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Raman spectrum method for characterization of pull-in voltages of graphene capacitive shunt switches

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An approach using Raman spectrum method is reported to measure pull-in voltages of graphene capacitive shunt switches. When the bias excesses the pull-in voltage, the Raman spectrum's intensity largely decreases. Two factors that contribute to the intensity reduction are investigated. Moreover, by monitoring the frequency shift of G peak and 2D band, we are able to detect the pull-in voltage and measure the strain change in graphene beams during switching. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4773183]

Graphene is a two-dimensional honeycomb crystal of carbon atoms.[1] Its high Young's modulus[2] (1 TPa, at least six times higher than that of silicon) and low density (2.23 g/cm^3) make it a desired material for nanoelectromechanical systems,[3–5] such as radio frequency (RF) switch. Two basic types of switches are mainly considered in RF circuit design: DC (direct current) contact switch and capacitive shunt switch.[6,7] The latter has a dielectric layer on top of a pull-in electrode. Compared with a DC contact switch, the reliability of a capacitive shunt switch can be higher, making it more suitable for higher frequency applications. Up to date, the graphene switches reported are mainly DC contact[8,9] because their pull-in voltages can be directly determined by a method of measuring current-voltage (I-V). However, this characterization approach cannot be applied to capacitive shunt switches. It is also challenging to measure the pull-in voltage by monitoring the capacitance change between a graphene beam and a pull-in electrode inasmuch as it is very small (approximately 10^{-5} pF), which can be overwhelmed by parasite capacitance. In this paper, we fabricated capacitive shunt switches based on graphene, and investigated the pull-in voltages by Raman microscope, which is frequently used in graphene research.[10–12]

The switch fabrication started from transferring mechanical exfoliated graphene flakes on a S_iO_2/S_i substrate, followed by C_r/A_u deposition and metal lift-off process to fabricate electrodes. Sequentially, buffered oxide etchant was used to remove S_iO_2 250–280 nm thick beneath graphene. As a result, the graphene flake was suspended, and a thin dielectric S_iO_2 layer existed between the graphene beam and the S_i pull-in electrode to provide DC isolation when the switch is actuated to the down-state position (see Fig. 1(a)).

Raman spectroscopy was performed on the graphene beam with an excitation A_r laser in a wavelength of 514.5 nm. A laser spot was moved at the center of the free-standing graphene membrane with the largest displacement along the beam during switching. Next, we adjusted the vertical distance between the Raman microscope and the graphene beam to obtain the largest spectrum intensity, making sure that the laser was focused on the beam well. A gradually increased DC bias was applied. When it excessed a certain value, a sudden significant intensity reduction of Raman spectrum was observed (see Fig. 1(d)). The DC bias value at the moment, when the Raman signal intensity reduction took place, equals to the pull-in voltage of the graphene switch. Figure 1(b) is the scanning electron microscope (SEM) image of a graphene beam which is collapsed onto a S_iO_2/S_i substrate. Figure 1(c) is the corresponding Raman mapping image (G peak) only highlighted the suspended part, proving that its Raman spectrum intensity will largely reduce when the center of beam is pulled down. Based on the Raman spectrum method (RSM), we measured the pull-in voltages of a few capacitive shunt graphene switches with different lengths and thicknesses. A trend is clearly shown that either reducing the length or increasing the thickness of graphene beams can result in a larger pull-in voltage (see Fig. 1(e)), agreeing well with the theoretical prediction. The theoretical prediction value of pull-in voltages is derived from the following equation:

$$V_{pull-in} = \sqrt{\frac{8kg_0^3}{27\varepsilon A}}, \tag{1}$$

where k is the spring constant of the graphene beam, g_o is the air gap between the graphene and the lower electrode, ε is the vacuum permittivity, and A is the size of the suspended graphene beam over the lower electrodes. Among the capacitive shunt graphene beam switches that we tested, 3 of them have the same length and thickness. The difference of their pull-in voltages is smaller than 1 V. Their pull-in voltages are not exactly the same mainly because the thickness of graphene beam measured by atomic force microscope (AFM) has an error about ± 0.2 nm. The RSM is also suitable for DC contact switches. Since it is an optical method, it cannot be affected by the parasite current which may short cut the upper and lower electrodes, a fatal to I-V method.

