Future Perspective of Ion Implantation: A review

Preeti Chhokkar

Department of Physics, Kurukshetra University Kurukshetra, Haryana, India

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 (N_max, cm⁻²), projected range (Rₚ, nm) and
range straggling (ΔR_p, nm).

![Fig. 2. The depth profile of implanted element](image)

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
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 (L_gate). 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.
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 needed 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 ions 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..

VII. REFERENCE:


    Clayton and C. W. White (eds.), Ion Implantation and
    Ion Beam Processing of Materials, North Holland,

[3]. H. Dimigen, K. Kobs, R. Leutenecker, H. Ryssel and


[7]. T. J. Sommerer, E. B. Hale, K. W. Burns and R. A.


    Kohser, in R. Kosowsky and S. C. Singhal (eds.),
    Surface Engineering, Martinus and Nijhoff, Boston,
    1984.

    227.

[15].  G. Dearnaley, in R. Kosowsky and S. C. Singhal
    (eds.), Surface Engineering, Martinus and Nijhoff,
    Boston, 1984.


    Lucke and J. K. Hirvonen, Thin Solid Films, 63
    (1979) 11.


    and S. C. Singhal (eds.), Surface Engineering,
    Martinus and Nijhoff, Boston, 1984.

[21].  M. D. Nahemow, R. E. Fromson, R. Kosowsky and
    J. L. Pack, in H. Ryssel and H. Glawishnig (eds.),
    Ion Implantation, Equipment and Techniques, Springer,

[22].  R. Leutenecker, H. Ryssel, K. H. Zeller and H. P.

    Methods B, 6 (1985) 70.

    8th EMIS Conf. Low Energy Ion Accelerators and