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Plasma Immersion Ion Implantation for Electronic Materials Applications

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ABSTRACT

Plasma immersion ion implantation (PIII) is an emerging technology which promises high dose-rate implantation and compatibility for large-area processing. Innovations of this techniques include: implantation time independent of implantation area, capability to perform concomitant deposition and implantation, and simplicity of machine design and maintenance. This review summarizes the current understanding of PIII plasma dynamics and electronic materials applications such as plasma doping for ultra-shallow junctions and high aspect ratio Si trenches, selective plating of metals, damage induced impurities gettering, and subsurface material synthesis of silicon-on-insulator.

I. Principle of PIII

The physical principle of plasma immersion ion implantation is illustrated in Figure 1. By immersing a negatively biased target inside a plasma, electrons will be repelled away near the target surface and a "sheath" of positive ions will be established. The positive ions inside the sheath region will be attracted by the negative target potential and gathers kinetic energy while traversing the sheath. Replenishment of the positive ions is provided by the bulk plasma vias a diffusion mechanism through the boundary of the sheath where the ions propagate at the Bohm velocity, ($\approx 10^5$ cm/sec). With efficient remote plasma sources (e.g., ECR or ICP) to maintain the high ion density ($\sim 10^{11}$/cm^3) , one can easily obtain a high ion flux of 10^{16}/ cm^2 -sec and the sheath thickness can be kept below 10 cm even with a bias of 100 kV. Typical gas pressures of 0.1-10 mTorr are used to minimize collisional scattering between the accelerating ions and the neutral atoms [1,2]. To avoid dielectric breakdown or thin-oxide stressing, a pulse waveform is necessary to capacitively couple the applied bias to the surface potential for wafers containing insulating layers. Modeling and experimental work have verified that thin-oxide charging effects is small if the pulsing frequency is kept below several kHz [3].

Sine the PIII technique does not involve ion mass separation, the plasma feed gas and ionization have to be properly chosen for each specific application. The reactor wall also has to be constructed with clean materials (e.g. quartz) to avoid contamination. However, having both high implantation rate and with the implantation time independent of implant area are very attractive as a production tool. In addition, the simple design of such machines leads to lower production cost when compared with conventional beam-line implanters.
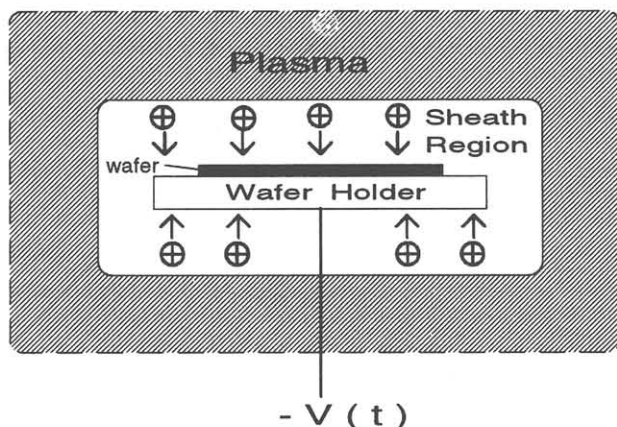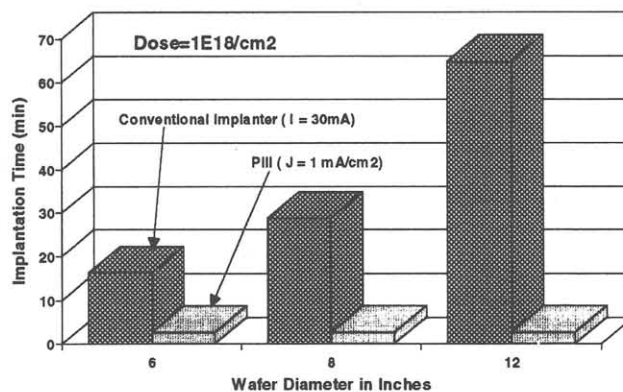

Fig.1 Principle of Plasma Immersion Implantation

Fig. 2 A nominal PIII ion current density of 1 mA/cm^2 outperforms a high current (30 mA) beamline implanter