The reasons why the sudden reduction of Raman signal intensity corresponds to the pull-in actuation were investigated. When the graphene beam is pulled down by a static electrical force, the laser from Raman microscope can no longer be focused well due to the out-of-plane motion. Thus, the reflected Raman laser signal becomes weak. To verify it, we left the suspended graphene beam still, and moved the Raman

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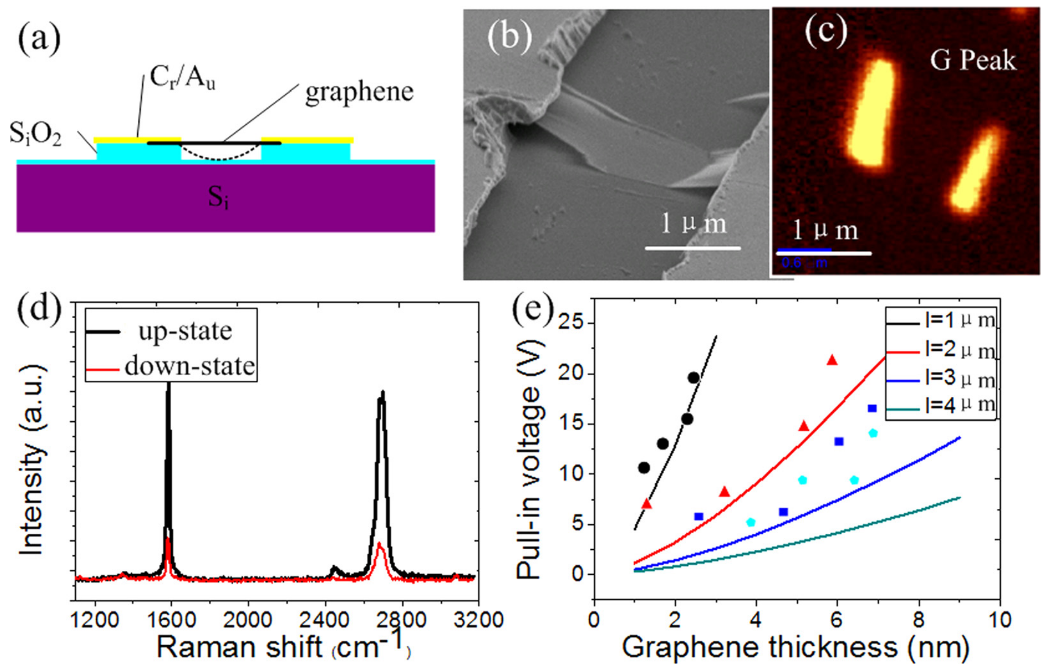

FIG. 1. Raman spectrum method. (a) Schematic view of a graphene capacitive shunt switch. (b) SEM image of a graphene beam collapsed on a S_iO_2/S_i substrate. (c) Raman G peak image of the graphene beam shown in (b). (d) Raman spectra of a graphene beam at "up-state" position and "down-state" position, respectively. (e) Theoretical prediction of pull-in voltages (lines) and pull-in voltages measured by RSM (dots). l is the length of the graphene beam.

