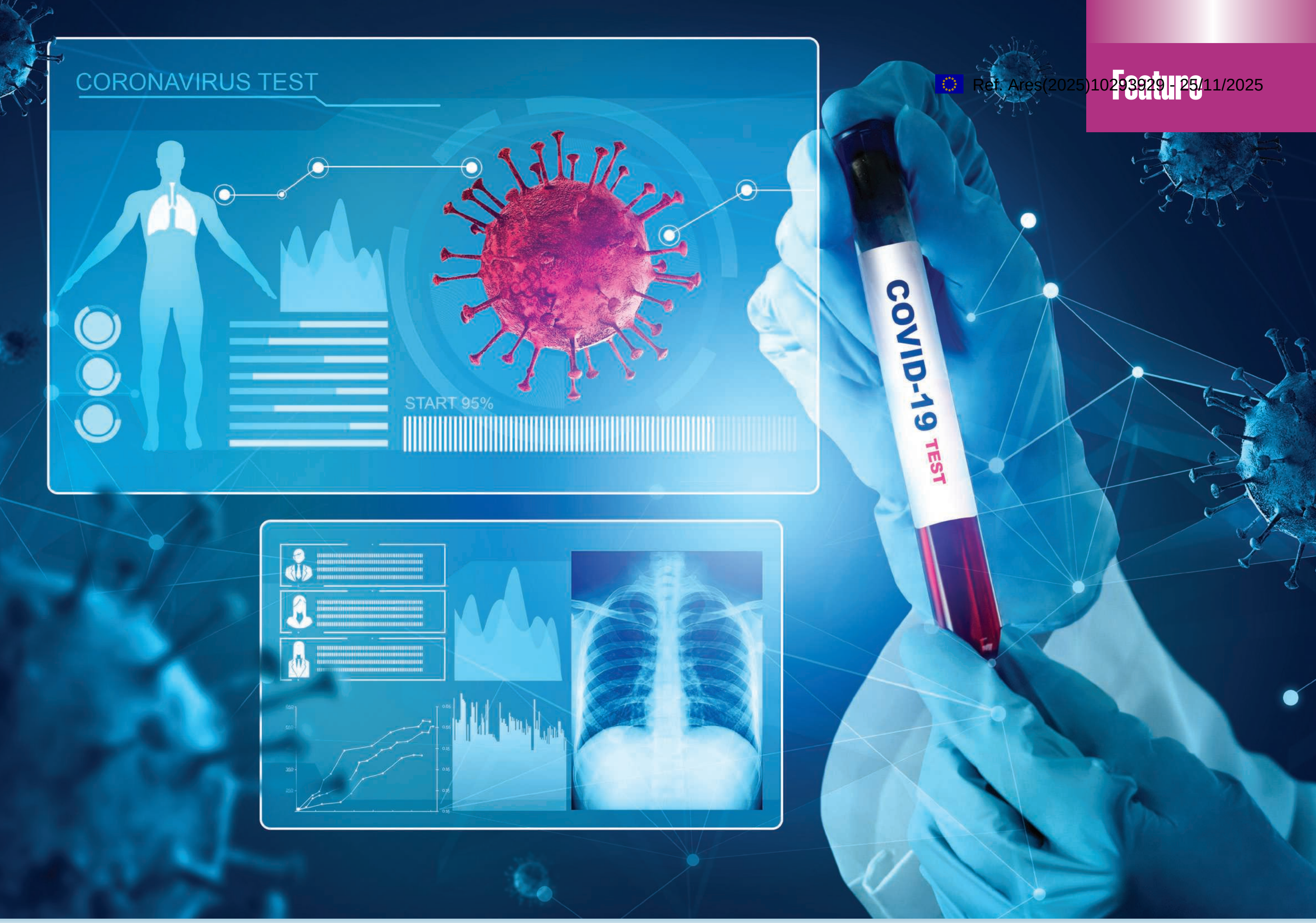

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Pandemic, Shortages, and Electronic Engineering

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Abstract

The COVID-19 pandemic and the current shortage of integrated circuits has highlighted that electronic components (chips) constitute the basis of our information society. However, chips and electronic systems are not static commodities, as they greatly evolve in terms of functionality and performance. It is not possible to sustain future developments by simply using the available electronics. Electronic engineers are specifically trained professionals who will ensure this continuous technological evolution by designing and optimizing electronic devices, circuits, and systems for tomorrow's applications. Unfortunately, teenagers seem to be losing interest in this field and a more serious chip shortage may happen which could be caused by the basic shortage of next-generation electronic engineers. It seems therefore quite important to revitalize the perception of this discipline in the imagination of young people, to inspire new talents at a time when chips and electronic systems are entering almost all areas of human life and new job opportunities are opening up. To this end, a key factor could be the realization of a motivating communication campaign for school students and their families, in which public and private stakeholders together with universities and professional associations like the IEEE act in a structured and coordinated way.

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1. Introduction

A shadow looms over the global economy already hit hard by the COVID-19 pandemic: the *chip shortage*, that is, the lack of integrated circuits (ICs), those electronic components manufactured by the semiconductor industry led by TSMC (Taiwan Semiconductor Manufacturing Company), South Korean Samsung, and U.S. Intel. Figure 1 shows the global semiconductor production in 2020, clearly dominated by Asian companies accounting for around 75% of the share.