Figures 2 illustrates the advantage of using PIII when we increase the wafer size from 6 inches to 12 inches for Si processing. To achieve an implant dose of 10^{18}/ cm^2 (e.g., SIMOX) and using the typical limit of high current conventional implanters (≈ 30 mA) , PIII can outperform the throughput by 10X for 6-inch wafers and gains another 4X when we move towards 12-inch wafers. Figure 3 shows the cluster-tool compatible design of a prototype machine developed at the University of California at Berkeley with a footprint of about 60×36 inches [4]. The maximum acceleration voltage such a reactor can sustain is about 100 kV.
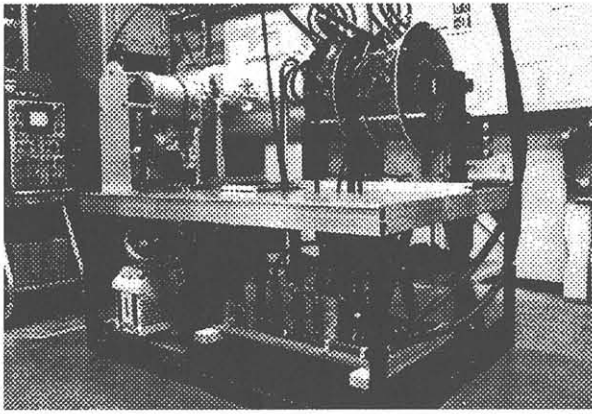
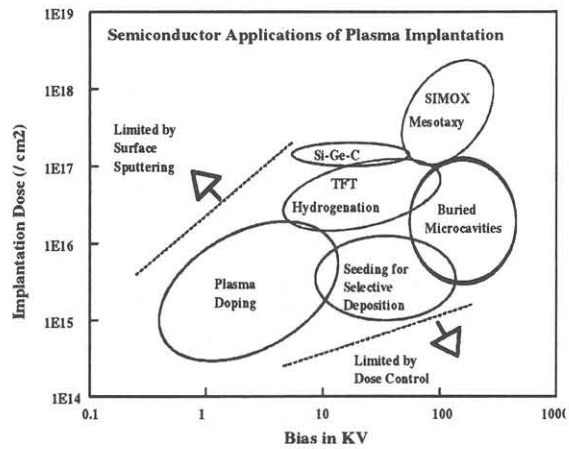Fig. 3 The Berkeley PIII reactor with ECR plasma.

Fig. 4 Demonstrated applications of PIII for semiconductor processing

II. Applications of PIII

Recent success of PIII in electronic materials processing are summarized in the dose-energy "phase-space" denoted by Figure 4 [5,6]. Plasma doping in the low dose/low energy regime is attractive for large-area Si wafer doping and TFT flat panel displays. These applications require high dose-rate but non-critical as-implanted profiles. For example, the final junction depth of sub-100nm p+/n junctions depends more on the post-annealing thermal cycle than the as-implanted depth profile[7,8]. Doping of poly-Si or silicides and hydrogenation of poly-Si thin-film transistors share similar requirements [9] . PIII is well suited for these predeposition applications although the implanted species consist of non-monoenergetic and multiply charged ion components. Using PIII, selective electroless plating of copper interconnects in SiO_2 trenches by Pd and Pd/Si seeding has been reported [10]. Backside gettering of metallic impurities in Si wafers were shown successful using Ar plasma [11]. In the high-dose regime where PIII excels, subsurface material synthesis such as SIMOX[12] , Si-Ge alloying [13], and microcavity formation have also been demonstrated. It should be noted that in the low energy regime (~ 1 kV) , dose incorporation in the substrate is limited by surface sputtering . In the high energy regime, the dose rate becomes so high that a reproducible control for low-dose implants may not be practical. Details of these applications can be found in various publications listed in the reference section. The following discussion will highlight plasma doping and SIMOX synthesis as examples of low-dose and high-dose applications respectively.

a) Ultra-Shallow Junction Formation

Ultra-shallow p+/n junctions can be formed by PIII using a two-step implant: a heavy ion (F or Si) is implanted into crystalline Si substrate to form an amorphous layer using SiF_4 plasma, followed by boron implantation with a BF_3 plasma [7]. These two steps can be performed sequentially without breaking vacuum. After implantation, secondary ion mass spectrometry (SIMS) profiling shows the PIII profiles peak slightly below the surface, followed by an exponential decrease of the implant depth profile. The amorphization step is used to reduce boron channeling and to retard the rapid boron diffusion during the dopant activation annealing thermal cycle. Using PIII for both pre-amorphization and doping, no end-of-range dislocation loops or stacking faults are detected after annealing (1060°C, 10sec). The fluorine concentration is also below the detection limit of SIMS after annealing. Similar defect-free results are also reported by Sheng et al using BF_3 PIII (-1 to -5 kV bias) but with two-step rapid thermal annealing (800°C for 5 sec and 1050°C for 10 sec)[8]. Sub-100nm p+/n junctions fabricated by PIII show diode ideality factor of 1.05 and bulk leakage current density about 2nA/cm^2 at -5V [7].

