Supporting Information

Graphene Membranes for Hall Sensors and Microphones Integrated with CMOS-Compatible Processes

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Calculation model for microphone sensitivity from graphene Raman modes

The dependence of the position of the G mode with doping n [1–3] is given in equation 1:

$$\omega_G = \omega_{G0} + \frac{\alpha}{2\pi c\hbar} \cdot 10^{-5} \int_{-\infty}^{\infty} \mathrm{sign}(E) \frac{\left(f_{FD}(E - E_F) - f_{FD}(E)\right) \cdot E^2}{E^2 - \left(\omega_{G0}\hbar/2\right)^2} dE \qquad (1)$$

with $\alpha = 4.39 \cdot 10^{-3}$ as a fitting parameter, $f_{FD}(E) = {}^{1}\!/\!\left(\exp\left({}^{E}\!/\!_{k_B T}\right) + 1\right)$ as the Fermi-Dirac distribution with $E_F = \mathrm{sign}(n) \cdot \sqrt{\left|n\ (10^{12}\mathrm{cm}^{-2})\right| / (10.36 \cdot 10^{-8})}$ and $\omega_{G0} \approx 1581\ \mathrm{cm}^{-1}$ as the position of the G mode nearly without doping and stress[4]. There exists no analytical solution for equation 1 at finite temperatures. The dependence of the G mode with electron/hole density n was thus determined by approximation with a square root function at 300 K, which results in equation 2:

$$\omega_G(n) = \omega_{G0} + \sqrt{p_1 \cdot |n| + p_2} + p_3 \qquad (2)$$

with the fitting parameters $p_1 = 12.13$, $p_2 = 1.088$ and $p_3 = -1.313$ and an electron/hole density of $n = 10^{12}\ \mathrm{cm}^{-2}$. The dispersion of the G mode with mechanical strain is in principle different for the two sub-modes G^+ and G^-, but for small elongations ε, the displacement of both sub-modes is equal and shifts with $-10.8\ \mathrm{cm}^{-1}/\%$[5]. Therefore the total dependence of the G mode with doping concentration and mechanical strain can be described with equation 3 in the present case.

$$\omega_G(n, \varepsilon) = \omega_{G0} + \sqrt{p_1 \cdot |n| + p_2} + p_3 - 10.8 \frac{cm^{-1}}{\%} \varepsilon \tag{3}$$

The dependence of the position of the 2D mode with excitation wavelength λ [6], doping n [7] and stress ε [5] can be described by equation 4.

$$\omega_{2D}(n, \varepsilon, \lambda) = \omega_{2D_0} + (514.5 - \lambda) \cdot 70.94 \cdot 10^{-3} \frac{cm^{-1}}{nm} + \frac{25\ cm^{-1}}{eV} \cdot |E_F| - \frac{21\ cm^{-1}}{\%} \varepsilon \tag{4}$$

Where $25\ cm^{-1}/eV$ is the dependence on charge carrier density (Fermi energy level) and $-21\ cm^{-1}/\%$ is the dependence with mechanical stress. From the dependencies of the G and the 2D mode on charge carrier density and mechanical stress, the elongation of the graphene plane due to mechanical stress can be calculated with equation 5:

$$\varepsilon(\Delta\omega_G, \Delta\omega_{2D}) = -\frac{q_1}{2 \cdot q_2} + \sqrt{\frac{q_1^2}{4 \cdot q_2^2} - q_3}\ \% \tag{5}$$

The following substitutions are required:

$$\Delta\omega_G(n,\varepsilon) = \omega_G(n,\varepsilon) - \omega_{G0} \tag{6}$$

$$\Delta\omega_{2D}(n,\varepsilon,\lambda) = \omega_{2D}(n,\varepsilon) - \omega_{2D_0} - (514.5 - \lambda) \cdot 70.94 \cdot 10^{-3}\ cm^{-1}/nm \tag{7}$$

$$q_1 = 42 \cdot \Delta\omega_{2D}(n,\varepsilon,\lambda) - 5.467532873 \cdot (\Delta\omega_G(n,\varepsilon) + 1.313) \tag{8}$$

$$q_2 = \Delta\omega_G(n,\varepsilon) - 1.420766436 \tag{9}$$

$$q_3 = (\Delta\omega_{2D}^2(n,\varepsilon,\lambda) + 0.08969)/(\Delta\omega_G(n,\varepsilon) - 1.420766436) \tag{10}$$

From the relation $\sigma = E \cdot \varepsilon$, with E as the E-modulus in graphene (1020 GPa [8]), the surface tension in the graphene plane can be calculated from the Raman spectra. The mechanical compliancy for circular membranes is defined in equation 11:[9]

$$C_m^* = \left(\frac{1}{1 + 1.1 \cdot (\sigma_c/\sigma)^{0.6}}\right) \cdot \left(\frac{1}{\sigma_c/\sigma + 1}\right) \cdot \frac{R^2}{8 \cdot t \cdot \sigma} \tag{11}$$

with σ_c as the characteristic surface tension[9]

$$\sigma_c = \frac{2 \cdot E \cdot t^2}{(1 - \nu^2) \cdot R^2} \tag{12}$$

and R as the membrane radius, t as the thickness of the membrane ($3.35 \cdot 10^{-10}$ m)[10] and $\nu = 0.16$ as the Poisson ratio of graphene[11]. From these equations the sensitivity of the graphene-based microphone can be calculated [9]:

$$S_\alpha = \frac{U_0}{U_p} \cdot \sqrt{\frac{8 \cdot x_0 \cdot C_m^*}{27 \cdot \varepsilon_0}} \tag{13}$$

with U_0 as the bias voltage of the microphone, U_p as the collapse voltage, x_0 as the distance between the graphene membrane and the perforated counter electrode ($x_0 = 2.2$ μm) and ε_0 as the permittivity of air.

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