Development of a virtual transmission electron microscope laboratory for educational applications

Wernhuar Tarng[a], Chi-Fen Tsai[a], Chih-Ming Lin[b], Chi-Young Lee[c] and Hsin-Hun Liou[d]
Graduate Institute of e-Learning Technology, National Hsinchu University of Education, Taiwan[a]
Department of Applied Science, National Hsinchu University of Education, Taiwan[b]
Department of Materials Science and Engineering, National Tsing Hua University, Taiwan[c]
Department of Computer Science and Information Engineering, National Central University, Taiwan[d]
Corresponding Author Email: viviliu0501@gmail.com

Structured abstract

BACKGROUND

In recent years, many high-tech instruments have been developed for investigating the nanostructures of materials. For example, the transmission electron microscope (TEM) can be used to obtain the diffraction patterns for analysing materials' 3D crystal structures. However, the TEM is very expensive and many students can not use it to conduct experiments, so they often have difficulty to understand its operating procedures and principles.

PURPOSE

In this study, a virtual TEM laboratory was developed to help students learn how to analyze the 3D crystal structures of materials such as diamond and graphite according to their diffraction patterns.

DESIGN/METHOD

When using the virtual TEM laboratory as a teaching tool, instructors may first introduce the principles of TEM and then ask students to use the virtual TEM laboratory for interactive operation. Students can select different samples according to the system direction and conduct experiments to observe the sample's diffraction patterns and crystal structures. If they make any mistakes during operation, the system will provide a verbal or textual reminder. After all tasks have been completed, the students can take the online test to assess their learning achievement.

RESULTS

A teaching experiment was conducted to evaluate the learning effectiveness of using the virtual TEM laboratory for educational applications. The results revealed that the virtual TEM laboratory could enhance students' learning motivation and achievement in nanostructure analysis.

CONCLUSIONS

This study developed a virtual TEM laboratory to solve the problems of requiring expensive and complicated equipment for teaching nanostructure analysis. It provides knowledge of nanotechnology through situated learning by allowing students to conduct experiments in a virtual TEM laboratory. In addition to becoming familiar with the TEM's principles and operating procedures, students can also enhance understanding about materials' 3D crystal structures.

KEYWORDS

Nanostructure, transmission electron microscope, virtual reality, diffraction pattern, 3D crystal structure

Introduction

Feynman (1960), the father of nanotechnology, proposed “There’s plenty of room at the bottom.” at a meeting of American Physical Society. These were the words of wisdom in nanotechnology, and they had gradually become well known in 1990. Feynman predicted that the development of technology will move forward to the micro scale. In the last two decades, the advanced countries invested a huge amount of money and human resource in the research of nanotechnology, which appeared as the new hope of economy in the 21st century. It changes the industrial structure and human lifestyle, and is therefore considered as the fourth industrial revolution. Some people even predict that its impact on human life is greater than that of information technology and semiconductor industry.

Considering the importance of nanotechnology, the National Science Council (NSC), Taiwan started the National Nanoscience and Nanotechnology Program (NNNP) in 2002. It was aimed to establish a nanotechnology personnel training mechanism for the promotion and development of local nanotechnology industry. In order to promote the training mechanism, NSC launched the National Nanoscience Training Project to reinforce nanotechnology education. The goal was to enhance the literacy of nanotechnology from school teachers to K12 students and the general public.

With the rapid development of nanotechnology and the semiconductor industry, scientists are able to explore materials at the atomic level now. In order to observe substances at such a small scale, a series of new laboratory equipment has been developed. In recent years, several high-resolution microscopes such as atomic force microscopes (Tsai et al., 2007), transmission electron microscopes (Neogy et al., 2006) and magnetic force microscopes (Rugar et al., 1990) were created to exam the nanostructures and of substances.

