ISSN 2229-5518

Comparative Study and Design Optimization of Supercapacitors for High Powered LED Flashlight Camera Phones

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Abstract — A supercapacitor (SC), sometimes ultracapacitor, formerly electric double-layer capacitor (EDLC) is an electrical energy storage device which offers high energy density compared to conventional capacitors. One recent application of supercapacitors is to power the LED flashlight of high resolution camera phones. To eliminate dark and blurry photos, the camera phone designers have to meet three possible requirements while using LED flashlight: high capacitance, low ESR and suitable device thickness. Cap-XX Inc. is one of the supplier of supercapacitor to meet these requirements. In this paper, a thorough study has been done to evaluate that compared to the prismatic supercapacitor of Cap-XX Company, laser-scribed graphene (LSG) supercapacitor with gelled electrolyte is comparatively smaller in size and can provide more capacitance. Moreover, the proposed research is to optimize the capacitance of LSG supercapacitor by choosing suitable electrolyte, size and shape of electrode, and mobile ion of electrolyte for the purpose of powering LED flashlight of camera phones. The validation of the design has been done by analyzing three models of EDLC structure through MATLAB simulation tools.

Index Terms— Supercapacitor, LED flashlight, laser scribed Graphene (LSG), electric double layer capacitor (EDLC), capacitance, equivalent series resistance (ESR).

1 Introduction

IN recent times, the public's growing demand for quality camera phone is seeking technological advancement in the limited space of smart phones. In mobile camera, the battery cannot provide sufficient high pulse current to illuminate LED for high resolution images. However, xenon flash is a better alternate [1], but it requires bulky storage capacitor, creates circuit safety issue due to high voltage requirement and drain battery power faster. Hence, considering the power limitation from battery, the effective solution is to power the current consuming LEDs via supercapacitors rather than lithium battery. Based on existing technology, supercapacitors possess high power and energy density compared to electrolytic capacitors [2], can charge and discharge faster [3], have low equivalent series resistance (ESR) [3], allowing them to deliver and absorb high currents during few milliseconds [4], and has unlimited life cycle [5]. Thus, this paper optimize the supercapacitor design for high powered LED flashlight of camera phones.

Supercapacitors are convenient device for powering LEDs as flashlights because they can supply higher current than batteries [6], charge and discharge several hundred thousand cycles [7, 8], and their leakage rate and series resistance are quite small [9, 10]. The high capacitance of supercapacitors is achieved by increasing the surface area offered by the electrodes by choosing appropriate porous material such as activated carbon and by reducing the distance over which electric field is experienced to Debye length by using mobile ions in an electrolyte [11]. The supercapacitor store charges only at the electrolyte electrode interface of active materials through rapid and reversible adsorption/desorption of ions [12]. Thus, in this paper the electrodes and ions in supercapacitors will be considered for design optimization.

Recently, researchers in UCLA like Maher F. El-Kady have produced Laser Scribed Graphene supercapacitor by coating graphite oxide over DVD disc and then laser treating inside a LightScribe DVD which is a very cost effective production approach [13]. It is an open network structure and the simultaneous reduction and exfoliation of graphene oxide provide more accessible area and hence has the ability to deliver ultrahigh power in a short time [13], which is a demanding attribute for the purpose of powering LEDs in mobile camera phones. Also the micro size of the device make it the best choice to optimize space in electronic design of mobile phones. Additionally, LSG electrodes are mechanically robust and show high conductivity (greater than 1700 S/m) compared to activated carbons (10-100 S/m) [13]. This means LSG supercapacitor can be directly used as supercapacitor electrodes without the need for binders and current collectors which are needed for conventional activated carbon ECs. Moreover, the use of polymer gelled electrolyte rather than the liquid electrolyte has considerably reduced the device thickness.

