Computational Investigation of Pulsed Plasma Doping

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***Abstract*–**Quasi-DC pulsed plasmas are gaining interest for the formation of ultra-shallow junctions (USJ). In this paper, the scaling of plasma doping for USJ is discussed using results from a 2-dimensional model. A pulsed plasma is generated adjacent to the silicon wafer using biases up to 20 kV in pressures of 10s mTorr. The consequences of pulse width, bias voltage waveform, ICP power, and pressure on discharge characteristics and ion energy distributions (IEADs) will be discussed.

Introduction

Ultra-shallow junctions (USJ) are required for fabrication of sub-0.1 µm transistors in semiconductor integrated circuits. The most direct fabrication method is to extend beam-line ion implantation technology used for deep junctions to ultra-low energies (100s eV to a few keV). Due to space charge induced divergence, low energy beams are restricted to low currents which results in lower throughputs. Several alternative techniques have been proposed. Promising candidates include plasma implantation methods – plasma doping, pulsed plasma doping (P^2LAD), and plasma immersion ion implantation (PIII).[1]

P^2LAD is attractive as a simple and low cost doping technique, as it is capable of high dose rates at ultra-low energies (100 eV-20 keV) using conventional plasma processing technologies. In one variation of P^2LAD, a pulsed negative voltage applied to the substrate creates a plasma containing the desired dopant species and also accelerates the positive dopant ions from the plasma across the cathode sheath into the wafer. Typical pulse lengths are many to tens of microseconds. For sufficiently low pressures, the ions are implanted into the wafer with energies largely determined by the pulse voltage and the ion charge. The plasma is ignited with each pulse and extinguishes after each pulse ends.[2] An alternate configuration uses an auxiliary plasma source, such as an inductively coupled plasma (ICP), to provide a readily available source of ions and to reduce issues associated with restarting the plasma with each pulse. The disadvantage of having the plasma continually on is possible unwanted production of etching species.

The characteristics of the ion energy and angular distributions (IEADs) incident onto the wafer are sensitive functions of the bias voltage waveform. The IEADs also critically depend on the plasma parameters that determine the sheath properties (e.g. pressure, power, reactor configuration). Characterizing these parameters is important with respect to improving uniformity, repeatability and reliability. In this paper, the effect of pulse width, wafer bias voltage, and ICP power on pulsed plasma characteristics and IEADs to the wafer are discussed for a Ar/NF_3 (a surrogate for Ar/BF_3) plasma.

Description of the Model

The Hybrid Plasma Equipment Model (HPEM) was used to obtain plasma characteristics and reactant fluxes to the wafer. The HPEM has been previously described and so will only be discussed briefly here.[3,4] The HPEM is two-dimensional simulator which addresses equipment scale plasma chemistry and hydrodynamics, and consists of three modules. Electromagnetic and magneto-static fields are calculated in the Electromagnetics Module. These fields are then used in the Electron Energy Transport Module to obtain electron impact source functions and transport coefficients. This is achieved by either solving the electron energy equation or by a Monte Carlo simulation. These results are then passed to the Fluid Kinetics Module in which separate continuity, momentum and energy equations are solved for ions and neutral species. A drift diffusion formulation is used for electrons to enable an implicit solution of Poisson's equation for the time varying electrostatic potential. Output from the Fluid Kinetics Module (densities and electrostatic fields) is then transferred to the other modules. This process is iterated until a converged solution is obtained. The Plasma Chemistry Monte Carlo Module in the HPEM produces the energy and angular distributions for neutrals and ions striking the wafer surface.

Effect of pulsed-dc bias on ion energy distributions and plasma characteristics

The model tool is an ICP reactor schematically shown in Fig. 1. For the base case, a 10 mTorr Ar/NF_3=80/20 gas mixture was used which served as a surrogate for a Ar/BF_3 gas mixture. The flow rate was 100 sccm, the coil source was powered at 10 MHz and delivered an inductive power of 500 W. The shape and amplitude of the dc bias waveform will be varied at the electrode.

The pulsed-dc bias voltage waveform used in this work is shown in Fig. 2. The investigation was carried out for 250 µs using two pulses of widths 45 µs with a pulse-off time of 70 µs between the pulses. The voltage pulse characteristics (rise-time, pulse width, and fall-time) are very critical in determining plasma characteristics and dosimetry.