To get an idea of the turnover involving this field, consider that U.S. exports of semiconductors totaled $49 billion in 2020, behind only airplanes ($72 billion), refined oil ($65 billion), and crude oil ($50 billion) [1].

Chips are ubiquitous, being the basis of the so-called *digitalization*. They also make possible that close interconnection of data processing and production which characterizes the fourth industrial revolution (industry 4.0). For this reason, the chip shortage produces effects so sensitive that they make it appear insistently on the pages of newspapers, magazines and web news [2]–[6]. The semiconductor industry, previously almost disregarded by the mass media and tech-savvy observers, is now on the spotlight, overwhelmingly attracting public attention, investments, and governments plan to reinforce semiconductor manufacturing facilities at a national or continental basis. The semiconductor supply chain is in fact extremely critical, especially for the most advanced technologies required for the implementation of high-performance logic chips such as microprocessors. These technologies correspond to technology nodes of less than 10 nanometers and are currently concentrated in Taiwan for 90% of global capacity.

However, just upgrading the chip factories, will presumably not achieve the desired effects unless accompanied by a parallel increase in the number of specialized personnel and, mainly, electronic engineers whose specific skills are hardly found in other engineers. In fact, there is a global downward trend in student enrollment in academic electronics programs and, as a result, companies are unlikely to find qualified staff to hire in this specific field[1].

It becomes therefore of upmost importance to invert this downward trend and one key action to be carried out could be the promotion of a global, long-term information campaign aimed at explaining to young people and their families the role of the electronic engineering in the digital value chain. To this end, governments, universities, semiconductor/high-tech companies and voluntary associations, including the *IEEE*, need to work closely on practical initiatives to address this skills shortage.

2. The Chip Shortage and the Semiconductor Industry

The worldwide shortage of semiconductors began primarily with IC's for specific applications such as power management, display controllers and microcontrollers, that are manufactured in "mature" technology nodes (roughly, >28nm). The shortage has now spread to cutting-edge nodes and other devices (like smartphones, game consoles, computers and medical equipment), and there are capacity limits for substrates, passive components, cable connections, and testing, which are all part of the supply chain beyond the chip factories.

The reasons for this largely unexpected shortage are many and may be partly related to the COVID-19 pandemic. During the last two years, distance working, distance learning and remote health care have boosted the request for personal computers and medical devices at a global level[2]. Social distancing has greatly increased the demand for game stations and multimedia accessories, such as graphic cards[3]. The need for better connectivity has necessitated many more broadband servers for data centers[4]. Furthermore, the ongoing trade war between the U.S. and China has severely limited

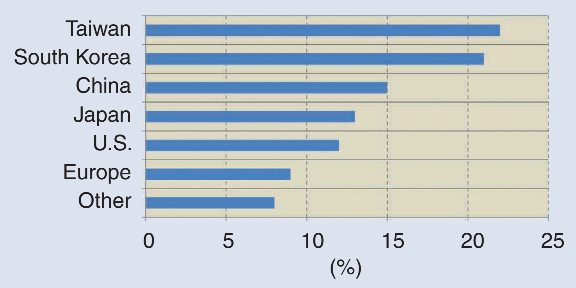

Figure 1. Percentage of global semiconductor chip manufacturing market in 2020.

[1]To cite just one example, electronics engineers have been added to the UK's list of deficient jobs since October 2019. This makes it easier to hire skilled foreign workers, especially from emerging economies.

[2]Worldwide shipments of PCs, inclusive of desktops, notebooks, and workstations, reached 84.2 million units in the second quarter of 2021, with an increase of 13.4% from the same period of 2020. The chip shortage had a strong impact on notebook offering, which resulted in desktop growth outperforming notebooks during the quarter.

[3]In addition, the price of Bitcoin has made *mining* using graphic processing units more profitable.

[4]Data centers played one of the most critical roles in preventing the potential collapse of the world economy due to the COVID-19 pandemic which in turn has caused record spending levels for data centers led by AWS (Amazon), Microsoft and Google, reaching $37 billion in the third quarter of 2020 alone. The global data center systems market reached $220 billion in 2021, an increase of more than 7% year-over-year, according to IT research firm Gartner's.

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China's chip manufacturing capacity, as the U.S. does not want state-of-the-art equipment installed anywhere in China. Finally, the recovery in the automotive market started earlier than expected. Figure 2 shows monthly year-over-year sales of application-specific chips used in the automotive sector which clearly shows the rapid recovery in sales after the sudden drop in February and March 2020 [7]. Chips are here used to help ensuring safety and providing an enhanced driving experience, from high-performance satellite navigation systems to advanced driver assistance and infotainment systems. Intel CEO Pat Gelsinger predicted that chips would make up 20% of the cost of an auto in 2030, compared with 4% in 2019.

The resulting huge demand for electronic components has displaced manufacturers who are receiving more orders than they are able to fulfill, even with factories working well above the normal utilization level of 80%. Figure 3 depicts the year-over-year percent monthly chip sales growth in the period between January 2020 and June 2021 for three main sectors, namely consumer, communication, and computer (other relevant ones are industrial and automotive) highlighting a rapid increase for both communication and computer sectors.

Overall semiconductor shipments reached all-time highs in the third quarter of 2021. On a regional basis, the year-over-year increase was: Americas (33.5%), Europe (32.3%), Asia Pacific/All Other (27.2%), Japan (24.5%), and China (24.0%) [8]. In 2020, the worldwide semiconductor market reached $446.1 billion, up 8.34% over 2019. In 2021, the growth of the semiconductor market was 26.3%.

