International Conference on Engineering Education and Research "Progress Through Partnership"

Engineering Education in the Nanomachining Technology Curriculum

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KEYWORDS: *nanotechnology, E-beam lithography, NSOM, AFM machining, SPM machining*

ABSTRACT: *Prospective and current machining technologies in nano-scale features are introduced in this subject. Conventional machining technologies are based on the top-down method to make engineering products. Using various tooling machines to fabricate components in all kinds of materials is included in this category. It also extends to engineering features in nano-scale. However, the bottom-up method is the other approach to create engineering products. It is based on the basic chemical reaction using atoms accumulation and atomic synthesis for super molecule formation. These two principles provide main trends for nanomachining technologies. In view of engineering aspects, both theories and experiments of nanotechnology should be connected into a practical object. This subject includes practical machining methods and related theories for engineering education in nanotechnology.*

Fundamental processing technologies in the nanomachining are based on MEMS (microelectromechanical system) technology. MEMS technology opens a window to explore nanomachining technology and provides a step to jump into quantum devices. The curriculum has to start MEMS technology and scale effect on the nano-world. Tools and techniques of nanofabrication are introduced for students' understanding on present machining progress. Nanolithography process is based on microlithography development for advanced ULSI application. It is an important technique in the nano-patterns fabrication. Particle beam nanofabrication is related to electron and ion lithography process. They provide nano particles as bombards to create nano-patterns and form functional structures. Near-field scanning optical microscopy (NSOM) machining is a convenient machining to pattern nano objects. It exceeds the Rayleigh limit to observe and pattern objects within subwavelength. SPM (scanning probe microscopy) has played a machining role in the nanomachining process, such as atomic fore microscopy (AFM) using its nano-probes to pattern nano wires and manipulate other nano-objects. Nano-tip fabrication methods are explored for SPM applications. Other related nano-machining technologies, such as positional control, stages, and metrology are essential in this subject. After teaching sessions, student presentations are required for individual case. Peer evaluation for student presentation is practiced. The results show a learning and instruction effect. It enhances and promotes students' attitude in the nanomachining technologies.

1 INTRODUCTION

Most physical magnitudes characterizing nanoscale objects differ enormously from those familiar in macro/meso scale objects. Nanotechnology and nanomachining process are essential targets to understand nowadays. Nanotechnology on the scales of atoms (Å) up to biomolecular systems as large as as cells (10's μm) is covered. Engineering systems today range from macroscopic to microscopic with active research on building electronic and mechanical systems on ever-smaller scales using microtechnologies. In microtechnology, "Top-down" – achieving increased minimaturization through extension of existing microfabrication schemes, the challenge is to make imprecise structures smaller. Other approach by using chemical synthesis, "Bottom-up" – capability to construct functional components, devices, and systems from building blocks of atoms and molecules, the challenge is to make precise structures larger. The micron scale is volumetrically 109 times larger than the nanometer scale, and existing microtechnologies provide no mechanism for gaining precise, molecular control of the surface and interior of a complex, three-dimensional strucuture [1]. As Richard Feyman's stimulating question gave in 1959, "What would happen if we could arrange the atoms one-by-one the way we want them?", it opened the era of nanotechnology [2]. However, it was realized into action until the invention of STM (scanning tunneling microscopy) in 1980. Human can really observe objects in nanoscale by using such high resolution measurement equipments. Based on the technology development categories, NIST (National Institute of Standard and Test) in the United States provides a vision for nanotechnology shown in Figure 1 [3]. They are originating from both top-down and bottom-up streams.

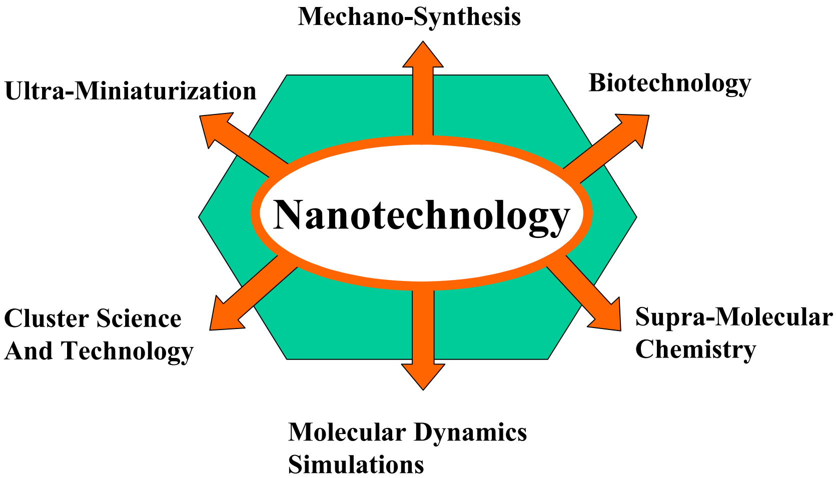

Figure 1. Development technologies for nanotechnology.

