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# Profile control in $BF_3$ plasma doping

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Plasma doping (PD) is an alternative technique to form shallow junctions in deep-submicrometer microelectronic devices. Previous studies have demonstrated that PD produces shallow junctions with better efficiency than those by conventional low energy beam-line doping (BD). In addition, even though cross-sectional transmission electron microscopy reveals that the surface layer is amorphized after high dose $BF_3$ PD or BD implantation, PD samples show less residual defects after rapid thermal annealing. For ultrashallow junctions, doping profiles with a high dopant concentration near the surface are required for the formation of low resistant contacts. In this article, we demonstrate the use of nonideal voltage pulse shape in achieving advantageous doping profiles that are difficult to obtain via BD. By performing particle-in-cell (PIC) simulation, we derive the ion energy distributions for different sample voltage pulse shapes for $BF_3$ PD. Comparison of the PD boron depth profiles simulated by PIC and an assumed Gaussian implant profile to the BD boron depth profiles simulated by TRIM shows a low energy component that does not exist in BD samples. The rise and fall time of the sample voltage pulse contributes to the overall energy distribution since a long rise or fall time increases the low energy component. We postulate that these low energy ions may also change the nature of the amorphized layer and are one of the reasons for the reduction of residual defects after rapid thermal annealing. The preferred sample voltage pulse for plasma doping is suggested to be a short one with a relatively long rise and fall time. This is something that is very difficult to achieve by beam-line ion implantation. [S0021-8979(00)01018-5]

## I. INTRODUCTION

Plasma doping (PD) is projected to be an alternative technique to beam-line doping (BD) in the fabrication of ultrashallow junctions in deep-submicrometer microelectronic devices. PD has been demonstrated to produce junctions as shallow as those by low energy beam-line ion implantation or BD. PD is more efficient and economical than BD as the entire wafer can be implanted simultaneously in PD and PD equipment is simpler.[1,2] It has been shown that microelectronic devices fabricated by PD have higher drive current.[3] In addition, cross-sectional transmission electron microscopy (XTEM) shows that even though high dose $BF_3$ PD or BD renders the silicon surface amorphous and indistinguishable by XTEM, there is less residual damage after rapid thermal annealing in PD devices.[4] It is one of the interesting and beneficial factors favoring PD in ultrashallow junction formation.

PD differs significantly from conventional beam-line implantation in several aspects.[5,6] In beam-line implantation, the ions are accelerated and filtered according to their mass-to-charge ratio. Therefore, with sufficient mass resolution, the output ''beam-line'' ions are unique in mass, charge state, and impact energy. In PD, the target is immersed in a plasma, and a series of negative voltage pulses are applied to the target to conduct implantation. When the target is negatively biased, electrons are repelled away from the sample surface almost instantaneously creating a sheath of heavy positive ions. An electric field is established between the sheath boundary and target surface, and positive ions are accelerated towards the target with the applied voltage provided that the gas pressure is low enough so that collisionless conditions are satisfied (that is, ion mean free path $\gg$ sheath thickness). To maintain the continuous flow of ions, the ion sheath expands until the end of the negative pulse or an equilibrium is reached. It should also be noted that the ion impact angle and implant dose uniformity depend on the shape of the target and to some extent the sample holder.[7,8]

There are several ways to alter the impact energy of the ions in PD. The plasma is usually composed of ion species with different masses and charge states. The higher the charge state, the bigger the impact energy. In most plasma conditions, there is one dominant ion species, for example, $BF_2^+$ in a $BF_3$ plasma. There is also a short period of rise and fall time at the beginning and end of each negative voltage pulse. During these periods, ions do not receive the full acceleration. As a result, the ion impact energy distribution and depth profile of a PD sample is intrinsically different from that of a conventional BD sample.

In this work, a one-dimensional particle-in-cell (PIC) model[9–11] is used to simulate $BF_3$ PD into a silicon wafer under different pulsing conditions. We compare the depth profiles of PD ($BF_3$ plasma consisting of 70% $BF_2^+$, 10%