In this paper, the Laser Scribed Graphene (LSG) supercapacitor of Kaner and El-Kandy [13], is evaluated as the better design solution of a supercapacitor for LED flash camera phone compared to the prismatic supercapacitor of CAP-XX Company. Then, the capacitance of LSG Supercapacitor is enhanced by studying and analyzing the three models of EDLC structure: Helmholtz Model, GouyChapman Model and Gouy-Chapman-Stern Model. Moreover, the sandwiched organic electrolyte tetraethylmethylammonium tetrafluoroborate is analyzed with four possible solvents for design optimization. Overall, the results of these studies are analyzed and validated by Matlab R2013a software tools [14].

2 The Design Implementation Specifications

Figure 1 shows a supercapacitor powered LED to give better

ISSN 2229-5518

flash in digital mobile camera. In the circuit, the charge pump pre-charges the dual-cell supercapacitor to 5.5V through Lithium mobile battery. The charge pump is current enabled to 300mA. The parallel resistors are used to reduce variation in leakage current. Once the supercapacitors are charged, the enabled current switch delivers high current small flash pulse to parallel high power LEDs through the supercapacitor rather than the battery.

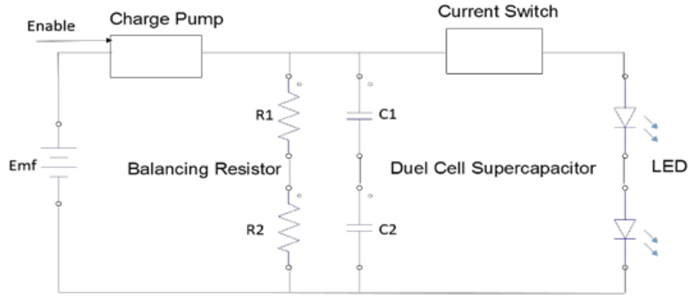


Fig. 1. Supercapacitor Powered LED Block Diagram [1]

To achieve adequate LED flashlight output for eliminating dark and blurry photos, the following specifications of supercapacitor has to be maintained by camera phone designers:

1) A high capacitance (0.4F to 1F).
2) Low ESR (less than 100 milliohms).
3) Thin (1 to 3 mm) prismatic supercapacitor.

$$dV = I\,ESR + \frac{I\,PW}{C} \quad (1)$$

Equation (1) shows that during the discharge cycle of the supercapacitor to power LEDs, the voltage drop across supercapacitor dV, is a function of equivalent series resistance (ESR), Capacitance (C), Discharge Current (I) which is equal to the total LED current, and flash pulse (PW). Hence, in this paper, the Capacitance, C has been optimized to provide adequate power supply to flash LEDs.

3 COMPARATIVE STUDY BETWEEN CAP-XX AND LASER-SCRIBED GRAPHENE (LSG) SUPERCAPACITOR

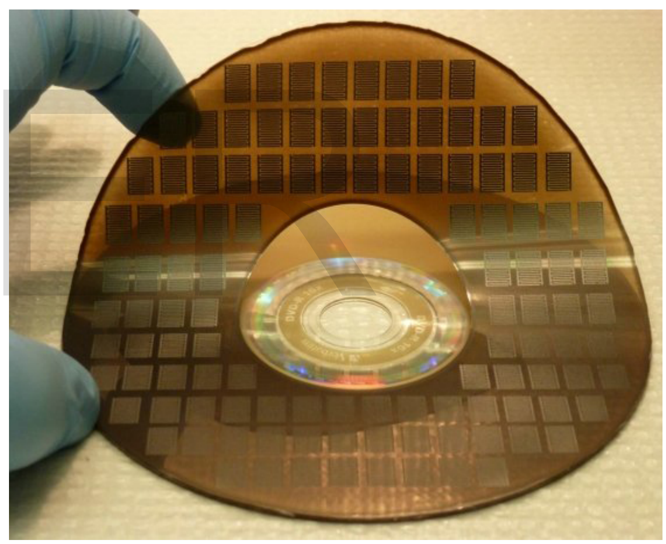
Figure 2 shows a Cap-XX prismatic supercapacitor which is used in some mobile phones for powering LED flash of camera in mobile phones. Table 1 shows two supercapacitor models of CAP-XX with equal to or less than 50 milliohm ESR to allow for ageing over life [1].

