QFSBLG, the change in work function is $\Delta W_{\text{f}} = -0.28 \pm 0.1$ eV and strongly implies an increase in n-type doping.⁸⁶ In the case of Mg-intercalation to form Mg-QFSBLG, as shown in Figure 8b, the change in work function from EMLG is $\Delta W_{\text{f}} = -0.18 \pm 0.1$ eV, also implying a significant increase in n-type doping. Further discussion pertaining to the accuracy of the SECO measurements can be found in Supporting Information Section 1.2. The results for Ca-intercalated H-QFSBLG (to form Ca-QFSBLG) are shown in the Supporting Information Section 1.3 and are almost identical to the results obtained for Ca-intercalated EMLG shown here.

Air Stability of Mg-QFSBLG. All the experiments presented thus far have been conducted in UHV, and with few exceptions,⁸⁷ highly doped intercalated graphene is not typically stable in ambient conditions due to the high reactivity of the intercalants used. Whether the applications of such intercalated materials are superconductors, batteries, or highly transparent and conductive surfaces, air stability is an important consideration, significantly aiding in the technological implementation of these materials. As expected, we found our Ca-QFSBLG samples begin oxidation within 30 min of ambient exposure, manifesting in a radical change of the XPS spectra. Surprisingly, we find that our newly synthesized Mg-QFSBLG sample appears to be much more stable to air exposure.

Figure 9 shows the Si 2p and C 1s core level spectra for the same sample shown in Figures 6 and 7 after exposure to ambient atmosphere for ≈ 6 h, followed by reintroduction to vacuum and subsequent annealing to remove surface contaminants (see Methods). We do not observe a significant shift in any of the Si 2p or C 1s components for our Mg-intercalated sample (see

Supporting Information Tables S13 and S14), suggesting that Mg-intercalated graphene is remarkably stable in ambient conditions. Upon closer inspection, we observe that component Mg_{Si} has decreased in intensity with respect to the other Si 2p components, as compared to the spectrum before ambient exposure (Figure 6c) suggesting that there may have been some reaction with ambient conditions. Nonetheless, it appears that Mg-intercalation yields a very low work function (3.78 eV) yet relatively air-stable graphene.

Scanning Tunneling Microscopy of Mg-Intercalated Graphene on SiC(0001). A second EMLG sample was intercalated with Mg in UHV and then exposed to air for approximately 45 min during transfer to the low temperature UHV STM. Prior to scanning, the sample was annealed in UHV (see Methods). Figure 10 shows the STM topography map of the Mg-intercalated sample surface. The surface of the Mg-intercalation is almost identical to that of the Ca-intercalation sample in Figure 4c and does not show the $(6\sqrt{3} \times 6\sqrt{3})\text{R}30^\circ$ Moiré pattern characteristic of pristine EMLG (Figure 4a). This

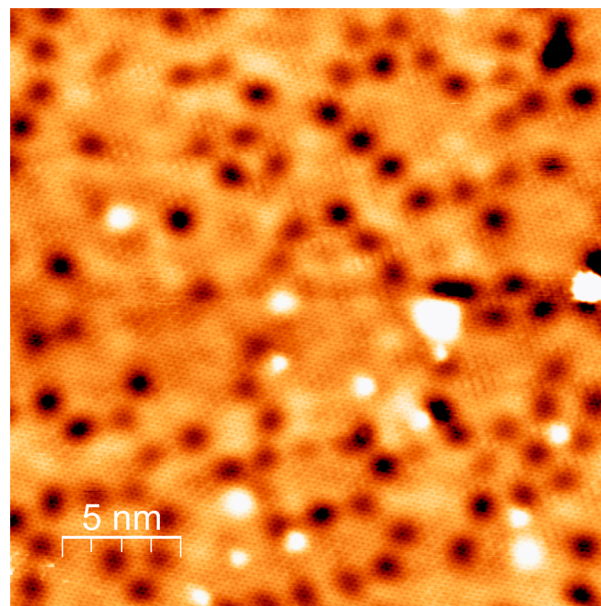


Figure 10. Scanning tunneling microscope (STM) micrograph of an Mg-QFSBLG sample exposed to air for ≈ 45 min before transferring to the STM (0.3 V, 200 pA, 77 K).

offers further support that Mg-QFSBLG is freestanding and furthermore, relatively air-stable, since the sample survived air exposure. The Mg-QFSBLG sample (Figure 10) also shows very similar postintercalation bright ($5 \times 10^{13} \text{ cm}^{-2}$) and dark ($4 \times 10^{14} \text{ cm}^{-2}$) spots as seen in Figure 4b,c, further supporting our claims that the dark and postintercalation bright spots are generic to graphenes intercalated at the SiC/buffer layer interface.

