Impact of hydrogen adsorption on the performance of a single electron transistor utilizing Fullerene quantum dots

Vahideh Khademhosseini[1], Daryoosh Dideban[1, 2,*], Mohammad Taghi Ahmadi [3,4], Razali Ismail[3], Hadi Heidari[5]

[1] Institute of Nanoscience and Nanotechnology, University of Kashan, Kashan, Iran

[2]Department of Electrical and Computer Engineering, University of Kashan, Kashan, Iran

[3]Faculty of Electrical Engineering, UniversitiTeknologi Malaysia, 81310, Johor Bahru, Johor, Malaysia

[4]Nanotechnology Research Center, Nano electronic Research Group, Physics Department, Urmia University, Urmia, Iran

[5]MicroElectronics Lab, Electronics and Nanoscale Engineering Research Division, School of Engineering, University of Glasgow, Glasgow, UK

Corresponding author email: dideban@kashanu.ac.ir

Abstract

The single electron transistor (SET) is a nanoscale electronic device with fast operation speed. The selection of quantum dot as its island can increase its speed. In this research, fullerene quantum dot is suggested as island of SET and also hydrogen atoms are added to fullerene molecule. Comparison study shows that the number of hydrogen atoms can decrease coulomb blockade and zero current range. Moreover, increasing the number of fullerene quantum dots has an impact on coulomb diamond area, so reliability of SET can be improved. Therefore choosing suitable number of fullerene quantum dots and hydrogen atoms can SET current to a desired value.

Keywords: Hydrogen Adsorption, Electron Tunneling, Quantum Dot, Single Electron Transistor.

Introduction

Progress in semiconductor industry necessitates nanoscale transistors with novel materials to produce chips with higher operation speeds and lower power consumption [1, 2]. The single electron transistor (SET) is a nanoscale switching device that controls electron tunneling between source and drain electrodes and quantum dot via its coulomb barriers. The only way for electrons to stop the tunneling is occurred via a physical process which is called coulomb blockade effect [3-10]. This phenomenon and the energy spectrum of a quantum dot are combined in constant interaction model [11]. The total energy of the quantum dot is given by:

$$E(N)=\sum_{i=1}^{N}\varepsilon_i+U(N)=\sum_{i=1}^{N}\varepsilon_i+\frac{e^2N^2}{2C\sum}+eN\left(\frac{Q_{bg}}{C\sum}+\sum_{j=1}^{n}\frac{C_{0j}}{C\sum}V_j\right) \quad (1)$$

where "ε_i" is the sum of single-particle energies of SET, "$U(N)$"is the electrostatic energy, "e" is the electron unit charge, "N" is the number of electrons, "$C\sum$" is sum of the drain, gate, and source capacitances, "Q_{bg}" is the charge that remains on the dot if all potentials are put to zero, "C_{oj}" is self-capacitance of the island and "V_j" is the applied gate voltage.

Adding an electron to the quantum dot needs an electrochemical potential (μ_N) which can be expressed as:

$$\mu_N=E(N)-E(N-1)=\varepsilon_N+\frac{e^2}{C\sum}\left(N-\frac{1}{2}\right)+e\left(\frac{Q_{bg}}{C\sum}+\sum_{j=1}^{n}\frac{C_{0j}}{C\sum}V_j\right) \quad (2)$$

The electron tunneling in a quantum dot transistor is depicted in Fig.1 that contains double tunnel barriers.

The coulomb blockade effect occurs at very small bias and low temperatures as shown in Fig.1(a). Not only electron tunneling is stopped but also their number is fixed on N electrons. When the gate voltage increases, the chemical potential (μ_N) inside the dot is equal to the chemical potential in the drain ($\mu_D = \mu_N$). Therefore electron can tunnel from quantum dot to the drain and consequently the number of electrons on the dot changes from N to N-1. In other words, the current can flow in SET [12-17].

The coulomb blockade can be characterized using a pattern which is called coulomb diamond. It is basically the diagram of the gate voltage as function of the bias voltage which clearly indicates coulomb blockade region as well as single electron tunneling region [18, 19]. It is marked in Fig.2. The variation of coulomb diamond area can be observed in SET that causes to increase the current oscillation.

