The Potential of Establishing Technology Computer Aided Design Industry: Africa - Sudan As a Case-Study

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ABSTRACT- Very-Large-Scale-Integration (VLSI) Integrated-Circuit (IC) designs have steadily grown in their capacity and complexity through the years. The need for technology simulations using technology computer-aided-design (TCAD) tools have become an essential part of design success. The TCAD simulations facilitate process optimization, highlight device performance tradeoffs, enable worst case analysis, and reveal device defects and weakness. Microelectronics higher education in African universities focuses mainly on the chip/circuit design instruction. Virtually little or no emphasis is applied to grow students TCAD simulation skills. This paper discusses the potential of African educational institutes of becoming the supplier of qualified TCAD simulation engineers for future African IC industry and/or worldwide VLSI job market. The African universities are encouraged to emphasize on establishing frameworks that would include TCAD simulation research and development into their curriculums and motivate students to venture the VLSI design and automation fields. This would enable African graduates to exploit the microelectronics job market worldwide and establish TCAD industries within Africa to industrialize African job market.

Keywords: *VLSI; Design; Automation; CAD; TCAD; EDA; Higher Education.*

المستخلص – لقد نمت تصميمات الدوائر المتكاملة (IC) ذات التكامل الكبير للغاية (VLSI) باستمرار في قدراتها وتعقيداتها على مر السنين.هذا التنامي استدعي الي ان تكون الحاجة إلى المحاكاة التقنيه باستخدام أدوات التصميم (TCAD) جزءًا أساسيًا من نجاح التصاميم. تسهل عمليه المحاكاة التقنيه (TCAD) ضبط عناصر التصنيع الالكتروني وتسليط الضوء على أداء الاجزاء الالكترونيه ، وتحليل نقاط ضعف و عيوب التصميم و الاجزاء الاكترونيه . يركز التعليم العالي للإلكترونيات الدقيقة في الجامعات الأفريقية بشكل أساسي على تدريس تصميم الشرائح و الدوائر. تدريس المحاكاه التقنيه للطلاب والباحثين في مجال الالكترونيات في هذه الجامعات ضعيف ان لم يكن منعدما. تناقش هذه الورقة إمكانيه تجهيزو تاهيل المعاهد التعليمية الأفريقية لتصبح المورد لمهندسي محاكاة التقنيه الالكترونيه (TCAD) المؤهلين لخلق صناعة الكترونيه في المستقبل للقاره الافريقيه (IC) الأفريقية لمد سوق العمل في مجال (VLSI) في جميع أنحاء العالم بكوادر قادره علي الابداع والانتاج. يتم تشجيع الجامعات الأفريقية على إنشاء أطر عمل تتضمن أبحاث وتطوير محاكاة (TCAD) في مناهجها الدراسية وتحفيز الطلاب على المغامرة في مجالات تصميم (VLSI) وامكانيه تصميم وانشاء تشغيلات آليه لعمليات التصاميم. هذه المجهودات ستمكن الخريجين الأفارقة من استغلال سوق عمل الإلكترونيات الدقيقة في جميع أنحاء العالم وإنشاء صناعات الكترونيه (TCAD) داخل إفريقيا لدعم ورفع شأن سوق العمل الأفريقي ككل.

Introduction

The field of TCAD simulations started early with bipolar device technologies. DeMan and Mertens [1] presented SITCAP TCAD simulation tool in 1973 to calculate parameter set of circuit models using bipolar transistors based on processing data, transport theory permitting accurate current gain predictions. Dutton and Antoniadis [2] have presented Process simulation for device design and control. Henceforth the TCAD simulation has shown tremendous growth in capacity and functionality. The TCAD industry constitute one of the key driving forces in today's global economy with an estimated $14.5 billion by the year 2026[3].

