The Effect of Fluorine on Boron Diffusion

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Abstract – The role of fluorine in a BF_2 implant has been investigated by implanting BF_2, B alone and different combinations of B and F at equivalent implant energies. Each combination was designed to test for something, such as the effect of fluorine after B was implanted or the F damage before B was implanted. The wafers from each group received a spike anneal at 1075°C. The resulting boron profiles after implant and after spike anneal were obtained by SIMS analysis. Sheet resistance was measured and compared with the values calculated from the profiles. The junctions with boron implant had the smallest sheet resistance whereas those obtained with boron implant following F implant had the largest sheet resistance. The SIMS profiles supported these results. The profiles do suggest that the presence of fluorine reduced the transient enhanced diffusion of boron.

1.INTRODUCTION

MOS devices are shrinking in lateral dimensions, leading to the need for ultra-shallow source/drain junctions. These depths are projected to be less than 500Å for 0.18μm and beyond technology nodes. The technology to produce these ultra-shallow junctions with low sheet resistance has yet to be fully developed. The implant techniques used currently need to be modified to get junction depths that shallow. These modifications include low energy implants, pre-amorphization of the substrate to minimize channeling, dopant activation by spike anneals or at low temperatures and/or minimize transient enhanced diffusion (TED). Transient enhanced diffusion is due to excess interstitials caused by the implant damage. At the end-of-range, where the damage from the implant meets the crystalline structure, the interstitials occur and may cause the TED of dopants further into the substrate increasing the junction depth. This is particularly a concern for boron.

To minimize this effect, BF_2 is commonly used to introduce boron into silicon. The main advantages in using BF_2 include reduction in channeling due to amorphization of the surface, being heavier than B so it doesn't travel as deep into the substrate and low temperature dopant activation by SPE (solid phase epitaxy) also due to amorphization. Another benefit of using BF_2 is that the beam current is higher in BF_3 gaseous source, therefore shorter implant time are made possible for heavy doses..

A cited paper shows a BF_2 ion implantation (compared to a B implant) produced a higher sheet resistance due to shallow junction depths [8]. This seems to be a common theme in other related papers. Many try to propose explanations to this phenomenon including the following. One found that the diffusion and interstitial population was consistently lower in the BF_2 implant compared to the B implant. This was attributed to residual F, increased stability of end-of-range defects, and the effect of amorphization on B clustering reactions. [4]. Another paper attributed it to lower energy. It claimed that it was one of the benefits of lowering the energy because of mobility reduction, retained dose and the fluorine depletion from the substrate. [2]. Some cited authors propose that the reduction in diffusion is due to a smaller concentration of interstitials. Although there has been much research and many proposed theories, there has been no final answer as to why fluorine retards boron diffusion.

2. EXPERIMENTAL DESIGN

The implants were done using 8-inch, n-type wafers with a resistivity of ~ 1 ohm cm. All the implants were done at Texas Instruments, using the LEAP in drift mode (no deceleration). The wafers were implanted for a total of six different splits. The first split was a BF_2 implant at a dose of 5E14 cm^{-2} at an energy of 10keV. This was the implant that was to be studied. The second split was a B implant at a dose of 5E14 cm^{-2} at an energy of 2.2keV. This was the equivalent energy for B [(11/49) of BF_2 energy]. The third split was F implanted at a dose of 1E15 cm^{-2} at an energy of 3.9keV and then B implanted second at a dose of 5E14cm^{-2} at an energy of 2.2keV (ratio of 2:1). This was done so the F could pre-amorphize the substrate before being implanted with B. The fourth split was implanted with F at a dose of 5E14 cm^{-2} at an energy of 3.9keV and then was implanted with B at an energy of 2.2kev and a dose of 5E14 cm^{-2} (a ratio of 1:1). This was done to study the extent of damage

fluorine causes to the substrate and how it effects the junction. The fifth split was implanted with B at a dose of 5E14 cm^{-2} at an energy of 2.2keV and then implanted with F at a dose of 1E15 cm^{-2} at an energy of 3.9keV (a ratio of 1:2). This was done to study the effect of F on Bboron diffusion. The sixth and final group was implanted with F only at an energy of 3.9keV at two different doses (5E14cm^{-2} and 1E15 cm^{-2}). This was done to study just the damage caused by F in silicon.