In 1934, Ruska created the first TEM by emitting an accelerated and concentrated electron beam at an extremely thin sample. When the electrons collide with the atoms in the sample and change their directions, the scattering angles are related to the density and thickness of the sample. An image of varied illumination by the diffracted electrons called the diffraction pattern is formed to show information about the 3D crystal structures of materials. Thus, the TEM can be used as an important tool in material identification (Chen, 2008).

In comparison with the visible light source of optical microscopy, the light source of TEM comes from the hot electrons emitted under high voltages. Because the wavelength of these hot electrons is extremely short, they can be magnified tens of thousand times by the effect of electric field lens. Therefore, the resolution is much higher than that of optical microscopy. As the electron beam with a very high voltage passes through the crystal slice, a raster with regular intervals is produced on the crystal plane to produce the phenomenon of electron diffraction. The imaging principle of diffraction pattern by the TEM’s electron beam obeys Braggs’s Law (Nave, 2008), and its wavelength is shorter and easier to concentrate within a diameter of 10nm or smaller. As a result, it is possible to display the structure and orientation of crystals for better observation. The TEM is a useful tool for measurement and analysis at a very small scale. Due to continual breakthrough, it can now detect the 3D crystal structures and materials’ interior elements at nano and atomic levels (Chen, 2012).

The basic structure of TEM is primarily made up of an electron gun and several electron lenses (Williams & Carter, 1996). The electron lenses include the condenser lens, objective lens, intermediate lens and projective lens; the electron gun is mainly composed of a cathode and an anode; the cathode is the electron emission source and the anode is used to accelerate electrons. The resolution of TEM is mainly related to the acceleration voltage of electrons and aberration. A higher acceleration voltage produces a shorter wavelength and thus a better resolution. As the kinetic energy of electrons increases, the ability of electron beam to penetrate the sample also increases (Jin et al, 2012). When using the TEM to test samples, the diffracted electrons form the bright and dark field images called the diffraction patterns which can be used to analyse the samples’ crystal structures.

Nanostructure analysis is an important technology in detecting the formation of substances. When teaching how to use the TEM to analyze the crystal structures at the nano level, the instructors often introduce the TEM's principles first, and then use a laser pointer to simulate the TEM's electron beam for explaining the diffraction phenomenon. Sometimes, they may ask students to calculate the slit width according to diffraction patterns. This kind of teaching tool only provides a simple simulation and students may not understand how to operate a real TEM to scan a sample for obtaining its diffraction patterns. Furthermore, due to the limitation in equipment, not all students can use a real TEM to carry out repeated training on it. Without a theoretical and practical foundation, it is very difficult for students to obtain correct results when given the opportunity to operate a real TEM because they are not familiar with its principles and operating procedures.

Virtual Reality (VR) is a technology to create an interactive environment for simulating the real world through our sense organs. The users can see, hear and even feel in the created scenes as if situated in the real world, and even interact with the objects in the virtual scenes. The most commonly used VR technique is the 3D visual simulation, allowing users to interact with the virtual situation by wearing stereo glasses or the head-mounted display (HMD) to enhance their initiative, operability and sensitivity (Heim, 1993). A few studies suggested the use of VR to improve students' learning interest and motivation as well as the ability and positive attitudes toward learning (Ferrington & Loge, 1992; Auld & Pantelidis, 1994).

Situated learning was first proposed by Brown et al. (1989) and its concept is to simulate a realistic environment to provide learners with learning situations for exploring knowledge by interacting with real or created environments. The learning activity is designed for learners to participate in the process of learning, thinking, investigation and feedback, and the objective is to adaptively develop suitable knowledge and ability for application in the future. Situated learning emphasises the reality of learning activities and it is similar to "Learning by Doing" (Dewey, 1938) and "Learning from Experiences" (Kolb, 1984).

The emerge of situated learning attracted a number of related theories and research, such as constructivism, anchored instruction and cognitive apprenticeship, and they also had many ripple effects and were applied in various teaching models (Wang, 2009). This study used the theory of situated learning to develop a virtual TEM laboratory, which allows students to actively explore and conduct virtual experiments to acquire meaningful knowledge for future applications. They will become familiar with the operation of TEM for analyzing the 3D crystal structures of materials at nano and atomic levels.