The SET operates based on the tunneling of small number of electrons (even one electron). Thus, it can be used in charge sensors. It is very sensitive, so it is also used in supersensitive electrometers. Moreover direction of electron spin can be used for binary coding in quantum computer where up spin seems as binary 1 and down spin can be binary 0. It can be utilized for the detection of infrared radiation and microwave radiation because its sensitivity is controlled by its coulomb blockade energy. Finally, since its current is in the nano-Amper range, it can be used for the measurement of very small DC currents [20].

SET operation depends on the tunneling of an electron form its channel but current flows in MOSFETs by transfer of thousands of electrons from its channel. Consequently decreasing number of transferred electrons from the transistor channel raises its operation speed and also possibility of circuit integration in higher level. Therefore it is possible to replace MOSFETs with SETs in next generation of electronic circuits in future [21].

Results and discussion

Island's material of SET affects on its operation speed [22]. Its important parameter is electron mobility which influences on speed of transferred electrons and consequently its coulomb blockade range [23]. Moreover SET needs a quantum dot island which should be stable in nanometer range dimensions. Thus fullerene as a zero dimension material with high electron mobility and high stability in nanoscale is selected for the SET island [24,25]. Furthermore utilizing fullerene as SET island presents lower leakage current and coulomb blockade range than SET with silicon island [26].

In this research, we proposed the idea of selecting fullerene as the quantum dot material of SET when different numbers of hydrogen atoms are added to fullerene molecule as used in other work [27]. They are considered as quantum dots in SET as shown in Fig.3.

The coulomb diamonds of different quantum dots are investigated and plotted using Atomistix Toolkit software [28] and thus their stability diagrams are presented in Fig.4(a-d). Their impacts on V_{ds}-V_g characteristics are compared together and also the best quantum dot is selected to design SET.

The coulomb blockade ranges associated with each coulomb diamond as well as their areas are extracted from Fig.4 and they are presented in Table1.

Table1: Important parameters extracted from center diamond of the stability diagrams presented in Fig 4.

Fullerene molecule	$V_{ds_{\min}}, V_{ds_{\max}}$	ΔV_{ds}	$Vg_{\min}, Vg_{\max}$	ΔVg	Diamond Area
a	-3.385,3.497	6.882	-3.043, 0.319	3.362	11.568
b	-4.464,4.501	8.965	-3.307,1.169	4.476	20.063
c	-4.352,4.427	8.779	-3.194, 1.132	4.326	18.988
d	-3.311,3.459	6.656	-3.194,0.225	3.419	11.378

The comparison study in Table 1 shows that center diamond area and coulomb blockade range of molecule"d" is lower than other molecules.This molecule has more hydrogen atoms than other molecules. Therefore the number of hydrogen atoms has direct effect on coulomb blockade range and zero current in SET.

Another effective factor in SET operation is the number of quantum dots, so this factor is explored in our study. The stability diagrams of SETs utilizing single, double and three QDs are plotted in Fig 5.

The Comparison study in Fig.5 indicates that increasing the number of quantum dots can decrease the coulomb blockade range in stability diagram of SET. Furthermore lower coulomb diamond area can lead to lower variation, so current oscillations as operation limiter of SET is reduced and consequently SET can operate in higher speeds.

The fabrication steps in producing the SET under study are investigated using other work and are shown in Fig. 6 [29]. Different materials are used for its fabrication. The silicon is selected for its substrate. It is cleaned with piranha solution and then Al_2O_3 layer is deposited on it. This layer is isolation layer between substrate and SET. A thin layer of Chromium as active layer is deposited on Al_2O_3 layer. Furthermore the SET has three electrodes which are produced by etching process in Focused Ion Beam (FIB) system. The pattern is generated and then device pad and electrodes are produced. Moreover fabrication of inter-electrode gaps and deposition of the nanoscale island are carried out with FIB system. Chemical oxidation is done and tunnel junctions form and finally a layer of Al_2O_3 is deposited which passivates the SET [29].