There were three wafers in each group except for the last one listed (this split only had two). After the implants, one wafer from each of the first five groups received a spike anneal at 1075°C (done using a laser pulsed for almost zero time). Table 1 shows the detailed experimental design for each wafer.

Table 1: A description of each wafer implantation

Wafer #	Dose (cm^{-2})	Energy (keV)	Species	Spike Anneal @ 1075°C
1	5E14	10	BF2	no
2	5E14	10	BF2	no
3	5E14	10	BF2	yes
4	1E15	3.9	F	no
5	1E15	3.9	F	no
	5E14	2.2	B	no
6	1E15	3.9	F	no
	5E14	2.2	B	no
7	1E15	3.9	F	yes
	5E14	2.2	B	yes
8	5E14	3.9	F	no
9	5E14	3.9	F	no
	5E14	2.2	B	no
10	5E14	3.9	F	no
	5E14	2.2	B	no
11	5E14	3.9	F	yes
	5E14	2.2	B	yes
12	5E14	2.2	B	no
13	5E14	2.2	B	no
14	5E14	2.2	B	yes
15	5E14	2.2	B	no
	1E15	3.9	F	no
16	5E14	2.2	B	no
	1E15	3.9	F	no
17	5E14	2.2	B	yes
	1E15	3.9	F	yes

The sheet resistance was measured using four point probe for each group following the spike anneal and SIMS analyses were performed for both as-implanted and annealed samples at Charles Evans & Associates.

3. RESULTS

A. TRIM Simulations

Figures 1 and 2 show the simulated profiles for F (3.9keV) and B (2.2kev) respectively. Each shows a projected range of around 110Å, which is an underestimate. This is because TRIM does not take into account secondary effects such as channeling backscattering, or dynamic annealing.

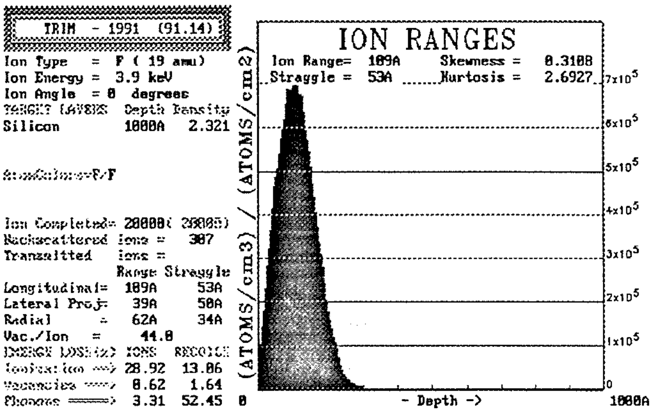

Figure 1: TRIM Simulation of F at an energy of 3.9keV

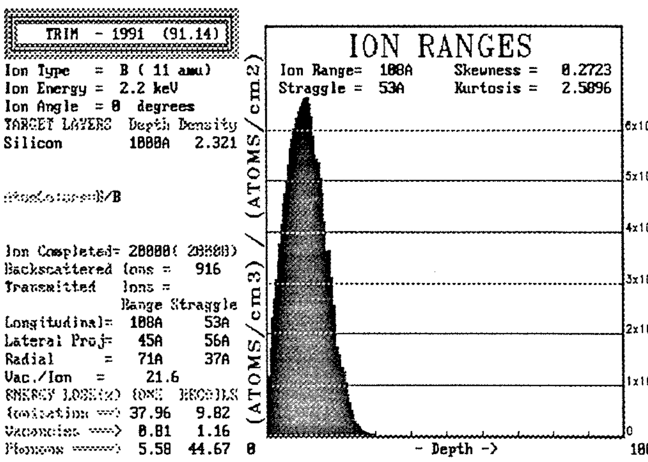

Figure 2: TRIM Simulation of B at an energy of 2.2keV

B. Sheet Resistance

The measured sheet resistance for the different combinations is given in Table II.

