Strain characteristics of free-standing graphene induced by low-energy electron beam irradiation

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Theory predicts free-standing graphene to have an intrinsic mobility above 2×10^5 cm^2 V^{-1} s^{-1}. However, experiments have been limited to measurements of ~10^4 cm^2 V^{-1} s^{-1}. We observed that low-energy electron beam irradiation during the lithography process severely damages graphene, where decreases and shifts of the Raman spectrum G peak coincided with the appearance of the D peak. We measured the micro Raman signal and the internal strain induced by mechanical bending of a suspended graphene sheet. We measured a large internal strain of about 0.2 %, and observed a damage mechanism that resulted in the appearance of the Raman D peak in graphene, which was induced under an electron dosage of 2 mC cm^{-2} at an electron energy of 1 keV.

We prepared a striped pattern of approximately 200-nm-thick NEB particles on SiO_2 as a graphene support (Fig. 1(a)). We measured the Raman shift of the free-standing graphene under an applied external stress by mechanically bending the substrate, and we obtained -38.1 cm^{-1}/% for the strain-dependent Raman coefficient for 10 keV electron irradiation. We also measured the Raman shift of a free-standing graphene sheet that comprised two or three graphene layers under 10 keV electron beam irradiation (Fig. 2). The Raman peak of the graphene G band shifted to lower wavenumbers with increasing electron dose, and lower-electron energies induced larger peak shifts. Thus, combined with the mechanically-induced strain coefficient, we found that free-standing graphene experienced a strain of ~0.25% at 17 mC cm^{-2} of 10 keV irradiation, and ~0.31% at 15 mC cm^{-2} for 1 keV. The internal strain increased linearly and saturated with carbon contamination (Fig. 3).

In contrast to that seen in the multi-layered graphene sheet, the induced strain experienced by single-layer graphene was much larger – ~0.2% for a dose of 2 mC cm^{-2} at 1 keV. An increase in internal damage was indicated by observed changes in the Raman D peak (Fig 4) where both single-layer and multi-layer graphene were sampled under identical conditions (see Fig. 4).

We believe the additional internal strain would result in substantial electron scattering. Thus, development of a method for effective reduction of electron-beam induced damage will be key in the realization of high-speed graphene-based devices. Artificial induction of internal strains by controlled electron dosage may produce a new methodology for electron confinement that could lead to 1D graphene nanoribbon electronics.

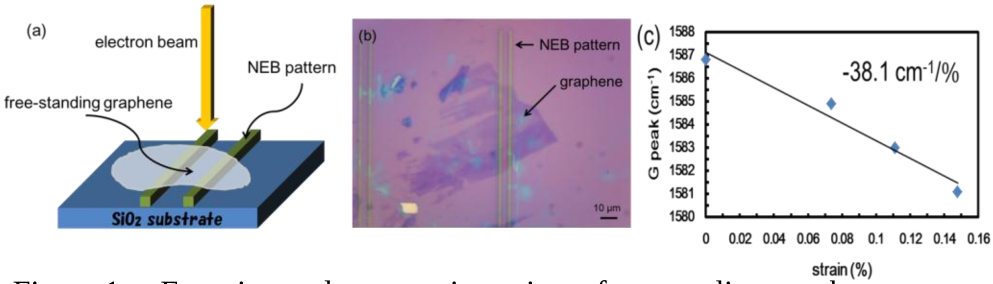

Figure 1. Experimental setup to investigate free-standing graphene. (a) Schematic of experimental setup. (b) The optical image of the free-standing graphene. Free-standing graphene was supported between two NEB patterns. (c) The coefficient of strain-dependent Raman shift obtained by mechanically bending of the substrate.

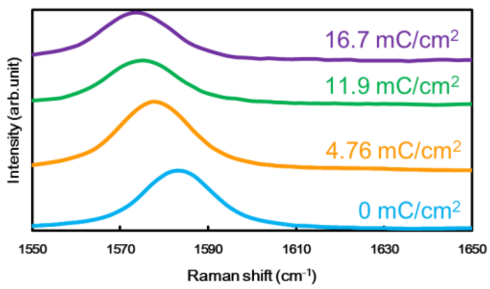

Figure 2. Raman spectra of graphene under irradiation of the 10keV electron beam. The Raman peak of the graphene G band shifted to lower wavenumbers with increasing electron dose.

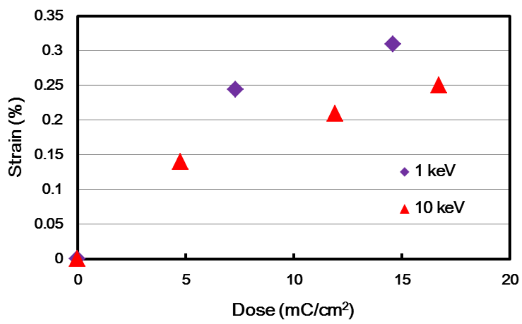

Figure 3. Electron dose-dependent strain. Internal strain increased lineally, but soon saturated because of carbon contamination. The strain at 1 keV is always larger than that at 10 keV.

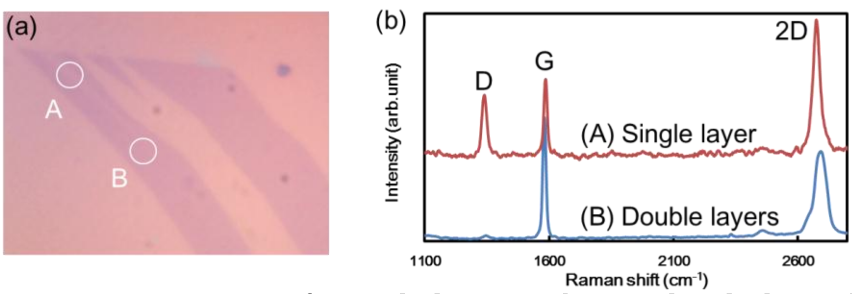

Figure 4. Raman spectrum for single-layer graphene and multi-layered graphene after 2 mC cm^{-2} of electron beam irradiation at 1 keV. Area "A" corresponds to single-layer graphene and area "B" comprises multi-layered graphene.