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APPLICATION OF PLASMA IN MICROELECTRONICS

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Abstract. The paper gives a brief review of issues related to the application of plasma techniques in microelectronics. As an illustration there are also presented and discussed exemplary results of applying plasma methods for GaN and SiC etching.

Keywords: plasma techniques, microelectronics, layer etching, GaN, SiC.

INTRODUCTION

Plasma – the fourth state of matter, although rarely occurring in our natural Earth environment, is the most common state of matter in the Universe. Due to specific physical properties, like the presence of highly energetic and reactive species (ions, excited molecules, electrons, photons), plasma has become interesting from the viewpoint of its application in various microelectronic technologies. Since these technologies mainly are concerned with processing of surface regions of solids (mostly semiconductors), they require: highest cleanliness of technological process, availability of processing structures in micron and nanometric scales and, what is relevant to that – the highest process precision.

In other words, for microelectronics plasma is a medium of specific chemical and energetic properties promoting creation of the particles and clusters, which are difficult to obtain under other conditions. It allows as well synthesizing of thin films on various substrates and formation of multilayered structures (for instance for amorphous superlattices).

From the same viewpoint plasma, as the processing medium containing the mixture of ionized atoms and ionic particles and electrons, enables: surface modification of various materials (e.g. semiconductor substrates, dielectrics or metals), internal reconstruction of film structure, deep (i.e. up to more than 1 micron) substrate and layer etching and finally, ion implantation into the semiconductor substrate [1].

In other words, using plasma has become the important component of many present microelectronics technologies.

PLASMA IN FILM DEPOSITION PROCESSES

Application of plasma environment in processes of thin film deposition includes such operations and phenomena like: substrate preparation, surface nucleation, formation of interface regions and of course synthesis of films [2].

Process of the substrate surface preparation means its plasma etching, performed chiefly in order to clean it, i.e., to remove any contaminants. Parameters of this process (critical strength of electric field *E*, gas pressure *p*) must be carefully controlled so as to prevent occurrence of the opposite event – growth of material on the treated substrate (Fig.1). Such unwanted deposits, which can be effect of the surface plasma cleaning, are primarily various chemical compounds, like: carbides, nitrides, oxides etc.

Surface nucleation is very important phenomenon occurring during plasma deposition processes, especially when substrates, like Si, SiC, Ir, titanates and tantalates are used [3,4]. For instance, in the course of diamond layers synthesis, diamond clusters are being driven into the substrate material, what is called Bias Enhanced Nucleation (BEN). Also growth of diamond nanocrystallites previously introduced into the substrate surface is observed [3-7].

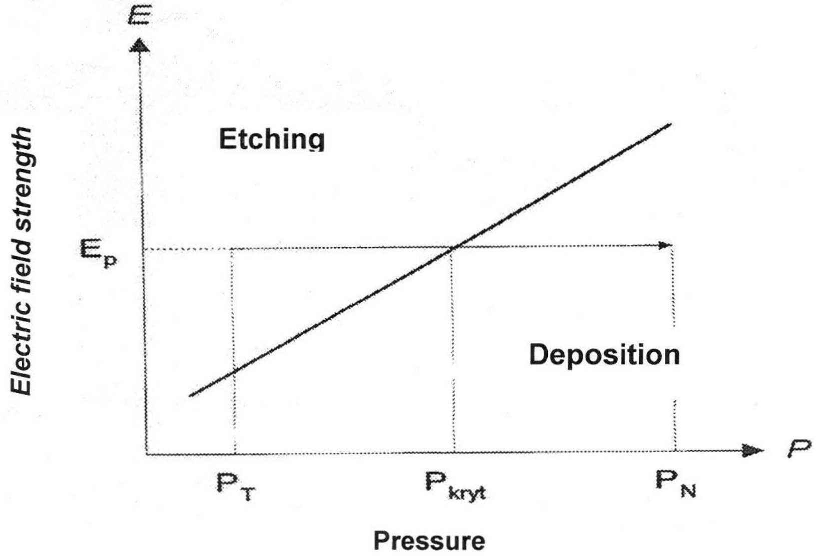

Fig. 1. Result of the plasma process as a function of its parameters.

