Re-inventing Postgraduate Level Teaching and Learning in Nanoelectronics

Mladen Božanić[1], *Senior Member, IEEE*, Saurabh Chaturvedi[1], *Senior Member, IEEE*, and Saurabh Sinha[2], *Senior Member, IEEE*

[1]Department of Electrical and Electronic Engineering Science, [2]Faculty of Engineering and the Built Environment
University of Johannesburg, Auckland Park Kingsway Campus
Johannesburg, South Africa
E-mail: mbozanic@ieee.org, chaturvedi.s.in@ieee.org, ssinha@ieee.org

Abstract*—In the world where technology changes almost daily, the field of microelectronics or nanoelectronics is becoming an area driving the future. Therefore, more engineers specializing in micro- and/or nanoelectronics are needed in industry internationally. Globally, a distinct shift in nanoelectronic education has already been observed, where postgraduate coursework and part-coursework degrees in microelectronics and nanoelectronics are now being offered alongside the traditional research or coursework degrees in electronics or electrical engineering (light currents). However, in South Africa the situation is lagging; microelectronic or nanoelectronic specializations are offered either as honors degrees or as the research-based studies mentioned, with no dedicated coursework specialization at the master's level. The Faculty of Engineering and the Built Environment of the University of Johannesburg (UJ) has, therefore, diversified the program and qualifications mix because of this need to teach nanoelectronics at the master's level as well, via global part-coursework and a part-research method of delivery. However, approval for a new degree takes a number of years to be completed. Therefore, as an alternative route, nanoelectronic modules with some cross-disciplinary and multi-disciplinary modules are offered as continuing education programs (CEPs) at National Qualification Framework levels 8 and 9. The CEPs bear continuing Engineering Council of South Africa professional development credits, and can be credited as modules in the envisaged master's degrees. The CEPs are delivered via an online approach, which develops student accessibility and brings about flexibility for students who are studying part-time. Enhanced accessibility and the fast-growing level of internet access in Africa will allow the UJ to serve students both regionally and internationally. This paper explores the rationale for the chosen content of the CEPs and ultimately the proposed master's degrees and discusses in detail the online mode of delivery and its benefits, as well as the approach taken to deliver courses according to this model, together with innovative opportunities.

***Keywords*—Nanoelectronics, Continuing education, Blackboard Learn platform, Electronic design automation (EDA), Virtual reality (VR) laboratory, Part-coursework.**

I. INTRODUCTION

Owing to rapid technological development, new and smart devices, including cell phones, tablets, fitness and health trackers, among others, which offer an increased number of features, are becoming ever more popular and widely used. The field of microelectronics, in view of the further decrease in minimum device size, often termed nanoelectronics, is becoming an area driving the future. Therefore, more engineers specializing in micro- and/or nanoelectronics are needed in industry internationally [1, 2]. Globally, a distinct shift in nanoelectronic education has already been observed [3, 4]. Many institutions, including top-ranked or Ivy League universities, offer postgraduate coursework and part-coursework degrees in nanoelectronics and similar fields as a continuing education step after traditional degrees in electrical, electronic or computer engineering. This is in addition to traditional research degrees already offered at master's level.

In South Africa, the situation is lagging. Most institutions offer microelectronic or nanoelectronic specializations either as honors degrees, or only as research master's or doctoral studies. This trend is evident when one repeatedly searches (by using different keywords) the South African Qualifications Authority database of the registered degrees in South Africa [5]. In addition, the University of Johannesburg (UJ), Johannesburg, South Africa is one of several South African institutions that does not offer or require honors degrees, i.e., National Qualification Framework (NQF) level 8 in electrical or electronic engineering, allowing students to enter the research-based master's degree studies (NQF level 9) directly after completing the four-year bachelor's degrees (also NQF level 8). Specialization can, however, assist to fast-track student development, thereby decreasing the minimum time to completion. The Faculty of Engineering and the Built Environment (FEBE) has therefore identified a need for teaching nanoelectronics at this level via global part-coursework ("specialization") and a part-research method of delivery.

