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Very shallow boron junctions in Si by implantation and SOD diffusion obtained by RTP

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Abstract

Because of their very large integration capabilities and continuous scaling, the CMOS devices are the basic element in the current-integrated circuits. Their scaling up to sub-micrometric scale presents advantages like diminution of power consumption, faster devices and a larger level of integration. But the physics limitations begin to be important at these dimensions, anomalous effects like hot electrons, leakage currents and punch through, among others, appear. These effects can be reduced if, at the source/drain region, shallow junctions are obtained with junction depth (x_j) less than 200 nm. To achieve this goal, new junction fabrication methods, which include pre-amorphization [S.D. Kim, C.M. Park, J.C.S. Woo, Formation and control of box-shaped ultra-shallow junction using laser annealing and pre-amorphization implantation, Solid State Electron. 49 (2005) 131–135] are required. Other alternative techniques that do not require ion implantation [T. Uchino, P. Ashburn, Y. Kiyota, T. Shiba, A CMOS-compatible rapid vapor-phase doping process for CMOS scaling, IEEE Trans. Electron Devices 51(1) (2004) 14–19.], in order to prevent surface crystal damage and as a consequence the inhibition of boron interstitial clusters and {3 1 1} defects [R.T. Crosby, K.S. Jones, M.E. Law, L. Radic, Dislocation loops in silicon–germanium alloys: the source of interstitials, Appl. Phys. Lett. 87 (192111) (2005) 1–3.], which are the trigger of the "transient enhanced diffusion" (TED) process are used. In this essay, it is shown that rapid thermal process, allow the fabrication of very shallow junctions with a x_j less than 300 nm by using with high energies and high doses of boron/BF_2 ions implantation. By this way the slow dissolution of the dislocation loops, present at the end of range (EOR) of the implanted boron, allow this process. These obtained junctions are compared with those prepared by using the spin on doping (SOD) technique. The diffusion profiles obtained by both processes and their electrical properties are measured and compared for their application as S–D regions in a current CMOS process.

Keywords: Shallow junctions; Boron implants; BF_2 implants; Boron SOD; High boron concentration

1. Introduction

Since the conception and, later, the implementation of the field effect transistor (FET) in Si/SiO_2 in 1960 by Kahng and Attala, the Si metal oxide semiconductor FET (MOS-FET) was incorporated into integrated circuits in the early 1970s, and progress since then has followed an exponential behavior that comes to be known as Moore's Law. Device dimensions have been steadily shrinking at a rate of $\sim 2x/6$ years, and circuit complexity and industry revenues have been similarly growing exponentially [1].

In the general scaling of the MOS-FET, a factor which yield smaller device is made following the principles of electrostatics. If dimensions, doping and voltages are all scaled, the electric field configuration in the scaled device will be the same as it was in the larger device. These constant electric filed scaling relationships use a factor α which turns out that the doping concentration should be multiplied by this factor and the junction depth (x_j) of the source and drain regions of the MOS-FET should decrease, by the same α factor. Therefore, there is a great interest in the development of techniques which allow the fabrication of very shallow x_j with the highest active impurity concentration.

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In order to get very shallow junctions, different approaches have been used, among them ion implantation (II) on a pre-amorphized surface in addition to rapid thermal annealing activation of the implanted impurities [2], very low energies of implantation [3], and the use of heavier implanted impurities like BF_2 [4]. However, processes like the transient enhanced diffusion (TED) [5] does not allow the implementation of very shallow diffusions as is required by the scaling of the TMOS. The problem is magnified for the case of boron because it is an impurity, which has a very high diffusion coefficient in silicon.

Ion implantation is a process which guarantees a doping free of contaminants, good control on the required dose and peak concentration. However, the implanted region should be subjected to a thermal treatment because of the damage induced during the implantation process. Among the produced damage it can be mentioned the generation of vacancies as type V defects, interstitials (type I defects), dislocation loops or end of range (EOR) defects (type II defects), among others, and all of them have a contribution to the effect known as TED [6–8]. TED is short-duration effect that appears during the activation of the implanted impurities, and this effect is responsible for the great difficulty in achieving very short junction depths of B in Si. When the implantation is performed at high doses and energies exceeding the threshold damage densities (TDD), the crystalline silicon region implanted becomes amorphous from the surface up to the EOR region [9]. For boron and BF_2, these TDD are 1.6×10^{15} and $4.2 \times 10^{13}\,\mathrm{cm}^{-2}$ for 100 and 120 keV implant energy, respectively. Therefore, a thermal treatment at temperatures above 1000 °C is required to restore the crystalline structure of the substrate [10], which will result in a deeper diffusion.

