Invited paper

History of Semiconductors

Lidia Łukasiak and Andrzej Jakubowski

Abstract—The history of semiconductors is presented beginning with the first documented observation of a semiconductor effect (Faraday), through the development of the first devices (point-contact rectifiers and transistors, early field-effect transistors) and the theory of semiconductors up to the contemporary devices (SOI and multigate devices).

Keywords—band theory, laser, Moore's law, semiconductor, transistor.

1. Introduction

There is no doubt that semiconductors changed the world beyond anything that could have been imagined before them. Although people have probably always needed to communicate and process data, it is thanks to the semiconductors that these two important tasks have become easy and take up infinitely less time than, e.g., at the time of vacuum tubes.

The history of semiconductors is long and complicated. Obviously, one cannot expect it to fit one short paper. Given this limitation the authors concentrated on the facts they considered the most important and this choice is never fully impartial. Therefore, we apologize in advance to all those Readers who will find that some vital moments of the semiconductor history are missing in this paper.

The rest of this paper is organized in four sections devoted to early history of semiconductors, theory of their operation, the actual devices and a short summary.

2. Early History of Semiconductors

According to G. Busch [1] the term "semiconducting" was used for the first time by Alessandro Volta in 1782. The first documented observation of a semiconductor effect is that of Michael Faraday (1833), who noticed that the resistance of silver sulfide decreased with temperature, which was different than the dependence observed in metals [2]. An extensive quantitative analysis of the temperature dependence of the electrical conductivity of Ag_2S and Cu_2S was published in 1851 by Johann Hittorf [1].

For some years to come the history of semiconductors focused around two important properties, i.e., rectification of metal-semiconductor junction and sensitivity of semiconductors to light and is briefly described in Subsections 2.1 and 2.2.

2.1. Rectification

In 1874 Karl Ferdinand Braun observed conduction and rectification in metal sulfides probed with a metal point (whisker) [3]. Although Braun's discovery was not immediately appreciated, later it played a significant role in the development of the radio and detection of microwave radiation in WWII radar systems [4] (in 1909 Braun shared a Nobel Prize in physics with Marconi). In 1874 rectification was observed by Arthur Schuster in a circuit made of copper wires bound by screws [4]. Schuster noticed that the effect appeared only after the circuit was not used for some time. As soon as he cleaned the ends of the wires (that is removed copper oxide), the rectification was gone. In this way he discovered copper oxide as a new semiconductor [5]. In 1929 Walter Schottky experimentally confirmed the presence of a barrier in a metal-semiconductor junction [5].

2.2. Photoconductivity and Photovoltaics

In 1839 Alexander Edmund Becquerel (the father of a great scientist Henri Becquerel) discovered the photovoltaic effect at a junction between a semiconductor and an electrolyte [6]. The photoconductivity in solids was discovered by Willoughby Smith in 1873 during his work on submarine cable testing that required reliable resistors with high resistance [7]. Smith experimented with selenium resistors and observed that light caused a dramatic decrease of their resistance. Adams and Day were the first to discover the photovoltaic effect in a solid material (1876). They noticed that the presence of light could change the direction of the current flowing through the selenium connected to a battery [8]. The first working solar cell was constructed by Charles Fritts in 1883. It consisted of a metal plate and a thin layer of selenium covered with a very thin layer of gold [8]. The efficiency of this cell was below 1% [9].

3. Theory

In 1878 Edwin Herbert Hall discovered that charge carriers in solids are deflected in magnetic field (Hall effect). This phenomenon was later used to study the properties of semiconductors [10]. Shortly after the discovery of the electron by J. J. Thomson several scientists proposed theories of electron-based conduction in metals. The theory of Eduard Riecke (1899) is particularly interesting, because he assumed the presence of both negative and positive charge carriers with different concentrations and mobilities [1]. Around 1908 Karl Baedeker observed the dependence of the conductivity of copper iodide on the stoichiometry (iodine content). He also measured the Hall effect in this material, which indicated carriers with positive charge [1]. In 1914 Johan Koenigsberger divided solid-state materials into three groups with respected to their conductivity: metals, insulators and "variable conductors" [1]. In 1928 Ferdinand Bloch developed the theory of electrons in lattices [10]. In 1930 Bernhard Gudden reported that the observed properties of semiconductors were due exclusively to the presence of impurities and that chemically pure semiconductor did not exist [1].

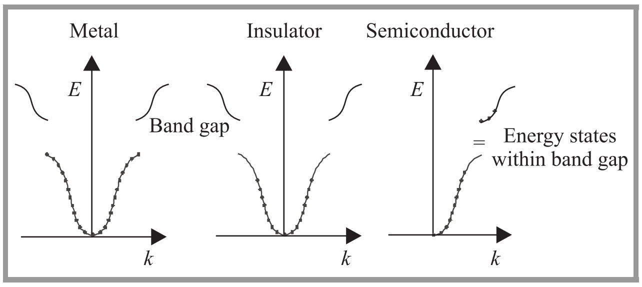


Fig. 1. Alan Wilson's theory of bands in solids.

