Deep Trench Doping by Plasma Immersion Ion Implantation in Silicon

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Abstract. The realization of three dimensional (3D) device structures remains a great challenge in microelectronics. One of the main technological breakthroughs for such devices is the ability to control dopant implantation along silicon trench sidewalls. Plasma Immersion Ion Implantation (PIII) has shown its wide efficiency for specific doping processing in semiconductor applications. In this work, we propose to study the capability of PIII method for large scale silicon trench doping. Ultra deep trenches with high aspect ratio were etched on 6" N type Si wafers. Wafers were then implanted with a PIII Pulsion system using BF_3 gas source at various pressures and energies. The obtained results evidence that PIII can be used and are of grateful help to define optimized processing conditions to uniformly dope silicon trench sidewalls through the wafers.

Keywords: Plasma Immersion Ion Implantation, deep trench, BF_3 doping, silicon
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INTRODUCTION

Plasma Immersion Ion Implantation (PIII) becomes key equipment for several microelectronic application developments [1]. Indeed, its benefits have been already demonstrated in Ultra Shallow Junction (USJ) formation [2], Silicon-On-Insulator (SOI) fabrication [3] or in other applications such as solar devices [4]. Among the various possible applications, trench doping using PIII technique has been intensively investigated during the last 15 years. Hence, the dimension reduction requested by the Semiconductor Industry Association (SIA) roadmap [5] has led to a large development of trench USJ based devices. In such a case, the trenches exhibit generally only submicron dimensions at the surface when the aspect ratio could reach up to 35:1. First research in this field led by B. Mizuno et al. [6] gave to PIII a great interest for micro trenches implantation. Later, other attractive results were reported on the sidewall doping for DRAM application and also confirmed the potentiality of PIII for efficient conformal trench doping [7, 8].

In the last few years, Deep Reactive Ion Etching (DRIE) has also demonstrated large progresses enabling to obtain very deep trenches in Silicon. The trenches may today cross an entire wafer with extremely sharp sidewalls. The combination of these two plasma techniques (PIII and DRIE) may lead to a new generation of applications going to real 3D devices. The first breakthrough requested to obtain such devices is the ability to dope trenches. Depending on the expected applications, the trench doping may be conformal or localized. Moreover, the scale of the designed trenches is here much larger than the one studied generally in the literature. X.Y. Qian et al. [9] already demonstrated that structures made of Si slices (0.5 mm wide and 12.5 mm deep), simulating a very large trench, can be doped by PIII. These interesting results enlighten that PIII is certainly usable for deep trench doping.

The goal of this work is to evaluate the capability of PIII method to dope large scale silicon trenches. After presenting the realization of ultra deep trenches with high aspect ratio on 6" Si wafers, we will shortly introduce the PIII Pulsion system developed by IBS as well as the implantations conditions that were performed. Through measurements such as cross-sectional observations, we will evidence the trench sidewall doping observed after annealing depending on plasma conditions.

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EXPERIMENTS

Sample preparation

For these experiments, bulk N-type <100> 5-10 Ω.cm 300 µm thick Si wafers were used. A 1.2 µm thick oxide was first thermally grown (wet conditions) on the wafers. The oxide was then patterned by a plasma dry etching. The remaining photoresist was removed using O_2 plasma. Subsequently, a DRIE stage was performed to obtain deep trenches. The deep etching of Si was operated in an ADIXEN AMS 200 reactor with $SF_6/C_4F_8/O_2$ plasma gas. Trench morphology varied with apertures going from 30 µm to 56 µm wide and 200 µm to 250 µm deep. The targeted aspect ratio for the used plasma conditions was around 5:1. In figure 1, we presented the optical image of the trench morphology that is obtained after plasma etching of silicon in defined conditions. It can observed that sidewalls are extremely sharp and that the trench depth is perfectly regular.