It is a vision of UJ that in the near future at least two master's degrees will be offered. One master's degree will be offered online fully by the FEBE's Department of Electrical and Electronic Engineering Science, and at least one more degree will be offered as a joint degree with a partner institution, also in part online. However, approval for a new degree takes a number of years to be completed, while a number of academic quality assurance steps are accomplished [6].

An alternative route to nanoelectronic education can thus be proposed. In this route, nanoelectronic modules, as well as some cross-disciplinary and multi-disciplinary modules, can be delivered as continuing education programs (CEPs). In the context of UJ, CEPs were formerly referred to as short learning programs (SLPs); in this manuscript "CEPs" and "SLPs" will be used interchangeably and mean the same. Since a typical coursework master's degree can contain modules at NQF levels 8 and 9 [5], the said SLPs can be presented at either of the two levels. In addition, the SLPs bear continuing professional development credits defined by the Engineering Council of South Africa [7] and can thus be credited as the modules in the envisaged master's degrees. In parallel with the ever-increasing cost of education and recent developments in South Africa striving to provide free (#FeesMustFall) high-quality education, UJ has risen to this challenge through online education innovation.

In this paper, the rationale for the chosen content of the SLPs and ultimately the two master's degrees is explored and the online mode of delivery and its benefits, as well as obstacles, are discussed in detail. The rest of the paper is organized as follows: In Section II, microelectronics and nanoelectronics are defined more formally, and the rationale behind teaching microelectronics and nanoelectronics in global and local context is discussed. In Section III, the approach of delivering SLPs is discussed. In Section IV, two proposed master's degrees are explained, and some of the challenges associated with instituting joint degrees are discussed. Finally, Section V concludes the paper.

II. MICROELECTRONICS AND NANOELECTRONICS: DEFINITIONS AND RATIONALE FOR TEACHING

Two related fields, microelectronics and more recently, nanoelectronics, can be defined as microtechnology and nanotechnology applied in the context of electronic circuits and systems, respectively [8]. Typically, microelectronics and nanoelectronics mean the same thing, that is, circuits that are fabricated in a sub-micrometer process, the so-called integrated circuits (ICs). Some researchers consider the emerging fabrication processes with transistor gate lengths below 100 nanometers as nano-processes rather than micro-processes. Since the focus is slowly but surely shifting towards "nano" as opposed to "micro", the term nanoelectronics will be used in the remainder of this paper. Furthermore, in the rest of the text, other electrical or electronic degrees, whether coursework or research-based, will be referred to as "traditional" degrees for ease of differentiation.

ICs typically include digital, analogue, mixed mode (or memory) and radio frequency (RF) circuitry. The scope of nanoelectronics is not limited to ICs alone and can include various other types of circuitry, such as sensors or actuators, micro-electro-mechanical systems, antennas or heat sinks, which are interconnected and packaged together to form a silicon on package (SOP) circuit [9].

Globally, nanoelectronics is taught at the postgraduate level, whereas only some basic theory is conveyed in undergraduate studies. The reason for this is the vastness of the field of electronics. The space for teaching nanoelectronics in the curriculum is limited; furthermore, advanced nanoelectronic concepts, such as device physics, could require prerequisite knowledge that in certain cases could only be obtained towards the undergraduate degree completion. In the past, undergraduate degrees used to be followed by research master's and doctoral degrees, but time has shown that students enrolling for research degrees typically lack the needed skills for timeous degree completion because of the inadequacy of undergraduate nanoelectronic or specialist education. The solution is sought, as mentioned in the introduction, in part-coursework or professional degrees. In a part-coursework nanoelectronic degree, the nanoelectronic modules need to cover many aspects of IC or SOP design flow, such as understanding of processes and technologies, physical circuit and component design, as well as practical aspects, such as design implementation, simulation and verification.

