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Future Perspective of Ion Implantation: A review

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Abstract: **The ion implantation process offers several unique advantages over other surfaces modifications techniques, in regard to ion release and material mechanical characteristics. The semiconductor industry relies on the implanting of impurities in semiconductors (doping). This is critical in integrated circuit manufacturing. One way of doping this is to fire ions into the material from an accelerator with its penetration dependent on the energy, hence they can be placed accurately in the material. Ion implanting is the only method to accurately control the ion position from the equipment settings. We investigate the future perspective of Ion Implantation.**

Keywords: **Ion Implantation, review, future trends**

I. INTRODUCTION

In 1999, Nissin Ion Equipment Co., Ltd., which was previously engaged in business under the name of Ion Equipment Department of Nissin Electric Co., Ltd., has become independent as a 100%-owned subsidiary of Nissin Electric Co., Ltd. At that time, EXCEED2000, an ion implanter that Nissin Electric had developed in 1994 with the new technology of energy contamination-free for the first time in the world, started gaining recognition for its value. That was also the time when EXCEED2000A was consecutively brought to the market with its greatly improved productivity.

As a result of the booming economy and growth in the IT sector in Asia since 1999, we have successfully managed to expand our business not only in Japan but also in the East Asia. Ever since then, the EXCEED series has been recognized as one of the most leading-edge ion implanters for its continuously upgraded performance in response to the sophistication of process needs.

In this paper, the technical history of ion implanters is described on the basis of technological enhancement in the EXCEED series and its expected future development is also presented.

Ion implantation is one of the fundamental processes used to make microchips. Raw silicon is neither a perfect insulator nor a perfect conductor. It's somewhere in the middle. Inserting a smattering of boron or phosphorus atoms into the silicon crystal lattice allows us to control the flow of electricity through the silicon and make transistors – the building block from which we make chips. Ion implantation [13-14] has been known for decades for modification of the near-surface regions of solid materials (targets) in material engineering process as a way of the introduction of foreign atoms. This process is used to change the physical (e.g. hardness, friction coefficient, wear resistance, fatigue resistance, durability, wettability, electrical conductivity, superconductivity, magnetic properties, optical properties, spintronic properties) and/or chemical (e.g. corrosion resistance) properties of the implanted material. Ion implantation is a low temperature treatment process. Only material surface is treated, and the treatment is therefore cheaper and faster than the volumetric one. Usually, the beam diameter exceeds 5 cm, thus enabling the treatment of relatively large surfaces. The modified region is not an additional layer, hence no adhesion problem occurs (no delamination), and a change of dimensions and of the surface finish of the implanted material is negligible. The combination of ion implantation with other techniques (duplex treatment) is also possible.

This process allows for non-stoichiometric concentrations and phases, and thereby new unique properties of modified material [15-16] can be attained. The scheme of ion implantation process is presented at Fig. 1.

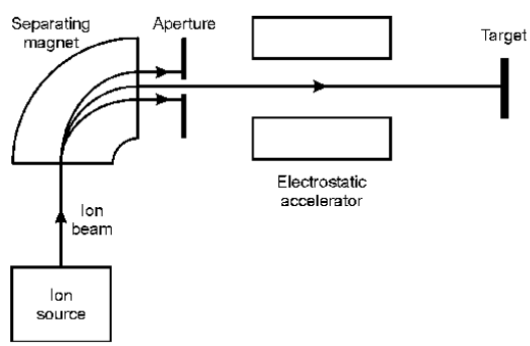

Fig. 1. The scheme of ion implantation method

The dopant atoms originating from ion source are first ionized. Gas, melted salt, metallic cathode and other devices can be used as a ion source. In the next step, the ion beam is formed and accelerated in an electrical field, and finally directed into a target. Often, a separating magnet is used for mass separation of ion beam in order to obtain the ionically homogenous beam. Ion beam interacts with the modified material, introduces new atoms, damages its crystal lattice, generates amorphization, creates vacancies and other defects. A part of the substrate atoms is ejected from the surface. The sputtering yield coefficient is a measure of this phenomenon. The value of this coefficient shows the average number of atoms sputtered from target per one incident ion, and it dependent, among others, on atomic masses of the ion and target atoms, ion energy, ion incidence angle and the surface binding energy of atoms in the implanted material.