CONCLUSION

In this communication we report on the structure of graphene on SiC(0001) intercalated with either Ca or Mg. By combining LEED, XPS, and STM with DFT modeling, we show that the favored route for Ca intercalation is insertion at the buffer layer–SiC(0001) interface, forming an ordered ($\sqrt{3} \times \sqrt{3}$)R30° reconstruction relative to the graphene and strong chemical interactions with the Si-termination of SiC. The intercalated Ca breaks the buffer layer–SiC covalent bonding, freestands the buffer layer to form Ca-QFSBLG, and decreases the graphene work function, implying high n-type doping. Similarly, we find that the Mg intercalates EMLG samples at the buffer layer–SiC(0001) interface to form Mg-QFSBLG and also exhibits high n-type doping. Stronger chemical interaction between Si and Mg drives the formation of an ordered ($\sqrt{3} \times \sqrt{3}$)R30° reconstruction to the SiC. Unlike Ca-QFSBLG, Mg-QFSBLG exhibits remarkable air stability even after ≈ 6 h of ambient air exposure. This work shows the first successful (to our knowledge) Mg-intercalation of graphene on SiC(0001) to form a low work function (n-type doped) and highly air stable graphene, which may find potential applications in highly conductive and transparent electrodes.

Furthermore, we see no evidence of Ca or Mg intercalation between the graphene layers under the conditions for intercalation used here, consistent with the predictions of our DFT modeling. While we cannot rule out that further processing could result in additional intercalation between graphene layers, our results already prompt a re-examination of previous studies where it was assumed that Ca intercalated *only* between graphene layers and *not* at the buffer layer–SiC interface.^{8,12,19,20,25}

METHODS

Samples and Intercalation Procedure. Two types of graphene samples were used in the experiments—epitaxial monolayer graphene synthesized on semi-insulating 6H-SiC(0001) (EMLG)³⁶ and hydrogen intercalated bilayer graphene synthesized on semi-insulating 6H-SiC(0001) (H-QFSBLG).³⁸ H-QFSBLG results are discussed in Supporting Information Section 1.3. The 6H-SiC(0001) semi-insulating substrates nominally on-axis ($\approx 0.1^\circ$ offcut) were obtained from II-VI Incorporated. Prior to graphene synthesis, the 6H-SiC(0001) substrates were etched in situ (in an Aixtron/Epigress VP508 horizontal hot wall reactor) with high purity H_2 (200 mbar) at ≈ 1843 K. Epitaxial monolayer graphene was then synthesized in ≈ 20 min on these substrates while holding the temperature at ≈ 1843 K in an Ar atmosphere (100 mbar). This results in a sample with majority monolayer coverage on the SiC(0001) terraces, as well as regions of bilayer and small amounts of trilayer (see Supporting Information Figure S27 for Raman spectroscopic characterization of the layer number for a sister sample). To fabricate H-QFSBLG, H_2 was flowed at 80 slm (900 mbar) for 15–75 min upon cooling to 1223–1423 K.³⁶ Large area Hall measurements on batch samples of this type show sheet density and carrier concentration vary by 10–15%. Prior to measurement and intercalation, all samples were cleaned via annealing in UHV ($\approx 1 \times 10^{-10}$ mbar) between 673 and 773 K (determined with a single-color pyrometer and thermocouple) for approximately 8 h (for

XPS/LEED/SECO measurements). All alkaline earth metal depositions were undertaken while the samples were at room temperature.