A virtual TEM laboratory was designed in this study to support the NNTP and the objective is to promote the knowledge of nanotechnology to K12 science education as well as general teaching in universities. The high interaction and real-time feedback of the virtual TEM laboratory allows students to become familiar with the principles and operational procedures of TEM, and it will achieve the following learning objectives:

- Recognising the basic components and major functions of the TEM.
- Familiar with the principles and operating procedures of the TEM.
- Understanding the relationship between samples' 3D crystal structures and their diffraction patterns.
- Increasing the interest of students in exploring the nanostructures of materials.

When using the virtual TEM laboratory as a teaching tool, instructors may first introduce the principles of the TEM and then ask students to use the virtual TEM laboratory for interactive operation. Students can select a sample according to the system direction and conduct experiments to observe the sample's diffraction patterns. If they make a mistake during operation, the system will provide a verbal or textual reminder. After all tasks have been completed, the students can take the online test to evaluate their learning achievements.

System Design

The development environment of the virtual TEM laboratory is Microsoft Windows 7 and the required software includes Shiva3D and 3ds Max. In addition, the tools of JDK, Android 1.5 SDK, Eclipse and Android Development Tool Plug-in software were also needed. After the completion of system design, the authoring tool of ShiVa3D is used to convert it into the installation file and then uploaded to Google Play for users to download.

Virtual TEM Model

In this study, the virtual TEM model was developed according to the 200KV field emission TEM (Figure 1) in the Nano-Microscopy Laboratory at Tamkang University, Taipei. This study used the software 3ds Max to develop the TEM model and used Photoshop to create the texture images required for the model. Finally, the VR software ShiVa3D was used to design the user interface and control programs to simulate the TEM's operation.

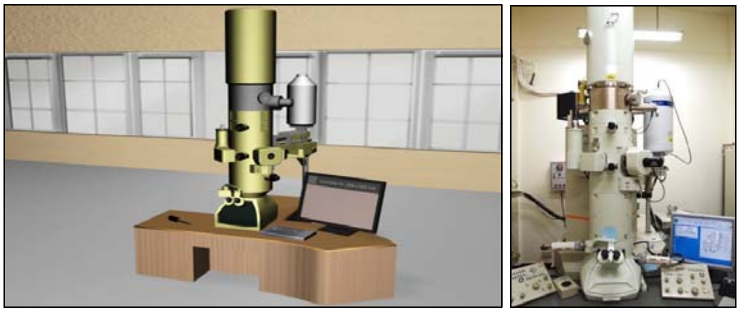

Figure 1: The virtual TEM model (left) and the real TEM (right)

Sample Holder Model

This study used the software 3ds Max to develop the sample holder model and then used Photoshop to create the required texture images (Figure 2). Finally, the software ShiVa3D was used to design the interactive user interface and control programs. Users can attach the sample for observation to the sample holder, and the sample holder is then slid into the TEM to obtain the sample's diffraction patterns.

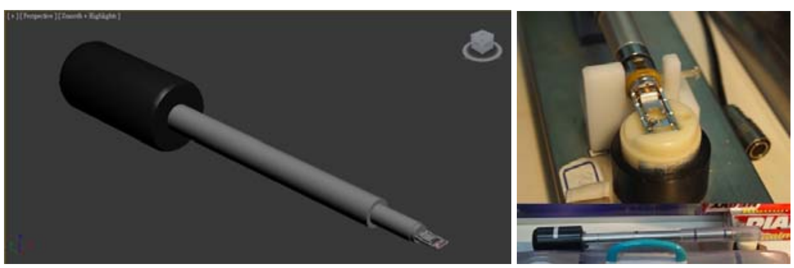

Figure 2: The virtual sample holder model (left) and the real sample holder (right)

Crystal Structure Model

The software Diamond was used to provide the 3D crystal information for various samples. This study used 3ds Max to develop the crystal structures of diamond, graphite and titanium dioxide (Figure 3). Finally, the VR software ShiVa3D was used to import the models from 3ds Max to combine with the virtual TEM laboratory for users to conduct experiments to enhance their knowledge about the 3D crystal structures of various samples.

