

## Article

# Design of Three-Dimensional Virtual Simulation Experiment Platform for Integrated Circuit Course

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**Abstract:** The integrated circuit (IC) is a subject for which researchers need practical experience, but its experiment cost is high, the risk involved is high, and it is not easy to carry out experiments on a large scale. This paper designs a three-dimensional integrated circuit virtual experiment platform based on Unity3d. The platform uses the Unity3d and 3ds Max tools to build a three-dimensional model of instruments, equipment, electronic components, and ultra cleanroom laboratory scenes in an integrated circuit experiment. In addition, it uses C# script to develop the functions and three-dimensional simulation of general virtual instruments and equipment and deploys the experimental website using the frame of the jspxcms open source website. The experimental platform arranges the three-dimensional web file WebGL file in the cloud. Students can use video and text materials to acquire basic IC knowledge at any time and conduct IC virtual experiments safely, efficiently, and without constraints. At present, the platform has been tested and used in teaching and has received high praise and recognition from students.

**Keywords:** 3D virtual experiment; integrated circuit course; Unity3d; WebGL



**Citation:** Lai, Z.; Cui, Y.; Zhao, T.; Wu, Q. Design of Three-Dimensional Virtual Simulation Experiment Platform for Integrated Circuit Course. *Electronics* **2022**, *11*, 1437. <https://doi.org/10.3390/electronics11091437>

Academic Editor: George A. Papakostas

Received: 19 March 2022

Accepted: 27 April 2022

Published: 29 April 2022

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## 1. Introduction

With the rapid development of the microelectronics industry, there is an urgent need for a large number of people with excellent and high-quality integrated circuit skills. An excellent integrated circuit design engineer not only needs to possess rich theoretical knowledge, but also must have extensive experimental and practical experience in order to design an integrated circuit chip with superior performance [1]. In order to cultivate students' abilities in integrated circuit design, students usually take courses such as analog integrated circuit analysis and design, fundamentals of integrated circuit layout design, and semiconductor integrated circuit technology. However, these courses are very practical and focus on engineering and technical aspects, requiring teaching conventional and traditional classroom theoretical knowledge and supplementing it with a large number of experimental and practical courses [2,3]. However, due to the large size of the experimental site required for the IC manufacturing and packaging test processes, expensive equipment cost, complex operation process, and high experimental loss cost, the supporting experiments offered in IC courses in most colleges and universities are often limited to IC design [4,5]. Therefore, this paper proposes a three-dimensional virtual simulation experiment platform for use in integrated circuit courses, which can make up for the lack of practical operation of traditional integrated circuit experiments.

The platform is presented in the form of web pages and can be accessed and used through the Internet. There is no need to consider the burden of equipment, laboratory capacity, student site management, and other issues in the real experiment. It is convenient for carrying out large-scale class experiments and open to society. The platform can support all current mainstream browsers, and the website of the experimental teaching management platform can be accessed through the browser. Students can carry out interactive and

autonomous learning on the platform, including downloading materials, watching videos, interactive discussion, completing virtual experiments, etc. The instructor of the experimental course can guide, score, and manage tasks on the platform [5]. The platform integrates remote desktop technology, 3D graphics development technology, human–computer interaction technology, and website construction technology in four modules: integrated circuit design and manufacturing, packaging, and testing [6]. The complete experiment includes 26 large steps and 166 small steps.

For the development and design of the integrated circuit design module, remote desktop technology is mainly used, and VNC (virtual network console) technology is used for development. This module includes the content of the traditional integrated circuit experiment simulation course. Through VNC, the experimenter can carry out the integrated circuit design simulation experiment on the remote desktop through the browser.

The manufacturing, packaging, and testing of integrated circuits is the most important module of the platform. It is also the most different from the traditional integrated circuit experiment course. This is a three-dimensional virtual simulation module involving three-dimensional modeling technology, human–computer interaction technology, network communication technology, and so on. For the modeling of the equipment required for the experiment, 3ds Max and PS software are used, which are based on the real equipment mode as the reference to model the chip, lithography machine equipment, gas washing cylinder, oxidation furnace console, and other devices, and make corresponding maps. After importing the model into Unity3d, Unity3d is used to realize interactive functions, such as experiment guidance, simulation logic, process control, and intelligent scoring. Finally, it is compiled, packaged, and exported as a WebGL project and deployed to the website. In the three-dimensional virtual laboratory, the experimenter can roam the laboratory at will and operate and control the experimental equipment according to the laboratory rules.

Moreover, as the carrier and supplement of the experimental platform, the website can be developed and configured specifically according to different actual needs by arranging it in the website cloud to meet different teaching needs. The website construction adopts jspxcms open-source network architecture, which has strong compatibility and good expansibility [7]. In addition to completing the simulation experiment, the website also includes report submission, teaching resource management, teacher scoring, user login and management, and other content and modules. For website layout, the front-end designs the page layout of the web front-end in the order of “design → manufacturing → packaging → test” according to the whole integrated circuit to be clear and easy to understand and meet the experimental requirements, while the back-end mainly builds the basic server environment and maintains the development database and communication port to provide strong support for the front-end [8].

## 2. Related Work

### 2.1. Current Situation of 3D Virtual Simulation

With the continuous development of computer graphics technology and network technology, 3D virtual simulation has progressed and developed. 3D virtual simulation technology has been applied in many fields, especially in teaching. In contrast to the traditional two-dimensional simulation, three-dimensional simulation has strong interaction and authenticity. The use of three-dimensional simulation in teaching can greatly improve students’ learning. Kanghyun Choi of Sejong University in Korea has developed a virtual experiment platform for marine biology education. The platform is dedicated to a higher level of immersion to improve the teaching effect. Kanghyun Choi and others found that by providing audio effects and animation effects, mutual inductance and immersion can be improved, which is helpful to stimulate students’ interest in learning [9]. Xiaoting Zhang of Jiangnan University has developed a set of 3D virtual weft knitting engineering learning systems using the Unreal4 engine. The system has significantly improved students’ mastery of knitting technology, and students’ scores have been greatly improved compared with traditional knitting teaching [10]. Mengying Hu of Xi’an University of science and technol-

ogy has developed a set of wind power virtual simulation experiment systems which not only train students to master wind power technology but also improve students' ability to solve complex problems. The excellence rate of students' graduation projects was greatly improved after using the system [11]. Xi Deng studied the application of VR teaching in animation art experiments. His research shows that the VR animation art experiment education system greatly stimulates students' learning enthusiasm and promotes students' independent creation, which is of great help to improve their professional skills. Moreover, they also emphasize that strengthening experimental assessment is an important means to ensure the experimental effect [12].

At the same time, compared with the traditional real experiment, virtual simulation can avoid the security risks brought by the real experiment and reduce the experimental cost to a great extent. Sejong University in South Korea has developed a multi-user UAV flight training system in hybrid reality. The system uses Microsoft hololens for access and interaction, which can help inexperienced novices master the operation skills of UAV through remote learning guidance, which greatly reduces the frequency of accidents caused by collisions in real training [13]. Yunli Nie used virtual reality technology to build a virtual marine environment for marine experiments, avoided the problems of complex sea conditions, painful process experiment and high cost in the sea experiment, and provided repeatable, controllable and safe experimental conditions for marine aircraft [14].

Based on the above examples, 3D virtual simulation has been more and more widely used in the field of teaching and skill training, which will promote the progress and development of education. The three-dimensional integrated circuit virtual experiment platform is compatible with all the above advantages, and is committed to improving students' interactive experience, improving students' learning efficiency and reducing the experimental cost of real experiments.

## 2.2. Advantages of Web-Based Virtual Simulation

One obvious difference between the above virtual simulation experiments is that the terminals used in the experiments are different [9–12,14]. Fuan Wen investigated and counted the common experimental forms; an ordinary web interface, a head-worn device screen, a three-dimensional desktop display, a mobile terminal device screen, naked eye three-dimensional screen, etc. This platform is a three-dimensional simulation, based on the web, which uses a mouse and keyboard to interact [15]. Compared with other simulation forms, web-based 3D interactive immersion is low [16]. However, the advantages of a three-dimensional simulation in the form of a website are obvious. Heavy VR devices are not needed, and one does not need to consider the configuration of devices too much. It has a lower cost and is more convenient to share and access [17]. Chang'an University has developed a three-dimensional virtual interactive platform for college physics, which can be accessed quickly through web pages that helps students better master the operation of physics experiments. After using the virtual platform, students' academic performance greatly improved [17]. Beijing University of Posts and Telecommunications has developed a cross-platform VR electronic circuit laboratory, which not only uses VR headgear for immersive learning but can also quickly access learning through the web. Moreover, the laboratory has been used for teaching during the epidemic period, which has greatly alleviated the experimental teaching pressure brought by the epidemic [4]. At the same time, this cross-platform method integrates the advantages of different virtual simulations and has a good reference significance.

## 2.3. Technical Support

### 2.3.1. 3D Simulation Technology

The three-dimensional simulation module of this platform mainly involves Unity3d, 3ds Max, and WebGL.

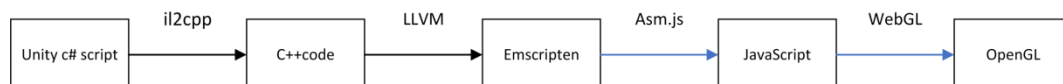
Unity3d is a mainstream cross-platform game development engine with an advanced and efficient graphics rendering engine and physics engine. Unity3d has the following advantages in developing a 3D virtual simulation laboratory [18–20]:

- (1) Unity3d supports the import of models required by projects created by many mainstream 3d modeling software, such as 3dsmax, Maya, C4d, etc.;
- (2) Unity3d optimizes the graphics rendering channels of OpenGL and DirectX, which enables it to ensure a certain quality of smooth virtual simulation even on low-end hardware;
- (3) After packaging and compiling, Unity3d can not only run on traditional systems such as Windows and macOS, but also on mobile devices such as IOS and Android. Most importantly, it also supports web platforms based on WebGL technology;
- (4) Unity3d has a built-in powerful mecanim animation system which can easily add smooth and realistic animation to various objects. It has a built-in editing controller and state machine, in which users can edit and use animation directly. Through script programming control, good animation effects can be created.

These advantages of Unity3d make it the best tool for developing a 3D virtual simulation laboratory [18–20].

3ds Max is an excellent 3D modeling and animation rendering software that can create real instrument models. It has many characteristics, such as advanced rendering and simulation functions, a powerful drawing, texture, and modeling toolset, and smoother multi-application workflow. At the same time, 3ds Max has a very good performance-price ratio, relatively low requirements for hardware systems, and low development cost [21].

WebGL is a javascript-based graphics API. WebGL technology can help developers present 3D graphics on web pages with high efficiency. Most of the previous virtual test experiments developed by Unity3d require users to download plug-ins when the browser loads web pages, such as the flash plug-in and web player plug-in of 3d [22]. Using WebGL technology, users can directly run virtual test experiments by directly entering the address of relevant web pages without downloading any plug-ins [23]. Moreover, WebGL interacts directly with the system's graphics card without secondary rendering through the browser, which improves its running performance [23]. The WebGL files required for 3D virtual simulation are generated by packaging and compiling Unity3d. Unity3d through il2cpp, emscripten, and Asm.js are three key technologies to realize WebGL. The packaging principle is shown in the following Figure 1 [20,24].



**Figure 1.** The Unity3d package WebGL compilation principle.

### 2.3.2. Remote Desktop Technology

The integrated circuit design module mainly adopts remote desktop technology.

VNC is an excellent remote control tool software. VNC is a free, open-source software based on the UNIX and Linux operating systems. It has strong remote control ability, high efficiency, and practicality. Synopsys is an excellent EDA software tool [25]. Synopsys provides advanced IC design and verification functions and is committed to the development of complex systems on chip (SOCS) [26]. Synopsys is equipped with a remote desktop, and students conduct integrated circuit design experiments in Synopsys through VNC.

