Learning from the past:
50 YEARS OF RESEARCH IN MICROELECTRONICS IN ROMANIA

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ABSTRACT

This paper is celebrating 50 years of research in semiconductor devices and microelectronics. The first research centre (1969), becoming later a research institute (ICCE, 1974) was created in the middle of the industrial platform for semiconductor industry and it was meant to facilitate the industrial growth and then to complement the activity of this industry. ICCE expanded and diversified its activity at the political demand (part of the unrealistic policy of avoiding any imports), collapsing after 1990 (the personnel decreased from 1500 to 200, in 1996). Still, the experience of engineers and researchers was extremely useful when ICCE merged with IMT, in a national institute focussed on microtechnologies, i. e. semiconductor technologies used to construct microsensors and microsystems, following the EU orientation. IMT was successful in participating to a record number of European projects, and also benefiting from the correlation of national programmes with EU policy, the structural funding a.s.o.

KEYWORDS: semiconductors, microelectronics, microtechnology, nanotechnology, microsensors, microsystems, cyber-physical systems, experimental infrastructure, Industry 4.0.

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There is still *plenty of room at the bottom*

1. Foreword

In the *motto* above we adapted the title of the famous talk *Plenty of room at the bottom*[2] presented by Richard P. Feynman (Nobel's Prize laureate) in December 1959, to the American Physical Society, in Pasadena, California. The idea was to miniaturize our tools or devices, going down in scale towards the fine structure of the matter. Incidentally or not, the *integrated circuit* was invented the same year (1959). The tiny electronic device called *transistor*, as a replacement of the bulky vacuum tube already existed. However, the integrated circuit was putting together, in the

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[2] We are quoting from the above talk *Miniaturizing the computer. I don't know how to do this on a small scale in a practical way, but I do know that computing machines are very large; they fill rooms. Why can't we make them very small, make them of little wires, little elements—and by little, I mean little. For instance, the wires should be 10 or 100 atoms in diameter, and the circuits should be a few thousand angstroms across. Everybody who has analyzed the logical theory of computers has come to the conclusion that the possibilities of computers are very interesting—if they could be made to be more complicated by several orders of magnitude. If they had millions of times as many elements, they could make judgments………………. There is nothing that I can see in the physical laws that says the computer elements cannot be made enormously smaller than they are now. In fact, there may be certain advantages.* For full text see https://web.pa.msu.edu/people/yang/RFeynman_plentySpace.pdf

same piece of semiconductor material, a number of transistors and their interconnections. This was the true vehicle of implementing the idea of miniaturization and exploit its immense potential, as predicted by Feynman (see the text selected in the footnote). The advantages proved to be not only reducing the dimensions, but also reducing the cost per function and improving the reliability. A few years later, Gordon Moore predicted an exponential increase of the number of transistors in an integrated circuit. The so-called *Moore's law* (purely empirical) was used for decades in planning the advances of semiconductor industry dedicated to integrated circuits. The performances of computers increased tremendously, not only by increasing the number of transistors *per* integrated circuit, but also adapting a system architecture inspired from the human brain. This physical complexity plus a new generation of *software* putting the *hardware* (based on electronic circuits) to work, allow us to speak today about the *artificial intelligence*, fulfilling the prediction of Richard Feynman about the computers *making judgements.*

The professors at the Electronics Department in Bucharest (Tudor Tănăsescu, Mihai Drăgănescu) introduced the study of transistors quite early and already in the sixties Romania developed a semiconductor factory (IPRS – Băneasa, established in 1962) envisaged to fulfil the requirements of a local electronic industry, with a Department of Integrated Circuits starting in 1970. Almost at the same time (1969) we can notice the occurrence within IPRS-Băneasa of the **Centre of Research and Design for Electronic Components** (CCPCE), an organisation becoming later the **Institute of Research for Electronic Components** (ICCE). In 1996 ICCE merged with the **Institute of Microtechnology**, becoming the National Institute for Research and Development in Microtechnologies (IMT Bucharest) we have today (www.imt.ro). Therefore, we can celebrate *half a century of institutional research in electronic components* (1969 - 2019). However, we cannot speak about this continuity ignoring (a) the tremendous technological progress of semiconductor industry in the *microelectronics era* (formally starting with the advent of the *microprocessor* in 1971), as well as (b) the dramatic change of the political and economic system in Romania. As a result, in an open economic landscape our semiconductor manufacturing disappeared, but due to the enormous investments required now in the field, *even the biggest companies and the richest economies in Europe can hardly keep pace with the global competition*. And, as clearly demonstrated in this new millennium, as far the progress of technology is concerned, *the research follows production*. Therefore, a natural question arises: is there *any future for research in this field in Europe in general and in Romania in particular*? Or, as suggested at the beginning of this paper, do we have anything to do today *at the bottom*?

In our vision the answer should be positive. First, because we can use in computing systems physical effects at the dimensional levels *below* those envisaged by Feynman (nanodevices, quantum effects) and this requires research. Suffice to say that Romania (and particularly IMT Bucharest) is involved in European research projects[3] devoted to such subjects. The details are left for **Annex I**.