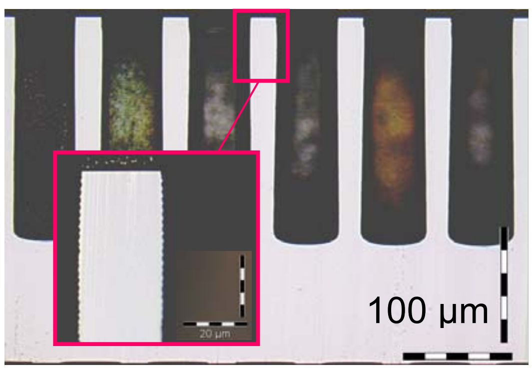

FIGURE 1. Trench morphology after plasma etching of silicon

To dope the so-formed trench sidewalls, PIII was performed using BF_3 as doping gas varying energy and process pressure conditions in the PULSION system developed by IBS. The system is presented in the next section. For all the conditions, Si plain wafers were implanted at the same time to serve as reference sample for the implanted dose. The reference samples were analyzed using spreading resistance profiling (SRP) measurements. Samples were then furnace annealed (FA) at high temperature (>1000°C) for several hours in nitrogen ambiance, leading to deep diffusion. Such annealing will allow sufficient dopant diffusion in order to obtain well-defined observations and measurements on trench sidewalls. Nitrogen environment was used during annealing in order to avoid silicon oxidation. Oxide thickness, measured by ellipsometry after annealing, had never exceeded 5nm.

PIII system and process description

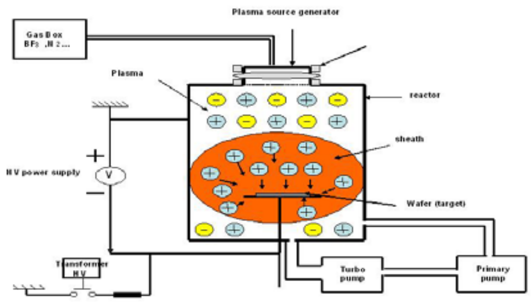

FIGURE 2. Schematic of the PIII PULSION system

In this section, plasma implantation, carried out in a PIII PULSION reactor developed by IBS [4], is described. The system has been designed to be versatile although it is generally used for USJ formation. Figure 2 presents a schematic of the PIII PULSION® system. In this work, we proposed to evaluate the capability of this technology to dope silicon trench sidewalls. For this purpose, first experiments were done using BF_3 gas at various pressures in the range 2.10^{-4} – $3.2.10^{-2}$ mbar. Silicon samples were negatively biased from 2 to 10 kV, plasma was pulsed. For all samples, the dose was adjusted at 10^{16} cm^{-2}. This dose was chosen in order to obtain a sufficient remaining dose along trench sidewalls assuming that dose at the wafer surface was probably higher that the one implanted in the trench.

Characterization methods

For this work, the measurements that enable to evaluate doping on these structures are extremely few and mainly related to staining techniques, allowing only qualitative information. Moreover, the quality of sample preparation for such measurements is crucial. Indeed, on the contrary to small trench analysis, a simple cleavage does not provide good surface topography for precise measurements. Only a meticulous sample preparation, comparable to SCM (Scanning Capacitance Measurement) one, allows to characterize the doping layer formed on the trench sidewalls. Samples were studied in both plan view and cross-section preparation. Figure 1 shows trench morphology after polishing where surface is extremely smooth. The preparation enables to visualize the roughness defaults created by the silicon plasma etching process, evidencing that the internal sidewall surface is not damaged by the polishing step. Scalloping phenomenon due to the consecutive etching and passivating steps is at the origin of the periodical little spikes (<1 µm) along the etched sidewalls.

The implantation of Boron in N-type Si indubitably leads to (p^+/n) junction formation. The junction depth can then be determined using staining techniques. For this purpose two techniques were used. First, samples can be immersed in a Sirtl etch solution. By preferentially etching P type doped regions, junction depth measurement is possible. Moreover, copper sulfate solution is then used to confirm our measurements. Indeed, with an appropriate illumination when dipped in a $CuSO_4$ solution, copper ions are reduced in Cu metal and specifically plated on the N-type silicon while the P region remained without copper. A precise measurement of the metallurgical junction is then observed, done by simple optical microscopy. As mentioned in previous section, such annealing will allow sufficient dopant diffusion in order to obtain well-defined observations and measurements on trench sidewalls.

Other requested information concerns the measurement implanted dose during PIII process. An evaluation of this dose, using SRP measurements in the reference sample after an annealing step, is also presented.