Formation of transition regions (frequently from nitrides, oxides or carbides) is a result of interaction between substrate surface and plasma environment. Many layers simply require the existence of the natural interface region between the substrate and growing layers in order to ensure their adhesion and satisfactory electrophysical properties, like in the case of so-called high-k films (i.e., materials with high dielectric constant value) [8-11].

Plasma allows synthesis of various materials. Oxide and nitride films have already become classic examples of using plasma-based deposition methods in silicon technologies. Another application of plasma is oxidizing of SiC surface. Plasma also enables obtaining various carbon layers: polycrystalline diamond, nanocrystalline diamond and diamond-like carbon (DLC) [3].

Surface modification inevitably occurs during substrate preparation, surface nucleation as well as in the course of the formation of interface regions (Fig.2). Plasma can be as well applied in processes of substrate pretreatment prior to epitaxy or for oxidizing metals (carried out in order to transform them into insulators, which can play then the role of substrates for active layers) [8,9,12-14].

During the internal reconstruction of films, depending on the process time and energy, structural reconstruction, as well as internal stress relaxation and changes of layer electrophysical properties take place (Fig.3).

Very important application of plasma in microelectronic technologies is etching [2,17,18]. For this purpose numerous techniques, like Electron-Cyclotron Resonance (ECR), Inductively Coupled Plasma (ICP), Reactive Ion Etching (RIE), Reactive Ion Beam Etching (RIBE) and various gas mixtures (primarily based on chlorine or fluorine) are used (Table 2). Plasma environment is also a comfortable tool for shallow ($x_j < 60$ nm) doping of semiconductors. Compared to classical ion implantation technique, it allows avoiding serious surface damaging as well as reduces problems with surface resistivity and dopant activation.

Table 1. Gas mixtures used in plasma etching of different semiconductor materials.

Substrate material	Gas mixtures
Si	$CF_3Br/SF_6 + Ar$, $CF_4 + O_2$, $C_2ClF_5 + O_2$
GaAs	Cl, CCl_4, BCl_3, $SiCl_4/Cl_2$, CCl_2F_2/Ar
SiC	SF_6/O_2, SF_6/Ar, CCl_2F_2, NF_3/O_2, NF_3/Ar, Cl_2
GaN	$SiCl_4$, BCl_3, $SiCl_4$, BCl_3, CCl_2F_2, $Cl_2/H_2/Ar$, $Cl_2/SF_6/Ar$

Plasma Immersion Ion Implantation (PIII) process is characterized by very advantageous feature – an additional impulse acceleration of ions, but on the other hand introduces defects and may lead to the surface oxidation (Fig.4) [19].

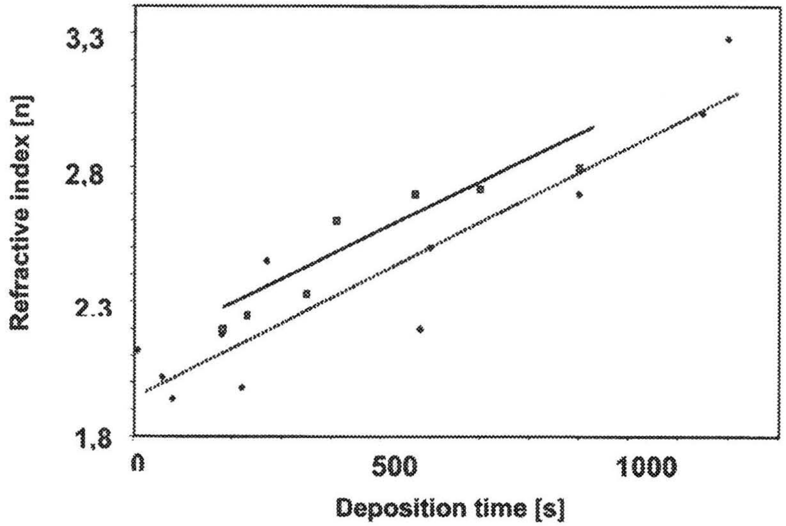

Fig. 2. Relationship between refractive index value and deposition time for NCD films produced on Si substrates in RF CVD process.

