University of Thi_Qar Journal for Engineering Sciences
http://www.doi.org/10.31663/tqujes.11.2.399(2021)
Vol 11.2(April 2021)

ISSN :2664- 5572 (online)
ISSN:2664-5564 (print)
Available at http://jeng.utq.edu.iq
utjeng@ utq.edu.iq

Brief review on: Fabrication of single electron nano-devices

Haider S. Manji Al-Mumen

Department of Electrical Engineering, University of Babylon, Iraq

Abstract

This paper discusses the fabrication techniques and the fabrication technique of single electron transistor (SET). The SET differs from the conventional CMOS in the sense that it has the ability to control an electron movement so that single electron can be transport at a time, meaning that one by one electron along the channel. This is due to its stunning technique that has the ability of controlling the electron tunneling. The SET represents a promising technology as it offers several unique advantages, example, small size, high operating frequency, and low power consumption. Several SET of fabrication technologies were reviewed in this paper, including quantum dot, carbon nanotube, graphene, and zinc oxide.

Keywords: Nano devices, single electron transistors, fabrication

1. Introduction

Recently ultra-power conception and fast devices became a demand for the new applications, particularly for the portable devices such as cellphones, video games, and telecommunication [١] . This requires thinking seriously about advanced architectural designs in terms of materials and fabrication technologies.

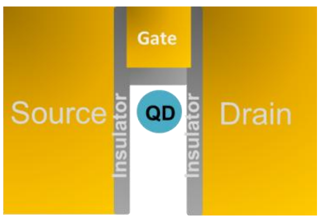
Since transistor is the building block of any electronic device, working on growing up its characteristics specially the frequency bandwidth and power conception, has been the key point for the researchers since the 1980s [2].

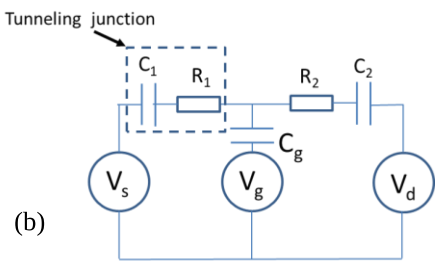
Based on Moor's law [3], the number of transistors integrated into a semiconductor circuit doubles every 18 months. It seems that Moor's low has become to represent a limitless capacity for the huge growth in electronics. Since the performance of the transistor is elevated with the shrinking of its dimensions, a fascinating transistor approach called single electron transistor (SET) has been designed and fabricated [4]. The architecture of the SET transistor is different from the conventional CMOS transistor as it contains one- or two-dimensional nanomaterial. The only way to characterize such nanoscale devices is by the aid of quantum mechanical effects. The SET has large potential for low-power applications [5]. In this device, the conductance fluctuates periodically due to the Coulomb blockade effect (discussed in the next section). However, the missing of repeatability of SET is a challenge due to the difficulty of device fabrication preciously in atomic level. And this leads to complexity or even impossibility of construction of integrated circuits. SET devices can be divided based on technique into four based on the fabrication and nanomaterials, SET based nanodot, SET based graphene nanoribbon, SET based on ZnO nanorods and SET based on CNTs. The above technologies have covered in the following sections individually.

2. SET constructing based on quantum dot

This SET is constructed by making drain and source and an island, the quantum dot, with a diameter 1<d<10 nm, is lies between them [6-9]. The dot is separated by a dialectic layers. Similar to the conventional transistors, SET has a gate to maintain the flowing of electrons (Figure 1).

(a)





(b)

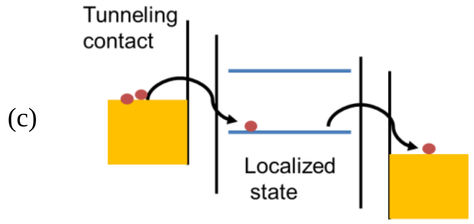


Fig. 1. (a) SET skematic (b) equivelent circuit of the SET (c) skematic of the tunneling in SET.