Table 1. Parameters of two Prismatic Supercapacitor Products by CAP-XX Inc.

Cap-XX product	Capacitance mF	ESR m*ohm*	Terminal Volt	Thickness mm
GS 203	250	45	4.5	2.20
GS 208	900	28	4.5	3.50

Fig. 2. CAP-XX Supercapacitor [1]

Figure 3 is a micro scale graphene based supercapacitor which has been produced using laser scribe technique on a DVD player surface. Correspondingly, figure 4 shows the



cross section of the

Fig. 3. Micro-Scale Graphene-Based Supercapacitor [13]

Fig. 4. Cross-Section of laser-scribed graphene supercapacitors with gelled Electrolyte [13]

ISSN 2229-5518

LSG supercapacitor where the effective device thickness is 68.2 um with an active area of 1cm² and a volume of 8.22X10⁻³ cm³ [13]. The capacitance of this device has been calculated from galvanostatic (CC) curves at different current densities. The Specific Capacitance is then calculated using equation (2), where C is the device capacitance and A is the electrode surface area.

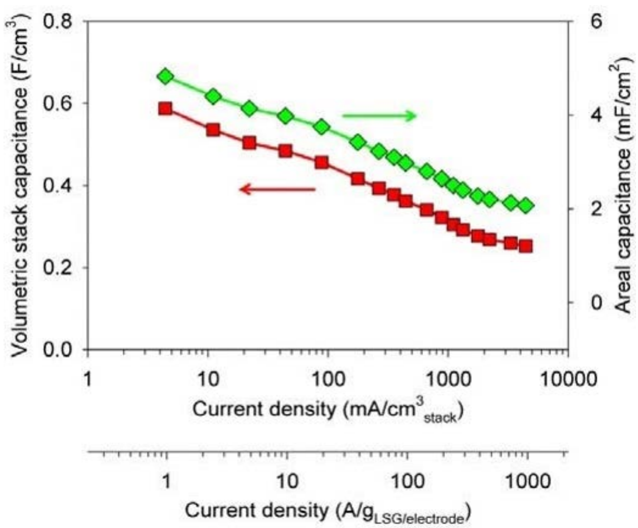


Fig. 5. The performance of an LSG electrochemical capacitor in an organic electrolyte of 1.0 M tetraethylammonium tetrafluoroborate (TEA-BF4) in acetonitrile [13]

$$Area\ Capacitance = \frac{C}{A} \quad (2)$$

For our analysis, the graph of figure 5 has been used to calculate the capacitance of LSG supercapacitor. The graph shows that the maximum area capacitance of LSG supercapacitor is 5mF/cm². Hence, the maximum electrode area capacitance is 4X5mF/cm² = 20mF/cm² for an active area of 1cm².

Compared to CAP-XX GS203 with capacitance 250mF and thickness 2.2mm, the LSG supercapacitor with 32 of these paralleled, to form the same device thickness of 68.2umX32 = 2.2mm, has capacitance of 20mFX32 = 640mF. So, a greater capacitance can be achieved by using LSG supercapacitor which is 156 percent greater than Cap-XX GS203. Similarly, compared to CAP-XX GS208 with capacitance 900mF and thickness 3.5mm, the LSG supercapacitor with 51 of these paralleled to form the same device thickness of 68.2umX51 = 3.5mm, has capacitance of 20mFX51 = 1020mF. This LSG capacitance of 1020mF is 13.33 percent greater than Cap-XX GS208. Therefore, LSG supercapacitors can contribute to greater capacitance value with the same device thickness than CAP-XX parasitic supercapacitors.