The chip shortage problem is so significant that prices of several high-tech products are rising and/or their fabrication severely delayed. For example, Fig. 4 shows the price index of the top 20 best-selling microprocessors which has clearly increased sharply since March 2021, [9]. Sony slowed the production of the PlayStation 5, Microsoft of its Xbox series X, and Qualcomm of its 4G and 5G wireless devices. General Motors, Honda, Volkswagen, Ford, Toyota, Nissan and Tesla, just to cite a few, have had to revise their business plans and likely postpone the release of new car models [10]–[12]. FCA also delayed the restart of the Toluca (Mexico) plants, where the Jeep Compass is produced, and the Brampton plants in Ontario [13].

Against this backdrop, the shortage has also greatly strengthened the influence of chip makers who are now increasingly able to choose which customers to get how many of their scarce chips [14]. This way, they can also filter out some of the customers who just want to make safety reservations and provide supplies to those who need the chips most. Chip stocks are very likely to be very limited at the moment. This comes in a completely new scenario in which not only the most advanced technology nodes are profitable and in demand, but also mature ones driven by automotive and IoT manufacturing, as most of these applications require more established technologies, which have better yields, costs and, above all, reliability.

Figure 2. Year-over-year monthly sales growth percent change in automotive ICs, 2020–2019, [7].

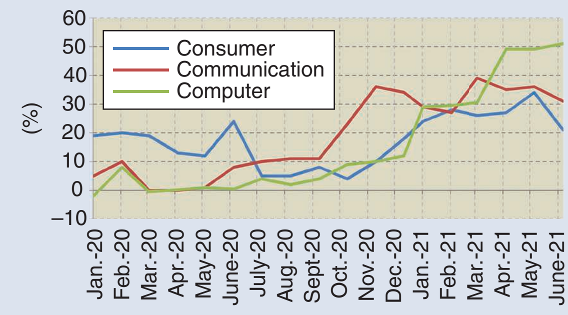

Figure 3. Year-over-year monthly chip sales growth percent change in three main areas [1].

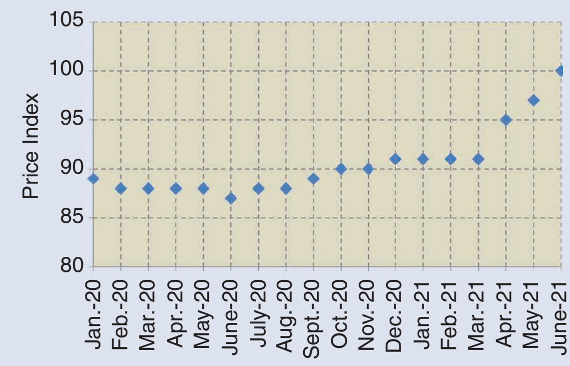

Figure 4. Price index of top 20 bestselling microcontrollers. Source: Supplyframe, [9].

3. Governments and Companies Reaction

Nowadays economies are linked together and it is not possible for a nation to become completely autonomous in the production of high-tech products. However, reliance on a single chip supplier like TSMC has proved very dangerous, and China's long-term concern over the independent status of Taiwan makes this worse. Through investment along the semiconductor value chain on equipment and materials, design, advanced manufacturing and packaging, and testing, the goal of governments is precisely to strengthen their resilience to external shocks and safeguard their technological sovereignty. Securing a stable supply of chips has become a national priority. Below is a summary of the main actions undertaken by the main players.

The U.S. Senate on June 8, 2021 passed the U.S. Innovation and Competition Act (USICA), which includes $52 billion in federal investments for the domestic semiconductor research, design, and manufacturing provisions in the CHIPS for America Act (passed in 2020 as a part of the National Defense Authorization Act, but left unfunded). Congress is also considering legislation called the FABS Act that would establish a semiconductor investment tax credit[5]. On September 2021 Intel announces $20 billion in two new plants in Arizona[6]. Intel announced also that it would invest up to $95 billion in European chip-making facilities, and on January 2022 announced plans for an initial investment of more than $20 billion in the construction of two new leading-edge chip factories in Ohio [15].

In October 2021 Micron announces over $150 billion in global manufacturing and R&D investments for memory chips [16]. In November 17, 2021, Texas Instruments announced a new semiconductor campus in Sherman, Texas, which could cost up to $30 billion and include up to four fabrication plants in total [17].

Taiwan's industry has likely years of growth ahead of it with only a few competitors over the next decade. Morris Chang, who founded TSMC says it would be impossible for the U.S. to have a full chip supply chain onshore [18]. In April 2021 TSMC announced it was planning to invest $100 billion over the next three years in new fabs to meet growing demand [19].

South Korea announced a plan in May 2021 to spend $450 billion over the next ten years on new semiconductor manufacturing capabilities. Semiconductors are already Korea's largest export (14.6%) most of which is memory products—DRAM and NAND Flash memory. The plan instead aims to boost the nation's advanced logic chip production [20].