### 2.3.3. Website Construction Technology

Jspxcms is an open-source, Java-based content management system (CMS). Technically, JavaEE is selected as the mainstream and stable technology in the industry, which is suitable for secondary development, function expansion, and plug-in development. Jspxcms integrates many excellent front-end and back-end frameworks, which means that it has many excellent designs based on templates, which can accelerate the speed of website

development and reduce the cost of development [7]. Jspxcms uses Mysql to store data, tomcat as the server, and JDK as the script compiler [7].

#### 2.4. Experiment Contents and Goal

The platform adheres to the teaching idea of improving skills, consolidating the foundation, and following the industry. At the same time, it is committed to refining the experimental content, optimizing the experimental process, and improving the experimental efficiency. The experimental content of the platform draws lessons from the achievements of international engineering education reform—CDIO (coherent, design, implement, operate) mode and OBE (output-based education) idea, and takes the knowledge chain and industrial chain of “design → manufacturing → packaging → test → finished product” of integrated circuit inverter as the development reference object [6,27]. After refining the content of the IC knowledge chain and industrial chain, a total of 26 steps are designed, which basically cover the whole process of IC. The whole experiment integrates the traditional IC design simulation and runs through the whole process of the IC knowledge chain, which is also an important advantage of the platform. Other IC simulation experiments often involve only part of the process content, such as the CVD experiment and magnetron sputtering experiment, but fail to achieve full coverage [28]. Compared with other IC virtual experiments, the coverage of the whole process of IC can enable students to master IC knowledge and cultivate corresponding abilities more comprehensively.

Table 1 shows the entire experiment content and process. Steps 1–4 belong to integrated circuit design, focusing on cultivating students’ design ability. Integrated circuit manufacturing is divided into steps 5–23, focusing on cultivating students’ realization and operation ability, which can be further divided into 158 small steps. Step 24 is integrated circuit packaging, which focuses on cultivating students’ implementation and operation ability, and can be further divided into six steps. Step 25 is integrated circuit testing, focusing on cultivating students’ implementation and operation ability. Step 26 is the report submission, focusing on cultivating students’ design and implementation ability.

**Table 1.** Knowledge chain of inverter.

1	Reverter schematic design
2	Inverter schematic diagram function simulation
3	Inverter layout layout
4	Layout parasitic parameter after simulation
5	Wafer cleaning experiment
6	Photolithography experiment
7	Double well process experiment
8	LOCOS isolation process experiment
9	Experiment of threshold injection technology
10	Polycrystalline silicon gate technology experiment
11	LDD injection process experiment
12	Side wall technology experiment
13	Source drain injection process experiment
14	ILD process experiment
15	Contact hole process experiment
16	Metal layer 1 process experiment
17	IMD1 process experiment
18	Via hole 1 process experiment
19	Metal layer 2 process experiment
20	IMD2 process experiment
21	Via hole 2 process experiment
22	Top metal process experiment
23	Passivation layer process experiment
24	Integrated circuit packaging experiment
25	Integrated circuit characteristic test experiment
26	Write and submit experiment report

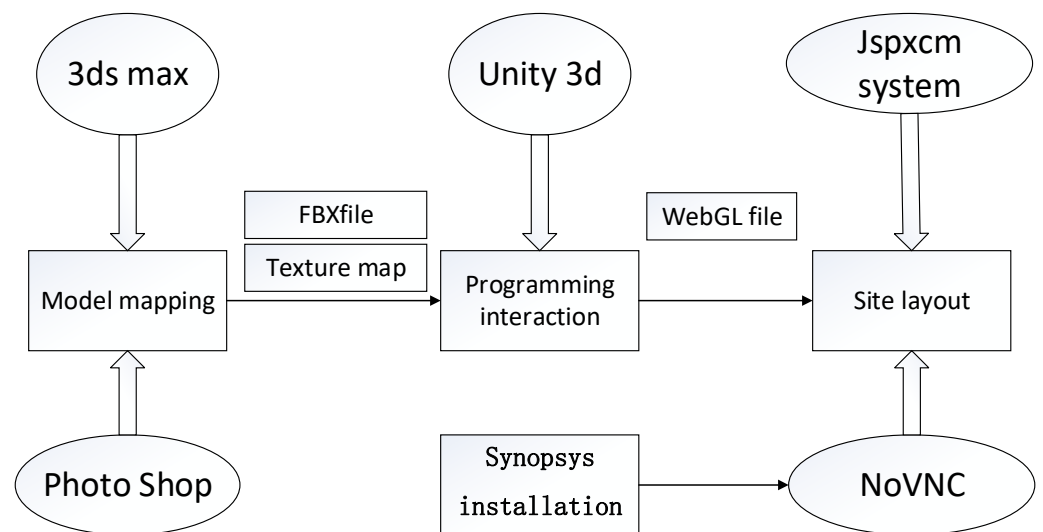
As the whole integrated circuit process steps are composed of the most basic processes, this provides a theoretical basis for the later functional module design [6,29]. Therefore, it is the focus of the experiment to let students master the principles and methods of these most basic processes, which are shown in Table 2 below. In addition, while mastering knowledge, students will also improve their ability to solve complex engineering problems, promote the integration of theory and practice through interactive experiments, and self-study through a large number of learning materials. Finally, the platform will also combine teachers' offline teaching, improving the overall teaching effect of the integrated circuit course [4,5].

**Table 2.** Basic technology of integrated circuit.

1	Integrated circuit schematic design and simulation
2	IC layout design and parasitic parameter simulation
3	Integrated circuit manufacturing and cleaning process
4	Integrated circuit manufacturing process
5	Integrated circuit manufacturing lithography process
6	Integrated circuit manufacturing and etching process
7	Integrated circuit manufacturing diffusion process
8	Integrated circuit manufacturing metal interconnection process
9	Integrated circuit packaging process
10	Integrated circuit performance test technology

2.5. Development Process

The overall development process scheme of the virtual simulation platform is shown in Figure 2 below.



**Figure 2.** Overall design process scheme of virtual simulation platform.

For the 3D simulation module, first, import the model made by 3ds Max and the texture map processed by PhotoShop into Unity3d [4]. Then, the programming and interactive development of the experimental process is carried out in Unity3d. After the interactive function is completed, package the project into a WebGL file in Unity3d and then embed the WebGL file into the front-end website [24]. The integrated circuit design module installs Synopsys software on the remote desktop and then arranges it to the website through noVNC [25,26].

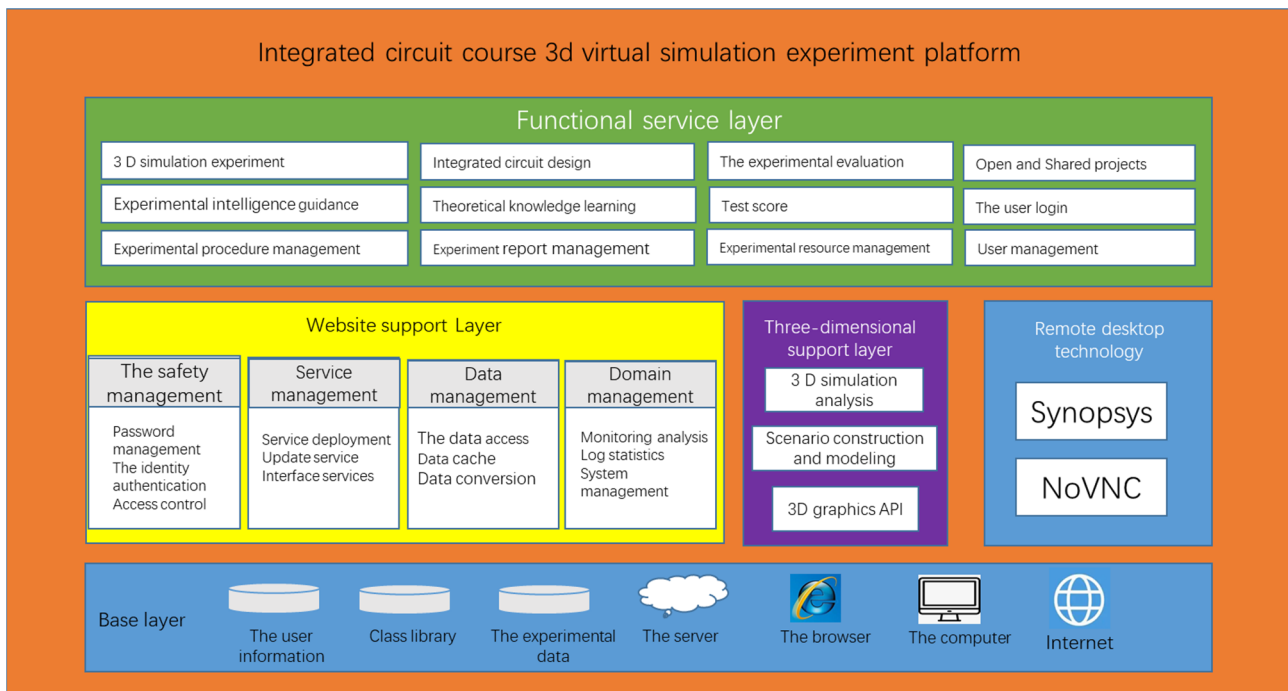
3. Method

3.1. Overall Framework

Relying on computer simulation technology, multimedia technology, and network technology, the three-dimensional virtual simulation experiment platform of the integrated

circuit course is developed with service-oriented software architecture, integrating physical simulation, innovative design, intelligent guidance, automatic correction of virtual experiment results, and teaching management. It is a virtual experiment teaching platform with good autonomy, interactivity, and scalability [30–32].

As shown in Figure 3, the platform supporting the project operation and the architecture of the project operation are divided into three layers, and each layer provides services for its upper layer until the construction of the three-dimensional virtual simulation experiment platform environment of the integrated circuit course is completed. The 3D support layer is the most important module of the platform [30–32].



**Figure 3.** Project system architecture.

### 3.1.1. Foundation Layer

The basic layer provides the most basic data resources and software and hardware support for the three-dimensional virtual simulation experiment platform of the integrated circuit course [30–32]. The data resources of the platform include at least the most basic user information, course resource database, and experimental data. In addition, the platform also needs the hardware equipment support of a server, computer, and the Internet, and users need to access the platform through a browser.