$$Volumetric\ Stack\ Capacitance = \frac{C}{V} \quad (3)$$

$$Energy\ Density = \frac{1}{2}\, C\, \frac{dV}{3600} \quad (4)$$

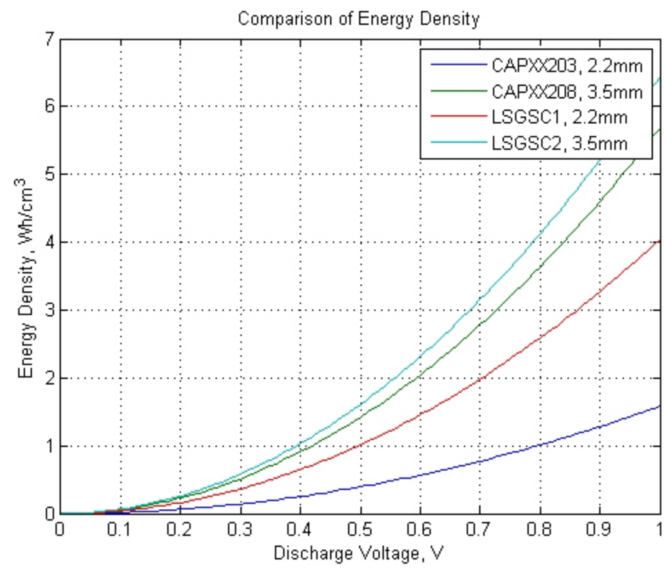


Fig. 6. Comparison of Energy Density

Equation (3), calculates the volumetric stack capacitance where C is the device capacitance and V in the volume of the electrode. Equation (4), evaluates the energy density of the supercapacitor, where C is the volumetric stack capacitance and dV is the voltage difference across the supercapacitor. The energy densities were calculated for two device thicknesses of the supercapacitors. The graph of figure 6 clearly demonstrates the comparative difference between energy density of CAP-XX prismatic supercapacitor and LSG supercapacitor. The comparative analysis illustrates that LSGSC1 has greater energy density compared to CapXX203 throughout the discharge voltage range with device thickness of 2.2mm. On the other hand, compared to CapXX208, LSGSC2 has greater energy density throughout the discharge voltage range with device thickness of 3.5mm. Thus greater capacitance and energy density can be achieved with LSG supercapacitor.

4 Optimization of LSG Capacitance

In the following study, we are going to optimize the specific capacitance of LSG supercapacitor by first choosing a suitable electrolyte. In the study of the LSG supercapacitor, an organic electrolyte of

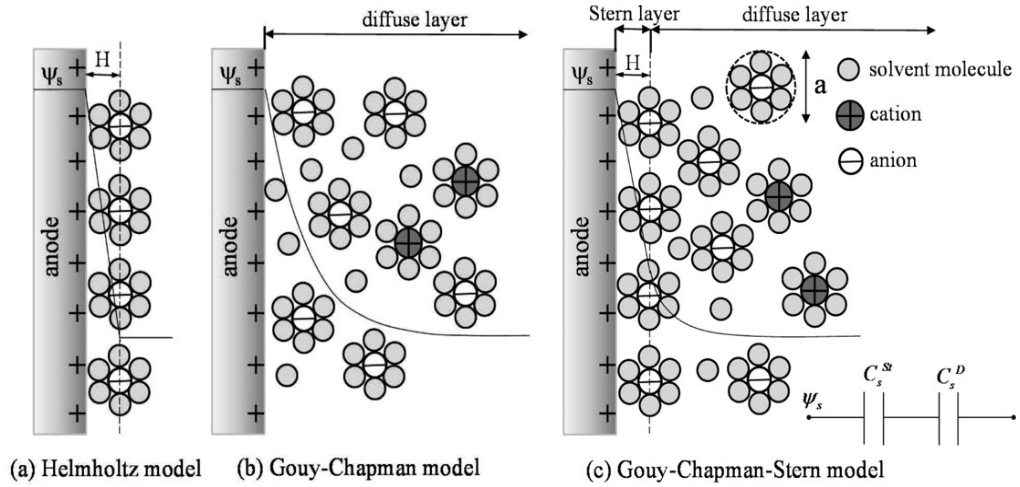


Fig. 7. Schematics of Electric Double Layer Structure [15]