Spin on dopant (SOD) is an alternative for introducing impurities to semiconductor materials, which shows low cost and allows its use as a solid source in the rapid thermal diffusion process. However, because it is a mixture of SiO_2 and an oxide of the dopant, when it is applied to the surface of the substrate stresses on the order of 200 MPa appear [11]. The resultant stress from the spun dopant may increase the diffusion coefficient, and as a result again, a deeper well of the impurity is obtained. A layer of SiO_2 thermally grown on the silicon surface may be used to alleviate the resultant stress from the application of the SOD. The uniformity of the spun film depends on both the viscosity of the mixture and spin speed, spinning at high velocities improves the uniformity of the spun dopant film [12]. SOD may be considered as an infinite source for diffusion; therefore, in contrast to the profiles obtained from the ion implanted process, the surface of silicon will have the maximum concentration of impurities, and the diffusion process may be performed at temperatures lower than 1000 °C, because there is no need to remove the damage produced by the implantation process, Therefore, a shallower junction may be expected from this process.

In this work, the use of ion implantation of B and BF_2 ions on Si at high energies and doses, and B-SOD are used in the formation of shallow junctions. RTA is used for both the activation of ion implantation and diffusion from the SOD. The results are compared in terms of the diffusion profiles obtained and the resultant resistivities of the diffused regions.

2. Experimental

Silicon CZ wafers of 2 in diameter with (1 0 0) orientation and resistivities of 5–10 ohm-cm were used in this work. A 16 nm of SiO_2 was thermally grown on the surface of the wafers before ion implanting and SOD spin, for protection of the Si surface during the II process and for decreasing the surface stress in the substrate because of the spun SOD film. The II process was performed at an angle of 7° with respect to the surface, dose and energy of B implantation were $5 \times 10^{15}\,\mathrm{cm}^{-2}$ and 60 keV, respectively. For the case of the BF_2 ions, the dose used was the same, but the II energy was changed to 100 keV in order to get the same projected range as that of the B. SOD used is the polyboron B155 of Filmtronics, spun at 4000 rpm for 20 s. The activation/diffusion process was performed in a RTP system in N_2 environment at temperatures of 780, 860, 940 and 1050 °C for 20 s at a ramp of 50 °C/s for all the samples. Resistivity measurements were performed by the conventional 4-point probe system and the impurity profile was measured with an electrochemical profiler CVP21.

3. Results and discussion

The measured profiles on all the samples show the high concentration effect, that is, the profiles do not follow a Gaussian or an error function. This is because the RTP is an out of equilibrium process. However, the main differences observed on the samples are the estimated value of the diffusion coefficient and, as a consequence, the different values obtained in the x_j.

3.1. BF_2 implanted samples

Fig. 1 shows the measured profiles of the samples implanted with BF_2. It can be seen x_j is in the range 60–260 nm, as the anneal temperature increases. The maximum active impurity concentration measured is $9 \times 10^{19}\,\mathrm{cm}^{-3}$ with the peak concentration placed at a depth of 90 nm. Also, it can be seen that the surface of the Si may have a surface concentration as low as $10^{18}\,\mathrm{cm}^{-3}$, which will inhibit the implementation of low resistance metal contacts to this diffusion. The measured resistivity showed a decrease with the annealing temperature ranging from 94 to 68 Ω/square for the range of temperatures 780–1050 °C.

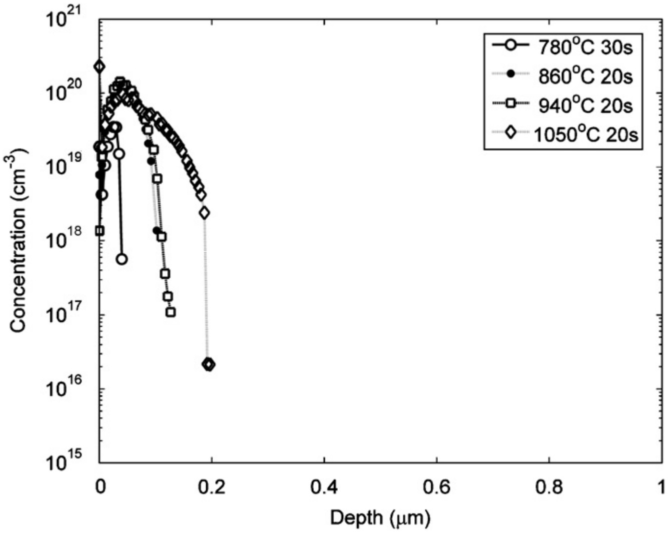

Fig. 1. Ions of BF_2 show the smaller diffusion coefficient and a bad degree of activation.