As in the schematic of Figure 1, there is just one way for an electron to travel from source to drain is by travelling through the dielectric layer. Since the electron is confined within a small volume then energy band is quantized. The value of gate voltage decides the number of electrons flowing through the island. Furthermore, the coulomb blockage causes blocking in the current whenever a single electron is escape from source to the dot [10, 11]. When the electron arrives at the drain, the energy band decreased and another electron jumps to the island. Hence, with applied gate voltage the device reveals conductance oscillations. This make the SET a candidate for interesting applications such as, very high sensitive sensors [12-16], logic gates and memories [15, 16].

The important idea to mention is that the coulomb gap voltage, which is equal to,

$e^2/2C_{s+d}$ .. ……………………………………………(1)

where, C_{s+d} is the source and drain capacitance, must be less than the thermal energy (KT). Moreover, the resistance of the channel must be greater than $2h/e^2$. Do not taking into account these limitations could probably result in a tunneling on the SET even with no gate voltage.

3- Fabrication technique of SET by Carbon nanotube (CNT)

The excellent electronic properties and nano-size dimensions make CNT a nominee for SET constructing [17-21]. The remarkable property in the CNTs is that the mobility of charge carriers are very high compare to conventional CMOS [22] and also the electrons flow on the surface of it. However, it is hard to control the flowing of electrons.

BJ Villis, et al [23] suggested a method to detect the single electron transport. The structure of the circuit includes CNT with gold nanoparticles as islands. The transfer of electrons were detected by measuring the conductance of the CNT during applying voltage to the gate. The required energy to add an electron to the particle is

$EC= e^2/(C_{tube-Au} +C_{Au-gate})$ [24] ……………………….. (2)

Figure (2) DISPLAYS s the architecture and the equivalent circuit of the CNT –SET.

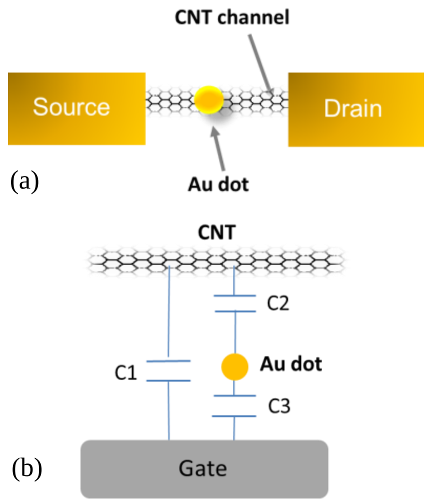


Fig. 2. (a) Structure of the SET carbon nanotube (b) The electrical equivelent circuit.

The resistance between the particle and the tube can be calculated by assuming the case

$\Delta E \approx KT \approx E_C$, ……………………………………….... (3)

Where ΔE is the energy difference. Then, the time constant is,

$\tau = RC_{tube-Au}$ …………………………………………….. (4)

Since

$C_{tube-Au} \approx e^2/E_C$ ……. ………………………………… (5)

Then,

$\tau = Re^2/E_C$ …………………………………………… (6)

This leads to,

$R = \tau E_C/e^2$ …………………………………………… (7)

At a given value of τ and temperature, the charged electrons for each discrete peak position shift can be determined based on the model depicted in Figure 2. Also,

$N=(\Delta V_P \Delta V_C C_{CG})/ e(\Delta V_C-V_P)$. …………………….. (8)

Where V_P is the peak voltage of charge electrons and ΔV_C charge voltage through the gate voltage and the C_{CG} is the capacitance between CNT and the Au dot. [25, 26].

4. Single-electron transistor with multiple islands

The condition for displaying the effect of one-electron is that the energy of the operating temperature must be less than the energy of the column island. Therefore, for the SET to be used at room temperature, the island size must be in an enough small size around 1- 5 nm [25, 27, 28]. However, it is a challenge to construct a reliable small size device since such size required a sophisticated fabrication technology. However, to increase the operating temperature, C_{eff} should be increased, which leads to increase the charge energy ($e^2/(2C_\Sigma)$). Figure (3) shows the architecture of the SET based on multi-island.

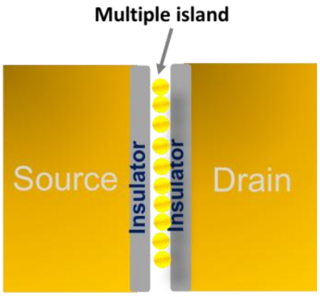


Fig. 3. Schematic of the SET based multiple island.

