# Regarding the Manufacture and Application of Integrated Circuits and Microprocessors (Microchips)

Emeritus Prof. Stefan Kartunov
Technical University of Gabrovo
Department Mechanical Engineering
Bulgaria
skartunov@abv.bg
PhD Milan Vesković, assistant profesor
University of Kragujevac
Faculty of technical sciences in Čačak
Serbia
milan.veskovic@ftn.kg.ac.rs

PhD Jelena Purenović, associate professor
University of Kragujevac
Faculty of technical sciences in Čačak
Serbia
jelena.purenovic@ftn.kg.ac.rs

*Abstract*—**The article describes a brief history of the development of microprocessors. The emphasis is mainly on the technology of manufacturing, silicon wafer fabrication and microstructuring operations, as well as assembly and fabrication equipment. In conclusion, the application of microprocessors is discussed with examples.**

***Keywords-component; integrated circuits, microprocessors, planar technology***

## I. INTRODUCTION

In April 1949, German scientist Werner Jacobi patented a device similar to an integrated circuit (IC) containing 5 transistors arranged in a 3-stage amplifier. The IC was later developed by the scientist Jeffrey Dummer (1909-2002), who unsuccessfully tried to create the circuit in 1956. The precursor to the IC was the idea of creating small ceramic pads, each containing a miniaturized component. An IC, microchip or chip is a miniature electronic circuit consisting of semiconductor devices and passive components. This idea seems very promising and in 1957 it was proposed to the US Army by Jack Kilby. In the course of the short-term Micromodule Program project, Kilby came up with a revolutionary new IC design. The first IC was created independently by two scientists: Jack Kilby of Texas Instruments, who patented his invention as a "Stable Circuit" made of germanium on February 6, 1959, and Robert Noyce of Fairchild Semiconductor, who patented a more complex "unified circuit" made of silicon on April 25, 1961. A microprocessor is a logical program-controlled computing device, in the structural scheme of which a number of basic elements participate. The central processing unit (CPU) is a thin silicon chip with a high degree of integration. The world's first 4-bit central processing unit was released by Intel Corporation on November 15, 1971. It was a single-chip mass-use i4004 microprocessor designed for a Japanese calculator. Its operating frequency is 740 kHz. Other companies also announced 4-bit microprocessors Rockwell International PPS4, NEC µCOM 4 and Toshiba T3472. Very quickly, processors combine modern micro-architecture technologies and a set of new capabilities, providing an optimal level of performance for computing and logic applications. 12- and 16-bit processors appear. Examples of the former are the IM 6100 Intersil and Toshiba T3190 and the latter are Intel 8086, Texas Instruments TMS 9940 and 9980, Fairchild 9440, Motorola M68000 (for Macintosh, as well as Amiga and Atari ST), Zilog Z670, AMD and Qualcomm, Elbrus ( Russia) etc. The first real hit on the market was the i8088, which appeared in '79 and 2 years later became part of the first popular business computer - the IBM PC. Those who are familiar with the history of the IBM PC and the computers that followed it know that the i8088/86 was followed by the 80286, 386, 486, after which in 2000 the Pentium family appeared, which is still popular today with its last member - P4. In 2007, the production of 64-bit processors with the new AMD K10 architecture, code named Phenom, began, and in recent years, those with more than one microprocessor core Pentium D, Pentium Extreme Edition, etc. The seventh generation of Core, namely Kaby Lake is released in 2017. In this regard, there are microprocessors installed in computers such as Core 13,14,15 and 16. This computer has the quality of running at high speed and works with a minimum of 4 cores. This helps to achieve transmission speeds of the order of 1 GHz. The same 14 nm process and LGA 1151 socket are used. Once again, Intel makes one of the computers with the fastest processors on the market.

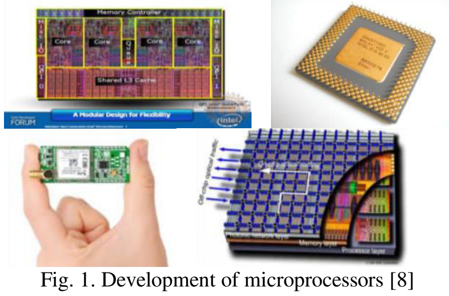


Fig. 1. Development of microprocessors [8]

Core 19, has 6 cores and speeds up to 3.5 GHz. AMD also developed a microprocessor called the Athlon X3 and along with the Phenom X4 it has four cores.The speeds of these processors have increased significantly compared to previous versions and reach up to 3.2 GHz. Next is a transition to the 10nm process by which CanonLake processors are manufactured. Improvements in the performance of processors lead to the rapid development of modern technology at the 7nm level from 2021. A modern installation of the ASML company for lithography is shown in [2]. Currently, microprocessors con-tinue to develop and find ever greater application and influence in all spheres of modern life.