China is keen to develop semiconductor independence, both in designing and manufacturing cutting-edge chips, as part of its *Made in China 2025* industrial strategy. In fact, semiconductors are the largest Chinese imports. In 2019, China set an objective of expanding its domestic production of semiconductors (including from foreign firms in China) to meet 70% of domestic demand by 2025 [21]. The urgency to do so has been aided by U.S. sanctions against Chinese telecom giant Huawei and its internal chip unit, HiSilicon. China's policies encourage foreign semiconductor companies to transfer technology, intellectual property (IP), talent, and research and development (R&D) to operations in China (though U.S. government expressly discouraged its companies, starting with Intel and AMD, from boosting chip production and design in China). The China's approach includes: 1) Tax, trade, and investment measures; 2) Forced joint ventures & partnerships; 3) Government subsidies; 4) Strategic foreign acquisitions; 5) Technology licensing & equipment import; 6) Talent recruitment and return of Chinese expatriates [22]. As a result, chipmakers worldwide started construction of 19 new fabs in 2021 in China, with another 10 in the works in 2022. Moreover, 17 fabs from Chinese-owned companies will start construction from 2021 to 2023. China's SMIC, the world's fifth largest silicon foundry in sales will invest $8.87 billion for new 14-nm chip plant in Shanghai [23]. But many other fabs in more mature technology nodes are in construction. China also is making a big push in the new segment of power semiconductors based on two wide-bandgap technologies, silicon carbide (SiC) and gallium nitride (GaN).

[5]In August 2022 President Biden signed the $280 billion CHIPS and Science Act into law, which includes $52 billion in semiconductor subsidies.

[6]The cost of building a new fabrication plant (fab) is >$20 billion for 5-nm nodes and the cost of designing a new chip (taping out) is > $500 million.

Figure 5. U.S. President Joe Biden holds a silicon wafer during the virtual *Semiconductor and Supply Chain Resilience CEO Summit* in the White House's Roosevelt Room, April 12, 2021. The CEOs and senior leaders were from industries affected by the chip shortage, including representatives from American semiconductor producers, tech companies, automotive manufacturers, and other companies that use semiconductors.

Well before the chip shortage, there was and still there is another shortage worldwide, that of *electronic engineers*.

The European Union has set itself, in September 2020, the goal of increasing in the short term its ability to design and manufacture nanometer chips, in its declaration signed by 22 EU countries: "*A European Initiative on Processors and semiconductor technologies*" [24], a key aspect of its open strategic autonomy [25], [26]. Having a production and design base of electronic components becomes not only necessary for the competitiveness of European companies, but also strategic for the security and resilience of the Union. Thierry Breton, EU Commissioner for Internal Market, said: "Europe has all it takes to diversify and reduce critical dependencies, while remaining open. We will therefore need to set ambitious plans, from design of chips to advanced manufacturing progressing towards 2-nm nodes, with the aim of differentiating and leading on our most important value chains." In March 2021, the EU announced its plan to increase its share of the global semiconductor market to 20% by 2030. With this in mind, the European Commission pledged $160 billion of its Covid-19 recovery fund to tech projects on the continent. In September 2021, German company Infineon Technologies opened its new €1.6 billion chip factory for power electronics on 300-millimeter thin wafers at its Villach site in Austria [27]. Also French-Italian STMicroelectronics, industry leader in the field of MEMS (Micro Electro-Mechanical Systems) and SiC devices, inaugurated in November 2020 a new 200-mm fab dedicated to MEMS and a $2 billion 300-mm fab in June 2021, both in Agrate, near Milan, Italy [28]. Besides, the company will build a new €2 billion module with new personnel in its Catania plant, focusing on SiC technology [29], and decided and expansion in the Crolles (France) plant.

4. Another Long-Termed Shortage: That of Electronic Engineers

Well before the chip shortage, there was and still there is another shortage worldwide, that of *electronic engineers* [30]–[33]. This lack affects companies' ability to fill key positions and replenish an aging workforce. Over a longer period of time, it can hinder the pace of growth of the entire sector.

The reasons for this shortage are several. The manufacturing industry is facing a wave of retirement unlike any other due to aging of the workforce [34]. Electronic engineers move into other engineering professions and even non-engineering ones that can offer either better salaries or more independence or better social status. Only a limited fraction of teenage girls is interested, despite the fact that the sector offers good careers with good gender equality. Women represent only 10–25% of the semiconductor workforce across all roles and functions [35].

However, the principal cause is the general decreased interest of the younger generations in a discipline, perhaps erroneously considered mature, which instead continues to evolve and provides answers to new challenges. One reason for this decline in interest is probably due to the markets and economic strategies of Western countries which in the recent past have focused on the advanced tertiary sector. From the new economy of the end of the previous century we moved to the web economy in which service companies such as Google, Amazon, Facebook, and Netflix rise in the collective imagination to models of successful brands and profit. Another reason is that software developments, especially app developments, requires simplicity of means, give the creator a quick sense of intellectual achievement and are economically rewarding at the same time. Intellectually satisfying jobs in integrated circuit design are instead rather limited to specialized circuit design or complex device engineering and such opportunities are like craftsmanship, requiring several years of previous industry experience or higher education before one is even allowed to begin work in such areas. But perhaps a subtler reason is that it is definitely not clear to public opinion -but also to the decision makers, opinion leaders and the mass media- what the electronic engineer does and what is his primary role in the digital revolution. This problem is even more serious than it apparently seems. To just cite one example, the word semiconductor never occurs in the Future of Job Reports 2020 of the World Economic Forum [36], while the word electronics is associated only to Electronics and Telecoms Installers and Repairers, jobs that are of course less and less in demand.