Two main parameters of ion implantation process are: ion energy and the dose of implanted ions. The ion energy is the result of the multiplication of the ion charge and the accelerating voltage. In the case of non-mass separated beam, the mean ion-charge value is used in calculations. The values of the energy affect the depth of ion implantation and the shape of the depth profile of the implanted element. Typically, the ion energy is of order of several hundreds keV. MeV ion implanters are used less frequently.

The applied dose is proportional to ion beam current and implantation time and inversely proportional to implanted area and the implanted ion charge. The implanted dose, i.e. the planned fluence and the retained dose, i.e. real implanted fluence, strongly depend on the sputtering yield.

The unit of the applied dose is ions per cm2, which means density of the implanted ions. The ion depth distribution is roughly given by a Gauss-shape depth profile of implanted element (Fig. 2) and described by: peak volume dopant concentrations (Nmax, cm-2), projected range (Rp, nm) and range straggling (ΔRp, nm).

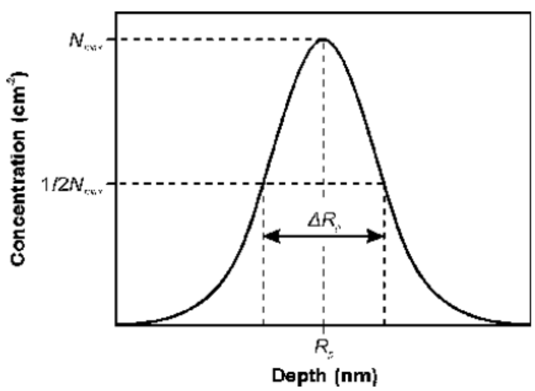

Fig. 2. The depth profile of implanted element

The depth profile and selected properties of implanted material can be modelled using several computer codes, e.g. based on a Monte Carlo simulation method SRIM (The Stopping and Range of Ions in Matter) [17] or a quick ion implantation calculator SUSPRE [18]. Usually, the implanted depth is relatively narrow, of order of several hundred nanometers. The multi-implantation procedure, e.g. the superposition of few different implantations at different energies is a way to extend the implanted profile [19].

II. GENERAL PRINCIPLE

Advantages of Ion Implantation are being described below:

- Precise control of dose and depth profile
- Low-temp. process (can use photoresist as mask)
- Wide selection of masking materials e.g. photoresist, oxide, poly-Si, metal
- Less sensitive to surface cleaning procedures
- Excellent lateral dose uniformity (< 1% variation across 12" wafer)

Ion implantation equipment typically consists of an ion source, where ions of the desired element are produced, an accelerator, where the ions are electrostatically accelerated to a high energy, and a target chamber, where the ions impinge on a target, which is the material to be implanted. Each ion is typically a single atom, and thus the actual amount of material implanted in the target is the integral over time of the ion current. This amount is called the dose. The currents supplied by implanters are typically small (microamperes), and thus the dose which can be implanted in a reasonable amount of time is small. Thus, ion implantation finds application in cases where the amount of chemical change required is small.

Typical ion energies are in the range of 10 to 500 keV (1,600 to 80,000 aJ). Energies in the range 1 to 10 keV (160 to 1,600 aJ) can be used, but result in a penetration of only a few nanometers or less. Energies lower than this result in very little damage to the target, and fall under the designation ion beam deposition. Higher energies can also be used: accelerators capable of 5 MeV (800,000 aJ) are common. However, there is often great structural damage to the target, and because the depth distribution is broad, the net composition change at any point in the target will be small.

The energy of the ions, as well as the ion species and the composition of the target determine the depth of penetration of the ions in the solid: A monoenergetic ion beam will generally have a broad depth distribution. The average penetration depth is called the range of the ions. Under typical circumstances ion ranges will be between 10 nanometers and 1 micrometer. Thus, ion implantation is especially useful in cases where the chemical or structural change is desired to be near the surface of the target. Ions gradually lose their energy as they travel through the solid, both from occasional collisions with target atoms (which cause abrupt energy transfers) and from a mild drag from overlap of electron orbitals, which is a continuous process. The loss of ion energy in the target is called stopping.