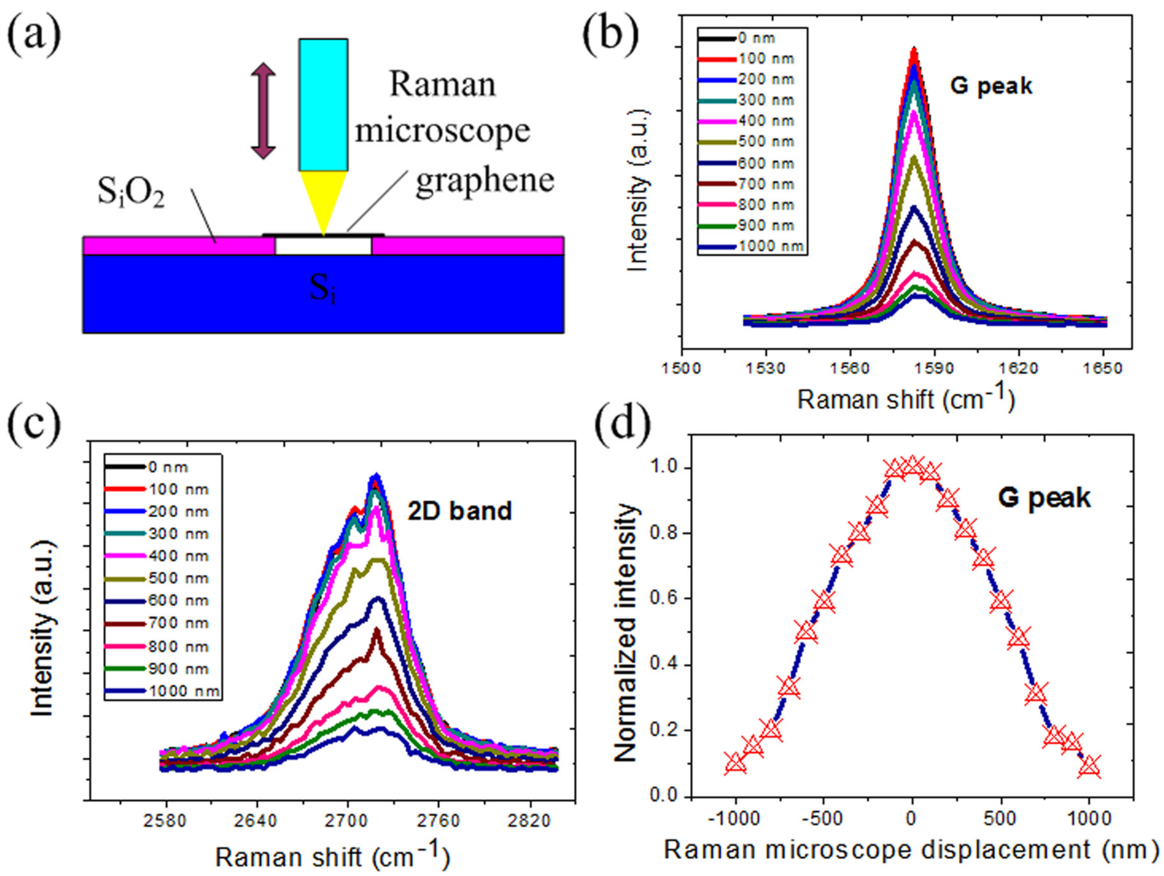

FIG. 2. Relation between the Raman spectrum intensity and out-of plane motion. (a) Schematic view of experimental set up. The graphene beam is kept still and the Raman microscope moves vertically. (b) The G peak intensity decreases when the microscope moves far away from the graphene beam. 0 nm indicates the best focused height. (c) The 2D band intensity decreases when the microscope moves far away from the graphene beam. (d) Relation between the normalized G peak intensity and microscope motion.

microscope vertically in the range from 0 nm to 1000 nm. This movement was precisely controlled by software. The results demonstrate that when the laser was not in focus, both G peak and 2D bands' intensity decreased (see Figs. 2(b) and 2(c)). For instance, when the microscope is 300 nm from the best focused height, the G peak's intensity is 80% of the original value approximately. Therefore, Raman microscopy is a powerful tool to monitor graphene's out-of-plane motion in the range of a few hundreds nanometers.

