TECHNOLOGIES AND MATERIALS FOR MICRO AND NANO-ELECTRONICS

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ABSTRACT

In the article technologies used in micro and nanoelectronics there are shortly described. Attention is devoted to lithography as a basic technology. Principles of electron and ion lithography are mentioned as well as progressive ion projection lithography. Some remarks to nanotubes as means of cold cathodes for vacuum electron tubes for nanoelectronics are presented.

Keywords: *electron beam lithography, ion projected lithography, microelectronics, nanoelectronics, focused beams*

1. INTRODUCTION

Since the discovery of integrated circuits there is a permanent interest about technology of making more and more complicated devices. The devices need reliable elements usually placed on one chip. The chip contains hundred of thousands of electronic elements (diodes, transistors, resistors, capacitors…). The dimensions of elements on the chip should be small. To fabricate such small features one needs to use special technologies. Curiously, smaller element fabrication needs larger machines to produce it. As "working tools" usually plasma and electron/ion beams are used. In plasma, many chemical substances can arise due to existing highly excited states of molecules/atoms. In this article we shall not deal with plasma, but we mention only about using of charged particle beams. The beams are very gently working tools which allow operation at micrometer or nanometer "working areas". The charged particle beams can be used for different technological steps like a deposition needed layers, modification of existing layers or for removing (etching) wasted layers. The most widely-known beam technologies are electron beam lithography, ion implantation and Ion Projection Lithography (IPL). In next parts we shall further explore these technologies.

2. LIGHT LITHOGRAPHY

The essential technology often applied to semiconductor manufacturing of microchips is photolithography. Photolithography is also commonly used in fabricating micro-electro-mechanical-systems (MEMS devices). Photolithography uses visible (or close ultraviolet) light and therefore is applicable for microelectronics. An advanced status of microelectronics is nanoelectronics, as details are smaller than micrometer. How to make the details will be dealt in the next parts. Nevertheless, it will be lithography, but for it the light will be not used. The word "lithography" comes from Greek and means a process of printing. In micro and nanoelectronics it is the printing process, by which is possible to create some image (i.e. exposed motives) on a sensitive slide. The sensitive slide, named resist (or photo resist) changes its property after the exposure. The exposure is feasible through a mask. There are known two kinds of the resists, positive and negative. The positive resist is after exposure soluble in a developer, but resistive at non irradiated places. The negative resist is after the irradiation resistive against developer, but soluble at non irradiated places. As the positive resist for micro-lithography or nanolithography polymethylene methacrylate (PMMA) is often used. The PMMA has atoms in the molecule bound by week forces. The photons, by which the area is exposed, break these weak bindings. The material in the exposed area is then soluble and can be removed. On surface, covered by the resist, there are opened 'windows'. The non-irradiated part of the resist (and windows) is called a motive. The opened windows give us possibility to change through them a property of silicon and to create PN junctions. The PN junctions are basic elements for the all semiconductor technology.

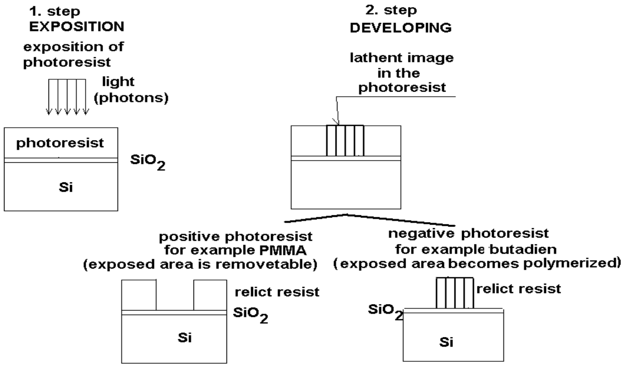

Fig. 1 Principle of light lithography

A negative resist is composed of a material which, under exposure by a photon, activates simple molecules. The molecules (vinyl molecules) are bound to aggregates (poly-vinyl molecules), where the binding forces are stronger as they are among the simple (vinyl) molecules. The aggregates (polyvinyl) are not soluble in a developer and after developing process stay on SiO_2 surface (Fig. 1). As we can see, the first step is covering of SiO_2/Si by a thin layer of the resist and then exposing it through the mask. In the second step the positive resist is removed, SiO_2 layer is removed by a selective etcher and purer Si surface is prepared for the next technological step.