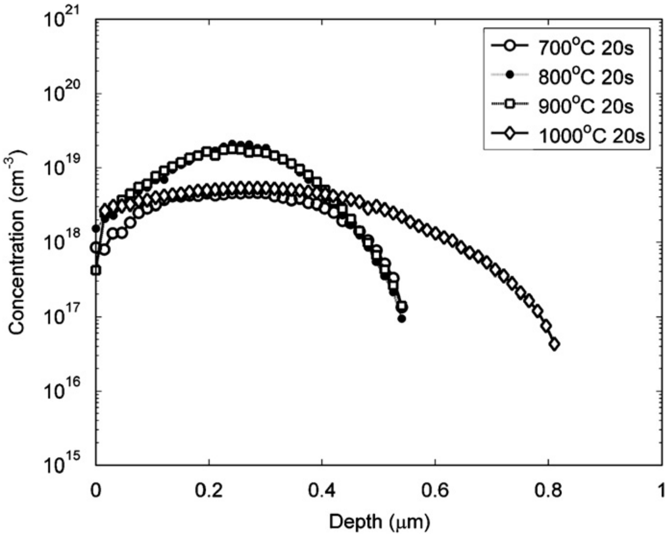

Fig. 2. Ions of B have a high degree of activation and diffusion coefficients of $10^{-12}\,cm^2\,s^{-1}$.

3.2. B implanted samples

The measured impurity profiles show, for the range of activation temperatures an x_j which goes from 600 to 900 nm, with concentration peaks of the order of $10^{19}\,cm^{-3}$. The measured R_s resulted higher than that of the implanted BF_2 samples, and of the order of 80 Ω/square. In spite of the higher implantation energy and because the reduced mass of the B ion, the concentration peak appears at 200 nm depth, which is the mainly responsible for the lower surface dopant concentration observed in the impurity profiles. Fig. 2 shows the measured impurity profiles for the B implanted samples.

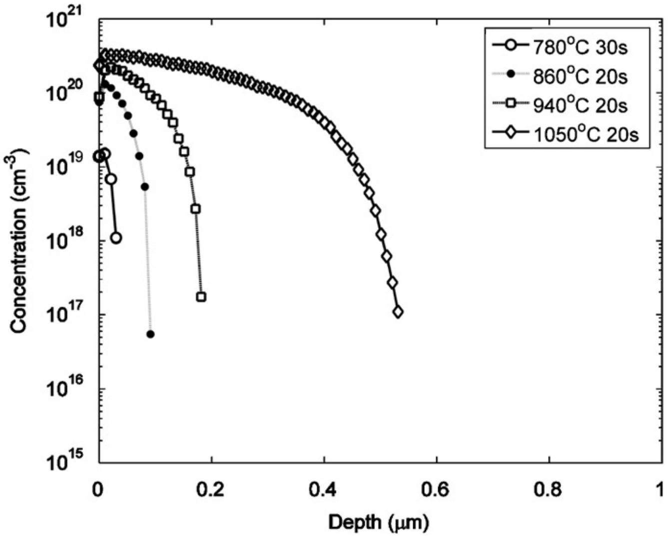

Fig. 3. Boron SOD shows a good activation and profiles of maximum surface concentration at $10^{20}\,cm^{-3}$.

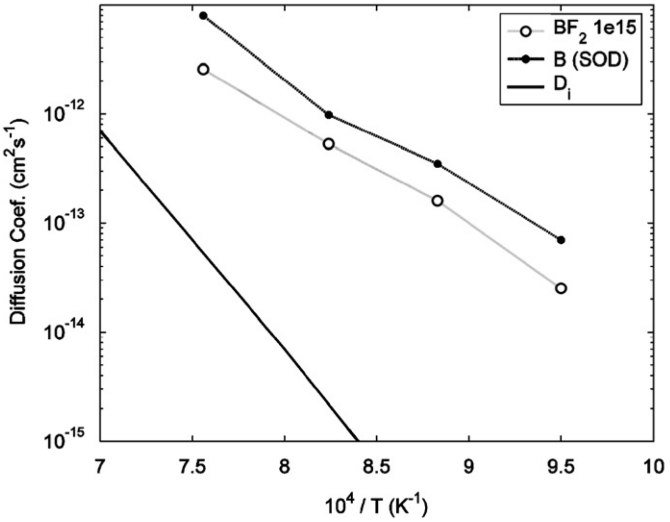

Fig. 4. Calculated boron diffusion coefficients for SOD and BF_2 as compared with the boron D_i.

3.3. SOD samples

Fig. 3 shows the obtained profiles from the SOD samples. It can be seen that the peak concentration is at the Si surface, which is expected form these samples. The surface concentration is of the order of $10^{20}\,cm^{-3}$, which is the highest value that resulted form this work. The R_s value ranges from 50 Ω/square for an activation temperature of 940 °C to a 14 Ω/square for the 1050 °C temperature anneal. The obtained x_j ranges from 30 up to 605 nm for the mentioned annealing temperature range. Because the peak concentration is found at the surface with values as high as $3.2 \times 10^{20}\,cm^{-3}$, this process is ideal for the implementation of low resistance metal–semiconductor contacts.