In 1930 Rudolf Peierls presented the concept of forbidden gaps that was applied to realistic solids by Brillouin the same year. Also in 1930 Kronig and Penney developed a simple, analytical model of periodic potential. In 1931 Alan Wilson developed the band theory of solids based on the idea of empty and filled energy bands (Fig. 1). Wilson also confirmed that the conductivity of semiconductors was due to impurities [10]. In the same year Heisenberg developed the concept of hole (which was implicit in the works of Rudolf Peierls [10]). In 1938 Walter Schottky and Neville F. Mott (Nobel Prize in 1977) independently developed models of the potential barrier and current flow through a metal-semiconductor junction. A year later Schottky improved his model including the presence of space charge. In 1938 Boris Davydov presented a theory of a copper-oxide rectifier including the presence of a p-n junction in the oxide, excess carriers and recombination. He also understood the importance of surface states [11]. In 1942 Hans Bethe developed the theory of thermionic emission (Nobel Prize in 1967).

4. Devices

4.1. Point-Contact Rectifiers

In 1904 J. C. Bose obtained a patent for PbS point-contact rectifiers [12]. G. Pickard was the first to show that silicon point-contact rectifiers were useful in detection of radio waves (patent in 1906) [10]. The selenium and copper oxide rectifiers were developed, respectively, in 1925 by E. Presser and 1926 by L. O. Grondahl [10]. The selenium rectifiers were heavily used in the WWII in military communications and radar equipment [10].

4.2. The p-n Junction

During his work on the detection of radio waves Russel Ohl realized that the problems with cat's whisker detectors were caused by bad quality of the semiconductor. Therefore he melted the silicon in quartz tubes and then let it cool down. The obtained material was still polycrystalline but the electrical tests demonstrated that the properties were much more uniform. Ohl identified the impurities that created the p-n junction that he accidentally obtained during his technological experiments. He held four patents on silicon detectors and p-n junction [13].

4.3. Bipolar Transistor

In 1945 William Shockley put forward a concept of a semiconductor amplifier operating by means of the field-effect principle. The idea was that the application of a transverse electric field would change the conductance of a semiconductor layer. Unfortunately this effect was not observed experimentally. John Bardeen thought that this was due to surface states screening the bulk of the material from the field (Fig. 2). His surface-theory was published in 1947 [14].

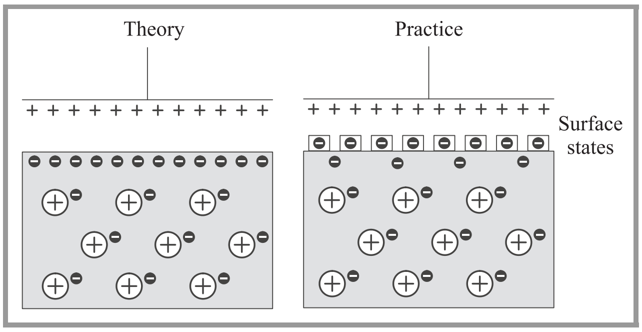


Fig. 2. The idea of surface states.

While working on the field-effect devices, in December 1947 John Bardeen and Walter Brattain built a germanium point-contact transistor (Fig. 3) and demonstrated that this device exhibited a power gain. There was, however, an uncertainty concerning the mechanism responsible for the transistor action [13]. Bardeen and Brattain were convinced that surface-related phenomena had the dominant role in the operation of the new device while Shockley favoured bulk conduction of minority carriers. About one month later he developed a theory of a p-n junction and a junction transistor [15]. Shockley, Bardeen and Brattain received the Nobel Prize in physics in 1956 (John Bardeen received another one in 1972 for his theory of superconductivity). In February 1948 John Shive demonstrated a correctly operating point-contact transistor with the emitter and collector placed on the opposite sides of a very thin slice of germanium (0.01 cm). This configuration indicated that the conduction was indeed taking place in the bulk, not along the surface (the distance between the emitter and collector along the surface would be much longer) [15]. It was only then that Shockley presented his theory of transistor operation to the coworkers [15], [16].
It is worth remembering that the crucial properties of semiconductors at the time were "structure sensitive"

(as Bardeen put it in [14]), that is they were strongly dependent on the purity of the sample. The semiconductor material with which Bardeen and Brattain worked was prepared using a technique developed by Gordon K. Teal and John B. Little based on the Czochralski method. The crystal was then purified using the zone refining method proposed by William G. Pfann [11].