Miniaturization of a microelectronic element needs the motives to be smaller and smaller. The question is how we can do it and where the limits of transversal dimensions of the windows are. We know that the photons have wavelength properties and for the smallest imaged patterns compared to the wavelength, diffraction effects can be taken into account. So the answer on the second question is – dimension limits are there, where the object has dimension equal to approximately the half of the photon's wavelength. For the integrity of the answer we mention a method of resist exposure. The exposure of resist can be done by the three methods. They are contact lithography, projection lithography and a mask-less lithography.

2.1. Contact lithography

In the contact lithography the mask is made of an optically transparent material (glass). On the transparent material there are areas, which are made of a non transparent material (say dark silver). The mask is placed on the resist and the resist is exposed through the mask by light. The mask should have the same dimensions as the resist (scale 1:1). The smallest motives of dimension b_{min} are given [1] due diffraction of light by the equation

$$2b_{\min} = 3\sqrt{\frac{\lambda d}{2}} \tag{1}$$

where: λ is wavelength of light, d is thickness of the resist. From a theoretical point of view, contact lithography gives the best resolving power of all other methods. Of course, there are other aspects which limit the using of this method in microelectronic industry.

2.2. Projection lithography

Projection lithography uses the same process as it is known and used in a photographic camera (Fig. 2).

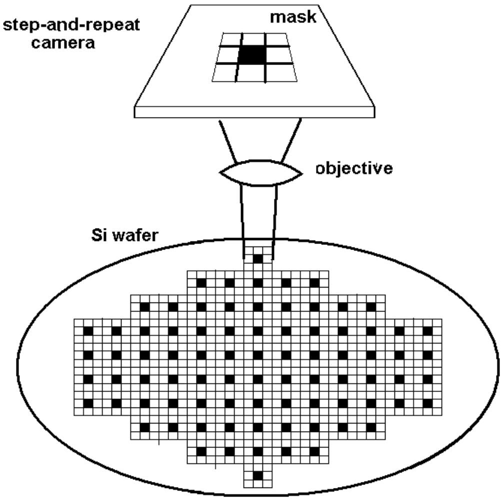

Fig. 2 Projection lithography, step-and-repeat method

Process step-and-repeat is widely used in the microelectronics industry. For short wavelengths (ultraviolet), there is a problem to make an appropriate objective with refractive lenses. To avoid it, a reflector-type of objective is used. Such lithography is known as a scan projection. Usually the magnification is 1:1. By using short-wave light produced by an Hg lamp it is possible to create details less than 1 μm. The modification of the scan projection is using a very thin beam and by common movement of the mask and wafer together to get details of dimension equal to a fraction of micrometer. To get the details under 0.5 μm means to use X-ray (roentgen) radiation.

2.3. Maskless lithography

The maskless lithography is in a principle similar to raster scan lithography. The movement of very thin beam can be derived by a driver (stepping driver or another micro-moving mechanism). Maskless lithography is not used with connection to optical light, but this principle is forwarded for other types of lithography, as they are X-ray or synchrotron lithography [2], or electron/ion lithography.

3. ELECTRON LITHOGRAPHY

Electron lithography is capable of much higher patterning resolution (sometimes as small as a few nanometers) [3]. One can say that it is really nanolithography. In principle, the electron lithography is similar to scan photolithography. But there is one big physical difference. When exposed details are very small (compared to the wavelength of light), the shadow is not sharp, but due to the diffraction of light the border of the details will be smooth. The wavelength of visible light is 800 nm up to 400 nm and ultraviolet light used in microelectronics from 400nm up to 300 nm. But the wavelengths belonging to electrons used for electron lithography are about 0.1 nm. So, the resolution power of electron lithography should be many orders better than the resolution power of the photolithography.

3.1. Principles of electron lithography

Electron beam lithography uses electrons for exposing of resist. As it is known, a responded wavelength to moving electron is given by the de Broglie equation

$$\lambda = \frac{h}{p} \tag{2}$$

where: λ_s – wavelength, p – quantity of electron motion.