These research fields for nanotechnology show general directions in practice. Realistic steps toward nanotechnology include:

- Materials : Nanostructured materials, Fullerenes, Buckyballs and Nanotubes, Self-assembled materials
- Tools and Processes: Light-structured environments for atoms, Mechano-synthesis with SPMs, Supra-molecular Chemistry, Molecular Dynamics Simulation
- Devices: Molecular wires, Nanometer electronic diodes, Nanometer-scale gears, Tetrabit/cm^2 data storage and retrieval
- Systems: Nanomanuipulator Workstations, Table-top factories, Feyman Machines, Overall complexity of self-replication

Supra-molecular chemistry can generate new nanostructured materials. They correspond to carbon nanotubes, fullerenes, buckyballs, and other self-assembled materials. Recent progress is still developing on hybrid elements for new nanostructured materials. More complex materials will be emerged in adding new chemical elements. Tools and processes mean that the development of ultra-miniaturization and mechano-synthesis. Machines and environment for nano-device fabrication are needed to develop. Atoms manipulation rely on ultra-fine positional control and stages and observation equipments. SPM (scanning probe microscopy) has to be used in the nanotechnology for nanomachining structures. Functional nano-devices such as photonic structures, nanometer electronic diodes, digital data storage media are more close to users. Nanomanuipulator workstations, table-top factories, Feyman Machines, overall complexity of self-replication may need for further development.

The above message indicates a principal rule from materials, structures, devices, circuits to systems in nanoscale. For efficient advancement of nanotechnolgy need to connect enabling technologies across all scales (nano, micro, meso, macro). Five items related materials listed below are necessary to investigate. New materials will generate new materials knowledge. Following with fabrication technologies and processes, test methods and modeling as well as simulation tools will be critical issues in nanomaterials.

- Knowledge of materials
- Materials and device characterization methods
- Fabrication technologies and processes
- Measurement and test methods
- Modeling & simulation tools

Some expected scientific and technological advances are realized below. They are based on available nanomachining equipments to develop useful technologies. For example, e-beam (EB) lithography, NSOM (near-field scanning optical microscopy), SPM, AFM (atomic force machining), FIB (focused ion beam). Tools may play essential roles in accompanying these future applications, including existing advanced IC industry, bioengineering, potential unknown industries.

- Nano-manipulation with SPMs
- Multi-tip arrays
- Assembly and linking of nano objects
- Room temperature SETs (single electron transistors)
- Self assembling nanostructures
- Biomotors
- Carbon nanotubes and bucky balls
- Nano imprinting

After the introduction of nanotechnology, nanomachining technology curriculum for engineering is considered. Practical approaches are based on using available nanomachining equipments and related applications to illustrate the nanomachining curriculum. In addition to explore nanomachining technologies, an evaluation method and results are reported.

2 NANOMACHINING CURRICULUM

Nanofabrication technologies include photons, electrons, x-rays, and ions classified into particle beam processes. The reactions are illustrated in Figure 2. Particle beams strike into the substrates bombards atoms outward from surface. Other effect on soft materials (photoresist) receiving particle beams, these deposited energies change certain photoresist chemical properties. After exposure and development, patterns on the substrate can be created in naonoscale. Using photons in nanofabrication can use the NSOM to illustrate. Electron beam lithography represents on Figure 2(b). X-rays fabrication is exclusively used for certain applications, it’s too complicate to describe for engineering education. Ion beam machining case can use FIB to describe it in detail. Illustration of NSOM and EB nanomaching equipment and processes is presented as examples in teaching.

2.1 NSOM nanomachining

In classic optical theory, the resolution of photolithography is about the half wavelength of light source. And it is well-known that the integrated circuits are getting more complex and smaller. That means the line-width of chips is getting smaller quickly. This situation made traditional photolithography embarrassed. So the engineers try to find the way can overcome the restrictions of classic optics. Since NSOM was developed, it shows the advantages in overcome the diffraction limit. The resolution of photolithography is no longer relative to the wavelength of light source but relative to the aperture size of light source.