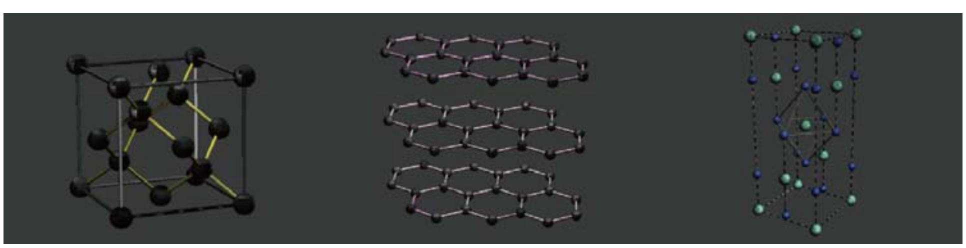

Figure 3: The 3D crystal structures of diamond, graphite and titanium dioxide

When creating the relation between the crystal structure and diffraction pattern of a sample, the software Diamond was used first to obtain the information about the sample's crystal structure. After that, the software CaRine Crystallography was used to simulate the diffraction patterns in different zone axes. Finally, Photoshop was used to set the illumination at the positions of atoms to simulate the diffraction patterns obtained from the TEM in the directions of different zone axes.

Operating Procedure

The users will see the welcome page first when the system is started up, and they can click the 'Introduction' button to see the learning objectives and learn to operate the TEM. After reading the introductory contents, they can enter the virtual TEM laboratory and the verbal direction will guide them to read the task checklist and perform virtual experiments. In the virtual TEM laboratory, there are three objects for selection and operation: (1) the TEM, (2) the sample holder, and (3) the samples. The operating procedures of the virtual TEM are explained in the following:

- When the system is started up, the users can read the introduction to understand the learning objectives as well as the TEM's principles and operating procedures.
- After entering the virtual TEM laboratory, the users can read the task checklist to see what items they have to complete in the experiment.
- When the users click the virtual TEM, they can learn about the principles of TEM and the major functions of its components.
- The users can manipulate the sample holder to know its structure and functions, and they can learn to attach the sample to it for observation.
- The users can select any samples on the table, i.e., diamond, graphite and titanium dioxide, to perform observation. By rotating the sample's crystal model and observing its diffraction patterns, they can learn about the crystal structure of the sample as well as its chemical and physical characteristics.
- The users can take the online test to evaluate how much they have learned after completing all assigned tasks.

There are three types of samples in the virtual TEM laboratory, i.e., diamond, graphite and titanium dioxide (Figure 4). The users can complete the task of inserting samples into the TEM for observing the diffraction patterns according to the system direction and the flashing outlines to manipulate the samples. The monitor will display the diffraction pattern of the sample after the scan has been completed. Users can select the zone axis to observe the sample and its diffraction pattern from different angles.

Figure 4: Observing the sample's diffraction patterns

Teaching Experiment

A teaching experiment was performed to evaluate the effectiveness of using the virtual TEM laboratory in teaching nanostructure analysis. A questionnaire survey was also conducted to investigate the attitudes of students after using the virtual TEM laboratory. This study randomly selected 38 students from the department of applied science in a university at Hsinchu as the experimental samples. They were divided into the control group (17 students) and experimental group A (21 students). The control group was given a lecture and requested to watch a TEM instructional video. The experimental group A was given the same lecture and used the virtual TEM laboratory as a teaching tool. To include samples of different ages, this study taught the virtual TEM laboratory at a science camp in Taoyuan where the 36 participants (mostly high school students) were used to form the experimental group B for allowing the comparison of learning achievements between users of different ages.