RESULTS AND DISCUSSION

As mentioned in the introduction, the trench doping may be influenced by the dimension of the trenches that here are almost crossing the entire wafer. In these first experiments, we have focused on 56 µm wide and 200 µm deep trenches. In figure 3, we present typical micrographs obtained after trench junction staining for the following plasma conditions: BF_3 gas flow at 9 sccm for a chamber pressure of 2.10^{-4}mbar and negatively biased sample at 5 kV. The annealing condition in this particular case was 1100°C for 18h. A visible (p+/n) junction is clearly formed along the trench sidewalls after staining. The P doped region delineation has been obtained with copper sulfate dipping and a direct illumination of the junction for 30 secondes. At first order, the doping is conformal all over the trench sidewall. This result is consistent with the observations already done on micron and submicron trenches [1,7,8] and tended to prove that the PIII technique may be generalized in trench doping.

In this work, the shallow junction depths compared to the trench dimension require to perform deep dopant diffusion for accurate observations. For such annealing condition, optical microscopy was sufficient to measure junction depth. A 3 µm deep junction was measured along vertical sidewalls. The trench bottom exhibits a slightly deeper junction of 4.5 to 5 µm. All these observations and measurements were confirmed using Sirtl etch.

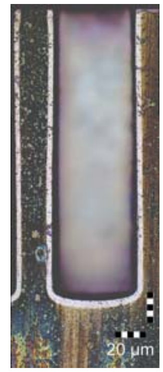

FIGURE 3. Junction staining on a conformaly doped 200 µm deep trenches

The observed junction variations between trench walls and trench bottom can be explained by the angular distribution of incoming ions as proposed by X.Y. Qian [9]. When negatively biased, silicon substrate becomes target for plasma positively charged ions. The formed plasma sheath in our conditions, despite on the large scale of trench, is supposed to be wider than the trench top opening. Consequently, ions are perpendicularly accelerated to the wafer surface, and anisotropic ion implantation happens. If ion angular distribution is probably the main doping source of vertical sidewall, the trench bottom is highly exposed to direct ion implantation and tends to receive the main dose of accelerated ions. This ratio between vertical and horizontal implanted dose is directly proportional to implant energy. In this condition, high energy implantation will certainly reduce angle distribution while low energy will increase it.

At this point of the study, it is important to notice that no specific variation of junction depth was observed depending of the pressure range studied [2.10^{-4} – $3.2.10^{-2}$mbar] or gas flow (3 to 9sccm) when low negatively biased. This result is in agreement with our expectations. On the contrary, noticeable changes should be found when increasing DC bias, i.e. ion acceleration energy probably combined with high pressure conditions. In order to verify this point, an experiment was set up using these conditions, i.e. high energy at high pressure. With such plasma conditions, the ion density is expected to be important but the ion angular distribution due to scattering is largely reduced compared to the low energy case. After plasma implantation, different annealing conditions were held. Figure 4 shows micrograph obtained after Sirtl etch for a plasma implantation using chamber pressure of 3.10^{-2} mbar and a negatively biased sample at 10kV further annealed for 18h at 1100°C under nitrogen ambient. As expected, only the trench bottom appears to be doped.

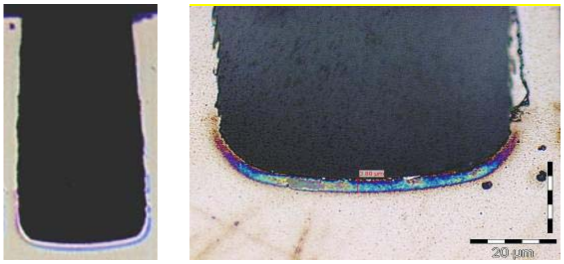

FIGURE 4. Sirtl etch sample for a plasma implantation (3.10^{-2} mbar, biased sample at 10kV) annealed for 18h at 1100°C under nitrogen ambient

The phenomenon, already observed for small trench features, is here increased as no doping is observed on vertical sidewalls. The whole ion dose seemed to be located at the bottom of the trench.