5- SET based on Graphene

a- Graphene quantum dot (GOD)

Graphene is 2D carbon material. It was prepared first by Andre Geim and he received Nobel prize for his work graphene [29]. Graphene has a lot of interesting properties, not only electronic [30, 31] but also mechanical [32, 33], thermal properties [34, 35], and optical properties [36, 37]. This makes it promising for future micro- and nano-devices.

Graphene quantum dot is a 0D carbon based material. It is a nano piece dimension of the graphene layer [38, 39]. Etching graphene sheet into quantum size will definitely change its properties because of sharp edges that usually appears after etching, in addition to electron confinement phenomenon [40] . Several techniques have been used to achieve quantum graphene size , such as, plasma etching [41], nanolithography [42], and chemical exfoliation [43].

The thickness of the graphene quantum dot is either single layer (0.34 nm) or few layers (~2 nm). Whereas the diameter of the quantum dots is around 1nm with a typically circular shape [44].

Graphene quantum dot is typically used in the sensing application particularly, in charge sensors [45]. Plasma etching after e-beam lithography have been used in the constricting of the quantum dots [46]. Furthermore, the GODs have also used as a humidity detector [47].

b- SET-based graphene double quantum dots

Using multi- island [48] in the structure of the SET is another technique to overcome the problem of coulomb blockade. It is reported that the number of quantum dots significantly affects the probability of electron tunneling [45].

Graphene has been used in the fabrication of multi-island SET. This feature reduces the gap conductance and raises the speed of electron transfer in SET.

6- Single electron transistor based on Zinc oxide

Zinc oxide (ZnO) nanrodes have a lot of interest properties due to its large surface area and wide bandgap (~3.4eV) [49]. It has been used in the design of several nano devices such as photo detector [50], high efficiency solar cell [51] and piezoelectric sensors [52]. The properties of the ZnO can also be modified to make it either n-type or p-type, depending on the dopants [53-55] .

SET based on ZnO belt [56] has been fabricated and tested at 4.2 ^{0}K. A few millimeter bias voltage was used to achieve the coulomb blockage. About 10 meV charging energy was measured that means the confine quantum dots exist at a radius of ~18nm. Figure (4) displays the skematic of the SET based on ZnO nano rode.

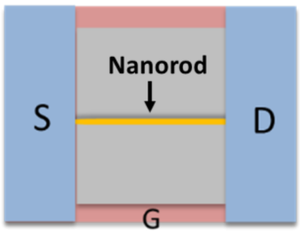


Fig. 4. Architecture of the SET based on ZnO rod.

Conclusions

This brief review summarized the fabrication techniques and materials that have been used in the design of the SET. It seems that the road towards the commercial SET is still long. Dealing with quantum size devices requires a particular fabrication instruments and technologies to transfer the above mentioned techniques to the market. However, promising attempts has been displayed recently, particularly in the direction of using zero, single, and two dimensions nanomaterials. In addition to the serious attempts to understand the theoretical basis and properties of the SET.

References

[1] C.-K. Tung, S.-H. Shieh, and C.-H. Cheng, "Low-power high-speed full adder for portable electronic applications," *Electronics Letters*, vol. 49, pp. 1063-1064, 2013.