Secondly, because the on-going 4th industrial revolution, or Industry 4.0 (see **Annex II**) is relying in particular upon the *cyber - physical systems*, such as *Internet of Things (IoT),* connecting, among others, such trivial and cheap thinks as packages and waste. Connection should be done with inexpensive devices for example by using paper instead of a semiconductor material and printing techniques instead of expensive microelectronic technology. Going down (at the bottom!) with cost in a variety of applications means also a broad field of research, and plenty of room for innovation in small companies.

[3] We are speaking about FET projects, FET meaning *Future Emerging Technologies*, i.e. potential revolutionary technologies with a possible impact at the time horizon of 10 years.

Therefore, *going briefly through the history,* in this paper we shall try to *envisage the future of the domain in this country.* Specifically, we shall look at the organizational assets and underline what we consider to be important for research and innovation in a group of high technologies, including microelectronics[4].

2. Chronology of organizational development

The geographical location for industry and research entities in the field of semiconductors and microelectronics is the so-called Băneasa industrial platform, North of Bucharest. The starting point was the set-up in 1962 of the *Enteprise for Radio Components and Semiconductors* (IPRS - Băneasa). Inside this factory, the **Centre of Research and Design for Electronic Components (CCPCE)** was established in 1969. The first Director was Prof. **Mihai Drăgănescu,** the head of the Departament for Electron Devices and Circuits from the University Politehnica of Bucharest, at that point in time leading a Governmental body for electronic computers. Since 1970 the Director was **Ioan Bătrâna** and the Scientific Director **Constantin Bulucea**. The centre was oriented on the most appropriate semiconductor material (silicon). Since 1974 the centre became the **Institute of Research for Electronic Components (ICCE)** and moved to separate buildings. The Director was Dr. Constantin Bulucea[5].

A characteristic feature for the following years was that the research groups from ICCE initiated new entities of fabrication or departments of the existing ones, sometimes using foreign licenses. The most important one was the enterprise *Microelectronica* (1993). The personnel acted for development of technologies on advanced equipment. Therefore, ICCE nurtured with human resources the extension of industry of electronic components on the Băneasa platform and beyond.

In the second decade of existence of CCPCE/ICCE (with Ioan Bătrâna as Director after 1983), the institute extended its activity beyond research in electronic components, reaching in 1989 the record number of 1500 employees. The national policy favoured isolation (reducing imports means that almost everything had to be produced inside the country). The first step was a department for *small-scale production* (1979) based on the research done within the institute, then a department *applications* (1980) and a department for *manufacturing equipment* (1985). This extreme broadening of the activity spectrum has determined its evolution after December 1989. In 1991, the institute separated in four entities, with about 500 people left in the research institute itself and the above three departments separated as independent commercial companies. These companies failed sooner or later in the open market economy and, to a certain extent ICCE lost its reason of existence, surviving with difficulties until 1996 (only 200 people), when it merged with IMT, as shown below.

It is worthwhile to have a look at the fate of the industrial companies still existing in 1990 on the Băneasa industrial platform. The oldest of them, IPRS – Băneasa, was much better prepared for competition in the open market, due to a number of factors. With less financial help from the communist state and the experience to adapt to internal and external markets, IPRS was ready to

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[4] This paper uses some information from the presentation Dascălu, Dan. Marius Bâzu. *Jubileul cercetării românești în domeniul semiconductori /microelectronică. 50 de ani de la înființarea primei unități de cercetare în domeniu,* Spring session (28 March 2019) of CRIFST/DIT (ppt presentation, in Romanian, available at www.link2nano.ro/50micro). For the history of the National Institute for R&D in Microtechnologies (IMT Bucharest), two other references (also in Romanian), elaborated by the same author are available: the web page www.link2nano.ro/retroIMT, and the paper Dascălu, Dan. *IMT București,retrospectiva ultimilor 20 de ani de evoluție,* Market Watch, Nr. 184, mai 2016, pp. 26-28

[5] For a more detailed history of ICCE, see Chapter 4 (author Marius Bâzu) in the volume *Romanian school of micro- and nanoelectronics* (in Romanian, coordinated by Dan Dascălu), Publishing House of the Romanian Academy, 2018.

develop appropriate policies for the new economic environment[6]. The organizational culture was open to internal interactions, providing flexibility to challenges and opportunities. The engineers had already experience in developing new products and new technologies, in scientific research[7] or in cooperating for the development of needed equipment[8]. IPRS Băneasa became, soon after 1990, Băneasa S.A., then splitting in a few factories, corresponding to previous departments. These factories had a different survival chance. The chance was lower for integrated circuits (with a fierce global competition) and higher for power semiconductor devices (especially for automotive industry), a field emerging in the nineties. Finally, the lack of national policy related to industry and the disaster of privatization put an end to all activities (2008).

On the other hand, **Microelectronica S.A (ME)**, with the most advanced technological capabilities, was to a large extent captive to a system of economic and technical cooperation developed in the former socialist countries (the so-called COMECON/CAER). The East-European system provided cooperation in production[9], as well as a common market for the products of ME. The company was at the top of its production in 1990, but the disappearance of the economic cooperation within the former communist system brought ME in a very difficult situation, with a very small and continuously reducing local market, no cooperation opportunities on the Băneasa platform, and the key leading persons simply leaving the country. The survival of ME was provided for a few more years, under very special conditions, as shown below.