It is necessary to make it clear that electronics is not a static, inexhaustible and ready to use commodity. On the contrary, it is in continuous development in order to support the acceleration undertaken by the knowledge society and this development is enabled by electronics. The automotive sector is only the last in which the introduction of electronics adds value, efficiency, intelligence and functionality, revolutionizing the market. In the recent past this was the case for many other mechanical

Focusing on tertiary services without giving a parallel boost to enabling technologies, including training highly skilled personnel, can only lead to unsustainable progress.

equipment: the typewriter has been transformed into a personal computer, the analog camera into a digital camera, the pinball machine into a game station, the telephone into a smartphone.

The reason for this success is linked to the exceptional qualities that semiconductor technology has shown: its progressive miniaturization capability with a parallel increase in performance, the extraordinary containment of the electrical power required for the same function and, last but not least, the remarkable reduction of costs. An incessant investment in research and development has made semiconductors the most refined technology that man has managed to invent, a technology at the nanoscale dimension that has allowed the explosion of portable battery-powered applications with enormous data processing and connectivity capabilities. After the breakthrough in the automotive market and electric cars, electronics is preparing to permeate more and more the biomedical, health and wellness fields. Chips implanted in the human body will allow recovery from accidents and serious neurological diseases such as epilepsy, Alzheimer's and Parkinson's [37]. In the future, nanoelectronics will cover increasingly broad areas, many of which are still to be explored. For these reasons there will be a continuously increasing need for specialized personnel who are already very scarce and sought after.

According to the Semiconductor Research Corporation, five fundamental breakthroughs will define the next decade of semiconductors and information and communication technologies [38]: 1) Implementing smarter world-machine interfaces that can sense, perceive, and reason, to pursue analog-to-information compression with a practical ratio of 105:1 analogous to the human brain; 2) Designing radically new memory and storage solutions with new storage systems and technologies with >100× storage density capability; 3) Addressing the imbalance of communication capacity vs. data-generation rates enabling data transmission of 100-1000 zettabyte/year at the peak rate of 1Tbps; 4) Addressing emerging security challenges in highly interconnected trustworthy AI systems, secure hardware platforms, and emerging postquantum and distributed cryptographic algorithms; 5) New computing paradigms are needed demonstrating dramatic >1,000,000× improvement to meet ever-rising energy demand for computing versus global energy production.

Glenn O'Donnell, research director at analyst firm Forrester, said there is a shortage of people in Silicon Valley with the skills required to design high end-processors. "Despite its name, Silicon Valley now employs relatively few real silicon engineers. Silicon Valley put so much emphasis on software over the past few decades that hardware engineering was seen as a bit of an anachronism. It became *uncool* to do hardware" [39].

5. Promoting Electronics to Young People

In a very general view, electronic engineering transforms basic research technologies into reliable new devices and products that can improve human life and experiences. There will be little advancement of truly innovative applications and services if we stop at the electronics available today [38]. And today's applications could not exist with the electronics of just 5 years ago. In the near future, new semiconductor devices, new integrated circuits and new electronic systems will be needed to create 5G/6G networks, smart cities and smart industries, IoT, self-driving cars, artificial intelligence, telesurgery, quantum computers or other innovations yet to be invented. Digitalization doesn't just focus on data management as a core skill. Data is obviously a strategic asset, but a fully integrated digital value chain requires hardware infrastructures that have to be often invented or optimized for the purpose[7]. Those improvements are mainly managed by electronic engineers.

Specifically, the semiconductor industry needs several specialized professional profiles including: Process Engineer, Design Engineer, Design Verification Engineer, Device Engineer, Packaging Engineer, Application Engineer, Field Application Engineer, System Engineer, Test Engineer, Validation Engineer, Technology Engineer, Technical Sales Engineer, Software and CAD Engineer, Product Marketing Engineer, Information Technology Engineer, Facilities Engineer, Maintenance Engineer, Quality Engineer, Reliability Engineer. Many of these specializations require almost exclusively a master's degree in electronic engineering. A subset of these jobs can be found in many other high-tech companies, not primarily focused on electronics, from aerospace to telecommunications and robotics, from

[7]For example, for many companies, the inability to locate a critical component in the warehouse can compromise an entire assembly cycle. Today, technologies such as RFID (radio frequency identification) tags use an attachable tag containing a microchip that stores the unique identification (ID) of each object. Improvements in this technology made it possible to write the RFID memory chip at any time, other than read only it, and allowed the identification of a large number of tags simultaneously with a reading range of several meters. Wider and more interesting applications are enabled by addressing the miniaturization of antenna, sensors, battery, including power harvesting and data encryption capabilities.

instrumentation to biomedical, and research centers as well. They all have at least one department that requires electronic engineers devoted to hardware development and embedded systems[8] design in innovative products.

To give an idea how the role of electronics and of electronic engineers in our society is not fully understood, not only by public opinion, but also at the highest decisional levels, it would be enough to mention the letter that the Semiconductor Industry Association, SIA, (which includes Intel, IBM, Nvidia, Texas Instruments, AMD, Analog Devices, etc.) sent U.S. President Joe Biden on February 11th, 2021 [40]:

> "Dear Mr. President,… Semiconductors are critical to the U.S. economy, American technology leadership, and our national security. They enable the technologies needed to realize your Build Back Better goals, including smarter and safer transportation, greater broadband access, cleaner energy, and a more efficient energy grid, while also providing high-paying jobs for Americans and strengthening our advanced manufacturing base. During the pandemic, semiconductor-enabled technologies have aided researchers in developing life-saving vaccines and helped Americans work and learn remotely. Investments in domestic semiconductor manufacturing and research will allow more of the components fueling U.S. economic growth, jobs, and infrastructure to be made here, while simultaneously enhancing our national security and supply chain resilience to meet future challenges. … We therefore urge you to include in your recovery and infrastructure plan substantial funding for incentives for semiconductor manufacturing, in the form of grants and/or tax credits, and for basic and applied semiconductor research."

