PROSPECTS OF NANOELECTRONICS FOR INFORMATION PROCESSING

Victor Borisenko

Belarusian State University of Informatics and Radioelectronics, Minsk, Belarus
borisenko@bsuir.by

Nanoelectronics is the field of science and engineering dealing with development, fabrication, study and application of nanosize electronic devices for information processing which operational principles are generally determined by quantum effects [1]. It originated from microelectronics in the end of the XX-th century as a result of the general trend to reduce the size of electronic devices in order to increase both packaging density of the elements in integrated circuits and their operational frequencies. Its theoretical and experimental background was formed by quantum mechanics, physics of solid state, material science and technology in the first part of that century. Nanotechnologies rapidly progressing in the XXI-th century provide an extended implementation of nanoelectronic devices for information processing.

This paper briefly reviews operational principles of main groups of recently developed nanoelectronic devices focusing to their applicability to information processing. The trends predicting by device and technology roadmaps [2,3] are accounted.

Three fundamental phenomena which are quantum confinement, tunneling and ballistic transport of charge carriers in solid state nanostructures form a principle background of nanoelectronics (Fig. 1). These phenomena are quantum in nature. Their manifestation is affected by the spin of charge carriers.

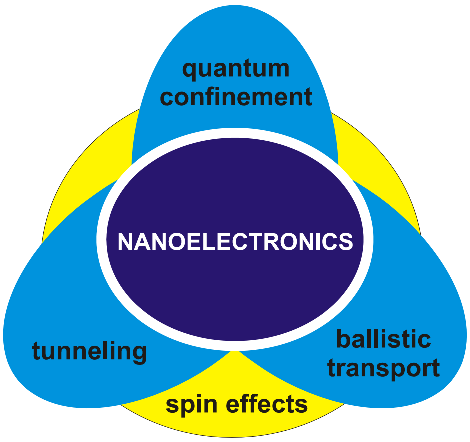

Fig. 1. Phenomenological background of nanoelectronics.

The quantum confinement appears as soon as a free motion of an electron at least along one direction occurs to be restricted by potential barriers forming boundaries of the nanostructure to which this electron belongs. As a result the nonzero lowest energy and quantization of the allowed energy levels in nanostructures arise to influence the charge carrier behaviour.

As for the transport of charge carriers, in principle it can occur parallel or perpendicular to potential barriers. In case of the motion parallel to the barriers, ballistic transport and quantum interference become to be dominating effects. In the perpendicular transport, carrier tunneling through potential barriers appears to be the main mechanism of the carrier motion from one region of a nanoelectronic device into another. The quantum nature of electrons and their confinement in nanostructures significantly influences the tunneling phenomena yielding their specific peculiarities in the form of single electron tunneling and resonant tunneling.

The transport phenomena are sensitive to the spin of charge carriers. It gives a possibility to use this characteristic of the carriers for information processing along with their charge. More details about the above mentioned phenomena and effects can be found in the recent textbooks [4-7].

As a consequence of an operational principle nanoelectronic devices can be distinguished within four main groups: ballistic transport and quantum interference devices, single-electron devices, resonant tunneling devices and spintronic devices.

Ballistic transport and quantum interference devices rely on the phase coherence of electron waves when traveling ballistically through a mesoscopic conduction channel. Controlling the interference condition (constructive or destructive) using the Aharonov-Bohm effect or gate controlled electron path allow to emulate transistor switching with unrivalled power/delay products in the operation frequency range extended to hundreds GHz . Meanwhile, in order to achieve ballistic transport and related effects in typical nanostructures, cooling to very low temperatures (to 77 K and lower) is required to suppress inelastic phonon scattering. For this reason, device concepts based on the ballistic transport and quantum interference remain mainly to be used only for special implementations.

Single-electron devices employ the Coulomb blockade effect mediating electron tunneling via small islands (quantum dots). Their operation conditions demand meeting the requirement $e^2/2C>>kT$, where e is the electron charge, C is the electric capacitance of the island, k is the Boltzmann constant, T is the absolute temperature. It supposes that the island capacitance has to be smaller than 10^{-17} F in order to provide room temperature operation. Thus, the islands should be of a few nanometers in size which can be currently fabricated with unique nanotechnologies. Moreover, the very nature of correlated single electron tunneling requires tunnel barriers around the islands to be higher than the quantum resistance (25 kOhm). It limits operation frequencies of such devices at the level of tens GHz.

