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The discovery that graphene, a single layer of sp² hybridized carbon atoms arranged in a honeycomb registry, is stable, has resulted in numerous intriguing and exciting scientific breakthroughs [1,2]. The electrons in graphene behave as relativistic massless fermions that are described by the Dirac equation, i.e., the relativistic variant of the Schrödinger equation. One might anticipate that elements with a similar electronic configuration, such as silicon (Si), germanium (Ge), and tin (Sn), also have a “graphenelike” allotrope. Unfortunately, silicene (the silicon analogue of graphene), germanene (the germanium analogue of graphene), and stanene (the tin analogue of graphene) have not been found in nature and therefore these two-dimensional (2D) materials have to be synthesized. Theoretical calculations have revealed that the honeycomb lattices of the graphenelike allotropes of silicon and germanium are not fully planar, but slightly buckled [3,4]. The honeycomb lattices of these 2D materials consist of two triangular sub-lattices that are slightly displaced with respect to each other in a direction normal to the honeycomb lattice. Despite this buckling the 2D Dirac nature of the electrons is predicted to be preserved [3,4]. Another salient difference with graphene is that silicene and germanene have a substantially larger spin-orbit gap than graphene (< 0.05 meV). Silicene’s spin-orbit gap is predicted to be 1.55 meV, whereas the predicted spin-orbit gap of germanene is 23.9 meV. This is very interesting because graphene and also silicene and germanene are, in principle, 2D topological insulators and thus ideal candidates to exhibit the quantum spin Hall effect [5]. The interior of a 2D topological insulator exhibits a spin-orbit gap, whereas topologically protected helical edge modes exist at the edges of the material [6,7]. The two topologically protected spin-polarized edge modes have opposite propagation directions and therefore the charge conductance vanishes, whereas the spin conductance has a nonzero value.

In the past few years various groups have successfully synthesized silicene [8–10] and germanene [11–14] on a variety of substrates. To date germanene has only been grown on metallic substrates, such as Pt(111) [11], Au(111) [12], Ge₂Pt [13,15], and Al(111) [14], which might hinder a proper decoupling of the key electronic states of germanene near the Fermi level from the underlying substrate. Only Bampoulis et al. [13] managed to resolve the primitive cell of the buckled honeycomb structure of germanene.

Here we report the growth of germanene on a band gap material, namely, MoS₂. We found that the germanene layer, which is only weakly coupled to the MoS₂ substrate, exhibits a clear V-shaped density of states. These experimental observations are in very good agreement with density functional theory calculations. The synthesis of germanene on MoS₂ is a first step towards future germanene-based device applications.

The scanning tunneling microscopy (STM) and spectroscopy (STS) experiments have been performed at room temperature with an ultrahigh vacuum STM (Omicron STM-1). The base pressure of the ultrahigh vacuum system is 3 × 10⁻¹¹ mbar. We have used electrochemically etched tungsten STM tips. The MoS₂ samples were freshly cleaved from synthesized 2H-MoS₂ (acquired from 2D semiconductors) and mounted on a Mo sample holder and subsequently introduced into the ultrahigh vacuum system. Ge was deposited onto the MoS₂ substrate, which was held...
at room temperature, by resistively heating a clean Ge(001) wafer at \( \sim 1150 \) K. The Ge wafer was located at a distance of \( \sim 10 \) nm from the MoS\(_2\) substrate. Prior to the deposition the Ge(001) wafer was cleaned by a preanneal at 700 K for about 24 h followed by several cycles of argon ion bombardment at 800 eV at room temperature and annealing at 1100 K [16]. After the deposition of germanium, the MoS\(_2\) sample was immediately inserted into the STM. The deposition rate was estimated by analyzing several STM images after the deposition of monolayer amounts of germanium on the MoS\(_2\) substrate.

The density functional theory (DFT) calculations were performed using the projected augmented wave (PAW) formalism [17] as implemented in the Vienna \textit{ab initio} simulation package (VASP) [18,19]. Exchange-correlation effects were taken into account within the dispersion-corrected nonlocal optB88-vdW functional [20]. An energy cutoff of 600 eV for the plane-waves and a convergence threshold of \( 10^{-5} \) eV were employed. To avoid interactions between the supercells, a 25 Å thick vacuum slab was added in the direction normal to the surface. The Brillouin zone was sampled by a \((4 \times 4) k\)-point mesh. Structural relaxation was performed, while keeping the lowermost layer of sulfur atoms fixed, until the forces acting on the other atoms were less than \( 10^{-2} \) eV/Å.