### 3.1.2. Support Layer

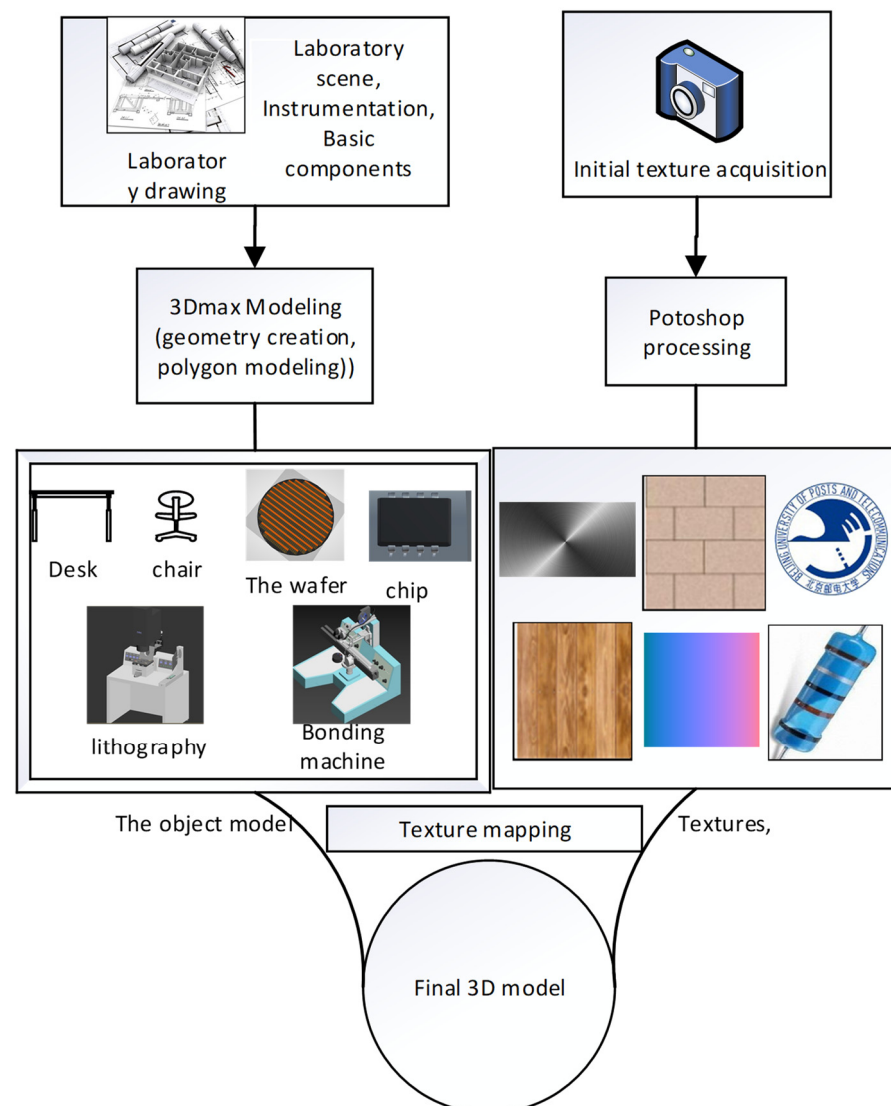
The support layer is responsible for the operation, maintenance, and management of the whole basic system. The website support layer should support the whole website and ensure the service operation of the website, including security management, service container, data management, and domain management [30–32]. The three-dimensional support layer is responsible for supporting the operation of the three-dimensional simulation module, including three-dimensional simulation analysis, scene construction and modeling, and three-dimensional graphics API. Remote desktop technology supports the operation of integrated circuit design. The design simulation software is Synopsys (Version N-2017.12-SP1-2 Synopsys, Inc. Mountain View, CA, USA), which is remotely connected and controlled through noVNC.

### 3.1.3. Function Layer

The function layer is the final presentation, and use of the developed platform functions and services and generally includes the experimental function, experimental teaching management, theoretical knowledge learning, experimental resource management, experimental report management, teaching effect evaluation, project opening and sharing, etc. [30–32].

### 3.2. 3D Modeling

The model-making process of the experimental site, virtual equipment, and various components in the platform mainly includes real model data acquisition, modeling, scene material setting, and texture mapping. The quality of the 3D model will directly affect the rendering effect of the virtual laboratory scene. The following Figure 4 is the model-making flow chart [15,33].



**Figure 4.** Production process of laboratory 3D scene.

The modeling development adopts the 3DS Max modeling tool and strives to restore the real scene of the laboratory one by one according to the principle of from large to small and from simple to complex. All models of the platform are modeled according to the structure and proportion of the actual model. The main instrument models include a cleaning tank, drying machine, oxidation diffusion furnace, glue homogenizer, glue



dryer, lithography machine, hot acid tank, oven, dry etching machine, plasma degumming machine, wet etching machine, annealing equipment, deposition equipment, ion implantation machine, CMP equipment, dispensing machine, oven, bonding machine, injection molding machine, laser engraving machine, wafer cutting machine, oscilloscope, DC voltage stabilizing source, and function signal generator. Figures 5 and 6 show the laboratory model.

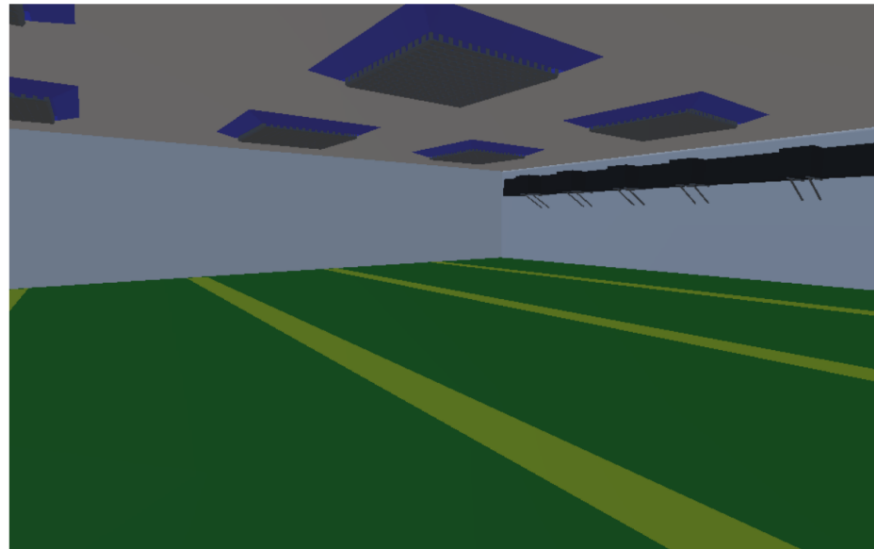


Figure 5. Integrated circuit clean room.

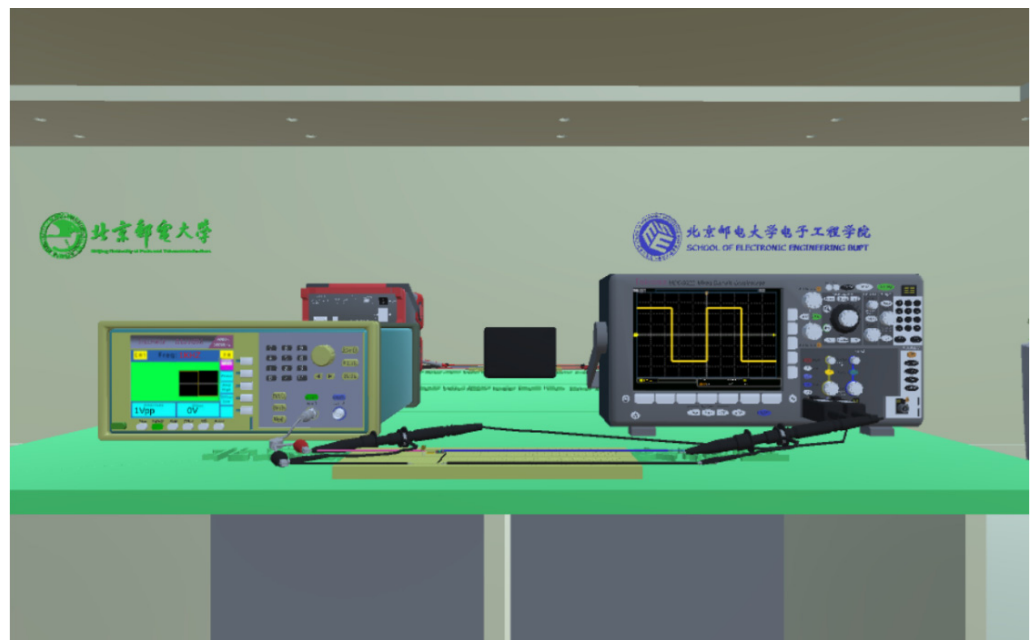


Figure 6. Electronic Circuit Laboratory. The non-English part is the emblem, name or the website title of BUPT.

There are two points to note when importing the model into the unit.

First, the unit proportion, and by default, the proportion of the 3DS MAX models imported in Unity3d is 0.01:1. In addition, there are three conditions when importing Unity3d from the 3DS MAX model: the 3DS MAX unit setting, the exported 3D file format, and the scale of Unity3d. In 3DS MAX, you need to set the model units to 1 m and set the export format to FBX, while setting the zoom ratio to 1 in Unity3d [34].

Secondly, it should be noted that various model resources made by 3ds MAX must be “ungrouped” in the export process. After ungrouping, the 3D model will become a tree structure model. At this time, the 3D model is composed of sub-models in the tree model, and the sub-model may contain sub-models, as shown in Figure 7. At this time, each node in the model is closely connected and contains its own model information. Only the tree structure model can add corresponding functions to each part of the virtual instrument [20].

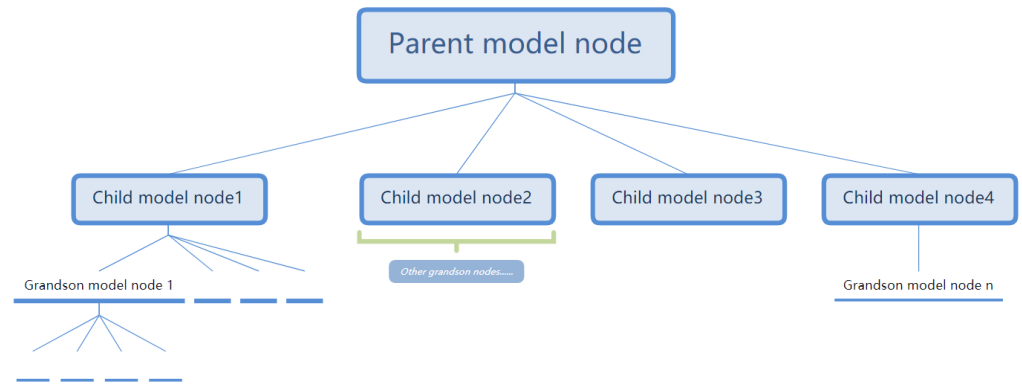


Figure 7. Tree view of 3D model disassembly.

### 3.3. 3D Simulation Development

The Unity3d engine is used for 3D simulation development. The overall 3D development is divided into the presentation layer, application layer, and resource layer. The overall architecture of the 3D simulation module is shown below in Figure 8 [14,35]. The bottom layer is the most basic resource and presentation layer. The presentation layer provides us with visual effects, auditory effects, and human–computer interaction. The application layer is a logic control module which generates corresponding feedback to the interaction, controls the resource allocation of the whole three-dimensional virtual simulation experiment, and records the experimental steps through network communication. The presentation layer provides corresponding resources and effects for the application layer, and the application layer will control the presentation effect of the presentation layer.