Conclusion

The single electron transistor (SET) can increase the speed of electronic circuits due to its fast operation. The important factor of SET operation is the coulomb blockade range that shows zero tunneling current. This range can be decreased by fullerene quantum dot with unique properties. In this research, hydrogen atoms added to fullerene quantum dot. Comparison study indicated that the number of hydrogen atoms had direct impact on the coulomb blockade range and coulomb diamond area. On the other hand increasing the number of quantum dots can reduce thecoulomb blockade range in stability diagram of SET. Therefore the current of SETcan be tuned with the appropriate selection of the number of quantum dots and hydrogen atoms.

Acknowledgement

This research was supported by University of Kashan, under supervision of Dr. Daryoosh Dideban. Authors are also thankful to the support received for this work from Microelectronics Lab (meLAB) at the University of Glasgow. Also thanks to the Research Management Center (RMC) of Universiti Teknologi Malaysia (UTM) for providing an excellent research environment in which to simulate this research by Atomistix ToolKit and to complete this work.

References:

1. M. Akbari Eshkalak and M.K. Anvarifard, " A novel graphene nanoribbon FET with an extra peak electric field (EFP-GNRFET) for enhancing the electrical performances", Physics Letters A, Vol. 381, Issue 16, p. 1379, 2017.
2. M. Akbari Eshkalak and M. K. Anvarifard, "A guideline for achieving the best electrical performance with strategy of halo in graphene nanoribbon field effect transistor", ECS Journal of Solid State Science and Technology, Vol. 5, No.12,p.141, 2016.
3. VV .Shorokhov, DE. Presnov, SV. Amitonov, YA .Pashkin and V.A. Krupenin, "Single-electron tunneling through an individual arsenic dopant in silicon", Nanoscale, Vol.9, p.613, 2017.
4. F. Wang, J. Fang, Sh. Chang, Sh. Qin, X. Zhang, H. Xu ," Room temperature Coulomb blockade mediated field emission via self-assembled gold nanoparticles" , Physics Letters A, Vol .381, p.476 ,2017.
5. V. KhademHosseini, M T.Ahmadi, S. Afrang and R. Ismail, "Current analysis and modelling on fullerene single electron transistor at room temperature", Journal of Electronic Materials, Vol.46, No.7, p. 4294, 2017.
6. W. A.Schoonveld, J.Wildeman, D. Fichou, P. A. Bobbert, B. J.van Wees , T. M.Klapwijk, "Coulomb-blockade transport in single-crystal organic thin-film transistors", Nature, Vol. 404, pp.977, 2000.

7. J.Park, A. N.Pasupathy, J. I.Goldsmith, C.Chang, Y.Yaish, J.R. Petta, M.Rinkoski, J.P. Sethna, H. D.Abruña, P. L. McEuen, D .C.Ralph," Coulomb blockade and the Kondo effect in single-atom transistors". Nature, Vol.417, p.722, 2002.

8. M.Ejrnaes, M .T.Savolainen b, M.Manscher , a J.Mygind, "Microwave induced co-tunneling in single electron tunneling transistors". Physica C: Superconductivity, Vol. 372, p.1353, 2002.

9. H. Zheng, M. Asbahi, S. Mukherjee, C. J Mathai, K. Gangopadhyay, J. K W Yang, Sh.Gangopadhyay," Room temperature Coulomb blockade effects in Au nanocluster/pentacene single electron transistors", Nanotechnology.Vol. 26, p.35, 2015.

10. F. Willy , Y. Darma , "Modeling and simulation of single electron transistor with master equation approach", Journal of Physics: Conference Series 739 IOP science , 2016.

11. C. W. J. Beenakker, "Theory of Coulomb-blockade oscillations in the conductance of a quantum dot", Physical Review B ,Vol.44, 1646 ,1991.

12. W. A.Schoonveld, J.Wildeman, D. Fichou, P. A. Bobbert, B. J.van Wees , T. M.Klapwijk, "Coulomb-blockade transport in single-crystal organic thin-film transistors". Nature, Vol.404 , p.977,2000.

13. V. KhademHosseini, MT. Ahmadi, S. Afrang, R. Ismail ," The Analysis of Coulomb Blockade in Fullerene Single Electron Transistor at RoomTemperature" Journal Nanoanalysis., Vol. 4, No. 2, p. 120, 2017.