The second reason resulting in the Raman signal reduction is the contact between the graphene beam and the S_iO_2/S_i substrate when the switch is at down-state. To prove this assumption, we first etched a few trenches on a S_i substrate by SF_6. Sequentially, S_iO_2 was deposited on the S_i surface. Next, we transferred graphene on top of trenches (see Fig. 3(a)). Three samples were studied by Raman mapping (100×100 pixels), and their top S_iO_2 were 6 nm, 20 nm, and 100 nm in thickness, respectively. The intensity difference of the G peak and 2D band was clearly shown between the suspended part and supported part of each graphene flakes. The S_i-S_i peak images help us to figure out the position of suspended part and supported part. In addition, intensities of the supported parts are proved to be a strong function of the thickness of S_iO_2 layer. For the graphene transferred on thin S_iO_2 (6 nm and 20 nm), the suspended part has much larger G peak and 2D band intensity than that of supported part (see Figs. 3(d)–3(i)). If the thickness of S_iO_2 is100 nm, the suspended graphene's intensity is slightly smaller (see Figs. 3(j)–3(l)) because the

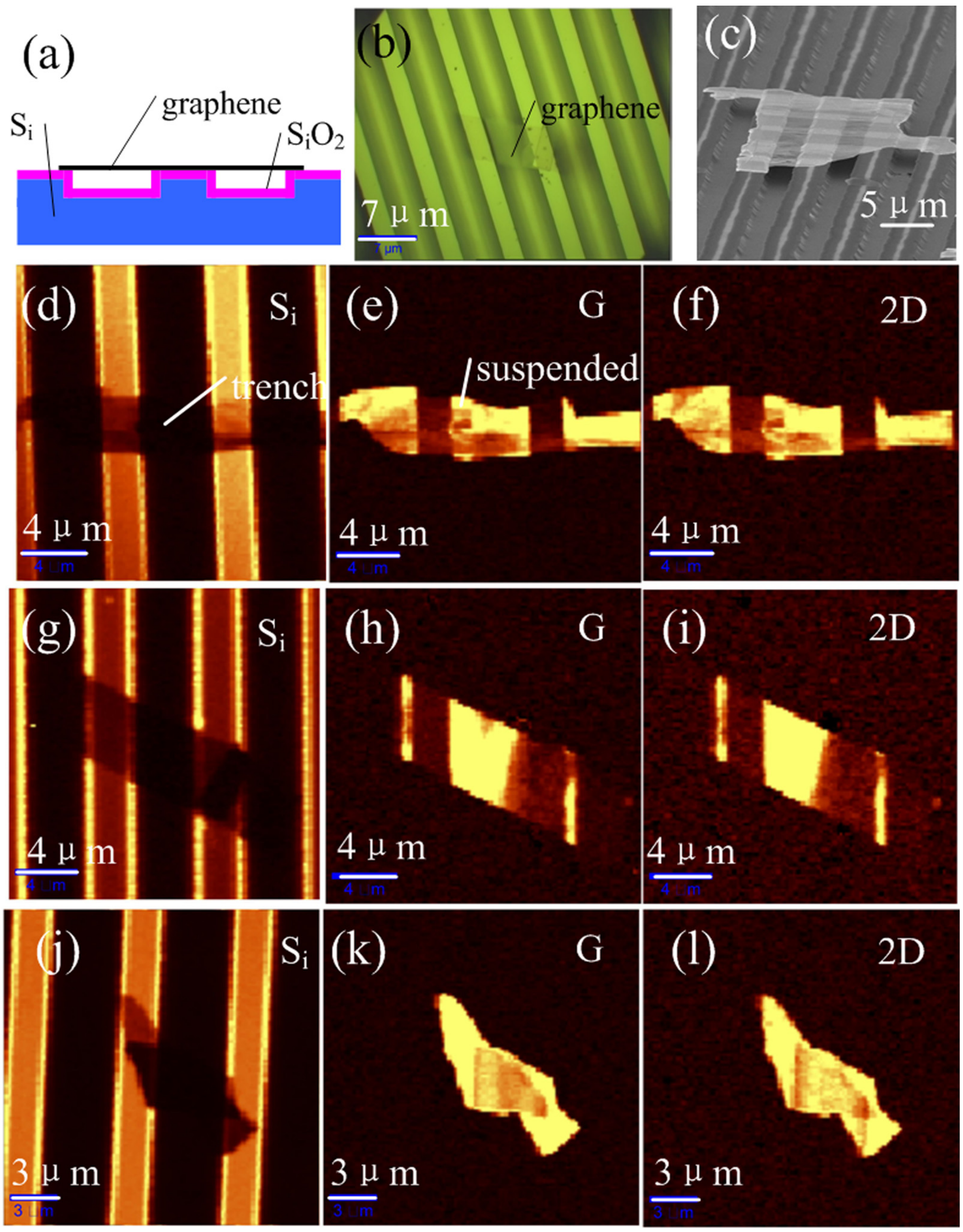

FIG. 3. Relation between the Raman spectrum intensity and S_iO_2/S_i substrate. (a) Schematic view of experimental setup. Graphene is on top of S_iO_2/S_i trenches. (b) and (c) Optical and SEM image of graphene flake over trenches, respectively. (d)–(f) Raman mapping images of a graphene flake on top of S_iO_2 6 nm thick. (d)–(f) are images of S_i-S_i peak, G peak, and 2D band, respectively. (g)–(i) S_i-S_i peak, G peak, and 2D band Raman images of graphene on top of S_iO_2 20 nm thick. (j)–(l) S_i-S_i peak, G peak, and 2D band Raman images of graphene on top of S_iO_2 100 nm thick.

thickness of the S_iO_2 layer is crucial for the enhancement of the Raman intensity. The enhancement factor F is[13]

$$F = N\int_0^{d_1} |F_{ab}F_{sc}|^2 dx, \qquad (2)$$

where N is a normalization factor, F_{ab} is net absorption term, F_{sc} is the net scattering term, and d_1 is the thickness of graphene. When the thickness of S_iO_2 reduces from 100 nm to 0 nm, F largely decreases (much smaller than that of suspended graphene). When the graphene beam contacts the pull-in electrode with a thin layer of S_iO_2 on top, its Raman spectrum intensity decreases.