The term “near-field” means that the distance between the aperture of light source and the sample’s surface (such as photoresist film) is smaller than a fraction of the wavelength of light source. The mechanism of the near-field photolithography is very simple. When the aperture of near-field light approach the photoresist film and maintain the near-field distance, the exposed range of photoresist film is equal to the aperture size of light source. That means the linewidth of photolithography can be defined by aperture size, and won’t be influenced by diffraction. There are several means to realize near-field technologies. Like solid-immersion lens (SIL)[4], super-resolution near-field structure (super-RENS)[5], and Hemi-Paraboloid SIM, etc. According to Ref. [4], they exposed 190nm grooves in photoresist by focusing a laser beam which wavelength is 442nm in a solid immersion lens that is mounted on a flexible cantilever and scanned by a modified commercial atomic force microscope with 1 cm/sec scan rate. In this paper, we use an optical fiber probe to realize the near-field photolithography. The instrument scheme is shown in Figure 3. The mechanism of near-field distance control is utilizing a mechanical driven tuning fork in shear force mode. The fiber probe is attached to the one tine and the other tine is fixed on a Z-axis stage. This asymmetry causes a voltage difference between two electrodes of the tuning fork under excitation. The two electrodes of tuning fork are connected through a low noise preamplifier to the lock-in amplifier. When the fiber probe attaches close to the sample’s surface (such as photoresist film) at near-field distance, atomic force will apply to the fiber probe and cause the vibration amplitude of tuning fork changed. Hence the output voltage of tuning fork is changed. By feeding the output voltage of the tuning fork to the controller of the Z-axis stage and keeping the output voltage constant, the Z-axis stage is controlled to maintain a constant near-filed distance between the probe and photoresist film.

The photoresist is SHIPLEY SPR3001, the same as Ref. [4], which is a g-line (436nm), positive photoresist which penetration rate of SPR3001. The SPR3001 is spun on silicon substrates and soft-bake at 95℃ on hotplate for 1minute. Then it begins to near-field photolithograph. When the fiber probe scans over the photoresist surface and maintain near-field distance at several scan rates, the radiation from the probe tip will expose the photoresist film. The light source of photolithography is an Argon Laser which wavelength is 488nm. After exposure, the specimen post-exposure was baked at 115℃ on the hotplate for 1 minute and developed in MF-319 for different times. The process for NSOM experiment is shown in Figure 4.

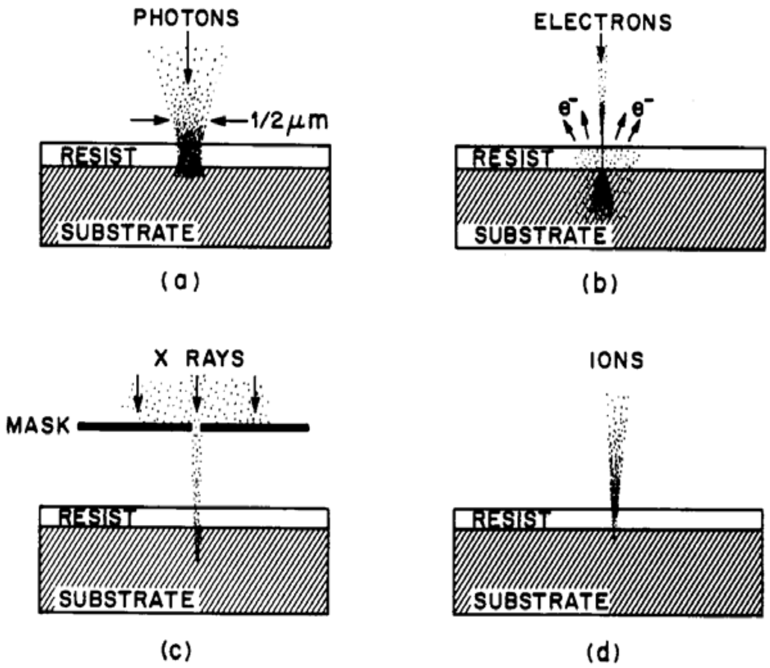

Figure 2. Nanolithography machining processes; (a) photon beam, (b) electron beam, (c) x-rays, (d) ion beam.