The letter from the SIA (but there is another one, very similar, from lobbying groups for the auto, healthcare and telecommunications sectors [41]) prompts us to two thoughts. First, focusing on tertiary services without giving a parallel boost to enabling technologies, including training highly skilled personnel, can only lead to unsustainable progress and a future full of dangers, such as looming chip shortages. Second, if giant companies like IBM or Intel feel the need to explain the fundamental function of electronics and semiconductors to the U.S. President, then public opinion must also be informed on the professions and opportunities of the electronics industry, especially families and teenagers that have to decide for their future working careers.

It is the author's opinion that one of the most important actions that seems to be missing is an effective, long-term communication program towards the younger generations and their families to raise awareness of Electronics. In fact, to reverse the trend of talent shortage, universities have been discussing and implementing renewed teaching programs and learning environments for years, increasing and improving laboratory activities, creating information days for high school students, setting up scholarships, startup ecosystems, etc. Communication alone is obviously not enough. Many universities have outdated infrastructure, metrology equipments and research facilities, which are essential to remain relevant to semiconductor industry and its state-of-the-art tools. National program investments in university are therefore needed to improve infrastructure, to create new faculty positions and to engage industry researchers in university activities [43].

Also in line with the above claims, the industry has come up with new and different programs. Among them: contacting STEM high school students and exposing them to the industry; strengthening partnerships and research and development efforts with universities, business incubators and accelerators; organizing internships and summer schools; improving branding programs. In addition, national/international associations and foundations have worked to promote electronics through publications[9], video clips, electronic games[10], competitions, by providing greater visibility of female models in the sector[11], etc. But all these operations remained isolated and were only partially successful.

The job market today is global and requires global solutions. The time has come to definitely intensify partnership between governments, universities, industry, and associations to promote and perhaps pretend the

[8]An embedded system is a combination of hardware and software designed for a specific function. It has a central computational component (e.g. a microcontroller) that may be interfaced with internal memory and input/output components. Hardware is strictly limited to the function in order to reduce cost, time and tools required for its implementation.

[9]For instance, the author is member of the Italian Society of Electronics (*SIE*) which produced a brochure titled "L'elettronica inventa il tuo futuro" (Electronics invents your future) [42]. The brochure is realized with the contribution of some important Italian industrial companies and is intended for use by the SIE affiliated research units of virtually all Italian universities during the orientation days with high-school students. In pandemic years, with distance learning, the brochure revealed quite timely and useful.

[10]*IEEE Volta* is an app developed by *IEEE Solid-State Circuits Society* (SSCS) aiming at educating the general public about the importance and the history of ICs over the years. *Zappy Squirrel* is an edutainment app developed by Juego Studios for the *IEEE* and designed around the core idea of the IEEE 1264-2015 standards with methods and designs to protect electric power supply substations from animal intrusions. Also UK Electronics Skills Foundation (https://www.ukesf.org), with the contribution of the *IET* and *IEEE CAS* has developed several tools.

[11]The *Women's Leadership Council* harnesses the leadership of those women who have risen to the top ranks of the semiconductor industry to provide inspiration and sponsorship for the next generation of female leaders.

inclusion of Electronics in career guidance, to motivate high school students and to upskill and reskill workers. Specialized diplomas recognized by companies promising reasonable pay packages should be further developed specifically for emerging regions.

In this context the *IEEE* is highly sensitive, and has already provided resources for STEM pre-university education through platforms such as the *IEEE* Learning Network (ILN). The *IEEE* could effectively serve as an international reference, also by developing expressly designed materials and tools, freely accessible by teenagers, for the worldwide implementation of an efficient information campaign.

5. Conclusion

The paper discussed the effects of COVID-19 on the ecosystem of the semiconductor industry and the reaction of governments and companies through global investment programs and policies aimed at building new factories and facilities. However, strengthening semiconductor manufacturing infrastructures alone will not be enough, if this is not accompanied by a policy aimed at inspiring, encouraging and motivating the training of young students who need to be informed about the opportunities and the relevance of electronic engineering for our society and economy. The availability of good engineers is indeed one of the key elements that makes the difference in this highly competitive market, even without building new fabs. According to [44], 90% of the labor force in the United States and South Korea is composed of high school graduates (as of 2015) and of more than 98% in Japan and Taiwan. Although China's level of innovation is high, China currently cannot compete effectively with developed countries due to its low education rates (30%). Moreover, while U.S. accounts for only 12% of global chip production in 2020 (down from 37% in 1990), U.S. companies account for 47% of global chip sales (over South Korea 20%, Japan 10%, Europe 10%, Taiwan 7%, and China 5%). **U.S. companies comparative advantage is engineering**[12].

Our future is more and more technology-driven: new materials have to be found and their physical properties must be optimized and engineered to obtain a piece of technology usable for data and energy conversion, storage and transmission, but the current shortage of IC's was preceded by a shortage of electronic engineers that continues until today. The demand for electronic engineers right now exceeds the number of graduates, and the gap would be more severe in the future. National investments in university are needed to improve infrastructure and to create new faculty positions.