TCAD simulation focuses on semiconductor manufacturing process and device functionality simulations [2]. These activities are performed usually before going into physical fabrication to investigate and test design specifications and identify design limitations. The Stanford University has released a first TCAD tool in the late 1970s named **S**tanford **U**niversity **PR**ocess **E**ngineering **M**odels (SUPREM). In late 80s, SUPREM was upgraded from one- to two-dimensional, and physical models were embedded to enhance its capability. Various subsequent versions SUPREM II and SUPREM III have been released [4-6].

Moreover, the two-dimensional and two-carrier device simulator tool for Poisson and Continuity Equation Solver (PISCES) was developed by Stanford University September 1984[7]. The PISCES and SUPREM have established the TCAD framework for silicon integrated circuit design, simulation, and fabrication. The University of Florida had developed TCAD tools by creating codes for extended functions, such as object-oriented codes, scripting, command line model implementation and post processing data analysis. These command codes are named as Florida Object Oriented Device Simulator (FLOODS) and Florida Object Oriented Process Simulator (FLOOPS)[8].

The teaching of VLSI circuit design courses as part of electrical and computer engineering curriculum has been established in the US and Europe for decades now. The use of open source and/or free tools has also been utilized in many schools. For example, Elias K et. al. have developed a course on Nano-scale CMOS and standard cell based design [9]. Also, The Integrated Circuits and Systems (ICAS) design group at the Institute of Microelectronics of Barcelona IMB-CNM as part of University of Barcelona, Spain focuses on conducting analog, mixed-signal, and RF CMOS design using freeware and open-source EDA tools. J. Pallares et. al. have presented an academic EDA tool suite for the full custom circuit design of mixed-mode integrated circuits [10].

Evidently, the initiation of the work was performed by universities which set the foundation of today's TCAD products available from vendors. However, there is very little work being done in the African universities regarding TCAD simulations research and development.

TABLE I: LIST OF IEEE SECTIONS ACROSS AFRICAN CONTINENT

Section	Website
Algeria	http://www.ieee-dz.org/
Botswana	http://ethw.org/IEEE_Botswana_Subsection_History
Egypt	http://www.ieee.org.eg/
Egypt (Alexandria)	http://www.ieeeghn.org/wiki/index.php/IEEE_Alexandria_Subsection_History
Ghana	http://www.ieeegh.org/
Kenya	http://sites.ieee.org/kenya/
Mauritius	https://r8.ieee.org/mauritius/
Morocco	http://www.ieee.ma/
Nigeria	http://sites.ieee.org/nigeria/
South Africa	http://www.ieee.org.za/
Sudan	http://ieeesudan.org/
Tanzania	https://ethw.org/IEEE_Tanzania_Subsection_History
Tunisia	http://ieee.tn/
Uganda	https://www.facebook.com/ieeeuganda/
Zambia	http://www.ieeeghn.org/wiki/index.php/IEEE_Zambia_Section_History

It appears that some African universities in Egypt, South Africa, and Morocco have small research groups that work with commercial TCAD tools such as SILVACO Athena to investigate semiconductor device performance. For Example, M. Elsaid [11] has presented a proposal to establish a VLSI industry in Egypt following the start of the Electron Factory owned by the Arab Industrial Authority (AIA) in 1998. Additionally, H. Bouzekri [12] presented a summary of the microelectronics ecosystem initiative in the Kingdom of Morocco.

It was reported that some of the Integrating Circuit (IC) and Electronic Design Automation (EDA) leading design companies such as STMicroelectronics, ST-Ericsson, and Mentor Graphics have established presence in Morocco with noticeable impact on higher education in the field of IC design and EDA development. Moreover, S. Selberherr [13] has presented an invited paper on Technology Computer-Aided Design South African Journal of Physics. Furthermore, The Institute of Electrical and Electronics Engineers (IEEE) has about 15 Sections and sub-Sections across the 54 countries of the African continent as listed in Table 1. These sections and sub-Sections have held various international conferences and seminars that played a critical role in exposing local electronics communities to research and studies performed locally and abroad.