14. R. Hanson, L. P. Kouwenhoven, J. R. Petta, S. Tarucha, and L. M. K. Vandersypen. "Spins in few-electron quantum dots", Review Modern Physics, Vol 79, p.1217 ,2007.

15. D.V. Averin, K.K. Likharev, "Coulomb blockade of single-electron tunneling, and coherent oscillations in small tunnel junctions" Journal of low temperature physics, Vol. 62, Issue 3–4, p 345, 1986.

16. J.R. Tucker," Complementary digital logic based on the Coulomb blockade", Journal of Applied Physics, Vol.72 , No. 9, p. 4399 , 1992.

17. K. Lee , G.Kulkarni , Z. Zhong ," Coulomb blockade in monolayer MoS2 single electron transistor ", Nanoscale ,Vol .8, p.7755, 2016.

18. Y. Azuma, Y. Onuma, M. Sakamoto , T Teranishi, " Rhombic Coulomb diamonds in a single-electron transistor based on an Au nanoparticle chemically anchored at both ends", Nanoscale, Vol.8, p.4720, 2016.

19. V. KhademHosseini, MT. Ahmadi, S. Afrang, R. Ismail " Analysis and Simulation of Coulomb Blockade and Coulomb Diamonds in Fullerene Single Electron Transistors", Journal of nanoelectronics and optoelectronics, Vol.13,p.138, 2018.

20. A. Kumar and D. Dubey, "Single Electron Transistor: Applications and Limitations", Advance in Electronic and Electric Engineering, Vol.3, No. 1 ,p. 57, 2013.

21. S. Goyal1, A. Tonk, "A Review towards Single Electron Transistor (SET)", International Journal of Advanced Research in Computer and Communication Engineering , Vol. 4, Issue 5, 2015

22. V. KhademHosseini, D. Dideban , M T. Ahmadi, R. Ismail, "Analysis and Modelling of Quantum Capacitance on Graphene Single Electron Transistor", International Journal of Modern Physics B,Vol. 32 ,1850235 ,2018.

23. V. KhademHosseini, D. Dideban , MT. Ahmadi, R. Ismail," An analytical approach to model capacitance and resistance of capped carbon nanotube single electron transistor", International Journal of Electronics and Communications (AEÜ), Vol. 90,p.97,2018.

24. V. KhademHosseini, M T. Ahmadi, R. Ismail " Analysis and Modeling of Fullerene Single Electron Transistor Based on Quantum Dot Arrays at Room Temperature", Journal of electronic materials,Vol .47, Issue 8, p 4799, 2018.

25. V. KhademHosseini, D. Dideban ,M T. Ahmadi, R. Ismail, "Single Electron Transistor Scheme Based on Multiple Quantum Dot Islands: Carbon Nanotube and Fullerene", ECS Journal of Solid State Science and Technology, Vol. 7, issue 10, M145-M152, 2018.

26. V. KhademHosseini, D. Dideban , M T. Ahmadi, R. Ismail "Analysis of Co-Tunneling Current in Fullerene Single-Electron Transistor", Brazilian Journal of Physics, Vol.48,Issue. 4 , p.406, 2018.

27. A. Kaiser, C. Leidlmair, P. Bartl, S. Zöttl, S. Denifl, A. Mauracher, M. Probst, P. Scheier, O. Echt, "Adsorption of hydrogen on neutral and charged fullerene: Experiment and theory", The Journal of Chemical Physics,Vol. 138, 2013.

28. https://quantumwise.com/products/atk

29. M. Acharya, "Development of room temperature operating single electron transistor using FIB etching and deposition technology", Ph.D thesis, Michigan Technological University, 2009.