## II. EXPOSURE

From an application point of view, a microprocessor, chip or microchip is an assembly of suitably interconnected miniaturized electronic elements manufactured on a monolithic basis of semiconductor material or disk (substrate). In many cases, modern chips are "digital" and perform logic functions and operations with binary numbers. In the not-too-distant past, there were also purely "analog" chips, as well as chips operating in mixed mode with digital and analog functions, for example in digital-to-analog converters. Today, the computer is essential for designing new electronic components and electronic circuits (Fig. 2).

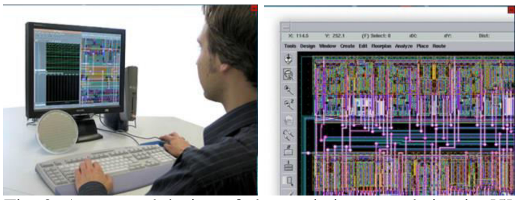


Fig. 2. Automated design of electronic integrated circuits [5]

### 2.1. Technology

Microprocessors can be distinguished by their internal and external speed, which determines the bits processed per second, as well as the ability to access memory and the repertoire of computer-level instructions and programs that can be processed. Each type of microprocessor has a model that indicates the prototype of which it is a copy. For each model there is a specific technology and internal data bus width, i.e. word length in bits (like clock frequency, which is measured in MHz). It varies usually between 333-400 MHz, up to 533-1000MHz and depends on the processor, motherboard and memory. If it does not work at the requested frequency, it is lowered to a lower one. That being said, microprocessor manufacturing technology is confidential and unique. The main manufacturers have specialized in some segment of the production chain, in design and conceptual development (ARM), in commercialization (Qualcomm, Nvidia, Broadcom), in manufacturing (Global Foundries), they do not produce the same chips, and some such as the Taiwanese firm TSMC are hyper specialized, which makes their manufacturing even more strategic. The principle technological process includes:

#### 2. 1. 1. Fabrication of silicon discs

The main material silicon dioxide ($SiO_2$) for them is obtained from quartz sand - a mineral, a chemical compound of silicon and oxygen. Thanks to a process known as the "Czochralski process", the quartz is heated to its melting point to remove oxygen from it. A silicon crystal is placed in the molten mixture, on which the silicon atoms adhere, and it begins to grow until all the silicon atoms in the mixture occupy their places in the crystal lattice. In fig. 3 shows a schematic of the process. The diameter of the resulting disc (called the pad) was 300 mm as of 2012 due to the limitation of the tech-nology and the specific physicochemical conditions under which the process is carried out, and as of 2015 it has grown to 400-450mm (Fig. 3). The larger the size of the pad and the smaller the size of the individual elements, the more single ICs are created at once and the correspondingly lower unit cost.

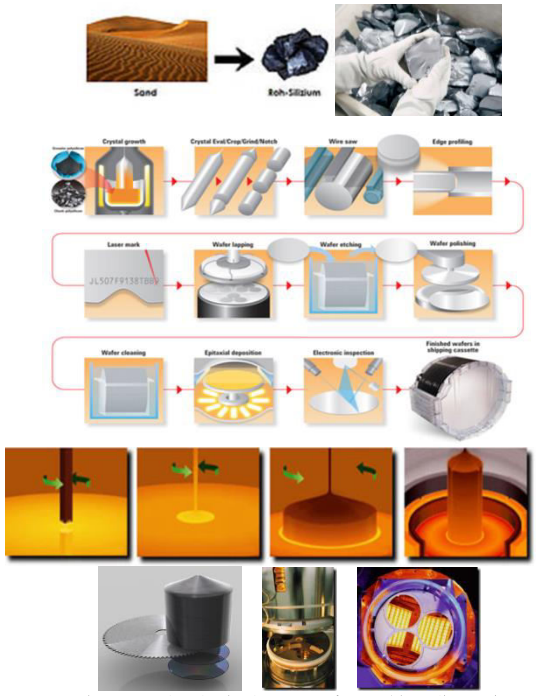



Fig. 3. Technological process for making discs [6]

**Legend:** Downloading silicon single crystals. Cutting the silicon single crystal into blanks (enlarged). Machining by circular grinding. Cutting $SiO_2$ single crystal into discs (substrates 0.75-1 mm thick). Laser engraving. Disc polishing. Disk Cleanup. Subject to epitaxial deposition (growth, arrangement for which is shown below). Inspection for possible defects. Ready-made silicon disks.