Besides, we focused the laser spot on the anchor part of the beam which is not in contact with the substrate even when the beam is at "down-state" (see Fig. 4(a)), thus the substrate doping effect can be avoided.[14] We observed a sudden frequency shift of both G peak and 2D band after the graphene beam was pulled down, while no frequency shift was observed for the S_i-S_i peak (see Fig. 4(b)). This phenomenon proves that the shift of G peak and 2D band is due to the strain in a graphene beam instead of a Raman system drift. The strain ε can be estimated[15]

$$\varepsilon = \frac{\Delta\omega/\omega}{\gamma}, \qquad (3)$$

where $\triangle\omega$ is the Raman wavenumber change from the unstrained value ω, and γ is the Grüneisen parameter, which is 1.8 and 2.7 for the G peak and 2D band, respectively.[16] Thus, the strain increase of the graphene beam is approximately 0.2%. By measuring the bias value that causes the sudden shift, we can also determine the pull-in voltage (see Fig. 4(e)). For the graphene switch we tested, the G peak shifted from 1586.7 cm^{-1} to 1582.5 cm^{-1} when the DC bias reached 5 V. Nevertheless, after the bias was removed, the G peak frequency did not recover because the graphene was stuck on the substrate. With this method, we are able to measure the pull-in voltage and also detect the *in situ* strain change of a graphene beam during switching.

In summary, capacitive shunt graphene switches are fabricated and a method is reported to characterize their pull-in voltages. When the DC bias is larger than the value of pull-in voltage, the intensities of G peak and 2D band dramatically decrease. Two influencing factors are studied: (1) The laser is no longer focused on the graphene beam due to the out-of-plane movement. (2) Graphene collapsed on a S_i substrate with a thin S_iO_2 layer has much smaller Raman signal enhancement factor than that of free-standing graphene. Moreover, by measuring the frequency shifts of G peak and 2D band we can detect the pull-in voltage and estimate the *in situ* strain change in a graphene beam during switching. In addition to the graphene beam, we believe that RSM is also able to characterize the pull-in voltage of a graphene cantilever or a grahene membrane. Moreover, Raman microscopy has been used to study a variety of materials, such as carbon nanotube,[17] silicon,[18] niobium sulfide,[19] molybdenum sulfide,[20] and boron nitride.[21] All of the materials mentioned above have characteristic peaks in Raman spectrum, and their intensities and frequencies are sensitive to the out-of-plane motion or the change of strain. Therefore, we believe RSM is a generic approach to characterize the pull-in voltage of various nano devices.