In 1991 the **Centre of Microtechnology** (directed by **Dan Dascălu**) was set up in order to take over most of the ME company (semiconductor fabrication line, design department) and develop research in the new field of *microsystems* (see **Annex I**) by using the production line of integrated circuits. The idea was a visionary one[10], because, years later, the semiconductor technology was indeed used industrially to fabricate micro-electro-mechanical systems (or MEMS). The Ministry of Scientific Research (Doru Dumitru Palade, see ***Fig.1***) provided funding for supporting this endeavour and even introduced in the National Plan a special topic called *microtechnologies* (i.e. technologies of microsystems). The financing of this topic in Romania was started in 1993, one year earlier than in European Union. In 1993, CMT became **Institute of Microtechnology (IMT)**. From 1993 to 1997 the fabrication line and the Computer Aided Design (CAD) for integrated circuits from ME have been managed by IMT and the personnel was detached to the institute. The subsidy from the research funds enabled continuation of manufacturing of integrated circuits, but at a level of only 10-15% from the production capacity (the domestic demand was very low). The attempts to extend the fabrication profile to power devices with a European company interested to invest, or to get an American licence for designing industrial processors failed due to the lack of support from authorities[11].

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[6] It was impressive to see how fast IPRS developed a policy of marketing, trying to make the resources and capabilities of the company visible to all potential clients and partners.

[7] Scientific research was done by IPRS in cooperation with ICCE, Faculty of Electronics from the Polytechnic Institute of Bucharest etc., resulting in products, technologies, patents, scientific publications. A few specialists completed their Ph. D. studies in electronics and physics

[8] To a certain extent we can speak about an *open innovation* philosophy. This is a very attractive concept characterized as follows *organization's boundaries become permeable and that allows combining the company resources with the external co-operators* (see https://www.innoget.com/open-innovation-definition).

[9] E.g. ME provided the packaging the microprocessor chips fabricated in Eastern Germany

[10] Dascălu, Dan, *O sămânță care a rodit,* Academica, Vol. XXVII, mai-iunie 2017, pp.53-55 (talk at the anniversary session *25 de ani de la înființarea Secției de știința și tehnologia informației, 29 mai 2017,* Aula Academiei Române).

[11] For details, see Dascălu, Dan. *O fereastră spre viitor,* Academica, Vol. XXVIII, iulie-august 2018, pp.72- 78.

The same Minister of Scientific Research initiated the merging of IMT with ICCE (see above), thus creating (1996) the **National Institute for Research and Development in Microtechnologies**, or **IMT Bucharest** (General Director **Dan Dascălu**, until 2011). The new institute employed at the beginning 370 people (including the ones detached from ME). However, in March 1997 the contract with ME was terminated (the enterprise was about to be privatized) with detached people going back to the factory. Only a few engineers from ME remained with IMT, and the access to the technological line of ME was discontinued. This ended the daring experiment of transforming a factory into a research institute, showing once again a lack of correlation between the policies of the Romanian government. Due to a number of valuable researchers striving to succeed in a new field, the institute survived during difficult times. From time to time an international success signalled that the institute was on the right track: the first European project, MEMSWAVE (1998-2001), the Samsung laboratory (2003-2004). A campaign of investments in experimental infrastructure started in 2006, with the last major investment finalized in 2015. By the end of the mandate of Dan Dascălu as the General Manager[12], IMT was certified by EC (report on innovation, section devoted to Romania) as the most performant national institute in European programmes.

Fig. 1 The visit of Minister for Scientific Research *Doru Dumitru Palade* (left) at IMT, in Microelectronica S.A. He is accompanied by Dr. *Marius Guran*, Counsellor at the Romanian Presidency and Acad. *Dan Dascălu* (right), General Manager of the institute.

3. The evolution of the intangible active assets – human resources

Our approach is to learn from the past by examining the evolution of key assets of ICCE – IMT. The **active assets** for a research institute are **tangible** (buildings, equipment, capital) or **intangible** (human expertise, intellectual property, connections[13], image). What we consider

[12] From July 2011 to January 2017, the policy of the former Director general was continued by Dr. Raluca Muller. Since January 2017, the institute is headed by Dr. Miron Adrian Dinescu.

[13] For a commercial company we should list licensing agreements, joint ventures, trade secrets etc.

relevant for our case is the evolution of human resources, the development and full use of experimental infrastructure, the communication policy (partnership, public relations, image).

The human resources have been essential for the evolution of the research in our domain, briefly described here as microelectronics: semiconductor devices – integrated circuits – microelectronic technology – micro-and nanosystems (see **Annex I**). The prominent role of the Faculty of Electronics and Communications, with a specialization related to the field, is beyond any doubt. On the other hand, the entire landscape of the domain, including research laboratories and production lines created a *school* in the broad sense of the word, with training in using equipment and learning in managing practical problems. Surprisingly enough, the doctoral school from the Department of Electron Devices and Circuits (at least until 1990, with Prof. Mihai Dragănescu as the only Ph. D. supervisor) played only a minor role in upgrading the specialization of researchers from ICCE. Only Constantin Bulucea sustained his thesis (1974) in this context, other Ph. D. students supervised by Prof. Drăgănescu worked out their thesis in various domains, including semiconductor devices, in the university labs, in IPRS – Băneasa and abroad. On the other hand, Constantin Bulucea, with a M. Sc. (1970) at the University of California, Berkeley proved to be a *mentor* for his colleagues at ICCE and also an excellent teacher for the students of the Electronics Department in Bucharest. It is also worth mentioning his scientific cooperation with Prof. Adrian Rusu, former Head of the Department of the Electron Devices and Circuits. Otherwise, before 1990 the specialization abroad (except short training stages) was of little importance and the interaction with foreign professors was an exception (***Fig. 2***).

