BN/Graphene/BN Transistors for RF Applications

Han Wang¹, Thiti Taychapanapat¹, Allen Hsu¹, Kenji Watanabe², Takashi Taniguchi², Pablo Jarillo-Herrero¹, and Tomas Palacios¹

Abstract—In this letter, we demonstrate the first BN/Graphene/BN field effect transistor for RF applications. The BN/Graphene/BN structure can preserve the high mobility of graphene, even when it is sandwiched between a substrate and a gate dielectric. Field effect transistors (FETs) using a bilayer graphene channel have been fabricated with a gate length \( L_g = 450 \) nm. A current density in excess of 1 A/mm and DC transconductance close to 250 mS/mm are achieved for both electron and hole conductances. RF characterization is performed for the first time on this device structure, giving a current-gain cut-off frequency \( f_c = 33 \) GHz and an \( f_t L_g \) product of 15 GHz\( \mu \)m. The improved performance obtained by the BN/Graphene/BN structure is very promising to enable the next generation of high frequency graphene RF electronics.

Index Terms—Graphene Field Effect Transistors (GFET), radio frequency (RF), hexagonal boron nitride (hBN).

I. INTRODUCTION

Graphene is a one-atom-thick layer of carbon atoms arranged in a honeycomb lattice through sp² bonding [1]. Considered for many years an impossible goal, the isolation of graphene triggered a revolution not only among condensed-matter physicists but also among chemists and engineers, eager to take advantage of its unique properties [2]. The advantages of graphene for radio-frequency (RF) applications derive in part from its high electron and hole mobility, which can exceed 100,000 cm²/V.s at \( T = 240 \) K [3]. In addition, the combination of the unique properties of this material, with new device concepts and nanotechnology may overcome some of the main limitations of traditional RF electronics in terms of maximum frequency, linearity and power dissipation [4, 5]. Recently, high frequency graphene field effect transistors (GFET) have been demonstrated by several groups [6, 7]. However, despite the excellent RF performance achieved, these devices have carrier mobilities below 2,000 cm²/V.s, which are mainly limited by the interaction of graphene with the substrate and gate dielectric.

Most of today’s RF GFETs are fabricated on either SiO₂ [7] or SiC [6] substrate. Graphene was first isolated on SiO₂ due to the ability to identify single layer graphene using optical microscopes while the growth of graphene on SiC provides a natural substrate for these devices. However, neither SiO₂ nor SiC are ideal substrates for graphene. One problem with thermally grown SiO₂ (a few hundred nm thick) is that it often leads to a high surface roughness, as shown in Figure 1(a). In addition, the oxide typically has a large density of charge traps and defects. Graphene on SiC, on the other hand, suffers from a terraced rough substrate surface that can limit device performance by scattering charge carriers flowing in the active graphene layer [8]. Hence, in order to take full advantage of the ultra high mobility promised by graphene, we need to either remove the substrate [3] or use a better one. Although suspended graphene sheets have shown the highest mobility ever measured at room temperature in any semiconductor, the fragile suspended graphene membrane leads to many fabrication challenges and reliability issues. An alternative approach is to use a better substrate, such as hexagonal boron nitride (hBN) [9-11], which has the same atomic structure as graphene and shares many of its properties. The 2D planar structure of hBN also gives this material an ultra flat surface (Figure 1(a)) that is also free of dangling bonds and charge traps. Hence, it provides an ideal environment for graphene to sit on. Recent work has shown carrier mobility as high as 40,000 cm²/V.s in bilayer graphene (BLG) on hBN at room temperature [9].

In this work, we demonstrate the first BN/Graphene/BN RF field effect transistor, which has hBN as both the substrate and the gate dielectric with bilayer graphene as the channel material. This novel structure can preserve the high carrier mobility in the bilayer graphene channel and hence has a great potential for high frequency transistor applications.

II. BN/GRAPHENE/BN FETS

The fabrication process of the BN/Graphene/BN devices studied in this work is summarized in Figure 2(a-d). A hexagonal boron nitride flake is first exfoliated on a SiO₂/Si substrate. A separate SiO₂/Si sample is then coated with polyvinyl acetates (PVA) and polymethyl methacrylate (PMMA); and bilayer graphene flakes from natural graphite are exfoliated on top of the PMMA and transferred using the technique described in Ref. [10]. A flip chip bonder is used in the transfer process to allow for an accurate alignment between the hBN flake and the bilayer graphene flake. The alignment accuracy is within 1-2 \( \mu \)m. Figure 2(e) shows an optical micrograph of a bilayer graphene flake transferred on top of an

![Image](https://example.com/image.png)

Fig. 1 (a) AFM images showing the surface roughness of hBN and 285 nm thermally grown SiO₂. (b) Raman spectra of bilayer graphene on hBN (the peak at \( \lambda = 1375 \) cm⁻¹ is due to hBN substrate); and bilayer graphene on SiO₂.
The contact, the 2-20 nm Ti/40 nm Au 2-s device is the fabricated and consisting of 285 nm SiO 2 substrate forms the bottom gate of the device with a dielectric of 8.6 nm as measured by atomic force microscopy (AFM), which active region is 3 μm. The top gate dielectric has a thick resistance is typically 200 Ωμm. The top gate dielectric has a thick resistance is typically 200 Ωμm. After that, a second layer of hBN substrate produced in our laboratory show Hall mobilities and the hBN top gate dielectric. Typically, bilayer graphene on hBN substrate produced in our laboratory show Hall mobilities and the hBN top gate dielectric. In addition, there is very little mobility degradation after the second hBN layer (i.e. the top gate dielectric) is transferred on top. The maximum transconductance g_m is close to 250 mS/mm. The extrinsic DC transconductance is mainly limited by the access resistances and gate capacitance, not the mobility.