[2] A. M. H. Kwan, K. Y. Wong, X. Liu, and K. J. Chen, "High-gain and high-bandwidth AlGaN/GaN high electron mobility transistor comparator with high-temperature operation," *Japanese Journal of Applied Physics,* vol. 50, p. 04DF02, 2011.
[3] G. Moore, "Moore's law," *Electronics Magazine,* vol. 38, p. 114, 1965.
[4] M. A. Kastner, "The single-electron transistor," *Reviews of modern physics,* vol. 64, p. 849, 1992.
[5] K. Uchida, J. Koga, R. Ohba, and A. Toriumi, "Programmable single-electron transistor logic for future low-power intelligent LSI: proposal and room-temperature operation," *IEEE Transactions on Electron Devices,* vol. 50, pp. 1623-1630, 2003.
[6] A. Kumar and D. Dubey, "Single electron transistor: Applications and limitations," *Advance in Electronic and Electric Engineering,* vol. 3, pp. 57-62, 2013.
[7] D. Berman, N. B. Zhitenev, R. C. Ashoori, H. I. Smith, and M. R. Melloch, "Single-electron transistor as a charge sensor for semiconductor applications," *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena,* vol. 15, pp. 2844-2847, 1997.
[8] O. Kumar and M. Kaur, "Single electron transistor: Applications & problems," *Int J VLSI Des Commun Syst (VLSICS),* vol. 1, pp. 24-29, 2010.
[9] Y. Yan, J. Gong, J. Chen, Z. Zeng, W. Huang, K. Pu, *et al.*, "Recent advances on graphene quantum dots: from chemistry and physics to applications," *Advanced Materials,* vol. 31, p. 1808283, 2019.
[10] H. Grabert, "Dynamical Coulomb blockade of tunnel junctions driven by alternating voltages," *Physical Review B,* vol. 92, p. 245433, 2015.
[11] V. K. Hosseini, M. T. Ahmadi, S. Afrang, and R. Ismail, "Analysis and simulation of coulomb blockade and coulomb diamonds in fullerene single electron transistors," *Journal of nanoelectronics and optoelectronics,* vol. 13, pp. 138-143, 2018.
[12] S. Rani and S. Ray, "Detection of gas molecule using C3N island single electron transistor," *Carbon,* vol. 144, pp. 235-240, 2019.
[13] D. Razmadze, D. Sabonis, F. K. Malinowski, G. C. Ménard, S. Pauka, H. Nguyen, *et al.*, "Radio-frequency methods for Majorana-based quantum devices: fast charge sensing and phase-diagram mapping," *Physical Review Applied,* vol. 11, p. 064011, 2019.
[14] R. G. Knobel and A. N. Cleland, "Nanometre-scale displacement sensing using a single electron transistor," *Nature,* vol. 424, pp. 291-293, 2003.
[15] V. KhademHosseini, D. Dideban, M. T. Ahmadi, and R. Ismail, "An analytical approach to model capacitance and resistance of capped carbon nanotube single electron transistor," *AEU-International Journal of Electronics and Communications,* vol. 90, pp. 97-102, 2018.
[16] S.-l. Wu, "Single electron transistor memory array," ed: Google Patents, 2001.
[17] A.-M. Haider, "Design and Fabrication of A Carbone Nanotube Field Effect Transistor Based on Dielectrophoresis Technique and Low Cost Photolithography," *Journal of University of Babylon for Engineering Sciences,* vol. 26, pp. 20-27, 2018.