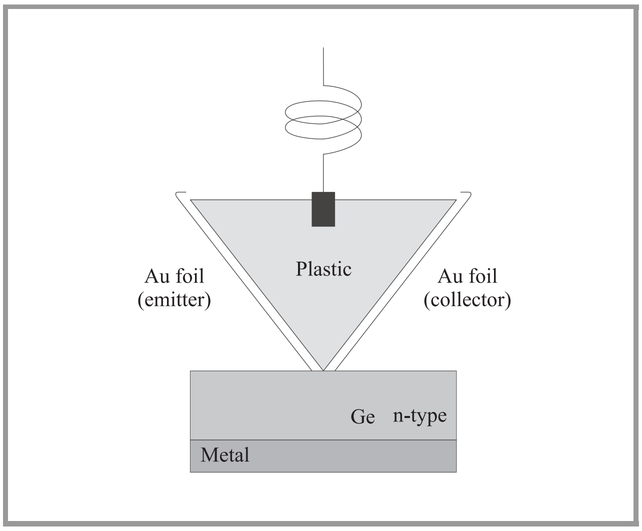


Fig. 3. The first point-contact transistor [16].

Point-contact transistors were the first to be produced, but they were extremely unstable and the electrical characteristics were hard to control. The first grown junction transistors were manufactured in 1952. They were much better when compared to their point-contact predecessor, but the production was much more difficult. As a result of a complicated doping procedure the grown crystal consisted of three regions forming an n-p-n structure. It had to be cut into individual devices and contacts had to be made. The process was difficult and could not be automated easily. Moreover, a lot of semiconductor material was wasted. In 1952 alloyed junction transistor was reported (two pellets of indium were alloyed on the opposite sides of a slice of silicon). Its production was simpler and less material-consuming and could be automated at least partially. The obtained base width was around 10 μm, which let the device operate up to a few MHz only. The first diffused Ge transistor (diffusion was used to form the base region, while the emitter was alloyed) with a characteristic "mesa" shape was reported in 1954. The base width was 1 μm and the cut-off frequency 500 MHz. It was generally understood that for most applications silicon transistors would be better than germanium ones due to lower reverse currents. The first commercially available silicon devices (grown junction) were manufactured in 1954 by Gordon Teal. The first diffused Si transistor appeared in 1955. To reduce the resistivity of the collector that limited the operation speed without lowering the breakdown voltage too much John Early thought of a collector consisting of two layers, i.e., high-resistivity one on top of a highly doped one. A transistor with epitaxial layer added was reported in 1960. In the same year Jean Hoerni proposed the planar transistor (both base and emitter regions diffused). The oxide that served as a mask was not removed and acted as a passivating layer [15].

Further improvement of speed was proposed by Herbert Kroemer. A built-in electric field could be introduced into the base by means of graded doping. Another way of introducing the electric field in the base he thought of was grading the composition of the semiconductor material itself, which resulted in graded band gap. This heterostructure concept could not be put to practice easily because of fabrication problems [17].

4.4. Integrated Circuit

The transistor was much more reliable, worked faster and generated less heat when compared to the vacuum tubes [18]. Thus it was anticipated that large systems could be built using these devices. The distance between them had, however, to be as short as possible to minimize delays caused by interconnects. In 1958 Jack Kilby demonstrated the first integrated circuit where several devices were fabricated in one silicon substrate and connected by means of wire bonding. Kilby realized that this would be a disadvantage therefore in his patent he proposed formation of interconnects by means of deposition of aluminum on a layer of SiO_2 covering the semiconductor material [15]. This has been achieved independently by Robert Noyce in 1959. In 2000 Jack Kilby received a Noble Prize in physics for his achievements.

4.5. Tunnel Diode

Leo Esaki studied heavily doped junctions to find out how high the base of a bipolar transistor could be doped before the injection at the emitter junction became inadequate. He was aware that in very narrow junctions tunneling could take place. He obtained the first Ge tunneling diode in 1957 and a silicon one in 1958. Esaki's presentation at the *International Conference of Solid State Physics in Electrons and Telecommunications* in 1958 was highly appreciated by Shockley [19]. Unfortunately, Shockley exhibited a complete lack of interest when Robert Noyce came to him to present his idea of a tunnel diode two years earlier. As a result Noyce moved to other projects [20]. The tunnel diode was extremely resistant to the environmental conditions due to the fact that conduction was not based on minority carriers or thermal effects. Moreover, its switching times were much shorter than those of the transistor. Leo Esaki received a Nobel Prize in physics in 1973 for his work on tunneling and superlattices [21], [22].

4.6. Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)

In 1930 and 1933 Julius Lilienfeld obtained patents for devices resembling today's MESFET and MOSFET, respectively. In 1934 Oskar Heil applied for a patent for his theoretical work on capacitive control in field-effect transistors [3].

The first bipolar transistors were quite unreliable because semiconductor surface was not properly passivated. A group directed by M. M. Atalla worked on this problem and found out that a layer of silicon dioxide could be the answer [23]. During the course of this work a new concept of a field-effect transistor was developed and the actual device manufactured [24]. Unfortunately, the device could not match the performance of bipolar transistors at the time and was largely forgotten [15]. Several years before Bell Laboratories demonstrated an MOS transistor Paul Weimer and Torkel Wallmark of RCA did work on such devices. Weimer made transistors of cadmium sulfide and cadmium selenide [11]. In 1963 Steven Hofstein and Fredric Heiman published a paper on a silicon MOSFET [25] (Fig. 4). In the same year the first CMOS circuit was proposed by Frank Wanlass [26]. In 1970 Willard Boyle and George Smith presented the concept of charge-coupled devices (CCD) – a semiconductor equivalent of magnetic bubbles [27]. Both scientists received a Nobel Prize in physics in 2009 for their work on CCD.