III. SEMICONDUCTOR MANUFACTURING PROCESSES AND ION IMPLANTATION EQUIPMENT

The basic structure of a semiconductor IC MOSFET (Metal Oxide Silicon Field Effect Transistor)(1) is schematically shown in Fig. 3. Dimensions of each element in a transistor are determined by a scaling law of the gate length (Lgate). Figure 2 shows types of transistors, which are classified according to the application as DRAM, Flash Memory, LSTP (Low Stand-by Power)(2), LOP (Low Operational Power)(3), MPU/ASIC (Micro-Processor/Application Specific Integrated Circuit)(4). Each Lgate and Line-Pitch is in a proportional relation. The half-length of DRAM Line-Pitch, called node, represents the reference.

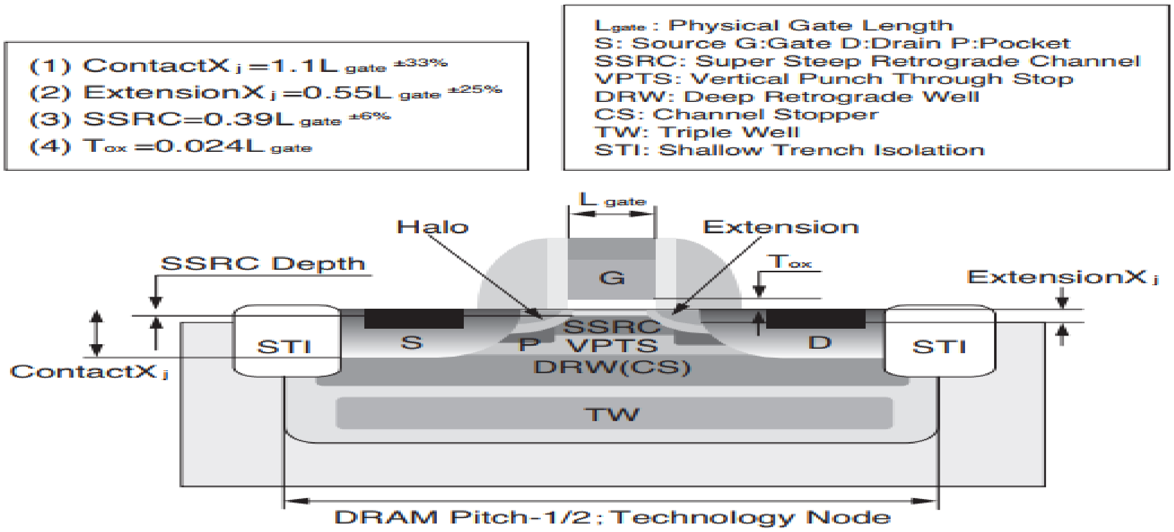

Fig. 3. Transistor Structure and Scaling Law for Implantation Process

ITRS 2007 Prospect for 1/2 Pitch & Gate Length

Year of production	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
DRAM 1/2 pitch (nm)	100	90	80	70	65	57	50	45	40	36	32	28	25	22	20	18	16	14	13	11
Flash Poly Si 1/2 pitch (nm)					54	45	40	36	32	28	25	23	20	18	16	14	13	11	10	9
MPU/ASIC Metal 1(M1) 1/2 pitch (nm)					68	59	52	45	40	36	32	28	25	22	20	18	16	14	13	11
LSTP Physical gate length (nm)	76	65	53	45	45	37	32	28	25	23	20	18	16	14	13	11	10	9	8	7
LOP Physical gate length (nm)	65	53	45	37	32	28	25	23	20	18	16	14	13	11	10	9	8	7	6.3	5.6
MPU physical gate length (nm)	45	37	32	28	25	23	20	18	16	14	13	11	10	9	8	7	6.3	5.6	5.0	4.5