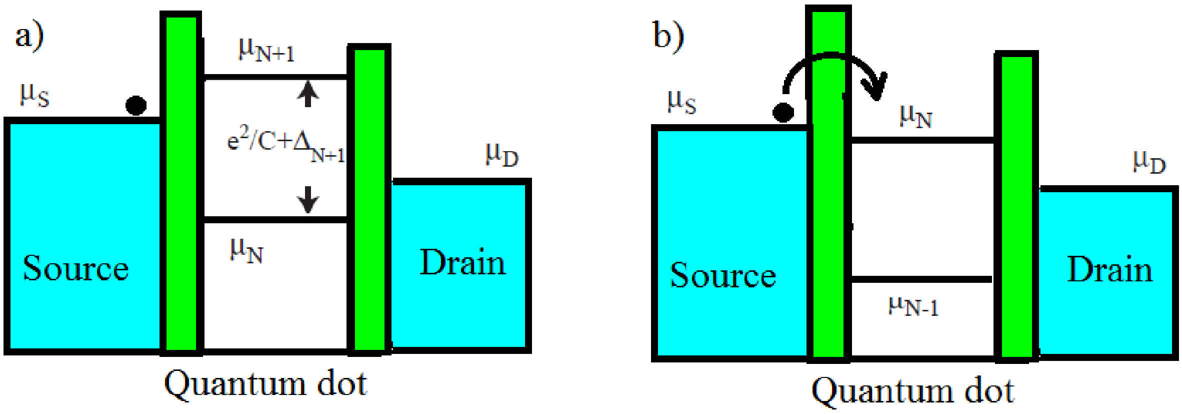


Figure1:a) Coulomb blockade phenomena, b) Electron tunneling in SET.

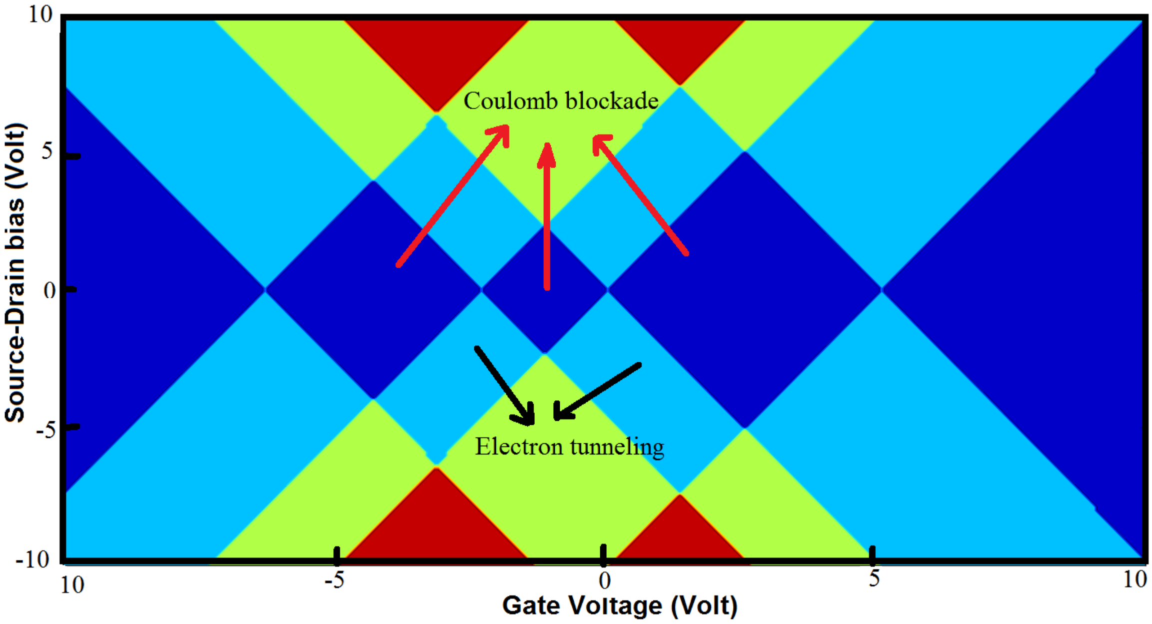
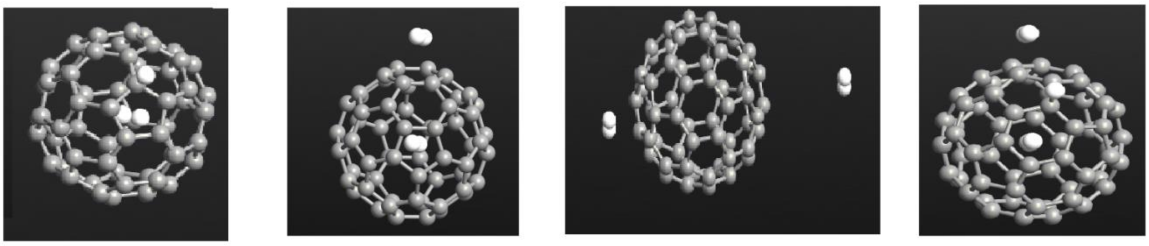
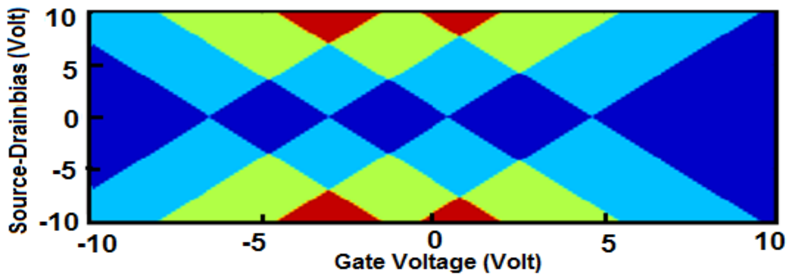