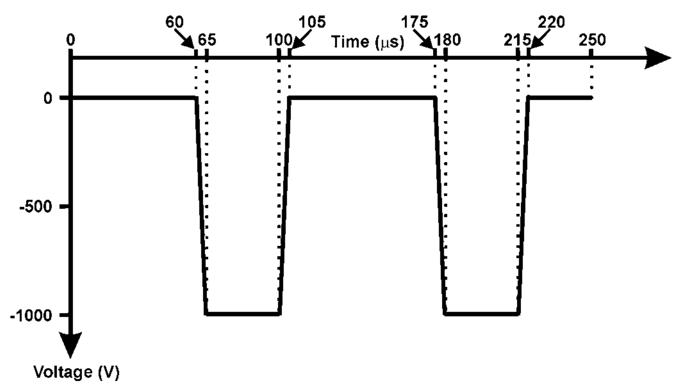

Fig. 2. Quasi-dc voltage pulses used in the investigation of P^2LAD.

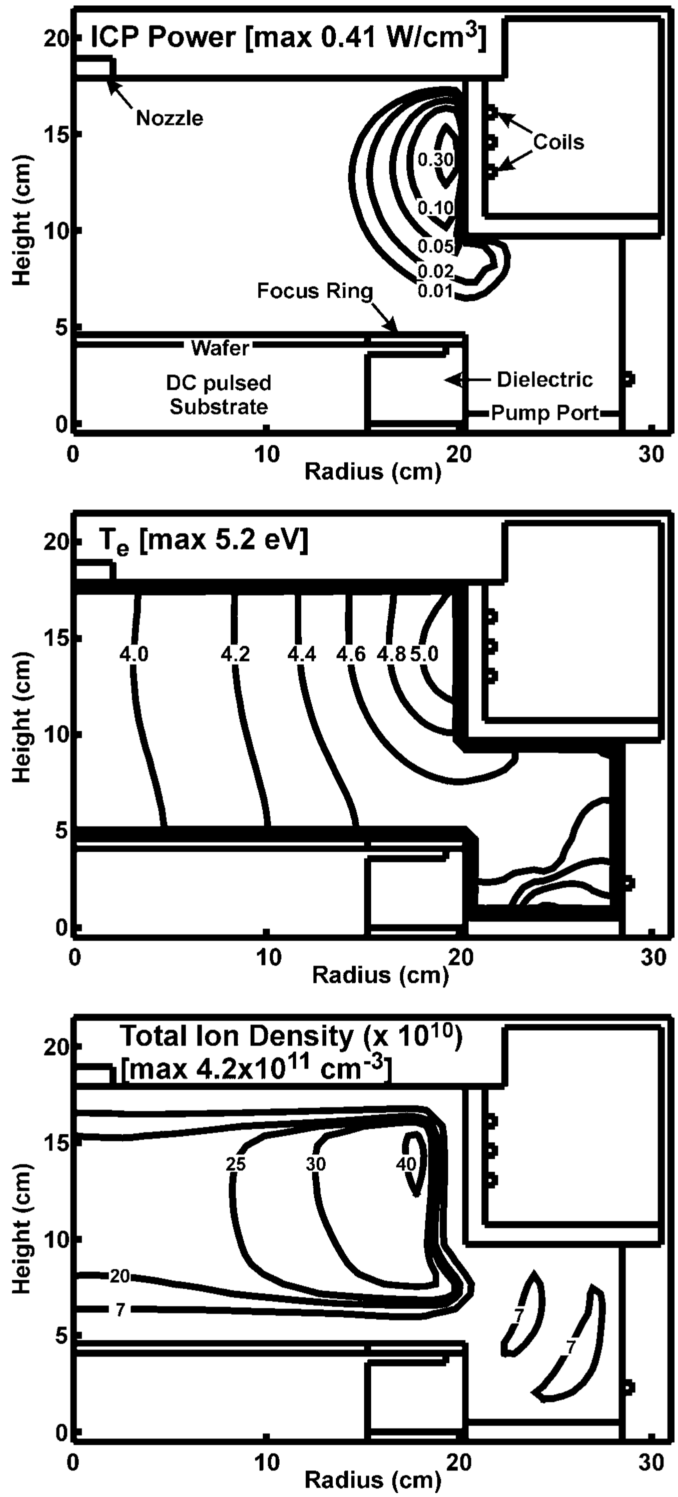

Fig. 1. ICP power, electron temperature and ion density for Ar/NF_3 (10 mTorr, 100 sccm, 500 W) and -1000 V substrate bias voltage

The ICP power, electron temperature and ion density are shown in Fig. 1, corresponding to a pulsed-dc bias voltage of -1000 V. The high thermal conductivity produces a fairly uniform electron temperature in spite of localized power deposition. The ion density maximizes near the peak in power deposition. Note the depletion of ions in the sheath above the wafer and the islands of positive ions in the periphery of the reactor.