In this paper, a proposal that enables African universities and higher institutions to establish TCAD infrastructures is presented. The proposal relies on installing and setting up open source TCAD simulation tools available currently to facilitate education, research, and hands on experience with TCAD simulations. A brief overview of modern TCAD simulation flow and steps is presented. The role of TCAD simulation engineering within the VLSI design flow is reviewed and opportunities of leveraging open source TCAD simulation tools by class and research work done by students is discussed.

TCAD Simulation Flow

The task of designing, validating, and fabricating a microelectronic integrated circuit is normally accomplished by a team of design engineers, fabrication engineers, and design automation engineers as shown in Figure 1. TCAD engineers are responsible for technology process simulations and identification. TCAD engineers are also expected to simulate device designs and identify performance tradeoffs such as latch-ups and spacing rules, breakdown voltages, threshold voltages, doping levels, etc.

These details are then used to build test structures that can be used to extract Spice model used during simulations of devices electrical performance. The design engineering team is responsible for producing a completed and validated design in accordance to spice models and process design rules. Design is then delivered to the fabrication engineering team who main responsibility is to realize the completed design in silicon. Furthermore, the fabrication engineers are responsible for delivering libraries of building components, and technology specifications to the design team.

This is needed to ensure designers use approved components in their design to guarantee design manufacturability. The design automation engineering team is responsible for installing, integrating, customizing, automating design tools, enabling EDA tools, producing primitive components and standard cell libraries in an integrated design environment. All of these items enable the designers to complete design and validation steps effectively and consistently.

A. Integrated Electronic Circuit Design Flows

Figure 2 shows a complete design flow starting with process specifications and ending with product documentation. There are various steps in the flow, and many can be broken to multiple sub steps. In general, there are various design flows for IC design. These include:

- Fully Digital (RTL based) synthesis design flow,
- Fully Custom (schematic based) design flow,
- Semi-custom design flow

Figure 4 shows the RTL based VLSI ASIC design flow, where the front and back end steps are demonstrated. Such a flow is suitable for IC applications that can be implemented fully with pre-characterized standard cells, such as simple digital circuit. On the other hand, Figure 5 shows the fully custom (schematic based) VLSI ASIC design flow steps. Such a design flow is suitable for the complete analog type of ICs, such as operational amplifiers, analog filters, etc… In today's IC applications, the semi-custom design flow is prevalent, where large scale of integration of digital and analog blocks is desired. This design flow requires the integration of the digital and full custom blocks at the full chip level.

All design flows consist of required design steps to be executed on the front and back end phases as illustrated in Figure3 and Figure4. Furthermore, the design flows involve design verification to be executed along the way to ensure functionality, timing, power consumption, noise, aging, etc… design specifications are met before full production is accomplished.

B. Microelectronic Design Automation and EDA

The design flow steps described in the previous section are executed through utilization of many design tools. These tools can be commercially available from Electronic Design Automation (EDA) vendors such as Synopsys, Cadence, SILVACO, etc... These tools can be also internally developed as in some large design house corporations. The design tools are categorized in general as follows:

- **TCAD Simulation Tools:** 2D, and 3D Mesh generators, and process simulations
- **Front-end Tools:** schematic generators, netlisters, simulators, synthesis, timing . . .
- **Back-end Tools:** layout generator, floor planning, place-and-route, extraction, LVS, DRC, etc.

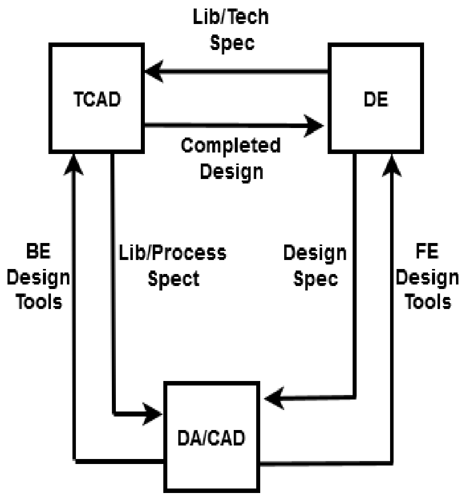

Figure 1: Diagram showing interactions between TCAD/Fab, Design Engineering (DE), and Design Automation (DA/CAD) with deliverables and receivables from each entity.