However, we have seen how the professional figure of the electronic engineer, and his fundamental role in digital transformation, is not adequately understood. The time has hence come to intensify partnership between government institutions, universities, professional and volunteering associations, and companies for a joint effort to motivate, upskill and reskill students and workers.

Of course, a strong, long-lasting motivating campaign cannot guarantee that a teenager is necessarily encouraged enough to invest his or her life and career in this field, as every person has his or her own inclinations and may or may not develop an interest. However, an information program is needed, at least to allow a teenager to consciously choose their future work by evaluating all the opportunities that the field of electronics and semiconductor offer. *IEEE* in this framework could play an important dissemination role.

The electron has been for decades and still is the most efficient and most economical physical means of enabling telecommunications and computers, that characterized the information and communication age and opened the doors to the digital era. If another cheaper, faster, and even more efficient physical medium is found in the future, electronic engineers will likely still design applications for it.

[12]Apple, for instance, has recognized that working closely with software and hardware engineers enables the design of more energy-efficient laptops and desktops, with better performance and new features and, possibly, cheaper. For this reason, Apple now has its own integrated circuit designers and having in-house chip designers could be the future policy of leading high-tech companies.

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He has published more than 100 international journal papers, 120 conference proceedings, and is the co-author of the books CMOS Current Amplifiers (1999), Feedback Amplifiers: Theory and Design (2001) both edited by Kluwer Academic Publishers, and Liquid Crystal Display Drivers-Techniques and Circuits (Springer 2009). His H-index (Scopus) is 32.

Dr. Pennisi is *Fellow IEEE* and is member of the *IEEE* CASS Analog Signal Processing Technical Committee and served as an Associate Editor of the *IEEE Transactions on Circuits and Systems-Part II: Express Briefs* and of the *International Journal of Circuit Theory and Applications*. He is also member of the national board of the Italian Society of Electronics (SIE).

References

[1] "2021 state of the U.S. semiconductor industry," Semiconductor Industry Association. [Online]. Available: https://www.semiconductors.org/wp-content/uploads/2021/09/2021-SIA-State-of-the-Industry-Report.pdf

[2] K. Hille, "Semiconductor cycle out of balance after customers stock up," Financial Times, Feb. 16, 2021.

[3] J. Whalen, J. Stein, and R. Albergotti, "Growing computer-chip shortage alarms Biden and Congress," The Washington Post, Feb. 24, 2021.

[4] G. De Vynck, "What you need to know about the global chip shortage," The Washington Post, Mar. 1, 2021.

[5] J. Partridge, "Global chip shortage hits car production in China and Japan," The Guardian, Jun. 30, 2021.

[6] A. Blum, "From cars to toasters, America's semiconductor shortage is wreaking havoc on our lives. Can We Fix It?," Time, Jun. 28, 2021.

[7] "Bluebook sales data," World Semiconductor Trade Statistics, 2020–2019.

[8] "Q3 global semiconductor sales increase 27.6% year-to-year," Semiconductor Industry Association, Nov. 1, 2021. [Online]. Available: https://www.semiconductors.org/q3-global-semiconductor-sales-increase-27-6-year-to-year/

[9] A. Fitch, "Chip shortages are starting to hit consumers. Higher prices are likely," *Wall Street J.*, Jun. 21, 2021.

[10] https://media.ford.com/content/dam/fordmedia/North%20America/US/2021/02/03/fin-4q20-ford.pdf

[11] https://media.gm.com/media/us/en/gm/home.detail.html/content/Pages/news/us/en/2021/feb/0203-semiconductor-statement.html

[12] "Chip shortage forces Ford, Toyota, Nissan, FCA to cut vehicle production," Reuters, Jan. 8, 2021. https://www.reuters.com/article/us-honda-output-idUSKBN29D1NF

[13] J. Szczesny, "FCA cuts production due to chip shortages: Automakers concerns growing with no easy answer in sight," The Detroit Bureau, Jan. 14, 2021. https://www.thedetroitbureau.com/2021/01/fca-cuts-production-due-to-chip-shortages/

[14] D. Clark "Chip shortage creates new power players," NY Times, Nov. 08, 2021.

[15] "Intel breaks ground on two new leading-edge chip factories in Arizona," Sep. 24, 2021. [Online]. Available: https://www.intel.com/content/www/us/en/newsroom/news/intel-breaks-ground-two-new-leading-edge-chip-factories-arizona.html#gs.h4s645. "Intel announces next US site with landmark investment in Ohio," Jan. 21,2022. [Online]. Available: https://www.intel.com/content/www/us/en/newsroom/news/intel-announces-next-us-site-landmark-investment-ohio.html#gs.n46wrl

[16] "Micron is investing more than $150 Billion in global manufacturing and R&D," Oct. 2021. [Online]. Available: https://www.micron.com/manufacturing-expansion

[17] "Texas Instruments to begin construction next year on new 300-mm semiconductor wafer fabrication plants," Nov. 17, 2021. [Online]. Available: https://news.ti.com/texas-instruments-to-begin-construction-next-year-on-new-300-mm-semiconductor-wafer-fabrication-plants

[18] C. Ting-Fang and L. Li, "TSMC founder chides US plan for full chip supply chain onshore: Chang calls domestic push unfeasible, with $52bn in subsidies far too little," Financial Times, Nov. 3, 2021.