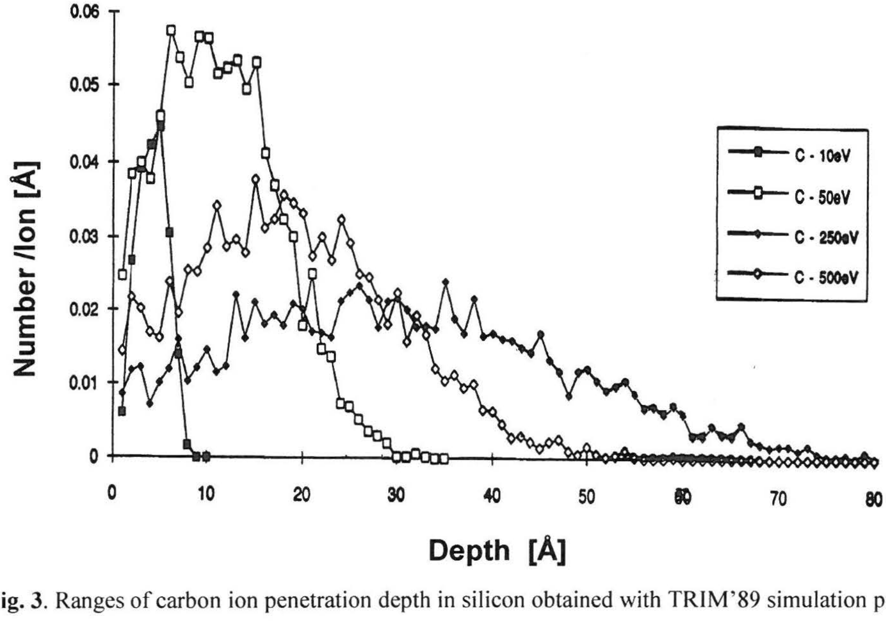

Fig. 3. Ranges of carbon ion penetration depth in silicon obtained with TRIM'89 simulation program.

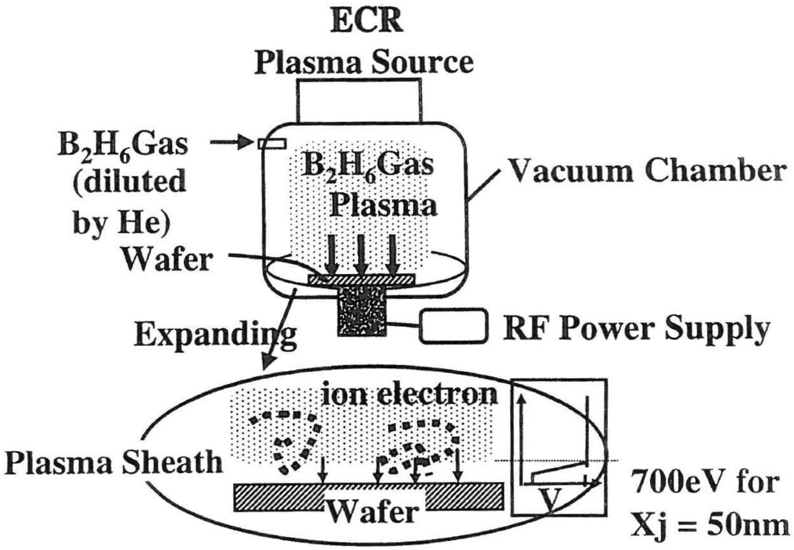

Fig. 4. Plasma doping equipment.

