Dynamic Behavior of Ion Liquid Electronic Devices

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Purpose

Field-effect transistors (FETs) are 3-terminal electronic devices consisting of a source, drain, and gate. The voltage applied to the gate terminal determines the current that flows between the drain and the source. In general, greater gate voltage allows a greater current. However, for a specific family of FETs called electronic double layer transistors (EDLTs), this is not exactly the case. As is clearly seen in Figure 1, there is a shift between the forward and reverse sweep characteristics. This shift is likely due to the slow dynamical response of the ion liquid to the applied bias. The dynamics of the 'gate material' is of critical importance in these unusual FETs. This model investigates the dynamics and provides a basis of understanding on which to build a physical model at a later date.

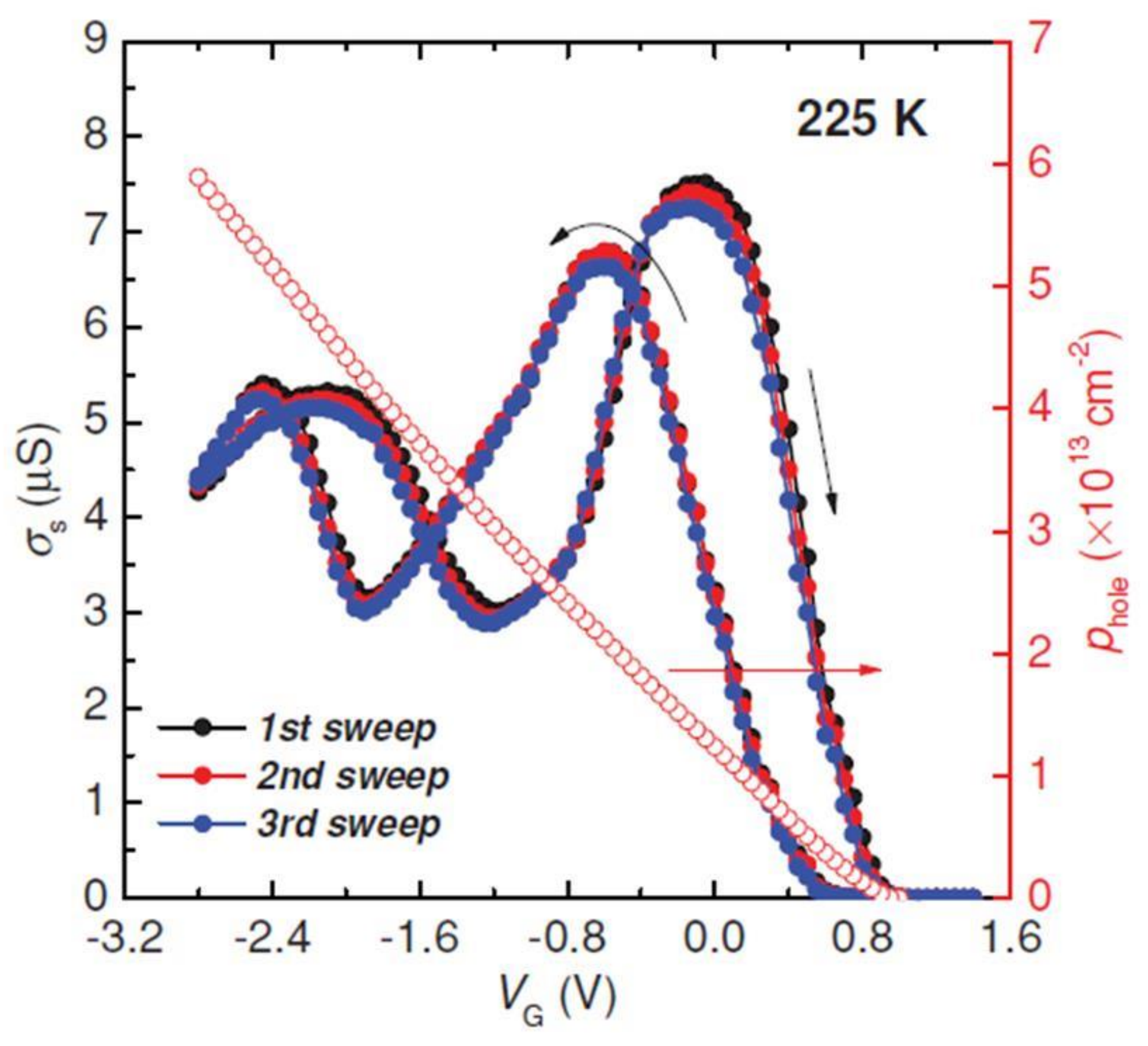

Figure 1: Experimental data for voltage sweep of EDLT[1]

