Graphene transistors with record mobilities on polyimide for high-performance flexible nanoelectronics

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Graphene devices offer promising properties that are ideally suited for flexible nanoelectronics. These properties include high-mobility, high stretchability and strength, and compatibility with roll to roll large area manufacturing.[1] In this work, we report high-speed embedded-gate graphene field-effect transistors (EGFETs) on smooth polyimide (PI) films with a maximum electron mobility of 4930cm^2/V-s. This value is comparable with the highest transistor mobilities from chemical vapor deposited (CVD) graphene realized on conventional substrates such as SiO_2,[2] indicating that the high-speed attributes of graphene can be accessed for flexible electronics and enable high-frequency GHz flexible systems. High-quality monolayer graphene was synthesized from methane CVD at 1000ºC on Cu films evaporated on SiO_2/Si substrates. Raman spectroscopy verified the growth of high-quality monolayer graphene with the following characteristics as shown in Fig. 1(a): i) the full width at half maximum of the 2D-peak is ~32cm^{-1}, ii) the 2D/G intensity ratio is 2.5-3, and iii) the D-peak intensity is small or negligible. The graphene device fabrication process is illustrated in Fig. 1(b). In brief, embedded gate electrodes were patterned on a PI-coated on Si_3N_4/Si substrate followed by atomic layer deposition of a 20-nm thick high-k (Al_2O_3) dielectric. Synthesized monolayer graphene was applied onto the PI-coated substrate using conventional wet-transfer process,[2] and patterned with oxygen plasma to define the channels. The gate and source/drain metals are Ni/Au and Ni respectively. Lastly, the Si_3N_4 layer was etched and the PI film released from the Si substrate. The EGFET and released PI film are shown in Fig. 1(c) and (d) respectively. AFM inspection revealed that the initial smooth PI surface was rougher after graphene transfer and fabrication (Fig. 2) likely due to resist residue. Electrical data for the EGFET can be seen in Fig. 3 with good agreement between measurement and a popular diffusive model.[3] The extracted mobilities are 4930cm^2/V-s and 1130cm^2/V-s for electrons and holes respectively. Temperature dependent measurements of the key device parameters (impurity density, mobility, contact resistance) are shown in Fig. 4. The weak impurity dependence indicates that unintentionally doping dominates over the intrinsic thermally generated charges. Mobility-temperature dependence suggests impurity and screening effect dominates the hole and electron transport respectively. The asymmetric contact resistance is a consequence of the high work-function Ni which preferentially favors hole injection over electron injection.[4]

In summary, we report record mobilities from CVD graphene featuring embedded gates and high-k dielectrics on polyimide films. Temperature dependent measurements indicate further enhancements in charge transport is possible with improved fabrication processes. Our work reveals that graphene transistors on polymeric substrates are promising for high-speed flexible nanoelectronics.

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1. S. Bae, et al., Nat Nanotechnol. 5 (8), 574 (2010). 2. X. Li, et al., Science 324 (5932), 1312 (2009). 3. S. Kim, et al., Appl. Phys. Lett. 94 (6), 062107 (2009). 4. K. Nagashio, T. Nishimura, K. Kita, and A. Toriumi, IEEE IEDM, 2009.

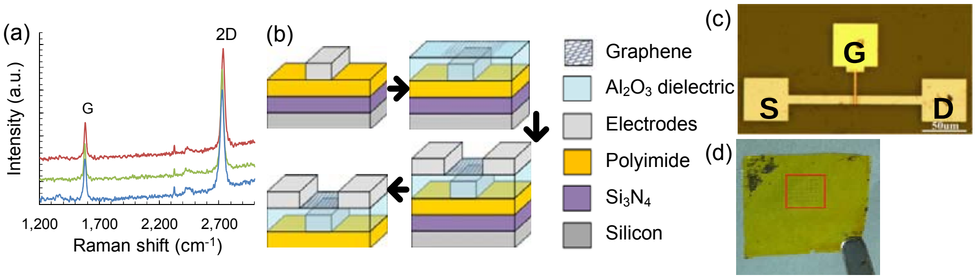

Figure 1: (a) Representative Raman spectra of monolayer graphene used for device fabrication. Raman spectra were taken with a 442 nm blue laser at three locations of the synthesized graphene on evaporated Cu film directly before transfer. (b) Illustration of the EGFET fabrication process on spin-coated PI on a Si_3N_4/Si substrate. (c) Optical image of a completed EGFET. The device length and width are 4 and 8 μm respectively. (d) Photograph of the flexible substrate with an array of EGFETs. The highlighted square shows the array of devices.

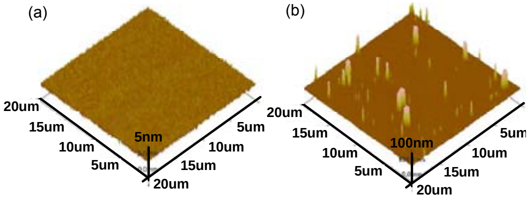

Figure 2: 3D AFM images PI surface before and after device fabrication. (a) AFM image of cured polyimide before graphene transfer with surface roughness <1nm, and (b) AFM image after EGFET fabrication. The surface roughness in the smooth areas is ~2nm.

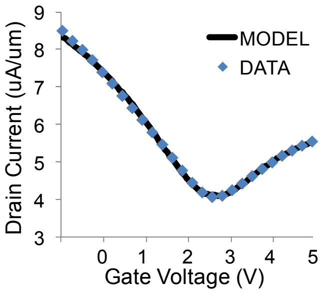

Figure 3: Experimental current–voltage characteristics of the EGFET with extracted electron and hole mobilities of 4930cm^2/V-s and 1130cm^2/V-s respectively. V_D=100mV.

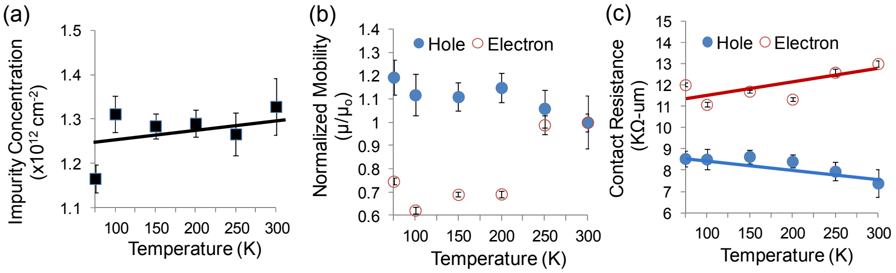

Figure 4: Temperature-dependent device characteristics. (a) charge impurity density, (b) mobility normalized to the 300K value (μ_o), and (c) contact resistance dependence on temperature. The contact resistance reported here is the total contribution from the source and drain contacts. μ_o is the reference mobility at 300K.