

Layer thickness and substrate effects on superconductivity in epitaxial FeSe films on BLG/SiC(0001)

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The layered nature and simple structure of FeSe reveal this iron-based superconductor as a unique building block for the design of artificial heterostructure materials. While superconductivity develops in ultrathin films of FeSe on SrTiO₃ substrates, it remains unclear whether it can be developed on more chemically inert, layered materials such as graphene. Here, we report on the characterization of the structural, chemical, and electronic properties of few-layer and multilayer FeSe on bilayer graphene grown on SiC(0001) using low-temperature scanning tunneling microscopy/spectroscopy (STM/STS) and x-ray photoelectron spectroscopy (XPS). STM imaging of our FeSe films with thicknesses up to three layers exhibits the tetragonal crystal structure of bulk FeSe, which is supported by XPS spectra consistent with the FeSe bulk counterpart. While our STS measurements at 340 mK reveal a metallic character for few-layer FeSe on BLG/SiC(0001), they show an absence of superconductivity, as the low-lying electronic structure exhibits a spatially anisotropic dip-like feature robust against magnetic fields. However, we find that superconductivity in FeSe/BLG/SiC(0001) starts to emerge from a thickness of five layers. Cooper pairing strength increases with film thickness, reaching critical temperatures up to 6 K above 20 layers. Our results underscore the significance of the substrate and thickness as key factors driving the suppression of superconductivity in FeSe in the 2D limit.

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I. INTRODUCTION

Iron-based materials exhibit a broad range of intriguing physical phenomena such as unconventional superconductivity, quantum criticality, and topological properties [1–7]. Among these materials, FeSe stands out due to its simple crystal structure, which shows tetragonal symmetry [see Figs. 1(a) and 1(b)] belonging to the P4/nmm space group, and its unique status as a layered material which has been possible to synthesize down to the monolayer level. This structural flexibility not only enables detailed investigation of its fundamental properties at the two-dimensional (2D) limit, but also makes FeSe an ideal candidate for use as a building block for the development of novel quantum materials in artificial heterostructures [4,5,8–20]. FeSe is mostly known for hosting superconductivity with marked layer-dependent properties. While bulk FeSe is a superconductor with a critical temperature (T_C) of ~ 8 K [21], single- and few-layer FeSe have shown the highest ever reported T_C within the iron-based

superconductors family, reaching up to 109 K when grown on strontium titanate (SrTiO₃) [16,22–48]. This enhancement of T_C has been attributed to interfacial coupling between FeSe and SrTiO₃ through different mechanisms, including increased electron-phonon coupling and charge transfer effects [24,27–29,33,39,49]. Therefore, the large sensitivity of the superconducting properties of ultrathin films of FeSe shown on SrTiO₃ has raised interest in achieving the epitaxial growth of them in van der Waals materials for diverse purposes.

Graphene, the most versatile among the 2D materials, is also an outstanding template for the epitaxial growth of various families of 2D materials since it preserves the electronic structure [50–52] and collective electronic phases such as superconductivity [53] of the as-grown 2D material. Regarding FeSe, previous efforts have shown that the epitaxial growth of ultrathin films of FeSe is plausible on graphene, although showing puzzling results [54–56]. While superconductivity was found to be absent in monolayers of FeSe grown on bilayer graphene (BLG) [54], it has been surprisingly detected in monolayers of FeSe on trilayer graphene (TLG) with a rather large superconducting gap of 1 meV [55,56]. However, bilayer and few-layer (up to eight layers) FeSe exhibit superconductivity on BLG, with an SC gap of ~ 2 meV [54].

In this work, we revisited the superconducting properties in the ultimate 2D limit of FeSe, from monolayer to trilayer, grown on epitaxial bilayer graphene substrates by combining a comprehensive structural, chemical, and electronic characterization using low-temperature (340 mK) scanning tunneling microscopy/spectroscopy (STM/STS) and