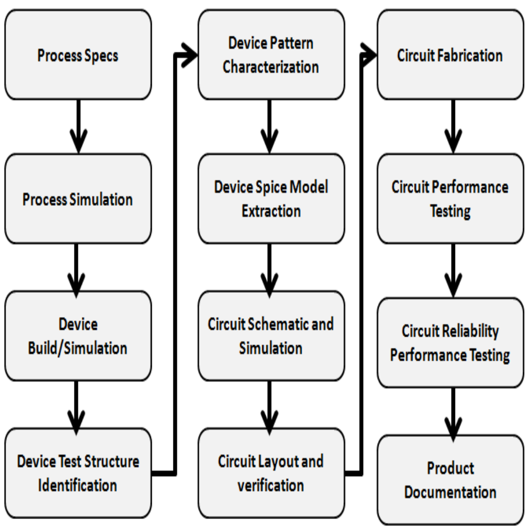

Figure 2: TCAD simulation flow from process spects to productions and documentation.

Figure 5 shows a schematic of a typical design step from design flows shown in Figure 3, and Figure 4 labeled "A". The input stage to step "A" would be undergoing some processing on inputs to be fit for use by step "A". The output of step "A" would also require some processing on the outputs to be consumed by the following design flow step. The processing that takes place at the input and output of a design step is usually performed by design automation tools and utilities.

One important role of design automation is tool installation and integration into design environment that would enable microelectronics design teams to work in synchronization and harmony. Osman et. al [14] elaborated on roles and responsibilities of design automation engineers.

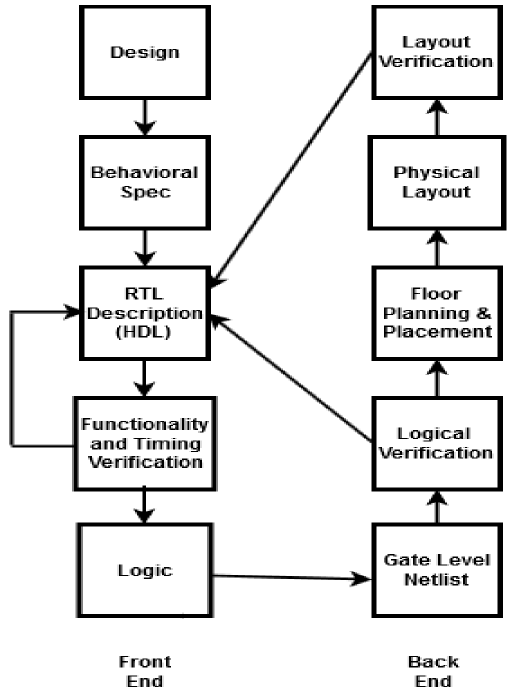

Figure 3: RTL (Digital) based VLSI ASIC design flow.

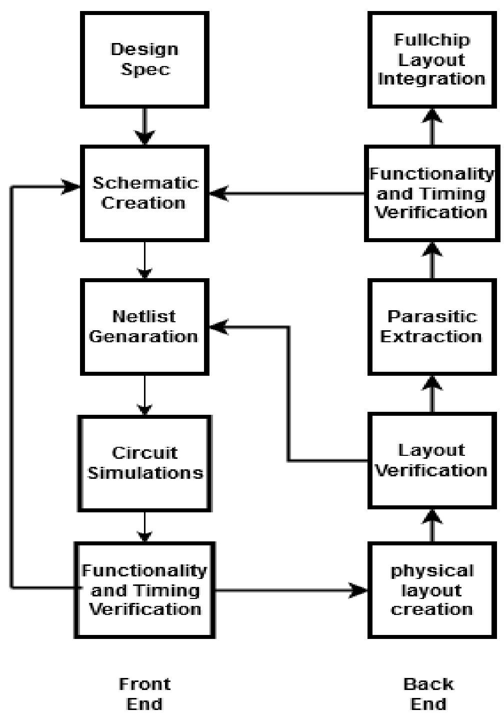

Figure 4: Custom (Schematic) based VLSI ASIC design flow.