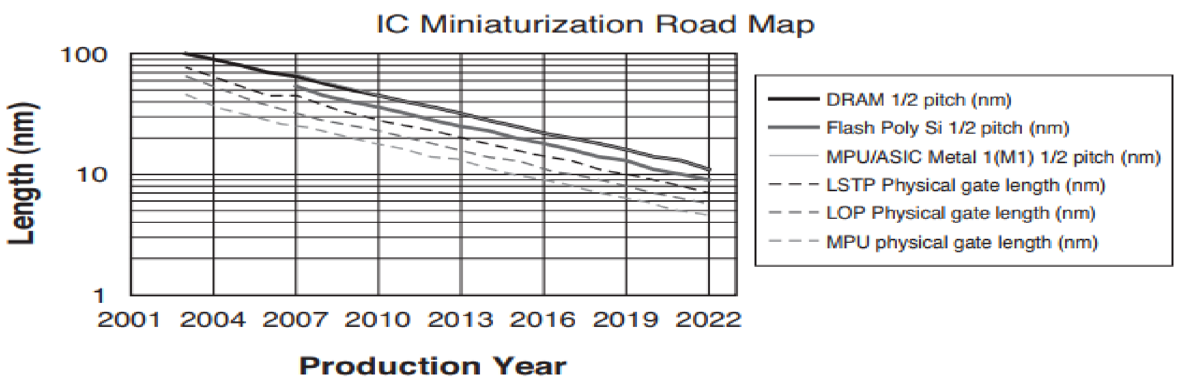

Fig. 2. IC Miniaturization Roadmap

IV. APPLICATION IN SEMICONDUCTOR DEVICE FABRICATION

Doping

Semiconductor doping with boron, phosphorus, or arsenic is a common application of ion implantation. When implanted in a semiconductor, each dopant atom can create a charge carrier in the semiconductor after annealing. A hole can be created for a p-type dopant, and an electron for an n-type dopant. This modifies the conductivity of the semiconductor in its vicinity. The technique is used, for example, for adjusting the threshold of a MOSFET.

Ion implantation was developed as a method of producing the p-n junction of photovoltaic devices in the late 1970s and early 1980s,[2] along with the use of pulsed-electron beam for rapid annealing,[3] although it has not to date been used for commercial production.

Silicon on insulator

One prominent method for preparing silicon on insulator (SOI) substrates from conventional silicon substrates is the SIMOX (separation by implantation of oxygen) process, wherein a buried high dose oxygen implant is converted to silicon oxide by a high temperature annealing process.

Mesotaxy

Mesotaxy is the term for the growth of a crystallographically matching phase underneath the surface of the host crystal (compare to epitaxy, which is the growth of the matching phase on the surface of a substrate). In this process, ions are implanted at a high enough energy and dose into a material to create a layer of a second phase, and the temperature is controlled so that the crystal structure of the target is not destroyed. The crystal orientation of the layer can be engineered to match that of the target, even though the exact crystal structure and lattice constant may be very different. For example, after the implantation of nickel ions into a silicon wafer, a layer of nickel silicide can be grown in which the crystal orientation of the silicide matches that of the silicon.

Application in metal finishing

Tool steel toughening

Nitrogen or other ions can be implanted into a tool steel target (drill bits, for example). The structural change caused by the implantation produces a surface compression in the steel, which prevents crack propagation and thus makes the material more resistant to fracture. The chemical change can also make the tool more resistant to corrosion.

Surface finishing

In some applications, for example prosthetic devices such as artificial joints, it is desired to have surfaces very resistant to both chemical corrosion and wear due to friction. Ion implantation is used in such cases to engineer the surfaces of such devices for more reliable performance. As in the case of tool steels, the surface modification caused by ion implantation includes both a surface compression which prevents crack propagation and an alloying of the surface to make it more chemically resistant to corrosion.

Other applications

Ion beam mixing

Ion implantation can be used to achieve ion beam mixing, i.e. mixing up atoms of different elements at an interface. This may be useful for achieving graded interfaces or strengthening adhesion between layers of immiscible materials.

Ion implantation-induced nanoparticle formation

Ion implantation may be used to induce nano-dimensional particles in oxides such as sapphire and silica. The particles may be formed as a result of precipitation of the ion implanted species, they may be formed as a result of the production of an mixed oxide species that contains both the ion-implanted element and the oxide substrate, and they may be formed as a result of a reduction of the substrate, first reported by Hunt and Hampikian.[4][5][6] Typical ion beam energies used to produce nanoparticles range from 50 to 150 keV, with ion fluences that range from 1016 to 1018 ions/cm2.