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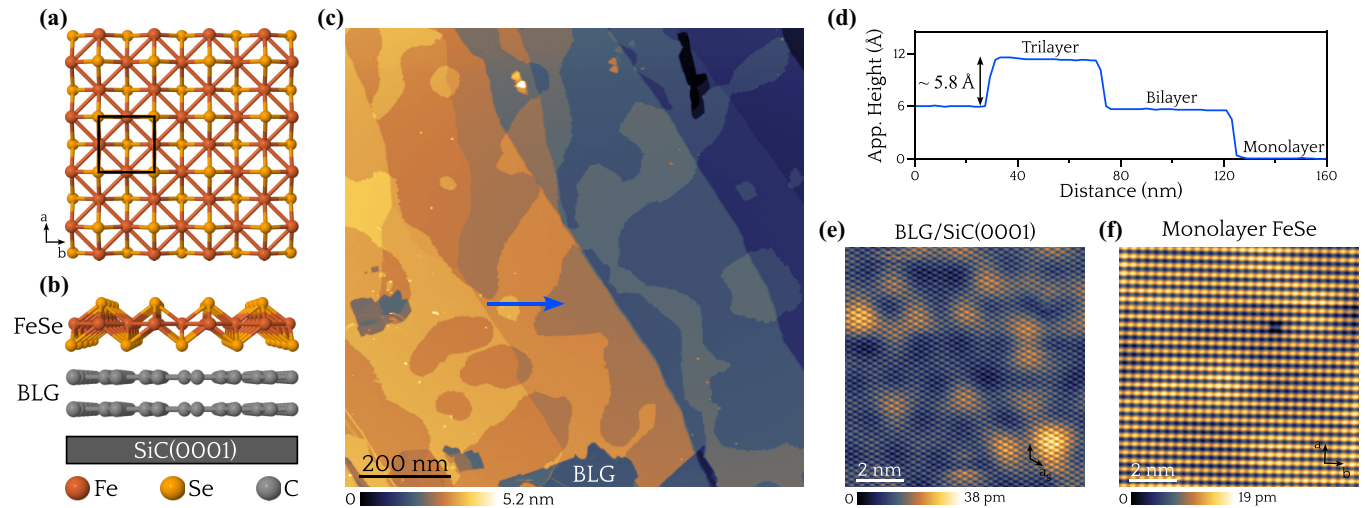


FIG. 1. Structural properties of few-layer FeSe grown on BLG/SiC(0001). (a) Surface atomic arrangement of monolayer FeSe. The black square indicates the surface unit cell, which has a periodicity of 3.9 Å. (b) Side view of the tetragonal crystal structure of monolayer FeSe grown on the surfaces of BLG/SiC(0001). (c) Large-scale STM topography image revealing the surface morphology of FeSe/BLG/SiC(0001) samples grown by MBE. (d) Apparent height profile measured along the direction marked by the blue arrow in (c), passing through regions of trilayer, bilayer, and monolayer FeSe. (e), (f) Atomically resolved STM images showing the different atomic registry of the surfaces of BLG/SiC(0001) and monolayer FeSe, respectively. Acquisition parameters: (c) $V_{\text{set}} = 1$ V, $I_{\text{set}} = 20$ pA, $T = 3.6$ K. (e) $V_{\text{set}} = -1$ V, $I_{\text{set}} = 0.1$ nA, $T = 3.6$ K. (f) $V_{\text{set}} = -1$ V, $I_{\text{set}} = 0.1$ nA, $T = 3.6$ K.

x-ray photoelectron spectroscopy (XPS). Our experimental STM/STS data indicate that the as-grown FeSe layers exhibit a tetragonal crystal structure and display metallic characteristics in their electronic spectrum, similar to their superconducting bulk counterpart. However, our high-resolution STS data near Fermi level (E_F) reveals a spatially anisotropic V-shape dip featuring a strong resilience against out-of-plane magnetic field of up to 11 T. Assuming spin-singlet, even-momentum-parity superconductivity as generally considered for FeSe in the 2D limit [34,57–59], this result allows us to preclude the existence of superconductivity in our FeSe samples for up to three layers down to 340 mK. In contrast, superconductivity requires five layers of FeSe on BLG to develop. Additionally, the superconducting strength in these cases shows a thickness-dependent behavior, with T_C reaching up to ~ 6 K for a thickness above 20 layers.

