High Performance, Large Area Graphene Transistors on Quasi-Free-Standing Graphene Using Synthetic Hexagonal Boron Nitride Gate Dielectrics

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In recent years, hexagonal boron nitride (h-BN) has gained interest as a material for use in graphene based electronics, where its ultra-smooth two-dimensional structure, lack of dangling bonds, and high energy surface optical phonon modes are desirable when considering the effect of dielectric materials in introducing additional sources of scattering for carriers within graphene. Initial work has indicated that use of h-BN in place of SiO_2 supporting substrates can lead to 2-3x improvements in device performance [1,2], suggesting that h-BN may be an excellent choice as top-gate dielectric for graphene devices. In this work, we integrate h-BN with quasi-free-standing graphene (QFEG) for the first time and demonstrate a 2x improvement in radio frequency (RF) performance and the highest $f_T{\cdot}L_g$ product yet reported for h-BN integrated graphene devices (25 GHz·μm).

QFEG is a form of large-area graphene derived from epitaxial graphene (EG) using a hydrogen passivation step, resulting in improved transport properties relative to conventional EG on SiC [3]. Integration of h-BN with QFEG is achieved utilizing a catalytic thermal chemical vapor deposition growth process on Cu substrates in conjunction with a large-area solution transfer process (Fig. 1). Two-finger RF transistors with gate length 750 nm are fabricated using conventional, production scale photolithographic methods. Fig. 1c shows the schematic cross section of a typical graphene transistor.

Room temperature Hall effect measurements and DC output characteristics of h-BN (t_{ox} = 50 nm) and HfO_2 (t_{ox} = 10 nm) coated QFEG transistors are shown in Fig. 2. Although extensive p-type doping is found to occur after hydrogen passivation, integration of HfO_2 dielectrics leads to significant electron doping and a shift in V_{Dirac} close to V_{gs}=0V while integration of h-BN leads to little change in the as-grown carrier density and V_{Dirac} remains at large positive values of V_{gs} (>10V). DC characteristics of h-BN gated transistors show reduced on-off ratios relative to HfO_2, yet demonstrate excellent drive current >1.6 A/mm at V_{ds}=1V (Fig. 2b,c). Peak transconductance is found to be <10 μS/μm (Fig. 3a), which is attributed to the relatively large EOT for these devices (~50 nm) as well as the increasing dominance of contact resistance at high drive currents (~200 Ω-μm). Normalizing transconductance with C_{ox}, we find that h-BN devices offer a very competitive g_m/C_{ox} ratio even for the limited range of testable voltages and despite the impact of contact resistance (Fig. 3b). Wafer scale testing confirms that use of solution transfer processing does not negatively impact wafer uniformity or device yield, which is found to be ~90% (Fig. 3c).

RF performance is excellent for h-BN gated transistors (Fig. 4a), exhibiting peak intrinsic f_T of 33.3 GHz at a gate length of 750 nm with V_{ds}=1V, which represents a 2x improvement relative to HfO_2 coated transistors, where intrinsic f_T was extracted from measured S-parameters using a standard short-open-load-thru de-embed process to calibrate out the effect of probe and pad parasitics. The increase in RF performance is found to be a result of improved transport properties relative to HfO_2 coated QFEG. Temperature dependent transport measurements indicate that h-BN dielectrics are effective in preserving carrier mobilities as high as 2700 cm^2/V sec, which is only ~10% smaller than the highest reported mobilities for un-coated QFEG, while modeling of the scattering processes indicates that use of h-BN dielectrics introduces less remote charged impurity and remote surface optical phonon scattering than HfO_2 dielectrics (Fig. 4b,c).

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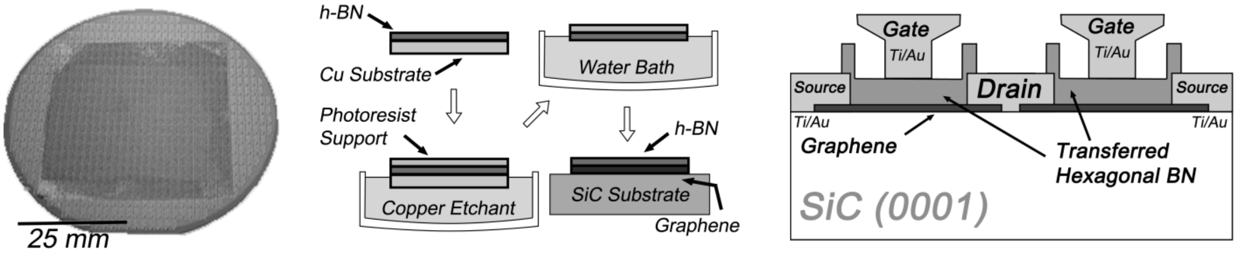
[1] Palacios et al, IEEE Elec. Dev. Lett., 32, 9, 2011