Figure 1(a) shows an empty state STM image of the molybdenum disulfide (MoS\(_2\)) substrate. MoS\(_2\) is a transition metal dichalcogenide. The elementary building block of a MoS\(_2\) crystal is a trilayer structure consisting of one close-packed Mo atomic layer encapsulated between two atomic layers of close-packed S atoms [see Figs. 2(g)–2(h)]. The atoms within this layer are strongly bonded by covalent interactions, whereas the interactions between the MoS\(_2\) layers are governed by weak van der Waals forces. MoS\(_2\) can easily be exfoliated and has a band gap that varies from 1.2 to 1.8 eV depending on its thickness. In most cases only the S atoms of the MoS\(_2\) substrate are resolved in STM images, resulting in a triangular structure with a lattice constant of 3.16 Å. Since the height of the germanene island is \( \sim 10\% \) of a monolayer of germanium at room temperature [here one monolayer corresponds to a \((5 \times 5)\) cell of germanene on a \((6 \times 6)\) cell of the MoS\(_2\) substrate]. Several germanium islands have been nucleated at preexisting defects of the MoS\(_2\) substrate. From image to image the shape and size of these germanium islands changes, which implies (1) attachment and detachment of germanium atoms at the edges of the germanium islands and (2) rapid diffusion of germanium atoms across the surface. Interestingly, there is a hexagonal shaped vacancy island in the center of all the nucleated germanium islands.

Figure 2(a) shows a small scale STM image of the MoS\(_2\)/germanium substrate. The frizzy appearance of the germanium islands is clearly visible. We cannot exclude that part of this dynamics is induced by the scanning process. In the upper left part of the image a germanium island changes abruptly in size. In Figs. 2(b) and 2(c) zoom-ins of a germanium-free part of the MoS\(_2\) substrate and a germanium island are shown, respectively. The lattice constant of the germanium islands is \( \sim 20\% \) larger than the lattice constant of the MoS\(_2\) substrate, i.e., \( 3.8 \pm 0.2 \) Å for germanium versus 3.16 Å for MoS\(_2\). The germanium islands exhibit a threefold symmetry as the underlying MoS\(_2\) substrate does. In addition, the high symmetry directions of the MoS\(_2\) substrate and the germanium islands are aligned [see Fig. 2(a)].

Differential conductivity \( (dI/dV) \) spectra recorded on a germanium island and the bare MoS\(_2\) substrate are depicted in Fig. 2(d). As expected, the MoS\(_2\) region has a band gap, whereas the differential conductivity of the germanium island reveals a well-defined \( V \) shape around zero bias \( (|V| < 0.5 \) V). For small sample biases the differential conductivity is proportional to the density of states and therefore also the density of states of the germanium islands exhibits a \( V \) shape, which is one of the hallmarks of a 2D Dirac system. Based on these observations we arrive at the conclusion that the germanium islands are actually germanene islands. This assignment does, however, not imply that these germanene islands also exhibit all the interesting and intriguing “graphene” properties.

In Figs. 2(e) and 2(f) line scans taken across the germanene island [see Fig. 2(a)] are depicted. The apparent height of the germanene island is \( \sim 3.2 \) Å. Since the

FIG. 1. (a) Scanning tunneling microscopy image of the MoS\(_2\) substrate. Inset: small scale image revealing the honeycomb structure of MoS\(_2\) (obtained after a fast Fourier transform operation of the raw data). The set points are 0.2 V and 1 nA, respectively. (b) Scanning tunneling microscopy image of the MoS\(_2\) surface after the deposition of \( \sim 10\% \) of a monolayer of germanium at room temperature. Small germanium islands are nucleated at preexisting defect sites of the MoS\(_2\) substrate. The set points are 0.5 V and 0.6 nA, respectively.
electronic structure of germanene and MoS$_2$ are substantially different it is not appropriate to compare this experimentally determined step height with theoretical predictions.

In Figs. 3(a) and 3(b) an STM image is shown after the deposition of $\sim$1 monolayer of germanium. The Germanene islands are now much larger and virtually the whole MoS$_2$ surface is covered with germanene. The hexagonal shaped vacancy islands have all disappeared. The periodicity of the structure in Figs 3(a) and 3(b) is again 3.8 $\pm$ 0.2 Å. It is pointed out that the resolution in Fig. 3(a) is somewhat lower than in the previous images. In Fig. 3(b) only one of the two triangular sublattices is resolved. We did not find any evidence for the presence of a moiré pattern. Because of the 20% difference in lattice constants between germanene and MoS$_2$ one expects only very small moiré periodicities ($< 2$ nm) [24].