II. METHODS

A. Growth of FeSe on BLG/SiC(0001)

Few-layer FeSe was fabricated on the surfaces of BLG terminated n-type doped 6H-SiC(0001) in a custom-built ultra-high vacuum (UHV) based molecular beam epitaxy (MBE) system. The growth starts by carrying out a slow and thorough outgassing of the SiC(0001) wafer at 800 °C and continued by annealing at 1400 °C for 35 min to graphitize the surface. High-quality iron and selenium (MaTeck, 99.999%) were employed as sources of Fe and Se, which were sublimated from an e-beam evaporator and a Knudsen cell, respectively. Both chemical elements were deposited simultaneously on BLG/SiC(0001) while keeping a constant substrate temperature of 450 °C. A typical growth time of 60 minutes was necessary to achieve a nominal surface coverage as that shown in Fig. 1(c) (nominal coverage ~ 2 ML), which encompasses the coexistence of regions with one and up to

three layers of FeSe. To obtain thicker films of FeSe as that shown in Fig. S5 [60], we followed the same procedure except for a lower substrate temperature (350 °C). Samples showing different thicknesses of FeSe are obtained by controlling the growth time. After the growth, we capped the FeSe layers with an amorphous thick layer of Se deposited at room temperature, which prevents oxidation during its transport in air between the MBE and the STM chambers. The Se capping layers were eliminated prior to the STM measurements by annealing at 300 °C for 30 min without compromising the pristine quality of FeSe/BLG/SiC(0001).

B. XPS measurements

XPS data were collected in a Phoibos 150 NAP (Specs GmbH) analyzer using a μ FOCUS 600 x-ray monochromator (Specs GmbH), with an Al $K\alpha$ anode (1486.7 eV) and a spot size of 300 μ m. The FeSe/BLG/SiC(0001) sample was directly transferred from the STM chamber (USM1800) to the XPS chamber in a UHV suitcase, without exposing it to air. The survey spectrum was collected at 30 eV pass energy, while the core levels of interest were collected at 20 eV. During measurements, the sample was at room temperature, and the system was under UHV conditions. Data was analyzed using CasaXPS (Casa Software Ltd, Teignmouth, UK) software. The binding energy scale is calibrated to the Fermi edge.

C. STM/STS measurements and tip calibration

STM/STS experiments were conducted in two independent UHV chambers, each housing a commercial STM (UNISOKU Co., Ltd) that operates under different temperature conditions. The first system, a cryogen-free closed-cycle STM (USM1800), enables stable measurements at a base

temperature of 3.6 K. The second STM (USM1300) allows experiments at temperatures of either 4.2 K or 340 mK and is equipped with a superconducting magnet capable of providing a magnetic field up to 11 T, normal to the sample surface. The specific temperatures at which data were collected are explicitly noted in the figure caption. STS data were acquired using a standard lock-in technique, where an AC modulation voltage (V_{mod}) was applied to the STM bias voltage during data acquisition, with modulation frequencies of $f = 911$ Hz (USM1800) or $f = 833$ Hz (USM1300). All STS spectra were always recorded on large and clean regions that are far away (at least 50 nm) from edges to avoid potential confinement effects that may suppress superconductivity. Prior to each experimental run, the STM tip (made of Pt/Ir) was metallized on single crystals of Au(111) or Cu(111) and calibrated against their respective Shockley surface states. Special attention was given to ensuring a flat density of states of the tip near E_F . All the acquired STM/STS data were processed and analyzed using the freeware WSxM [61].

III. RESULTS AND DISCUSSION

Few-layer FeSe was grown by MBE on high-quality BLG formed through the graphitization of the surface of SiC(0001) (see Sec. II). This gives rise to the formation of the vertical heterostructure FeSe/BLG/SiC(0001), which is schematically represented in Fig. 1(a). The surface morphology of the FeSe films is shown in the STM topography of Fig. 1(c), where exposed regions of BLG/SiC(0001) coexist with FeSe areas of varying thickness. From the apparent height profile recorded along the blue arrow direction, and depicted in Fig. 1(d), it is inferred that an interlayer separation between successive FeSe of 5.8 Å, in agreement with the c -axis unit cell size of bulk FeSe (~ 5.5 Å) [21]. Consequently, the surface is predominantly covered by monolayer FeSe, which grows continuously across the atomic steps of BLG/SiC with full rotational disorder over the graphene. In addition to the complete monolayer, large regions of bilayer and trilayer FeSe were present, the latter as large as 100×100 nm².