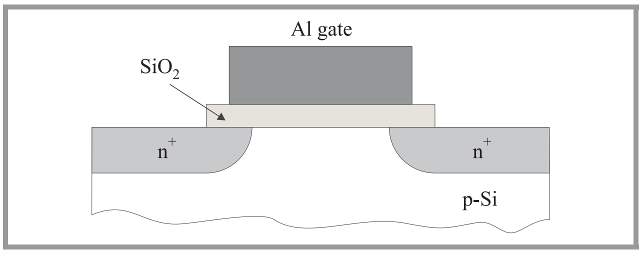


Fig. 4. A cross section of a metal-oxide-semiconductor transistor.

Early MOSFETs had aluminum gate. Development of a poly-Si gate [28] led to a self-aligned device, where the gate itself constitutes the mask for source and drain diffusion. In this way parasitic gate-to-source and gate-to-drain capacitances associated with gate overlap could be controlled. Since polysilicon had relatively high resistance, gates made of silicides of refractory metals were proposed (e.g., [29], [30]).

Reduction of the size of the device led to the so-called short-channel effects (SCE) including threshold voltage roll-off and drain-induced barrier lowering. The ways to cope with this problem include a reduction of the depth of source and drain [31] combined with efforts to avoid increased resistance (e.g., lightly doped drain [32], elevated source/drain (S/D) [33] or possibly Schottky barrier S/D [34]). Threshold voltage and punchthrough are controlled by means of the appropriate doping profile of the channel that makes it possible to maintain relatively good surface mobility (e.g., [35]). Short-channel effects are considerably reduced when gate oxide is thin. As a result of decreased thickness, gate leakage current obviously grows, increasing power consumption of the entire chip, which is an undesirable effect for battery-powered mobile systems. It is estimated that gate leakage current increases approximately 30 times every technology generation, as opposed to 3–5 times increase of channel leakage current [36]. Apart from leakage current, the reduction of gate-oxide thickness increases the susceptibility of the device to boron penetration from the poly-Si gate into the channel. A number of different high-*k* materials are extensively investigated.

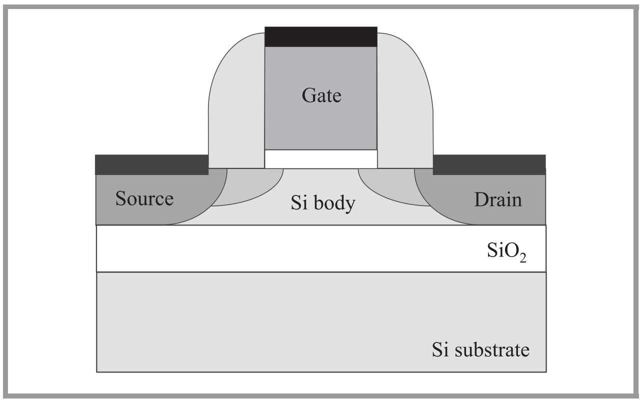


Fig. 5. A cross section of a SOI MOSFET.

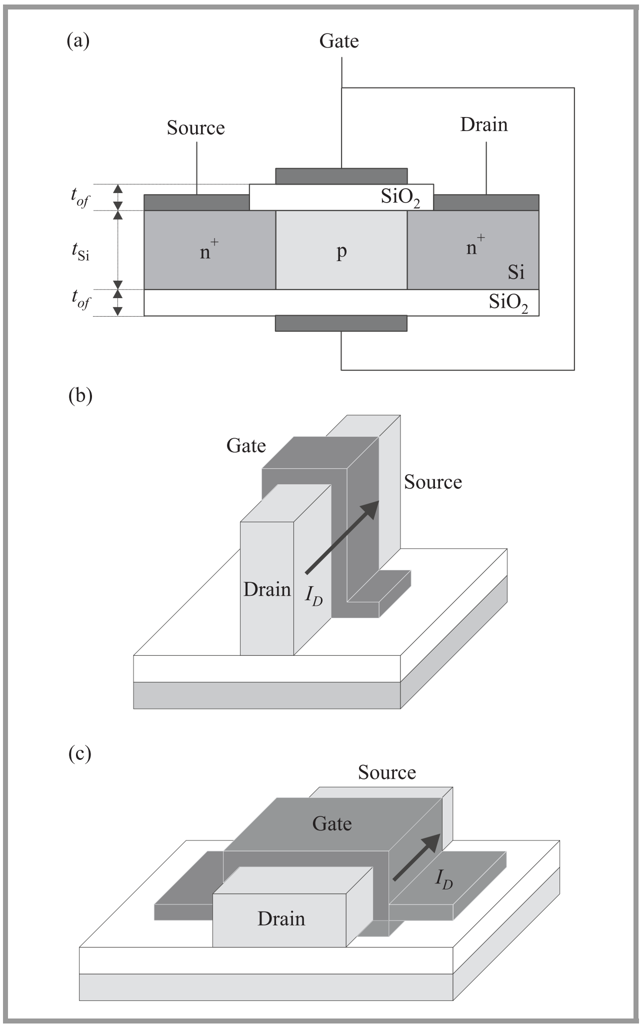


Fig. 6. Mutigate transistors: (a) double gate; (b) FinFET; (c) surrounding gate.