Fig. 2 This is the first collective image with young researchers from ICCE, attending a lecture about technology of very large-scale integrated (VLSI) circuits, delivered by Prof. *William G. Oldham* (University of California, at Berkeley) in the Polytechnic Institute of Bucharest (1977).

ICCE has grown valuable human resources in its basic domains of activity – research on semiconductor devices and design of integrated circuits. Some of these specialists left Romania before or after December 1989, sometimes developing an outstanding career abroad. The remaining professionals formed the basis for the new National Institute – IMT Bucharest, or contributed to the teams of CAD companies with subsidiaries in Romania. On the other hand, the huge diversity of activities around semiconductors, involving various technical activities and developed in a very short time, upon political demand, failed to have a similar contribution to valuable human resources, or at least they did not leave visible traces.

We already mentioned *the new orientation towards microtechnologies* (including microsensors and microsystems) promoted by CMT and IMT after 1991. We have also to underline the substantial contribution to the specialization of Romanian people from various disciplines and organizations in this multidisciplinary field by the *Physical Electronics Research Centre* (Prof. Dan Dascălu) at the Electronics Faculty, University "Politehnica" of Bucharest (UPB). We are speaking about the coordination (1991-1993) of two projects in the European programme TEMPUS. The partners of UPB have been the most reputable institutes and universities from Europe with pioneering activities in microtechnology. Some of the young people benefitting from these TEMPUS grants providing specialization in the above organization started in this way a brilliant international career. Others continued to work in IMT/ICCE or in other Romanian organizations. At this point, it is worthwhile to note that the funding under the *microtechnology* topic by Ministry of Research starting 1993 has been attributed not only to IMT, but also to ICCE and other organizations.

Merging of ICCE with IMT within the new national institute (IMT Bucharest) provided most of the human resources for research laboratories. Some of the *traditional ICCE laboratories* (microwave devices, photonic devices) have been maintained, but firmly reoriented towards microtechnology/microsystems. And a long time after, **the first centre of excellence** with European funding (2008-2011) after Romania joined UE has been the so-called **MIMOMEMS** centre grouping the above two labs from IMT. On the other hand, the *new Laboratory of Nanotechnology* (perhaps the first of this kind in Romania, 1996), established also with ICCE specialists, acquired an international recognition, whereas since 2002 until 2017 was placed *under the aegis* of the Romanian Academy, with the name *Centre of Nanotechnologies* (CNT-IMT). When Acad. Ionel Haiduc, the President of the Romanian Academy visited IMT in 2009 (***Fig. 3),*** CNT-IMT was already grouping three research laboratories. Other new laboratories, including specialists originating from ME (Microelectronica S.A.) have also been successful in European programmes, with IMT Bucharest recognized in June 2011 as the best Romanian National Institute in this respect. However, it was a long way towards this performance.

Fig. 3 Acad. *Ionel Haiduc* (left), former President of the Romanian Academy, is visiting IMT Bucharest, accompanied by Dr. *Irina Kleps*, the Coordinator of the Centre for Nanotechnologies (CNT-IMT) and Acad. *Dan Dascălu*, General Director of IMT

Shorter after merging with ICCE, as already mentioned, the contract with ME was terminated and IMT was left with the obsolete experimental infrastructure of the *small ICCE*, restructured after the separation of three commercial companies (1991). At the same time, a significant reduction in research funding brought the new IMT in difficulties. A new brain drain was unavoidable. Still, the quality of the specialists and the reorientation towards new topics provided a chance in European competition, even if the IMT researchers had to perform the most significant experiments in ……. foreign laboratories. However, the effort was visible and appreciated by the European Commission (EC). In February 2004, the European Commissioner for Research *Philippe Busquin*, visited the institute, calling IMT *a pioneer of integration in ERA (European Research Area).*

Gradually, after 2005 the financing of research improved, and significant investments in infrastructure have been possible. Around 2010 the brain drain was ………. reversed. Researchers with a Ph.D. abroad completed the teams, or entered the new laboratory headed by Dr. Radu Cristian Popa (Ph. D. at the University of Tokyo). On the other hand, doctoral studies in electronics, physics, chemistry, biology have been completed by young researchers from IMT, basically developing the experimental part of their doctoral thesis within the institute. Moreover, IMT was the coordinator of a project for postdoctoral studies with structural funding (2010-2013). A multidisciplinary team of professors (headed by Dan Dascălu) supervised the postdoctoral studies of 35 researchers (approximately half of them from IMT). The postdoctoral students received substantial grants for doing extra work in their organisations. The project had a significant impact on the scientific output (especially through papers published in high rank journals).