Representative atomically resolved STM topography images of the BLG/SiC(0001) and monolayer FeSe surfaces are shown in Figs. 1(e) and 1(f), respectively, revealing distinctive atomic arrangements. The BLG/SiC(0001) surface is characterized by a hexagonal atomic registry, as expected from the honeycomb structure of graphene, along with a superimposed superstructure arising from the reconstruction of the SiC(0001) surface beneath [62]. In contrast, the surface of the monolayer FeSe does not exhibit any long-range superstructures and features a square atomic arrangement, with an average separation between the topmost atoms of Se-Se of 3.7 ± 0.2 Å. This value agrees with the in-plane lattice constant of bulk FeSe [21,63,64], as well as those for FeSe in the monolayer limit [54–56]. Additionally, the observed square-like structure is consistent with the tetragonal crystal structure of FeSe, as reported in its bulk state [21,64]. It is noteworthy that the atomic registry of the bilayer and trilayer FeSe exhibits the same square symmetry and geometric characteristics as observed in the monolayer (see Fig. S1 [60]).

Next, we probe the chemical properties of few-layer FeSe by means of XPS measurements at room temperature using

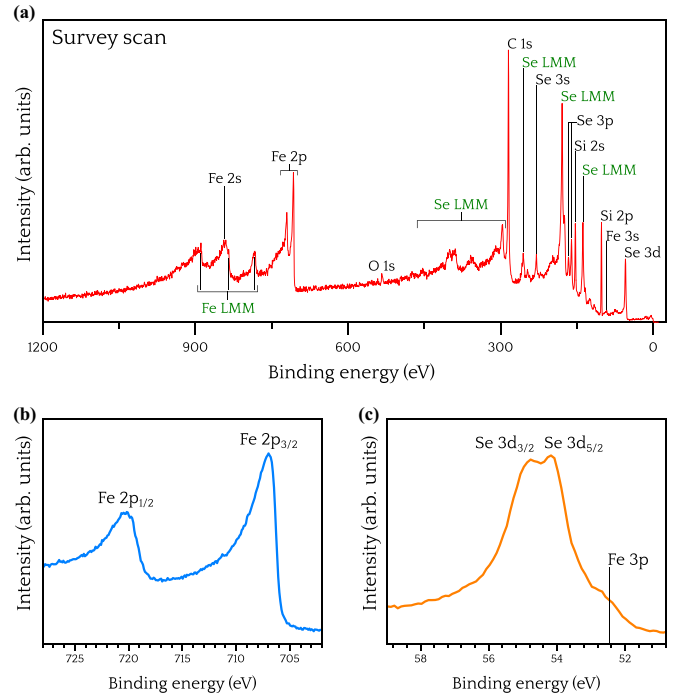


FIG. 2. Chemical properties of few-layer FeSe. (a) XPS survey scan spectrum. The main peaks are identified as the different core levels of Fe, Se, C, Si, and with a residual amount of O. LMM Auger transitions of the elements are highlighted in green as contrast. (b), (c) High-resolution XPS spectra probing the Fe 2p and Se 3d core levels, respectively. Both core levels show splitting due to the spin-orbit coupling effect.

the same samples previously employed for the STM/STS measurements. Figure 2(a) shows a survey scan XPS spectrum acquired on FeSe/BLG/SiC(0001). The main core level peaks of the different elements are highlighted in black, while LMM Auger transitions are indicated in green. As expected, carbon, silicon, iron, and selenium are the dominant chemical species resolved in the spectrum, along with a faint and minimal peak related to oxygen, which we associate with contaminants arising from the transfer procedure between the STM and XPS chambers (see Sec. II) and also inherent gas background from the XPS chamber (mainly H₂O). This corroborates the cleanliness of our MBE-grown samples of FeSe on BLG/SiC(0001), ruling out possible contaminants embedded in the FeSe layers. To further characterize the chemical state of Fe and Se, we measured the binding energies of the core levels of Fe 2p and Se 3d with higher resolution. The spectra of both core-level peaks are shown in Figs. 2(b) and 2(c), respectively, where the peaks are split due to spin-orbit coupling. The main peak of Fe 2p_{3/2} lies at a binding energy of 707.0 eV, and that of Se 3d_{5/2} at a binding energy of 54.1 eV. These values are in good agreement with those obtained for bulk tetragonal FeSe [65,66], indicating that our few-layer FeSe also hosts the same chemical bonding structure.