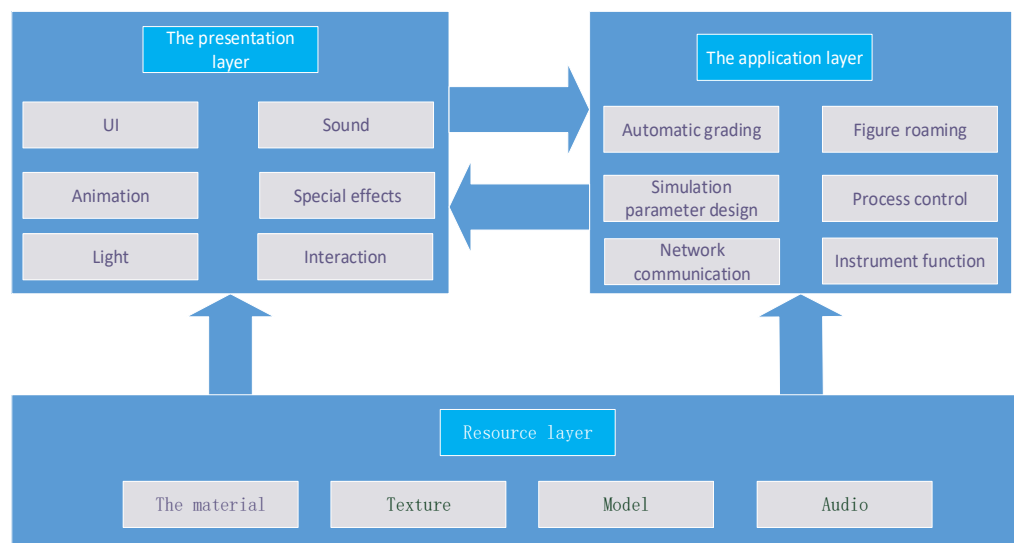
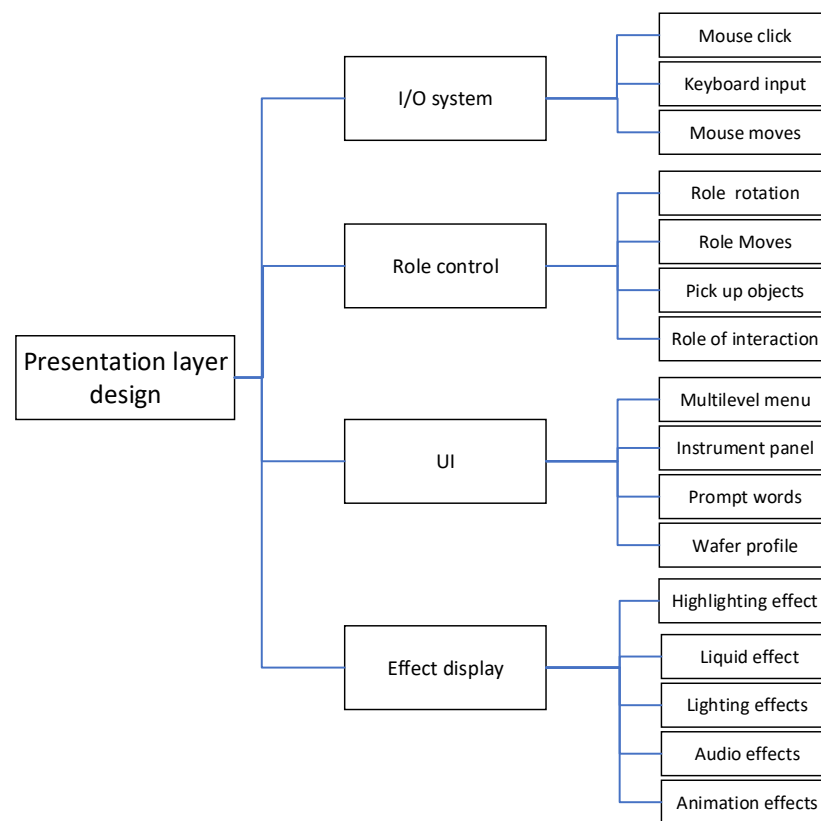


Figure 8. Overall architecture diagram of the 3D simulation module.

#### 3.3.1. Design of Presentation Layer

The interaction layer greatly affects the immersion of the experiment, which will greatly affect students’ learning efficiency and passion [12]. In order to improve the

interactivity, the system uses the first person plug-in first-person exploration kit (fpek) in the interaction design module. Fpek is the first-person functional plug-in of 3D, which has strong interactivity and expansibility, which is very conducive to expansion and development. Fpek has complete functions and the strong expansibility of the UI system, which can completely save and read the game. On the basis of fpek, the platform further develops and expands the original UI and related interactive settings of fpek, including a multi-level menu system, role controller (can walk, run, jump, squat), etc. In addition to fpek, the platform also develops an object highlighting function, instrument panel, task box, prompt text, current step prompt, light effect, liquid effect, and other display effects [36]. The overall functional structure of interaction design is in Figure 9.



**Figure 9.** Overall functional structure diagram of the interaction design.

Animation is the most important presentation effect in the system. Most of the interactive effects in the system are presented through animation. Two animation implementation methods are used in the platform; one is the animation plug-in dotween, and the other is the animator provided by Unity3d [37].

Dotween is an excellent animation plug-in. When using the plug-in function, you need to add “using DG.Tweening;” in the script, indicating that the library file is referenced. The dolocalmove function is mainly used in the script. For example, execute “g.transform.dolocalmove (New vector3 (0.1f,−0.1f,−0.1f), (1);” Statement, the object bound by the g variable will move from its current position to the position of the coordinate point corresponding to (0.1f,−0.1f,−0.1f) within 1 s. In addition, other practical functions of the dotween plug-in are also used, such as doplayforward() forward animation; Doplaybackwards(); Dotext() text printing effect; Docolor() modifies the color; Dofade() transparency gradient; Doshakeposition() vibration effect; Setease() sets the animation curve; Setloops() sets the number of playback cycles; Oncomplete() is an event function that runs when the animation ends; Onstart() is the event function when the animation first runs.

Compared with the dotween plug-in, animator is the most basic animation development system of Unity3d [37]. Trigger is commonly used in animator to switch from one

animation state to another. The first is the add animation event. Enter the animation panel, select the animation clip you need to monitor, select the triggered key frame, right-click to add the animation event, and then select the function you need to trigger. In this way, when the animation plays to this frame, it will trigger the function you choose.

Other corresponding performance effects can be seen in Figure 10 below.



Figure 10. Other performance examples. The arrow points to the explanatory text.

### 3.3.2. Function Development of Instruments and Equipment

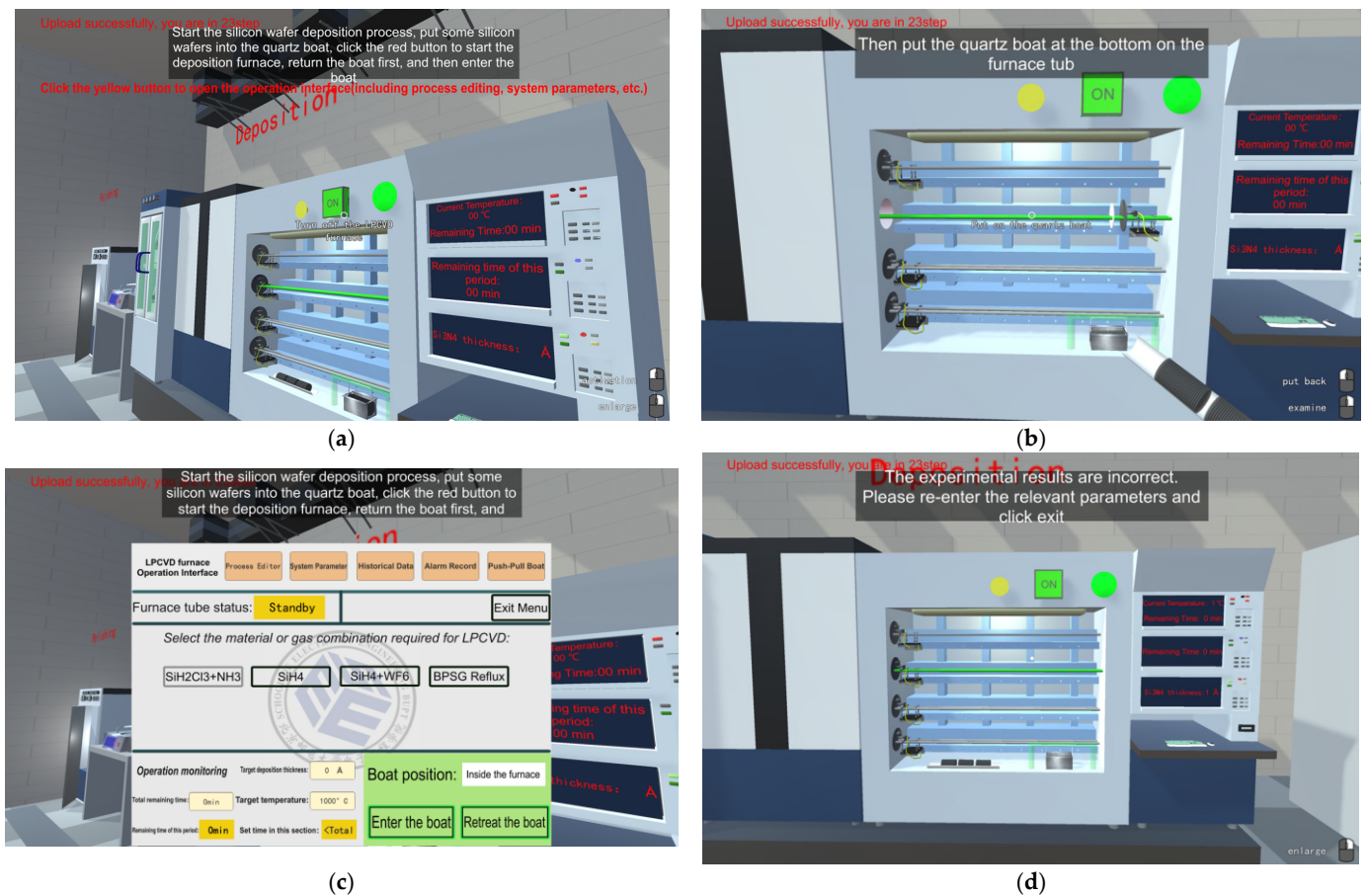
The manufacturing process of integrated circuits usually includes the following process technologies: the deposition process, the silicon thermal oxidation process, the silicon wafer lithography process, the etching process, the diffusion process, and the IC packaging process. The 158 small steps in the integrated circuit manufacturing process are composed of the above basic process technologies [6]. Therefore, in order to improve the reuse rate of instruments and equipment and reduce the coupling degree, the function of the equipment

is developed with the process technology as the module. Equipment functions are further divided into input functions: button click and parameter input. The output function is to present the animation effect and sound effect of the corresponding model materials and the feedback of UI text. Table 3 takes the film preparation in the oxidation process as an example to illustrate the scientific principle of the design, the required equipment, and the corresponding parameter design [38].

**Table 3.** The oxidation process as an example to illustrate the functional principle of the instrument and equipment development.

Principle Description	Design of Equipment and Parameters
<p>The oxidation process thermally grows a uniform layer of dielectric film on the surface of a silicon wafer, which is used as an insulating or masking material. The oxidation process includes high-temperature dry oxygen oxidation and high-temperature wet oxygen oxidation. The oxidation principle equation is as follows:</p> $Si + O_2 = SiO_2$ <p>The wet oxygen oxidation principle equation is</p> $Si + 2H_2O = SiO_2 + 2H_2$ <p>Derivation of principle formula: Through theoretical analysis and mathematical solution of the oxidation process, a general mathematical expression reflecting the oxidation law of thermal growth can be obtained:</p> $X^2 + DX = C(t + \tau) \quad (1)$ <p>The solution of the relationship between oxide layer thickness and oxidation time can be obtained from the above formula:</p> $\frac{X}{D/2} = \sqrt{1 + \frac{t+\tau}{D^2/4C}} - 1 \quad (2)$ <p>For longer oxidation time, <math>t \ll D^2/4C</math>, the general relation tends to a parabola, i.e.: <math>X^2 = Ct</math> (3)</p> <p>For shorter oxidation times, i.e., <math>(t + \tau) \ll D^2/4C</math>, the general relation tends to be linear, i.e.:</p> $X = (C/D)(t + \tau) \quad (4)$ <p>In the above formula, <math>X</math> is the thickness of oxide layer, <math>t</math> is the oxidation time, <math>C</math> is the parabolic rate constant, <math>C/D</math> is the linear rate constant, and <math>\tau</math> is the correction of the oxidation time after considering that there is a 100 ~ 200 Å natural oxide layer on the surface of the silicon wafer stored in the air. For wet oxygen oxidation, it is negligible.</p>	<p>Equipment: oxidation diffusion furnace Parameters: silicon oxide film thickness, oxidation time, oxidation temperature</p>

In chip manufacturing, CVD equipment is taken as an example to illustrate the equipment operation steps. First, click the switch through the center point and the left mouse button to start the CVD device and operate according to the contents of the prompt column above. Then, click the push boat button to exit the quartz boat, pick up the silicon wafer box, and put it on the quartz boat. Next, click the yellow button to open the equipment menu, select the materials required for the PECVD process, remaining time, target temperature, and other indicators, and click the boat entry button to wait for the verification of the experimental results. If the experimental data is inputted incorrectly, the experiment will be carried out again [39]. Figure 11 shows some basic operations of the CVD experiment.