1.0M tetraethylmethylammonium tetrafluoroborate has been sandwiched between LSG electrodes. In comparison to tetraethylammonium tetrafluoroborate [13], the tetraethylmethylammonium tetrafluoroborate has been used because of its high solubility in solvents at lower temperature and therefore higher conductivity of electrolyte can be achieved at lower temperature [4]. Four different electrolytes with 1.0M tetraethylmethylammonium tetrafluoroborate in different solvents like anhydrous acetonitrile, γ butyrolactone, propylene carbonate and dimethylketone has been charted on table 2. Based on an experimental study, the capacitance decrease from solvent Anhydrous Acetonitrile, -butyrolactone, Dimethylketone to Propylene Carbonate [4]. Hence, we can evaluate that tetraethylmethylammonium tetrafluoroborate in Anhydrous Acetonitrile is the best choice for the gelled electrolyte.

Table 2. The physical parameters of the solvent [14]

Solvent	Melting/Boiling Point (C)	Viscosity (Pa/s)	Dielectric Constant	Density kg/m^3
Anhydrous Acetonitrile	-43.8/81.6	0.369	36.64	0.786
γ Butyrolactone	-43.3/204	1.72	39.0	1.128
Propylene Carbonate	-48.8/241.7	2.513	66.14	1.205
Dimethylketone	-94.8/56.0	0.306	21.01	0.790

Figure 7 shows three models of EDLC structure which has been used to investigate and optimize the LSG capacitance. In the Helmholtz model, all the counterions are assumed to be adsorbed at the electrode surface [17, 18]. This structure is analogous to that of conventional dielectric capacitor with two planar electrodes separated by a distance H [17, 18]. Therefore the specific capacitance is given by equation 5 and 6 [15], expressed in F/m², where□0 and □r are the free space permi t-tivity and the relative permittivity of the electrolyte solutions, respectively. The thickness H of the Helmholtz double layer can be approximated as the solvated ions [17, 19, 20].

$$Cs^{H} = \frac{\epsilon 0\ \epsilon r}{H}\ \textit{planer electrode} \tag{5}$$

$$Cs^{H} = \frac{\epsilon 0\ \epsilon r\ (1+\frac{H}{Ro})}{H}\ \textit{spherical electrode} \tag{6}$$

In the Gouy-Chapman Model, they accounted the fact that the ions are mobile in the electrolyte solutions and are driven by the coupled influences of diffusion and electrostatic forces which results in a diffuse layer [17, 18, 20]. Assuming constant electrolyte permittivity, equation 7 and 8 [15], was derived, where λ_D is the Debye length for symmetric electrolytes, the absolute temperature is denoted by T, e is the elementary charge, k_B is the Boltzmann constant, N_A is the Avogadro's number, z is the valency, c_∞ is the molar concentration and ψ_D is the local electric potential in diffuse layer.

$$Cs^{D} = \frac{4zeN_A c_\infty \lambda_D \sin h\ \frac{z\ e\ \psi_D}{2\ k_B\ T}}{\psi_D}\ \textit{planar electrode} \tag{7}$$

$$Cs^{D} = \frac{\epsilon 0\ \epsilon r\ (1+\frac{\lambda_D}{Ro})}{\lambda_D}\ \textit{spherical electrode} \tag{8}$$

Stern combined the Helmholtz model and Gouy-Chapman Model and described the electric double layer as two layers: Helmholtz layer where compact layer of immobile ions are strongly adsorbed to the electrode surface and Diffuse layer where the ions are mobile. Hence, the total electric double layer capacitance consists of Stern layer and diffuse layer capacitance in series as in equation 9 [15]. The study on the optimization of design is done by accounting the Stern and diffuse layers.