This study adopted a nonequivalent pretest-posttest design involving different groups to investigate if there was a significant difference between the learning achievements of different groups. Before conducting any teaching activities, all students were asked to take a pretest for the background knowledge of TEM. After the teaching activities, they took the posttest and the experimental groups also filled out a questionnaire. To further realize the difference between the two teaching methods, the control group was asked to use the virtual TEM laboratory for 30 minutes at the end and then fill out an open-ended questionnaire. Its major parameters include the similarity and difference between instructional video and the virtual TEM laboratory and which one is more helpful to my learning. The achievement test (including the pretest and posttest) used by this study contained a number of 19 test items which were designed based on the research goal, teaching objectives and TEM learning contents. The test items were revised according to the suggestions of experts and science teachers for better reliability.

Learning Achievement Analysis

In the teaching experiment, the experimental groups used the virtual TEM laboratory and the control group watched a TEM instructional video for learning. An ANCOVA was conducted to see if there was a significant difference in learning effectiveness among these groups. The statistical software SPSS was used to analyze the test results (Table 2). This study used a Levene test to compare the pretest results to see if any significant differences about the background knowledge of nanostructure analysis existed among these groups; the results show that $F=1.33$ and $P=0.27>0.05$ (significant standard), indicating their background knowledge was about the same.

Table 2: Descriptive statistics of pretest scores for the three groups

Group	Students	Mean	Standard Error	Standard Deviation
Control Group	17	66.18	3.42	14.09
Experimental Group A	21	61.67	2.54	11.65
Experimental Group B	36	50.69	2.27	13.64

This study used a paired sample T-test to carry out a statistical analysis (Table 3) on the pretest and posttest for the control group and experimental groups A and B. For the control group, the T value is -5.13 and the significance $P<0.05$, indicating the lecture and instructional video is effective to enhance the control group's learning achievement. For the experimental group A, the T value is -9.91; for the experimental group B, the T value is -5.50. For both groups, the significance $P<0.05$, indicating the lecture and the virtual TEM laboratory can both enhance their learning achievements.

Table 3: The results of paired sample T-test

Group	Mean	Standard Error	Standard Deviation	T	Degree of Freedom	Significance
Control Group	-12.06	09.69	2.35	-5.13	16	.000*
Experimental Group A	-25.24	11.67	2.55	-9.91	20	.000*
Experimental Group B	-18.61	20.30	3.38	-5.50	35	.000*

Before conducting the ANCOVA, the assumptions for the homogeneity of variance and within-group regression coefficients have to be satisfied. The statistical results for the above analysis are described in the following:

Homogeneity of Variance

This study used a Levene test to verify if there was homogeneity of variance in samples. According to the test results, the value of $F=0.16$ and the significance $P=0.004<0.05$, indicating the assumption for homogeneity of variance was not satisfied. A further analysis revealed that it was caused by the experimental group B which consisted of high school students with less knowledge about TEM and materials' crystal structures. After excluding the experimental group B; the analysis was carried out by comparing the control group and the experimental group A only. The analytical results show that the significance $P=0.69>0.05$ and thus the assumption is satisfied now.

Homogeneity of Within-group Regression Coefficients

Before the ANCOVA, the test for homogeneity of within-group regression coefficients must be carried out for the control group and experimental group A. The results show that $F=1.74$ and $P=0.19>0.05$, which is greater than the standard of significance. As a result, the dependent variables and covariance are not influenced by the independent variable and the assumption is satisfied, so the ANCOVA can be continued.

ANCOVA Results

This study used an ANCOVA to compare the difference in learning achievements between the control group and the experimental group A (Table 4). After excluding the effect of covariance and dependent variables, the impact of independent variable (the teaching method) is obtained as $F=13.66$ and $P=0.001<0.05$. A significant difference exists between the learning achievements of control group and experimental group A, and the learning achievement of the latter is higher than that of the former. In other words, the virtual TEM laboratory is more effective than the TEM instructional video.