The diffusion coefficient (D) for each source of boron has been calculated and it is plotted in Fig. 4, where the intrinsic boron diffusion coefficient (D_{i}) is used as reference. For example, D_{i} at 1000 °C is $1.5\times10^{-14}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$. From Fig. 4 it can be seen that the D value, calculated form the impurity profiles is larger than that of D_{i}, regardless of the temperature value. In the same Fig. 4 it can be seen that the slope of the SOD doping source and of the BF_2 implanted samples and RTP activated diffusion, are very different from that shown by D_{i}. The latter results in an estimated activation energy of ~2 eV for both boron sources. Therefore, it is suggested that the dominant mechanism on the enhancement of the D values is due to high concentration effect, rather than the defect concentration in the wafer. It is also important to note a very subtle change in the activation energy for annealing temperatures above 860 °C, which suggest that for temperatures equal or below 860 °C, there is a D value less than that at higher annealing temperatures. This suggests that annealing at such low temperatures will help in reaching shallower x_j values. Of course this is a more feasible solution for the SOD case, in which the lower temperature will just set the surface concentration, and there is not need of higher temperatures for the re-crystallization of the damage substrate by the II process.

4. Conclusions

It has been demonstrated that it is possible to obtain small x_j values by implanting heavy boron impurities, like BF_2, by means of RTP annealing and getting R_{s} values as low as 20 Ω/square. But the effective activation of the total number of impurities requires temperatures of the order of 1000 °C and above, which limits the smallest value of x_j to be obtained. On the other hand, the use of SOD as a doping source allows the use of temperatures as low as 780 °C with very high surface concentration. From the data here presented it is suggested that by using temperatures equal or less than 860 °C, it possible to reach x_j of the order of 30 nm with a surface concentration as high as $10^{19}\,\mathrm{cm}^{-3}$. Further work in understanding the main mechanisms which promote this behavior have to be performed to improve the realization of very shallow junctions.

References

[1] D.J. Frank, Practical CMOS scaling, in: D. Oda, B. Ferry (Eds.), Silicon Nanoelectcronics, CRC Press, Shunri, 2006.

[2] A. Bratschun, The application of rapid thermal processing technology to the manufacture of integrated circuits—an overview, J. Electron. Mater. 28 (12) (1999) 1328–1332.

[3] A.T. Fiory, K.K. Bourdelle, Thermal activation of shallow boron-ion implants, J. Electron. Mater. 28 (12) (1999) 1345–1352.

[4] A. Sultan, M. Craig, S. Banejee, S. List, T. Grider, V. McNeil, Effect of F on B penetration through gate oxide for BF_2 implants used to obtain ultra-shallow junctions by RTA, in: Proceedings of the 11th International Conference on Ion Implantation Technology, 1996, pp. 29–32.

[5] S.C. Jain, W. Schoenmaker, R. Lindsay, P.A. Stolk, S. Decoutere, M. Willander, et al., Transient enhanced diffusion of boron in Si, J. Appl. Phys. 91 (11) (2002) 8919–8941.

[6] D.J. Eaglesham, P.A. Stolk, H.J. Gossmann, J.M. Poate, Implantation and transient B diffusion in Si: the source of the interstitials, Appl. Phys. Lett. 65 (18) (1994) 2305–2307.

[7] K.S. Jones, L.H. Zhang, V. Krishnamoorthy, M. Law, D.S. Simons, P. Chi, et al., Diffusion of ion implanted boron in pre-amorphized silicon, Appl. Phys. Lett. 68 (18) (1996) 2672–2674.

[8] G. Mannino, N.E.B. Cowern, F. Roozeboom, J.G.M. van Berkum, Role of self- and boron-interstitial clusters in transient enhanced diffusion in silicon, Appl. Phys. Lett. 76 (7) (2000) 855–857.

[9] S. Prussin, D.I. Margolese, R.N. Tauber, Formation of amorphous layers by ion implantation, J. Appl. Phys. 57 (2) (1985) 180–185.

[10] S. Mirabella, E. Bruno, F. Priolo, D. De Salvador, E. Napolitani, A.V. Drigo, et al., Dissolution kinetics of boron-interstitial clusters in silicon, Appl. Phys. Lett. 83 (4) (2003) 680–682.

[11] N.T. Nguyen, Spin-On Glass Materials and Applications in Advanced IC Technologies, Thesis, Universiteit Twente, Vietnam, 1970.

[12] FILMTRONICS Semiconductor Process Materials, SPIN-ON DIFFUSANTS, Catalog, July 2004.