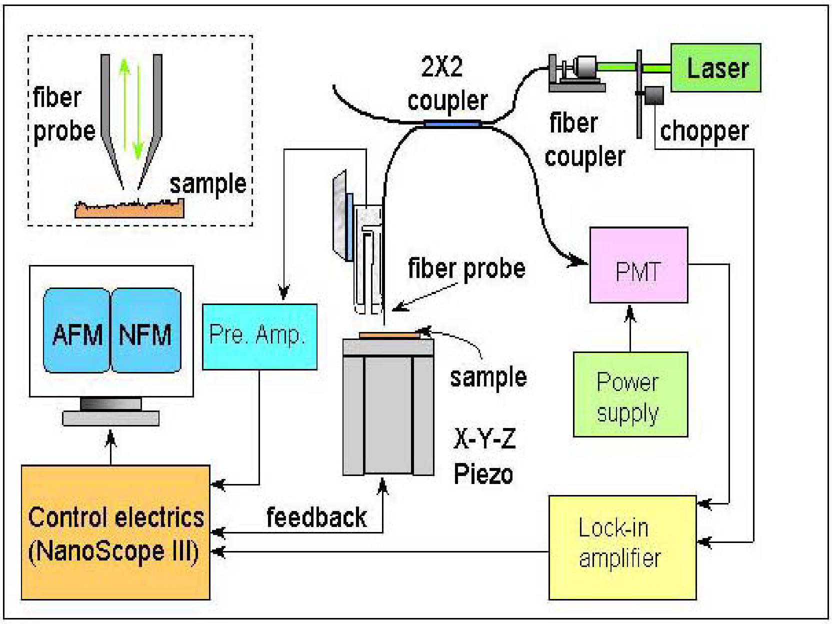

Figure 3. Near-field scanning optical microscopy structure.

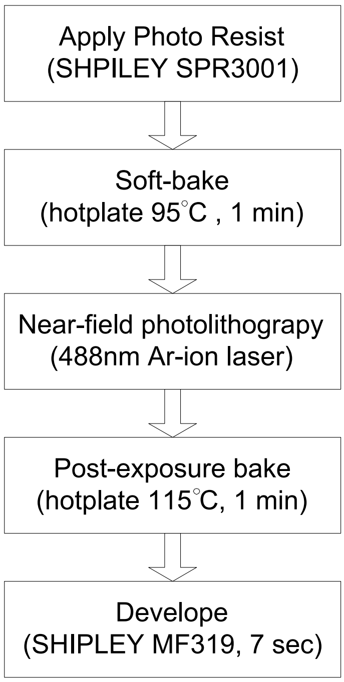

Figure 4. NSOM machining process to fabricate nano-patterns.

2.2 Electron beam fabrication

Nanostructure devices are now being fabricated in many laboratories to explore various effects. Figure 5 show the resolution capabilities of several lithography processes that use electrons, ions, and photons [6]. Electron beam lithography is the most widely used and versatile lithography tool used in fabricating nanostructure devices. The minimum beam diameters of scanning electron beam microscopes SEM and scanning transmission microscopies (STEM) are 1.5 and 2.5 nm, respectively. A further prospect in IC industrial revolution scheme is shown in Figure 6. Electron beam to write photomasks in ultrafine patterns is predicted.

The EB-mastering machine EBR-200 fabricated by Obducat Inc. is used to expose resist film. The outline of EBR-200 is shown in Figure 7. It is composed of an electron beam column with an acceleration voltage of 40kV (max), an air spindle motor with vacuum seat and a translation stage constructed in a vacuum chamber. The electron beam column, which is composed of a lanthanium hexaboride cathode

(LaB6), three electron lenses, two apertures, blanking plates and stigmator, is used to produce the electron beam and appropriately focus it on the surface of a substrate. Then, the air spindle motor and the translation stage are synchronously controlled to keep the focal spot of the electron beam moving across a substrate with resist film at constant linear velocity. The encoded data is transferred to the resist film by controlling blanking plates to deflect the electron beam.

