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Case Study

Curriculum Design of "Microelectronics Device Process Experiments" Based on an Integrated Circuit Process Experimental Teaching Simulation Platform

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Abstract. To address the substantial investment demands and scarcity of advanced integrated circuit (IC) mass production process equipment in traditional "Microelectronics Device Process Experiments" courses, an innovative IC process teaching simulation platform is introduced to reformulate the experimental curriculum. This approach encompasses the development and implementation of 17 experiments spanning two primary domains: pivotal IC manufacturing processes and crucial device fabrication techniques. Unlike conventional schematic simulation demonstrations, this simulation platform utilizes real-world industrial-grade simulators, enabling the numerical determination of device characteristics and process properties through the application of relevant physical models. Furthermore, the manufacturing process equipment emulated on the platform is intricately aligned with the theoretical course knowledge points within the specialized field. This methodology fosters students' proficiency in operating essential equipment, designing parameters, and analyzing outcomes in authentic manufacturing environments, thereby preparing them to meet the contemporary knowledge and skill requirements of the IC manufacturing industry.

Keywords: Integrated Circuit, Integrated Circuit Process, Microelectronic Devices, Device Process, Teaching Simulation.

INTRODUCTION

Integrated circuits (ICs) constitute the fundamental building blocks of the information industry, and their indispensability being evident in the absence of which modern communication systems, the internet, the Internet of Things (IoT), and artificial intelligence (AI) technologies, products, and services would be nonviable (Tianchun, 2019; Yongyi, 2022; Wei, 2022; Junchen, 2022). The IC industry chain encompasses several crucial stages, chief among them being wafer manufacturing, which serves as the pivotal link in translating chip designs into tangible products. However, wafer manufacturing is a capital-intensive process, demanding high-precision equipment, intricate systems, and significant financial investments. Furthermore, it necessitates a stringent manufacturing environment and personnel with a high level of technical proficiency, thereby leading to a notable talent deficit in the IC industry, particularly in the field of wafer manufacturing (Zili, 2021; Ying, 2014; Zhijian, 2022; Bing, 2021). In the context of higher education, the introduction of experimental courses pertaining to wafer manufacturing confronts significant challenges, including significant investment demands, high maintenance costs, and potential operational risks associated with the utilization of specialized equipment. Despite universities' efforts to arrange practical training opportunities for students in enterprises, ensuring they acquire meaningful hands-on experience remains a formidable task Zhanyun, 2021; Yan, 2022; Xinguo, 2021; Naiyun, 2016). Notably, while

China's IC mass production process has advanced to the 14 nm level, the corresponding teaching facilities, particularly high-end equipment such as extreme ultraviolet (EUV) lithography machines, lag significantly due to their exorbitant costs. This notable discrepancy between the knowledge imparted to students and the industry's current requirements has led to a disconnect between university education and industrial needs. Consequently, there is a pressing need to cultivate professionals in the field of IC wafer manufacturing who possess the requisite skills to adequately address the demands of the contemporary chip industry. To address the pressing need for professionals in IC wafer manufacturing, the undergraduate programs in Electronic Science and Technology (with a focus on Microelectronics Technology) at Chengdu University of Information Technology (CUIT) have incorporated "Microelectronics Device Process Experiments" as a pivotal practical course. This course is designed to foster students' proficiency in microelectronics (IC) materials and device manufacturing processes, particularly their ability to develop foundational IC device manufacturing processes, thus aligning with the knowledge and skill requirements of the IC wafer manufacturing stage. Recognizing the challenges associated with implementing wafer manufacturing-related experimental courses, an IC process teaching simulation platform has been integrated into the curriculum, and elaborate experimental projects and teaching content have been designed accordingly.

Course design based on teaching simulation platform

Theoretical teaching content

The prerequisite physics courses for the "Microelectronics Device Process Experiment" primarily encompass "University Physics," "Quantum Mechanics," and "Solid State Physics." Meanwhile, the prerequisite specialized foundation courses include "Semiconductor Physics and Devices," "Thin Film Physics and Technology," "Fundamentals of Semiconductor Materials," "Fundamentals of Integrated Circuit Design," and "Integrated Circuit Manufacturing Technology." This experimental course serves as a comprehensive platform following the completion of these prerequisite courses, aiming to assess students' proficiency in professional knowledge and encourage them to apply their acquired knowledge in designing and implementing specific device manufacturing processes.