Time-averaged IEADs for all ions are shown in Fig. 3, at base case conditions for dc bias voltages of -1000 V to -10,000 V. The peak value of the IEAD is located in energy near the applied dc bias voltage. The ions arriving at the sheath during the pulse-off period form the low energy wide angular spread part of the IEAD. The IEAD narrows as the bias voltage is increased. At high biases, the ions preferentially approach the wafer from the positive angle side with few ions approaching from the negative angle side. This effect is most prominent at higher bias voltages as the sheath thickness increases. The reactor configuration is such that the ion density is not entirely uniform in the reactor with the source of ions being off-axis near the coils. As a result most of the ions approach the wafer on application of the bias from near the coils where the ion density is the highest. This results in the sheath not being parallel to the substrate and providing an angular slant to the IEAD. The increase in bias voltage also increases the overall sheath thickness, thereby increasing the ion transit time. As a result the ions undergo more collisions. The tail of the IEAD is more prominent as the bias voltage is increased.

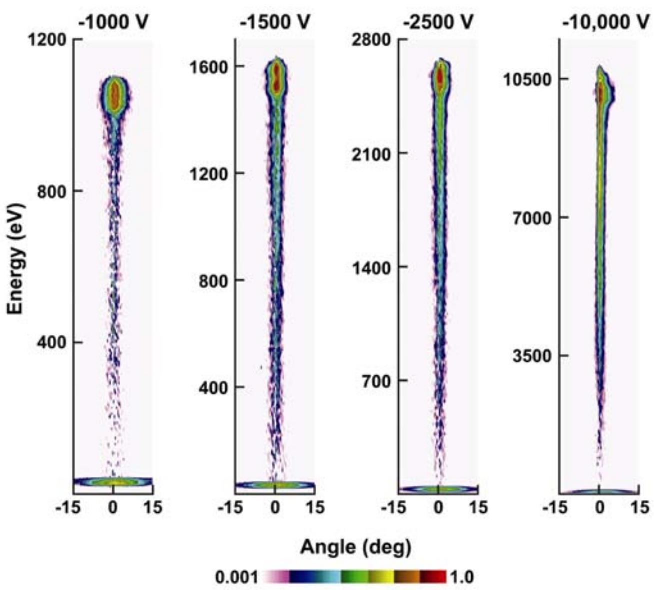

Fig. 3. Total IEADs, averaged over the wafer, for different voltage bias values.

Time-averaged IEADs for all ions are shown in Fig. 4 for a dc bias voltage of -1000 V at different ICP powers of 250 W to 1000 W. The increase in ICP power results in thinning of the sheath. The sheath becomes less collisional and the ion transit time decreases. As a result, the tail of the IEAD is less prominent at higher ICP powers. The maximum ion energy increases with increasing ICP power. This is a result of a higher flux at higher ICP powers coupled with the non-collisional sheath. As a result more ions are accelerated through the sheath to the wafer without loss of energy thus increasing the peak ion energy at higher ICP powers.

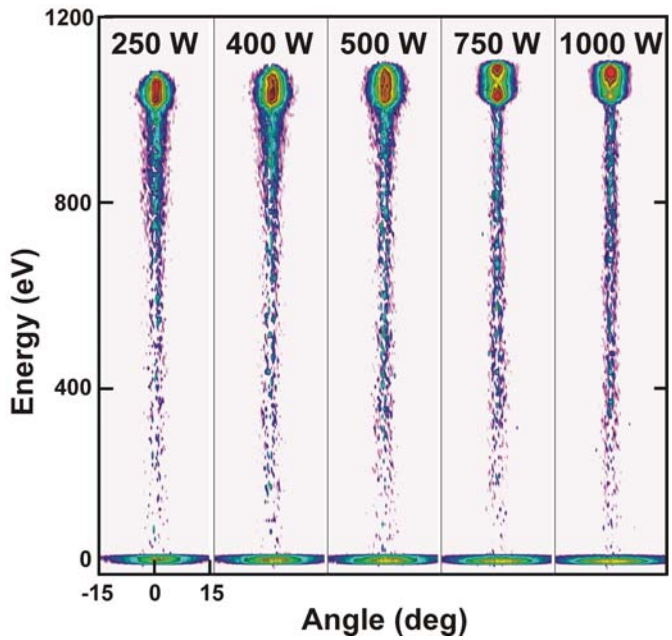

Fig. 4. Total IEADs, averaged over the wafer, for different ICP powers at a substrate voltage of -1000 V. (Log scale plotted over 3 decades)