ISSN 2229-5518

$$\frac{1}{C} = \frac{1}{Cs^H} + \frac{1}{Cs^D} \qquad (9)$$

From equation (5-8) we can clearly see that the variable H is only present in the equation of Helmholtz layer specific capacitance, i.e equation (5) and (6) [15], where H is the thickness of Helmholtz double layer which is approximated as the radius of solvated ions. Thus only Helmholtz layer specific capacitance is affected by the finite size of ions and thereby effecting the total specific capacitance.

5 Results and Discussion

The present study focuses on aqueous binary symmetric electrolyte solution at room temperature T=298K, characterized by the following properties: ε_r=36.64 [14], n=1.33. The effective ion diameter is taken as a=0.66nm and the valency as z=1 corresponding to solvated ions in aqueous solution, [21]. The electrolyte concentration was chosen as c_∞=1.0mol/L corresponding to typical values in EDLCs [15]. The local electric potential in diffuse layer is taken as ψ_D=0.5V. The variable H is the thickness of Helmholtz double layer which is approximated to the radius of solvated ions, that is H=0:33nm [17, 19, 20].

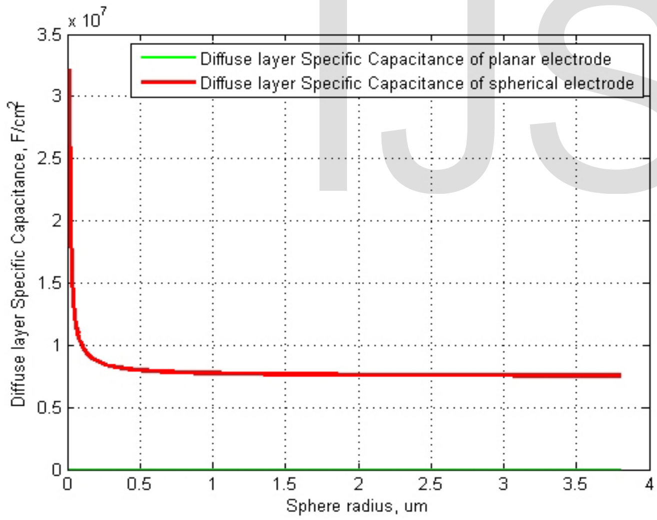


Fig. 8. The variation of Helmholtz layer specific capacitance for planar and spherical electrode

The thickness of the LSG electrode is 7.6um, so Ro is ranged from 0um- 3.8um.

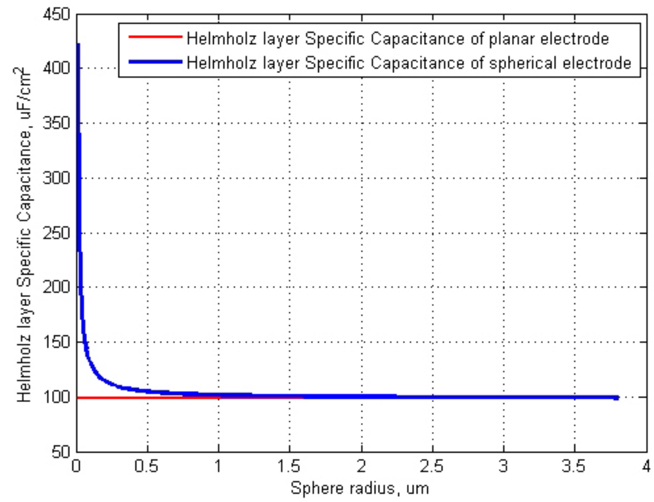


Fig. 9. The variation of diffuse layer specific capacitance for planar and spherical electrode