Each substrate is subjected to a series of treatments (planar multilayer technology) and when the process of creating the necessary layers and structures is completed, it is in turn divided into hundreds of rectangles - chips. Thus, one IC is formed in each chip, which completes the manufacturing process. It is known as semiconductor technology and is a fundamental process in the creation of ICs and microelectronic devices. It involves a number of separate operations in which an electrical circuit is formed and fabricated in a substrate of semiconductor material (Fig. 4). They are: Substrate production, Washing, Photolithography (or other type of lithography), Ion implantation, Dry and Wet etching, Plasma etching and its types, Thermal treatments, incl. Oxidation, Chemical Vapor Deposition, Physical Layer Deposition, Molecular Beam Epitaxy, Electrolytic Layer Deposition, Chemical Mechanical Polishing, Electrical Testing, Peripheral Wafer Thinning or Rounding, Chip Cutting, Packaging and Encapsulation, Final IC testing.

Fig. 4. Discs of different sizes [5]

2. 1. 2. Microstructuring technologies

A process in which, through the operations of lithography and microstructuring, a relief coating with a desired configuration of dielectric, semiconductor and metal layers is obtained, as the structuring is performed not only in a plane, but also in volume. The main lithographic processes are: photolithography, X-ray, electron, laser and ion lithography or nanoprint lithography [1]. They are based on the use of high molecular compounds - resistors, capable of changing their properties under the influence of different types of radiation, the wavelength of which determines the resolution [2]. Photolithography is the most widely used process in IC manufacturing. Photo templates are used, which are plane-parallel plates of transparent material on which a drawing is applied, which can be a positive or negative image of the photographic original. Borsilicate or quartz glass is used as a material for photo templates (Fig. 5).

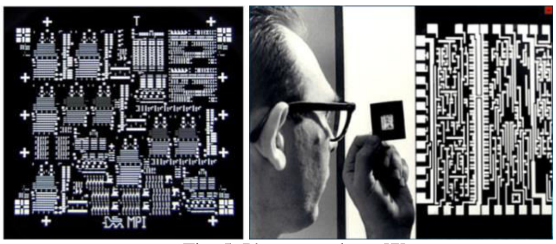


Fig. 5. Photo templates [7]

The sequence of the technological process in photolithography is shown at Fig. 6: A) Preparation of the substrate, B) Application of photoresist, C) Drying, D) Alignment of the photopatterns and exposure, E) Development of the photoresist, E) Re-drying and hardening of photoresist (fixation), G) Etching, H) Photoresist removal (stripping), I) Substrate washing.

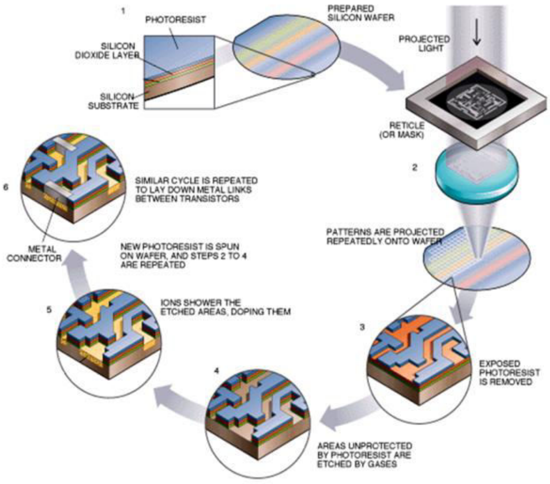



Fig. 6. Photolithography sequence [7]

Preparation of the substrate A) is carried out by cleaning with deionized water or isopropanol and applying a film of hexamethyldisilazane (HMDS) according to the type of material - silicon dioxide, borsilicate glass, phosphorosilicate glass and aluminum. To apply the photoresist B) to the substrate, centrifugation, sputtering, immersion in a solution and watering are used (Fig. 7).