The intercalation procedure at the Australian Synchrotron (in which the LEED, XPS, and SECO measurements were taken) is as follows. For Ca-intercalation, samples ($\approx 4 \text{ mm} \times 4 \text{ mm}$) were mounted on the same sample holder, consisting of two EMLG and two H-QFSBLG samples. Approximately 6 nm of Ca was deposited (as judged by a quartz crystal microbalance, QCM) using a WEZ effusion cell (MBE Komponenten) loaded with Ca metal (dendritic pieces, 99.99%, Sigma-Aldrich) in a pyrolytic boron nitride (PBN) crucible. The deposition required heating of the crucible to ≈ 698 K and exposure of 15 min to the Ca flux. After deposition, the sample was heated between ≈ 753 K for 1.5 h to intercalate and clean the sample surface. This procedure constituted the first intercalation step. This intercalation procedure was then repeated for the second intercalation step, except the anneal temperature was ≈ 736 K. All intercalation step data is shown Supporting Information Sections 1.2 and 2.2, whereas in the manuscript we show the results for only the pristine samples and final intercalation step.

For the Mg-intercalation, the samples were mounted similarly (1 EMLG, 1 H-QFSBLG), and an NTEZ effusion cell (MBE Komponenten) was used with a PBN crucible loaded with Mg (1/8-in. turnings, 99.95%, Sigma-Aldrich). In the first intercalation step, ≈ 7.5 nm was deposited onto the samples (cell temperature 673 K, 10 min of Mg flux exposure), which were then heated to ≈ 773 K for ≈ 2 h. Immediately afterward, ≈ 3.8 nm (cell temperature 673 K, 5 min of Mg flux exposure) of Mg was deposited before heating the sample to ≈ 773 K for ≈ 2 h. These steps constituted the first intercalation step. In the second intercalation step, the effusion cell was heated to 673 K, and the sample was exposed to 10 min of Mg flux before annealing at 623 K for 1.5 h. This sample was then exposed to ambient air for ≈ 6 h and annealed at ≈ 623 K for 1.5 h.

The Mg-QFSBLG sample in Figure 8b was a sister sample that was similarly intercalated at the Australian Synchrotron but this time in a three-step Mg-intercalation procedure with the final Mg-intercalation yielding similar results to the final (i.e., second) Mg-intercalation of the above sample. In the first Mg-intercalation step, ≈ 15 nm of Mg was deposited on the sample (cell temperature 673 K, 20 min of Mg flux exposure), which was then heated to 463 K for ≈ 1.5 h. For the second Mg-intercalation, ≈ 15 nm of Mg was deposited on the sample (cell temperature 673 K, 20 min of Mg flux exposure), which was then heated to 623 K for ≈ 1.5 h. For the third Mg-intercalation, ≈ 15 nm of Mg was deposited on the sample (cell temperature 673 K, 20 min of Mg flux exposure), which was then heated to 623 K for ≈ 1.5 h. See Supporting Information Figures S28 and S29 for the C 1s and Si 2p core levels, respectively.

The Mg-QFSBLG sample in Figure 10 was fabricated via the intercalation of an EMLG sample. The same evaporator (NTEZ, PBN cell) and Mg source were used in a different UHV chamber. For this sample, the cell was heated to a temperature of 673 K, and the sample was exposed to the Mg flux for 25 min (≈ 18.8 nm) before heating to 623 K for 30 min. The sample was then taken from storage in the UHV chamber after ≈ 1 month and mounted onto an STM holder in ambient conditions (exposed for ~ 45 min) before being loaded into the STM chamber. The sample was cleaned at ≈ 673 K for ≈ 2 h before scanning.

The Ca-intercalated graphene sample studied by STM (Figure 4) was prepared as follows. An EMLG sample was cleaned in the CreaTec Fischer & Co GmbH STM UHV ($\approx 1 \times 10^{-10}$ mbar) chamber by annealing at ≈ 743 K for 1.2 h (all temperatures for the STM were determined with a single-color pyrometer). The depositions were carried out with a CreaTec effusion cell using a PBN crucible loaded with Ca (dendritic pieces, 99.99%, Sigma-Aldrich) that was baked at 473 K overnight prior to depositions. In the first intercalation (Figure 4b), ≈ 1 nm of Ca was deposited while the sample was held at room temperature (all thicknesses were determined with a CreaTec QCM). After deposition, the sample was heated to a temperature of 653 K and held for 10 min, after which the sample was ramped to ≈ 743 K and held at this temperature for 1.5 h to facilitate intercalation and remove excess surface Ca. For the second Ca-intercalation, another 1 nm of Ca was deposited after recalibration with the QCM. After deposition, the

sample was heated to ≈ 653 K and held for 30 min and then ramped to ≈ 743 K and held for 1 h before allowing the sample to cool naturally.