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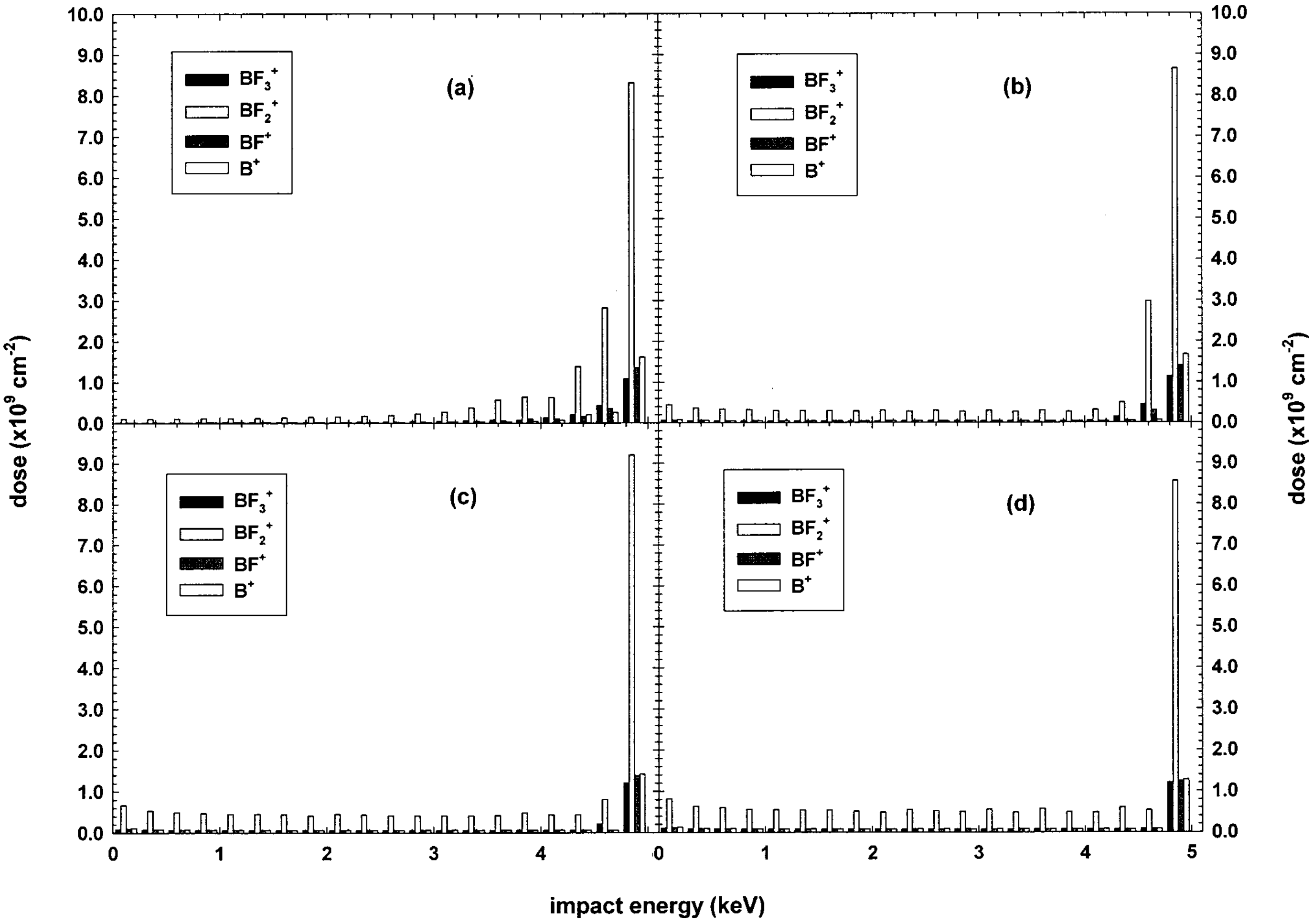

FIG. 1. Histograms of the simulated energy distribution of the implanted ions using (a) zero, (b) 1 μs, (c) 3 μs, and (d) 5 μs rise and fall time. The steady-state (constant voltage) period of the pulse is 10 μs.

$BF_3^+$, 10% $BF^+$, and 10% of $B^+$) with those of BD simulated by the TRIM code (100% $BF_2^+$).[12] It is observed that the implant peak is shallower in PD at the same implantation energy even for the zero rise and fall time case primarily due to the presence of multiple species in a $BF_3$ plasma. For finite rise and fall time, there exists a large surface peak not present in BD samples. These low energy ions favor the formation of good ohmic contacts and are the biggest discernable difference between PD and BD. In spite of their low energy, these ions can also cause subtle differences in the nature of the surface layer and are speculated to be the primary reason for the reduced residual damage after rapid thermal annealing reported by Takase *et al.*[4]

## II. MODELING

In our simulation, the wave form of each voltage pulse is divided into three intervals: rise time, steady-state or constant voltage period, and fall time. For simplicity, the steady-state period is set as 10 μs. Rise and fall times of 0, 1, 3, and 5 μs are used in the simulation giving the final pulse duration of 10, 12, 16, and 20 μs. Based on mass spectrometric measurement of the $BF_3$ plasma in our instrument, we set the plasma composition to be 70% $BF_2^+$, 10% $BF_3^+$, 10% $BF^+$, and 10% of $B^+$ in our model. The plasma density is 5.0 $\times 10^9$ cm$^{-3}$, i.e., $3.5\times 10^9$ cm$^{-3}$ $BF_2^+$, $5.0\times 10^8$ cm$^{-3}$ $BF_3^+$, $5.0\times 10^8$ cm$^{-3}$ $BF^+$, and $5.0\times 10^8$ cm$^{-3}$ $B^+$. The "collisionless" conditions are fulfilled due to the low working gas pressure. To accentuate the effects of the rise and fall time, we choose a sample voltage of $-5$ kV. The potential $\phi$ is related to the four ion densities, $n_{BF_3}$, $n_{BF_2}$, $n_{BF}$, $n_B$, and electron density, $n_e$, by Poisson's equation