The single-electron devices have been shown to be suitable for a large variety of analog and digital functions. These are single-electron charge trap, dynamic memory, electronic turnstile and generator, direct current and temperature standards, voltage and charge state logics. In the voltage state logic a bit is represented by the voltage of capacitor charged with many electrons. In the charge state logic in which a bit is represented by a single electron, typically implemented with single-electron manipulation/transfer devices. The merit of the charge state logic is that there is no static power dissipation. However, the high bit error rate requires unconventional circuit designs with fault-tolerant schemes, or novel applications such as stochastic information processing which use single electrons as physical random numbers.

The single-electron devices operate at rather low voltages with a very little gain. That makes them difficult to interconnect with the outer information processing environment. Therefore, the most practical strategy supposes their combination with conventional MOS-based (MOS – metal-oxyde-semiconductor) integrated circuits. Such examples include hybrid multi-value logic circuits and reconfigurable logic circuits, multiband filtering circuits, analog pattern matching circuits.

Resonant tunneling devices are based on the tunneling phenomenon exhibiting specific features when it occurs in nanostructures consisting of periodically arranged potential barriers separated by quantum wells. The simplest example of such device is a double-barrier structure that is a quantum well formed between two potential barriers with electric contacts to the barriers. It has N-type current-voltage characteristics with a well resolved region of negative differential resistance.

The resonant tunneling devices offer promises for very high frequency current sources as well as for compact memory/logic cells due to its multistability. Another asset of these device is its potential to operate at room temperature without the need for nanoscale patterning. The time constant of the devices of the order of 10-20 ps provides their operation frequencies as high as hundreds GHz.

An ultrahigh-speed functional logic gate called monostable-bistable transition logic element (MOBILE) has been developed to exploit the negative differential resistance of resonant tunneling devices. Its operating principle includes: i) to employ the monostable-to-bistable transition of a circuit consisting of two negative differential resistance devices connected serially, ii) to supply one (or both) the negative differential resistance device(s) with the third terminal to modulate its (their) peak current(s), ii) to drive this circuit by oscillating the bias voltage to produce the transition. Various extensions of the MOBILE concept were also proposed. A multiple valued logic cell consisting of three or more resonant tunneling structures connected serially is one of them. This device can handle multiple valued logic. This idea was successfully applied to the flash-type AD converter using multiple valued quantizer. Optical input-electrical output MOBILEs were designed for high speed optical communications demonstrated operating bit rates up to 80 Gb/s.

In general, a combination of resonant tunneling devices with classical bipolar and MOS transistors within integrated circuits looks to be the most promising concept of their practical applications.

Spintronic devices represent a fast developing group of electronic devices, in which electron spin as well as the electron charge are used for information processing.

There is a variety of spin transistors which output is controlled via electron spins and magnetization of particular regions of the devices. The developed spin transistors (spin field-effect transistor, transit time spin transistor, spin-valve transistor, magnetic tunneling transistor) are currently off vide practical applications mainly due to rather complex technology and poor compatibility with other elements of integrated circuits.

In contrast, discrete and integral devices implementing the giant magnetoresistance effect and tunneling magnetoresistance effect are widely used. Among them magnetic sensors and magnetic reading head, giant and tunneling magnetoresistance random access memory (MRAM) cells can be mentioned in the short list. They are characterized by high sensitivity to external and internal magnetic fields and response times in the picosecond range. Their based MRAM integrated circuits have writing and reading times in the range of 5-50 ns which is 1.5-3 time faster than in other types of RAMs. The storage time is infinitely long. Moreover, they possess radiation hardness much better than their competitors.

In conclusion, nanoelectronic devices represent new promising paradigm in information processing technology. Practical realization of their advantages supposes these devices to be introduced in the well developed bipolar and MOS integrated circuits and systems.

References

1. V. E. Borisenko, S. Ossicini. What is What in the Nanoworld. Second, Completely Revised and Enlarged Edition. Wiley-VCH, Weinheim (2008).
2. The International Technology Roadmap for Semiconductors, 2009 Edition, Emerging Research Devices.
3. IEEE Nanoelectronics Standards Roadmap. VERSION 1.0 (2007).
4. V. E. Borisebko, A. I. Vorobieva, E. A. Utkina. Nanoelectronics. (In Russian) Binom, Moscow (2009).
5. E. L. Wolf. Quantum Nanoelectronics. An Introduction to Electronic Nanotechnology and Quantum Computing. Wiley-VCH, Weinheim (2009).
6. S. Bandyopadhyay, M. Cahay. Introduction to Spintronics. CRC, Broken Sound Parkway (2008).
7. J. H. Davies. The Physics of Low-Dimensional Semiconductors: An Introduction. Cambridge University Press, Cambridge (1998).