V. ISSUES RELATED TO ION IMPLANTATION

In this section, we will discuss charge neutralization, energy contamination, wafer charging, wafer heating, photoresist outgassing, implant angle effects, and ultrashallow junction formation.

The first process challenge we'll discuss is charge neutralization. We know that the ions need to maintain a specific charge state during the implant process. However, these ions can be neutralized by collisions with gas atoms in the chamber. This is a big problem during boron deceleration, which is used in some implant systems to create shallow junctions. Neutral atoms are a problem because they cannot be accelerated and steered properly with electrostatic plates. They will not be implanted to the correct depth if the neutralization occurs early on; they will not be spread uniformly across the wafer if the system employs electrostatic scanning, and they will not be counted by the dose measurement system.

A different problem happens at higher energies—collisions between ions and atoms can caused increased ionization. The solution is to remove, as much as possible, the atoms from the chamber. This means ultra high vacuum is required in the beamline and in the chamber. This in turn means that one must use high capacity pumps and perform frequent regeneration of cryopumps. One should also avoid decelerating the beam, and one should provide neutral traps or beam filters to remove neutral species.

Charge neutralization brings up a broader issue, that of energy contamination. This situation occurs when ions of the wrong energy are implanted. This leads to incorrect doping profiles. The main causes are charge neutralization, which we discussed, and contaminants of the same mass-to-charge ratio not being removed by the mass analysis magnet. An example of this would be a double-charged dual phosphorus ion in a single-charged single phosphorus ion beam. One would use the same solutions for this problem as with charge neutralization.

Another concern is contamination control. Contaminants can come from apertures, wafer holders, and metals used in the beam line hardware. They can also come from other dopant atoms used in the system that have been implanted into the hardware and then resputtered. And they can come from particles of material flaked off from the beamline hardware or wafer handling system and then transported in the beam by the electrostatic forces. This problem can be minimized by routine cleaning of the components, using materials with low sputter yield in the beamline like carbon, and dedicating implanters by species to prevent cross contamination.

Another significant problem is wafer charging. This can result in device damage due to ESD as charge builds up in sensitive gates. It can also result in non-uniformity, due to the charge on the surface distorting the incoming beam. This is typically a problem with high current implanters. One solution is to use a system to reduce wafer charge. A common method is to use a plasma flood gun. This produces low energy electrons at the surface that can recombine with the charged ions. The goal here is to balance the charge and charge flow at the surface. Another solution is to minimize the beam density by employing dual mechanical or ribbon scanning methods, moving to batch processing to increase the implant area, and increasing scan speeds to lower dwell times. This reduces the time for charge buildup.

Another significant problem is heat generation. High-energy ions decelerate in the wafer, and much of that energy is dissipated as heat. This excess heat can damage photoresist masks, leading to critical dimension changes, or even blistering, flaking or popping. High temperatures can also lead to dopant redistribution, as diffusion processes accelerate exponentially at higher temperatures. This can also lead to undesirable forms of crystal defects. This is mainly a problem with high power, high mass implants where the energy dissipation is significant. The equation below helps to illustrate the dependence on both accelerating voltage and current.

The solutions for this problem include proper wafer cooling, performing hard bake or other resist stabilization techniques, and minimizing the power density with larger beam sizes, faster scanning, and so on.

Still another problem is photoresist outgassing. Energetic ions will break the resist polymer bonds, releasing hydrogen. This problem is strongly related to beam power density. The increased heat makes the resist more susceptible to this problem. There are two main issues here. One is charge neutralization, and the other is resist mask damage. Liberated hydrogen will interfere with charge neutralization efforts.

The solutions here are to optimize the resist process through hard bakes or ultraviolet photostabilization, increasing the equipment chamber size to reduce local hydrogen concentrations or use high pump speed vacuum systems, minimizing the beam power density, and conditioning the resist through a controlled ramp-up of beam current.

VI. CONCLUSION

The ion implanter has to be continuously upgraded in its performance in order to meet the needs for high precision and productivity associated with progressing IC device miniaturization. We have been working on the development of new model implanters and released such products in every two years by improving our original technologies, such as magnetic filtering of energy contamination, high precise monitoring of implantation angle and high throughput end station. We intend to provide advanced implanters that meet the needs of ever-evolving technology for the semiconductor industry..

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