Methods

Using knowledge of the physical structure of the EDLT and the Drude model to describe ion liquid conduction, I found that the equivalent circuit would be as pictured in Figure 2. The complex impedance, Z_D is equivalent to a resistor and inductor in series. Three important equations were obtained from equivalent circuit. The first two are the total impedance Z for Z_D purely real and complex.

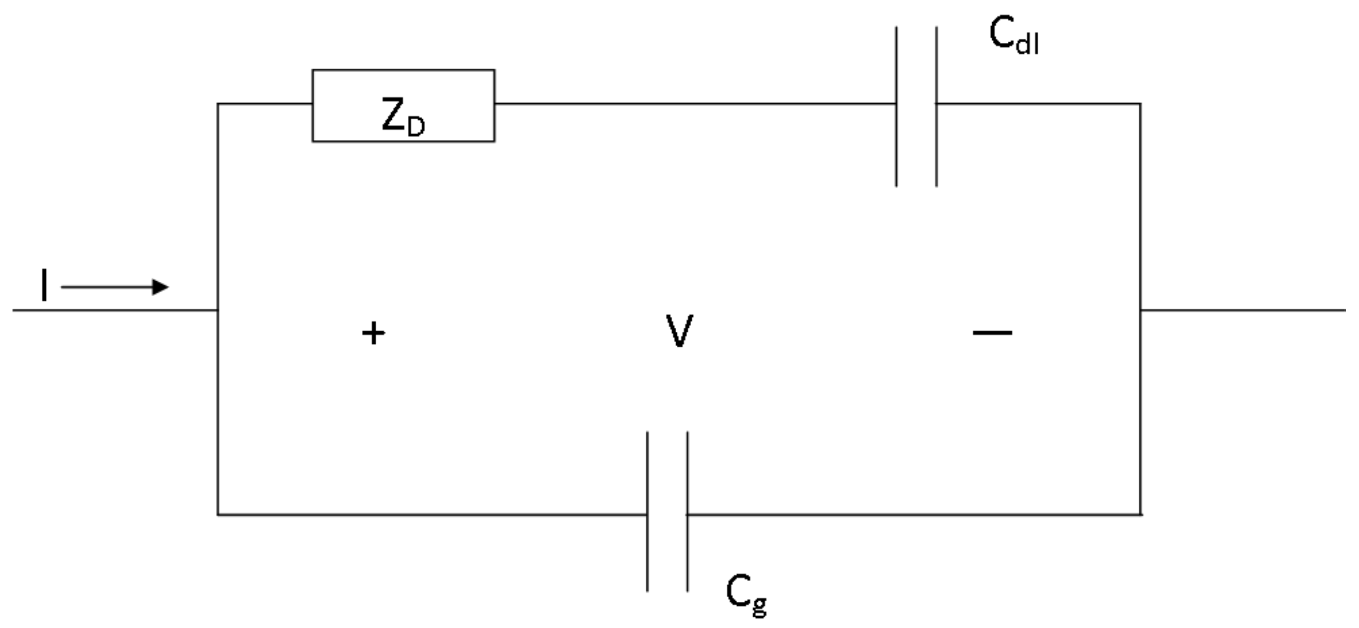

Figure 2: Equivalent circuit for EDLT

For Z_D purely real (L=0):

$$Z = \frac{\tau s + 1}{\tau C_g s^2 + (C_{dl} + C_g)s}$$

For $Z_D = R_0 + L$:

$$Z = \frac{C_{dl} L s^2 + \tau s + 1}{C_{dl} C_g L s^3 + \tau C_g s^2 + (C_{dl} + C_g)s}$$

Where τ is the time constant equivalent to $R_0 * C_{dl}$. R_0 was determined using the Drude model and is proportional to the distance between the plates of the EDLT and is inversely proportional to and the area of the plates of the EDLT and to the conductivity of the liquid, σ_0. The value of σ_0 is given by the literature as on the order of .1 to 1 S/m. These values yield a value of .001 sec for τ.

