Suspended few-layer graphene beam electromechanical switch with abrupt on-off characteristics and minimal leakage current

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Suspended few-layer graphene beam electro-mechanical switches (SGSs) with 0.15 μm air-gap are fabricated and electrically characterized. The SGS shows an abrupt on/off current characteristics with minimal off current. In conjunction with the narrow air-gap, the outstanding mechanical properties of graphene enable the mechanical switch to operate at a very low pull-in voltage (V_{PI}) of 1.85 V, which is compatible with conventional complimentary metal-oxide-semiconductor (CMOS) circuit requirements. In addition, we show that the pull-in voltage exhibits an inverse dependence on the beam length. © *2011 American Institute of Physics*. [doi:10.1063/1.3610571]

Graphene has recently received great attention for its unique electronic[1] and mechanical[2] properties and has been considered as a promising candidate to replace conventional semiconducting materials used in metal-oxide-semiconductor field-effect transistors (MOSFETs) and micro/nano electromechanical switch (MEMS/NEMS) devices. Graphene field-effect transistors, however, possess fundamental issues, such as high off-leakage current, because of its semi-metallic zero bandgap electronic structure. Mechanical switching, on the other hand, enables electronic systems to operate with a zero off-leakage current and an abrupt on-off transition,[3–5] which can both reduce the static and dynamic power consumption in electronic switching devices.[6] By incorporating MEMS/NEMS devices into CMOS circuits, the inherent problems in short-channel devices can be resolved.[7–9]

In order to reduce the switching voltage and speed of mechanical switches, the moving parts need to be miniaturized and thinned. In general, three-dimensional (3D) materials, such as metals or poly-Si, have been used for the active part of MEMS/NEMS devices. However, they become brittle when they are scaled down to nanometers. Contrarily, 1D and 2D materials, such as carbon-nanotubes and graphene, sustain its mechanical properties even at the nanoscale.[10–13] Moreover, they exhibit outstanding electronic properties suitable for low-power and high-speed MEMS/NEMS applications. Recently, large scale pattern growth of graphene technology has been demonstrated and could provide effective solutions satisfying selectivity and mass production.[14]

In this letter, we present a unique fabrication method and the switching characteristics of suspended few-layer graphene (FLG) beam mechanical switches with ideal-like on/off characteristics and minimal off-current. Furthermore, we investigate the pull-in voltage characteristics depending on the length of the suspended graphene beam.

Figure 1 illustrates the fabrication steps of SGS. First, a 100 nm-thick SiO_2 was thermally grown on a highly doped n-type Si wafer. The chemical vapor deposited (CVD) FLG films grown on Ni catalyst were characterized by Raman spectroscopy [Fig. 1(b)] and transferred onto the SiO_2 using thermal release tape [Fig. 1(a)-1].[15] Next, FLG beams were defined through photolithography, etched by oxygen plasma, and characterized by atomic force microscopy to confirm the thickness of the actual FLG beam (<2.5 nm) [Fig. 1(a)-2]. After depositing Cr/Au for the top electrode formation [Fig. 1(a)-3], the FLG beam is suspended by selectively removing the exposed rectangular region of 100 nm-thick SiO_2 using

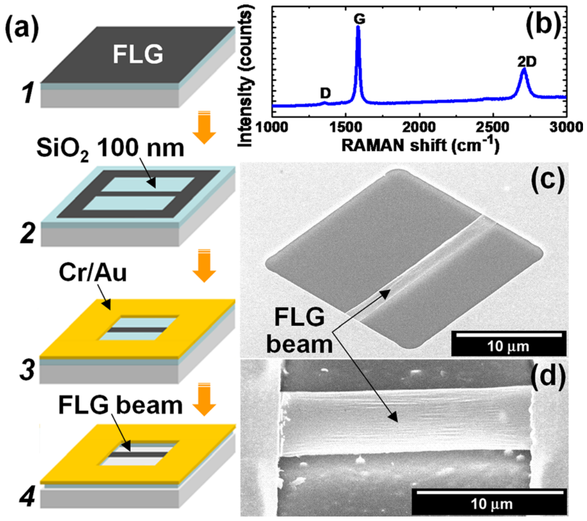

FIG. 1. (Color online) Schematic of the fabrication steps of SGS. (a)-1. A 6-in. wafer-scale CVD grown FLG film is transferred onto a 100 nm-SiO_2/Si substrate using thermal release tape. (a)-2. FLG beam is defined using photolithography and O_2 plasma. (a)-3. Top electrode is formed by Cr/Au deposition and lift-off. (a)-4. FLG beam is suspended by selectively removing SiO_2 using diluted HF, and the height of the air-gap is controlled by successively etching the Si substrate using diluted KOH solution. (b) Raman spectroscopy of CVD grown FLG transferred onto 100 nm-SiO_2. (c) Bird's eye-view SEM image of SGS ($l/w \sim 20$ μm/2 μm, $h \sim 0.15$ μm). (d) Tilted-view SEM image of SGS ($l/w \sim 20$ μm/5 μm, $h \sim 2$ μm).