**Figure 11.** CVD device operation. (a) Turn on the CVD device switch; (b) Put the quartz boat on the furnace tube; (c) CVD device control page; (d) If the experimental results are incorrect, it will indicate that the experiment has failed.

The experimental objects and parameter designs of other manufacturing process related process technologies are as follows [6]:

- Preset parameters of the virtual simulation experiment of lithography process: mask selection, number of rotating gluing revolutions, photoresist thickness, exposure time, development time, etc.;
- Preset parameters of the virtual simulation experiment of the etching process: type of etching gas, density of etching gas, etching pressure, etching time, etc.;
- Preset parameters of the diffusion process of the virtual simulation experiment: implanted ion, implanted energy, implantation metering, etc.;
- Preset parameters of the packaging process virtual simulation experiment: wafer segmentation, chip adhesion, resin curing, pin bonding, chip injection molding, laser coding, etc.;
- Preset parameters of the integrated circuit test virtual simulation experiment: test circuit, function signal generator, oscilloscope, DC voltage stabilizing source, etc.

For more detailed principle descriptions, please visit the experiment website: "Integrated Circuit Virtual Simulation Experiment Platform, <http://www.ilab-x.com/details/2020?id=6480&isView=true#1001>, accessed on 28 April 2022". On the experimental website, you can also refer to the specific guidance process of 166 small steps of the whole platform, but the platform is developed in Chinese, and English users may need the help of translation tools to understand it.

### 3.3.3. Step Management

According to the overall process steps, a total of 26 large steps and 166 small steps are designed. The overall level clearance mode is adopted. The use of levels is of great help to improve students' sense of immersion [12]. In order to better control the operation of steps, each small step needs to be written as a corresponding function module [40,41]. Certain parameter controls and conditions are set for each step. The next step can be triggered and unlocked only after meeting the requirements, which also ensures the normal progress of the virtual experiment. At the same time, in order to better manage large and small steps, a multi-level menu is introduced. The relationship between large steps and small steps can be well presented through multi-level menus.

The principle of step control is shown in Figure 12 When logging in, the user needs to use js front-end technology to store the user ID and then pass the user ID to Unity3d through the corresponding communication module. Unity3d then obtains the step data from the remote cloud through the HTTP get request. When receiving the information returned remotely, it needs to use the litjson plug-in to help parse the JSON data. If the return status is successful, the step acquisition module returns the global int variable process. Then pass the process into the step location module to unlock the step. In order to call the step function in a process, the step function is named in the form of "process1()", which is convenient to call the corresponding step function using c#'s reflection feature [40,41]. C #'s reflection property call statement, such as "this. GetType(). GetField ("process" + i). GetValue (this) as GameObject". Triggering the corresponding step function is equivalent to unlocking a new level. Therefore, in the step function, in addition to the function of initializing the corresponding equipment, it is also necessary to open the corresponding collision body of the new step, replace the relevant materials, import the relevant animation, and update the wafer diagram. Figure 13 shows the change process of the wafer diagram [6].

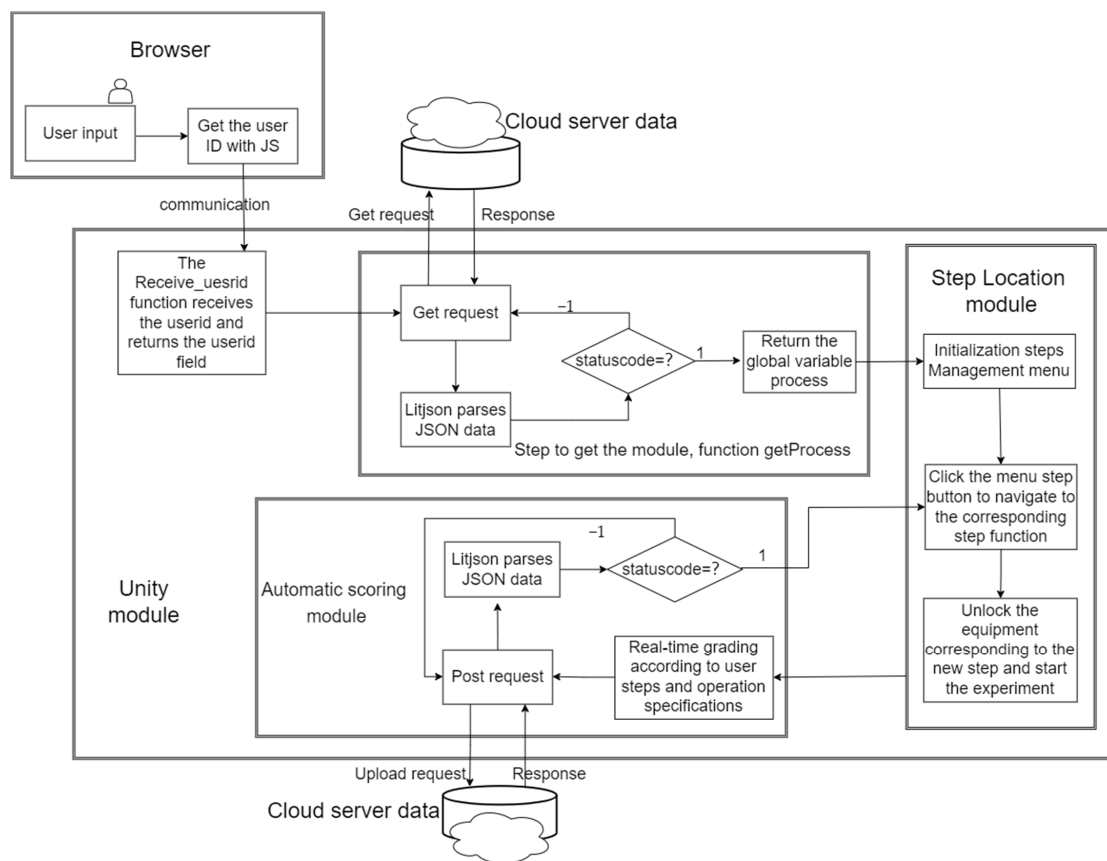


Figure 12. Step control flow chart.

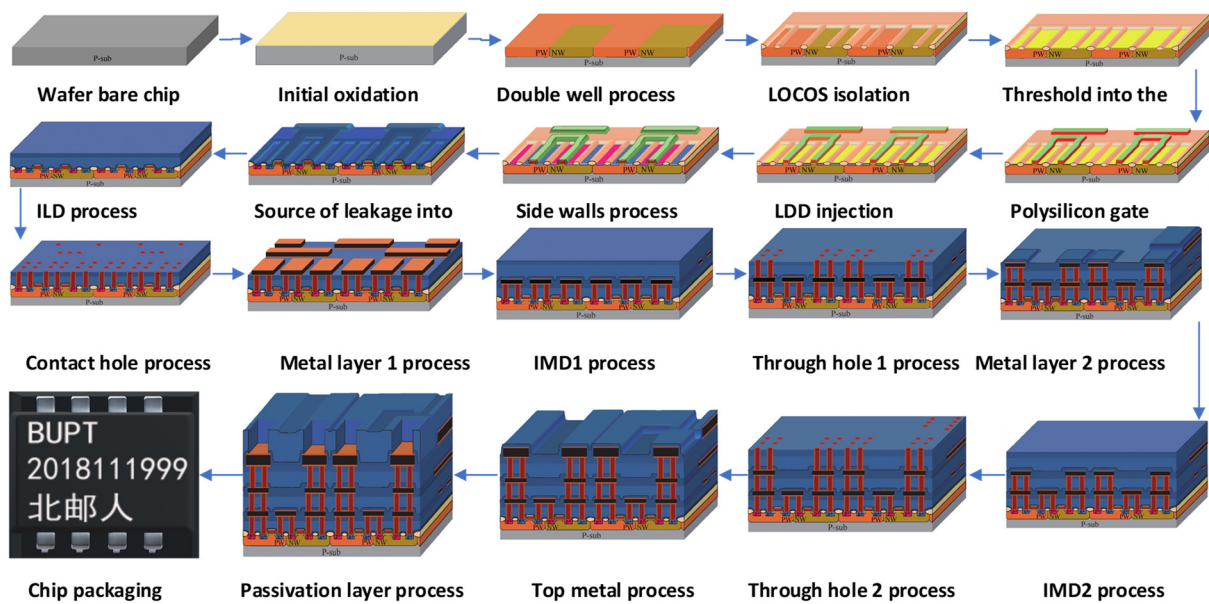


Figure 13. Wafer change flow chart. The non-English part is the emblem, name or the website title of BUPT.

After unlocking the corresponding steps, the automatic scoring module will monitor the user’s operation specifications and steps in real-time, evaluate and score them, and then upload the data to the remote cloud through HTTP post request and unlock the next new step [40,41]. Automatic scoring is an important means to ensure the quality of teaching [12]. Automatic scoring can greatly reduce teachers’ review workload and improve the flexibility of teaching. For the scoring rules of steps, please refer to the experiment website: “Integrated Circuit Virtual Simulation Experiment Platform, <http://www.ilab-x.com/details/2020?id=6480&isView=true#1001>, accessed on 28 April 2022”.

### 3.3.4. Compiling and Exporting Scenarios

After the completion of the project of Unity3d programming software development, due to the cross-platform nature of Unity3d, the project can be easily packaged into various required formats through the packaging tool. Since the platform is to run on the web, it is packaged into WebGL format [19].

Optimize the project using Profiler tools before packaging. Profiler is a tool used in Unity3d to monitor resource consumption in real-time. Users can observe the usage of each resource in a graphical window and optimize it according to the usage. As the integrated circuit manufacturing module needs the most resources in the whole 3D virtual experiment, it is taken as an optimization case.

Run the game first, then click under Memory to select Simple mode, which gives you a rough view of how much Memory is allocated. After clicking the Profiler at the bottom, analyze that the total memory occupied by this virtual test experiment was 1.02 GB, among which 0.74 GB was occupied by Unity3d. Among them, Texture and Mesh resources are large in number, while Mesh occupies the most resources in the scene. The GameObject in the whole scene is 6362, and the Object in the whole scene is 26,767. Figure 14 provides us with CPU usage and memory.



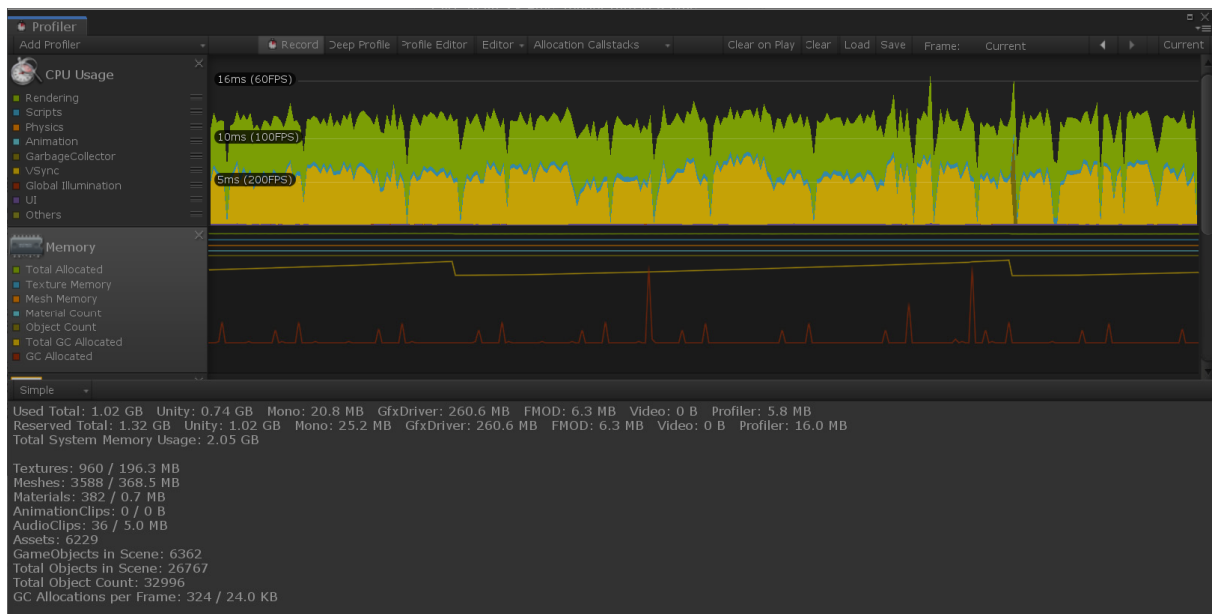


Figure 14. Unity3d Profiler Tool.