Within the curriculum of the Electronics Science and Technology program (Microelectronics Specialization), the manufacturing phase of integrated circuits is positioned at the forefront. The educational objective is to cultivate applied technical talents who possess proficiency in the design and manufacturing of microelectronics device processes. To achieve this, the "Microelectronics Device Process Experiment" course and its prerequisite theoretical courses systematically introduce the principles, crucial parameters, and implementation methodologies of various single-step processes, including physical vapor deposition (PVD), chemical vapor deposition (CVD), plasma-enhanced chemical vapor deposition (PECVD), atomic layer deposition (ALD), molecular beam epitaxy (MBE), chemical mechanical planarization (CMP), photolithography, thermal oxidation, ion implantation, reactive ion etching (RIE), diffusion, and annealing. Furthermore, through the "Integrated Circuit Manufacturing Technology" course, students are enabled to integrate and interconnect these single-step processes, fostering a profound understanding of the comprehensive process flow involved in integrated circuit manufacturing.

Through such theoretical teaching, it has successfully transformed the original "course-centered" teaching philosophy into one that is "guided by industrial needs." This shift has further clarified the knowledge base and skill enhancement necessary for students to meet the demands of the integrated circuit manufacturing process, laying a solid foundation for their future career development.

Integrated Circuit Process Experiment Teaching Simulation Platform

To address the challenge of conducting comprehensive "Microelectronics Device Process Experiments" without relying solely on real-world equipment, an innovative simulation platform was introduced for integrated circuit process experimental teaching. This semi-virtualized teaching tool significantly reduces the gap between classroom instruction and the actual demands of integrated circuit manufacturing. Its applications encompass: 1) simulating the manufacturing processes of modern advanced integrated circuits as an experimental tool; 2) visually demonstrating the manufacturing processes of typical devices, such as metal-oxide-semiconductor field-effect transistor (MOSFETs), Fin field-effect transistor (FinFETs), and GaAs devices, as a teaching tool.

In contrast to traditional schematic-based simulation platforms, this simulation platform is grounded in real-world industrial-grade simulation program with integrated circuit emphasis (SPICE) and technology computer aided design (TCAD) simulators for numerical simulations of authentic device and process characteristics. During experiments, parameters can be freely adjusted and set, and each set parameter undergoes numerical calculations based on corresponding physical models to ensure accurate results, thereby avoiding the limitations of traditional schematic simulations.

The platform boasts a comprehensive set of virtual manufacturing equipment, including oxidation furnaces, CVD equipment, PVD equipment, EUV lithography

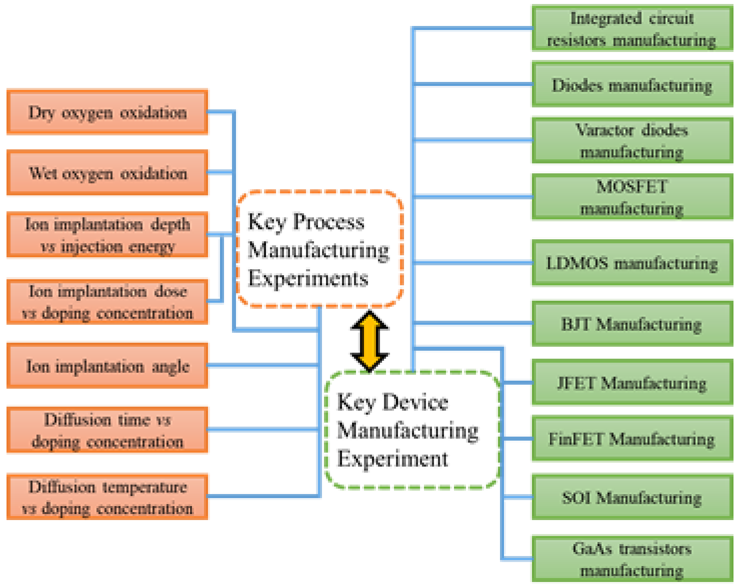

Figure 1. Experimental project design based on integrated circuit process teaching simulation platform.

machines, etching machines, ion implanters, high-temperature annealing furnaces, rapid thermal processing chambers, and vapor-phase epitaxy equipment. It covers the key single-step processes in modern integrated circuit manufacturing, such as oxidation, deposition, lithography, etching, ion implantation, diffusion, annealing, and epitaxy, encompassing the manufacturing processes of various crucial integrated circuit devices like diodes, MOSFETs, FinFETs, silicon-on-insulator (SOI), bipolar junction transistor (BJTs), and laterally diffused metal oxide semiconductor (LDMOSs).