Methods, cont'd.

The third equation describes the response of the equivalent circuit to a linearly increasing voltage across the terminals.

$$q(t) = v'(C_{dl} + C_g)t + v'\tau C_{dl}(e^{\frac{-t}{\tau}} - 1)$$

This equation is the response of the charge, q(t), to a voltage that increases linearly with time from 0volts with a slope of v'.

Results

I discovered two notable characteristics: little frequency dependence in our range of measurement and differing conductance from expected value. The Bode plot for the overall impedance of the equivalent circuit (Figure 3) proves to be the same at low frequencies (1-10^8Hz) for both real and complex Z_D. This shows that the assumed frequency dependence (L in the model) is insignificant for low frequencies.

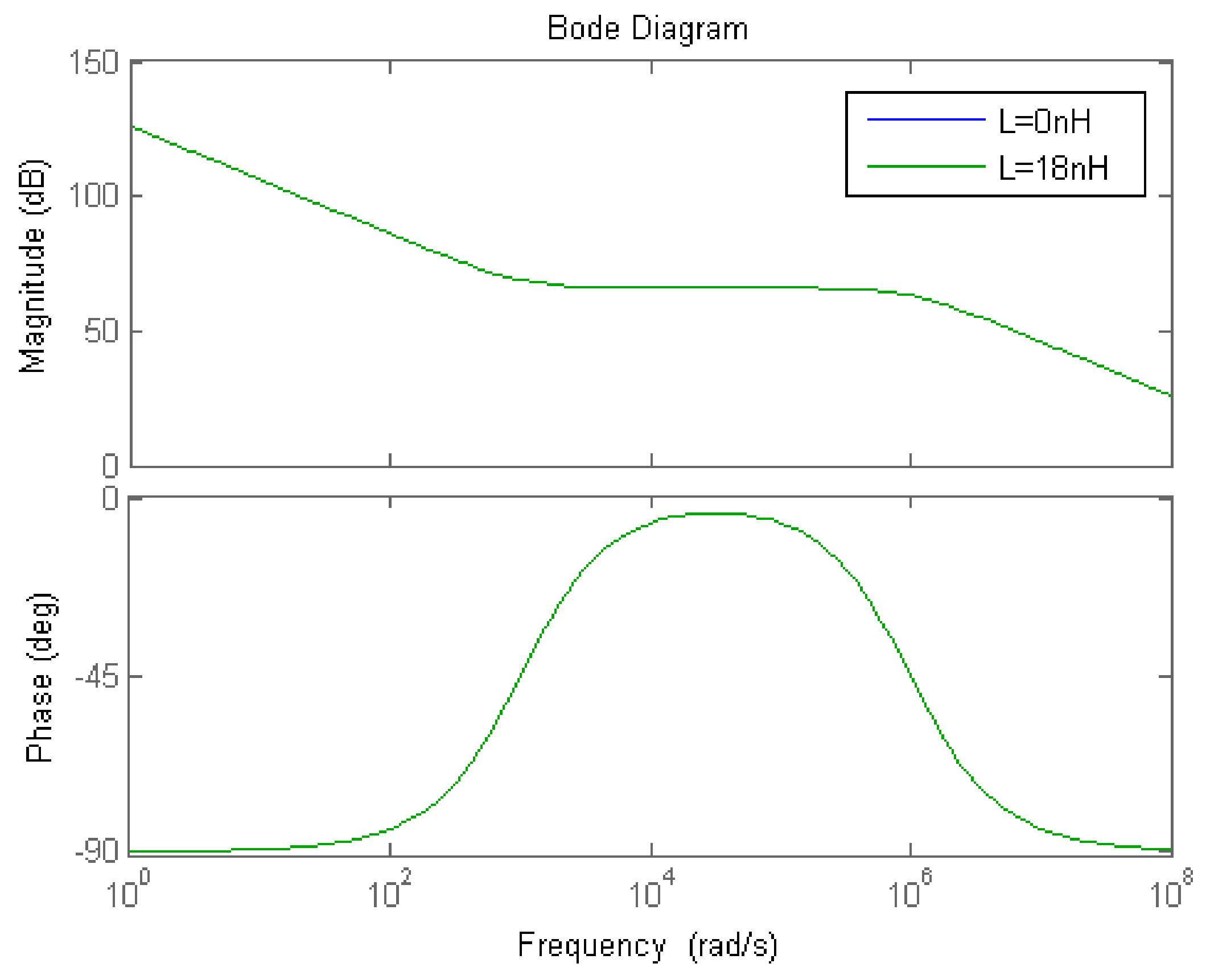

Figure 3: Bode plot for Z_D purely real and Z_D purely imaginary. The line for L=0 is under the line for L=18nH so it is not visible on this graph.