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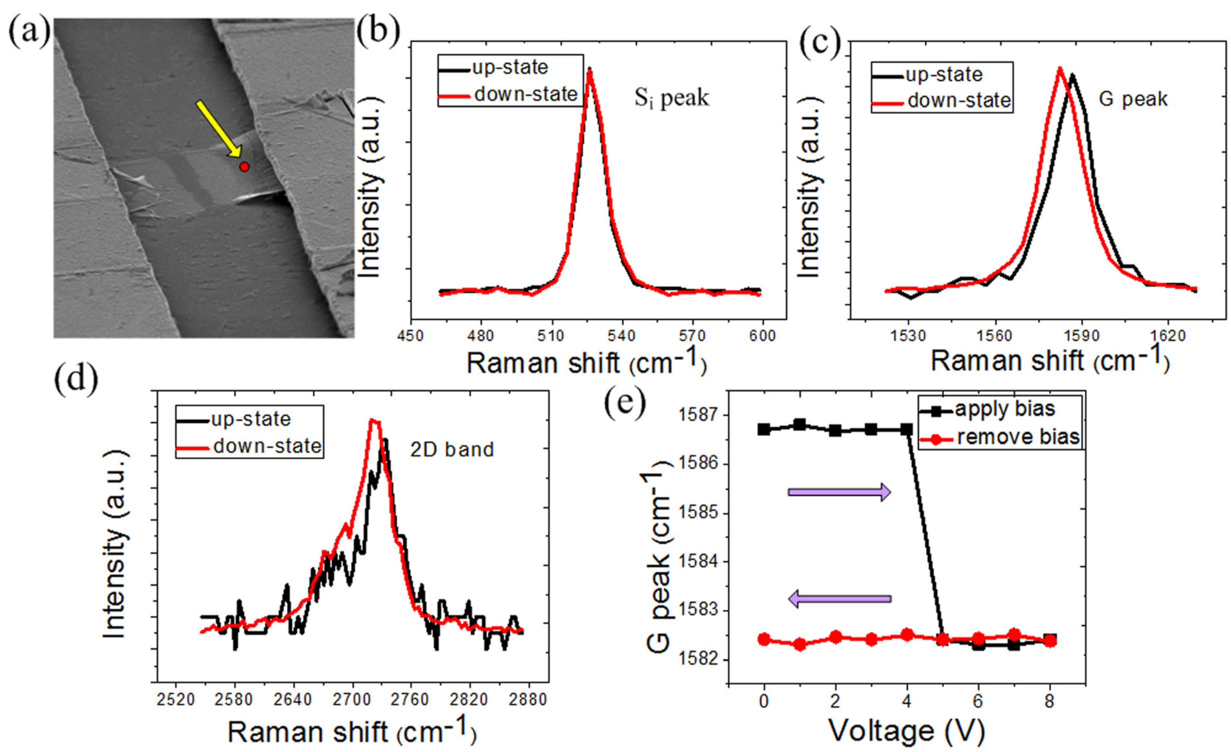

FIG. 4. Detection of pull-in voltages from Raman spectrum shifts. (a) SEM image of a graphene beam at "down-state" position. The red spot demonstrates the position of Raman laser spot. (b) S_i-S_i peak at "up-state" position and "down-state" position. (c) G peak at "up-state" position and "down-state" position. (d) 2D band at "up-state" position and "down-state" position. (e) G peak frequency shift during switching.

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