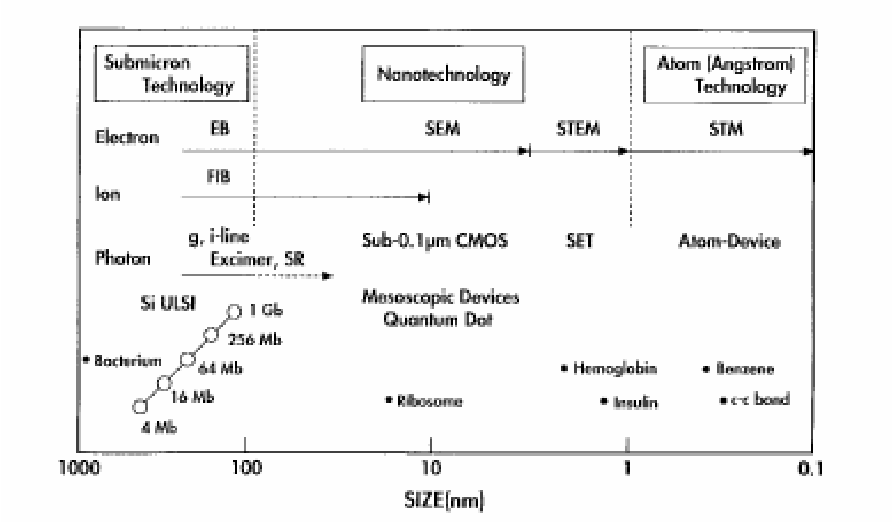

Figure 5. Microfabrication and nanofabrication using electrons, ions, and photons [6].

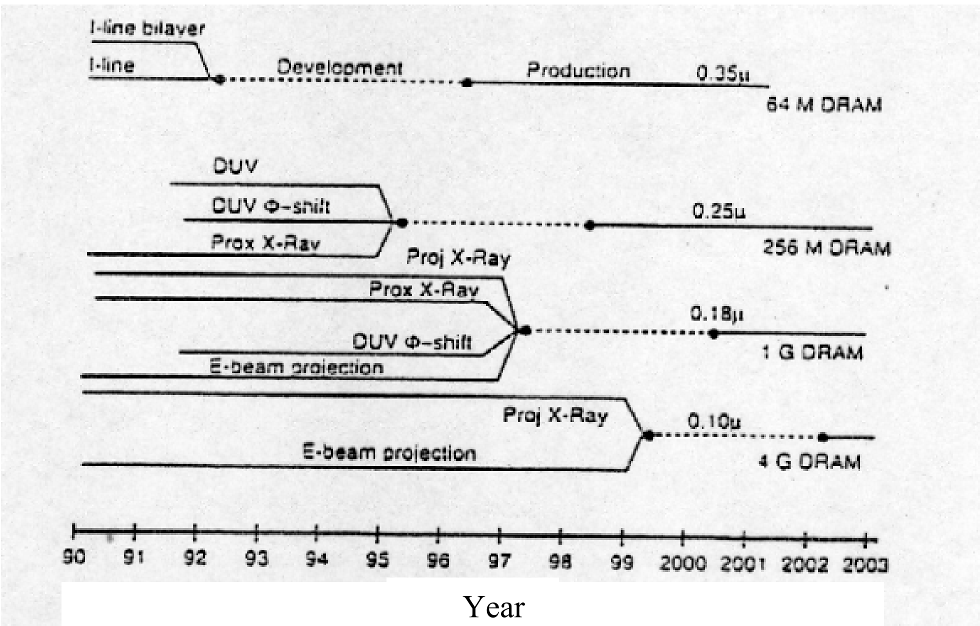

Figure 6. Nanomachining techniques used in IC industry.

The electron beam mastering process is described below. A silicon wafer with a thickness of 525μm and a diameter of 100mm is used to be a substrate, and its resistivity is less than 0.01 Ω-cm to prevent the charge up effect. Positive EB resist with high resolution, ZEP520A, is spun on a substrate. In order to improve the adhesion between the resist and the substrate, the specimen is prebaked for 3 minutes at 160 ℃ on a hot plate. After that, resist film is exposed by the electron beam and developed by a high resolution developer, ZED-N50, at 23℃. At the end, the fabricated pattern is inspected using atomic force microscope. Resists for EB to fabricate nanostructures can be divided into organic, inorganic, and deposition [6] as shown in Figure 8. A PMMA positive resist can be used to pattern 10 nm linewidth structures. The CALIXARENE negative resist for EB can transfer dot array patterns having 12 nm diameter with 35 nm pitch. Inorganic resists have a finer resolution than organic resists. The AlF3-doped LiF resist films were fabricated by using conventional multi-target [LiF, (Li0.9Al0.1)Fx, and (Li0.7Al0.3)Fx] ion beam sputtering. The result demonstrated that sub-10 nm lithography can be achieved by SEM using an inorganic resist. In situ processes using beam-induced chemistry were promising to fabricate nanostructures, too. A tungsten rod with 15 nm diameter was realized.