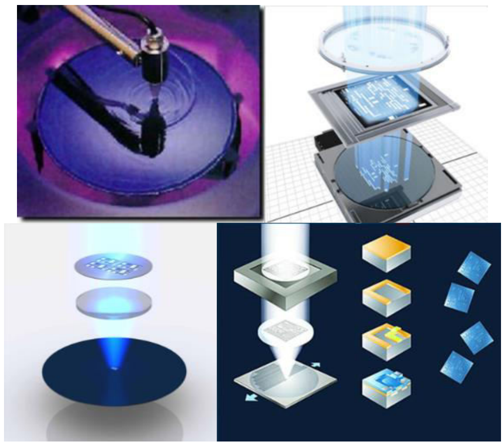
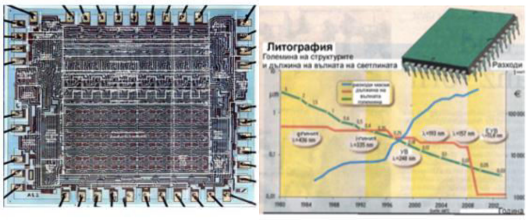


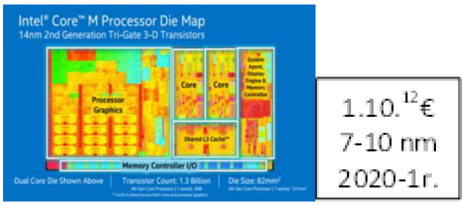
Fig. 7. Centrifugation and projection exposure [7]

In centrifugation and atomization, drops of liquid resist are applied via a metering pump, whereby the pad is attached to a rotating base with a vacuum suction port. The first drying operation B) of the applied photoresist is done in order to remove the solvent. The temperature is around 70-90$^o$C, and the time 15-30 min depending on the photoresist. In the adjustment and exposure devices, the photo templates and the support D) are brought together until they match. Irradiation of the photoresist D) through the photopattern with UV-light with a wavelength of 200-300 nm. Virtually all the leading chip manufacturers as of 2004 primarily use a process called 193nm deep ultraviolet (DUV) lithography, where light from a 193 nm wavelength laser is refracted through a liquid on a photoresist to create multiple layers and patterns [2]. A second drying operation E) of the photoresist follows. Etching G) is a shape-changing process during the interaction of chemical reagents with the surface of the substrate, as a result of which both impurities are removed and a pattern is transferred to its surface layer. Stripping 3) in this process the structuring photoresist is located under the metal layer. As a rule, metal layers of aluminum, gold, titanium are used, most often applied by vacuum methods.

As the main characteristic of the technological process, the minimum achievable line width is often indicated in the circuits or the resolution, which, as a consequence, determines the dimensions of the transistors and other semiconductor elements on the substrate (Fig. 8). The basic operations of microstructuring use repeated operations for structuring layers, with which the main processes (also called base technologies) are realized, which are united in the following classification [1]:




10 µm — 1971 г. Lithography 1980 – 2012




14 (13,5-13,8) nm — 2014 г. EUV

Fig. 8. Evolution of resolution over the years [2]

Deposition of layers on the substrate or on the previous layer: physical methods for making details and elements by applying thin layers by vacuum evaporation and cathodic sputtering methods; materials – metals and dielectrics, for example silicon dioxide ($SiO_2$); chemical methods for gas phase deposition of polycrystalline silicon and amorphous layers, for example silicon dioxide and three silicon four nitride ($Si_3N_4$); epitaxy-deposition of a single crystal layer, for example a doped silicon layer on a silicon substrate; electrolytic deposition of galvanic and chemical coatings, for example nickel (Ni), gold (Au) and copper (Cu).

• Modification of the surface layer of the substrate, as well as of an already finished layer, so as to form a new layer with other physical properties different from the initial state: thermal oxidation; diffusion; ion implantation of foreign atoms in the crystal lattice of the semiconductor;

• Structuring of a protective layer – production of a protective layer by photolithography as a mask for the next etching operation: application of resist; exposure; manifestation; photoresist removal.

• Removal of layers by etching the mask-free areas of the substrate, respectively the areas of the layer: liquid etching; dry etching - plasma, reactive-ion, ion-beam, etc.