4. The evolution of the tangible active assets – experimental infrastructure

How to use the research infrastructure? The importance of the experimental infrastructure for research in high-tech domains (and not only) is beyond any doubt. On the other hand, just the existence of new and performant equipment, sometimes simply exposed as a piece of expensive furniture, can be misleading. The new pieces of equipment are almost always computerized, helping the researcher to control the function and extract useful data. However, the researcher is not simply an operator. He or she has a specific scientific experience, a competence in a certain domain. In micro- or nanotechnology is extremely important to define the objectives to be attained with a specific equipment and to be able to adequately prepare the *probes* for a certain experiment[14]. Things may become much more interesting when a colleague with a completely different experience and a different scientific interest approaches you in order to use your equipment. The exchange of knowledge can be simply useful, but this could also be *the beginning of a beautiful ..... cooperation in research* (just to mimic the famous reply at the end of the celebrated movie *Casablanca*). In fact, even for characterization of a probe (a sample from a new material, an experimental device) you need quite often a few pieces of equipment, each of them managed by a different researcher. Can you imagine[15] how complex the interaction between people could be in such a case?

[14] We all know in Romania that the laser of ELI-NP (Extreme Light Infrastructure, Nuclear Physics) is already able to provide pulses with instantaneous power of 10 petawatts. However, the experiments should be done with the laser beam interacting with specifically prepared targets. These targets should be constructed by micro- and nanostructuring.

[15] However, this is just imagination! Maybe you, a valuable Romanian researcher, do not want to share ideas with your colleague, because any idea may lead to a project proposal, and a financed project means … money and glory you do not want to share! *Let's see what happens abroad.* In experimental facilities of campuses (e.g. in Grenoble, France) the Ph. D. students have individual access to each piece of equipment, after a preliminary (hands-on) training. *Just like that! But do not ask about the maintenance costs!* This approach is not valid for very complex and expensive equipment such as a transmission electron microscope (TEM). Companies also can access the experimental infrastructure, after paying a fee. For obvious reasons, the company wants to keep all other people away, when experimenting new ideas, leading to a potentially new product.

IMT is exploting opportunities for investments in infrastructure. One decade after the merging of IMT with ICCE, the new institute took the opportunity of a call for proposals financing investments in new laboratories. IMT submitted eight proposals, all of them successful (sharing the first place in the competition, with the University *Babeș-Bolyai* from Cluj-Napoca having the same number of projects).

A combined investment and equipment available to all researchers. The IMT proposals came from several different research groups. However, because proper operation of equipment required mechanical stability and clean atmosphere, all new labs have been established in different rooms, along the same corridor, at the ground floor, in the *clean room* area[16]. Each equipment was operated by a specialized researcher, as an extra-job, as he or she had to help a colleague. The practical result was sharing the use of the above equipment between different laboratories[17]. At this point we are mentioning the fact that sharing the knowledge is not important only for an efficient research, but also for the most acclaimed *open innovation.* Likewise, an experimental infrastructure open to various external users is simply called *open infrastructure.*

International visibility is important. In May 2009, IMT was launching in Brussels IMT – MINAFAB (IMT centre for MIcro – and NAnoFABrication), the first *open infrastructure in this field in Eastern Europe.* The event was attended by EC officials and country representatives.

How the infrastructure is open to various customers? The philosophy of this facility[18] was to provide various types of services to various categories of customers or partners, as shown in **the following Table 1** (see www.imt.ro/MINAFAB).

An important step in making IMT-MINAFAB attractive for industry was providing ISO certification for the quality of services of this facility (since 2011), whereas the **systematic use by the companies** had to wait the implementation (2016-2021) of the structural funding project TGE-PLAT (www.imt.ro/TGE-PLAT). Within this project, funding was also provided for dedicated research interesting industrial companies.

Another significant project with structural funding was launched by IMT in 2010 and finalized in 2015. It resulted in a new infrastructure, a **centre of nanotechnology and carbon-based nanomaterials** called CENASIC[19]. The infrastructure of this centre is used by a multidisciplinary group of researchers from various laboratories of IMT.

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[16] At this point we have to underline the fact that, when reconstructing and exploiting the specific infrastructure, IMT benefitted from the experience of personnel working previously on the semiconductor platform. This was making a difference, which was obvious when comparing the performances achieved by different research institutes in the attempt to construct and exploit *clean-room* type facilities.

[17] This practice is not as natural as it seems. The author knows the example of a prestigious research institute from Bucharest. It had to purchase two identical pieces of equipment for two laboratories, because the laboratory heads thought that this the natural solution. 15 years ago, at the Cornell University, Ithaca, N.Y. I heard the confession of a professor in charge of a research centre. I am quoting. *Coming from IBM research, I had to tell to my university colleagues that is not important who is the owner of a certain equipment, but what are you doing with this equipment.*

[18] Dascălu, Dan. Raluca Müller, Rodica Voicu, Andrei Avram, Alexandru Müller, Ioana Giangu, Mihaela Kusko. *Infrastructura de cercetare a IMT – o platformă de interacţiune şi parteneriat*, „Market Watch", Nr. 180, noiembrie-decembrie 2015.