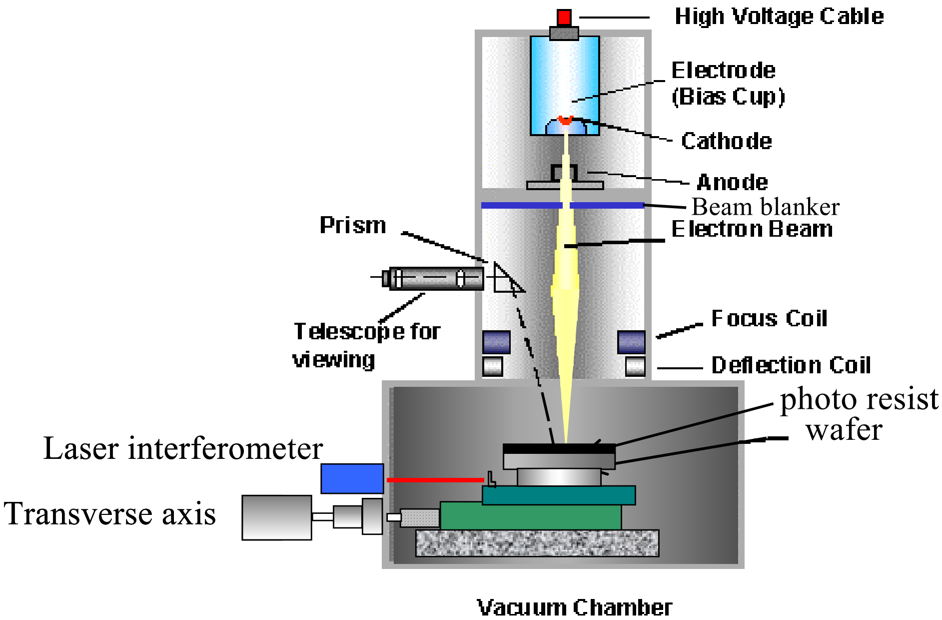

Figure 7. The outline of the electron beam mastering machine EBR-200

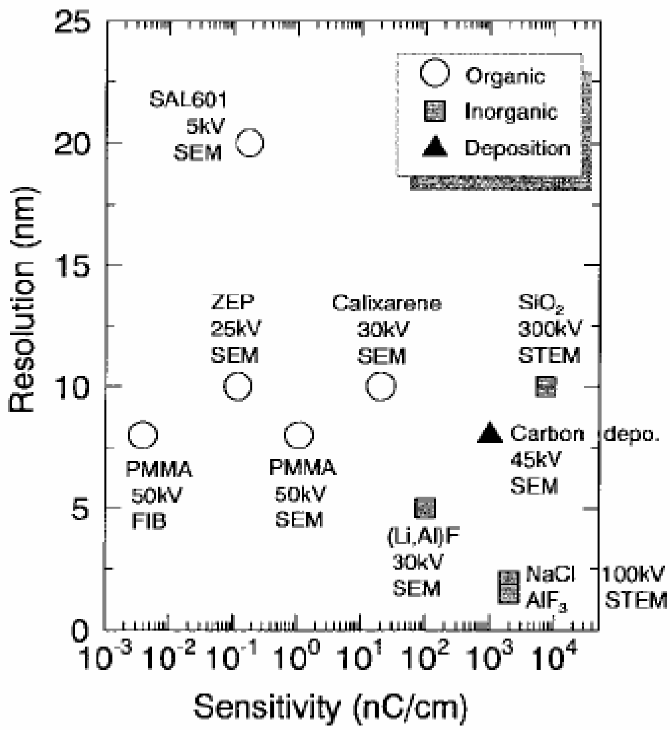

Figure 8. Various resist fro electrons and ions [6].

3 NANOMACHINING APPLICATIONS AND FUTURE

Engineering education should put the educational direction toward industries. Besides nannomachining technology training, their applications should point out for students. Data storage media is an example to show nanostructure devices. As the capacity of an optical disk increased from CD 650 Mbytes to DVD 4.7 Gbytes, the minimum pit length had been reduced from 830nm to 400nm. According to the developing trend, the capacity of the next generation optical disk will be over 15 Gbytes in 2005, and the minimum pit length will relatively reduce to 190nm or less.