Because WebGL projects work in browsers, and because browsers have other types of memory overhead, the virtual lab project takes up 0.28 GB of memory. For Texture, replace the UI resources in the project with a more streamlined UI format while maintaining the appearance. Many maps in this project are in Format format, which occupies a large amount of memory although the picture is relatively clear. Therefore, using ARGB 16bit compression for maps reduces memory consumption. Since 3ds MAX was used in the project selection, the exported FBX file was also a model with a high compression ratio to reduce the memory consumption, which controlled the memory consumption of the whole project to be between 0.2 GB and 0.3 GB. Since most computers used for students' remote operation experiments have more than 8G memory, browsers can allocate sufficient memory space for WebGL projects, which can ensure the normal operation of the projects [19,20]. After the scene is optimized, click the Stats button in the Game window to observe the parameters of each Graphics rendering of the 3D virtual experiment. In this project, the FPS is 71.8, which is more than 60 FPS, and the refresh rate change is almost imperceptible to the human eye. The size of Tris and Batch parameters. Tris refers to the current Batches of fandon. The total number of fandon in this project is 6.3 m, which is 921, both of which are within the controllable scope of project operation, as shown in Figure 15 below.

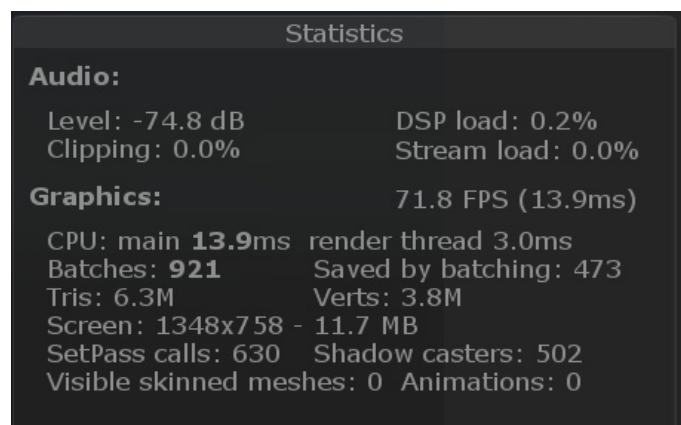


Figure 15. Unity3d scene information.

The following points are worth noting in the export section:

- (1) In “other settings”, you need to set color space to gamma correctly. Using gamma color space, the standard shader will be written into the color cache in Unity3d, and then visual correction will be carried out in the display stage of the screen and then displayed on the computer screen in brightness. It will correct the light and objects in the virtual space, and make the scene brighter and more realistic;
- (2) It should also be noted that the default Aerial font should not be used in Chinese before packaging. Other fonts supporting Chinese packaging should be imported, such as Simeon. Set the Icon image to the virtual simulation lab logo, which will show the simulation lab logo when loading;
- (3) There are two mainstream package compression methods: Gzip and Brotli. In Brotli compression mode, the resource compression rate is high after a project is packaged, and the waiting time during the loading and startup phases is short, but the packaging process is long. Gzip, on the other hand, is about 2/3 as efficient as Brotli according to tests by Damiano Perri. However, considering that Gzip supports all major browsers and the platform updates frequently, Gzip packaging is finally selected [19];
- (4) Checking the data caching option during packaging and export enables the fast loading function during the second loading. Its principle essence is to use the caching function of the browser [42]. This setting can greatly reduce the waiting time of users. However, we need to pay attention to the memory capacity allowed by the browser and reasonably set the browser cache space.

### 3.4. Integrated Circuit Design Module Implementation

The experimental content of IC design mainly includes chip schematic design, chip schematic simulation, chip Layout design (Layout), CHIP Layout check (DRC and LVS), parasitic parameter extraction, and post-simulation. The students complete the design of the inverter through the above steps. The inverter of the design part is mainly composed of an nMOS tube connected with pMOS. In addition, students can also design and simulate other circuits on the IC design platform.

#### 3.4.1. Set up NoVNC

The front-end page of this experimental platform contains the chip design part, which needs to connect to the remote Linux server through noVNC, and then use the chip design software. The platform consists of the following five steps [25,26]:

Install the VNC service → Start the VNC service → noVNC deployment → set the self.pem file → vncserver@.service to start.

#### 3.4.2. Synopsys

It mainly includes the following steps:

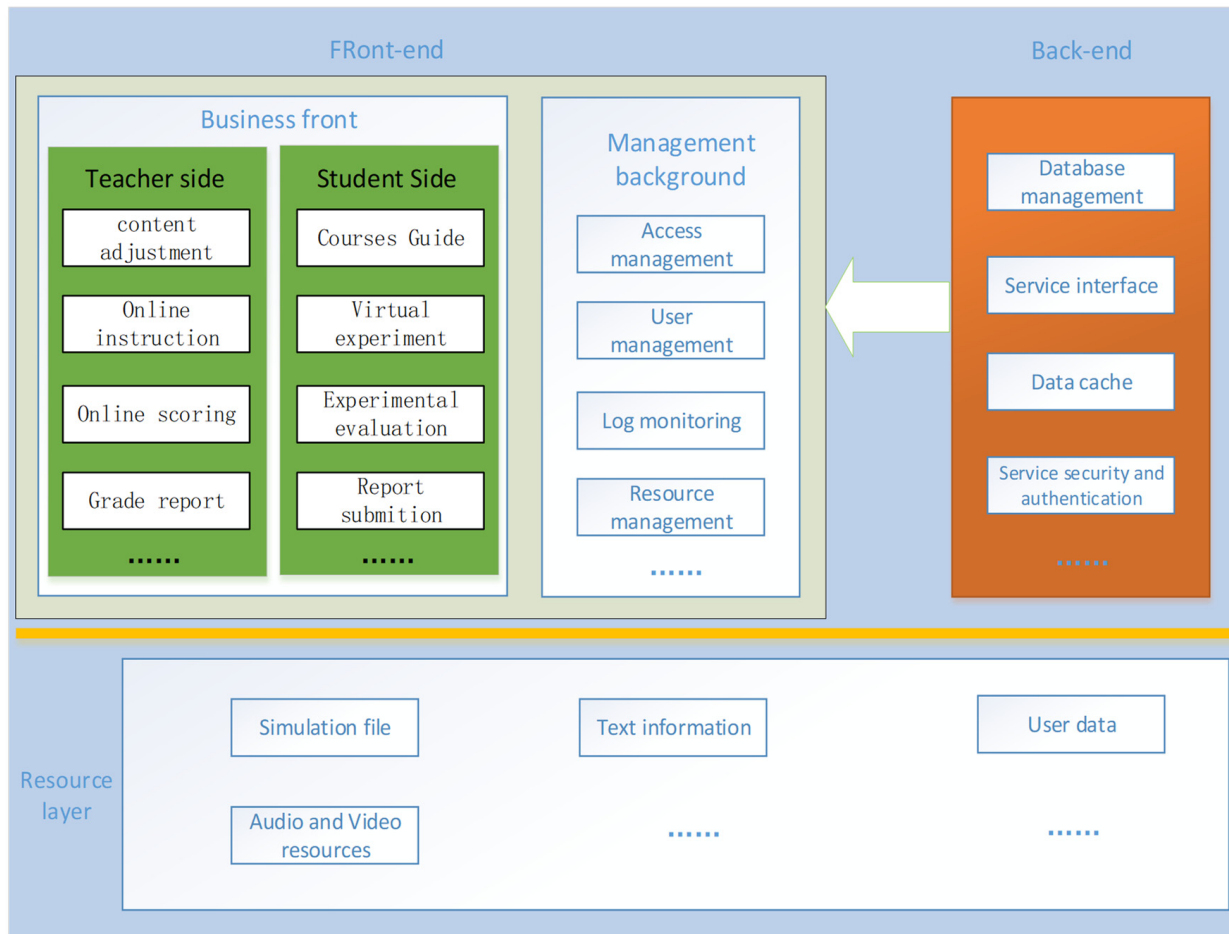
Download and install installer → Set environment variables → Set license.

The students need to design an inverter based on p-type monocrystalline silicon substrate. The target parameters are as follows [43]:

- (1) N-groove polycrystalline silicon gate MOSFET: Threshold voltage  $V_{TN} = 0.5$  V, drain-saturation current  $I_{Dsat} \geq 1$  mA, drain-source saturation voltage  $V_{Dsat} \leq 3$  V, drain-source breakdown voltage  $V_{DS} = 35$  V, gate-source breakdown voltage  $V_{GS} \geq 20$  V, transconductance  $g_m \geq 2$  mS, Cut-off frequency  $f_{max} \geq 3$  GHz (mobility  $\mu_n = 600$  cm<sup>2</sup>/Vs);
- (2) P-groove polycrystalline silicon gate MOSFET: Threshold voltage  $V_{TP} = -1$  V, drain saturation current  $I_{Dsat} \geq 1$  mA, drain-source saturation voltage  $V_{Dsat} \leq 3$  V, drain-source breakdown voltage  $V_{DS} = 35$  V, gate source breakdown voltage  $V_{GS} \geq 20$  V, transconductance  $g_m \geq 0.5$  mS, Cut-off frequency  $f_{max} \geq 1$  GHz (mobility  $\mu_p = 220$  cm<sup>2</sup>/Vs);
- (3) The chip package adopts diP-8 form, the power supply voltage is 1.8 V, and the chip power consumption is less than 10 mW;

### 3.5. Website Deployment

The overall framework for site deployment is shown in Figure 16 below. The resource layer is the lowest layer and provides the most basic support and guarantee for the front and back ends. At the same time, the front and back ends are separated, and the back end also provides the corresponding interface services and data services for the front end [30–32,40].



**Figure 16.** Overall framework diagram of the website deployment.

The front end of the web page includes the front end of the business and the back end of management, as shown in Figures 17 and 18. The front end of the business also includes the student end and the teacher end, which are controlled by the user’s account. If the user logs in with the teacher account, the teacher end will be entered, and if the user logs in with the student account, the student end will be entered. Only administrators can log in to the management background to view, access data, manage resources, and update the 3d virtual simulation version. The back-end part provides user security authentication and service interface such as a step management interface to ensure the normal operation of the whole website [41].