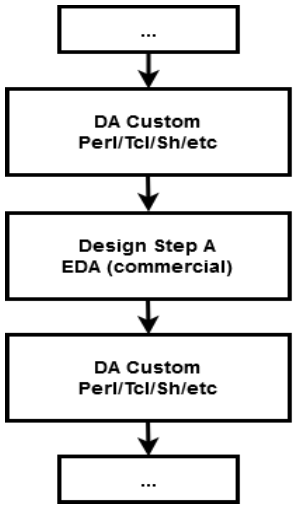

Figure 5: A mini chart showing need for DA automation before and after a design step.

In this paper we would like to propose an approach that would enable start activities on TCAD simulation with no bindings to hefty licensing fees required by commercial EDA tools. They would need to install and integrate TCAD tools into the design environment. Connections between TCAD and the rest of design tools should be enabled and smooth transfer of data would be needed.

As discussed in the Introduction section, the cost level of developing TCAD simulation tools can be prohibitive for developing countries such as countries in Africa. However, it could be quite possible for African universities to educate and graduate resources with adequate TCAD simulation skills set using:

- Discounted tool licenses for academic institutions.
- Start from open source TCAD tools and start developing upon these tools to establish knowledge base and skills.

To enable TCAD simulation activities, DAs can install open source TCAD tools into design environment. Table II shows a list of commercial and open source TCAD simulation tools.

The following steps may be considered as a guideline:

- It would be wise to evaluate tools that are available currently, and decide on best one or two and get them installed
- DAs and TCAD engineers should be using these tools extensively and train groups of students to build knowledge base.
- DAs and TCAD should embark on enhancement on the tools to work on more complex technologies.
- All developments made should be documented to enable future team to continue development and enhancement
- DAs and software engineers can be collaborating to build new macros, modules, or even re-write tools using newer programming languages to mitigate tool limitations.
- Work should be conducted in collaboration between multiple institutions to increase usage and knowledge base

Microelectronics Education in African Universities- Sudan as a study case

I. African Universities Analysis

Integrated circuit electronics is taught in African higher education institutes and universities in the undergraduate and postgraduate levels. Table III shows a sample of African universities and status of coursework in microelectronics. The details of Table III are gathered from respective universities web sites of engineering and computer departments. Very limited details on number of microelectronic programs offered, number of current students, level of instruction, research facilities, and annual number of graduates are offered. For example, the Ain-Shams university, in Egypt, has an Integrated Circuit lab that was established about 15 years ago as reported by M. Dessouky[15]. In that lab, team has been able to design and manufacture a 0.6µm technology chip.

II. Sudan Universities Analysis

In this paper the Sudan is taken as a case study to represent status of African education of TCAD simulation field. Sudan represents one of the largest countries in Africa with a population of 41 million people and 47 universities. A summary of current status is as follows:

- Microelectronics courses are offered only in limited number of Sudanese universities such as University of Khartoum (U.Of.K), Sudan University of Science and technology (SUST), and Al-Neelain University.
- Only few schools offer courses on VHDL and Verilog hardware description languages as part of an integrated circuit design topics.