[18] H. Al-Mumen, "Characterisation of SU-8 n-doping carbon nanotube-based electronic devices," *Micro & Nano Letters,* vol. 10, pp. 670-673, 2015.
[19] C. Qiu, Z. Zhang, M. Xiao, Y. Yang, D. Zhong, and L.-M. Peng, "Scaling carbon nanotube complementary transistors to 5-nm gate lengths," *Science,* vol. 355, pp. 271-276, 2017.
[20] S. J. Pace, P. F. Man, A. P. Patil, and K. F. Tan, "CNT-based sensors: devices, processes and uses thereof," ed: Google Patents, 2014.
[21] S. Wang, M. H. Nai, and Z. Miao, "CNT devices, low-temperature fabrication of CNT and CNT photo-resists," ed: Google Patents, 2011.
[22] S. Mahapatra, V. Vaish, C. Wasshuber, K. Banerjee, and A. M. Ionescu, "Analytical modeling of single electron transistor for hybrid CMOS-SET analog IC design," *IEEE Transactions on Electron Devices,* vol. 51, pp. 1772-1782, 2004.
[23] B. Villis, A. Orlov, S. Barraud, M. Vinet, M. Sanquer, P. Fay, *et al.*, "Direct detection of a transport-blocking trap in a nanoscaled silicon single-electron transistor by radio-frequency reflectometry," *Applied Physics Letters,* vol. 104, p. 233503, 2014.
[24] J. Göres, D. Goldhaber-Gordon, S. Heemeyer, M. Kastner, H. Shtrikman, D. Mahalu, *et al.*, "Fano resonances in electronic transport through a single-electron transistor," *Physical Review B,* vol. 62, p. 2188, 2000.
[25] V. Khademhosseini, D. Dideban, M. Ahmadi, R. Ismail, and H. Heidari, "Single electron transistor scheme based on multiple quantum dot islands: carbon nanotube and fullerene," *ECS Journal of Solid State Science and Technology,* vol. 7, p. M145, 2018.
[26] V. Khademhosseini, D. Dideban, M. T. Ahmadi, and R. Ismail, "The impact of vacancy defects on the performance of a single-electron transistor with a carbon nanotube island," *Journal of Computational Electronics,* vol. 18, pp. 428-435, 2019.
[27] K. Ohkura, T. Kitade, and A. Nakajima, "Periodic Coulomb oscillations in Si single-electron transistor based on multiple islands," *Journal of Applied Physics,* vol. 98, p. 124503, 2005.
[28] A. Boubaker, M. Troudi, N. Sghaier, A. Souifi, N. Baboux, and A. Kalboussi, "Electrical characteristics and modelling of multi-island single-electron transistor using SIMON simulator," *Microelectronics journal,* vol. 40, pp. 543-546, 2009.
[29] M. S. Dresselhaus and P. T. Araujo, "Perspectives on the 2010 nobel prize in physics for graphene," ed: ACS Publications, 2010.
[30] H. Al-Mumen, L. Dong, and W. Li, "SU-8 doped and encapsulated n-type graphene nanomesh with high air stability," *Applied Physics Letters,* vol. 103, p. 232113, 2013.
[31] H. Al-Mumen and W. Li, "Complementary metal-SU8-graphene method for making integrated graphene nanocircuits," *Micro & Nano Letters,* vol. 13, pp. 465-468, 2018.