As shown in Fig. 3(c) the differential conductivity has a well-defined V shape and thus confirms our earlier assignment that we are dealing with germanene. The differential conductivity does, however, not completely vanish at the Dirac point, indicating that the system is metallic and hence not an ideal 2D Dirac system. Freestanding low-buckled germanene is known to be a 2D Dirac system that shares many properties with its famous counterpart graphene [25]. Here we are dealing with a germanene layer on a substrate and even though the interaction between germanene and MoS$_2$ is rather weak, the structural and electronic properties of germanene are affected by the substrate.

To support our experimental observations of germanene, we have performed first-principles calculations using DFT. Unlike earlier DFT studies, where germanene has been considered on MoS$_2$ in its freestanding configuration with a lattice constant of 3.97 Å [26,27], we consider...
here germanene laterally contracted by \( \sim 5\% \) in accordance with the experimental observations. Particularly, we use a \((5 \times 5)\) unit cell of germanene placed on top of a \((6 \times 6)\) unit cell of a MoS\(_2\) monolayer with a lattice constant \(a_{\text{MoS}_2} = 3.18\) Å, which yields a contracted germanene lattice constant \(a_{\text{Ge}} = 3.82\) Å. Subsequently, we optimize the atomic structure by taking van der Waals interactions into account and find an average equilibrium buckling parameter of \(\Delta = 0.86 \pm 0.10\) Å and a corresponding interlayer distance \(d = 5.02\) Å, defined as the distance between the in-plane averaged centers of mass of germanene and MoS\(_2\).

The density of states (DOS) is depicted in Fig. 4 and shows a pronounced V shape in the energy range of \(\sim 1\) eV near the Fermi energy stemming from electronic states of germanium. Furthermore, the shape of both germanene and MoS\(_2\) DOS are found to be in very good agreement with the experimental \(dI/dV\) spectra shown in Fig. 2(d). Moreover, the nonzero DOS at the Dirac point observed in experimental spectra is also reproduced. The only difference concerns the position of the Fermi energy, which is shifted relative to the Dirac point, whereas unoccupied \(\sigma\) bands produce a finite DOS in the relevant energy region. The \(\sigma\) states contribution to the DOS is weakly dependent on energy as the corresponding dispersion is nearly quadratic \([E_{\sigma}(k) \sim k^2]\). Therefore, we conclude that the observed V shape of the total DOS originates predominantly from the \(\pi\) states of germanene.

After having performed the STM and STS measurements we took the MoS\(_2\)/germanene sample out of the ultrahigh vacuum system for an \textit{ex situ} analysis. X-ray photoelectron spectroscopy measurements revealed that the germanene which makes the occupation of \(\sigma\) states energetically less favorable [25] and leads to a \(\sigma-\pi\) charge transfer. As a consequence of this process, the Fermi energy is shifted relative to the Dirac point, whereas unoccupied \(\sigma\) bands produce a finite DOS in the relevant energy region. The \(\sigma\) states contribution to the DOS is weakly dependent on energy as the corresponding dispersion is nearly quadratic \([E_{\sigma}(k) \sim k^2]\). Therefore, we conclude that the observed V shape of the total DOS originates predominantly from the \(\pi\) states of germanene.

To gain more insight into the origin of the finite DOS at the Dirac point as well as the observed doping, we calculate the band structure and perform orbital analysis of contracted freestanding germanene with the above-mentioned structural parameters \(a_{\text{Ge}}\) and \(\Delta\). The results are shown in Fig. 5. In addition to the \(\pi\) bands leading to the formation of a Dirac cone in the vicinity of the \(K\) point, there are two \(\sigma\) bands close to the \(\Gamma\) point. The emergence of those bands is related to the relatively large buckling of germanene,
had been oxidized. As a final remark, we want to point out that hexagonal boron nitride is another very appealing substrate for the synthesis of germanene [28]. Hexagonal boron nitride has a band gap of 5.9 eV and a nearly perfect lattice match with germanene.

In summary, we have synthesized large continuous layers of germanene on a band gap material. The germanene islands preferentially nucleate at preexisting defects of the MoS$_2$ surface. Germanene’s lattice constant is about 20% larger than that of MoS$_2$ and the angle between the two lattices is 0°. The density of states of the germanene layer exhibits a well-defined V shape around the Fermi level, which hints to a 2D Dirac system. Unfortunately, the buckled germanene layer also has two parabolic bands that cross the Fermi level at the Γ point. These states might suppress the anomalous quantum Hall effect as well as the 2D Dirac transport properties.

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