Nowadays (2009) are possible to create by this method details as small as 10 nm. The limitation is not given due to the diffraction, as it is in photolithography, but due to the lens aberrations. Generally one can say that electron's lenses have more aberrations compared to the lenses used in light optics. To have some usable results, only very paraxial electron beams must be used. Small apertures and small aperture angles cause low production efficiency and therefore the electron lithography is not widely used for mass production. Aberrations are geometrical and chromatic. In photolithography the achromatic aberrations are possible to suppress by using a chromatic objective and by using monochromatic light. In electron lithography the chromaticity of electrons is a special problem. The reason is that the electrons are coming from a hot cathode. The cathode is heated up to temperature 2000 K and therefore the electrons have a continuous spectrum of energy and quantity of motion *p* (see eq. 2). Unfortunately we cannot make optics for electrons as an "achromatic projector", as it is possible for light optics lenses. The next problem is straggling of electrons in the resist. This is a big problem which restricts using electron projection lithography at all. Using cold cathodes can solve this problem, but for it an ultrahigh vacuum condition in vicinity of the cold cathode is needed. The cold cathode is very sensitive for clean environments and lifetimes of cold cathodes are short. For industrial usage, electron lithography is suitable only for mask production. The masks can be then used for light or X-rays (synchrotron) lithography.

3.2. Electron-optical scheme of the electron beam lithography machine

The optical scheme of electron lithography machine [4] is on Fig. 3.

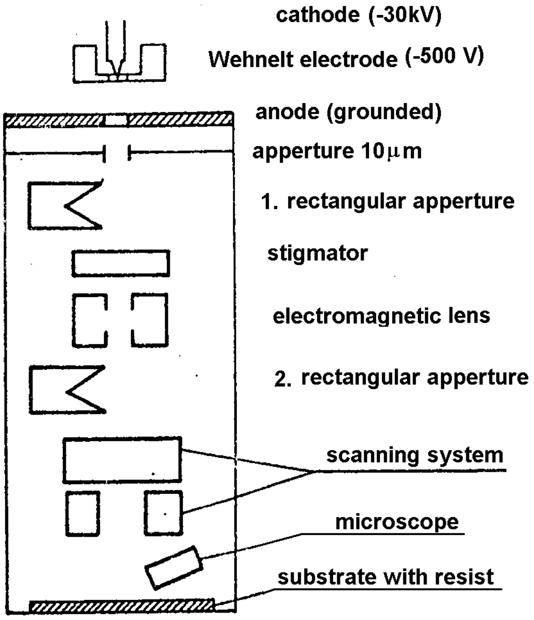

Fig. 3 The electron beam lithography machine

4. ION LITHOGRAPHY

The next step of electron beam lithography is ion beam lithography. The charged ions have wavelengths even smaller than the electrons, and due to the three orders of magnitude greater mass, straggling of ions compared to electrons is negligible. Efficiency to expose the resist is much better than in case of electrons. The next advantage is that ions can be used not only for modification of the resist, but they can be used for deposition of materials on the places of nanometers dimensions, for sputtering of material at places of nanometers dimensions and of course for modifying of character (electrons or holes) conductivity. These are advantages of ion lithography. A disadvantage is worse manipulation with ion beams. Many modes of ion lithography are possible. Today, the most interesting is ion projection lithography (IPL) [5].

4.1. IPL

As it is known to the author of this article, IPL is used only in laboratories or under special conditions [6], [7] and is not used in routine manufacturing. Only partial information about IPL is found in literature. They remain on an academic level and no specific details are published. The principle is shown in Fig. 4.

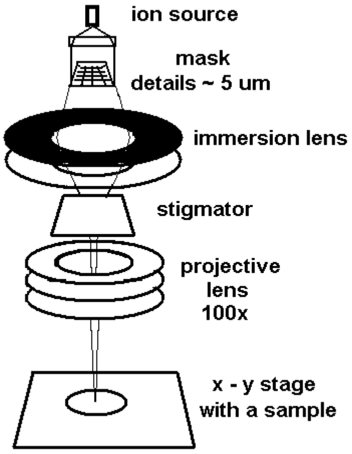

Fig. 4 The projection ion beam lithography

Other modification of previous method uses programmable aperture plate system [8], [9]. The optical scheme is on Fig. 5.