[19] "TSMC to invest $100 billion over 3 years to meet chip demand," Reuters, Apr. 1, 2021. [Online]. Available: https://www.reuters.com/article/us-tsmc-investment-plan-idUSKBN2BO3ZJ

[20] S.K. Moore, "South Korea's $450-billion investment latest in chip making push," *IEEE Spectr.*, May 26, 2021.

[21] *China's New Semiconductor Policies: Issues for Congress*. Congressional Research Services, Apr. 20, 2021. [Online]. Available: https://crsreports.congress.gov/product/pdf/R/R46767

[22] M. Lapedus, "China accelerates foundry, power semi efforts," Semiconductor Engineering, Nov. 22, 2021. [Online]. Available: https://semiengineering.com/china-accelerates-foundry-power-semi-efforts/

[23] "China's SMIC to invest $8.87 bln for new chip plant in Shanghai," Reuters, Sep. 3, 2021. [Online]. Available: https://www.reuters.com/technology/chinas-smic-invest-887-bln-new-chip-plant-shanghai-2021-09-03/

[24] https://www.eusemiconductors.eu/sites/default/files/uploads/20201209_EuropeanInitiativeonProcessorsandsemiconductortechnologies.pdf

[25] L. Kelion, "EU seeks to supercharge computer chip production," BBC News, Mar. 9, 2021. https://www.bbc.com/news/technology-56334210

[26] "Communication from the commission-annual sustainable growth strategy 2021," European Commission, Sep. 17, 2020. [Online]. Available: https://eur-lex.europa.eu/legal-content/en/TXT/?qid=1600708827568&uri=CELEX%3A52020DC0575

[27] "Infineon opens high-tech chip factory for power electronics on 300-millimeter thin wafers," Sep. 17, 2021. [Online]. Available: https://www.infineon.com/cms/en/about-infineon/press/press-releases/2021/INFXX202109-098.html

[28] "STMicroelectronics inaugurates new state-of-the-art 200mm MEMS production line in Italy," Nov. 27, 2021. [Online]. Available: https://investors.st.com/news-releases/news-release-details/stmicroelectronics-inaugurates-new-state-art-200mm-mems

[29] A. Larizza, "Catania, STMicroelectronics punta sul super silicio per l'auto elettrica," Il Sole 24 ore, Mar. 30, 2019.

[30] A.L. Robinson, "A way to end the IC designer shortage," *Science*, vol. 209 no. 4453, pp. 260–261, Jul. 1980, doi: 10.1126/science.209.4453.260.

[31] "EE shortage hits U.K.," EETimes, Nov. 13, 2000. https://www.eetimes.com/ee-shortage-hits-u-k

[32] "IET skills and demand in industry." 2019 Survey. https://www.theiet.org/media/4812/skills-survey2019.pdf

[33] Y. Tsividis, "Turning students on to circuits," *IEEE Circuits Syst. Mag.*, vol. 9, no. 1, pp. 58–63, 2009, doi: 10.1109/MCAS.2008.931746.

[34] "The aging of the manufacturing workforce: Challenges and best practices," The Manufacturing Institute, Jul. 2019. [Online]. Available: https://www.themanufacturinginstitute.org/wp-content/uploads/2020/03/MI-Sloan-Aging-in-the-MFG-Workforce-Report.pdf

[35] "GSA: Women in the semiconductor industry survey results 2019," Global Semiconductor Alliance and Accenture. [Online]. Available: https://www.gsaglobal.org/wp-content/uploads/2020/05/BRIEF-GSA-Women-in-the-Semiconductor-Industry-Survey-Results-2019.pdf

[36] "The future of jobs report 2020," World Economic Forum, Oct. 20, 2020. [Online]. Available: https://www.weforum.org/reports/the-future-of-jobs-report-2020

[37] C. Mora Lopez, "Unraveling the brain with high-density CMOS neural probes: Tackling the challenges of neural interfacing," *IEEE Solid-State Circuits Mag.*, vol. 11, no. 4, pp. 43–50, Fall 2019, doi: 10.1109/MSSC.2019.2939338.

[38] "The decadal plan for semiconductors: a pivotal roadmap outlining research priorities," Semiconductor Research Corporation, Oct. 2020. https://www.src.org/about/decadal-plan/

[39] S. Shead, "Tech giants are rushing to develop their own chips — Here's why," CNBC Interview, SEP 6 20217. [Online]. Available: https://www.cnbc.com/2021/09/06/why-tesla-apple-google-and-facebook-are-designing-their-own-chips.html

[40] https://www.semiconductors.org/wp-content/uploads/2021/02/SIA-Letter-to-Pres-Biden-re-CHIPS-Act-Funding.pdf

[41] https://www.semiconductors.org/wp-content/uploads/2021/02/CHIPS-multi-assn-letter-feb-18-2021_1.pdf

[42] https://www.associazione-sie.it/images/2020/brochure_sie.pdf

[43] "Reasserting U.S. leadership in microelectronics-the role of universities," MIT White Paper, Jan. 2022. [Online]. Available: https://usmicroelectronics.mit.edu/

[44] H. Li, L. Prashant, R. Scott, and W. Binzhen, "Human capital and China's future growth," *J. Econ. Perspectives*, vol. 31 no. 1, pp. 25–48, 2017, doi: 10.1257/jep.31.1.25.