Results, cont'd.

Additionally, the equations can be used to show that the conductance of the ionic liquid used to make the device differs greatly (several orders of magnitude) from what has been published in literature.

Figure 4 shows the response of the model, q(t), versus time for two different values of τ.

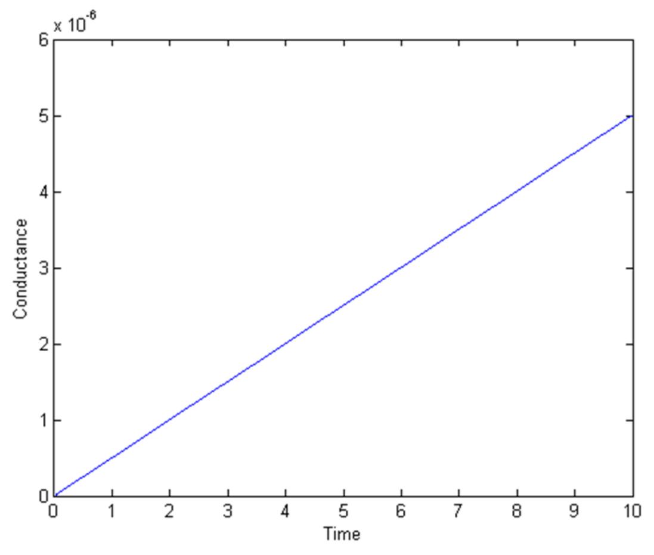

Figure 4a: q(t) for τ=.001

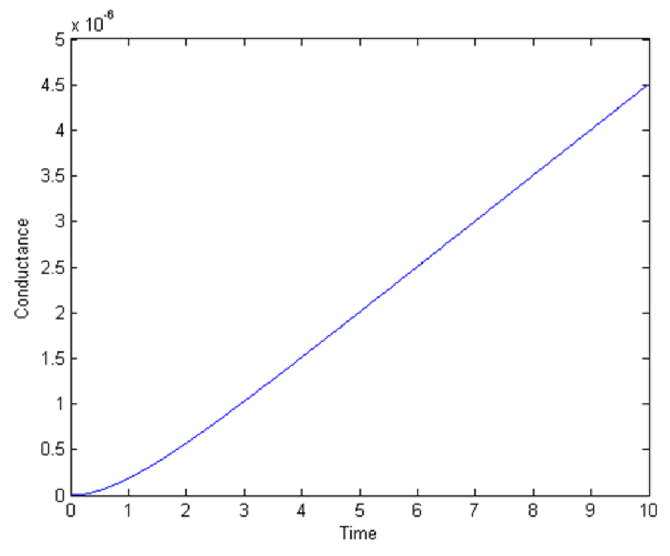

Figure 4b: q(t) for τ=1

Figure 4b shows the time-delay characteristics when t<1 as expected from the experimental data, but the value of τ is three orders of magnitudes greater than that of Figure 4a which has the value of τ. This shows that the conductance of the liquid must be much lower than literature values. The result is not entirely surprising since the ion liquids used in current experiments are close to their freeze points. Hence the ion mobility and the ion liquid conductivity should indeed be larger than the initially expected.

Recommendations

The next step in investigating EDLTs using this model is to find the model response to a voltage that starts at a positive value and decreases linearly with time. Additional investigations could include the use of different types of ionic liquid which would affect the values of C_{dl} and C_g.

Reference

[1]W. Xie, F. Liu, S. Shi, P. P. Ruden, and C. D. Frisbie. Charge Density Dependent Two-Channel Conduction in Organic Electric Double Layer Transistors (EDLTs). Adv. Mater. (2014).

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