An interesting extension of the classical bulk MOSFET is silicon-on-insulator (SOI) – see Fig. 5 [37]. The advantage of SOI is the ease of electrical isolation of a device from the rest of the integrated circuit, which increases packing density. Moreover, the area of source and drain junctions is significantly reduced, thus decreasing parasitic capacitances. Finally, the depletion width is limited by the Si body thickness, therefore it is widely believed that SOI helps reduce short channel effects unless source-to-drain coupling through channel and BOX cannot be neglected. The properties of SOI devices are improved with the reduction of body thickness. It is believed that fully depleted ultra-thin-body SOI (FD UTB SOI) is one of the best scaling solutions. Due to excellent gate control of the channel these devices may be undoped or very lightly doped. In this way mobility is not degraded and threshold voltage is less dependent on the fluctuations of doping concentration [38]. Another advantage of SOI is that it facilitates development of new device concepts [39] (Fig. 6), but this is another story.

4.7. Semiconductor Lasers

Semiconductors are widely used for emission and detection of radiation. The first report on light emitted by a semiconductor appeared in 1907 in a note by H. J. Round. Fundamental work in this area was conducted, among other, by Losev. A very interesting description of the development of light-emitting diodes may be found in [40] while the history of photovoltaics is discussed in [8]. In this section only semiconductor lasers are mentioned briefly.

The first semiconductor lasers were developed around 1962 by four American research teams [41]. Further research in this area went in two directions, i.e., wider spectrum of materials to obtain wider wavelength range and concepts of new device structures. Herbert Kroemer and Zhores Alferov have independently come up with the idea that semiconductor lasers should be built on heterostructures. Zhores Alferov was a member of the team that created the first Soviet p-n junction transistor in 1953. He was directly involved in research aimed at development of specialized semiconductor devices for Russian nuclear submarines. The matter was of such importance for the Soviet authorities that he used to receive phone calls from very high government officials who wanted the work done faster. To fulfill those requests Alferov had to move to the lab and literally live there [42]. Later he worked on power devices and became familiar with p-i-n and p-n-n structures. When the first report on semiconductor lasers appeared, he realized that double heterostructures of the p-i-n type should be used in these devices [41]. He obtained the first practical heterostructure devices and the first heterostructure laser [42]. In 2000 Alferov and Kroemer (mentioned in Subsection 4.4) received a Nobel Prize in physics for their achievements in the area of semiconductor heterostructures used in high-speed- and optoelectronics.

Significant progress in semiconductor lasers is associated, among other, with the use of quantum wells and new materials, especially gallium nitride.

5. Summary

Silicon may be considered as the information carrier of our times. In the history of information there were two revolutions (approximately 500 years apart). The first was that of Johan Gutenberg who made information available to many, the other is the invention of the transistor. Currently the global amount of information doubles every year. Many things we are taking for granted (such as, e.g., computers, Internet and mobile phones) would not be possible without silicon microelectronics. Electronic circuits are also present in cars, home appliances, machinery, etc. Optoelectronic devices are equally important in everyday life, e.g., fiber-optic communications for data transfer, data storage (CD and DVD recorders), digital cameras, etc.

Since the beginning of semiconductor electronics the number of transistors in an integrated circuit has been increasing exponentially with time. This trend had been first noticed by Gordon Moore [43] and is called Moore's law. This law is illustrated in Fig. 7, where the number of transistors in successive Intel processors is plotted as a function of time (data after [44]).

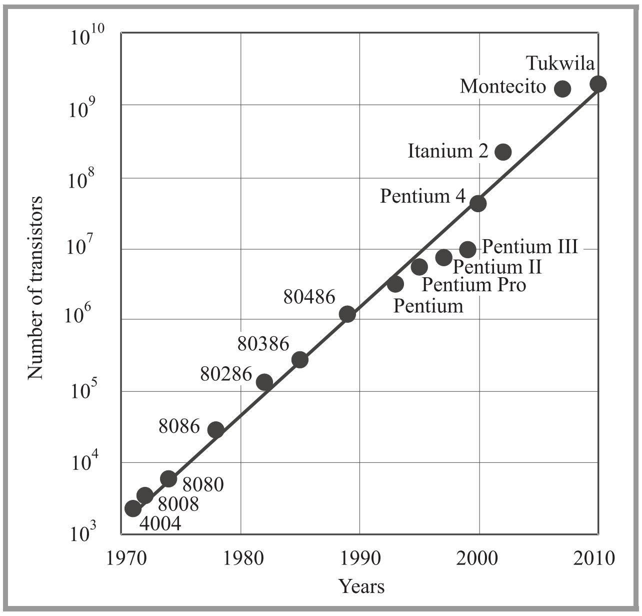


Fig. 7. Number of transistors in successive Intel processors as a function of time (data after [44]).