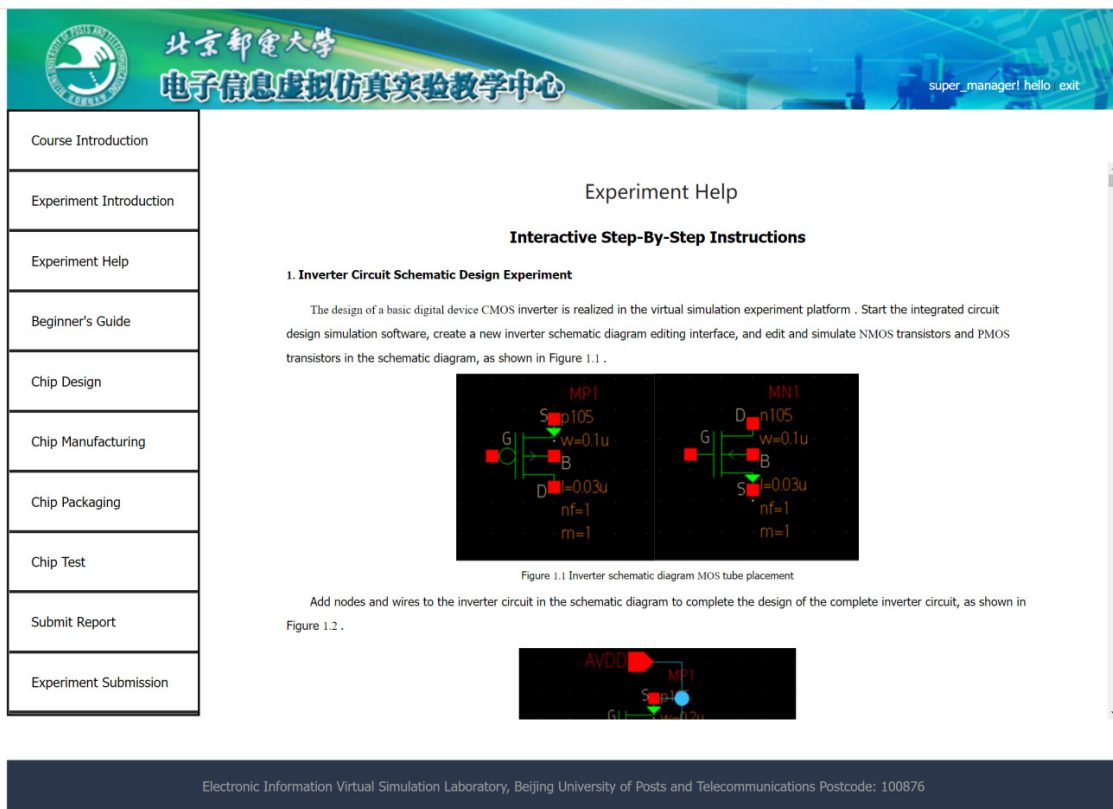


Figure 17. Front page of website. The non-English part is the emblem, name or the website title of BUPT.

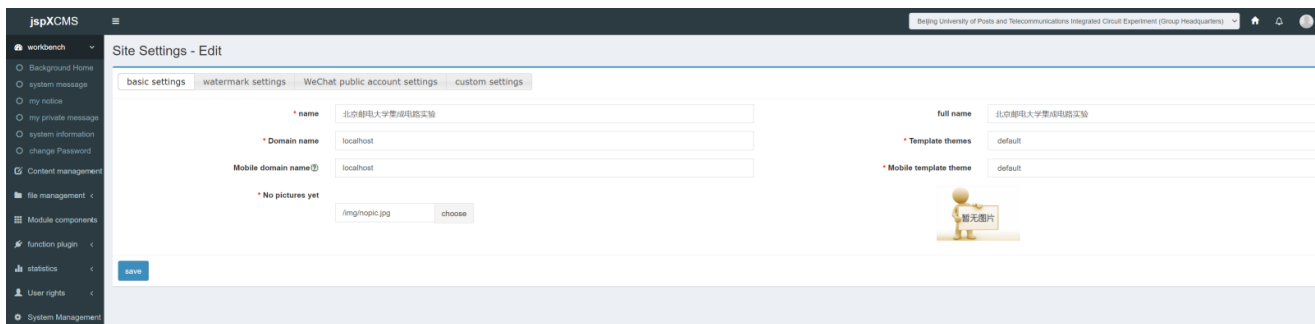


Figure 18. Website back-end management system interface. The non-English part is the emblem, name or the website title of BUPT.

## 4. Result and Test

### 4.1. Testing Configuration Requirements

According to the memory and CPU operating requirements of the project and the operating requirements of WebGL, the recommended computer configuration is as follows in Table 4 [4].

Table 4. Recommended computer configuration.

CPU	Intel® i5-4590/AMD FX 8350 same or higher configuration
GPU	NVIDIA GT 920 M same or higher configuration
RAM	4 GB or higher
OS	Windows 7 SP1 same or higher version/Mac OS10.9 or higher
Network speed	Higher than 2 M

#### 4.2. Browser Performance Test

The browser is tested on a Windows 10, RAM 8.0 GB, CPU Intel(R) Core(TM) i7-4710MQ CPU @ 2.50 GHz, and NVIDIA GT 940 M. The test results are presented in Table 5. During the test, you do not need to download any plug-ins, just open the web page in the browser.

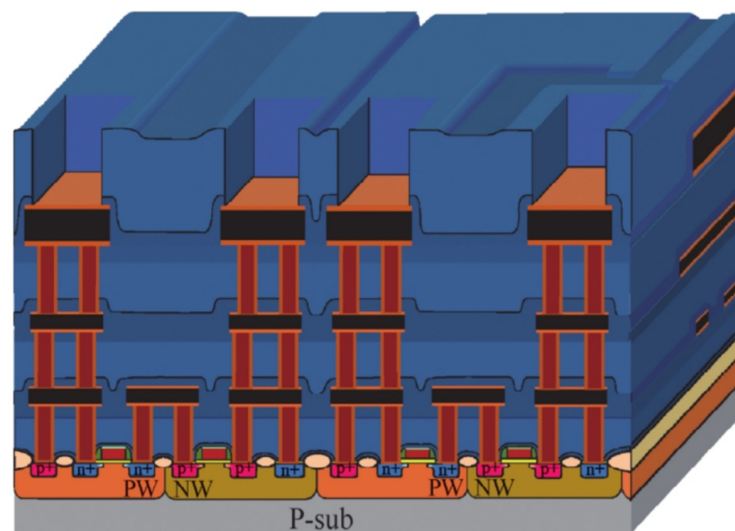
**Table 5.** Performance test results of different browsers.

Browser Name	First Loading Time	Secondary Loading Time	Compatibility
CHROME9	289 s	Less than 10 s	Compatible
FIREFOX9	142 s	Less than 10 s	Compatible
EDGE	138 s	Less than 10 s	Compatible
IE11	NULL	NULL	Not compatible

Based on the final test results, FIREFOX9 or Edge are recommended for the experiment. The second load is tested when the browser enables the cache function [42]. Compared with the first loading time, the efficiency of the second loading has been greatly improved. Therefore, users are advised to enable the browser cache.

#### 4.3. Experimental Results

The final wafer profile is shown below in Figures 19 and 20:



**Figure 19.** Final wafer profile.



**Figure 20.** The result is a piece of inverter in a Dip8 package. The non-English part is the emblem, name or the website title of BUPT.

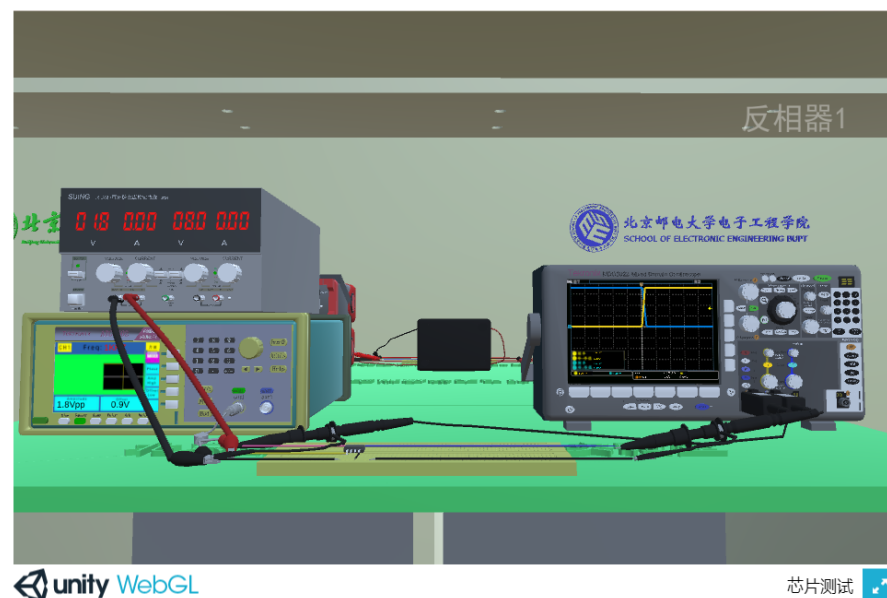
### Integrated Circuit Test Results

The inverter chip adopts a 1.8 V power supply. Input rectangular wave, corresponding input, and output information are as follows in Table 6.

**Table 6.** Integrated circuit test results.

Input Frequency	Peak-to-Peak Value of Input Signal	Input Bias	The Output Voltage	The Output Frequency
1 KHZ	1.8 vpp	0.9 v	Reverse to input voltage	1 KHZ
2 KHZ	0.3 vpp	0.3 v	1.8 v	2 KHZ
2 KHZ	0.2 vpp	2.0 v	0 v	2 KHZ

Compared with inverter input and output logic, the inverter chip conforms to inverter output logic. The final rendered input and output data are shown in Figure 21.



**Figure 21.** Inverter input/output waveform. The non-English part is the emblem, name or the website title of BUPT.

#### 4.4. Student Completion and Evaluation

##### 4.4.1. Analysis of Students' Experimental Results

As can be seen from Table 7, the current number of users has reached 1367, and the passing rate of the whole experiment is 100%, but the excellent rate is only 66%. Most of the registered users are students from many different universities, of which the number of students from Beijing University of Posts and Telecommunications is the largest, up to 70%. The average time for students to complete the whole experiment is 6 to 7 h. The expected excellent rate of students was 60%, and the completion time was 6 h. Therefore, the passing rate and excellent rate of students' experiments are kept at a reasonable level, and the experimental time is moderate. Through the score data of the website background statistics, because the relevant data is difficult to quantify, the qualitative analysis of students' performance is as follows:

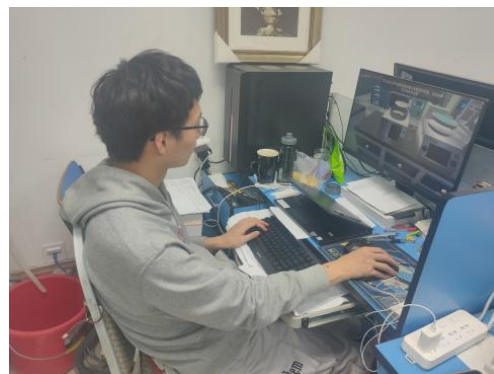
- (1) The score rate of the integrated circuit design module is low, and the completion time is about 2.5 h. However, this part only has four steps, while the whole experiment has 26 steps, so this part takes too much time. The reason for the poor performance of this part by students may be that this part belongs to the traditional simulation experiment, with poor interactivity and high difficulty in using the software. At the same time, it also shows that students' design ability needs to be further strengthened.

- (2) The remaining modules are mainly three-dimensional simulation modules. At the beginning of the module, students' operation time is longer, while the completion time of other steps is shorter and shorter. To some extent, this reflects that students' operation proficiency and knowledge application are getting higher and higher. Students reported that the sputtering experiment and oxidation experiment in this module is more difficult, and the failure rate of the experiment is higher. They often have to repeat the experiment several times to get the correct results.
- (3) Because the IC manufacturing module has the most steps, the completion time is also the longest. This part takes about 3.5 h. The rest is relatively simple, and the students' completion speed is relatively fast. Finally, most students can get perfect test results as expected and write experimental reports reasonably.

**Table 7.** Number of users and completion of experiment.

Number of User	Pass Rate (Score $\geq 60$ )	Excellent Rate (Score $\geq 80$ )	Average Completion Time
1367	100%	66%	6 to 7 h

Figure 22 depicts a scene in which students cannot return to school and instead perform experiments at home during the epidemic. During the epidemic period, the course was carried out in the mode of students' independent learning and completing the experiment through teachers' online teaching guidance. Due to the automatic scoring function, teachers do not need to monitor the students in real-time. Students can also independently learn the learning materials in the platform and choose the time to complete the experiment and obtain the corresponding experimental score. This intelligent teaching mode has greatly improved teaching efficiency during the epidemic.