Low Energy Electron Diffraction (LEED). LEED measurements were conducted at the Australian Synchrotron on the Soft X-ray beamline using an 8-in. LEED spectrometer (OCI Vacuum Micro-engineering Inc.). Initial measurement coordinates on pristine samples were recorded, and for each subsequent intercalation/deposition, the same measurement positions were recorded. All measurements were taken at an energy of 100 eV. In Figure 1a we show an example of a pristine EMLG, and Figure 1b,c shows a sister sample (grown in the same growth run) that was intercalated (hence the rotation of the sample). The LEED images in Figure 1 are color inverted in order to enhance visibility.

X-ray Photoelectron Spectroscopy (XPS). XPS data was taken at the soft X-ray beamline at the Australian Synchrotron,⁸⁸ equipped with a PHOIBOS 150 (9 channeltrons) detector. The pass energy of the analyzer was set at 10 eV for the O 1s core levels (energy step of 0.1 eV—see Supporting Information Sections 1.5 and 2.4) and 5 eV for all other core levels (energy step of 0.05 eV). Each recorded spectrum was energy calibrated using the Au 4f_{7/2} line at 84.0 eV from a Au foil in electrical contact with the sample. Inelastic contributions were removed from each XPS spectrum in the main manuscript by subtraction of a Shirley line shape (except for the Ca 2p spectra—see Supporting Information Section 1.5). The Si 2p spectra were obtained at E_{hv} = 600 eV (bulk sensitive) and 150 eV (surface sensitive) and were fit with Voigt functions with a Lorentzian full width at half-maximum (fwhm) of 0.1 eV and Gaussian fwhm of 0.4 or 0.5 eV. The Lorentzian fwhm, which was kept constant, was determined from pristine QFSBLG samples, as these samples were relatively pure and acted as standards in the experiment. Additionally, the area ratio of the Si 2p spin–orbit split peaks (and Mg 2p/Ca 2p core levels) was strictly kept as $2p_{1/2}:2p_{3/2} = 1:2$.⁸⁹ The spin–orbit splitting of the Si 2p core level after averaging and taking the standard deviation of all values was found to be 0.61 ± 0.02 eV, in excellent agreement with previously measured values.^{89,90}

The C 1s “graphene” peak (unintercalated) was fit with a Breit–Wigner–Fano (BWF) asymmetric line shape⁶⁶ (a type of asymmetric Lorentzian; see Supporting Information Section 1.1 for further details); as this line shape was found to fit component G more accurately than the often used Doniach–Šunjić line shape.⁶⁷ Upon intercalation, the doped graphene peak component G' was phenomenologically fit using a model that incorporated a BWF line shape convoluted with three Voigt functions (the details of which can be found in Supporting Information Sections 1.1, 1.2, and 2.2), to approximate the plasmon effects expected for a highly doped graphene line shape which was recently described.^{69,70} All C 1s core level SiC-related components were fit with Voigt line shapes using a Gaussian width of 0.4 eV and Lorentzian width of 0.2 eV⁴⁹ (resulting in a fwhm = 0.52 eV; all parameters are outlined in Table S3 and Table S12 in Supporting Information Sections 1.1 and 2.1, respectively). Care was taken to keep the Gaussian and Lorentzian contributions constant; i.e., the width of the Voigt functions did not change for the same components. Additionally, stringent conditions were placed on the binding energy location of the fitted peaks, which typically did not vary more than the uncertainty of the measurement, taken as ± 0.05 eV. The position of each component was calculated by averaging the available measurements (including the first intercalation step which was omitted in the main text—see Supporting Information, Sections 1.1 and 2.1) of the same component (in the same sample) across the various X-ray energies (E_{hv}). If the standard deviation was higher than the uncertainty in the measurement (i.e., > 0.05 eV), then the standard deviation was taken as the uncertainty in the measurement.