Table 4: Statistics results of learning achievements for the two groups

Group	Mean	Standard Deviation	No. of Students
Control Group	78.24	12.37	17
Experimental Group A	86.90	9.68	21
Total	83.03	11.65	38

Questionnaire Results

This study carried out a statistical analysis on questionnaire results by the experimental groups as a system satisfaction survey. A comparison of significant differences in evaluation items between the experimental group A and B was also conducted to find out the items showing distinct results due to different-aged users.

Learning Contents

This section investigated users' satisfaction about the learning contents of the virtual TEM laboratory. Most students thought they could understand the textual explanation in the virtual TEM laboratory and the images were clear. They agreed that the virtual TEM laboratory provided adequate explanation and its contents taught them the knowledge about the samples' 3D crystal structures. In addition, such information allowed them to understand the nanostructures of different samples. The statistical results revealed that the average score of 'Learning Contents' is 4.37 for the experimental group A and is 4.15 for the experimental group B. For each evaluation item, a comparison between the scores given by two groups is done by the Levene test, and the results show that the P value is higher than the standard of significance. Therefore, there is no major difference for the two groups in their attitudes regarding learning contents.

Interface Design

This section investigates users' satisfaction towards the system's interface design. Most students considered the operation of virtual TEM laboratory is easy and the text is clear. They thought the verbal direction in the virtual TEM laboratory is simple and easy to understand and its operation is intuitive. They felt the visual design of the virtual TEM laboratory is delightful and consistent and the system runs smoothly. The statistical results revealed the average score of 'Interface Design' is 4.36 for the experimental group A and is 3.97 for the experimental group B. According to the results of Levene test, the significance for "I feel intuitive to operate the virtual TEM laboratory." "The visual design of the virtual TEM laboratory is delightful and consistent." and "The virtual TEM laboratory runs smoothly." are lower than the standard of significance (0.05) and thus distinct differences were found in these evaluation items. It is inferred from the fact that high school students were less familiar with the operation of tablet computers and thus gave a lower score for these evaluation items.

Operating Experiences

This section investigates users' operating experiences. Most students found that the virtual TEM laboratory could help them understand the functions of TEM and the nanostructures of materials. They would like to learn more about crystal structures using the virtual TEM laboratory. They had completed the assigned tasks, taken the test, and clicked on the keywords to learn about the TEM principles. After using the virtual TEM laboratory, they became more interested in nanostructure analysis. Completion of all tasks gave them a great sense of achievement, so they would like to use the virtual TEM laboratory as a teaching tool. According to the results of Levene test, there is no significant difference for each evaluation item in this section.

Open-ended Questionnaire

After the teaching experiment, the control group was asked to use the virtual TEM laboratory for 30 minutes and fill out an open-ended questionnaire about the difference between the instructional video and the virtual TEM laboratory. The majority of students thought both the instructional video and virtual TEM laboratory provided them with a clear introduction about the principles and operating procedures of TEM. However, the latter gave them the sense of operating a real TEM and the online test could be used for evaluating their learning achievement. Basically, they thought using the virtual TEM is easier and less expensive than using a real TEM, so there is no need to worry about the damage of equipment and the difficulty of preparing samples. Besides, it is easy to obtain the test results and see the crystal structures of different samples. Compared with watching the instructional video, most students believed that it is easier to learn knowledge in nanostructure analysis by using the virtual TEM laboratory.