Figure 2: The coulomb diamond pattern in SET.

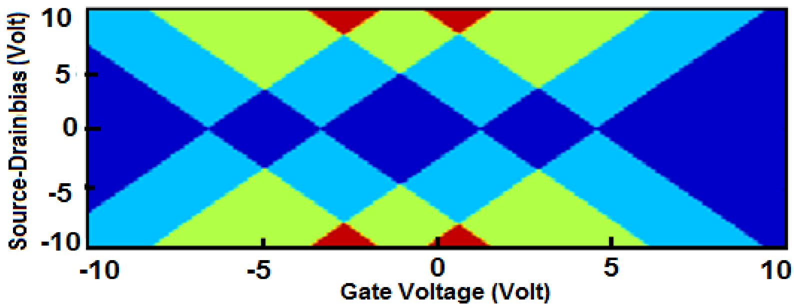


(a) (b) (c) (d)

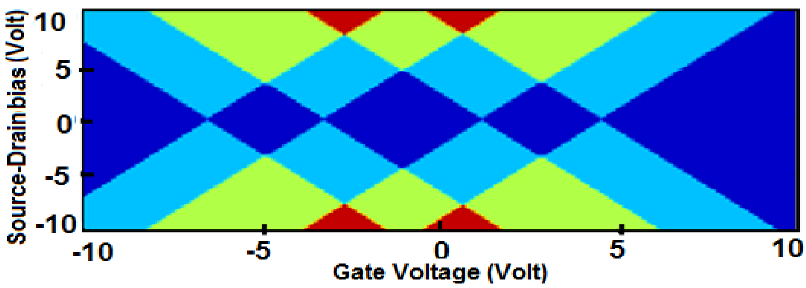
Figure3: Hydrogen Adsorption on fullerene molecules, a) fullerene molecule and three hydrogen atoms, b) fullerene molecule and four hydrogen atoms where two are located in the center of fullerene, c)fullerene molecule and four hydrogen atoms outside of fullerene, d)fullerene molecule and five hydrogen atoms.



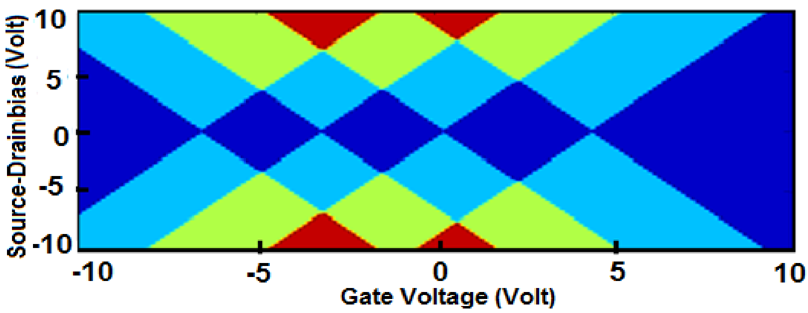
(4-a)



(4-b)