Furthermore, in the South African context, on a yearly basis, only a handful of students graduate with a postgraduate specialization in the field of nanoelectronics, which has resulted in a scarcity of qualified electronic engineers with advanced knowledge. With typical students wanting to move to postgraduate studies choosing a postgraduate degree or a specialization that is offered by the institution where they completed their undergraduate studies, it can be observed that most microelectronic engineers in South Africa come from either Pretoria or Stellenbosch. This is where South Africa's only universities offering microelectronic studies are located. By offering SLPs and later master's degrees via an online model, which will be discussed in much more detail in Section III, the geographical location of the UJ in Gauteng province is overcome through virtualization, and the courses would appeal to students all over South Africa and Africa who would otherwise enroll for other degrees at other institutions or simply decide not to continue with postgraduate studies at all. Since South Africa is a developing country and emerging economies have a tendency to have a program and qualification mix (PQM) that allows for specializations and also somewhat 'generalist'-level specializations in engineering, the addition of master's degrees in nanoelectronics aids in diversifying the PQM.

III. ONLINE MODE OF DELIVERY OF SHORT LEARNING PROGRAMS

In addition to the rationale presented in Section II, in the quest for the simultaneous efficiency and effectiveness of aspiring continuing education students of today, online

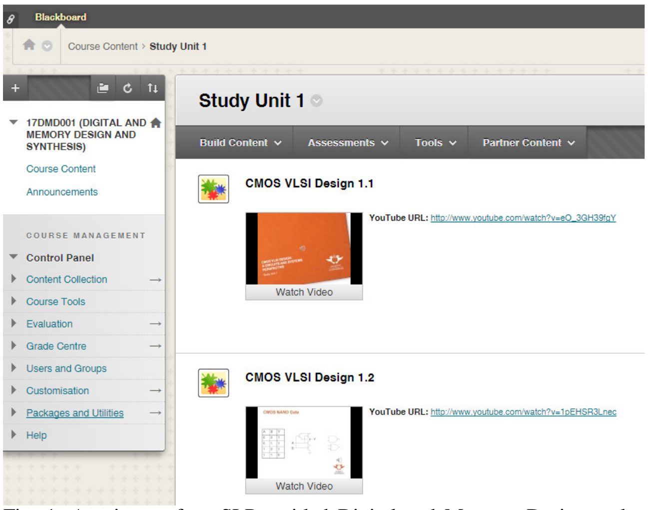

Fig. 1. A snippet of an SLP entitled Digital and Memory Design and Synthesis presented on Blackboard Learn.

education becomes a natural alternative for the nanoelectronics field. An online approach develops student accessibility and brings about flexibility for students who are studying part-time, which reflects the graduate-level student majority in engineering and engineering technology programs. Enhanced accessibility and the fast-growing level of internet access in Africa will allow UJ to serve students both regionally and internationally. An online approach further allows for cutting costs on various levels. Student costs are decreased because of removal of the need for lodging, visas for international students, etc. Lecturing costs are also cut in this approach because the lectures are recorded once, requiring once-off involvement of, typically, experts from industry on a part-time basis. In addition, physical lecture halls are not required in this approach. The same is the case with lecture laboratories, since the fabless approach, described later, is used in the practical component.

Additional benefits of offering CEPs online are found in the fact that the CEPs can run on the carousel (on demand) model, that is, as soon as the student registers and is ready to take the module, he/she can access the online content and assignments. When each student is ready, he/she can attempt completing the take-home examination assignment. In this model, the involvement of lecturers is minimal, since they are only needed to consult (using electronic means) with students and to evaluate the assignments and examinations. This means that the modules can be presented even by visiting personnel, that is, professionals practising in industry, typically those who have already been involved in module development and presentation.