Even though the bipolar technology was largely replaced by CMOS (more than 90 percent of integrated circuits are manufactured in CMOS technology), Moore's law is still true in many aspects of the development trends of silicon microelectronics (obviously, with the appropriate time constant). The MOS transistor has been improved countless times but above everything else it has been miniaturized

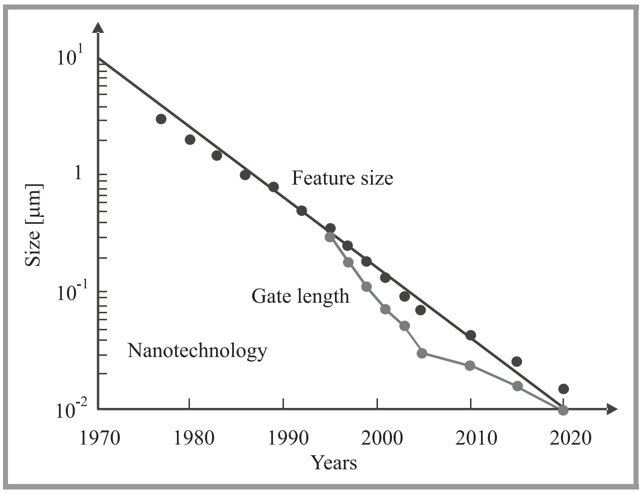


Fig. 8. Feature size as a function of time (data after [45]).

beyond imagination. The reduction of the feature size, presented in Fig. 8, is more or less exponential. The number of transistors produced per year and the average price are shown as a function of time in Fig. 9 (again the change is exponential). It is being anticipated that in 2010 approximately one billion transistors will be produced for every person living on the Earth.

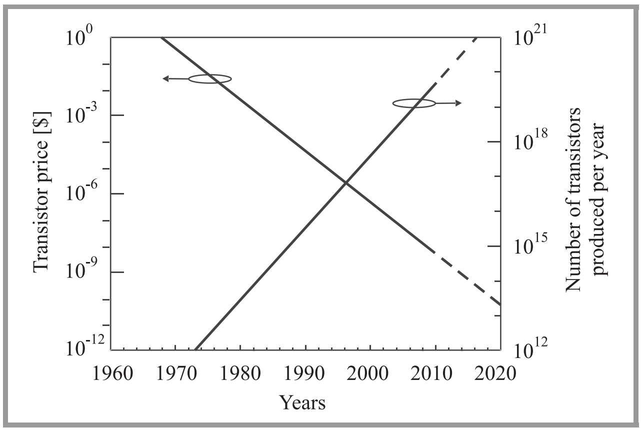


Fig. 9. Number of transistors produced per year and transistor price as a function of time (data after [46]).

We are pretty sure the future still holds a few surprises. Extensive research is being carried out on graphene, organic electronics, quantum devices, microsystems, integration of silicon with other materials and many other issues, but that is another story…

References

[1] G. Busch, "Early history of the physics and chemistry of semiconductors – from doubts to fact in a hundred years", *Eur. J. Phys.*, vol. 10, no. 4, pp. 254–263, 1989.

[2] F. Laeri, F. Schüth, U. Simon, and M. Wark, *Host-Guest-Systems Based on Nanoporous Crystals*. Weinheim: Wiley, 2003, pp. 435–436.

[3] T. K. Sarkar, R. Mailloux, A. A. Oliner, M. Salazar-Palma, and D. L. Sengupta, *The History of Wireless*. Hoboken: Wiley, 2006.

[4] J. Orton, *Semiconductors and the Information Revolution: Magic Crystals that Made IT Happen*. Amsterdam: Academic Press/Elsevier, 2009, pp. 35–36

[5] W. Mönch, *Semiconductor Surfaces and Interfaces*. Berlin-Heidelberg: Springer, 2001.

[6] Z. A. Smith and K. D. Taylor, *Renewable and Alternative Energy Sources: A Reference Handbook*. Santa Barbara: ABC-CLIO Inc., 2008, p. 157.

[7] J. Orton, *The Story of Semiconductors*. Oxford: Oxford University Press, 2004, p. 359.

[8] J. Perlin, *From Space to Earth: The Story of Solar Electricity*. Cambridge: Harvard University Press, 2002, p. 17.

[9] M. Grundman, *The Physics of Semiconductors*. Berlin-Heidelberg: Springer, 2006.