MOST IMPORTANT PROBLEMS AND LIMITATIONS OF PLASMA METHODS

Despite numerous advantages, plasma techniques have also certain shortcomings. As far as plasma etching is concerned, these are: unavoidable implantation of etchant atoms into the processed material (depth of doping depends on ion energies), damaging of crystalline structure of the substrate surface by driving substrate atoms into the interstitial positions, secondary ionization of atoms already adsorbed on the substrate surface and generation of internal stress (Figs 5 and 6) [17,18].

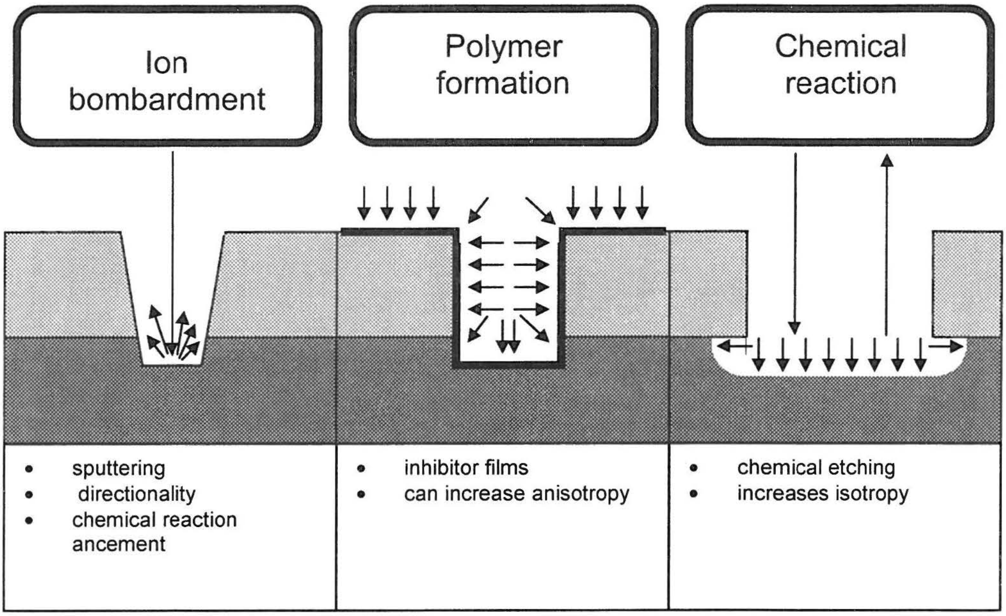

Fig. 5. Basic physical and chemical phenomena in plasma – solid interaction.

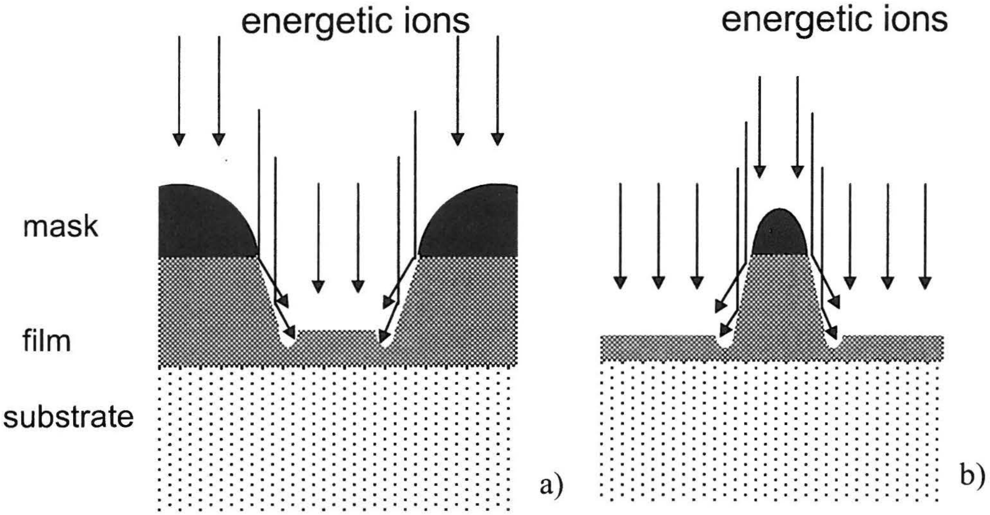

Fig. 6. Distortions of etched profiles being result of ions reflection from side walls of etched film: a) window etching, b) island etching.

