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Dielectric properties of multi-layer graphene on $LiNbO_3$ crystal

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1. Introduction

The band structure of multi-layer graphene depends on the number of its layers. Single-layer graphene has a band gap of zero, but as the number of layers increases, the band gap is formed. It has also been noted that electrical and mechanical properties of the multi-layer graphene, which was prepared on a substrate, are strongly influenced by the substrate.[1-3)]

In this study, we studied dielectric properties of the multi-layer graphene/$LiNbO_3$ structure applied to piezoelectric devices, especially evaluating effects of the $LiNbO_3$ substrate to dielectric properties of the graphene thin films.

2. Experimental

A 5-layer graphene/$LiNbO_3$ sample was prepared by transferring CVD monolayer graphene onto the optically polished $LiNbO_3$ substrate five times. In addition, the Au films were prepared on both sides of the sample, and was cut out with area $S = 2.8 \times 3.1\text{mm}^2$. The structure of the samples used in this study is shown in Fig. 1. Two types of samples were prepared: Au/5-layer graphene/$LiNbO_3$/Au and Au/$LiNbO_3$/Au. The samples were placed in a vacuum chamber and their capacitance and resistance were measured using an impedance analyzer. In the measurements, frequency was varied from 4 Hz to 5 MHz, and AC amplitude was fixed at 1.0 V.

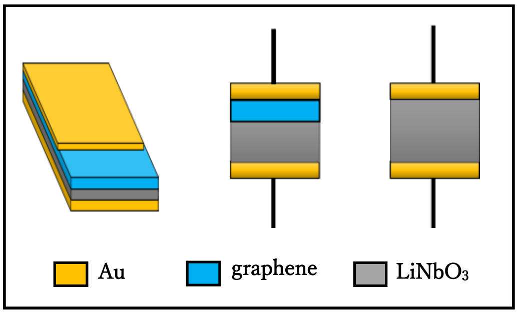

Fig. 1 Structures of Au/5-layer graphene/$LiNbO_3$/Au and Au/$LiNbO_3$/Au samples

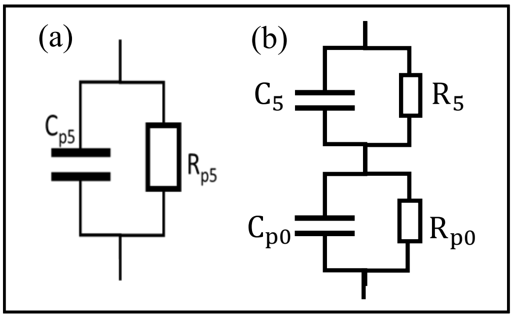

Fig. 2 Equivalent circuits of (a) Au/5-layer graphene/$LiNbO_3$/Au sample and (b) 5-layer graphene and $LiNbO_3$

3. Results

In general, a sample sandwiched between two electrodes can be regarded as a parallel circuit of capacitance and resistance. The equivalent circuits of the composite 5-layer graphene film/$LiNbO_3$, 5-layer graphene film alone and $LiNbO_3$ substrate alone are shown in Fig. 2. The capacitance C_{p5} and resistance R_{p5} of the composite sample, the capacitance C_5 and resistance R_5 of the 5-layer graphene thin film alone, and the capacitance C_{p0} and resistance R_{p0} of the $LiNbO_3$ substrate alone are also shown in the figure, respectively. In this study, the C_5 and R_5 are obtained by measuring C_{p5}, R_{p5}, C_{p0} and R_{p0}.

The C_5 and R_5 can also be obtained from four measurement parameters of C_{p5}, R_{p5}, C_{p0} and R_{p0} from theoretical calculations as follows.

$$R_5 = a - \frac{R_{p0}}{l} - \frac{\left(\omega C_{p0} R_{p0}{}^2 - bl\right)^2}{l\left(R_{p0} - al\right)}$$

$$C_5 = \frac{l\left(bl - \omega C_{p0} R_{p0}{}^2\right)}{\omega\left\{\left(al - R_{p0}\right)^2 + \left(\omega C_{p0} R_{p0}{}^2 - bl\right)^2\right\}}$$

$$l = 1 + \left(\omega C_{p0} R_{p0}\right)^2 \qquad a = \frac{R_{p5}}{1 + \left(\omega C_{p5} R_{p5}\right)^2} \qquad b = \frac{\omega C_{p5} R_{p5}{}^2}{1 + \left(\omega C_{p5} R_{p5}\right)^2}$$

The absolute values of C_5 and R_5 are shown in Fig. 3 as a function of frequency. As can be seen from this figure, the resistance of the 5-layer graphene thin film decreases by seven orders of magnitude with increasing frequency, while its capacitance is almost constant at about 10 pF. Incidentally, the minimum measurement capacitance of the instrument is 1 pF.