Online content and examinations are delivered via the UJ Blackboard Learn platform [14] to registered students. A snippet of a module presented on Blackboard is shown in Fig. 1. This platform also allows for tracking of learning activities. Lecture videos can be watched multiple times, paused and resumed, allowing students to make the most of the recording. A built-in feature of the learning platform allows for delivery in subtitles – thus catering for multiple languages. Students are further encouraged to use electronic media to communicate with the module lecturers. Typically, this involves email and chat/voice services such as Skype or Google Hangouts ("Hangouts On Air with YouTube Live"), and file sharing using Google Drive or open-access platforms. With this approach, neither a student nor a module presenter has to be physically present on any of the campuses of the university. The contact sessions between the students and lecturers can be arranged at the convenience of both student and lecturer and can take place during or outside office hours. This also means that the potential time-zone differences, if a student enrolls from abroad, could become transparent, allowing industry professionals to remain involved. Even with limited contact with students, issues such as plagiarism are not a concern, because with a smaller number of students, for design-type questions, a unique solution is expected from each student.

A major drawback of the online model is the difficulty of implementing the practical component of an SLP. Fortunately, by the nature of the nanoelectronics industry, there has been a recent clear global shift towards the fabless approach and outsourced manufacturing, with the technology mediating the possibility to complete both theoretical and laboratory components using internet resources, e.g., computer-aided design tools, virtual or remote laboratories [11]. This approach is not possible, for example, in traditional low-current and high-current electrical engineering degrees. Typically, modules are designed so that open-access electronic design automation (EDA) tools can be used and can be included in assignments. In future, even virtual reality (VR) laboratory access is envisaged. Students are also motivated to develop and share their own EDA solutions, for example following a methodology described in [12]. The assignments will attempt, where possible, to make use of the learning-by-developing approach described by Laurea University of Applied Sciences, Vantaa, Finland [13]. In this student-centered approach, assignments give students an opportunity to do research based on current needs, use their research to come up with creative solutions and get practical experience.

To date, at least three SLPs are in the process of marketing and are rolling out, with additional SLPs expected to be rolled out during 2018. UJ is expected to see at least five students per SLP in the second semester of 2017.

The three SLPs that have been rolled out cover three vast topics that are important in nanoelectronics. The first module, Analogue and RF Microelectronics Design and Simulation, covers analogue and RF aspects of nanoelectronic design, and is seen as one of the two core specializations of nanoelectronics. Its digital counterpart is the second core module, Digital and Memory Design and Synthesis, covering the basics of digital and mixed-mode design. The addition of the third module, Engineering Research Proposal Writing, enables students to obtain credits for writing a research proposal for research to be pursued in their master's studies. In this SLP, students continuing towards research master's study have the opportunity to choose and work with a supervisor.

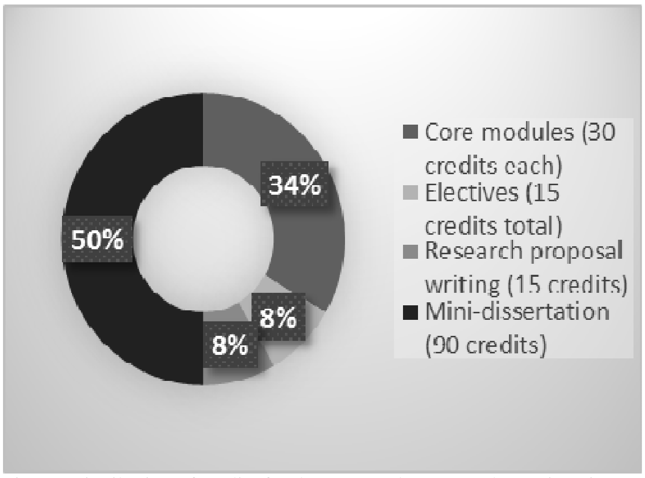

Fig. 2. Distribution of credits for the proposed master's degree in Micro- and Nanoelectronic Engineering at UJ.

The SLPs that are being developed in 2017 and 2018 are expected to cover aspects of power electronics, systems engineering, semiconductor processing and EDA, among other topics, and will later be used to build a pool of electives for proposed master's degrees, as discussed in the following section.

IV. TURNING SLPs INTO MASTER'S DEGREES

The vision of UJ FEBE is to utilize the prepared SLPs in at least two master's degrees. These master's degrees will have both coursework and research components, where one degree will be presented by the FEBE alone, and the second degree will be a result of collaboration with a partner institution.