Equipped with a graphical user interface and an experimental box integrated with a touchscreen liquid crystal display (LCD) display, the simulation platform mimics the operational panels and parameter settings of real-world process equipment, enhancing the practicality of process learning. The ProcessLab software displays the results of each process step and facilitates parameter analysis through its software modules. The integrated circuit manufacturing processes and equipment on this platform are highly aligned with the theoretical principles taught in the electronics science and technology program (specializing in microelectronics). This alignment facilitates students' cognitive transition from theoretical principles to experimental operations, enabling them to master the operation of crucial equipment, parameter design, and process result analysis in real-world integrated circuit manufacturing. Ultimately, it bridges the gap between theory and practice, cultivating professionals who are well-suited to the current demands of the integrated circuit manufacturing industry.

Teaching simulation experimental project setting

In the teaching practice of the "Microelectronics Device In the teaching practice of the "Microelectronics Device Processing Experiments" course, it has leveraged the integrated circuit process teaching simulation platform to elaborate seven pivotal process experiment projects that encapsulate the core of integrated circuit manufacturing and ten experimental initiatives focusing on the fabrication of critical integrated circuit devices, as illustrated in Figure 1. These core process experiments primarily encompass critical technological steps such as oxidation, ion implantation, and diffusion. Meanwhile, the key device manufacturing experiments are centered on the fabrication of fundamental integrated circuit components, including resistors, diodes, MOSFETs, LDMOSs, BJTs, JFETs, FinFETs, and GaAs transistors.

Given the temporal disparity between theoretical and experimental courses and the potential forgetting of some prerequisite theoretical knowledge, the "Micro-Nanoelectronics Teaching Experiment Integrated Service Platform" was introduced as an auxiliary tool for previewing and reviewing. The detailed guides for all experimental projects, theoretical course materials, equipment operation videos, and typical experimental teaching videos were uploaded on this platform. Students can utilize the online platform to preview or review anytime, anywhere. This flexible learning approach has effectively sparked students' interest in learning and significantly enhanced the quality of course instruction.

Experimental Teaching Case

Key Process Experiment Teaching Case

Case 1: Oxidation Process

The oxidation process comprehends both dry and wet oxidation methodologies. Utilizing the integrated circuit process teaching simulation platform, a vertical oxidation furnace was manipulated to delve into the correlation between oxide layer thickness and oxidation duration for silicon materials across a temperature spectrum spanning from 700℃ to 1300℃. Furthermore, the trends in oxide growth rate and their contributory factors were subjected to a detailed analysis. Through a comparative evaluation of the experimental outcomes, a profound comprehension of the distinctiveness between dry and wet oxidation processes was attained, along with an assessment of their respective merits and demerits.

Case 2: Ion implantation process

Ion implantation assumes a pivotal role in the doping process. Leveraging the integrated circuit process teaching simulation platform, an ion implanter was operated to delineate the relationship between the projected range and implantation energy for B, P, Sb, and As ions at varying implantation energies. Additionally, the interplay between different implantation doses and doping concentrations, as well as the influence of varied implantation angles on implantation depth and doping concentration, was comprehensively analyzed. This examination facilitated a thorough understanding of the intricate steps involved in the ion implantation process, as well as a profound comprehension of the mechanisms underlying the effects of implantation energy, dose, and angle on the resulting process outcomes.

Case 3: Diffusion Process

Utilizing the integrated circuit process teaching simulation platform, a high-temperature diffusion furnace was operated to investigate the correlation between diffusion temperature, time, and material doping concentration for P, B, Sb, and As diffusion impurity sources at varying diffusion concentrations. This experimental endeavor fostered a more nuanced understanding of the pivotal role played by the diffusion process in semiconductor preparation, while also imparting a mastery of the specific steps involved in the diffusion process.