$$\nabla^2\phi = -\frac{(n_{BF_3}+n_{BF_2}+n_{BF}+n_B-n_e)}{\epsilon_0}, \tag{1}$$

where $\epsilon_0$ is the dielectric constant. The electron temperature $T_e$ is 2 eV, and $n_e$ is given by Boltzmann's function

$$n_e = n_0 \exp\left(\frac{q\phi}{T_e}\right), \tag{2}$$

where $q$ is the elemental charge. The potential $\phi$ is solved by Eq. (1) and finite difference. The acceleration $a$ initial velocity $v_i$ final velocity $v_f$ and displacement $x$ of each ion species within a time step, $\Delta t$, are derived by Newton's equations

$$v_f = v_i + a\Delta t, \tag{3a}$$

$$x = v_i\Delta t + \tfrac{1}{2}a(\Delta t)^2. \tag{3b}$$

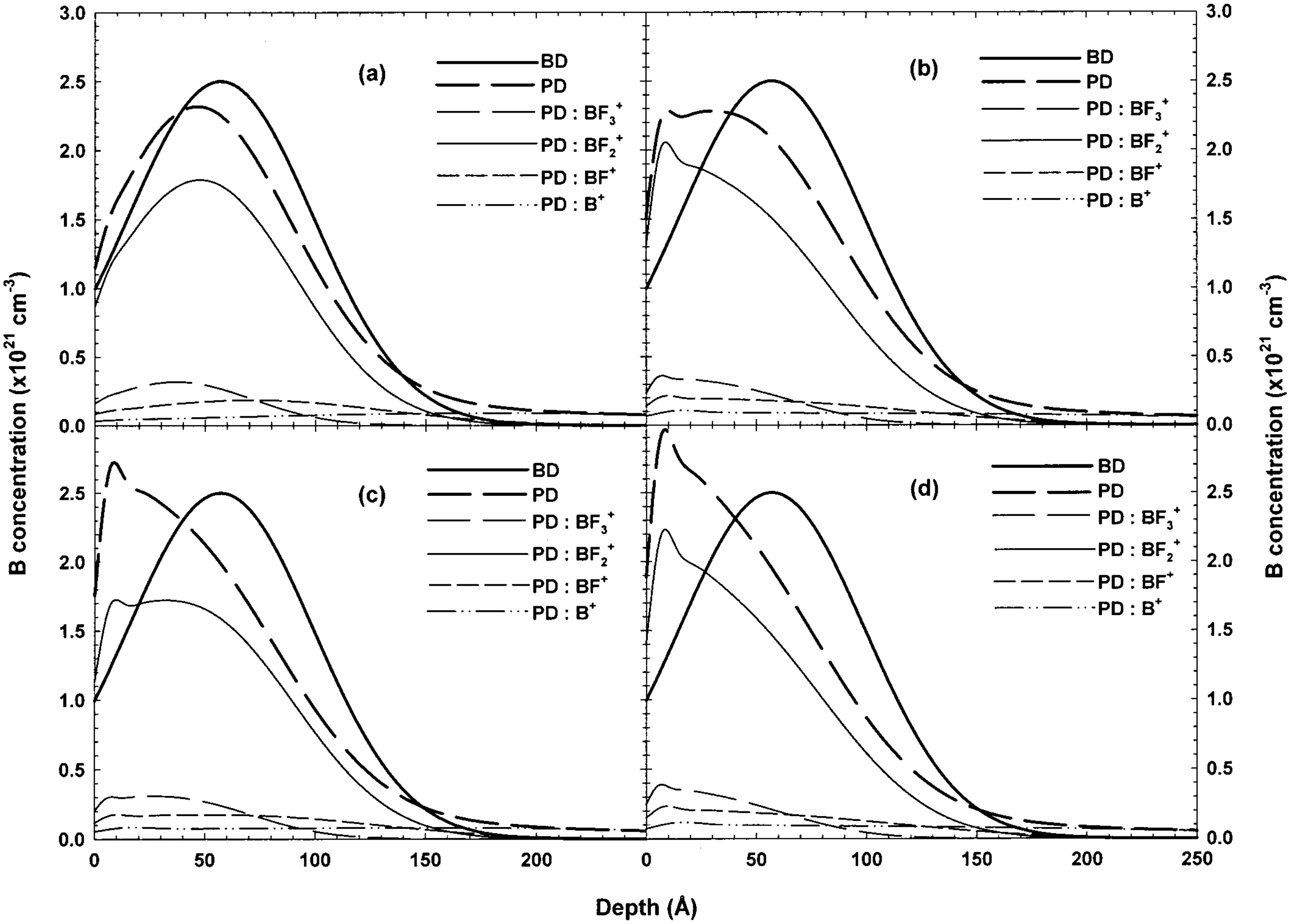

FIG. 2. Simulated depth profiles of implanted boron for different pulse durations: (a) zero, (b) 1 $\mu$s, (c) 3 $\mu$s, and (d) 5 $\mu$s rise and fall time. The steady-state (constant voltage) period of the pulse is 10 $\mu$s. The B profile in beam-line $BF_2^+$ implant is shown for comparison.

A total of 240 000 particles and 60 000 for each species, are used in the simulation. Each particle represents 583 333 $cm^{-2}$ density for $BF_2^+$, 83 333 $cm^{-2}$ density for $BF_3^+$, 83 333 $cm^{-2}$ density for $BF^+$, 83 333 $cm^{-2}$ density for $B^+$. The grid spacing is $5\times10^{-2}$ cm and the time step is $1.4\times10^{-4}$ $\mu$s.

## III. RESULTS AND DISCUSSION

Figure 1 displays the histogram of the simulated energy distribution of the implanted ions. The relative concentration of low energy ions (below 2.5 keV) is 7.4% for a zero rise and fall time pulse. These ions are initially quite close to the surface of the silicon wafer and do not receive the full acceleration during rapid sheath expansion. The contribution of low energy ions is higher for a longer pulse width and they are implanted mainly during the rise and fall time of the negative pulse. The relative proportion of this low energy component rises to 18.7% for 1 $\mu$s, 26.5% for 3 $\mu$s, and 30.5% for 5 $\mu$s rise and fall time pulses. For a longer rise and fall time, the ratio of the combined duration of the rise and fall time to that of the total pulse is larger, and the proportion of these low energy ions is thus bigger.

The simulated boron depth profiles for pulse widths of 10, 12, 16, and 20 $\mu$s are depicted in Fig. 2. Each depth profile is calculated by summing the weighted contributions at different energies and ions according to Fig. 1. The net impact energy of B is 11/49 of the sample bias for $BF_2^+$ ions. We use a Gaussian distribution