Once the structural and chemical properties of few-layer FeSe are clarified and shown to match those of the superconducting bulk FeSe crystals, we now focus on its electronic properties in the few-layer limit using STS measurements at 4.2 K. Figure 3(a) shows typical dI/dV spectra measured

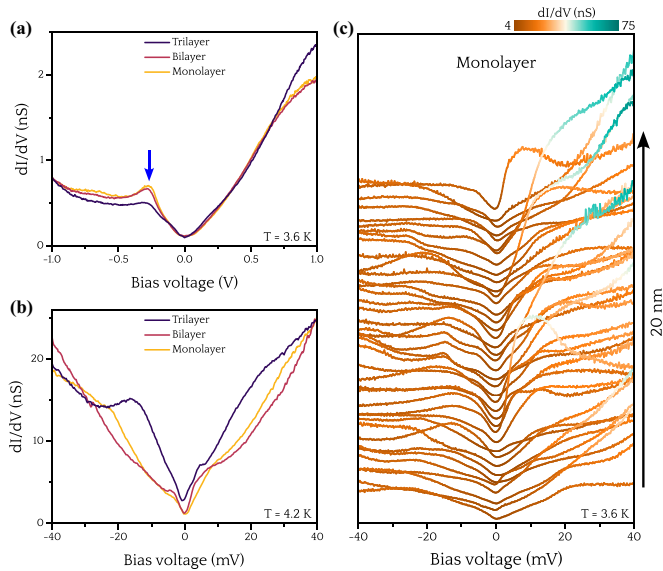


FIG. 3. Electronic structure of few-layer FeSe. (a) Large-scale dI/dV curves showing the electronic structure of FeSe for different layer thicknesses. (b) Higher-resolution dI/dV curves acquired near the E_F ($V_s = 0$ V). (c) Waterfall plot of spatially resolved high-resolution dI/dV spectra measured around E_F in monolayer FeSe along a linear path of 20 nm. Acquisition parameters: (a) $V_{\text{mod}} = 3.5$ mV, $T = 3.6$ K. (b) $V_{\text{mod}} = 200$ μ V, $T = 4.2$ K. (c) $V_{\text{mod}} = 250$ μ V, $T = 3.6$ K.

on one to three layers of FeSe over a large bias range [see Figs. S1(a)–(c) for the associated STM topography images [60]]. In all cases, the large-scale electronic structure shows the same main features, i.e., a broad peak at a bias voltage $V_s = -0.28$ V for occupied states (indicated by a blue arrow) and a V-shape local density of states (LDOS) with a nonzero minimum at the Fermi level. The broad peak, previously observed in few-layer FeSe [54], is tentatively attributed to the Fe-derived band of d_{zx} and d_{zy} orbital character and small dispersion along Γ -M calculated for the isolated monolayer of FeSe [19,67–69]. This suggests a weak interaction of FeSe with the graphene underneath. A close-up high-resolution

dI/dV spectra acquired at 4.2 K around E_F is shown in Fig. 3(b). As seen, the typical width of the V-shape dip feature is 25 ± 10 mV. Although this feature can be, in principle, associated with a superconducting gap like the one reported for monolayers of FeSe grown on SrTiO_3 [16,27,29,34,38,39,42], the significant spatial fluctuations in the shape and width of the dip feature at the nanometer scale (Fig. 3(c), and see also Figs. S2 and S3 [60]), despite the high crystallinity of the FeSe layers, suggest a different origin. Indeed, similar dip features unrelated to superconductivity have been previously observed in monolayers of transition metal dichalcogenides on graphene substrates [53,70,71], whose origin has been attributed to the Coulomb blockade effect in the STM tunneling junction [72] or phonon-assisted inelastic tunneling [73].

To better probe the existence of superconductivity in these films, we carried out high-resolution STS measurements at 340 mK, the base temperature of our STM instrument. Figure 4(a) shows typical high-resolution dI/dV spectra acquired from monolayer to trilayer FeSe, where we resolve an additional second dip around E_F that features a spatially dependent width in the range of 1 to 3 meV (Fig. S4 [60]). We note here that the larger V-shape dip discussed above persists at 340 mK (Fig. S4 [60]). The spatial-dependent behavior of the second dip closely resembles that observed in STS data recorded at higher temperatures and discussed above (note the difference in the energy window), suggesting that it is unrelated to superconductivity. To unambiguously evaluate this possibility, we characterized the evolution of this dip feature under an out-of-plane magnetic field ($B_{\perp}$). To minimize the impact of the inherent spatial variations of the dip structure, we performed spatially averaged STS measurements over regions of 3×3 nm² (not strictly in the same area for all field values due to slight spatial shifts that occur during magnetic field ramping). Figures 4(b)–(d) show the results obtained for monolayer, bilayer, and trilayer FeSe, respectively (see Figs. S1(d)–(f) for the associated STM topography images [60]). We observe that the dip structure—its shape, depth, and full width at half maximum—remains largely unaffected by the magnetic field up to 11 T. Assuming spin-singlet superconductivity, which is commonly associated with FeSe