A. Master's Degree in Micro- and Nanoelectronic Engineering

The duration of the study for a master's degree in Micro- and Nanoelectronic Engineering will be one year (two semesters, 90 credits each) and the requirements will be the two core modules (initially presented as SLPs described in the previous section), two electives, Engineering Research Proposal Writing and a mini-dissertation. As already mentioned, the electives are chosen from a pool of electives, which is currently being developed in the form of SLPs. The degree credit distribution is illustrated in Fig. 2.

Typically, research conducted in traditional postgraduate degrees is already conducted by the student in isolation (whether on campus or off campus), with some support by the supervisor through a limited number of contact sessions. As is the case with SLPs, the degree supervision will primarily be conducted using online communication tools, and general support to students will be offered via the existing university structures, such as the Centre for Academic Technologies (CAT), as well as library and administration staff. The mini-dissertation in the proposed degree will be done in a similar manner, with the exception that the open-access EDA tools will allow the student to work purely from home under supervision via electronic means. The online model will allow both full-time and part-time university personnel to be involved in supervision, thus opening up the opportunity for industry or science council experts to be brought in to assist with supervision as well.

B. Master's Degree in Engineering in Nanoelectronics

As a second alternative to formulating the curriculum, the BRICS initiative (Brazil, Russia, India, China, South Africa) seems to offer a solution where a version of the proposed nanoelectronic degree could be offered jointly with a BRICS partner. The first identified partner is the National University of Science and Technology (NUST), MISiS, of Moscow, Russia. MISiS is a university with a history of almost 90 years and remains one of Russia's leading teaching and research educational centers [15]. MISiS already offers several master's programs in English, with at least two having a very similar scope to that of the UJ's proposed master's degree in nanoelectronics. With roughly half of the modules of the degree entitled Quantum Physics for Advanced Materials Engineering fitting the proposed UJ degree, collaboration with the MISiS Department of Theoretical Physics towards a joint degree was established by means of signing applicable memoranda of agreement.

In order to instate the joint degree, the new degree has to be accredited in both Russia and South Africa. The process in South Africa would normally take between one and two years. In Russia, however, the process lasts for up to five years, but this issue was overcome by MISiS and UJ agreeing that the new degree would be presented as a variation of the existing accredited degree, namely the above-mentioned master's degree: Quantum Physics for Advanced Materials Engineering, albeit with 50 percent of the subject matter presented by the UJ, which is the requirement for the degree to be considered joint and for program recognition for subsidy in South Africa. The misalignment in credits is offset by the shared mini-dissertation module.

Several administrative challenges were anticipated and more are expected while implementing the joint degree. First, the joint degree needs to comply with the quality assurance requirements of the educational systems of both Russia and South Africa, most notably with regard to the credit distribution. Compliance with both systems was ensured by determining the duration of the degree as two years (four semesters) and 240 credits in total (a minimum requirement in Russia). Second, for entry into the existing master's qualification and for scholarship, the UJ electrical and electronic engineering undergraduate qualification or program prerequisite needed to be approved by the Russian system.

A number of technical challenges were encountered because of the geographical location of these two countries, that is, Russia in the northern hemisphere and South Africa in the southern hemisphere, as illustrated in Fig. 3, resulting in academic semester timing differences. This is closely related to when and where a particular module could be delivered. At each institution, for a typical degree, whether undergraduate or postgraduate, a student must enroll in the autumn semester. As a first attempt to a solution, the universities agreed that students should officially always start (enroll for the first semester) in September and commence studying in Russia in the Russian autumn semester; if they want to enroll in February, they should first complete modules offered by the UJ. A challenge closely related to this approach was aligning the prerequisites for the delivery of certain modules, as well as the timing of each module delivery. This was eased by the fact that the UJ modules were developed as online CEPs, only requiring the students to be physically present in Russia when enrolled for the modules presented by the MISiS, and in alternate semesters (when enrolled at the UJ), students can attend from anywhere in the world (Moscow included).