[19] Müller, Raluca. Adrian Dinescu, Mircea Dragoman, Radu Popa, Dan Dascălu. *IMT relansează ofensiva high-tech via CENASIC: Un centru performant de nanotehnologie și nanomateriale bazate pe carbon* (cover story), „Market Watch", Nr. 182, februarie-martie 2016, 22 martie 2016.

Table 1. Services provided by IMT-MINAFAB for various categories of customers.

	Partnership in RTD activities, sharing the IP resulting from research	Scientific and technological services, including design and consultancy	Direct access, "hands-on" activities (after appropriate training)
Research groups outside IMT	Usually financed by a contract of partnership. Direct access of researchers from partner organizations.	Typically, specific activities performed by IMT as subcontractor (computer design, characterization, technological processing etc.), with no IP rights.	Typically, as part of common research and technology development (RTD) activities.
Educational bodies for Ph.D. and postdoctoral studies, M.Sc. studies, "hands-on" training etc.	Supported by individual grants or following an agreement with universities, specifying the cost and intellectual property issues.	Occasional.	As part of a common research activity, or providing training on a commercial basis.
Companies (industry)	Special NDA (non-disclosure agreement) and IP (industrial property) use agreements.	Providing services on a commercial basis.	Companies may use their own IP rights.

Fig. 4 shows an equipment for Atomic Layer Deposition (ALD). The most important material studied in CENASIC is the so-called *graphene* i.e. a one-atom thick layer of carbon, with extremely promising properties for electronics (Nobel Prize for Physics, 2010). This is much below the dimension level considered by Richard Feynman, demonstrating again *how much room is* still *at the bottom* (see the *motto* of the present paper).

Communication

Communication (and whenever possible - collaboration) between people, organisations and countries should be a *must* for research organisations.

Fig. 4 A picture taken from the *clean room of the CENASIC experimental infrastructure* (the new centre within IMT), showing an equipment for *Atomic Layer Deposition* (ALD)

In 1978 ICCE organized the first edition of the **Annual Semiconductor Conference** (CAS). The conference was conceived by Dr. Constantin Bulucea, Director of ICCE at international standards. It was an extremely important opportunity for scientific communication in Romania, as far as the access to scientific events taking place abroad was strongly limited. People from university, industry and research meet every year outside Bucharest, for a 3-day conference. It was also an opportunity for social events including families (***Fig. 5***).

Fig. 5 Group photo with the participants to the 1984 edition of the *Annual Semiconductor Conference* (CAS).

It was the merit of ICCE to transform CAS into an international event (International Semiconductor Conference, CAS) in 1991, and then into an IEEE event (1995). After merging with ICCE, IMT continued to organize the conference and to extend it with satellite events, mainly related to the European projects[20]. CAS reaches in 2019 its 42nd edition (9-11 October, Sinaia), see www.imt.ro/cas. IMT played a key role in local organization of ESSCIRC/ESSDERC[21] in September 2013, in Bucharest (for the first time in Eastern Europe, after four decades).

The policy of communication of IMT was promoting the following strategic targets: a) research in micro- and nanotechnologies at the national scale; b) European cooperation; c) interaction with industry.

IMT Bucharest organized, from 2000 to 2017, the **National Seminar for Nanoscience and Nanotechnogy**, under the aegis of the Romanian Academy. Some of the editions of this seminar were devoted to the promotion of national programmes and/or European cooperation. IMT was (2004-2008) the coordinator of a number of **three support projects financed by European Commission.** They have been devoted to promotion of European cooperation in research at the national level, at the level of Estearn Europe, and in UE, respectively. The last two have been focussed on micro- and nanotechnologies. A prospective study of nanotechnology in Romania (2010-2011) was developed and the results are still accessible at www.imt.ro/NANOPROSPECT. The micro- and nanotechnology topics in the national plans for research and the participation of Romania in European programmes proved the success of the above efforts.

The interaction with industry was promoted by IMT, first by creating specific infrastructures: Centre for Technology Transfer (CTT-Băneasa), Science and Technology Park (MINATECH-RO). Then IMT was involved in projects devoted to technology transfer and support of research required by companies. Last, but not least, IMT contributed to the organization (2010) of the **NanoElRei Summit** (NanoElectronics in Romania: Research-education-industry), see ***Fig. 6***.

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[20] Dascălu, Dan, *Cea de a 40-a ediţie a Conferinţei Anuale de Semiconductori*, Academica, XXVII, septembrie 2017, pp.42-45.

[21] We are speaking about the *European Solid State CIrcuit Research Conference* (ESSCIRC) and *European Solid State DEvice REsearch Conference* (ESSDERC).

Fig. 6. NanoElRei Summit (Bucharest, 20th of April,2010). From left to right Dr. *Raluca Muller*, Scientific Director of IMT, Dr. *Andreas Wild,* Excutive Director of ENIAC JU, Prof. dr. ing. *Sorin Dimitru,* President of CCAB (Chamber of Commerce and Industry Bucharest), Prof. dr. ing. *Adrian Curaj*, President of ANCS (National Authority for Scientific Research).