• Separation of the substrate into individual chips (Fig. 9). The main methods of separating individual chips and pads into individual "boards" are: mechanical scribing with a diamond cutter and breaking; cutting with diamond or metal-ceramic discs; cutting with a laser beam (laser scribing).

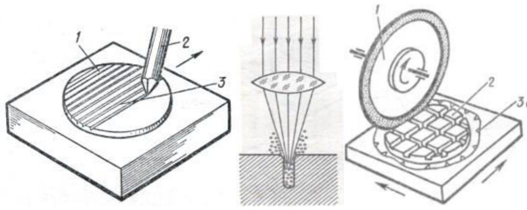


Fig. 9. Basic methods of separating the macro-substrates into individual chips. Cutting with a diamond disc a) Scribing with a diamond cutter, b) Laser scribing c) Diamond disc cutting [1]

Legend: 1 - macromat; 1 - diamond disc; 2 - Diamond cutter; 2 - pad; 3 - shear groove; 3 - glue

The peculiarities of these processes are: the need for precise orientation along the cutting lines between the contact pads of the individual chips; ensuring the integrity of the elements, structures and metallization at the expense of reducing to a minimum the mechanical stresses in the cutting site; ensuring the size and shape of chips and "boards" with reproducible accuracy; minimum cutting line width. The main separation methods are presented in Fig. 10 and a comparative characteristic between them is shown in Table 1 [1].

• Installation of the chip on the base of the case.

A reduction in the usability factor of the IC case is achieved by the use of the so-called "matrix enclosures" with the pins arranged on all four sides of the "chip-carrier" type enclosure, as in some microprocessor ICs and single-chip microcomputers (Fig. 10) [1]. The number of conclusions in this case does not exceed a hundred. The use of pins in the form of a raster on the underside of the chip-carrier or multichip-carrier ceramic substrate solves to a certain extent the issue of the large number of pins, which can reach several hundreds. Using a PLUG-IN package improves power dissipation in oversized ICs.

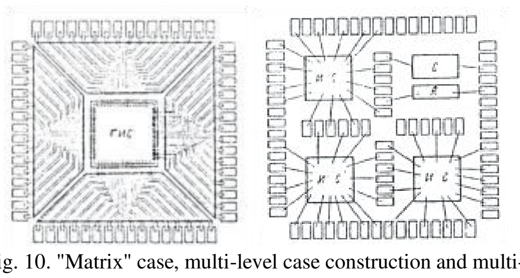


Fig. 10. "Matrix" case, multi-level case construction and multi-chip-carrier type case [1]

The factor of usability also suggests another solution for ultra-high degree of integration of ICs or microprocessors - the use of multi-level housing construction, where it is close to unity. Multi-chip modules (MCMs) are a fundamentally new approach in the field of packaging and assembly in microtechnology, adapted from the surface mount technology of SMD printed circuit boards.

Table 1. COMPARISON BETWEEN SEPARATION METHODS (* for modern metal-ceramic discs up to 3 μm thick)

| Parameter | Scribing with a diamond incisor | Cutting | Scribing with a laser beam |
|---|---|---|---|
| Line width, μm | 1 - 5 | 35 - 50; (5 - 10)* | 25 - 20 |
| Depth of channels, μm | 1 - 5 | 10 - 400 | 50 - 170 |
| Processing speed, mm/s | 20 - 60 | 60 (max) | 200 (max) |
| Direction of movement of the cutting tool | 1D | 1D; 2D | 1D; 2D |
| Tool type | Diamond incisor | Diamond disc Metal-ceramic disc | Laser |
| Randeman, % | 98,0 | 99,5 | 99,5 |
| Processed material | Silicon, sital | Any kind | Any kind |
| Additional processing | Etching | Sticking and peeling | - |
| Operator qualification | high | average | Any kind |

In the development of high-speed ICs and micro-processors, it is of particular importance to achieve a minimum length of the conductive buses between the chips and the elements in them. This led to the development of MCMs, where many chips are joined together in a common module (Fig. 10). The module is most often made on a ceramic or flexible polymer substrate with metallized busbars integrated on or in its volume between the individual functional blocks and devices (made as independent non-encased or encased chips) and mounting contact pads for connecting the components. Depending on the type of carrier pads in the multichip technique, thick-layer or thin-layer technologies are used for metallization integration. In this way, a very complex microcircuit containing up to 100 non-encased chips can be integrated within a common package. One of the options for preparing multichip substrates is presented in Fig.11. Some more exotic technologies also include processes where multi-layer multi-chip modules can be made to stack the chips on top of each other.