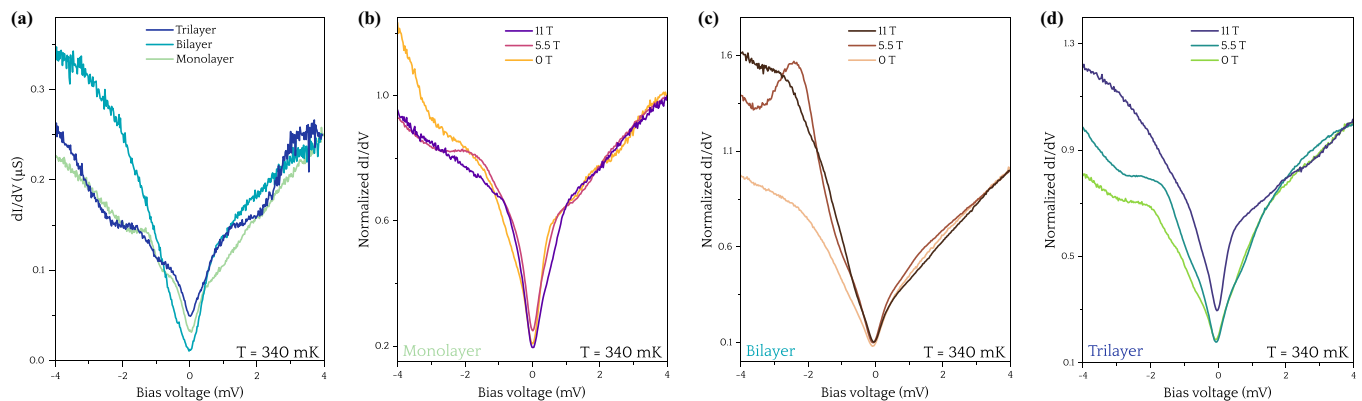


FIG. 4. Absence of superconductivity in few-layer FeSe down to 340 mK. (a) Set of high-resolution dI/dV spectra displaying the dip feature for different layer thicknesses of FeSe. (b)–(d) Out-of-plane magnetic field dependent dI/dV spectra showing the resilience of the dip feature in monolayer, bilayer, and trilayer FeSe, respectively. All curves are spatially averaged over regions of 3×3 nm². Acquisition parameters: (a) $V_{\text{mod}} = 20$ μ V, $T = 340$ mK. (b)–(d) $V_{\text{mod}} = 30$ μ V, $T = 340$ mK.