Figure 4(a) shows the RF performance of the device. With L_G=450 nm and at V_D=1 V, the device has a current-gain cut-off frequency f_T=5 GHz and f_T=22 GHz before and after de-embedding the coplanar-wavguide (CPW) pad capacitances, respectively. The de-embedding procedure follows the well-established standard open-short method [13, 6, 7]. In these measurements, the back-gate, i.e. substrate, was grounded.

The substrate bias has a significant effect on the RF performance of the device. With the substrate grounded, the un-gated access regions on both the source and the drain side of the device have their Fermi energy levels located near the Dirac point (the minimum conduction point). This leads to relatively large source and drain access resistances (R_s and R_d). The resistances of these un-gated regions can be reduced through electrostatically doping them by biasing the substrate. This reduction in the resistances significantly increases the frequency performance of the device [14]. For example, Figure 4(b) shows that when the substrate is biased at -30 V, the current gain cut-off frequency increases to 6 GHz and 33 GHz before and after de-embedding.

The DC and RF performance of this device was also compared to a control device fabricated on a SiO 2 substrate and with a 16 nm Al 2 O 3 gate dielectric. This control device also uses a bilayer graphene flake exfoliated from natural graphite as the channel material. The Al 2 O 3 gate dielectric is formed by naturally oxidizing 3 nm of e-beam evaporated Al followed by atomic layer deposition of 13 nm Al 2 O 3. The thickness of the Al 2 O 3 gate dielectric was chosen to render the same top gate capacitance as in the BN/Graphene/BN FET. The Hall mobility of our bilayer graphene on SiO 2 is typically between 1,500 and 2,000 cm 2/V.s [15]. This low mobility is mainly due to the scattering introduced by the SiO 2 substrate. The mobility

III. RESULTS AND DISCUSSIONS

Figure 3(a) shows the transfer characteristics (I_DS vs. V_GS) of the fabricated transistor. At V_D=1 V, the device achieves a high current density close to 1.2 A/mm. The minimum conduction point of the transistor is very close to 0 V. This indicates negligible doping effects from both the hBN substrate and the hBN top gate dielectric. Typically, bilayer graphene on hBN substrate forms the bottom gate of the device with a dielectric thickness of 8.6 nm as measured by atomic force microscopy (AFM), which active region is 3 μm. The top gate dielectric has a thick resistance is typically 200 Ωμm. After that, a second layer of hBN substrate produced in our laboratory show Hall mobilities and the hBN top gate dielectric. In addition, there is very little mobility degradation after the second hBN layer (i.e. the top gate dielectric) is transferred on top. The maximum transconductance g_m is close to 250 mS/mm. The extrinsic DC transconductance is mainly limited by the access resistances and gate capacitance, not the mobility.

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Fig. 4 RF performance of the fabricated BN/Graphene/BN FET with $L_G=450$ nm when (a) the substrate is biased at $V_{DS}=0$ V, and (b) the substrate is biased at $V_{DS}=30$ V. In both (a) and (b), the $\beta_T$ data and $f_T$ before de-embedding are shown in red; and that after de-embedding are shown in blue. $V_{GS}=1$ V. The top gate bias is $V_{G}=1$ V for (a) and $V_{G}=0$ V for (b), such that the device is very close to the maximum $g_m$ in each case.

degraded by ~30% after oxide deposition due to the additional impurities introduce to the system.

For similar device dimension and gate capacitances, the BN/Graphene/BN FET shows a peak transconductance ($g_m$) of 250 mS/mm, which is about 70% higher than that in the control sample that has a peak $g_m$ of only 140 mS/mm (Figure 3). To further analyze and compare the two devices, the virtual source model proposed in Ref. [12] is used to fit their DC characteristics (Figure 3). The model extracts a field effect mobility of 6,500 cm²/V.s in the BN/Graphene/BN FET and 1,200 cm²/V.s in the control device, respectively. This carrier mobility, while much higher than the control device but relatively low compared to other reported mobility values of bilayer graphene on hBN, is possibly due to bubbles and ripples created during the transfer process; and the measurements being taken at high drain biases ($V_{DS}=1$ V) and high current density. The carrier injection velocities are estimated to be about 3.5x10⁷ cm/s in the BN/Graphene/BN FET and 2.5x10⁷ cm/s in the control device. This gives an indication of the significant advantage that an hBN substrate and dielectric can have over SiO₂ and Al₂O₃ in terms of preserving the high carrier mobility and carrier velocity in graphene. Figure 5 compares the peak $f_T$ of these two devices of equal gate length and gate capacitance. For $V_{DS}=1$ V, the BN/Graphene/BN FET has its highest $f_T=33$ GHz at $V_{BG}=-30$ V, and $V_{TG}=0$ V while the control sample has its highest $f_T=18$ GHz at $V_{BG}=-10$ V, and $V_{TG}=1$ V, demonstrating a significant improvement in peak $f_T$ due to the change of substrate and the gate dielectric material.

IV. CONCLUSION

In this letter, we fabricated the first BN/Graphene/BN RF FET and characterized its DC and RF performances. This new device is also compared to a control GFET with a SiO₂ substrate and an Al₂O₃ gate dielectric. The BN/Graphene/BN structure allows a much higher mobility and carrier velocity than in the case of SiO₂ substrates and Al₂O₃ gate dielectrics. With the same device dimensions, the BN/Graphene/BN device shows a significant improvement in $f_T$ compared to the control device, demonstrating its great potential for applications in high frequency electronic circuits. In addition, recent developments

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