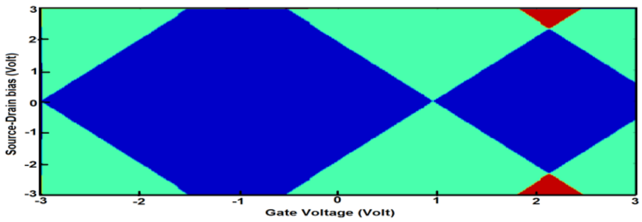


(4-c)

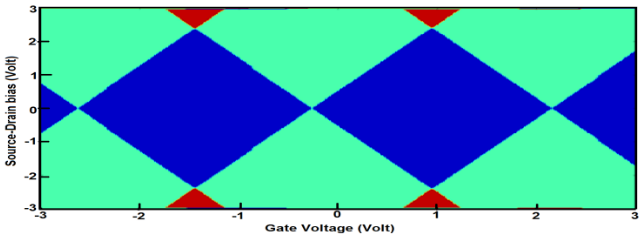


(4-d)

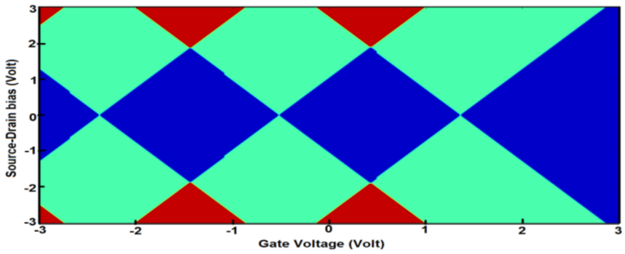
Figure 4: The stability diagrams of SET with single quantum dot as a) fullerene molecule and three hydrogen atoms, b) fullerene molecule and four hydrogen atoms where two are located in the center of fullerene, c)fullerene molecule and four hydrogen atoms outside of fullerene, d) fullerene molecule and five hydrogen atoms.



(5-a)



(5-b)



(5-c)

Figure5: stability diagrams of SET with hydrogen adsorption on fullerene as island, a) single QD SET b) Double QDs SET c) three QDs SET.

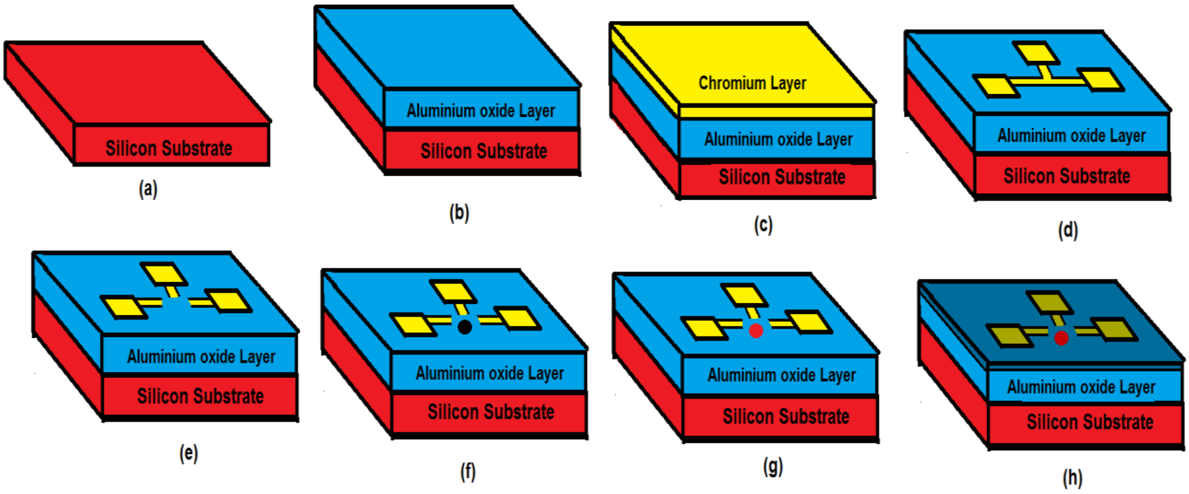


Figure 6: The step of SET fabrication: a) Silicon substrate, b) adding Al_2O_3 layer c) adding Chromium layer, d) fabrication of SET electrodes with FIB, e) fabrication of a gap between SET electrodes, f) deposition of island, g) formation of tunnel junctions, h) Al_2O_3 layer deposition and SET passivation.