$$N(x)=\sum N_i(x)=\sum \frac{d_i}{\sqrt{2\pi}\Delta R_p}\exp\left[\frac{-(x-R_p)^2}{2\Delta R_p^2}\right], \quad (4)$$

where $N_i(x)$, $d_i$, $R_p$, and $\Delta R_p$ are the concentration, dose, projected range, and standard deviation, respectively, for each implant energy and ion. The TRIM code is employed to obtain the projected range $R_p$ and standard deviation $\Delta R_p$ at each implant energy.

The B depth profiles generated for the zero rise and fall time PD case are displayed in Fig. 2(a). Compared to BD, the PD profiles are shallower and more skewed towards the surface. In reality, no power modulator is perfect and the rise and fall time of the voltage pulse is always nonzero. As the rise and fall time increases, the depth profile dramatically changes from a near-Gaussian distribution to a broad distribution skewed towards the surface and a sharp surface peak also results as shown in Figs. 2(b)–2(d). The surface peak becomes sharper and more prominent at a longer rise and fall time since this extremely low energy ion component (below

1 keV) increases from 2.4% at zero rise and fall time to 8.5% at 1 $\mu$s, 12.0% at 3 $\mu$s, and 13.8% at 5 $\mu$s.

As shown in our simulation results, an almost flat-top dopant profile with a surface spike can be achieved by tailoring the voltage pulse shape, and one can obtain doping profiles that are extremely difficult via BD. The existence of such a surface peak which has been shown experimentally[1,4,13] may be advantageous to the formation of low resistance contacts for ultrashallow junctions.

## IV. CONCLUSION

Based on our results, the biggest discernable difference between PD and BD is the low energy component. It is speculated to be the primary reason why PD samples show less residual defects after rapid thermal annealing. Even though XTEM discloses that the surface layers in both high dose $BF_3$ BD and PD samples have been amorphized,[4] the concentration of these low energy ions is quite large in PD with finite rise and fall time. Their presence in the surface layer and the extra surface damage created facilitate more effective regrowth during subsequent rapid thermal annealing. A longer rise and fall time increases this surface component and may be preferred in the formation of shallow junctions. As a short voltage pulse alleviates sample charging on patterned wafers,[13] we propose that for plasma doping, the optimal voltage pulse should have a short duration with relatively long rise and fall time. This is not something easily attainable by conventional beam-line ion implantation.

## ACKNOWLEDGMENTS

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