It is well known that the spot size of a conventional laser beam can be expressed as 0.61λ/NA, where λ is the wavelength of a laser, NA is the numerical aperture of an objective lens and 0.61 is a constant related to the photoresist and the process. Thus, two major approaches can be taken to reduce the spot size. One is using a shorter wavelength laser, and the other is using an objective lens with a larger NA value. For the current DVD master code cutter, the wavelength of a laser and the numerical aperture of an objective lens are about 413nm and 0.9, respectively. For the next generation optical disk, it is necessary to use a DUV laser with 266nm in wavelength. At the same time, the photoresist and the material of an objective lens need to be changed for a DUV laser. However, the new photoresist is not fully stable, and the new material of an objective lens is expensive and difficult to manufacture. With regard to the numerical aperture of an objective lens, its theoretical upper limit is 1.0, so a larger NA value than 0.9 has just a little effect. Thus, the conventional laser beam mastering is difficult to satisfy the requirement of the next generation optical disk.

In contrast to the conventional laser beam mastering, the electron beam mastering aren't restricted by the optical diffraction limit because it uses a high-energy electron beam with the characteristic of a short material wavelength and an electron beam column to replace a laser and an objective lens respectively. Besides, many investigations [6] had been successfully fabricated the nano-structure and the nano-device using the electron beam. There is also an investigation in developing the electron-beam-mastering machine for a high-density disk [7]. Thus, the electron beam mastering can easily fabricate smaller pit length than that of the conventional laser beam mastering. Figure 9 shows other advanced nanomachining processes correspond to ultra-dense data storage media mastering capabilities. Other applications such as SETs, high frequency SAW (surface acoustic wave) filters, nano imprinting moldings, and more accessible nanodevices can be included in this curriculum.

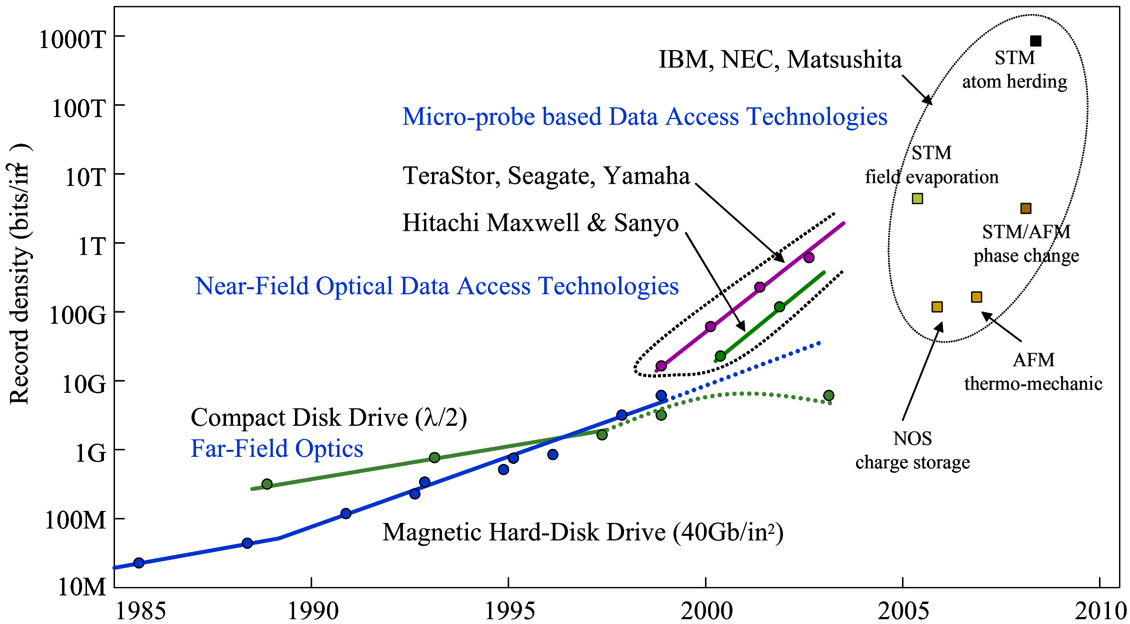

Figure 9. Comparison of recording techniques for data storage media.