Table II – The calculated and measured sheet resistance (plus standard deviation) for the different implant splits.

Species	**R_s-meas. (Ω/sq)**	**S.D.– meas. (%)**	**R_s-calc. (Ω/sq)**
BF_2	390	1.0	376.2
2F + B	417	0.9	394.1
F + B	380	1.3	363.1
B	363	2.3	328.3
B + 2F	389	1.7	328.0

B. SIMS Results

The SIMS plots for different samples are shown in Figures 3-6. Figure 3 shows the boron profile after the spike anneal for BF2 implant. The comparison between BF_2 and B implant shows that the B implant travels much further into the substrate (Figure 4). The B + 2F implant vs. 2F + B implant shows that the B + 2F implant travels deeper into the substrate. This is shown in Figures 5 and 6, the latter having a shallower slope.

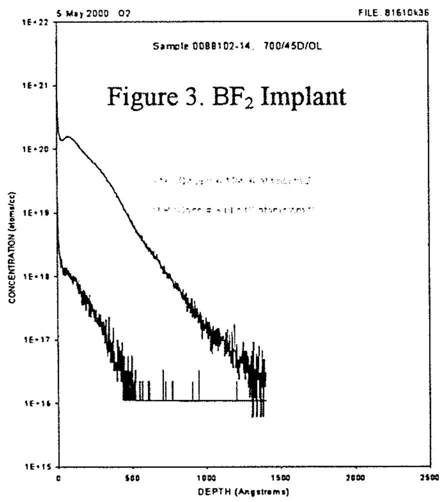

Figure 3. BF_2 Implant

Figure 3.-6. SIMS plot showing boron profiles for various implant conditions following spike anneal at 1075 C.