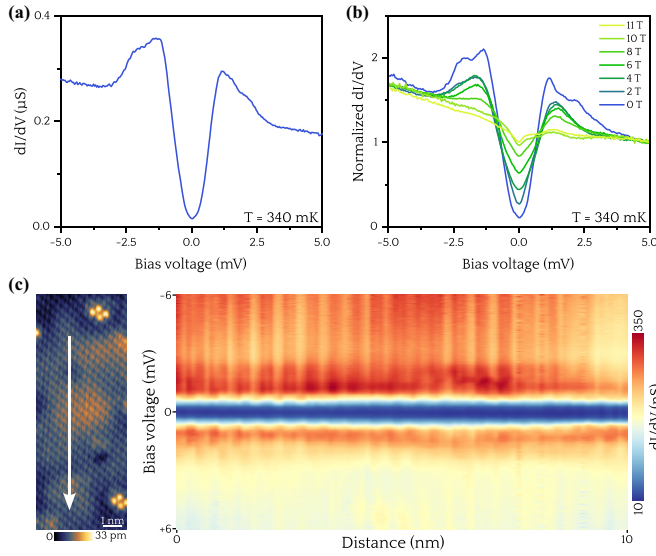


FIG. 5. Emergence of robust superconductivity in multilayer (>20 layers) FeSe. (a) High-resolution dI/dV spectra displaying the typical tunneling superconducting gap structure recorded on multilayer FeSe. (b) Sequentially measured dI/dV spectra as a function of the out-of-plane magnetic field. (c) Spatially resolved dI/dV spectra recorded along the white arrow indicated in the topography image on the left. Acquisition parameters: (a) $V_{\text{mod}} = 50$ μV , $T = 340$ mK. (b) $V_{\text{mod}} = 50$ μV , $T = 340$ mK. (c) $V_{\text{set}} = 100$ mV, $I_{\text{set}} = 50$ pA, $T = 340$ mK (topography image), and $V_{\text{mod}} = 50$ μV , $T = 340$ mK (STS).

both in bulk and the 2D limit, this result rules out the possibility of superconductivity in our few-layer FeSe samples.

We also carried out similar STS measurements on multilayer FeSe (>20 layers) on BLG/SiC(0001) (see Sec. II). In these samples, FeSe retains the same atomic configuration and a similar electronic structure to that in the ultrathin layer limit FeSe (see Figs. S5(a)–(d) [60]). However, our high-resolution dI/dV spectra acquired on multilayer FeSe now show a robust superconducting gap around E_F , as shown in Fig. 5(a) (see also Fig. S6 [60]). This superconducting gap remains visible in our dI/dV spectra at temperatures of 4.2 K (see Figs. S5(e) and S5(f) [60]), and shows a $T_C \sim 6$ K (see Fig. S7 [60]). The width of this gap, measured as the distance between the coherence peaks' position, is 2.5 ± 0.5 meV, which is comparable to those reported for bulk crystals [74–76] and multilayers [23,25,32]. From the characteristics of the quasiparticle tunneling gap, we infer that superconductivity in multilayer FeSe falls beyond the conventional s -wave BCS theory description, thus being compatible with recently proposed symmetries such as nodal superconductivity [23,32,74–76]. To confirm that this gap has a superconducting origin, in Fig. 5(b) we show the evolution of this gap under the presence of an out-of-plane magnetic field ($B_{\perp}$), from which we observe a gradual weakening of the gap with the applied field. Finally, the superconducting gap in multilayer FeSe exhibits strong robustness and spatial homogeneity, as evidenced by the $dI/dV(r,V)$ map depicted in Fig. 5(c).

The emergence of superconductivity in multilayer (>20 layers) contrasts with its suppression in few-layer (1–3 layers) FeSe on BLG observed in this work. To shed light

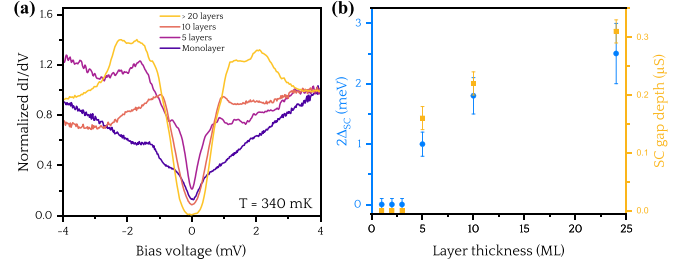


FIG. 6. Thickness-dependent superconductivity in FeSe grown on BLG. (a) Representative high-resolution dI/dV spectra measured at different FeSe thicknesses. (b) Extracted superconducting gap (Δ_{SC}), measured as the position of the coherence peaks, and superconducting gap depth as a function of layer thickness. Acquisition parameters: $V_{\text{mod}} = 20$ μV , $T = 340$ mK.

on the potential impact of the layer thickness of FeSe on its superconducting properties, we have grown samples with intermediate FeSe thickness (5 layers and 10 layers). Our STM/STS characterization indicates the development of spatially homogeneous tunneling superconducting gaps at 340 mK for both layer thicknesses (Figs. S8 and S9 [60]). The suppression of these gaps with increasing out-of-plane magnetic field and temperature upholds their superconducting nature (Figs. S8 and S9 [60]). The behavior of superconductivity of this iron-based superconductor with the layer thickness is summarized in Fig. 6(a). While superconductivity is suppressed in 1–3 layer-FeSe, it develops for five layers, and gradually strengthens with layer thickness, as denoted by the gap size, until it reaches a bulk-like superconductivity >20 layers [see Fig. 6(b)].