**Figure 22.** Student performing an experiment at home.

#### 4.4.2. Analysis of Students' Course Performance

In order to verify the teaching effect after using the integrated circuit virtual experiment platform, we make a statistical analysis of the final exam grades of the classes that have set up the integrated circuit courses in Beijing University of Posts and Telecommunications in the last three years. There are 40 students in the class offering the course, which are junior college students. The score statistics of students are shown in Figure 23 below. The integrated circuit virtual experiment platform has been used since 2020, and the integrated circuit virtual experiment platform was not used in 2019. By observing the figure, it can be found that after using the integrated circuit virtual experiment platform, the average score and excellent rate of students (score  $\geq 80$  is excellent) has been greatly improved. Compared with 2019, the average score in 2020 increased by 3.37 points and the excellence rate increased by 17.7%. In 2021, the average score increased by 3.97 points and the excellence rate increased by 17.2%. The significant improvement of students' scores in the

integrated circuit course shows that the integrated circuit virtual experiment platform is of great help in improving students’ mastery and understanding of integrated circuit course knowledge.

In the comments of students, about 5% of students reported that they would feel dizzy during the experiment, which belongs to the content of the operation experience. Dizziness often occurs in virtual, three-dimensional experiences. The main reason is that the visual information received by students is inconsistent with the sensory information. This is likely because the rotation speed of the perspective in the three-dimensional experiment is too fast, or the students’ visual fatigue is caused by the too long experimental time [44]. Students think that the rotation speed of the mouse can be appropriately reduced to reduce their dizziness. At the same time, we also suggest that students reasonably arrange the experimental time and do not experiment for too long at one time. Some students also reported that the network stability is poor, which may be related to the server arranged on the website. This also shows that the platform needs to strengthen the network stability when the number of users is large. In addition, some students were shocked by the complexity and difficulty of the whole chip manufacturing process. Most students commented that the virtual experiment has a reasonable arrangement, detailed steps, vivid and interesting experiments, and strong interaction, which can help them master the theoretical knowledge of integrated circuits [18], which is a new way of teaching. From the students’ high scores and positive comments on the experimental platform, we can see that students have a high degree of recognition of the three-dimensional virtual experimental platform, which also shows that the three-dimensional virtual experimental platform is very helpful in stimulating students’ learning interest and mastering skills and knowledge. For more comments, please visit: “IC Virtual Experience Platform Student Message, <http://www.ilab-x.com/details/vote?id=6480>, accessed on 28 April 2022”.

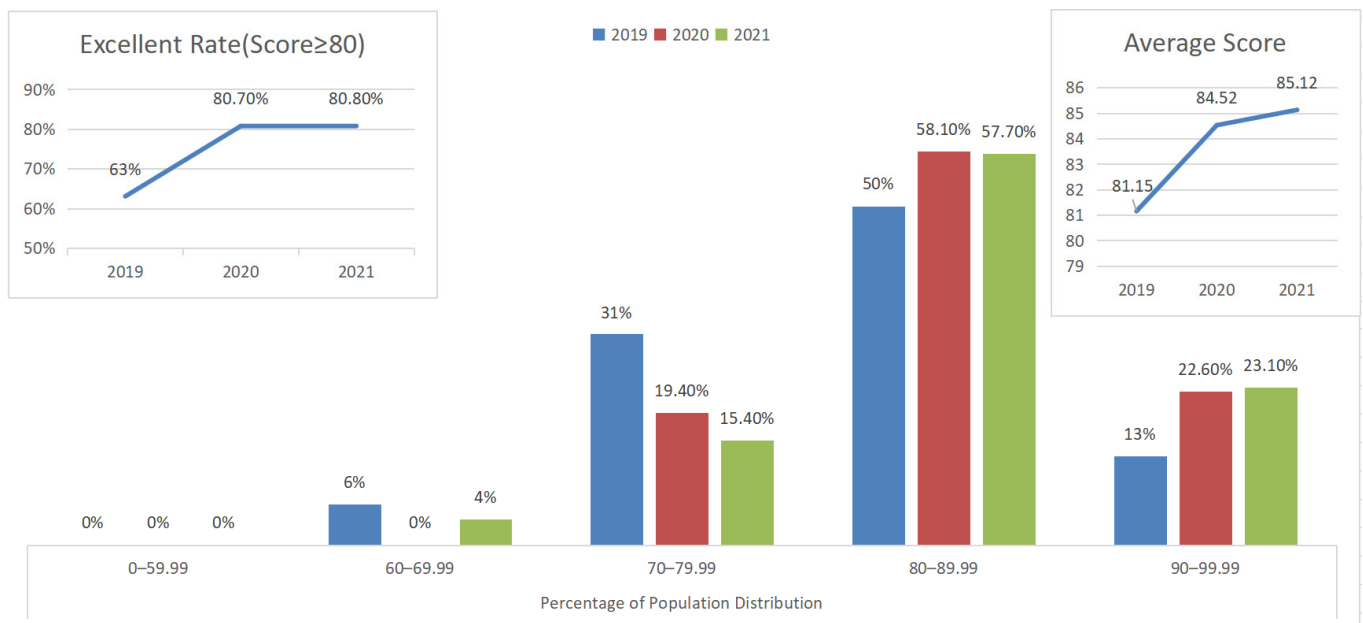


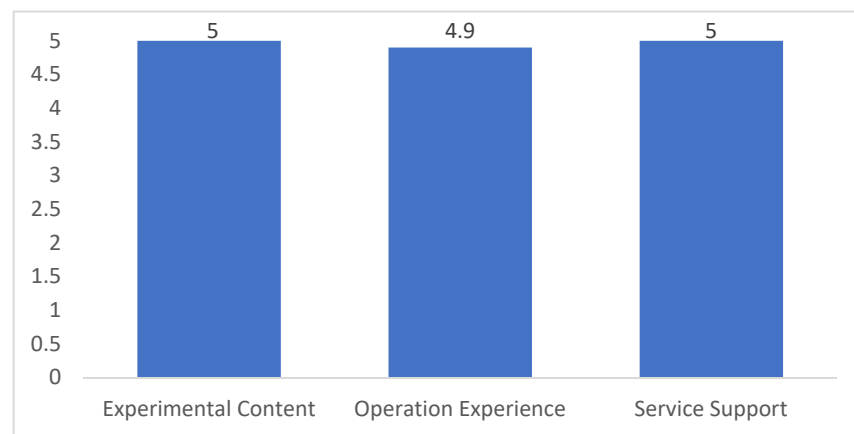
Figure 23. Analysis and statistics of students’ scores in integrated circuit course.

#### 4.4.3. Student Evaluation

After the students finish the experiment, they can grade the experiment and leave a message. At present, our online user evaluation system has received effective evaluations from 89 students, mainly junior college students in electronic information, who account for 70% of the responses. The evaluation is conducted from three perspectives: experimental content, operation experience, and support service. The full score of the evaluation is 5 points. The higher the score, the higher the students’ satisfaction with the evaluation.



The above figure is the average score of the final statistical student evaluation. As shown in Figure 24, the evaluation items of the experimental content include the rationality of steps, logical correctness, and the adequacy of prompt information. The evaluation items of operation experience include experimental loading time, visual effects, auditory effects, operation fluency, and network stability. The evaluation items of service support include online guidance service and teaching materials. From the students' scores, the experimental content and service content satisfaction are full marks, which shows that the platform performs very well in the overall content logic and supporting services. However, there is still room for improvement in the operation experience. From the students' reflection, the visual and auditory effects are good, but the first loading time of the experiment is still long, and there is still room for improvement in operation fluency and network stability.



**Figure 24.** Students grade the system from three aspects.

## 5. Discussion and Conclusions

### 5.1. Advantages of IC Virtual Experiment Platform

The virtual simulation experiment platform effectively overcomes the problems existing in traditional IC design, manufacturing, and test experiment teaching, such as expensive IC manufacturing equipment, insufficient experimental space, high experimental consumption, high cost, experimental equipment updates that are not timely, students being unable to use the fragmented time for experiments, etc. [31,40,41] The experimental teaching platform also combines the curriculum cloud classroom with virtual reality simulation technology, breaking through the shortcomings of the traditional virtual simulation technology such as poor user experience, weak interaction, and a big gap between virtual instruments and real objects, creating an experience for students in the extracurricular environment as if they were in the school laboratory. The virtual experiment also integrates the traditional integrated circuit design experiment and the three-dimensional virtual experiment and effectively gives full play to the respective advantages of the two simulation forms. From design to manufacturing to packaging and testing, the full coverage of integrated circuit content by the platform is more conducive to opening up the students' integrated circuit knowledge chain.

The experimental platform closely follows the current educational trend and can integrate traditional face-to-face learning with online networked learning. Offline support when online, and online empowerment offline; the advantages of the two complement each other. Especially under the influence of the current COVID-19 epidemic, many universities face the dilemma of not being able to take online classes, which greatly affects experimental teaching [45]. A 3D virtual laboratory can be a good solution to this dilemma. In traditional offline laboratory teaching, teachers make full use of various teaching platforms in lecture courses related to knowledge; students learn by platform course content in addition to finishing the experiment in the lab course time, using an online VR integrated circuit experiment platform to complete the review tasks such as the experiment preparation

and the experiment itself. The whole process is traceable online, and the offline hybrid experimental teaching model and experimental platform data provide a strong guarantee for the improvement of teaching quality [29,31,40,41].

### 5.2. Cultivation and Promotion of Students' Ability

In addition to enabling students to attain knowledge of and skills in integrated circuits, the platform is also committed to promoting the cultivation of students' ability and quality [1,5,11,17]:

- (1) **Autonomous Learning Ability:** The platform contains a large number of video and text materials through which students independently learn relevant knowledge of integrated circuits. Moreover, there are three-dimensional interactive experiments with strong interaction which stimulate students' interest in independent exploration. In the process of learning and completing the experiment, it can greatly improve students' self-study ability.
- (2) **Design and exploration ability:** Students can independently customize the process objectives of the inverter and independently design, manufacture, package, and test the inverter. Students can also achieve their own design goals and verify the results by operating experimental equipment. In the process of design and verification, students' design exploration ability and practical ability will be improved.
- (3) **Ability to analyze and solve problems:** Students need to independently analyze the errors in their operation process and find solutions through the experimental results. For example, in the film preparation in the oxidation process, the wrong setting of a parameter may lead to the error of the whole result. Students can repeatedly analyze the cause of the error according to the wrong experimental results. In the process of this analysis, students' ability to analyze and solve problems will be exercised and improved.
- (4) **Innovation ability:** The whole experiment includes three-dimensional virtual simulation, which is highly interactive and interesting and can greatly stimulate students' interest in learning and desire for exploration. In IC design, students will repeatedly think about whether the design indicators can be innovated and optimized and constantly improve the experimental optimization results. In the process of independent learning, independent design, and independent exploration, students' innovative consciousness and innovative ability can be cultivated.
- (5) **Emotional attitude cultivation:** The experiment covers the whole process of the integrated circuit. There are many steps, including 166 small steps, and they involve a lot of integrated circuit-related knowledge. The experiment is challenging. By completing such a challenging experiment, students' scientific research ability and scientific research literacy can be improved. Moreover, they can more clearly understand the complexity and difficulty of the integrated circuit industry. For example, only one step of film preparation in the oxidation process is needed to do so many steps, and even repeated failures will be repeated to recalculate the operation. Although the experiment is very difficult, it also exercises the students' quality of fearing and overcoming difficulties in scientific research.

**Author Contributions:** Conceptualization, Z.L. and Y.C.; Formal analysis, Z.L. and Y.C.; Methodology, Z.L. and Y.C.; Supervision, T.Z.; Visualization, Z.L. and Q.W.; Writing—original draft, Z.L.; Writing—review and editing, Y.C. and T.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Beijing University of Posts and Telecommunications under the Education and Teaching Reform Project (2020CXCY05).

**Acknowledgments:** We would like to thank the 3D modeling team and website development team for their support of this research.

**Conflicts of Interest:** The authors declare that they have no conflict of interest.

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