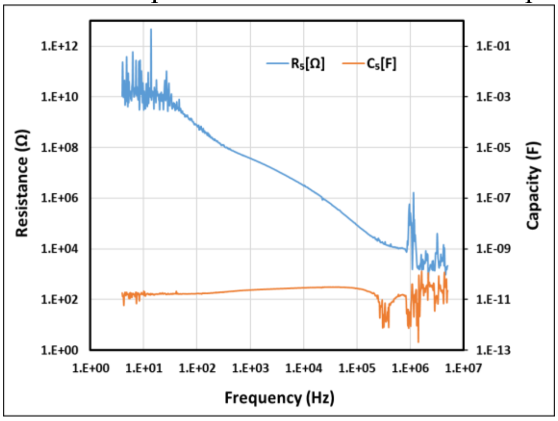

Fig. 3 Frequency dependences of C_5 and R_5

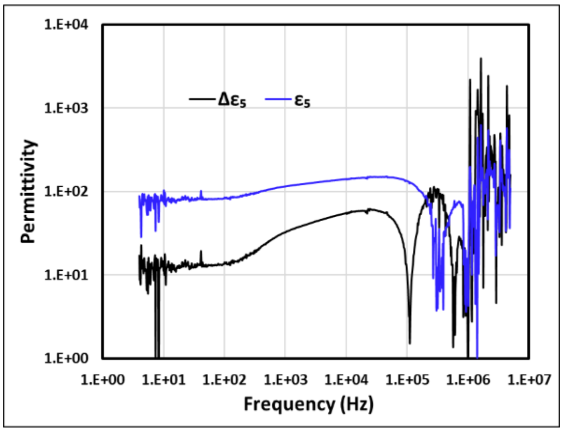

Fig. 4 Frequency dependences of ε_5 and $\Delta\varepsilon_5$

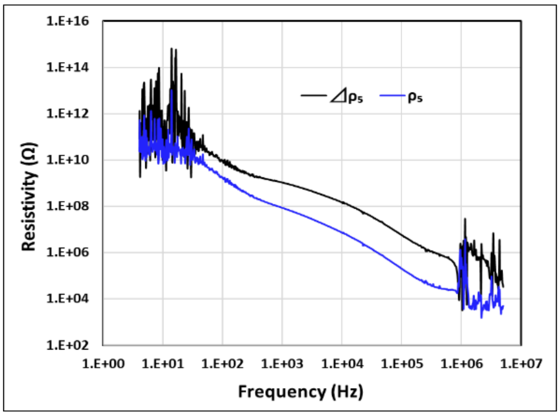

Fig. 5 Frequency dependences of ρ_5 and $\Delta\rho_5$

4. Discussion

First, the capacitance of the graphene film are almost constant with increasing frequency as shown in Fig. 3, while its resistance in direction perpendicular to the graphene planes decreases linearly. This is related to electrical properties of the graphene film sample. The capacitance value reflects polarization characteristics of graphene lattice, while the resistance depends on carrier current passing through the graphene film. The nearly constant capacitance value is due to polarizations of the 5-layer graphene lattice and $LiNbO_3$ crystal substrate.

Second, the C_5 and R_5 are from the theoretical calculations of equivalent circuit, it is need to verify their errors from the true values. The propagation law was used to determine the errors of the calculations, the errors of R_5 and C_5, ΔC_5 and ΔR_5, can be expressed by following equations. Also, we also obtain dielectric constant and resistivity of the 5-layer graphene thin film and their errors, ε_5, ρ_5, $\Delta\varepsilon_5$ and $\Delta\rho_5$, from C_5, R_5, ΔC_5 and ΔR_5.

The frequency dependences of the ε_5 and $\Delta\varepsilon_5$

$$\begin{cases} \Delta R_5 = f(R_{p5}, C_{p5}, R_{p0}, C_{p0}) \\ \Delta C_5 = g(R_{p5}, C_{p5}, R_{p0}, C_{p0}) \end{cases}$$

$$\begin{cases} \Delta R_5 = \dfrac{\partial R_5}{\partial R_{p5}}\Delta R_{p5} + \dfrac{\partial R_5}{\partial C_{p5}}\Delta C_{p5} + \dfrac{\partial R_5}{\partial R_{p0}}\Delta R_{p0} + \dfrac{\partial R_5}{\partial C_{p0}}\Delta C_{p0} \\ \Delta C_5 = \dfrac{\partial C_5}{\partial R_{p5}}\Delta R_{p5} + \dfrac{\partial C_5}{\partial C_{p5}}\Delta C_{p5} + \dfrac{\partial C_5}{\partial R_{p0}}\Delta R_{p0} + \dfrac{\partial C_5}{\partial C_{p0}}\Delta C_{p0} \end{cases}$$

of the 5-layer graphene thin film are shown in Fig. 4. As seen from the figure, the error in the capacitance measurement is about 1/10 of the measurement capacitance value. On the other hand, the frequency dependences of the resistivity and its error of the 5-layer graphene thin film, ρ_5 and $\Delta\rho_5$, are shown in Fig. 5. The measurement error of the resistivity of the 5-layer graphene thin film is several times larger than its measurement value. The results suggest that there is a large error in current measurement of the 5-layer graphene film on the thicker $LiNbO_3$ substrates.

5. Conclusion

The dielectric properties of the 5-layer graphene/ $LiNbO_3$ structure were characterized by measuring its AC impedance. The capacitance was obtained by sufficient accuracy, but there is a risk of large error in its resistance measurement due to the thicker $LiNbO_3$ substrate.

References

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