To qualitatively assess the surface sensitivity of the fitted components, the relative intensity (RI) was calculated by using the bulk SiC components of EMLG: B_{Si}/B_C as the intensity reference (i.e., the RI of B_{Si} and $B_C = 1$). The RI ratio (RI_R) was then used as a qualitative metric of the surface sensitivity of a particular component by division of the lower E_{hv} RI with the RI of the same component at higher E_{hv} . In this regime, an $RI_R > 1$ signifies a more surface-like component, and an $RI_R \leq 1$ signifies a more bulk-like component.

Secondary Electron Cut-Off (SECO). SECO data (Figure 8) was taken at $E_{hv} = 100$ eV to find the work function (W_f) of the clean and intercalated graphene samples. The pass energy of the analyzer was set at 2 eV. A bias of -9 V was applied to the sample in order to effectively measure the low energy cutoff, and all samples were measured while perpendicular to the analyzer, as this is known to increase the accuracy of W_f measurement.⁹¹ The W_f was then determined by the intersection of two linear fits to the steep edge and background, as is common with SECO determinations of the W_f .^{92,93}

Scanning Tunneling Microscopy (STM). All STM images were taken with a CreaTec Fischer & Co GmbH low temperature STM. The micrographs shown in Figure 4a and Figure 10 were taken at 77 K, whereas the micrographs in Figure 4b,c were taken at 4.6 K. In Figure 4, a cut Pt–Ir tip was used, whereas an etched W tip was used in Figure 10. Micrographs were analyzed using WSxM.⁹⁴

Density Functional Theory (DFT). We use density functional theory (DFT) calculations as implemented in the Vienna ab initio Simulation Package (VASP) to calculate the intercalation energy of Ca on SiC and graphene.⁹⁵ The electron exchange and correlation is described using the Perdew–Burke–Ernzerhof (PBE) form of the generalized gradient approximation (GGA).⁹⁶ A semiempirical functional (DFT–D2) is employed to describe van der Waals interactions in the system.⁹⁷ The kinetic energy cutoff for the plane-wave basis set is set to 500 eV. We use a $9 \times 9 \times 1$ Γ -centered k-point mesh for sampling the Brillouin zone. In all cases, the SiC/graphene system is modeled by a supercell comprised of three layers of 3×3 SiC crystal along with $2\sqrt{3} \times 2\sqrt{3}$ graphene layers. The graphene is under a tensile strain of 7.6%. The intercalation energy (E_i) of Ca is calculated by

$$E_i = E(\text{SiC/graphene} + \text{Ca}) - E(\text{SiC/graphene}) - E(\text{Ca})$$

where $E(\text{SiC/graphene})$, $E(\text{Ca})$, and $E(\text{SiC/graphene} + \text{Ca})$ are the energy of the SiC/graphene heterostructure, the atomic energy of Ca in its bulk state, and the energy of the SiC/graphene system upon Ca intercalation, respectively. Here, a negative number signifies that the coordination is thermodynamically/energetically favorable, whereas a positive number signifies that the coordination is not energetically favorable.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.chemmater.0c01729>.

Elucidation of all Ca- and Mg-intercalation steps of EMLG, along with detailed tables outlining parameters of the component fits including the omitted first intercalation steps; Ca-intercalation of H-QFSBLG—LEED, XPS (C 1s and Si 2p core level spectra), and SECO measurements; measured C 1s graphene line shapes for Ca- and Mg-intercalated EMLG (i.e. Ca- and Mg-QFSBLG) are compared to theoretical line shapes for highly doped graphene; O 1s and Ca 2p XPS spectra for Ca-intercalated EMLG and H-QFSBLG; STM micrographs of Ca deposition on top of EMLG, as well as the method for cleaning the graphene surface of excess Ca; detailed STM micrographs of the dark and post-intercalation bright features; C 1s and Si 2p core level spectra of the attempted Mg-intercalation of H-QFSBLG; O 1s and Mg 2p core level spectra of Mg-intercalated EMLG; Mg 2p spectra of H-QFSBLG; effect of long-term ambient exposure of Mg-QFSBLG via lab-based C 1s/Si 2p XPS spectra and Raman mapping spectra; and Si 2p and C 1s core levels of the Mg-intercalated sample in Figure 8b (PDF)

AUTHOR INFORMATION

Corresponding Authors

Jimmy C. Kotsakidis – School of Physics and Astronomy, Monash University, Melbourne, Victoria 3800, Australia; orcid.org/0000-0002-7167-5617; Email: jimmy.kotsakidis@monash.edu