The results presented in this work provide valuable new insights into the electronic properties and superconductivity development of ultrathin FeSe films on graphene substrates. Our high-resolution STS data, obtained following rigorous structural and chemical characterization of the films, align with previous reports indicating the absence of superconductivity in monolayer FeSe [54,55]. However, they contrast with observations of superconductivity in bilayer and trilayer FeSe. In these cases, reported quasiparticle tunneling spectra exhibit a V-shaped dip with gap widths of 2 meV and 0.6 meV, respectively, corresponding to a $T_C \sim 3$ K [54,55]. While our STS measurements at 340 mK also exhibit a V-shape dip in the electronic structure at E_F on single-to-three layers of FeSe, superconductivity can be ruled out given the insensitivity of this feature to the perpendicular magnetic field, as described in our $B_{\perp}$ -dependent STS data.

Our results highlight the influence of the substrate and the thickness on the emergence of a superconducting phase in this FeSe material. First, the role of the substrate is utterly relevant for few-layer (1–3 layers) FeSe. While monolayer FeSe grown on SrTiO_3 is superconducting [22,24,27–29,34,37], on graphene substrates, the superconductivity is suppressed in the 2D limit, as shown in this work. This can be tentatively attributed to the difference at the interface of both systems. In the case of FeSe/ SrTiO_3 , strong electron-phonon coupling at the interface is likely the key mechanism that triggers superconductivity [28,29,39,49,77], a strong interfacial effect that seems unique to this substrate. Indeed, the suppression

of superconductivity in FeSe in the 2D limit has also been reported on other substrates of totally different nature, like on the van der Waals topological insulator Bi_2Se_3 [78,79] or on the insulating substrate MgO [80].

In a similar way, the layer thickness of FeSe is also crucial in determining the superconducting properties of this material. We have shown in this work that a robust bulk-like superconducting state is present in FeSe for films above 20 layers and a threshold thickness of five layers for the emergence of superconductivity. Qualitatively, our results are in good agreement with previous transport experiments, where superconductivity in mechanically exfoliated FeSe flakes from bulk crystals is suppressed below a certain thickness [81]. Additionally, it also aligns with the other types of superconductors, like on $\text{LaAlO}_3/\text{SrTiO}_3$ [82,83] or some materials within the cuprate family [84,85], where the superconductivity only emerges above a certain critical thickness. Nevertheless, we emphasize that the precise interfacial mechanisms that lead to superconductivity in FeSe in the 2D limit in the presence of substrates, or an increase in FeSe layer thickness, enhance superconductivity and still require further experimental and theoretical efforts.

IV. CONCLUSIONS

In summary, we have grown epitaxial few-layer FeSe on BLG/SiC(0001) to investigate their structural, chemical, and electronic properties via XPS and low-temperature (340 mK) STM/STS. Our STM and XPS data demonstrate the high-quality synthesis from the monolayer up to three layers of FeSe on BLG/SiC(0001), which display a tetragonal atomic structure as in bulk FeSe. In particular, the XPS experiments rule out the existence of contaminants embedded in the crystal structure that could affect superconductivity. Our subsequent high-resolution STS measurements provide evidence for the absence of superconductivity in 1 to 3 layers of FeSe down to 340 mK, as evidenced from the static quasiparticle spectra at E_F with a magnetic field. However, superconductivity does emerge in FeSe for thicker layers, with a determined superconducting critical thickness of five layers, and a critical transition temperature as high as 6 K for layer thickness >20

layers. Our work provides accurate information regarding the structural quality of epitaxial ultrathin FeSe films as well as the development of superconductivity in the ultimate 2D limit, in particular when it becomes part of a graphene-based vertical heterostructure.

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M.M.U. conceived the initial project. H.G. and M.M.U. designed the research strategy. Y.S. grew the samples with input from H.G. and M.M.U. Y.S. and H.G. measured the STM/STS data with the help of S.S. and M.M.U. H.G. and Y.S. analyzed the STM/STS data. A.E. measured and analyzed the XPS data. H.G. wrote the manuscript with input from A.E. and M.M.U. H.G. and M.M.U. coordinated this project. S.B. participated in the coordination of the STM and XPS experiments. All authors contributed to the scientific discussion and manuscript revisions.

The authors declare no competing interests.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible, and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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