One has to mention no less harmful aspects of substrate penetration by electrons and photons, which are present in any plasma environment. These are: changes in metal-semiconductor work functions difference, growth of the density of the all charge types typically present in insulator-semiconductor systems, drift of threshold voltage value in MOS structures, growth of generation-recombination process rates, rise of leakage currents, drop in minority carrier lifetimes, growth of oxide defects density and reduction of the critical electric field value [1-3,11,17,18].

EXEMPLARY RESULTS OF PLASMA APPLICATION IN GAN AND SIC ETCHING

An illustration of the above discussed issues, especially with respect to patterning of microelectronic structures by means of plasma, are results of our recent investigations on deep selective plasma etching of gallium nitride (GaN) and silicon carbide (SiC).

Deep etching of GaN

Our investigations show that the mixture of CF_4 and Ar is suitable for etching of gallium nitride. Its application allows obtaining of satisfactory etch rates and at the same time enables precise control of etch depth together with maintaining the well defined geometry of etched patterns. Using a pure Ar plasma (physical phenomenon of sputtering by ions) for this purpose also results in high etch rates of GaN but simultaneously produces highly defected material. Therefore the whole process of etching requires maintaining of proper proportions between competing physical and chemical mechanisms of etching, what means controlling of chemical composition of plasma (Fig.7) [21,22].

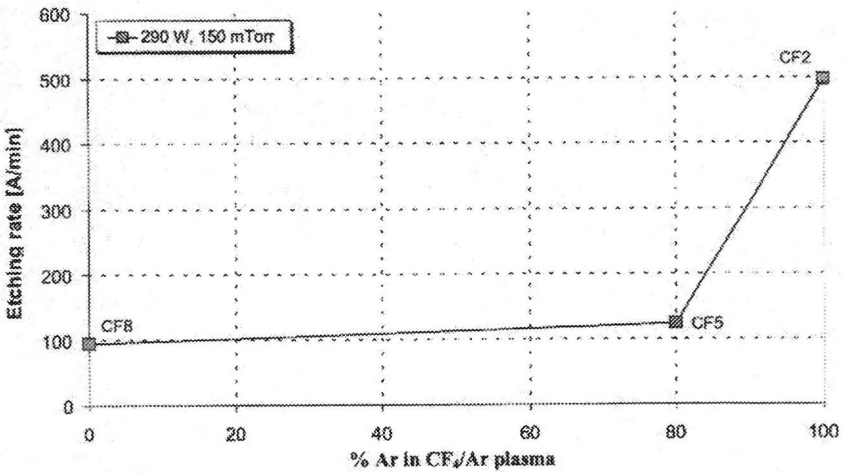

Fig. 7. Relationship between etching rate of GaN and the plasma composition.

Deep etching of SiC

Our experiments demonstrate that relatively high etch rates of SiC can be obtained in CF_4 plasma with addition of O_2 or Ar. The process is highly anisotropic and results in a good quality of the surface after etching. In this case the etching process is primarily of chemical nature but the role of ion bombardment is also important (Fig. 8) [23,24].