5. Lessons to be learnt

A. National policy. Our presentation has been focussed on the industrial platform Băneasa. The policy of industrialization had at the beginning a positive effect, creating the semiconductor industry, fabricating electronic components to be used in all electronic industries. The research institute, ICCE, contributed to the diversification of this industry. During the last decade of the communist regime, avoiding any imports put a high pressure on the industry (and on the citizens, as well). The research institute experienced an explosive growth, in order develop everything internally. It was an artificial construction, collapsing after 1990. The new authorities ignored almost completely the problems of industry, subjected to an overwhelming competition by the imported products. The *help* provided to Microelectronica SA through IMT was also without any industrial perspective. For a few years, the industrial research institutes (losing their industries!) benefitted from support ……. before collapsing. Today, as a UE country, we have a very low level of funding in research and a very low performance in innovation. Therefore, the competitivity is low with no sign that the authorities understand what does this mean on a long term. Apart from the well acclaimed ELI-NP project, there are no clear priorities, concentrating the efforts of universities, research universities, companies. This makes the development of the strategy at the institute level a difficult task.

B. Research management. Beyond any doubt, ICCE contributed to the development of valuable human resources in the field of semiconductors/microelectronics. As shown above, no clear perspective existed for ICCE after 1990, before merging with IMT. *The chance of IMT was to use the existing expertise to benefit from the new opportunities*. The domain of competence was the lucky choice for IMT, because it had a long-term evolution, allowing the institute to couple to the European research[22]. Despite the rapid progress of the industry at the global scale, there is still some work to do in the field of micro- and nanotechnologies, either for the local innovative companies (see the project TGE-PLAT, mentioned above), or for advanced technological research[23]. Perhaps the merit of the IMT management was to **keep the track despite any**

[22] The Romanian research authorities had also the merit to acknowledge and support this process.

[23] In 2019 IMT is active in four new European projects, three of them within the FET-OPEN programme of advanced technological research (note the fact that Romania is involved in a total of four such projects). Two of the FET-OPEN projects (namely CHIRON an IQubits) are related to *spintronics* for *quantum computing*, mentioned above as being beyond the limits foreseen by Richard P. Feynman. For details see Nicoloiu, Alexandra, Aldrigo, Martino, Müller,

difficulties and exploit fully the opportunities (visibility in European research, availability of funds for investments in infrastructure etc.). We also think that it was a good idea to *play the card* of new technologies benefitting *all* potential actors, and advocate the funding of meaningful topics in national programmes. This is because you need both a *critical mass* and a *positive feedback* at the national level.

C. Human resources. Any successful strategy at the national or organisational level must have in mind the researcher. He is the main actor in research and innovation. It is not an easy job to be researcher in Romania today, fighting to get financing from various sources, especially within calls for proposals. You have to compete against your colleagues, to waste a lot of time in writing unsuccessful proposals, to lose your focus when looking for various calls and partnerships. Even if you are successful in one call or another, you will have your funding delayed, for example you will have to provide salaries for your team for five years, instead of three, wasting money for materials or equipment, loosing opportunity to valorise your idea at the proper time. Nobody can blame you that you lack big achievements and your work is fragmented and superficial. **The politicians do not understand your problems, but your research manager has to!** At the level of your research unit, the management should strive to provide you, as an honest researcher, a proper climate for a true research work, beyond any constraints of formalism and bureaucracy. And, above all, to facilitate an open communication and cooperation between various teams.

Final message for the manager (or *captain)*. Is the above task too difficult? It seems risky to *sail* through such turbulent waters? Yes, of course, but **you are the leader**, **you have the responsibility** of your *ship* and of your *team*. So, be *strong in will/ To strive, to seek, to find, and not to yield* (**Ulysses**, by *Alfred, Lord Tennyson*)[24]

6. Annex I Basic concepts of microelectronics

The **information and communications technologies** (ICT) are based on **electronic technology**. Information processing is done by **electronic circuits**, i.e. electric circuits with specific functions, having **electron devices** as key components. Their name comes from the fact that their behaviour is governed by the control of electron flow, the electron being the elementary particle, carrying a negative electric charge, part of the atoms. The unique property of certain electron devices (called *active*) is their ability to deliver power (extracted from a direct current source, e.g. a battery) to a signal carrying information. This is the way we perform **amplification** of signals, e.g. amplify very weak signals received in an antenna of a radio receiver.

The electronics of the first half of the XX century was dominated by **vacuum valves** as electron devices, with **triode** as the basic active devices. The triode was also used as a switch in digital circuits, manipulating binary information (represented with only two digits, 0 and 1). The first digital computer built with vacuum tubes was bulky, power consuming and unreliable. The replacement of the vacuum tube with a solid-state triode called **transistor** (1947) was extremely promising, because the new electron device, constructed in a semiconductor material, was smaller, cheaper and more reliable. But the second major step was the integration of circuit components and connecting wires in a single piece of semiconductor, called **integrated circuit** (1959). The continuous miniaturization increased the complexity of integrated circuits, constructed in **silicon** as

Alexandru *IMT își confirmă vocația europeană: 4 noi proiecte câştigate în Horizon 2020 (3 FET-OPEN + 1 ICT),* Market Watch, martie 2019, pp. 20-22.