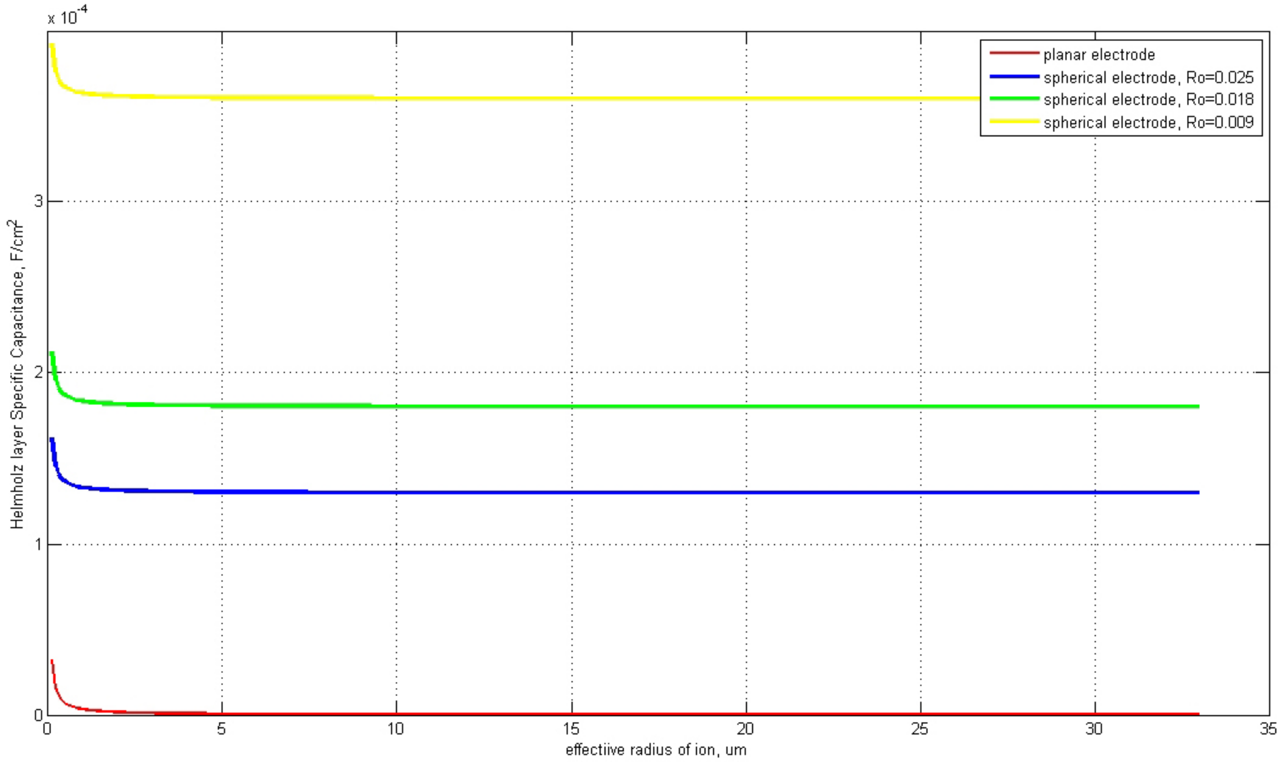


Fig. 10. The Helmholtz layer specific capacitance for variation in ion size

Few assumptions has been made to simulate and study the equation 5 to equation 9; the electric potential and ion concentration were invariant with time and reached equilibrium state, the effective diameter of anions and cations are same, isothermal conditions prevailed throughout the electrode and electrolyte, advection of the electrolyte was assumed to be negligible, the ions could only accumulate at the electrode surface and could not diffuse into the electrode particle.

Figure 8 shows the Helmholtz layer specific capacitance C_S^H as a function of sphere radius R_o. Equation 5 and 6 are used to generate this graph using Matlab R2013a tool and by plugging the stated parameter values in the equations. The graph shows that C_S^H decreases with increasing radius of spherical electrode. However, C_S^H remains constant with the change in radius of planar electrode. Moreover, the study evaluates that we can increase the specific capacitance of LSG supercapacitor by using a spherical electrode rather than a planar electrode. A spherical electrode radius of less than 1um may optimize the LSG supercapacitor capacitance that can be an effective approach for the supercapacitor enhancement in LED flashlight of mobile camera.