- Field Programmable Arrays (FPGAs) are taught at University of Gezira as part of microelectronics coursework.
- Some schools provide design kits of XLINX for design experiments such as U.of.K, University of Gezira (UofG), Al-Neelain and SUST.
- Some of these schools offer post graduate degrees with limited microelectronics course work.
- For example, Al-Neelain university offers an MS program in Embedded Systems with small number of students enrolled. The program offers courses and lab work using C, C++, Java, all microcontrollers languages (more often MiKroC) and Linux and Android operating systems.
- Details of programs and produced research and reports are difficult to find. Research results, experiments setup and data, student projects and dissertations are not readily available specially not available or posted online to enable search engines to enable information-seekers and researchers find information and run studies

TABLE 2: LIST OF COMMERCIAL AND OPEN SOURCE TCAD SIMULATION TOOLS

Commercial	Open Source
Synopsys	GSS
Silvaco	Achimedes
CrossLight	Aeneas
Cogenda VisualTCAD	NanoTCAD
	DEVSIM
	GENIUS

The VLSI and microelectronics courses offered in African universities including Sudan are tailored towards computer engineering and general telecommunication systems. Published research involving TCAD tools is generally executed using commercially available EDA tools. No emphasis on establishing TCAD simulation platforms to train and educate large number of students and researchers nourishing expertise in TCAD simulation is highlighted. As a result, the African graduates are faced with a big challenge between what they learned in school and what modern microelectronics field requires as far as skill sets.

This fact has limited graduates' ability to exploit job opportunities in the microelectronics field. Moreover, microelectronics industry is virtually nonexistent for TCAD, design, or design automation. Such industries could be valuable sources of new work opportunities and could present significant economical impact to African citizens income. As we have noticed from the requirements of design automation engineers in section II, African universities could have enormous potential in filling the gap of graduating skilled design automation engineers. This can be accomplished through:

- Emphasize on design automation field of engineering
- Upgrade instruction material and research development to improve student knowledge in the automation field
- Gain hands-on familiarity with available open source design and programming tools
- Integrate open source tools within class work through installation, experimentation, enhancing, customizing, and development these tools for internal use.

Efforts such as these recommendations were employed in universities in the west, US, and ASIA-Pacific regions and resulted in booming in the microelectronic industries as well as number of skilled graduates in these regions.

Conclusions

In this paper, the status of the TCAD simulation in universities and higher education institutes is presented. It was noted that integrated circuits are becoming more complex due to increased number of devices used.

TABLE 3: A SAMPLE OF AFRICAN UNIVERSITIES AND STATUS ON VLSI AND ELECTRONICS COURSEWORK AT UNDER/POST GRADUATE LEVEL. UNIVERSITY RANK IN AFRICA IS BASED ON WEB METRICS RANKING [16].

Institute Name	Country	Rank Africa	VLSI	Electronics
Ain-Shams Univ.	Egypt	22	Grad	Grad
Univ. of Nairobi	Kenya	11	NA	NA
Univ. of Khartoum	Sudan	37	Grad/Undergrad	Grad/Undergrad
Al-Neelain Univ.	Sudan	201	Grad	Undergrad
Sudan Univ. of Sci. & Technology	Sudan	113	Grad	Undergrad

Also, it was noted that the establishing of silicon fabrication facilities has reached high level of cost that would not be possible for developing countries such in Africa to compete. The paper has reviewed the different types of circuit design flows and demonstrated the need to design automation engineers for efficiency of design teams. An analysis of African and Sudanese universities in the field of TCAD simulation is provided. It is noted that the main emphasis is on circuit design, and limited attention is directed towards design automation skills and tools. There seems to be scattered activity and course work that are offered in the field of microelectronics, however, there seem to be no comprehensive plan exist to exploit the potential of establishing microelectronics industry in Africa. Moreover, there is certainly limited emphasis on teaching the required skill set of TCAD simulations as part of complete design automation education. The authors proposed that African universities should start emphasizing more on design automation to increase number of graduates in that field. The benefit of this will be two folds, enable African graduates to exploit jobs in the microelectronics field and eventually help encourage industries be established within Africa for growth opportunities.

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