Key Device Manufacturing Experimental Teaching Case

Case 1: Resistor Manufacturing Process

In the design of integrated circuits, resistors are typically fabricated using boron diffusion and ion implantation techniques, which involve doping the silicon substrate surface to create a regular conductive layer exhibiting a conductivity type contrasting with the substrate. Integrated resistors commonly possess three terminals: a high-voltage terminal, a low-voltage terminal, and a substrate potential terminal. To guarantee the proper functioning of the diffused resistor, regardless of whether it is connected to a high or low potential, the substrate potential terminal must maintain a reverse-biased state with respect to the resistor PN junction. The resistor manufacturing process encompasses crucial steps such as cleaning, oxidation, diffusion, photolithography, evaporation, and alloying.

Utilizing an integrated circuit process teaching simulation platform, the entire resistor manufacturing process can be designed and simulated. This process enables an in-depth analysis of the doping type and concentration of the resistor substrate, along with the type and concentration of implanted ions, leading to a comprehensive understanding of the resistor's operating characteristics. Furthermore, the distribution of doping concentration is analyzed before and after the resistor annealing process, clarifying the effects of ion implantation and annealing on resistor performance. Ultimately, the goal is to achieve mastery of the complete resistor manufacturing process and key steps in integrated circuits, as well as gaining a profound understanding of the role of annealing in the ion implantation process.

Case 2: Transistor Manufacturing Process

The transistor, a core and extensively applied semiconductor device in integrated circuits, is classified into PNP and NPN types. Considering the NPN transistor as a representative example, its manufacturing process commences with the utilization of lightly doped P-type silicon as the substrate. Subsequently, a layer of silicon dioxide is grown on the surface, and the buried layer region is formed via photolithography and etching techniques. Following this, a layer of lightly doped silicon is epitaxially grown to constitute the collector region. The base region is then defined through photolithography and etching, with boron implanted and annealed to diffuse into the silicon, forming the desired base region. Next, the emitter region is delineated via photolithography and etching, with phosphorus or arsenic implanted and annealed to constitute the emitter region. The transistor manufacturing process encompasses crucial steps such as oxidation, ion implantation, photolithography, etching, chemical vapor deposition, sputtering, and annealing. Leveraging an integrated circuit process teaching simulation platform, the manufacturing process for the NPN transistor has been designed. Key process steps, including ion implantation and annealing, have been investigated. Furthermore, an analysis has been conducted to examine the substrate doping type and concentration, as well as the implanted ion type and concentration in the buried and epitaxial layers, thereby gaining an understanding of the transistor's performance characteristics. Additionally, an exploration has been made into the changes in doping concentration before and after the annealing process, the role of annealing post-ion implantation, and the formation process of the base, emitter, and collector regions of the transistor. This comprehensive analysis provides a profound understanding of the transistor's working principles.

Case 3: MOSFET Device Manufacturing Process

The Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) is a device that employs a metal layer (M), separated by an oxide layer (O), to modulate the conductivity of a semiconductor (S) via the electric field effect. A notable feature of this device is its capacity to regulate the drain current through the application of gate voltage. As a fundamental element in modern electronics, the continuous miniaturization of MOSFETs has significantly propelled the rapid progression of electronic semiconductor technology, enabling the realization of high-density chips, including memory chips and microprocessors. Utilizing an integrated circuit process teaching simulation platform, this study has devised a comprehensive manufacturing process for MOSFET devices, encompassing crucial techniques such as Retrograde Doping Well, Polysilicon Gate fabrication, Halo Ion Implantation, and Lightly Doped Drain (LDD). Following the completion of the MOSFET's front-end process, the backend process, which encompasses the design and preparation of contacts, interconnections, vias, and dielectric layers, becomes necessary. Through this exhaustive series of process steps, the objective is to gain a profound understanding of each stage in the MOSFET device manufacturing process, along with the underlying principles and parameters that govern it.

Case 4: FinFET Device Manufacturing Process

FinFET, an innovative design for complementary metal-oxide-semiconductor (CMOS) transistors, exhibits a distinct non-planar architecture. Fabricated on a substrate, its source/drain regions manifest a unique fin-like three-dimensional structure on the silicon surface. This design features a gate positioned on the sides of the channel, or even wrapped circumferentially, enabling circuit control from multiple angles. This configuration significantly mitigates leakage current while enhancing the effective gate length. Owing to its compatibility with mainstream CMOS technology and its dual attributes of high integration and low power consumption, FinFET has found widespread application in mobile microprocessors. Leveraging an integrated circuit process teaching simulation platform, this study endeavors to devise the manufacturing process steps for FinFET devices. Through a rigorous analysis of critical process parameters, including ion implantation, deposition, etching, and rapid thermal processing, the objective is to master the single-step process techniques in FinFET manufacturing and acquire a profound comprehension of the effect mechanisms of each step on device performance. Furthermore, the study examines the influence of parameters such as doping types and concentrations in the FinFET substrate, as well as the types and concentrations of implanted ions, on the characteristics of FinFET devices.