This observation is confirmed and even enhanced using higher temperature conditions. Indeed, annealing at 1280°C for 12h under nitrogen atmosphere has created an extremely deep diffusion at the trench bottom as presented in Figure 5. This result evidences that a local ion implantation can be obtained using specific conditions while vertical sidewalls remain visibly unaffected by the PIII process. Another important point to remind is that silicon trench profile may also greatly impact implantation efficiency.

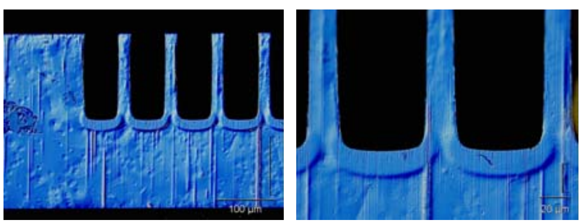

FIGURE 5. Localized doping on trench bottom after long time high temperature annealing

Finally, it is important to evaluate the dopant dose obtained in such conditions. In figure 6, we present a typical SRP profile obtained for a reference sample after an annealing of 5h at 1000°C. The SRP measured dose is only $\sim 10^{15}$ cm^{-2}. Several assumptions can explain this observation such as dopant out diffusion during annealing, already observed in similar conditions or sputtering effects at low energy implantation, which tend to saturate the implanted dose. However, measured dose in the plasma system itself can drift by a factor up to 10 as the implantation current is composed of multiple charges and various elements. The encouraging result is that a high dose remains in the sample to form p^+/n junction in such annealing conditions.

CONCLUSION

Recent progresses in both DRIE and PIII processes has open a way to a new generation of applications going to real 3D devices. In this work, we enlighten that PIII treatment followed by furnace annealing can be suitable for conformal doping of vertical silicon trench sidewalls. Nevertheless, unsuited plasma conditions may lead to localize dopant at the trench bottom. By controlling plasma conditions and silicon trench morphology, PIII has a great potential efficiency as a future doping technology for complex shape doping even for large scale structures

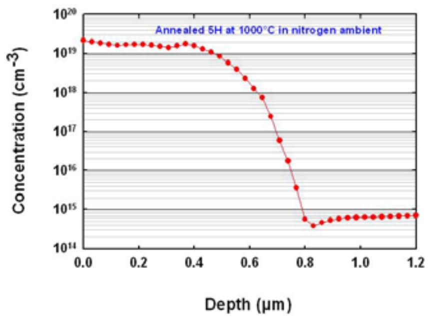

FIGURE 6. Typical SRP profile obtained after a 1000°C /5h annealing for a reference sample

REFERENCES

[1] P. K. Chu, "Semiconductor application of Plasma Immersion Ion Implantation", Plasma Phys. Control. Fusion 45 (2003), 555-570

[2] D. Lenoble and A. Grouillet, "The fabrication of advanced transistors with plasma doping", Surface and Coatings Technology Volume 156, (2002) 262-266

[3] P.K. Chu et al. "Instrumental and process considerations for fabrication of silicon-on-insulator (SOI) with Plasma Immersion Ion Implantation", IEEE Trans. Plasma Sci. 26 (1998) 79

[4]F. Torregrosa et al. " Realization of ultra shallow junctions by PIII, application to solar cells.", VIIth international workshop on Plasma Based Ion Implantation (PBII-2003), San Antonio, USA, 16-19 Sept. 2003.

[5] Semiconductor Industry Association, The International Technology Roadmap for Semiconductors, Front end processes, January 2005, 1-20

[6] B. Mizuno et al."New doping method for subhalf micron trench sidewalls by using an electron cyclotron resonance plasma", Appl. Phys. Lett. 53 (21), 21 November 1988.

[7] K. Lee, "Plasma Immersion Ion Implantation as an Alternative Doping Technology for ULSI" International workshop on Junction technology, 2001

[8] Crid Yu and Nathan W. Cheung, "Trench Doping Conformality by Plasma Immersion Ion Implantation (PIII)" IEEE Electron Device Letters, Vol. 15, No. 6, June 1994.

[9] X. Y. Qian et al., "Conformal implantation for trench doping with plasma immersion ion implantation", Nuclear Instruments and Methods in Physics Research B55 (1991) 898 - 901