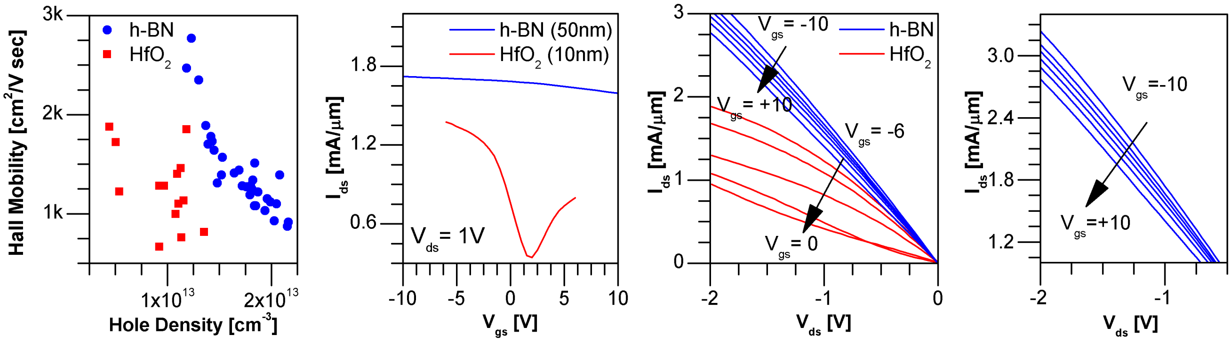
[2] Kim et al, Nano Lett. 12, 2, 2012

[3] Robinson et al, Nano Lett. 11, 9, 2011



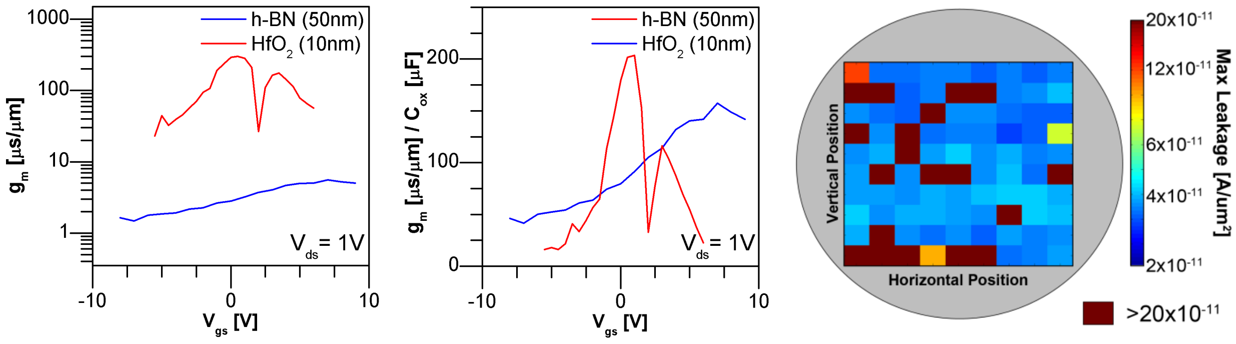
(a) (b) (c)

Figure 1. Photograph of 3-inch QFEG wafer with h-BN top-gate dielectric (a) and schematic representation of solution transfer process used to integrate h-BN with QFEG after catalytic synthesis (b). Schematic cross section of two finger graphene transistor (c).



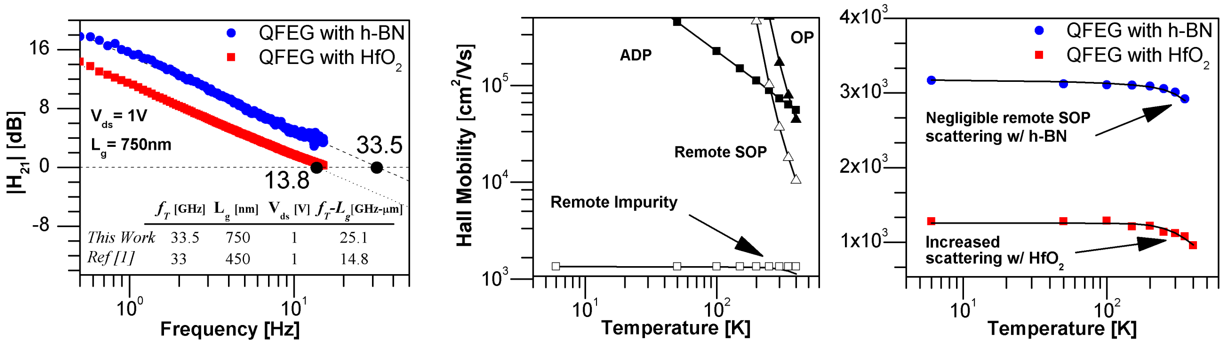
(a) (b) (c) (d)

Figure 2. Scatter plot of Hall mobility versus carrier concentration (a) compared to DC output characteristics of h-BN and HfO_2 coated graphene transistors (b),(c),(d).



(a) (b) (c)

Figure 3. g_m and g_m/C_{ox} of QFEG transistors (a),(b). Wafer map of peak gate current density (c).



	f_T [GHz]	L_g [nm]	V_{ds} [V]	f_T-L_g [GHz-µm]
This Work	33.5	750	1	25.1
Ref [1]	33	450	1	14.8

(a) (b) (c)

Figure 4. Intrinsic RF characteristics of h-BN and HfO_2 coated transistors (a). Temperature dependent modeling of h-BN and HfO_2 coated QFEG showing the reduction in remote SOP and impurity scattering with h-BN gates (b),(c).