As apparent from the discussion above, MISiS modules are to retain their traditional walk-in method of delivery, primarily because of the strong practical component of the physics-oriented modules. As the degree gains momentum and the technology advances even more (e.g., already mentioned VR in laboratories), MISiS might benefit from an online mode of delivery as well. For the UJ modules, the online approach to the practical component of CEPs remains unchanged in the scope of the joint degree as well. As a result, the joint degree is a part-contact, part-online degree, with the costs cut to about half when compared to the alternative, that is, students enrolling for a physics degree offered solely by MISiS. A further benefit of the joint approach is that the student receives a degree recognized in both Europe and Africa.

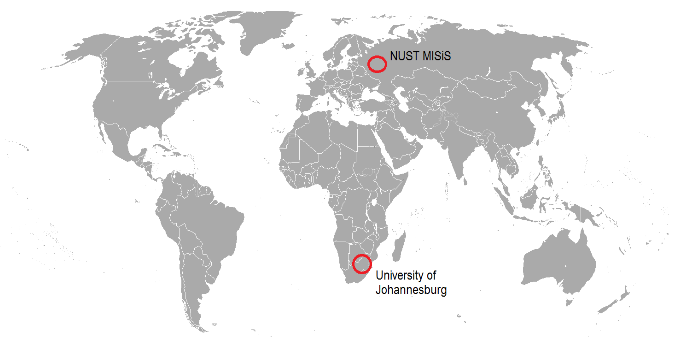

Fig. 3. Location of UJ and MISiS on the world map.

The research component (mini-dissertation) of the joint degree is shared by the two universities, where students can be supervised by lecturers from either university. The approach to the research module from the side of UJ remains the same as described in the case of the master's degree in Micro- and Nanoelectronics in Section IV.A.

The curriculum of the joint degree thus looks as follows: The joint master's degree in Nanoelectronics also has core modules (initially presented in the form of SLPs described in Section II, similar to the master's degree in Micro- and Nanoelectronic Engineering), totaling 60 credits. Electives of the original degree are replaced by the nanotechnology modules from MISiS, totaling 90 credits. The research component, once again, consists of Engineering Research Proposal Writing and a mini-dissertation, with the latter shared between the two universities, totaling 90 credits. The distribution of modules is shown in Fig. 4.

V. CONCLUSION

In this paper, a re-invented online method of delivery of postgraduate nanoelectronic education has been described. Postgraduate content is presented via the part-coursework and part-research route, where the coursework is presented via an online model with pre-recorded lecture content and interactive involvement of lecturing staff during the deployment phase. Initially, modules are presented as stand-alone online SLPs and the same SLPs are later used to build at least two master's degrees. One of the two degrees is a fully online-presented master's degree in Micro- and Nanoelectronic Engineering, while the second degree is a joint part-contact part-online master's degree in Nanoelectronics, to be presented in partnership with the NUST MISiS, Moscow, Russia, as a result of BRICS collaboration.

ACKNOWLEDGMENTS

The collaboration with the MISiS started as a result of a speech by Prof Angina Parekh, UJ Deputy Vice-Chancellor (DVC): Academic and one by her counterpart, Prof Timothy Edward O'Connor, MISiS Vice-Rector for Academic Affairs. Both presented the vision of joint qualifications at the BRICS Global University Summit themed "Education as resource for the global development," Moscow, 26-28 Oct. 2015.

The project implementation was further supported by Prof Tshilidzi Marwala, DVC: Research and Internationalisation, and the UJ Division: Internationalisation, under the leadership of Dr Pinkie Mekgwe.

Access to the UJ Blackboard was provided by the UJ CAT, specifically the Project Manager, Dr Wilma Elston, and CAT Director, Prof Thea de Wet.

The authors would like to thank Prof Sergei Mukhin and Dr Ekaterina Smirnova for driving the process of joint degree preparation from the side of MISiS.