Practical Effectiveness

The "Microelectronics Device Process Experiment" course, tailored utilizing an integrated circuit process experimental teaching simulation platform, has been effectively integrated into the undergraduate curriculum for electronic science and technology majors (microelectronics technology specialization) for students spanning the 2021 to 2023 academic years, comprising a total of 48 class hours. Over a three-year period of curriculum development and refinement, a comprehensive experimental course system has been established, integrating virtual and physical elements, software, and hardware, encompassing all professional courses within the specified training orientation. According to course evaluations and graduate surveys, the course has garnered widespread praise from students for its engaging nature and high degree of professionalism. Notably, the implementation processes of multiple experimental projects align closely with actual process manufacturing procedures in semiconductor device manufacturing facilities, even resembling the operational interfaces of certain equipment. Consequently, this experimental course has achieved noteworthy outcomes in enhancing students' design, analytical, and practical skills, deepening their understanding of the professional direction, and fostering a keen interest in professional courses.

Conclusion

In response to the challenges stemming from the significant demands for teaching resources and implementation environments in the "Microelectronics Device Process Experiment" course, particularly the substantial investment required for acquiring advanced integrated circuit production equipment, such as extreme ultraviolet (EUV) lithography machines, which are often beyond the financial reach of universities for educational purposes, a notable disparity has emerged between the knowledge and skills attained by students within academic institutions and the industry's requirements. To bridge this gap, an integrated circuit process teaching simulation platform has been introduced. This platform has facilitated the development of a comprehensive curriculum encompassing 17 experimental projects and teaching content focused on crucial integrated circuit manufacturing processes and device fabrication. Utilizing industry-grade

SPICE and TCAD simulators, the simulation platform numerically calculates device and process characteristics based on corresponding physical models. Furthermore, the manufacturing processes and equipment featured on this platform are closely aligned with the theoretical course knowledge points in the specialized field. By adopting this approach, students are enabled to gain proficiency in operating critical equipment, designing parameters, and analyzing results in real-world manufacturing processes. This fosters an organic integration of theoretical principles and experimental operations, aligning with the current demands of the integrated circuit manufacturing industry.

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REFERENCES

Tianchun Y (2019). Research progress on leading technology of integrated circuit device process. Sci. Technol. Rev., 37(3):77-81.

Yongyi Q (2022). Innovation Chain Catches Up: Innovation and Development of China's IC industry. Bus. Manage. J.,. 44(09):5-26.

Wei Z (2022). Breaking through key core technologies and vigorously developing the integrated circuit industry. Zhangjiang Technol. Rev., (1):24-25.

Junchen D (2022). Prospects of Advanced Integrated Circuit Technologies in Post-Moore Era. Sci. Technol. Foresight. 1(3):42-51.

Zili D (2021). Cracking the Talent Challenge in the Integrated Circuit Industry. (8):35-37.

Ying W (2014). Talent shortage in wafer manufacturing, school enterprise collaboration and on-the-job training are indispensable. Electronic Engineering & Product World. 21(7):18-19.

Zhijian L (2022). Exploration and Research on the Cultivation Model of Innovative Talents in Integrated Circuits Based on the Deep Integration of Science, Industry and Education. Ind. Inform. Technol. Edu., (9):23-26+30.

Bing L (2021). Study on the Training Model of IC Talents Based on Industry Needs. Educ. Teach. Forum. (14):73-76.

Zhanyun H (2021). Exploration and practice of microelectronics process teaching laboratory construction. Lab. Sci. 24(6):126-129.

Yan L (2022). Practice of Teaching Integrated Circuit Technology Course. Application of IC. 39(3):20-22.

Xinguo M (2021). Practice of Teaching Microelectronic Technology Comprehensive Experiment Course. Electronic Technol., 50(1):24-26.

Naiyun T (2016). Building a multi-level and multi-channel practical teaching system for integrated circuit technology. Course Educ. Res., 38:29-31.