

Single – electron transistor

D. Davelou*

**Department of Materials Science and Technology, University of Crete, Greece*

Abstract

Digital technology is continuously improving in terms of data reading speed and device size reduction. Until now the most common transistors have been the field – effect transistors (FETs) [1],[2] and specifically the metal-oxide semiconductor field – effect transistors (MOSFETs) [1],[2]. However, recent research has led to the creation of a more powerful tool, the single – electron transistor (SET)[3],[4],[5], which allows the devices to approach significantly small sizes, by taking under consideration quantum phenomena.

Operating principle of MOSFETs

The structure of the metal-oxide semiconductor field – effect transistors as shown in Figure 1.a, consists of three electrodes called source, drain and gate where the first two are attached to a semiconductor (channel) and the gate and the channel are interfered by a capacitor (insulating layer).

The operating principle is quite simple. When a voltage (V_g) is applied to the gate which communicates with the source, a current and a source-drain voltage (V_{ds}) are created in the channel directing the charge carriers from the source to the drain. [1],[2] Accordingly, as the gate voltage increases the current in the channel increases too. (Fig. 1.b,c,d).

The operation of MOSFETs can be described simply by classical mechanics, since the only factors that affect the current, are the density and the mobility of the conductive electrons. In this case the only quantum criteria we need to take under consideration refer to the physical properties of the semiconducting material. However, when the size of the transistor is reduced to a nanoscale, quantum pheno-

mena become of great importance, creating a need for a device with high energy sensitivity and single electron motion control.[1]

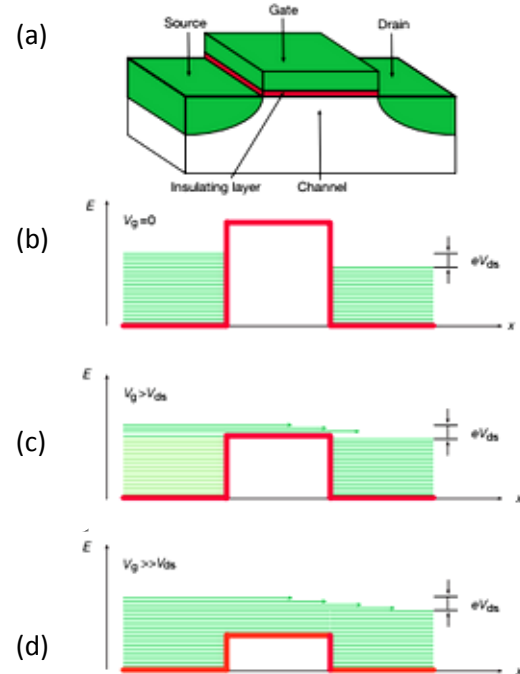


Figure 1. a. Schematical presentation of a MOSFET device's operating principle. **b,c and d** Representation of the increasing population of electrons that participate in the current due to gate voltage increase. (In this example we take the charge carriers to be electrons.) [1]

Introduction of the SETs

Similarly to MOSFETs the single - electron transistor requires a gate, a source, a drain, a semiconducting area in this case called the island and a capacitor between the last two. However, in SETs there are two extra insulating areas the tunnel junctions that interfere between the source and the island and the drain and the island. This leads to the basic difference between those two devices and at these tunnels the quantum phenomena that now take place, are observed.

While in MOSFETs the current is created by a population of electrons in SETs digital signal zero and one is created by discrete electrons that are able to overcome the energy barrier of the tunnel junctions. In order to overcome the conductance gap the energy difference is quantized and of the value of $e^2/2C$ creating a Coulomb staircase as opposed to MOSFET's characteristic curve, shown in Figures 2.b and 2.a respectively. The only case that a current can flow through the junction is when the initiative charge is $Q_0 = -(N+1/2)e$, which leads to degeneration of the states with N and $N+1$ electrons and the energy barriers disappear. However every time a single electron enters the tunnel junction the resistance of the tunnel increases dramatically forbidding other electrons to get through which produces the signal zero and one. [3],[4]

In order to achieve a functional single-electron transistor and a charge quantization, the Coulomb blockade must be taken into account. This meets three criteria. First of all the bias voltage must be low, $V_{bias} < e/C$, whereas the resistance of the tunnel must be great enough following the Heisenberg's uncertainty principle, and approximately $R > h/e^2$. Finally thermal

fluctuations must be avoided, hence the charge energy must be greater than thermal energy, $k_B T \ll U$ [3],[5],[6],[7].