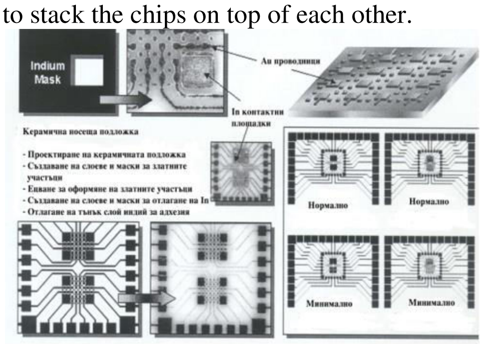


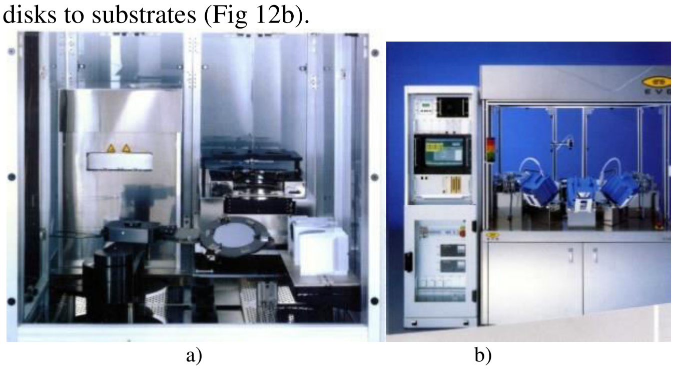

Fig. 11. Preparation of a carrier pad for a multichip module [1]

The processor is basically a single chip and, like any chip, it has terminals through which it is connected to the motherboard - a socket. The socket is a plastic frame with many holes in which the processor is placed. Below these holes are metal pins that connect to the processor's legs. With the 486, a standard 169-pin Socket 1 socket appeared. In recent days, the standards are as follows - for Intel - Socket 478, for the old Pentium 4, Celeron and P4 EE, or Socket 775 - for the newer Pentium D and Celeron D. On the AMD front,the situation is as follows-Socket754for the new Athlon and Turion64.

• Making contact connections between the chip and the pins. Assembling the chips to the base part (the supporting base). The purpose of connecting (bonding) chips to metal, ceramic, glass or silicon substrates is to achieve mechanical strength of the structure, make electrical contact or isolate elements and improve heat dissipation. When assembling the microelements, a problem is the mechanical stresses obtained due to the different coefficients of thermal expansion of the chips and the base part (the supporting substrate). Therefore, materials for them should be selected with close coefficients of thermal expansion or elastic binders should be used between them.

- *Direct assembly methods*

In this method, the chips are assembled to the carrier pad, housing base, or frame (the carrier strip or base piece) up with the work surface. Bonding takes place with or without an intermediate bonding layer using low- or high-temperature process operations: Direct thermal bonding; Anodic bonding (bonding); Eutectic soldering - contact-reactive and with eutectic alloys [1]. In Fig. 12. combined production systems designed to simultaneously carry out several assembly operations are shown. In the equipment of Fig. 12a the temperatures of the upper and lower pads are controlled through one degree ($500^0$C max) independently of each other to compensate for the coefficient of thermal expansion of the two pads. It is intended for anodic bonding, direct thermo-compression bonding with glass, metal or eutectic, or silicon-gold eutectic bonding. The other is for assembling silicon disks to substrates (Fig 12b).



a) b)

Fig. 12. Combined production systems designed to simultaneously carry out several assembly operations [1]

a). Equipment for combined assembly by the methods of thermocompression, anodic, eutectic adhesive bonding by adhesives of the company Karl Süss, Germany; b). Robotic system for assembling silicon wafers to insulating carrier substrates (SOI-Bonding) of EVGroup [1]

• Sealing (Hermetization)

Body and non-body protection are used depending on the specific design, purpose, field of application and economic requirements. Depending on the design and material of the case, sealing of ICs, microcomponents and microsystems is carried out by different methods, as shown in [1]. Soldering and welding (vacuum-tight sealing) are most often used to seal the casings.