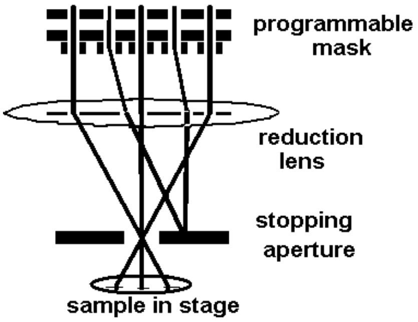

Fig. 5 The programmable aperture plate system

5. STIMULATED GROWTH OF NANOSCALE OBJECTS

Stimulated growth of nanoparticles and nanoobjects can also be used for creating very dense integrated circles crated from nanotubes. The nanotubes are fabricated from various materials, preferably from carbon. Carbon is a very odd material. It lies above Si and Ge in Mendelejev's table of elements, which are known as semiconductors. Carbon can have a similar lattice as they have. The lattice is known as diamond. The diamond has been known (according to the first written reference) in 300 years B.C., but its semiconductor's properties were not used because of its price. Only when artificial diamond was prepared, interest from industry increased. The diamond has unique electrical properties. Pure diamond is an excellent insulator. Doped diamond can be a P-type semiconductor with a mobility of 2200 cm/Vs. Another allotrope form of carbon is the fullerene.

5.1. Nanotubes

The fullerene is any molecule consisting entirely of carbon atoms, in the form of a hollow sphere. Usually it is composed of 60 atoms but fullerenes with a different number of atoms (even up to 100 atoms) are commonly obtained. Fullerenes that form a linear tube of carbon atoms are named nanotubes. The diameter of the nanotube is usually only a few nanometers, but its length can be up to several millimetres. There are many technologies to prepare nanotubes. For microelectronics only determinate growth is needed. The determinate growth can be stimulated by nanoparticles, often of Fe or Ni. Such nanoparticles can be created by ion projection lithography, when Fe (or Ni) ions are used. The nanotubes from the point of view electric field distribution are sharp objects and a cold electron emission occurs at a value of about 100 V. Application of nanotubes will be in optoelectronics and high frequency techniques. The high frequency "vacuum tube" with a nanotube's cathode is known.

5.2. Nanotube triode

The scheme of such vacuum triode is schematically shown on fig. 6 [10].

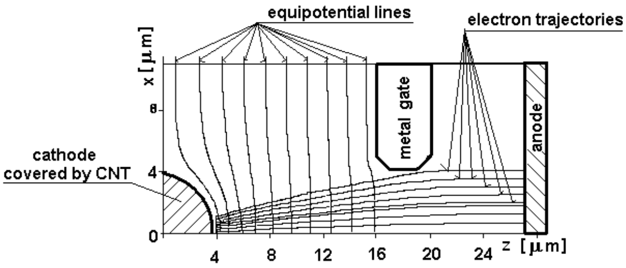

Fig. 6 The principle of vacutron

The gate electrode controls a current between the anode and cathode. Small dimensions and high voltage (high electron velocity) predict the working frequency in terahertz region.

6. CONCLUSIONS

Presented were technologies and materials applicable in nanoelectronics. Also, possibilities of using new technologies in research and industry were shown. Advantageous and disadvantageous properties of new material and technologies were mentioned.

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BIOGRAPHIES

Ján Janík was born on 23.12.1946 in Handlová. In 1970 he graduated (MSc) at the Faculty of Electrical Engineering and Information Technology at Slovak University of Technology (FEI STU) in Bratislava. He defended his PhD in the field of "Applied physics" in 1981; his thesis title was "A study of radiation damage in silicon wafers after ion implantation process". At home university he read lecture on "Electron and ion beams technology" for students at FEI SUT. Since 1987 to 1989 he was working as a senior researcher at the "Joint Institute of Nuclear Research", Laboratory of Nuclear Reaction in Dubna (Russia). He spent some time at CERN, Geneva (Switzerland) and GSI Darmstadt (Germany) as an ion beam optics designer. His research activity is focused on study of carbon nanotubes (prepared the first time at KME in April 2003) and theirs cold emission properties. He also worked at group, which prepared in Slovakia the first crystals of diamond (January 29, 1999) and carbon nanotubes (2003). Now he has a permanent stay position as the "Associate professor" at SUT Bratislava.