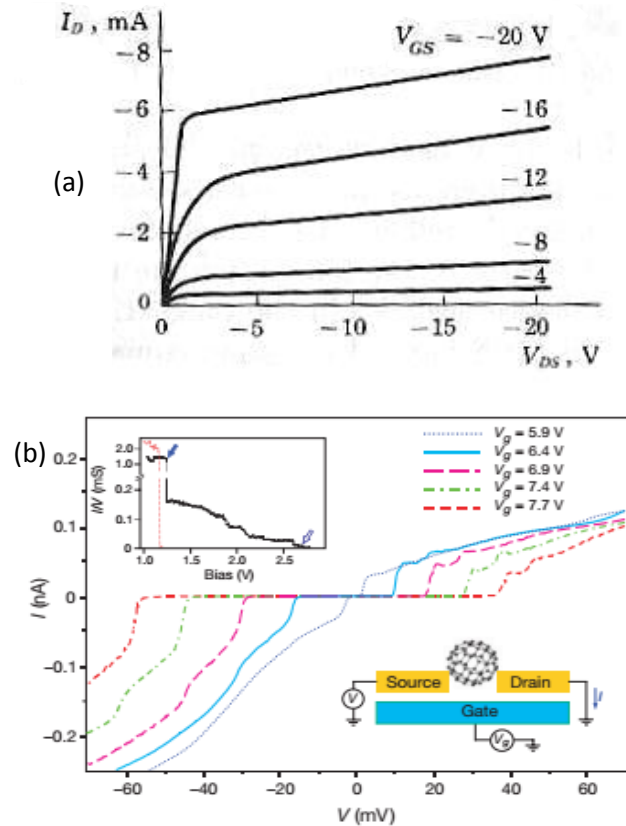


Figure 2.a. Typical I-V curve for an p-channel mosfet transistor.[2] **b.** I-V curve with step- like jumps for transfer of electrons through a quantum dot in single- C_{60} transistor.[5]

Limitations

Already the existence of thermal energy limitations has become obvious. For a conducting energy of the order of $\sim 100 k_B T$ to be achieved the islands' size must be reduced to sub-nanometer dimensions. Not only this will allow the quantum kinetic energy to affect the energy spectrum and the device signal, but the fabrication of an island of this size will most probably have defects. On the other hand the SET devices

must be integrated into larger devices such as MOSFETs, which contradicts the initiative need for the fabrication of smaller devices. Finally the rate of simultaneous tunneling of multiple electrons through different barriers, roughly differs from that of a single electron, making it difficult to control the process. [4]

Applications of SETs

Single – electron transistors find multiple applications, for example as various kinds of detectors. Since they are highly charge sensitive SETs can be used as electrometers in the measurement of extremely low currents. Another example is the ability to measure electron addition energies in quantum dots, by using the QD as the island of the SET (Fig.2.b) and applying very low bias (Single – electron spectroscopy). And their usage does not stop at these. Microwave or infrared radiation detection can be accomplished with single – electron transistors. [4]

Conclusion

With the continuous increase of the technology new systems have to be developed. Recent research has brought in the spotlight a highly sensitive to charge and energy device, the single – electron transistor, which is based on the single electron tunneling effect. Even though some problems have yet to be overcome in the fabrication of these transistors, they are very promising devices and they are about to find multiple applications in high technology systems.

References

- [1] Michel H. Devoret and Robert J. Schoelkopf 2000 *Nature* **406**, 1039-1046
- [2] J. Millman and Christos C. Halkias 1972 *Integrated Electronics* (McGraw-Hill Inc.) pp. 310 - 326
- [3] M.A. Kastner 2000 *ann. phys.* Vol.9 issue 11-12 pp.885-894
- [4] Anil Kumar and Dharmender Dubey 2013 *AEEE* Vol. 3 Num. 1 pp.57-62
- [5] Hongkun Park, Jiwoong Park, Andrew K. L. Lim, Erik H. Anderson, A. Paul Alivisatos and Paul L. McEuen 2000 *Nature* **407**, 57-60
- [6] http://en.wikipedia.org/wiki/Coulomb_blockade
- [7] Jiwoong Park, Abhay N. Pasupathy, Jonas I. Goldsmith, Connie Chang, Yuval Yaish, Jason R. Petta, Marie Rinkoski, James P. Sethna, Héctor D. Abruña, Paul L. McEuen and Daniel C. Ralph 2002 *Nature* **417**, 722-725