4 EVALUATION METHOD FOR STUDENT PRESENTAIONS

This course was designed to develop new knowledge on nanomachining technologies. Besides, instructing session taught by the professor, students were expected to explore new messages from contemporary journal papers. Investigating new nanomachining fields is absolutely necessary. Students were requested to prepare an oral presentation on nanomachining related topics in the beginning of the course. They took two weeks for selecting a proper subject and reviewed by course instructor. It prevented same topics and similar titles would be presented in the class. At least five newly references should be included in their presentations. Students were trained to sort new progress researches on nanomachining technologies in certain topics. Once students selected their topics and found their references, written reports were due before their oral presentations. The professor checked their written materials to confirm their assignments in full requirement. A flowchart on the student presentation progress is shown in Figure 10. In later classes, oral presentations were performed by students. Their visual aids were requested by using Power Point files to project on screen in the classroom. Ten criteria for making good presentations were explained by the professor and for students to evaluate peers. Those criteria are listed in Table 1 [8]. Figure 11 shows the evaluation result of year 2002 and 2003. The majority of grades are around 80 and the distribution expresses normal curves for both years. This peer evaluation result is similar to general professors' evaluation results and this evaluation training method is workable.

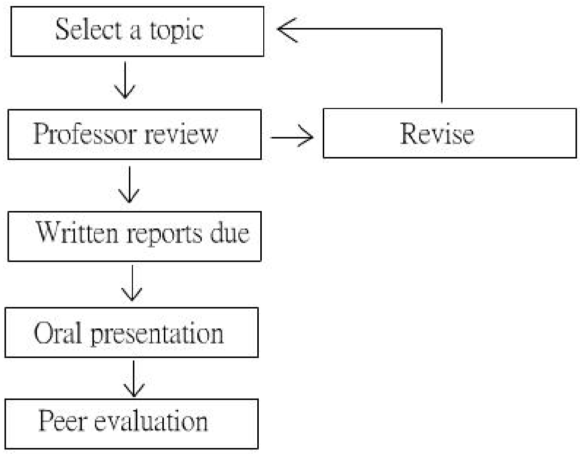

Figure 10. Flowchart of student assignment on the course.

Table 1. Criteria for student oral presentation evaluation.

Item	Criteria	Student A	Student B	……
1	Focus on main points			
2	Well practice			
3	Use the Preacher's maxim			
4	Maintain eye contact			
5	Appropriate gestures and posture			
6	Avoid filler words			
7	Clear statement on the subject			
8	Presentation logics			
9	Utilization of visual aids			
10	Timing control			

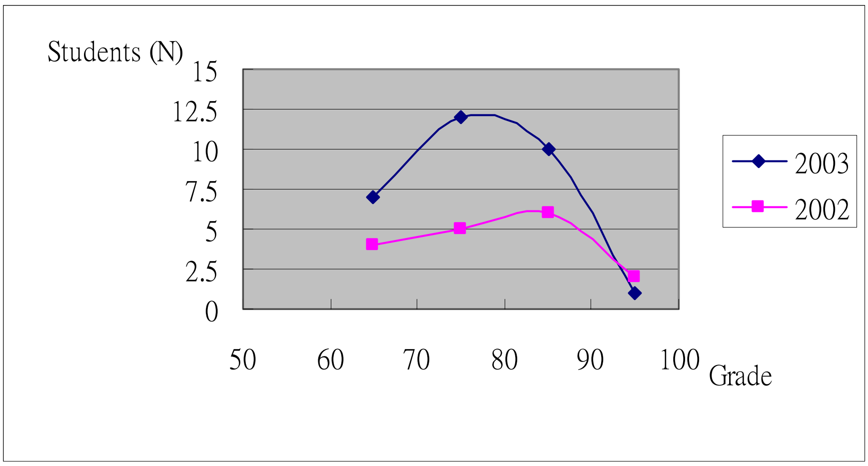

Figure 11. Statistics of student grades taking the nanomachining course in years 2002 and 2003.

4 CONCLUSION

The advanced manufacturing technology using nanomachining equipments is an essential subject in engineering education. Global competition is forcing the manufacturing technology toward high precise and fine feature devices. Through these developed nanomachining subjects for the advanced engineering education, we can see the further development of nano-parts can be applied widely to industrial applications. Micro- to nano-fabrication technologies play important roles in the fabrication of microfluidic devices for biochemical assays. These technologies are directly related human welfares. With respect to nanomachining curriculum, there are still more new progresses in the development. It's just a start and will contribute more in the future engineering education.

ACKNOWLEDGEMENTS

Thanks are due to the Opto-Mechatronics Education Resource Center (OERC) in the education project of enhancement for manufacturing science and technology funded by the Ministry of Education (MOE) in Taiwan. This work was partially supported by the National Science Council (series no. NSC92-2212-E-005-005) of Taiwan.

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