Figure 9 shows that the diffusion layer specific capacitance C_S^D of planer electrode is almost negligible with a value of 0.0028 F/cm². As the planar electrode does not show a variation with the radius of electrode, we are not taking planer electrode into consideration for design optimization. However, if figure 8 and 9 are compared, then it can be analyzed that the diffuse layer specific capacitance C_S^D of spherical electrode is significantly higher than the Helmholtz layer specific capacitance C_S^H for spherical electrode. Thus the total specific capacitance of spherical electrode will be dominated by Helmholtz layer specific capacitance.

Figure 10 shows that the Helmholtz (Stern) layer specific capacitance C_S^H varies with the finite ion size of electrolyte. Equation (6) has been used to plot this graph by plugging the stated variable values where the radius of electrode, R_o is varied with three values 0.025 um, 0.018 um and 0.009 um and the ion radius has been varied from 0 um to 33 um. We can evaluate from the graph that Helmholtz (Stern) layer specific capacitance shows a response to the ion size of less than 1 um. Moreover, the specific capacitance of spherical electrode is greater with R_o = 0:009um and decreased as the radius of the spherical electrode increased. However, small ion size of electrolyte may cause a little diffusion into the electrode particle. In general, atoms vary in size according to the element, but their diameters are of the order of 0.1 nm [21]. So we can find a suitable atom with ion size of less than 1um. Hence, we may evaluate that a small radius of spherical electrode of around 0.009 um with electrolyte ion size of less than 1 um may contribute to higher specific capacitance of a supercapacitor.

The advantage of using a LSG supercapacitor to flash LED in mobile camera are high energy storage capacity, low equivalent series resistance contributes to high current output, low temperature performance, fast charging and discharging ability, and a very cost effective process of forming LSG layer over DVD surface [13]. The disadvantage of using a LSG supercapacitor to flash LED in mobile camera is that limited output voltage is offered per unit cell. Hence, these devices have to be connected in series to get the desired cell voltage for user application.

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4 Conclusion

Based on the simulation analysis, it can be concluded that the Laser Scribed Graphene (LSG) Supercapacitor of Kaner and El-Kandy can optimize the design solution of a LED flashlight camera phone compared to the prismatic supercapacitor of CAP-XX Company. The designer can use this design solution to flash high powered LED which can enhance the resolution of the pictures that are taken by LED flashed camera phones. Furthermore, compared to the prismatic supercapacitor of CAP-XX, the LSG supercapacitor have an advantage of overall smaller size to fit in the limited space of cellular mobile phones. However, the capacitance of LSG Supercapacitor is further enhanced in this paper by studying the three models of EDLC structure: Helmholtz Model, Gouy- Chapman Model and Gouy-Chapman-Stern Model. The study shows that instead of using a planar electrode in the LSG Supercapacitor design, a spherical electrode can provide higher Helmholtz layer specific capacitance and diffusion layer specific capacitance, contributing to an overall increased total capacitance. Thus spherical electrode can optimize the required design solution. Moreover, the sandwitched organic electrolyte has been analyzed with four possible solvents of which 1.0M tetraethylmethylammonium tetrafluoroborate in anhydrous acetonitrile is the best choice for gelled electrolyte. Lastly, the simulations shows that smaller size of ions in the electrolyte can contribute to higher capacitance although smaller ions may cause slight diffusion in the electrode particle. Therefore, the optimized LSG supercapacitor can provide the demanding tech market a better and economical mobile phone camera to meet the current consumer demand.

Acknowledgment

First and foremost I offer my sincerest gratitude to my supervisor, Dr K. M. A Salam, who has supported me to conduct this research with his vast knowledge in the field of semiconductor whilst allowing me the room to work independently. Nevertheless, the department of Electrical and Computer Engineering has helped me to avail updated necessary software tools to validate my analysis.

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