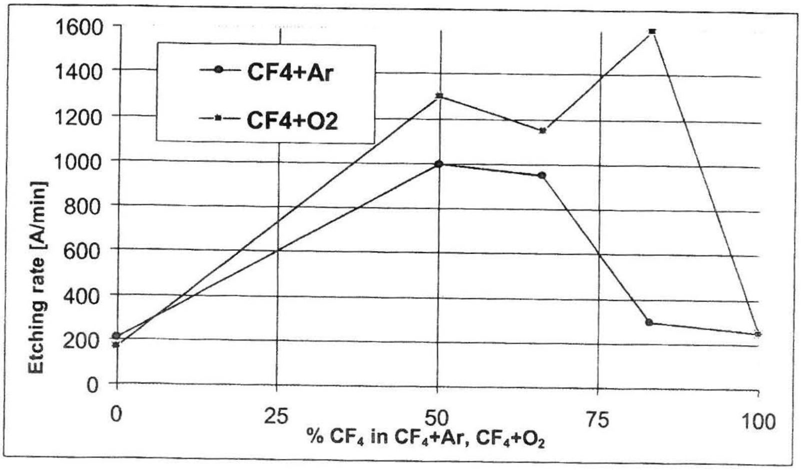

Fig. 8. Relationship between etching rate of SiC and the plasma composition; total flow 30 ml/min, pressure p = 50 mTorr; power P = 270 W.

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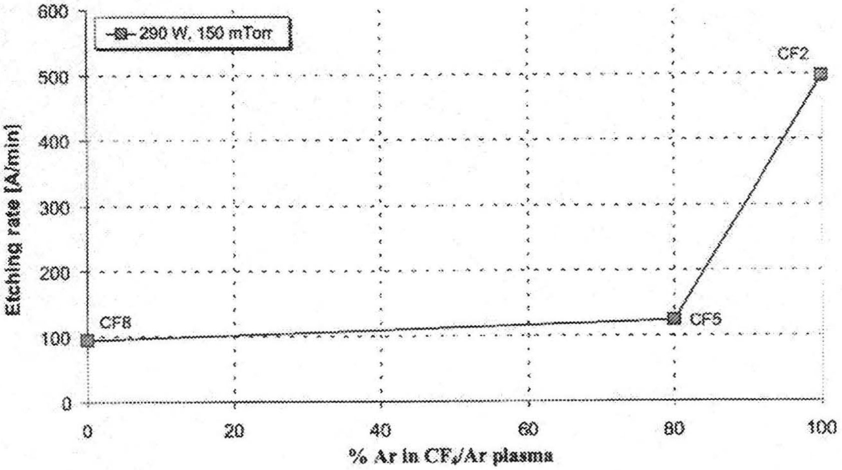

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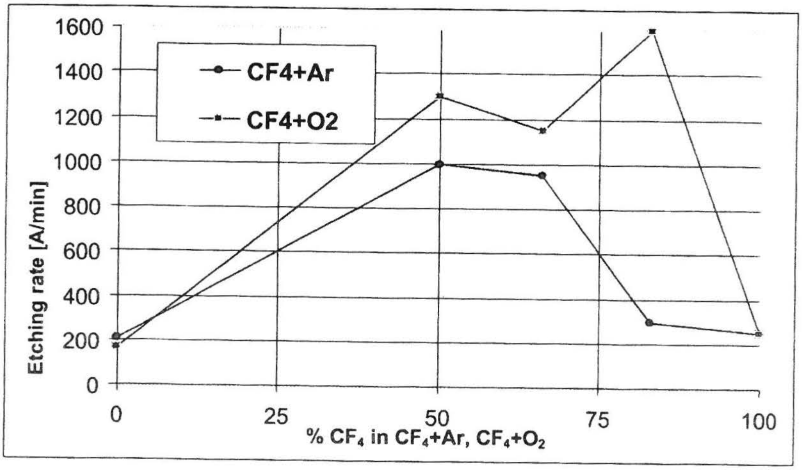

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PLAZMA W MIKROELEKTRONICE

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Streszczenie. Referat w zwięzły sposób przedstawia przykłady zastosowań plazmy nieizotermicznej w procesach technologicznych wytwarzania struktur mikro- i nano-elektroniki. Jako ilustracja przedstawione są przykłady zastosowania plazmy do trawienia GaN i SiC.

Słowa kluczowe : plazma nieizotermiczna, mikroelektronika, trawienie warstw, GaN, SiC.