[10] L. Hoddeson, E. Braun, J. Teichmann, and S. Weart, *Out of the Crystal Maze: Chapters in the History of Solid State Physics.* New York: Oxford University Press, 1992.

[11] B. Lojek, *History of Semiconductor Engineering.* Berlin-Heidelberg: Springer, 2007.

[12] P. K. Bondyopathyay, "Sir J. C. Bose's diode detector received Marconi's first transatlantic wireless signal of December 1901 (the "Italian navy coherer" scandal revisited)", *Proc. IEEE*, vol. 86, no. 1, pp. 259–285, 1998.

[13] M. Riordan and L. Hoddeson, "The origins of the p-n junction", *IEEE Spectrum*, vol. 34, no. 6, p. 46, 1997.

[14] J. Bardeen, "Solid state physics – 1947", *Solid State Technol.*, vol. 30, no. 12, pp. 69–71, 1987.

[15] I. M. Ross, "The invention of the transistor", *Proc. IEEE*, vol. 86, no. 1, pp. 7–27, 1998.

[16] M. Riordan, L. Hoddeson, and C. Herring, "The invention of the transistor", *Rev. Mod. Phys.*, vol. 71, no. 2, pp. S336–S345, 1999.

[17] T. S. Perry, "Not just blue sky", *IEEE Spectrum*, vol. 39, no. 6, pp. 33–37, 2002.

[18] J. A. Armstrong, "Solid state technology and the computer: 40 years later small is still beautiful", *Solid State Technol.*, vol. 30, no. 12, pp. 81–83, 1987.

[19] L. Esaki, "Discovery of the tunnel diode", *IEEE Trans. Electron Dev.*, vol. 23, no. 7, pp. 644–647, 1976.

[20] L. Berlin and H. Casey, Jr., "Robert Noyce and the tunnel diode", *IEEE Spectrum*, vol. 42, no. 5, pp. 49–53, 2005.

[21] L. Esaki and R. Tsu, "Superlattice and negative conductivity in semiconductors", IBM Res. Note, RC-2418, March 1969.

[22] L. Esaki and R. Tsu, "Superlattice and negative differential conductivity in semiconductors", *IBM J. Res. Develop.*, vol. 14, pp. 61–65, Jan. 1970.

[23] M. M. Atalla, E. Tannenbaum, and E. J. Scheibner, "Stabilization of silicon surfaces by thermally grown oxides", *Bell. Syst. Tech. J.*, vol. 38, no. 3, pp. 749–783, 1959.

[24] D. Kahng and M. M. Atalla, "Silicon-silicon dioxide field induced surface devices", in *Solid State Res. Conf.*, Pittsburgh, USA, 1960.

[25] S. R. Hofstein and F. P. Heiman, "Silicon insulated-gate field-effect transistor", *Proc. IEEE*, vol. 51, no. 9, pp. 1190–1202, 1963.

[26] F. M. Wanlass and C. T. Sah, "Nanowatt logic using field-effect metal-oxide semiconductor triodes", in *Proc. Techn. Dig. IEEE 1963, Int. Solid-State Circ. Conf.*, Philadelphia, USA, 1963, pp. 32–33.

[27] W. S. Boyle and G. E. Smith, "The inception of charge-coupled devices", *IEEE Trans. Electron Dev.*, vol. 23, no. 7, pp. 661–663, 1976.

[28] R. E Kerwin, D. L. Klein, and J. C. Sarace, "Method for making MIS structures", US Patent 3 475 234, filed March 27, 1967, issued Oct. 28, 1969.

[29] T. Mochizuki, K. Shibata, T. Inoue, K. Obuchi, and M. Kashiwogi, "A new gate material for MOS devices – molybdenum silicide ($MoSi_2$)", in *Proc. ECS Conf.*, Atlanta, USA, 1977, vol. 72–2, pp. 331–332.

[30] K. C. Saraswat, F. Mohammedi, and J. D. Meindl, "WSi_2 gate MOS devices", in *Proc. IEDM Tech. Dig.*, Washington, USA, 1979, pp. 462–464.

[31] J. R. Brews, W. Fichtner, E. H. Nicollian, and S. N. Sze, "Generalized guide for MOSFET miniaturization", *IEEE Electron Dev. Lett.*, vol. 1, no. 1, pp. 2–4, 1980.

[32] W. R. Hunter, T. C. Holloway, P. K. Chatterjee, and A. F. Tasch, "New edge-defined vertical-etch approaches for submicrometer MOSFET fabrication", in *Proc. IEDM Tech. Dig.*, Washington, USA, 1980, pp. 764–767.

[33] S. S. Wong, D. R. Bradbury, D. C. Chen, and K. Y. Chiu, "Elevated source/drain MOSFET", in *Proc. IEDM Tech. Dig.*, San Francisco, USA, 1984, pp. 634–637.

[34] T. Mochizuki and K. D. Wise, "An n-channel MOSFET with Schottky source and drain", *IEEE Electron Dev. Lett.*, vol. 5, no. 4, pp. 108–110, 1984.