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diluted hydrofluoric (HF) acid [Fig. 1(a)-4]. In order to prevent HF acid from infiltrating into the interface of graphene and SiO_2, the top electrodes were intentionally designed to be larger in size than the underlying graphene sheet. In addition, to avoid initial stiction from capillary forces, a critical point drier is used.[15] The air-gap between the suspended FLG bridge and the underlying Si is modified by controlling the KOH etching time. Finally, a thin Al_2O_3 layer of 30 Å was coated onto the underlying Si substrate by atomic layer deposition to prevent possible welding of FLG beam onto Si during switching operations. As shown in Figs. 1(c) and 1(d), the scanning electron microscope (SEM) images of as-fabricated SGS structures display suspension of FLG beams over the Si substrate.

The electromechanical motions of the suspended FLG beam switches are investigated by measuring the current-voltage (*I*-*V*) characteristics. Upon applying a voltage between the FLG and Si substrate, the electrostatic force pulls the suspended FLG beam towards the bottom Si electrode. A pull-in operation is achieved once the FLG bridge makes a physical contact to the substrate, which is indicated through an abrupt increase of current.[16,17] The voltage where the abrupt transition occurs is the V_{PI} of an electromechanical switch, which is an important parameter relevant to the power consumption of MEMS/NEMS devices. As shown in Fig. 2, the SGS (length/width $= l/w \sim 20\ \mu m/2\ \mu m$, air-gap $= h \sim 0.15\ \mu m$) shows an abrupt on/off current transition with a sub-threshold swing below 7 mV/dec at an average V_{PI} of 1.85 V. This value is similar to the operation voltage of conventional MOSFET devices and is well suited for integrating MEMS/NEMS switches with CMOS. Here, we note that the V_{PI} is not consistent on a run-to-run basis. We propose two possible reasons. One is that the physical contact point and/or the air-gap height are not guaranteed to be identical among successive switching operations. The other is that, when the switch is ON, the Joule heating can cause ambient molecular species to adsorb/desorb onto graphene and thus modify the mechanical and surface properties of the FLG beam.[18] In order to minimize such undesirable effects, a cross-bar beam-gate SGS structure with encapsulation techniques, such as electrostatic bonding of Pyrex glass[19] and deposition of silicon nitride[20] or polysilicon,[21] can be implemented to form a hermetically vacuum sealed capsule. Considering that the noncapsulated SGS degrades after performing 4–6 successive switching operations, protection from moisture and contaminants is mandatory for reliable long-term usage.

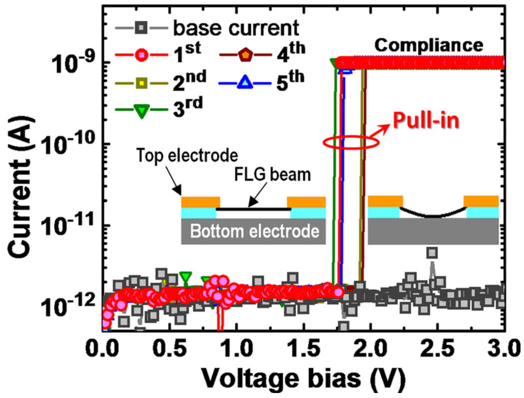

FIG. 2. (Color online) *I*-*V* characteristics of SGS. The average V_{PI} of SGS ($l/w \sim 20\ \mu m/2\ \mu m$, $h \sim 0.15\ \mu m$) is 1.85 V. To prevent in-use stiction caused by Joule heating, a current compliance was set at 1 nA.

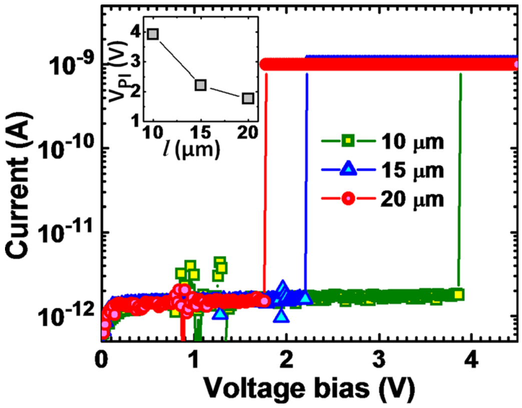

FIG. 3. (Color online) *I*-*V* characteristics of SGS for different beam length. (Inset shows V_{PI} dependence on FLG beam length.)

Furthermore, we characterize the *I*-*V* characteristics of SGS for various beam lengths (Fig. 3). As shown in the inset of Fig. 3, the V_{PI} decreases ($\sim 1/l^2$) as the beam length increases for a constant beam width, which is consistent with the model proposed by Pamidighantam *et al.*[22] and is attributed to the lowering of the bending stiffness.

Another important parameter for a mechanical switch is the switching time. In general, conventional MEMS/NEMS has a switching time of a few microseconds.[23,24] In graphene-based MEMS/NEMS, however, the extremely low mass density and high Young's modulus results in a very large resonant frequency ($\sim$tens of MHz),[10,18] which shows possible operation in the nanosecond regime. Based on Muldavind and Rebeiz's model,[25] the switching time is estimated to be $t_s = 3.67\ (V_{PI}/V_{op}\omega_o) = 40$ ns ($V_{PI} = 1.85$ V, $V_{op} = 1.3V_{PI}$, and $\omega_o = 70$ MHz), where V_{op} is the operation voltage and ω_o is the resonant frequency.

In summary, we demonstrate a FLG mechanical switch that shows ideal switching characteristics at low operation voltages, which arises from the astonishing mechanical properties of 2D graphene. We believe that this study will benefit future applications of graphene for MEMS/NEMS devices.

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