b) Microscopic Conformal Doping of Trench Sidewalls

With PIII operating at higher gas pressures (several mTorr), the slight beam divergence due to ion-neutral collisions can enhance microscopic conformal doping of nonplanar device structures (e.g., sidewalls of trenches). Sidewall doping is accomplished by both direct implantation and reflected implantation. The first Si trench doping was demonstrated by Mizuno et al using a bias of -700V for submicron wide trenches [14]. Further work using pulsed PIII have shown conformal doping of 1:12 aspect-ratio trenches (1 μm opening) using BF_3 PIII [15]. No beam shadowing effect was observed. At lower substrate bias, a higher fraction of the incoming ions is found with larger angular spread, creating less dopant at the bottom of the trenches.

c) SIMOX Synthesis

SIMOX stands for Separation by IMplantation of OXygen, where a high dose of oxygen ($> 2 \times 10^{17}/cm^2$) is implanted into a Si wafer followed by high-temperature annealing to create a buried oxide layer under a crystalline Si surface film. The work performed at UC-Berkeley has recently demonstrated this high-dose rate SIMOX synthesis using an oxygen plasma [12]. High voltages (>80 kV)can be maintained across the plasma sheath by using extremely low gas pressure (sub-mTorr). An oxygen dose of $3 \times 10^{17}/cm^2$ can be implanted within 3 minutes as compared with hours when compared with conventional ion implantation. Three different modes of SIMOX microstructures (oxide precipitates, single SIMOX and double SIMOX) were observed to be caused by the relative concentration of the O^+ and O_2^+ implantation profiles. Continuous buried oxide can only be obtained if the relative abundance of O_2^+ and O^+ is above 9:1. In Figure 5 , we show the XTEM micrograph of a continuous buried SiO_2 layer formed by the PIII synthesis method. The SIMOX structure was obtained by a 60kV oxygen plasma implant, followed by 1270 °C annealing. Double SIMOX (i.e., Si/ SiO_2/ Si/ SiO_2/ Si substrate) has also been demonstrated in a single implantation step by tuning the oxygen plasma to achieve an approximately 1:2 ratio of O_2^+: O^+ ion concentrations [Fig.6]
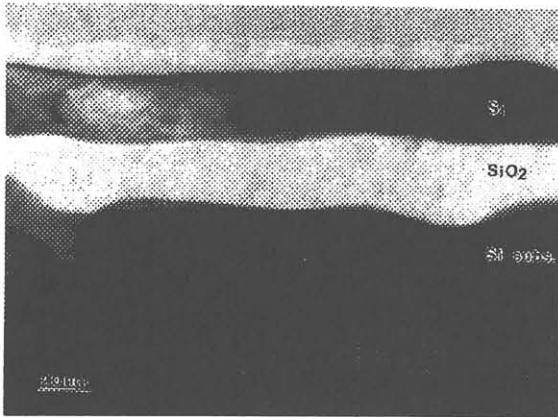

Fig. 5 XTEM micrograph of SIMOX structure using the PIII technique. The buried oxide is about 40nm thick under the 30nm thick Si layer.
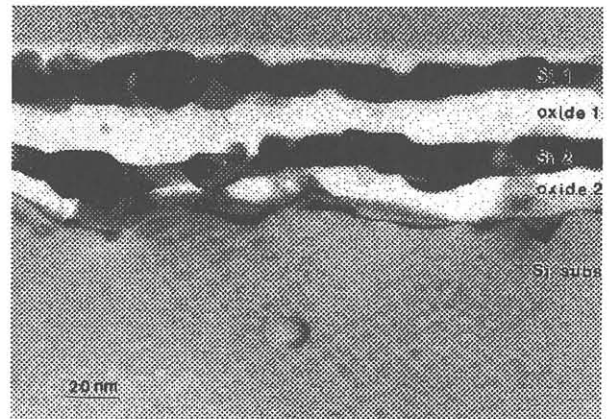

Fig. 6 XTEM micrograph of double SIMOX formed by PIII using a single implant from an oxygen plasma.

III. Summary

Using conventional implanters, high dose applications ($> 10^{16}/cm^2$) are often viewed by users as impractical due to the excess implantation time required. The emerging plasma implantation technology can break this bottleneck since it is a large-area technique that can have extremely high current density capability. The unique features of PIII provide a unique capability to investigate new areas of defect engineering, ion beam mixing, material synthesis, and large-area doping.

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