Conclusions

Because nanostructures are extremely small and cannot be seen with the naked eye, it is necessary to use a high resolution electron microscope or special scientific equipment to observe them. This kind of equipment is extremely expensive such that users must be familiar with the operational steps to avoid damaging it. For ordinary people to learn about the nanostructures of certain materials, they can only search for images on the Internet or go to the library to look for the related images in books. Acting in coordination with the NNTP promoted by Taiwanese government, this study developed a virtual TEM laboratory for execution on mobile devices to help students learn about using the TEM for the analysis of materials' nanostructures. Furthermore, a teaching experiment was conducted to investigate the learning effectiveness and attitudes of students after using the virtual TEM laboratory. The experimental results revealed that: (1) The learning achievement of using the virtual TEM laboratory was better than using the instructional video, indicating that the interactive operation under a virtual environment helps improve the learning achievement; (2) Students gave a positive evaluation towards the learning contents, interface design and user experiences of the virtual TEM laboratory, showing that it is useful to learn TEM knowledge using the proposed system. Furthermore, after using the virtual TEM laboratory, the students became more interested in exploring the materials' nanostructures.

This study developed a virtual TEM laboratory to solve the problems of using expensive and complicated equipment such as the TEM for teaching. It provides the knowledge related to nanotechnology through situated learning by allowing students to conduct experiments using the virtual TEM laboratory. In addition to becoming familiar with the TEM's principles and operating procedures, students can also enhance their understanding of nanotechnology and the related concepts in nanostructure analysis. The use of the virtual TEM laboratory is not limited by time or space, and the 3D visual effects and highly interactive design make students' learning more interesting and effective. As a result, it is a suitable assistant tool for learning nanotechnology in high schools and universities.

References

Auld, L. W. S. & Pantelidis, V. S. (1994). Exploring virtual reality for classroom use: the Virtual Reality Education Lab at East Carolina University. *Tech Trends, 39*(2), 29-31.

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher, 18*(1), 32-42.

Chen, B. L. (2012). Introduction to sample preparation technology in transmission electron microscopy. *ITRC Newsletter, 110*, 8-9.

Chen, D. H. (2008). Application of the convergent beam electron diffraction in transmission electron microscopy to analyze semiconductor materials. *Nano Communication, 15*(4), 2-5.

Chou, W. W., Chao, W., Chen, Y. H., & Wang, F. W. (2012). Applications of Diamond software in teaching crystal structure. *Examination Weekly, 2*, 135-136.

Dewey, J. (1938). *Theories of education*. New York: Macmillan.

Ferrington, G., & Loge, K. (1992). Virtual reality: a new learning environment. *The Computing Teacher, 19*(7), 16-19.

Feynman, R. P. (1960). There's plenty of room at the bottom. *Caltech Engineering and Science, 23*, 5.

Jin, H. H., Cho, H. D., Kwon, S. C., Shin, C., & Kwon, J. (2012). Modified preparation technique of TEM sample for various TEM analyses of structural materials. *Materials Letters, 89*, 133-136.

Kolb, D. A. (1984). *Experiential learning: experience as the source of learning and development*. Englewood Cliffs, NJ: Prentice-Hall.

Heim, M. (1993). *The metaphysics of virtual reality*. New York: Oxford University Press.

Nave, C. R. (2008). *Bragg's Law*. Hyper Physics, Georgia State University.

Neogy, S., Savalia, R. T., Tewari, R., Srivastava, D., & Dey, G. K. (2006). Transmission electron microscopy of nano materials. *Indian Journal of Pure & Applied Physics, 44*(2), 119-124.

Rugar, D., Mamin, H. J., & Guenther, P. (1990). Magnetic force microscopy: general principles and application to longitudinal recording media. *Journal of Applied Physics, 68*(3), 1169–1183.

Tsai, Y. C., Shieu, F. S., Lu, F. H., & Wu, C. M. (2007). *Atomic force microscope practical training materials*. Taipei: Wu-Nan.

Wang, R. K. (2009). Applications of situated learning in elementary school English teaching. *Taipei County Education, 69*, 87-91.

Williams, D. B., & Carter, C. B. (1996). *Transmission electron microscopy: a textbook for materials science*. New York: Plenum press.

Acknowledgements

The authors would like to thank for the financial support of National Science Council, Taiwan under the contract number NSC 102-2120-S-007-008.