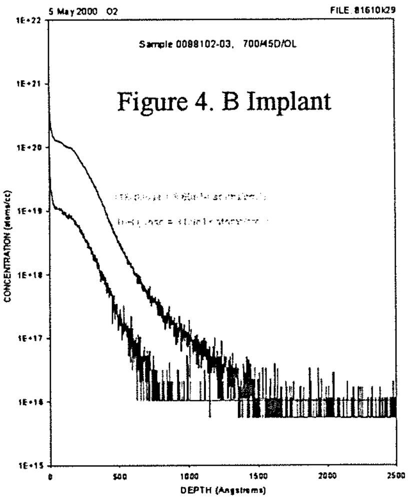

Figure 4. B Implant

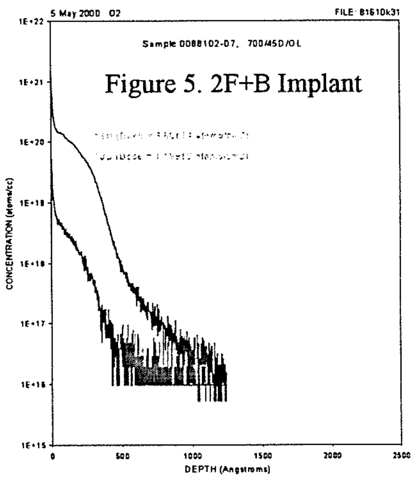

Figure 5. 2F+B Implant

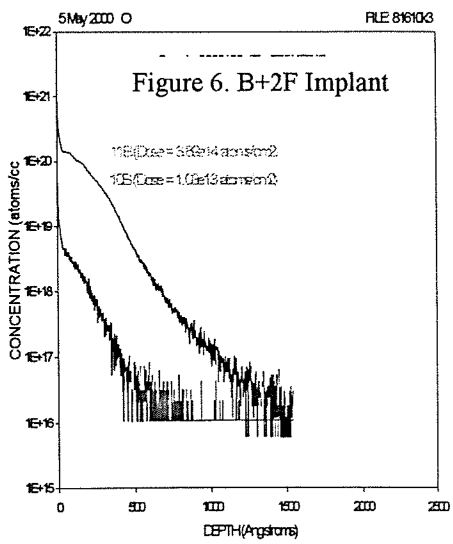

Figure 6. B+2F Implant

4. DISCUSSION

The Sheet resistance was calculated from the boron profiles using the relation

$$R_s = \frac{1}{q\int_0^{x_j} C_B(x)\mu_p(x)dx} \qquad (1)$$

where the x position is taken from the SIMS results at every other Angstrom, starting at 2A into the substrate. The doping at each of these x positions, $C_A(x)$ is also obtained from the SIMS analysis. The mobility is calculated using the doping value (at each x value) from the following equation

$$\mu_p = 54.3 + \frac{407}{1 + 3.745E-18 * C_B(x)} \qquad (2)$$

The integral in the sheet resistance calculation goes until the junction depth is reached. This depth is taken when the doping dropped down to 1E16 cm^{-3}. These calculated values are listed in Table II. The calculated sheet resistance is a little lower than the measured sheet resistance for a few possible explanations. There could be inactive dopant in the junction, which differs because the calculation assumes that all the boron in the profile is electrically active. Other reasons could be that the depletion region is not taken into account or that the mobility model assumed may not by accurate.

The table shows that the boron implant gives the smallest sheet resistance (363 Ω/sq). This is because channeling and transient enhanced diffusion causes deeper boron penetration. The highest sheet resistance (417 Ω/sq.) was measured for the 2F + B implant. This is due to the pre-amorphization caused by the fluorine, which prevents channeling and produces shallower junctions. The F + B implant gives a sheet resistance value in between the BF_2 implant and the B implant (380 Ω/sq.). This shows that the fluorine does help reduce the the TED of boron and that the more implanted (up until a certain limit), the more reduction seen in TED and junction depth. The B + 2F implant shows a similar sheet resistance value as the BF_2 implant. This shows that the fluorine has a chemical influence on the boron diffusion. This finding was also reported in another cited paper [3]. This showed that fluorine effect on TED was independent of the effects of the implant and any pre-amorphization (reduction of channeling) that may occur. Another experiment showed that fluorine accumulated near the surface and end-of-range defects. The paper tried to explain the retardation of boron diffusion by saying that the interactions of F with the defects reduced the number of interstitials in the substrate. [6]

Another study tried to determine whether the influence of fluorine was chemical or damage related. To eliminate the damage factor, the substrate was pre-amorphized before the implant to see if fluorine still played a role in the boron diffusion. A chemical effect was determined to occur. Some possible explanations given in this paper were (1) F may bind with Si interstitials chemically and reduce B diffusing using them, (2) F may bind with B at low temperatures, preventing boron to form a mobile pair with an interstitial and (3) F may enhance interstitial recombination reducing the number of interstitials in the substrate for the boron to diffuse through. [7]. These are just a few of the many possible explanations found in the cited works of how fluorine effects the diffusion of the boron (chemically).

5. CONCLUSION

The effect of fluorine on boron diffusion has been studied. From the results, B gave the smallest sheet resistance. This is because channeling and TED caused deeper boron penetration. The combination of 2F + B gave the largest sheet resistance. This is due to the fluorine causing pre-amorphization, which prevents channeling, therefore producing a shallower junction. The group 1F + B gives smaller sheet resistance than BF_2 but larger than B alone. This shows that fluorine does help in reducing TED and the more implanted (up until a certain limit) the more reduction seen in TED and junction depth. The final observation is that the sheet resistance for B + 2F is similar to BF2. This shows that the fluorine has a chemical effect on boron diffusion because the damage part of fluorine does not come into play.

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