Michael S. Fuhrer – School of Physics and Astronomy, Monash University, Melbourne, Victoria 3800, Australia; orcid.org/0000-0001-6183-2773; Email: michael.fuhrer@monash.edu

Amadeo L. Vázquez de Parga – Dep. Física de la Materia Condensada and Condensed Matter Physics Center (IFIMAC), Universidad Autónoma de Madrid, 28049 Madrid, Spain; IMDEA Nanociencia, 28049 Madrid, Spain; orcid.org/0000-0003-0551-1603; Email: al.vazquezdeparga@uam.es

Authors

Antonija Grubišić-Čabo – School of Physics and Astronomy, Monash University, Melbourne, Victoria 3800, Australia; orcid.org/0000-0001-7683-0295

Yuefeng Yin – Department of Materials Science and Engineering, Monash University, Melbourne, Victoria 3800, Australia

Anton Tadich – Australian Synchrotron, Melbourne, Victoria 3168, Australia

Rachael L. Myers-Ward – U.S. Naval Research Laboratory, Washington D.C. 20375, United States

Matthew DeJarld – U.S. Naval Research Laboratory, Washington D.C. 20375, United States

Shojan P. Pavunny – U.S. Naval Research Laboratory, Washington D.C. 20375, United States; orcid.org/0000-0003-4844-8675

Marc Currie – U.S. Naval Research Laboratory, Washington D.C. 20375, United States

Kevin M. Daniels – Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, Maryland 20742, United States

Chang Liu – School of Physics and Astronomy, Monash University, Melbourne, Victoria 3800, Australia; orcid.org/0000-0002-0244-1999

Mark T. Edmonds – School of Physics and Astronomy, Monash University, Melbourne, Victoria 3800, Australia; orcid.org/0000-0001-8054-5470

Nikhil V. Medhekar – Department of Materials Science and Engineering, Monash University, Melbourne, Victoria 3800, Australia; orcid.org/0000-0003-3124-4430

D. Kurt Gaskill – Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, Maryland 20742, United States; orcid.org/0000-0001-7106-3605

Complete contact information is available at:

<https://pubs.acs.org/10.1021/acs.chemmater.0c01729>

Author Contributions

J.C.K. and A.L.V.P. performed the first Ca intercalations in the STM, from which a method was developed and guided future intercalation experiments at the Australian Synchrotron. J.C.K. suggested performing the Mg experiments and developed the method for Mg-intercalation based upon the Ca-intercalation method. J.C.K. wrote the experimental proposal (including the methods) for the Australian Synchrotron experiments with necessary assistance from A.T. and M.S.F. and some grammatical corrections from A.G.-C. The data at the Australian Synchrotron was collected by J.C.K., A.G.-C., A.L.V.P., A.T., C.L., and M.T.E. Ca and Mg crucibles were first loaded at Monash University and transported to the Australian Synchro-

tron by J.C.K. (under vacuum) and mounted with help from A.T. All starting samples were grown by D.K.G., R.L.M.-W., M.D., S.P.P., and K.M.D., and M.C. postprocessed the samples. S.P.P. and J.C.K. performed lab-based XPS, which was later analyzed by J.C.K. J.C.K. performed Raman spectroscopy measurements with the aid of D.K.G. and R.L.M.-W., which was analyzed by J.C.K. Y.Y. and N.V.M. performed the DFT calculations. J.C.K. composed the manuscript and created all the figures, with intellectual contributions from D.K.G. and M.S.F. The manuscript was written through contributions given by all authors. All authors have given approval to the final version of the manuscript.

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Notes

The authors declare no competing financial interest.

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ABBREVIATIONS

Ca-QFSBLG, Ca-intercalated quasi-freestanding bilayer graphene; E_b , binding energy; E_{hv} , X-ray energy; EMLG, epitaxial monolayer graphene; H-QFSBLG, H-intercalated quasi-freestanding bilayer graphene; LEED, low energy electron diffraction; Mg-QFSBLG, Mg-intercalated quasi-freestanding bilayer graphene; SECO, secondary electron cutoff; STM, scanning tunneling microscopy; QFSBLG, quasi-freestanding bilayer graphene; XPS, X-ray photoelectron spectroscopy

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