The electron density for a dc bias of -10,000 V is shown in Fig. 5 for times of 58 µs to 107 µs. The peak electron density is 4.5×10^{10} cm^{-3}. Note the thickening of the sheath as the applied voltage becomes more negative; and the collapse of the sheath as the voltage is removed. The switching on of the negative pulse causes the electrons to move rapidly out of the sheath. At the same time positive ions are slowly accelerated in the opposite direction towards the wafer. This charge separation leads to launching of electrostatic waves which may disrupt the plasma. These electrostatic waves traverse through the entire reactor. As the voltage pulse terminates, electrons quickly repopulate the sheath so as to recover the charge neutrality as the sheath collapses. The launching of electrostatic waves is more significant as the bias becomes more negative. The choice of pulse length is also more important at high voltage biases. The sheath expansion at higher biases extends deeper into the plasma and may not reach a steady state if the pulse is too short. This incomplete sheath development can significantly affect the dosimetry that can be attained in a single voltage pulse.

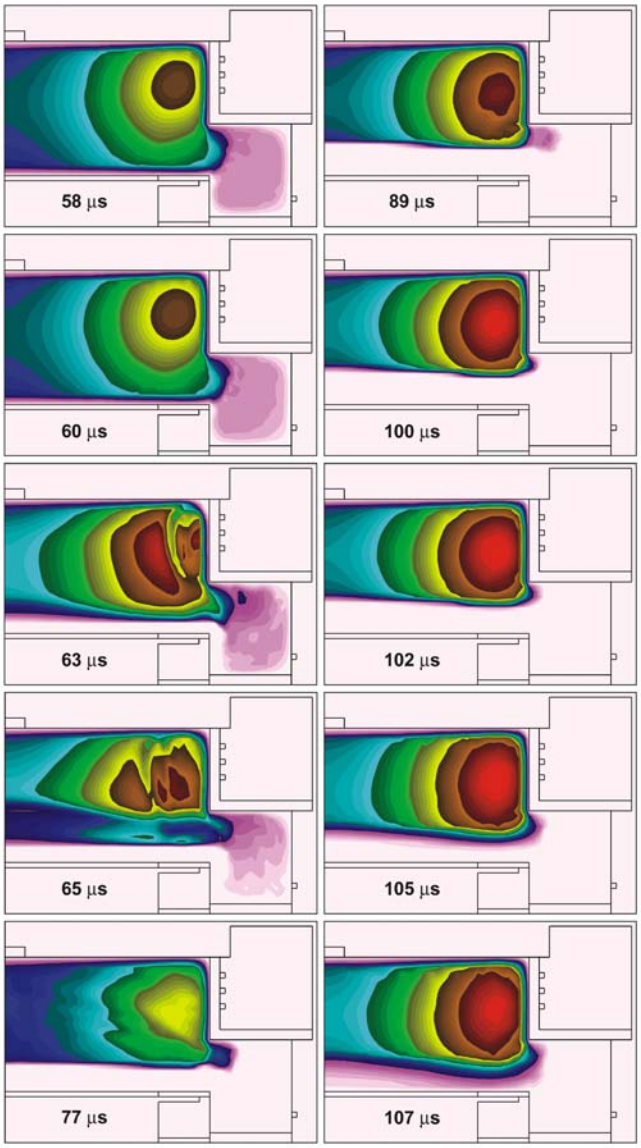

Fig. 5. Electron density for the base case and -10,000 V substrate bias at different times during the pulse, as indicated in each figure. Log scale plotted over 2 decades.

Conclusions

The influence of the pulsed dc voltage waveform on ion energy and angular distributions and plasma characteristics has been discussed based on results from a computational investigation of P^2LAD for low energy ion implantation for the formation of ultra-shallow junctions. The plasma characteristics obtained have led to a deeper insight to the operation of the pulsed plasma doping. Pulsation effects were observed as a result of charge separation leading to launching of electrostatic waves upon applying the bias to the substrate. The electrostatic wave traverses through the bulk reactor, and reflects off boundaries. The IEADs at higher bias voltages produced skewed distributions which are the result of the displaced source of ion production and the reactor geometry.

Acknowledgement

Work was supported by Semiconductor Research Corp., VSEA, Inc., and the National Science Foundation (CTS03-15353).

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