[32] I. Ovid'Ko, "Mechanical properties of graphene," *Rev. Adv. Mater. Sci*, vol. 34, pp. 1-11, 2013.
[33] D. G. Papageorgiou, I. A. Kinloch, and R. J. Young, "Mechanical properties of graphene and graphene-based nanocomposites," *Progress in Materials Science*, vol. 90, pp. 75-127, 2017.
[34] H. Al-Mumen, F. Rao, L. Dong, and W. Li, "Characterization of surface heat convection of bilayer graphene," in *2012 12th IEEE International Conference on Nanotechnology (IEEE-NANO)*, 2012, pp. 1-4.
[35] H. Al-Mumen, F. Rao, L. Dong, and W. Li, "Thermo-flow and temperature sensing behaviour of graphene based on surface heat convection," *Micro & Nano Letters,* vol. 8, pp. 681-685, 2013.
[36] X. Yu, Y. Li, X. Hu, D. Zhang, Y. Tao, Z. Liu, *et al.*, "Narrow bandgap oxide nanoparticles coupled with graphene for high performance mid-infrared photodetection," *Nature communications,* vol. 9, pp. 1-8, 2018.
[37] T. Deng, Z. Zhang, Y. Liu, Y. Wang, F. Su, S. Li, *et al.*, "Three-dimensional graphene field-effect transistors as high-performance photodetectors," *Nano letters,* vol. 19, pp. 1494-1503, 2019.
[38] S. Benítez-Martínez and M. Valcárcel, "Graphene quantum dots in analytical science," *TrAC Trends in Analytical Chemistry,* vol. 72, pp. 93-113, 2015.
[39] F. Rao, H. Almumen, L. Dong, and W. Li, "Highly sensitive bilayer structured graphene sensor," in *2011 16th International Solid-State Sensors, Actuators and Microsystems Conference*, 2011, pp. 2738-2741.
[40] H. Lim, J. Jung, R. S. Ruoff, and Y. Kim, "Structurally driven one-dimensional electron confinement in sub-5-nm graphene nanowrinkles," *Nature communications,* vol. 6, pp. 1-6, 2015.
[41] H. Al-Mumen, F. Rao, W. Li, and L. Dong, "Singular sheet etching of graphene with oxygen plasma," *Nano-Micro Letters,* vol. 6, pp. 116-124, 2014.
[42] Z. Jin, W. Sun, Y. Ke, C.-J. Shih, G. L. Paulus, Q. H. Wang, *et al.*, "Metallized DNA nanolithography for encoding and transferring spatial information for graphene patterning," *Nature communications,* vol. 4, pp. 1-9, 2013.
[43] L. Zhang, J. Liang, Y. Huang, Y. Ma, Y. Wang, and Y. Chen, "Size-controlled synthesis of graphene oxide sheets on a large scale using chemical exfoliation," *Carbon,* vol. 47, pp. 3365-3368, 2009.
[44] M. Mirzakhani, F. Peeters, and M. Zarenia, "Circular quantum dots in twisted bilayer graphene," *Physical Review B*, vol. 101, p. 075413, 2020.
[45] L.-J. Wang, G. Cao, T. Tu, H.-O. Li, C. Zhou, X.-J. Hao, *et al.*, "A graphene quantum dot with a single electron transistor as an integrated charge sensor," *Applied Physics Letters,* vol. 97, p. 262113, 2010.
[46] A. El Fatimy, R. L. Myers-Ward, A. K. Boyd, K. M. Daniels, D. K. Gaskill, and P. Barbara, "Epitaxial graphene quantum dots for high-performance terahertz bolometers," *Nature nanotechnology,* vol. 11, pp. 335-338, 2016.
[47] H. Kalita, V. S. Palaparthy, M. S. Baghini, and M. Aslam, "Graphene quantum dot soil moisture sensor," *Sensors and Actuators B: Chemical,* vol. 233, pp. 582-590, 2016.
[48] V. Khademhosseini, D. Dideban, M. Ahmadi, and R. Ismail, "Current analysis of single electron transistor based on graphene double quantum dots," *ECS Journal of Solid State Science and Technology,* vol. 9, p. 021003, 2020.
[49] A. B. Djurišić, X. Chen, Y. H. Leung, and A. M. C. Ng, "ZnO nanostructures: growth, properties and applications," *Journal of Materials Chemistry,* vol. 22, pp. 6526-6535, 2012.
[50] H. L-MUMEN, "Optoelectronic Properties of Dome-Shaped Substrate UV Detector with Optical Coating," *International Journal of Applied Engineering Research,* vol. 11, pp. 8916-8919, 2016.
[51] D.-Y. Son, J.-H. Im, H.-S. Kim, and N.-G. Park, "11% efficient perovskite solar cell based on ZnO nanorods: an effective charge collection system," *The Journal of Physical Chemistry C,* vol. 118, pp. 16567-16573, 2014.
[52] D. Sinar and G. K. Knopf, "Disposable piezoelectric vibration sensors with PDMS/ZnO transducers on printed graphene-cellulose electrodes," *Sensors and Actuators A: Physical,* vol. 302, p. 111800, 2020.
[53] S. Hosseini, I. A. Sarsari, P. Kameli, and H. Salamati, "Effect of Ag doping on structural, optical, and photocatalytic properties of ZnO nanoparticles," *Journal of Alloys and Compounds,* vol. 640, pp. 408-415, 2015.
[54] A. Khataee, A. Karimi, S. Arefi-Oskoui, R. D. C. Soltani, Y. Hanifehpour, B. Soltani, *et al.*, "Sonochemical synthesis of Pr-doped ZnO nanoparticles for sonocatalytic degradation of Acid Red 17," *Ultrasonics sonochemistry,* vol. 22, pp. 371-381, 2015.
[55] D. P. Norton, Y. Heo, M. Ivill, K. Ip, S. Pearton, M. F. Chisholm, *et al.*, "ZnO: growth, doping & processing," *Materials today,* vol. 7, pp. 34-40, 2004.
[56] J. Xiao-Fan, X. Zheng, C. Shuo, Q. Kang-Sheng, T. Jing, Z. Xi-Tian, *et al.*, "Single-ZnO-nanobelt-based single-electron transistors," *Chinese Physics Letters,* vol. 31, p. 067303, 2014.