[24] See https://www.poetryfoundation.org/poems/45392/ulysses.

the semiconductor material. The most important device in the present-day integrated circuits is the **MOS transistor**. Its key structure consists in a metal (M) oxide (O) semiconductor (S) capacitor, and the basic physical phenomenon is electrostatic control of the current flow at the semiconductor surface. The device parameters are controlled by the geometry at the semiconductor surface. The dimensions of the transistor surface geometry can be scaled-down maintaining the device parameters, thus opening the way of miniaturization[25]. The first microprocessor, with 4,000 transistors, was constructed in 1971. The advent of MOS microprocessor marks the occurrence of the **microelectronic industry** (key dimensions of the transistors of the order of microns, or micrometres). Today the number of transistors integrated on a *chip* (a piece of semiconductor) was increased by more than six orders of magnitude, due to extreme miniaturization. We are speaking about **nanoelectronics**, with key dimensions brought down to tens of nanometres. The functionality/cost ratio increased considerably making complex systems for computing and communications affordable. The cost of fabrication facilities is measured in billions of USD and, more important, the miniaturizing process seems to be limited due to physical constraints. However, other phenomena could be exploited in the future, e.g. quantum effects at the atomic level (*quantum computing)*, so ….. it seems that it will be still *room at the bottom.*

Another important concept is the integration of a complete system into a single component. An electronic system should have an interface with the external world. The interface is provided by transducers, namely **input transducers** (sensors) and **output transducers** (actuators). Sensors are converting physical signals (such as variation of temperature or variation of the intensity of a magnetic field) into an electrical signal, to be processed by the electron circuit. An important technological achievement was using microelectronic technology to construct miniaturized transducers, i.e. **microsensors** and **microactuators**. This was opening the possibility to construct the entire system in one piece of semiconductor, for example an intelligent sensor comprising a microsensor and the electronic circuit for signal processing. Such an integrated system is called a **microsystem,** or a micro-nanosystem. For example we can have micro-electro-mechanical systems (MEMS) or a micro-opto-electro-mechanical systems (MOEMS). The MicroSystem Technology (MST) is also called microtechology[26]. In the broad sense, microtechnologies (i.e. technologies allowing fabrication of features of the order of micrometers) is not restricted to electronics and can be also used in traditional industries (see the advent of *mechatronics*).

Quite often, fabrication of microtransducers requires materials and processes which are not common with the fabrication of integrated microelectronic circuits and therefore they are requiring a separate fabrication line. Still, the microsystems can be integrated in hybrid technologies, with microtrasducers and the integrated circuit for signal processing packaged in a single component. It is worthwhile to note that microtechnology is extremely attractive for a) arrays of microsensors, b) chemical sensors, and biosensors. For example, integrated microfluidic systems, or **laboratories on a chip** (lab on chip) are useful in various applications.

The on-going *Horizon 2020* (2014-2020) is promoting micro- and nanotechnologies in the new form of Key Enabling Technologies (KETs), involving (among others) micro- and

[25] Another important consequence was the fact that the design of integrated circuits, based on surface geometry, was separated from the technology of fabrication, and *fabless* companies of *computer aided design* (CAD) proliferated. At the same time, *silicon foundries* concentrated on fabrication only, providing the execution of new components developed by different companies for various applications. This specialization on CAD and fabrication, respectively, was shortening the duration of development of new products, critically dependent upon the performance of integrated circuits.

[26] The birth of the present Institute of Microtechnology is related to the idea of Acad. Mihai Drăgănescu of using the existing microelectronic fabrication line for developing microsensors and microsystems in a research institute.

nanoelectronics, micro- and nanophotonics, nanotechnology, advanced materials (including nanomaterials). This approach is now confirmed for *Horizon Europe* (2021-2020) and reshaped in connection with digital technology[27].

7. Annex II From the 3rd to the 4th industrial revolution

The 1st industrial revolution was related to mechanization by using water power and steam power. The second one (with mass production and assembly lines) was driven by electricity. The 3rd industrial revolution (with computer and automation) is based upon digital technology supported by the integrated circuits fabricated with microelectronic technology. We are now at the beginning of **the 4th industrial revolution**, characterized by **Cyber Physical Systems[28]**. The limits between physical, digital and biological spheres are blurred. A simple example is provided by the *Internet of Things* (IoT), where sensors are placed on various objects, information is collected by wireless communication, partially processed in a local network and then transferred through *cloud* technology to the final users. The complexity of the 5th generation of wireless technology (5G) is also at the level of CPS. In cyber-physical systems, *physical and software components are deeply intertwined, each operating on different spatial and temporal scales, exhibiting multiple and distinct behavioral modalities, and interacting with each other in a lot of ways that change with context.* Examples of CPS include smart grid, autonomous automobile systems, medical monitoring, process control systems, robotics systems, automated pilot avionics, medical diagnosis etc[29].

We are stressing the following facts implied by the extension of CPS. *First*, we need a broad range of transducers for the interface with the physical world (including chemical and biological signals), involved in a variety of system architectures. *Secondly*, some applications require producing this interface at very low cost, and the microelectronic silicon techn-ology is no longer able to produce solutions[30]. Therefore, there is *plenty of room* for innovative small companies to come with solutions for *niche* applications.

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[28] See for example https://en.wikipedia.org/wiki/Cyber-physical_system.

[29] Pathology goes digital, see *This is how a pathologist could save your life,* IEEE Spectrum, pp. 24-29, December 2018.

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