2.2. Application

Microchips are becoming vital to the global economy and thus becoming a strategic challenge to major world powers and developing countries. To choose a specific type of microprocessor, it is necessary to take into account its main operating parameters, clock frequency, memory, word length and others, taking into account the price. A study by the Semiconductor Industry Association and Boston Consulting Group in April 2021 shows that 75% of the world's processor manufacturing capacity is concentrated in China and East Asia, and 100% of the world's production of last-generation semiconductors (smaller than 10nm base) are located in Taiwan (92%) and South Korea (8%) [3]. China produces 36% of the world's electronics, but only 7.6% of the semiconductors sold on the international market. It is for this reason that 'technological independence' was put at the center of attention in the adoption of the 14th Five-Year Plan (2021-2025). The European Union is betting on the "European Chips Act", a European law on semiconductors, which also aims to protect technological independence. By 2030, the EU has ambitions to produce 20% of the world's semiconductors, doubling its current share. The demand for electronic chips is increasing due to their use in various fields not only in computer technology: the production of flash memories, of smartphones and the infrastructure for them with the development of 5G networks, automotive (electric, hybrid and traditional cars for the control of airbag systems, the distance, the engine, the battery, the "start and stop" system, the air conditioning, etc.), the entertainment industry with video game consoles (Playstation 5 and Xbox Series X), the Internet of Things (Internet of Things), which allows individual objects with embedded electronic devices to interact with each other, artificial intelligence, big data (systematic extraction of information from large databases) with specific processors such as Intel's Xeon Ice Lake, military industry, etc. Gradually, all objects of our life are digitized: from the coffee machine to the vacuum cleaner and the ordinary door. In fig. 14 shows examples of this. The demand for electronics of all kinds has increased dramatically since the beginning of the Covid-pandemic due to the increase in the number of people working from home and spending their free time at home. In 2020, the turnover amounted to 442 billion dollars, which is an increase of 5.4% compared to 2019, and for 2021 it will increase by another 17.3% [3].


Fig. 13. Application of microprocessors [9]

## III. Conclusion

Microprocessors have been a part of our lives since they first appeared on the market in late 1971. A brief history of their development is described. The report highlights their fabrication technology, silicon wafer fabrication and microstructuring operations in multilayer planar technology, as well as assembly and equipment for the purpose, which are largely confidential and little known. The basic parameters and application of microprocessors are discussed with examples and market developments. Processors represent an ever-evolving market. Development that continues!

**Acknowledgement**

This research is a part of investigations performed within the scope of the project 451-03-47/2023-01/200132. The authors gratefully acknowledge the financial support of Serbian Ministry of Education, Science and Technological Development.

## References

[1] Кънтунов С., Технологични основи в мехатрониката, микро- и наносистемната техника, Technological foundations in mechatronics, micro- and nanosystem engineering, Габрово, УИ „В. Априлов", 2012, ISBN 978-954-683-482-9, стр. 383, COBISS.BG-ID – 1259450340 (in Bulgarian)

[2] Кънтунов С., Състояние, развитие, потенциал и приложение на лазерната литография в микро- и наномехатрониката, Status, development, potential and application of laser lithography in micro- and nanomechatronics, Созопол, XXX МНТК "АДП – 2021, Издателство на ТУ София, Автоматизация на инженерното производство, бр.3/03.21, ISSN 2682-9584, стр. 4-8 (in Bulgarian)

[3] https://ikj.bg/e-zona/svetovnata-promishlenost-v-syankata-na-mikrochipa/

[4] https://czochlarski precess of silicon wafer.mpg, www.svtii.com, Technical Institute Silicon Walley, 2013

[5] https://intel_32nm.mpg, Invention, Innovation, Investmet, Intel Corporation, 2009

[6] https://Making_of_Processor_From_Sand_to_Processor_or_How_a_CPU_is_made.mpg, Intel Corporation, 2009

[7] Сумров В., Технология за изработване на микрочипове, Габрово, ТУ Габрово, презентация, 2015 (in Bulgarian)

[8] Алтънски Х., Микротехника, Габрово, ТУ Габрово, презентация, 2014 (in Bulgarian)

[9] Катов Х., Производство на микрочипове, Габрово, ТУ Габрово, презентация, 2022 (in Bulgarian)