Transfer-Free Fabrication of Large-Area Nanocrystalline Graphene

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Graphene, with its low thickness and ultra-high Young’s modulus of ~1 TPa, is a promising candidate for future nanoelectromechanical (NEM) switches with minimal electrical leakage, sharp switching, low actuation voltage and high on/off ratio [1]. Despite these advantages, graphene has yet to outperform its regular polycrystalline counterparts, graphene on metal catalysts, along with its transfer techniques, offers the prospect to establish large-scale graphene electronics. Nevertheless, directly grown graphene on insulating substrates is still desirable. In this work, we demonstrate a large-scale array of NEM switches fabricated from nanocrystalline graphene (NCG) that was deposited directly onto an insulator via catalyst-free plasma enhanced CVD. Here we use regular thin film process techniques, with no transfer required, and achieve high performance, i.e. low pull-in voltage of 8.5 V, reversible operations, minimal leakage current of ~1 pA, and high on/off ratio of ~104. The Young’s modulus of ~0.74 TPa is estimated from measured device characteristics.

The NCG was deposited on a silicon wafer covered with 250-nm-thick thermal SiO2 at 800 °C in an Oxford Instruments Nanofab 1000 system [2]. Before growth, the wafer was cleaned in H2 ambient for 15 min at the same temperature. During deposition, CH4 and H2 were introduced (40 sccm, 50 sccm, 1500 mTorr) with the RF plasma generated at 100 W. Five minutes growth resulted in an 8.5-nm-thick film, which was verified by ellipsometry. A significant D peak is observed in its Raman spectrum (Fig. 1), indicating the defects at the polycrystalline grain boundaries. The grain size of the NCG is calculated as 2.1 nm from \( L_g = C(\lambda)\ell_0/\ell_0 \), where \( \ell_0 \) and \( I_0 \) are the G and D peak intensities, respectively, and \( C(\lambda) \) is a wavelength dependent coefficient. AFM measurement shows the smooth surface of the NCG with RMS roughness of 0.53 nm (Fig. 2).

The fabrication process of the NCG switch is illustrated in Fig. 3: (a) growth of NCG; (b) definition of bottom electrode with Cr/Au; (c) patterning NCG into ribbons by oxygen plasma with a hydrogen silsesquioxane (HSQ) mask; (d) deposition of a SiO2 sacrificial layer to define the air gap; (e) definition of top electrodes with Cr/Au on the sacrificial layer; (f) releasing NCG ribbons in buffered hydrofluoric acid. Finally, the sample is dried in a critical point drier. The fabricated switch array is shown in Fig. 4. Figure 5 plots the electrical characterization results of one switch measured in the two-terminal configuration depicted in the inset of Fig. 4(a). In the off-state, only noise in pico-ampere range is observed. At ~8.5 V, the pull-in of the NCG ribbon is evidenced by an abrupt current increase. High on/off ratio of ~104 and sharp slope of <10 mV/dec are thereby obtained. In the reverse operation, the pull-out occurred at ~5 V. The consistency of \( L_g \)-\( V_{th} \) responses measured in consecutive cycles highlights a good reliability. The pull-in voltage of an ideal double-clamped NCG ribbon is approximated by \( V_{th} = \sqrt{8kW_{SC}(27\pi/kW_{SC})} \), where \( k = 32E_{silicon}(dL/V)^3 \) is the spring constant of the ribbon, \( g_0 \) is the initial air gap, \( \pi \) is the vacuum permittivity, \( W \) is the width of the top electrode, \( W_{SC} \), and \( L \) and \( d \) are the width, thickness and length of the NCG ribbon, respectively. By fitting this model to measured \( V_{th} \) values obtained from switches with different \( L \), we extract the high Young’s modulus \( E \) for NCG of ~0.74 TPa as shown in Fig. 6.

Figure 1. Raman spectrum of the NCG film. Red curves are the component curves obtained from peak fitting.

Figure 2. AFM topography of the as-grown NCG film on SiO2/Si substrate. Area: 1 μm × 1 μm.

Figure 3. Schematic of the NCG switch fabrication. B and T denote the bottom and top electrodes, respectively.

Figure 4. (a) Optical image of NEM switch array. Inset: measurement configuration. The zoomed-in detail of a single switch: (b) Optical and (c) SEM images.

Figure 5. Current-voltage response of the NEM switch shown in Fig. 4(c) under repeated cycling. (\( W_c \): 550 nm; \( W_{SC} \): 500 nm; \( L \): 1.5 μm; \( g_0 \): 70 nm)

Figure 6. Pull-in voltages measured as a function of the NCG ribbon length. The Young’s modulus of the NCG is estimated from fitting to the experimental data (blue line).