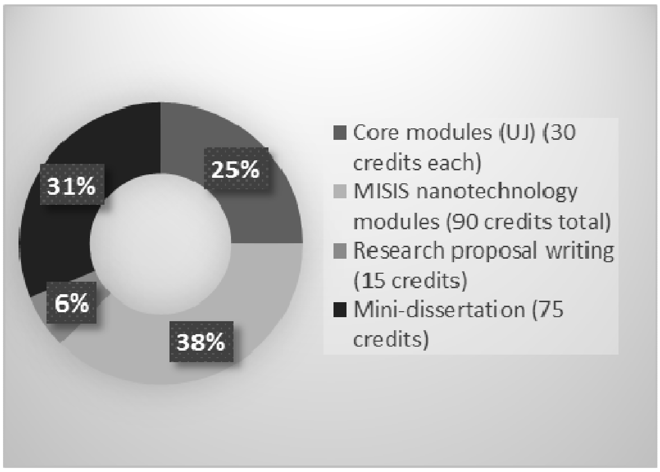

Fig. 4. Distribution of credits for the proposed master's degree in Nanoelectronics, a joint degree offered by UJ and NUST MISiS.

REFERENCES

[1] K. Wall, *Engineering: issues, challenges and opportunities for development,* UNESCO, 2010.

[2] M. Annegarn, L. Baldi, R. Hartman, N. Lehner, G. Matheron and F. Van Roosmalen. (2012) *Innovation for the Future of Europe: Nanoelectronics beyond 2020* [Online]. Available: http://www.catrene.org/web/downloads/form_downloads/Position_Paper_Final.pdf

[3] E Bruun and I. R. Nielsen, "Trends in university programs in nanoelectronics and microsystems", in *Proc. 2013 IEEE NORCHIP*, 2013, pp. 1-6.

[4] K. Galatsis, P. Gargini, T. Hiramoto, D. Beernaert, R. De Keersmaecker, J. Pelka and L. Pfitzner, "Nanoelectronics Research Gaps and Recommendations: A Report from the International Planning Working Group on Nanoelectronics (IPWGN)[Commentary]", *IEEE Technology and Society Magazine*, vol. 34, no. 2, pp.21-30, June 2015.

[5] South African Qualifications Authority. (2014). *The South African National Qualifications Framework* [Online]. Available: http://www.saqa.org.za/list.php?e=NQF

[6] M. Božanić, S. Chaturvedi, and S. Sinha, "Evolving the BRICS multi-lateral qualification through online education innovation," in *Proc. Int. Conf. Empowerment through Education, Ethics & Entrepreneurship (IC-4E) - The Next Agenda for BRICS*, 2017.

[7] Engineering Council of South Africa. (2013). *Policy on Continuing Professional Development* [Online]. Available: https://www.ecsa.co.za/cpd/MaintainReg/CPD_Policy.pdf

[8] E. Bruun, D. Demarchi, and I. R. Nielsen, "European master programs in nanoelectronics and microsystems," in *Proc. IEEE 10th European Workshop Microelectron. Educ. (EWME)*, 2014, pp. 53-57.

[9] M. Božanić and S. Sinha, *Power Amplifiers for the S-, C-, X- and Ku-bands: An EDA Perspective*, 1st ed. Cham: Springer Int. Publishing, 2016.

[10] W. Rice, *Blackboard Essentials for Teachers*, 1st ed. Birmingham: Packt Publishing, 2012.

[11] R. Kumar, *Fabless Semiconductor Implementation*, 1st ed. New York: McGraw-Hill, 2008.

[12] M. Božanić and S. Sinha, "Design flow for CMOS based class-E and class-F power amplifiers," in *Proc. 2009 IEEE AFRICON*, 2009, pp. 1-6.

[13] K. Raij, *Learning by Developing Action Model*, vol. 36, Espoo: Laurea Publications, 2014.

[14] Blackboard Learn. (2017). *Learning Management System* [Online]. Available: http://www.blackboard.com/learning-management-system/blackboard-learn.aspx

[15] National University of Science and Technology MISiS. (2017). *About University* [Online]. Available: http://en.misis.ru/university/