[35] H. Tian, R. B. Hulfachor, J. J. Ellis-Monaghan, K. W. Kim, M. A. Littlejohn, J. R. Hauser, and N. A. Masnari, "An evaluation of super-steep-retrograde channel doping for deep-submicron MOSFT applications", *IEEE Trans. Electron Dev.*, vol. 41, no. 10, pp. 1880–1882, 1994.

[36] C.-T. Chuang, K. Bernstein, R. V. Joshi, R. Puri, K. Kim, E. J. Nowak, T. Ludwig, and I. Aller, "Focusing on planar device structures and strained silicon for handling silicon scaling issues in the deep sub-100 nm regime", *IEEE Circ. Dev. Mag.*, vol. 20, no. 1, pp. 6–19, 2004.

[37] J.-P. Collinge, S*ilicon-on-Insulator Technology: Materials to VLSI*. Boston/Dordrecht/London: Kluwer, 2004.

[38] T. Skotnicki, J. A. Hutchby, T.-J. King, H.-S. P. Wong, and F. Boeuf, "The end of CMOS scaling", *IEEE Circ. Dev. Mag.*, vol. 21, no. 1, pp. 16–26, 2005.

[39] J.-P. Colinge, "Multiple-gate SOI MOSFETs", *Solid-State Electron.*, vol. 48, no. 6, pp. 897–905, 2004.

[40] E. E. Loebner, "Subhistories of the light emitting diode", *IEEE Trans. Electron Dev.*, vol. 23, no. 7, pp. 675–698, 1976.

[41] N. Holonyak, "The semiconductor laser: a thirty-five year perspective", *Proc. IEEE*, vol. 85, no. 11, pp. 1678–1693, 1997.

[42] Z. I. Alferov, "Autobiography", http://nobelprize.org/nobel_prizes/physics/laureates/2000/alferov-autobio.html

[43] G. E. Moore, "Progress in digital integrated electronics", in *Proc. IEDM Tech. Dig.*, Washington, USA, 1975, p. 103.

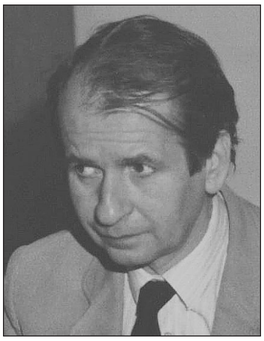
[44] Hardware components, Intel processor history, http://www.interfacebus.com/intel-processor-types-release-date.html

[45] International Technology Roadmap for Semiconductors, 2008, http://www.itrs.net/Links/2008ITRS/home2008.htm

[46] The singularity is near, http://singularity.com/charts

Lidia Łukasiak graduated from the Faculty of Electronics, Warsaw University of Technology, Poland, in 1988 and joined the Institute of Microelectronics and Optoelectronics the same year. She received the Ph.D. and D.Sc. degrees from the same university in 1994 and 2002, respectively. Since 2004 she has been the Vice-Director for Teaching of the Institute of Microelectronics and Optoelectronics. Her research interests include modeling and characterization of semiconductor devices and microprocessor systems.

e-mail: lukasiak@imio.pw.edu.pl
Institute of Microelectronics and Optoelectronics
Warsaw University of Technology
Koszykowa st 75
00-662 Warsaw, Poland



Andrzej Jakubowski received the M.Sc., Ph.D. and D.Sc. degrees in electrical engineering from the Warsaw University of Technology (WUT), Poland. In the years 1984–1990 and 1993–2001 the Head of the Division of Microelectronics of the Institute of Microelectronics and Optoelectronics (IMiO) and in the years 2001–2004 the Head of the Division of Microelectronics and Nanoelectronics Devices of IMiO. He was the Director of the Institute of Electron Technology (ITE) in the years 1989–1992 and Director of IMiO from 2004 till 2008. Between 1990 and 1991 he was the Chairman of the Committee of Applied Research and a member of the Prime Minister's Committee of Science and Technical Progress. He was the Vice-chairman of the Committee of Electronics and Telecommunications of Polish Academy of Sciences between 1989 and 2007. He was also the Chairman of the Microelectronics Section of this Committee from 1988 till 2003. He was the editor-in-chief of "Electron Technology" between 1990 and 1994. He is the author or co-author of more than 600 publications (journal and conference papers, monographs) and several textbooks for students, as well as popular-science papers. He delivered many invited lectures at foreign universities and international conferences in Europe, United States and Asia. He supervised 23 Ph.D. theses and more than 150 B.Sc., and M.Sc. theses. He received 5 Awards of the Minister of National Education. The main areas of his research are modeling, characterization and fabrication of semiconductor structures (e.g., MOS, SOI MOS, HBT, SiGe MOS).

e-mail: jakubowski@imio.pw.edu.pl
Institute of Microelectronics and Optoelectronics
Warsaw University of Technology
Koszykowa st 75
00-662 Warsaw, Poland